area of research of renormalization group techniques which are intimately related to limit theorems in probability theory[19].

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Diffusion and Scattering of Test Particles in a Turbulent Plasma

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A small-diameter, low-energy, test electron beam is injected along $\vec{B}_0$ into a collisionless plasma in which current-driven ion sound turbulence can be generated. The scattering of the test particles across $\vec{B}_0$ due to fluctuating fields $\vec{E}_w \perp \vec{B}_0$ gives a direct measure for the turbulent spatial diffusion coefficient $D_{e\perp}$. Investigation of the velocity-space diffusion shows strong pitch-angle scattering effects. No significant anomalous resistivity is observed.

Although ion sound turbulence has been studied by many authors[1] the direct interplay of particles and waves has rarely been observed directly. In this Letter we describe an experiment where test particles (electrons) are injected into a turbulent plasma and subsequently followed in real and velocity space. Diffusion coefficients and resistivity are obtained in a case where the turbulence spectrum $\omega(\vec{k})$ has been carefully analyzed. We show that Bohm-like diffusion arises from random $\vec{E}_w \times \vec{B}_0$ drifts due to perpendicular-wave electric fields, $\vec{E}_w$.

The experiment is performed in a large, magnetized, nearly collisionless discharge plasma[2] of parameters $n_e \simeq 10^9$ cm^{-3}, $T_e \simeq 10T_i \simeq 2$ eV, $B_0 \simeq 130$ G, $\nu_i/\omega_{pi} \simeq 10^{-3}$, Ar and He. As is schematically shown in Fig. 1(a), the uniformly magnetized plasma column is divided by a fine wire mesh into two regions: the experimental section in which a field-aligned current is drawn to an end anode, and the source region of higher density which supplies the electrons to maintain the current. Aside from the use of Langmuir probes and resonance cones, the diagnostics include movable rf probes to perform three-dimensional cross-correlation measurements, and a test electron-beam source which projects a low-energy (1–10 eV), low-density ($n_b/n_e \ll 1$), pencil beam (2 mm^2) along $\vec{B}_0$. In order to distinguish the test electrons from the background electrons the beam is weakly velocity modulated ($f_m \simeq 50$ kHz $\ll f_{pi}$) and resonantly detected, and its relative distribution is displayed versus probe voltage referenced to ground.

By drawing a field-aligned electron current to the end anode, ion acoustic waves are driven un-

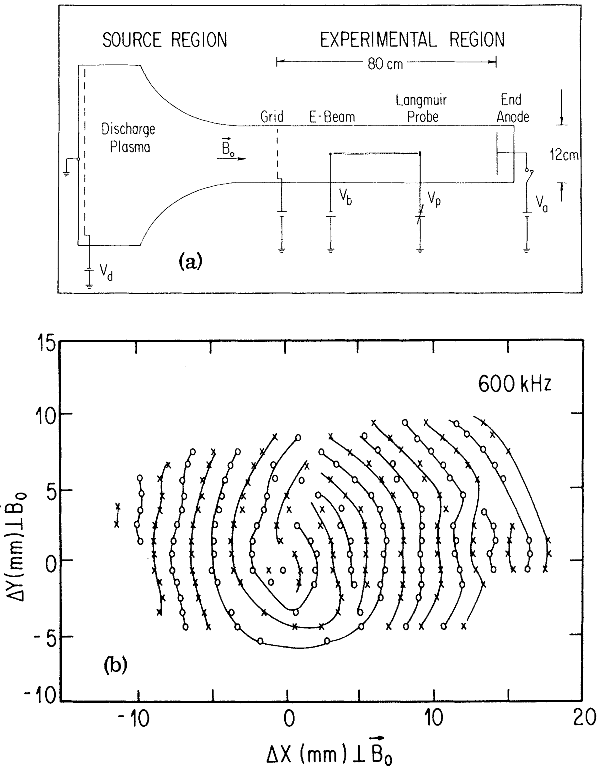

FIG. 1. (a) Schematic of the experimental setup. (b) Typical cross-power spectrum (phase contours) of unstable ion acoustic waves propagating nearly across $\vec{B}_0$ ($k_\parallel << k_\perp \simeq \omega/c_s$; $kr_{ce} < 1$; $kr_{ci} >> 1$). Ar, 2×10^{-4} Torr, $B_0 = 125$ G.

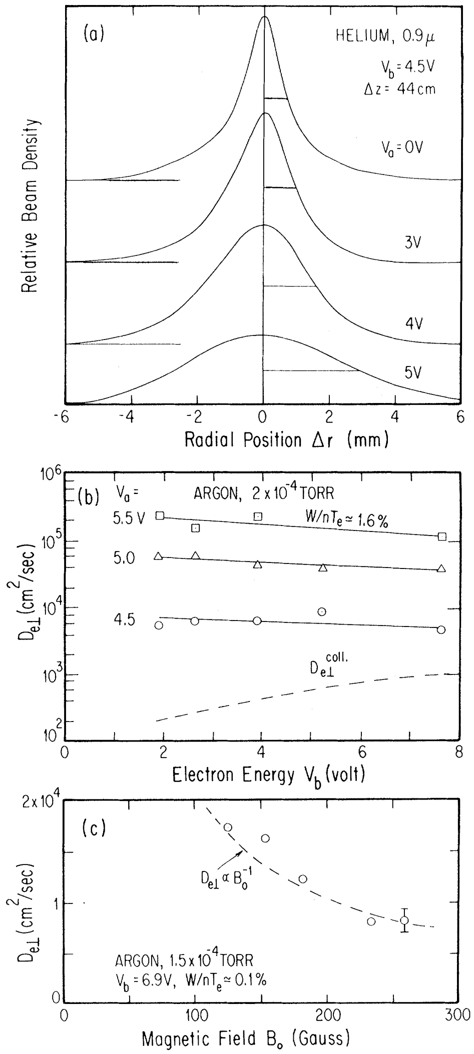

FIG. 2. (a) Radial profiles of the test electron beam at different end anode voltages V_a. Note beam spread across $\vec{B}_0$ with increasing level of turbulence. (b) Diffusion coefficient vs test-particle energy at different anode voltages. The diffusion is nonresonant and well above the classical value (dashed line). $B_0 = 125$ G, $T_b \simeq 0.8$ eV. (c) Diffusion coefficient vs magnetic field indicating Bohm-like scaling ($D_{e\perp} \propto B_0^{-1}$, dashed line).

stable ($c_s \ll v_d \lesssim 0.3 v_e$). The frequency spectrum of the observed density fluctuations extends throughout the ion acoustic branch with a relative maximum near $\omega/\omega_{pi} \simeq 0.8$ ($k\lambda_D \simeq 1.1$). The normalized wave-energy density is $W/nT_e \simeq (\delta n/n)^2 \lesssim 10^{-2}$, where $\delta n/n$ are the rms density fluctuations. The turbulence level can be varied with voltage V_a applied to the end anode. By measuring cross-power spectral intensity functions of two probe signals along three coordinates, the unstable waves are found to propagate for $\omega/\omega_{pi} \lesssim 0.8$ mainly at angles $\theta \simeq \arccos(c_s/v_d) \lesssim 90°$ with respect to $\vec{B}_0$, while for $\omega/\omega_{pi} \gtrsim 0.8$ propagation is mainly along $\vec{B}_0$. Figure 1(b) shows the phase contours of correlated waves at 600 kHz in a plane perpendicular to B_0, indicating a wide spread of k-vector directions in the perpendicular plane. The waves satisfy the dispersion relation $\omega = kc_s$ with $c_s \simeq 2\times 10^5$ cm/sec independently established by temperature measurements. Ion cyclotron effects are not important ($\omega \gg \omega_{ci} \simeq 2\pi \times 6$ kHz). The radial correlation length ($\Delta r_c \simeq 2$ cm) is small compared with the column diameter. Details of the turbulence analysis will be presented elsewhere.[3]

The test electron beam is injected along the column axis parallel to $\vec{v}_d$. Figure 2(a) shows radial beam profiles at a distance $\Delta z \simeq 44$ cm from the beam source for different anode voltages. With increasing turbulence level the beam radius increases from its minimum value $r \simeq r(0) \simeq 0.75$ mm to $r(z) \simeq 3$ mm. The beam spread lowers the peak flux but the total current, $I_b = 2\pi\int j(r) r\, dr$, is measured to be approximately conserved. The perpendicular diffusion coefficient is $D_{e\perp}=v_{\perp D}(n_b/\nabla_\perp n_b)$, where $n_b/\nabla_\perp n_b$ is the radial gradient scale length of the beam density and $v_{\perp D}$ is the diffusion velocity across $\vec{B}_0$ which is obtained from the increase in beam radius, $\Delta r = r(z) - r(0)$, and the axial transit time of the electrons, $t_\parallel \simeq \Delta z/v_\parallel$, according to $v_{\perp D}=v_\parallel(\Delta r/\Delta z)$. For 4.5-eV test particles at a turbulence level $W/nT_e \simeq 0.5\%$ ($V_a = 4$ V) we find $v_\perp \simeq 2.3\times10^5$ cm/sec, $n_b/\nabla_\perp n_b \simeq 3$ mm, hence $D_{e\perp}\simeq 7\times10^4$ cm^2/sec which is ~24 times larger than the classical diffusion coefficient $D_{e\perp}=\nu_{en} r_{ce}{}^2 = 2.86\times10^3$ cm^2/sec based upon dominant electron-neutral collisions[4] ($\nu_{e-n}\simeq 1.7\times10^6$ sec^{-1}).

Figure 2(b) shows that the enhanced diffusion is not restricted to a narrow group of resonant particles, but occurs over a wide energy range. Thus, the background electrons are expected to undergo the same diffusion process as the test particles and will then, on account of their slower parallel velocities, cross magnetic field lines for appreciable distances (~1 cm) during their lifetime in the device.

The dependence of the diffusion coefficient on magnetic field shown in Fig. 2(c) indicates Bohm-like diffusion ($D_{e\perp}\propto B_0{}^{-1}$).[5] Only a limited range of magnetic fields has been explored so as to maintain constant plasma parameters and turbulence level. It has been theoretically shown[6] that turbulent $\vec{E}_w\times\vec{B}_0$ drift leads to Bohm diffusion, and the present observation is in accord with this picture.

Associated with the enhanced transverse diffusion, one may expect an increase in the longitudinal resistivity.[7] We have therefore investigated the velocity-space diffusion of test particles along $\vec{B}_0$. Figure 3(a) shows the test-particle distribution at various levels of turbulence increasing with V_a. A pronounced shift ΔV_b of the peak of the distribution function as well as an increase in the half-width is observed. This is seen with the beam injected both with and against the background electron drift. The beam voltage change ΔV_b increases with axial distance from the source [Fig. 3(b)] but a fraction of ΔV_b originates near the emitter. The axial increase of the beam potential is found to be much larger than that of the background plasma potential. Although the latter cannot be established with high accuracy from the knee of the Langmuir-probe characteristics, axial changes of 1 to 2 V would have been noticeable beyond doubt. For example, at high pressures ($p \simeq 10$ mTorr) the axial ambipolar field $E_\parallel = (T_e/e)(n_e/\nabla_\parallel n_e) \simeq 25$ mV/cm has

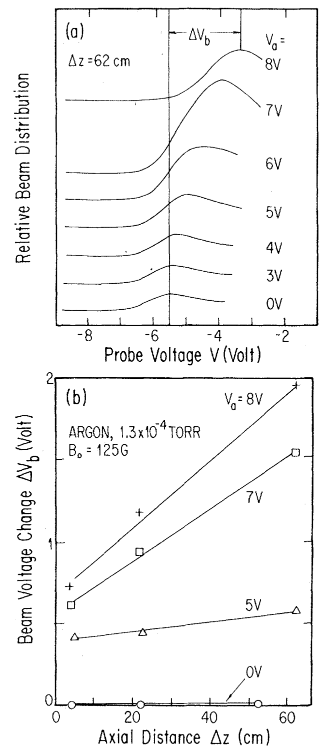

FIG. 3. (a) Test-particle distribution at different end anode voltages. Vertical line indicates beam voltage, $V_b = -5.5$ V. Note beam-voltage drop ΔV_b at increasing turbulence levels. (b) Beam voltage change vs axial distance from test-particle source indicating continuous slowing down of the test electrons within the turbulent plasma.

been measured readily. It should also be noted that electric-field measurements from gradients in the *floating* potential can be highly erroneous in discharge devices with energetic electrons.[8]

We interpret the potential shift and broadening of the beam distribution by a process of wave-particle scattering. The detected beam voltage reflects the *parallel* particle velocity, and its decrease ($\Delta V_b/V_b \simeq 10\%$) indicates a loss in parallel momentum $mv_\parallel$ or energy $mv_\parallel{}^2/2$. Electrons can only be scattered from short-wavelength modes ($k\lambda_D \simeq 1$, $\lambda_D \simeq r_{ce} \simeq 0.3$ mm), and these are observed in the spectrum with both $k_\parallel$ and $k_\perp$. Because of their random nature, waves superimpose to form localized potential spikes with which electrons collide and acquire $v_\perp$ at the expense of $v_\parallel$. The electron energy is approximately conserved since the total wave energy amounts to only $W \simeq 10^{-2} nT_e$; i.e., the waves could not have absorbed the parallel electron energy loss $\Delta eV_b \simeq 1$ eV. While a direct measurement of the perpendicular test-electron energy proved too difficult, we could, however, verify the increase in $T_{e\perp}$ of the background electrons using a plane probe with surface normal $\vec{n} \perp \vec{B}_0$. This observation confirms the electron diffusion in velocity space which has to be distinguished from the diffusion in real space by $\vec{E} \times \vec{B}$ drifts. In the latter process the electron velocity changes negligibly ($E/B \ll v_{\parallel}, v_{\perp}$); in the former process the increase in Larmor radius and collisions cannot account for the observed strong cross-field motion.

From the above observations one can also draw some conclusions on parallel fields and anomalous resistivity. First, there is a negligibly small dc electric field ($E_{\parallel} < 10$ mV/cm). Thus, energy dissipation is negligible ($j \cdot E < 3 \times 10^{-5}$ W/cm$^3 \ll nT_e/\tau_e$), and whatever electron heating is observed ($\Delta T_e/T_e \simeq 1$) arises from randomization of the predominantly parallel injection velocity acquired from the potential drop at the grid. No runaway electrons are observed or expected with $E_{\parallel} < 10$ mV/cm. Second, the standard expression for the effective collision frequently of ion sound turbulence in unmagnetized plasmas,[9] $\nu^* = \omega_{pe} W/(nT_e) \simeq 2 \times 10^7$ sec^{-1}, leads to an overestimate of the anomalous resistivity $\eta = m\nu^*/(ne^2) \simeq 70$ Ω cm and associated parallel fields $E_{\parallel} = \eta j \simeq 190$ mV/cm. Finally, it should be noted that in spite of the axial velocity decrease the total current $I = Anev_d$ has to be conserved. This is accomplished by an increase in the cross section A due to enhanced diffusion.

In summary, we have presented direct observations of electron diffusion and pitch-angle scattering due to ion sound turbulence. The test-particle technique should be useful in other cases of turbulence in space and laboratory plasmas.

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