PLASMA TURBULENCE IN THE PRESENCE OF A DRIFT INSTABILITY

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Plasma turbulence and diffusion in the presence of a drift instability have been investigated in a potassium plasma at large oscillation amplitudes: $\tilde{n}/n \sim 1$. It is found that while the plasma is turbulent, the oscillations are not completely random. The phase correlation time is approximately 10 oscillation periods. The diffusion coefficient increases with increasing oscillation amplitude, reaching a value $D \sim 10^3$ cm^2/sec at $\tilde{n}/n \sim 1$ and $H \sim 1000$ Oe which is three orders of magnitude larger than the classical diffusion coefficient.

IN the present work we have investigated the turbulent state of a plasma [1,2] and diffusion across a magnetic field in the presence of the drift instability [3] for the case of high-oscillation amplitudes: $\tilde{n}/n \sim 1$ (n and $\tilde{n}$ are the plasma density and its fluctuating component respectively).

One expects that at these amplitudes the plasma will be highly turbulent. It turns out, however, that although the plasma is turbulent the oscillation phases are not completely random: the phase correlation time is approximately 10 periods. Diffusion across the magnetic field increases with amplitude. When $\tilde{n}/n \sim 1$ and $H = 1000$ Oe the diffusion coefficient is approximately three orders of magnitude greater than the classical value. Under these conditions the diffusion is convective in nature.

EXPERIMENTAL METHOD

These experiments have been carried out in a device [4] in which the plasma is produced by thermal ionization of potassium on a tungsten plate (ionizer) of radius $R = 2$ cm which is heated to a temperature of approximately 2000°K. A second plate located at a distance $L = 36$ cm from the first is not heated. The plasma density in this system has a maximum at the axis and falls off in the radial direction. Experiments have been carried out at plasma densities 10^9—10^{10} cm^{-3} and magnetic fields 600—3000 Oe.

The plasma density and oscillation amplitude are measured with Langmuir probes by observing the dc and ac components of the ion saturation current respectively.[5] The oscillation spectrum is investigated with a tuned amplifier IUU-300 (bandwidth approximately 1 kHz) and a S5-3 harmonic analyzer S5-3 (bandwidth approximately 200 Hz), which measure the effective amplitude.

In investigating the turbulent state of the plasma we measure the correlation function and perform a qualitative correlation analysis:[1,2,6] the analysis is carried out as follows. The signal from the probe (total signal or at a specified frequency) is applied to an oscilloscope which is operated in the free-running mode or in the single-sweep mode. In the former mode one can distinguish between regular signals and noise fluctuations and also determine qualitatively the phase correlation time. In the latter mode one can determine the time between significant changes in amplitude and phase, that is, the lifetime of the wave packets.[1]

The correlation function (CF) is measured by an automatic correlation device [2,7] which records the polarity-coincidence correlation function $F(\tau)$. The delay time can be varied from zero to 1200 μsec in steps of 12 μsec. The integration time is 500 msec. We note that the polarity coincidence correlation function $F(\tau)$ is connected with the conventional correlation function $\rho(\tau)$ by the relation $\rho(\tau) = -\cos 2\pi F(\tau)$.[2,8]

The diffusion coefficient is measured by determining the plasma flux across the magnetic field $(nv)_r$. The flux measuring device [5] is made up of two plates located at the edge of the plasma column; a potential is applied between the plates which is sufficient for complete separation of the electrons and ions. By knowing the radial density gradient $dn/dr \sim n_0/R$ (n_0 is the density at the axis) one can compute the diffusion coefficient

$$D = (nv)_r/(dn/dr).$$

The diffusion coefficient can also be estimated from the longitudinal density gradient.[2] Assuming that the longitudinal drift velocity of the plasma is constant over the cross section and over the length of the plasma column and that this drift velocity is equal to the ion-thermal velocity v_i, we find

$$D = \frac{\alpha R}{2} v_i \frac{dn/dz}{dn/dr},$$

where $\alpha < 1$ is a numerical factor that takes account of the radial density distribution.

EXPERIMENTAL RESULTS

1. It has been shown earlier on the same apparatus [3] that the inhomogeneous plasma is unstable against the drift instability even in the absence of electric fields and currents. The instability is manifest in the excitation of azimuthal waves which have a longitudinal component. The wave is standing in the axial direction and traveling in the azimuthal direction, and the wavelengths of the various harmonics are multiples of the circumference of the plasma cylinder. The waves are potential, that is to say, $\tilde{n}/n \approx e\tilde{\varphi}/T$.[5]

In [3], in which the investigations were carried out in a system with two hot plates, the instability was observed with ion and electron sheaths at the surface of the ionizer. However, in these experiments, the amplitude of the oscillations could not be controlled. It was found that in the transition to the electron-sheath mode, the amplitude of the oscillations was reduced. When working with a single cold plate, in the transition to the electron-sheath mode the instability is damped. The origin of the damping mechanism is evidently the short circuiting of the azimuthal perturbations by virtue of the Simon short-circuit effect.[9]

In the presence of an ion sheath, the amplitude grows and reaches a value $\tilde{n}/n \sim 1$ for a sufficiently strong ion sheath. It should be kept in mind that in the transition to the ion-sheath mode one observes the excitation of oscillations that occupy simultaneously a broad spectrum in which both the discrete lines and noise at intermediate frequencies can be seen (Fig. 1). Thus, it can be said that the turbulent state of the plasma does not develop as a consequence of the successive excitation of the degrees of freedom of the system and the interaction of harmonics [10], but rather as a result of the growth of initial fluctuations over the entire spectral region in which the instability can be excited. This conclusion is in agreement with the theoretical results [11–13], which have shown that on approaching the instability boundary the fluctuations grow without limit (in the linear theory).

2. The following questions had to be clarified in the investigation of the plasma state with fully

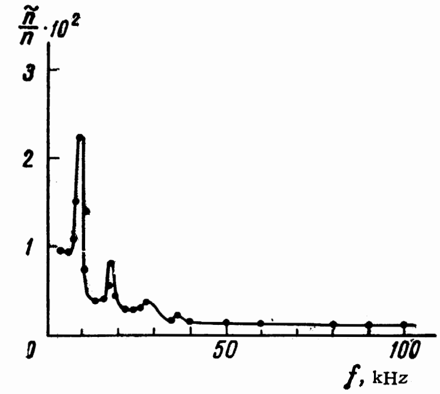

FIG. 1. Oscillation spectrum for low amplitudes. H = 1000 Oe, n = 6 × 10^9 cm^{-3}, $\tilde{n}/n \sim 0.1$.

developed instabilities. If the plasma is not turbulent but the oscillations represent a stationary wave one should observe a regular pattern which is maintained in time. In the case of the turbulent state the oscillations exhibit a noise-like nature. In this case the weakly turbulent state is characterized by the fact that the wave interaction is small. As a result, each frequency corresponds to a single wave number k (the spectral density function is a δ-function) [14] and the lifetime of the wave packets is large compared with the oscillation period.[1)] Thus, the correlation of the phase of a given point is maintained for a large number of periods. The distance over which the phase correlation is maintained is large compared with the wavelength.

In the transition to the highly turbulent state the wave interaction increases and the lifetime is reduced, becoming comparable with the oscillation period and leading to a spread with respect to k of the spectral density function, that is to say, each value of ω now corresponds to a number of values of k. In this case the correlation lifetime at a given point is small, as is the distance over which the phase correlation is maintained.

The plasma state under conditions of low-amplitude oscillations (fundamental frequency $\tilde{n}/n \sim 10^{-2}$ and total signal $\tilde{n}/n \sim 0.1$) has been investigated earlier.[6] It was shown that the plasma is weakly turbulent and that the oscillations at the harmonic frequencies are approximately coherent and the intermediate frequencies are random. In the present work we have measured the lifetime by determining the total signal and the fundamental frequency. It is found that the har-

1)We note that the notion of a weakly turbulent state required in the theory, in contrast to the present case, exhibits complete randomization of the phases.

monics are not completely coherent but are characterized by long lifetimes, at least 50–60 cycles long.

When the oscillation amplitude is increased the lifetime is reduced. A typical oscillation spectrum characteristic of large amplitudes is shown in Fig. 2. It is evident that the amplitude of the fundamental reaches $\tilde{n}/n \sim 0.25$ and that under these conditions the total signal $\tilde{n}/n \sim 0.5$–0.6.

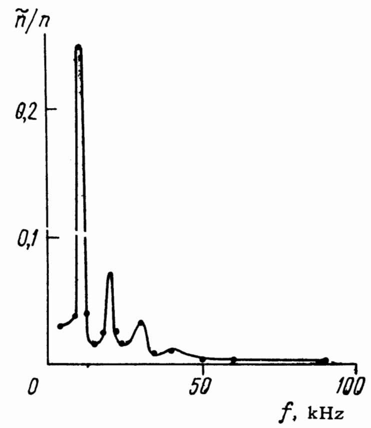

FIG. 2. Oscillation spectrum for large amplitudes. H = 1000 Oe, $n = 4 \times 10^9\ cm^{-3}$, $\tilde{n}/n \sim 0.5$.

We recall that the effective amplitude is measured. The true amplitude can be obtained from the oscillograms of the density oscillations shown in Fig. 3 (free-running sweep). It is evident that the density falls almost completely to zero so that the amplitude of the oscillations is characterized by $\tilde{n}/n \sim 1$. We note that the oscillation frequency in the total signal coincides with the fundamental frequency.

We note modulation of the oscillations in the upper portion of the spectrum at the frequency of the total signal (Fig. 4). Under these conditions the amplitude of the high frequencies is a maximum in the region of phase of the maximum density, whence we conclude that these oscillations are concentrated in a "plasmoid" corresponding to the fundamental.

It is evident from the oscillograms (Fig. 3) that the oscillations are noise-like and that the phase is randomized in 6–7 periods.

In Fig. 5 we show an oscillogram taken under single-sweep conditions. The discontinuities in the phase are clearly evident. The mean value of the lifetime is approximately 10 cycles. We note that after a break in the phase the amplitude of the oscillations increases to its maximum value

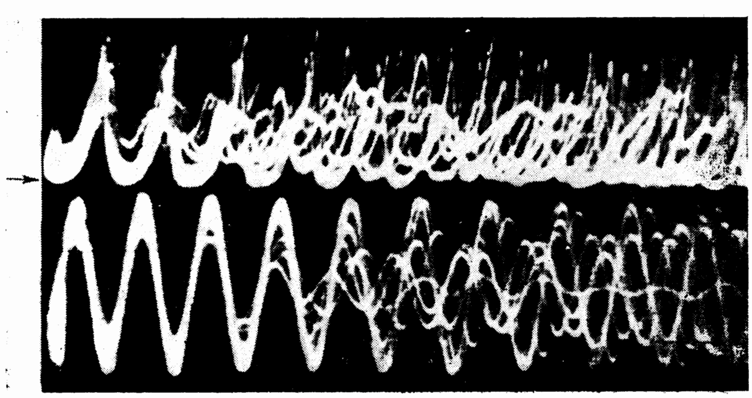

FIG. 3. Density oscillations (free-running sweep). The upper pattern is the total signal (the arrow indicates the zero level) and the lower pattern shows the oscillations of the fundamental frequency. H = 1000 Oe, $n = 3 \times 10^9\ cm^{-3}$.

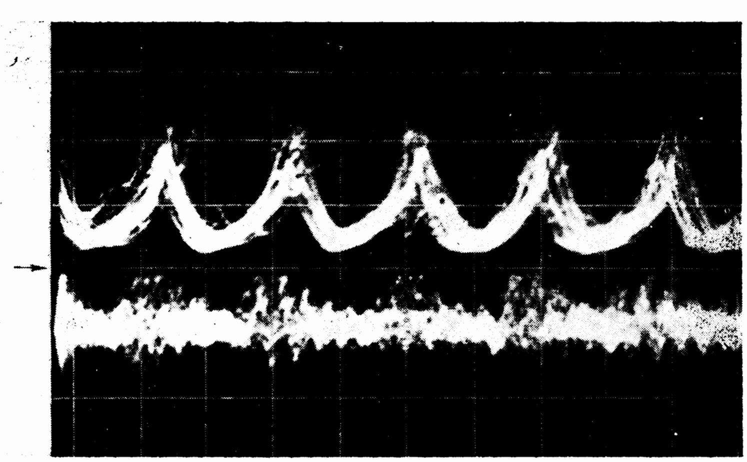

FIG. 4. Modulation of the oscillations in the upper region of the spectrum. The upper curve is the density oscillations (total signal); the lower curve is the signal from the plasma as passed through a selective amplifier with a band pass of approximately 20 kHz tuned to the frequency f = 90 kHz. H = 1000 Oe, $n = 3 \times 10^9\ cm^{-3}$.

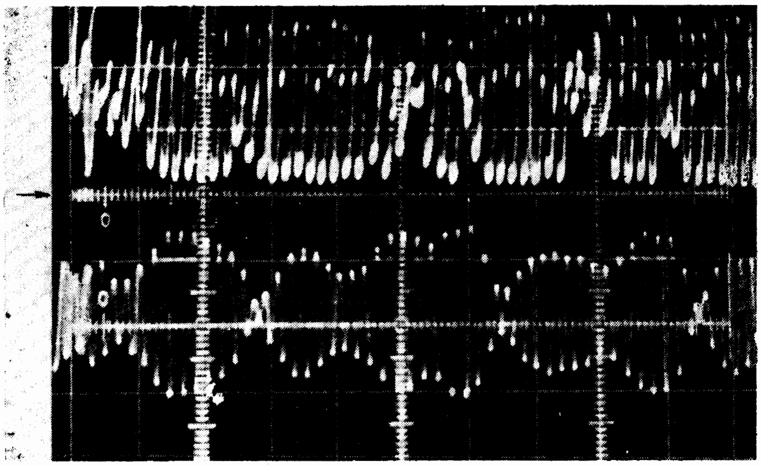

FIG. 5. Density oscillations (single sweep). The upper curve shows the total signal (the arrow indicates the zero level) and the lower curve shows the oscillations at the fundamental frequency. H = 1000 Oe, n = 3×10^3 cm^{-3}.

in several (3—4) cycles whence we conclude that the growth rate of the instability is comparable with the frequency ($\gamma \sim \omega$).

In Fig. 6 we show the autocorrelation function for the density oscillations. Along the ordinate scale for the autocorrelation is plotted the amplitude of the autocorrelation function of a sinusoidal signal. It is evident that the amplitude of the autocorrelation signal diminishes, indicating a randomization of the oscillation phase. The amplitude of the autocorrelation signal vanishes (complete randomization of the phase) in approximately 10 periods. We note that the autocorrelation of the total signal is essentially the same as the autocorrelation of the fundamental.

Thus, the various methods of measurement yield essentially the same phase coherence time, approximately 10 periods.

We note that both the autocorrelation signal and the free-running sweep record phase changes (including small changes) and spread with respect to k (the free-running sweep also indicates variations in amplitude); on the other hand, the life-time characterizes only the phase. The similar values of the loss-time from the autocorrelation measurements and the life-time measurements show that there is essentially no spread in **k**. The fact that the cross-correlation function shows essentially no change with variation of distance between probes (with the exception of the inherent phase shift) supports this. In Fig. 7 we show a cross correlation function taken with probes oriented at an angle of 180°. The phase shift of π is clearly evident; in all other respects the cross-correlation function agrees with the autocorrelation function. Thus, it may be concluded that at a distance of the order of a half wavelength there is essentially no phase randomization.

Thus, the analysis of the plasma state in the presence of the drift instability in the case of large amplitude oscillations $\tilde{n}/n \sim 1$ indicates that the plasma is turbulent although a phase correlation is maintained over some 10 cycles while there is no spreading in k.

3. As has been indicated earlier [6] the azimuthal phase velocity is constant over the spec-

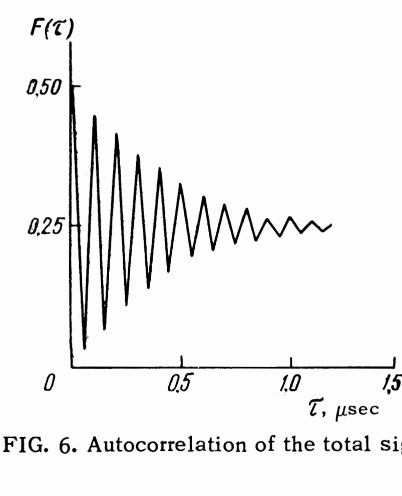

FIG. 6. Autocorrelation of the total signal.

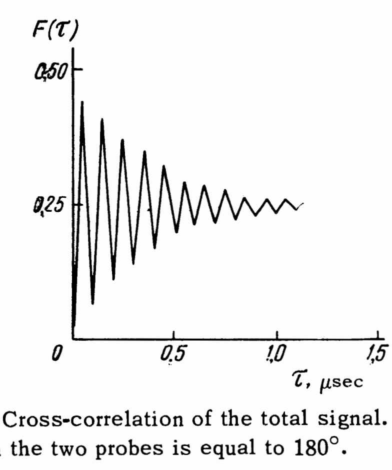

FIG. 7. Cross-correlation of the total signal. The spacing between the two probes is equal to 180°.

trum. Thus, the azimuthal wavelength is inversely proportional to the frequency, that is to say, the spectrum is a linear function of **k**.

When the magnetic field is increased the frequency of the harmonics is reduced inversely as the magnetic field and there is a corresponding reduction in the longitudinal phase velocity ω/k_z (we recall that $\lambda_z \sim 2L$ [3]). The amplitudes of the harmonics, the ratio between the harmonics, and the half-widths of the peaks remain constant to H ~ 1100—1200 Oe (the experiments were carried out at $\tilde{n}/n \sim 1$). As the field is increased further the amplitude of the fundamental is reduced while that of the second harmonic is increased (Fig. 8). When the field reaches a value such that $\omega/k_z \sim 3.5\, v_i$ the fundamental is quenched. As the field is increased further the second harmonic is quenched (under these conditions $\omega/k_z \sim 5\, v_i$ if $\lambda_z = 2L$).

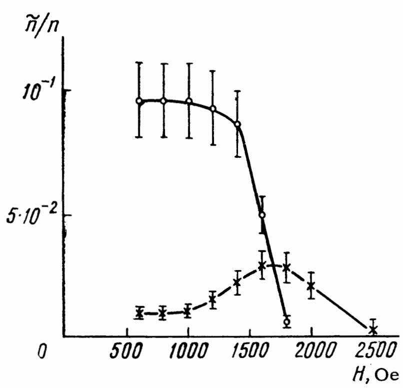

FIG. 8. The dependence of the amplitude (above the noise level) of the fundamental (o) and second harmonic (x) on magnetic field.

Similar phenomena have been investigated in detail by Lashinsky [15] in the case of low-amplitude oscillations. It was shown in this work that successive damping of the harmonics can be attributed to ion Landau damping which should be observed for $\omega/k_z \sim 3\, v_i$ for drift waves in a collisionless plasma. Lashinsky has also observed the transfer of energy from one harmonic to another as individual harmonics are damped and this was attributed to nonlinear effects. Reference is made to this work and we shall not analyze these results in any greater detail (cf. note added in proof at the end of the paper).

As the amplitude is reduced the half-width of the peaks increases, corresponding to a reduction in the lifetime. Following the quenching of the second harmonic the spectrum exhibits a purely noise-like nature (Fig. 9). The maximum ampli-

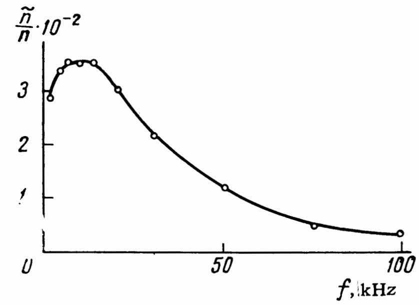

FIG. 9. Noise spectrum. H = 2500 Oe, n = 5 × 10⁹ cm⁻³, ñ/n ~ 0.4.

tude lies in the low-frequency region (the amplitudes in this region $\tilde{n}/n \sim (1—3) \times 10^{-2}$) in spite of the fact that the instability condition $\omega/k_z \gg v_i$ is still satisfied at the higher frequencies. We note that in the high-frequency region the amplitude is appreciably higher at higher fields. One may assume that the noise level in the low-frequency region is the "pre-unstable" state.

4. Measurements of the diffusion have shown that the diffusion coefficient increases with increasing oscillation amplitude. In the electron-sheath regime the instability is essentially quenched and the amplitude of the density oscillations is $\tilde{n}/n \sim 10^{-2}—10^{-3}$; under these conditions the spectrum is purely noise-like and the amplitude is essentially constant function of frequency over the spectrum, amounting to $\tilde{n}/n \lesssim 10^{-4}$. Under these conditions the diffusion coefficient satisfies $D \lesssim 10—20\ cm^2/sec$. Since the classical coefficient D_{ei} should be $\leq 1\ cm^2/sec$ under these conditions we may assume that the measured value of D is due to spurious flux to the measurement

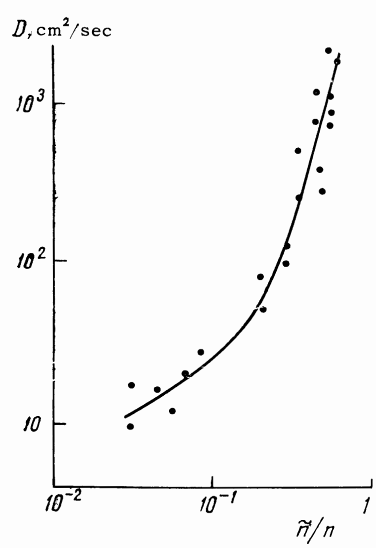

FIG. 10. The diffusion coefficient as a function of the oscillation amplitude; H = 1000 Oe.

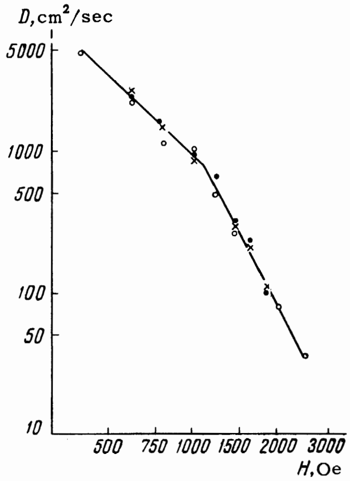

FIG. 11. The diffusion coefficient as a function of magnetic field (results of three experiments): •) $n = 3.5 \times 10^9$ cm^{3}, ×) $n = 4.5 \times 10^9$ cm^{-3}, ○) $n = 6 \times 10^9$ cm^{-3}; $\tilde{n}/n \sim 1$.

device and take this value to be the limit of accuracy of measurements.

In Fig. 10 we show the diffusion coefficient as a function of amplitude; the abscissa axis shows the amplitude of the total signal at the point of maximum signal in the radial direction. It is evident that D increases approximately as $(\tilde{n}/n)^2$. We note that when the amplitude of the fundamental $\tilde{n}/n \sim 10^{-2}$ (the case investigated in [5]) the diffusion coefficient is $\sim 10^2$ cm^2/sec, which coincides with the result given above.

When H = 1000 Oe and $\tilde{n}/n \sim 1$ the diffusion coefficient reaches a value 10^3 cm^2 sec. Actually the mean value of D is obtained by the measurement device is $(1.2 \pm 0.2) \times 10^3$ cm^2/sec while the estimate obtained from the longitudinal gradient is $(2.1 \pm 0.2) \times 10^3$ cm^2/sec. We note that when D is determined by measuring the gradient the plasma contains no measuring element other than a single probe. Thus, the diffusion coefficient is approximately three orders of magnitude greater than the classical value and when H = 1000 Oe the absolute value of the diffusion coefficient approaches the Bohm value [16] which is given by $D_B = cT/16eH = 2 \times 10^3$ cm^2/sec.

However, the dependence of D on H is appreciably stronger than H^{-1}. A typical D(H) curve is shown in Fig. 11. It is evident that for magnetic fields below some critical value H_0, the quantity D varies as H^{-2}; at higher fields we find $D \propto H^{-4}$. The data obtained by the measurement device and from the longitudinal density gradient are in agreement. It is found that the value $H_0 \sim 1100$–1200 Oe, that is to say, it coincides with the field at which one observes the onset of quenching of the fundamental frequency (Fig. 8).

The dependence of D on H has not been investigated in any detail for low amplitudes, although it has been observed that D is still a rather strong function of H. This result does not agree with the earlier result obtained in [5] in which it was found that D is independent of H for fundamental-frequency amplitudes $\sim 10^{-2}$. The origin of this discrepancy is not known. It is possible that it lies in a difference in boundary conditions, since the earlier experiments were carried out in a system with two hot plates whereas the present experiments were carried out in a system with one cold plate.

The mechanism of the diffusion across the magnetic field has been investigated. It is found that the current to the measurement device or to a probe outside the plasma column both exhibit peaks which agree in phase with the maximum density in the wave (Fig. 12). Thus, the flux of plasma across the magnetic field is in the form of tongues which are correlated with the oscillations in the drift wave. The tongue appears essentially simultaneously over the entire length of the column (there is no longitudinal phase shift) and moves together with the wave in the azimuthal direction (the azimuthal phase shift of the tongues coincides with the phase shift of the density oscillations). At H = 1000 Oe the tongue is observed at distances up to 5.5 cm (~3R) from the axis of the column. The velocity of the tongue across the field, as determined by the radial phase shift, is

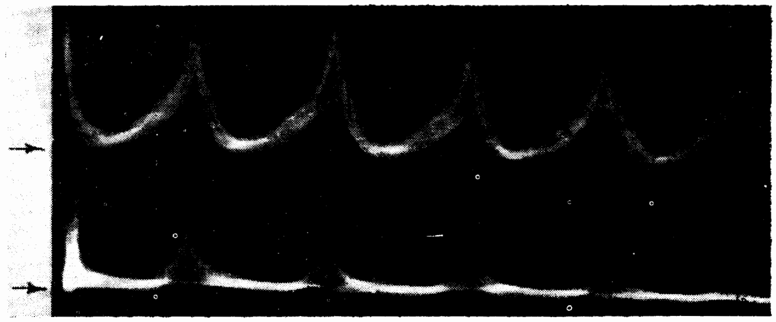

FIG. 12. Correlation of the current in the diffusion measurement device with the density oscillation. The upper curve shows the density oscillations and the lower curve shows the current in the measurement device. The arrows indicate zero level. H = 1000 Oe, $n = 3 \times 10^9$ cm^{-3}.

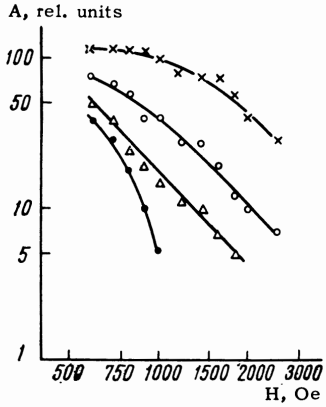

FIG. 13. The amplitude of the tongue at various radii as a function of magnetic field: ●) r = 20 mm, △) r = 25 mm, ○) r = 30 mm, ×) r = 35 mm; $n = 4.5 \times 10^9$ cm^{-3}.

approximately 4×10^4 cm/sec under these conditions. The diffusion exhibits the tongue-like nature at low amplitudes as well.

When the magnetic field is increased the amplitudes of the tongues falls off sharply (Fig. 13) and there is a simultaneous reduction in the maximum distance over which the tongue is observed.

We note that the diffusion coefficient as determined by means of the measurement device or by the longitudinal density gradient characterizes the mean plasma flux across the magnetic field.

DISCUSSION OF THE RESULTS

1. We now consider in greater detail the observed instability, taking account of data which have been obtained earlier.[3,6,17] The plasma being investigated is in the form of a cylinder with $L/R = 18$; the following plasma conditions prevail:

$$T_e \sim T_i = T, \quad \beta = \frac{8\pi nT}{H^2} < \frac{m}{M} \ll 1, \quad \lambda_{ei} \gtrsim L$$

(λ_{ei} is the mean free path for electron ion collisions), $a = (n^{-1} dn/dr)^{-1} \sim 1-2$ cm so that the ion Larmor radius $\rho_i < a$ ($\rho_i = 0.37$ cm for $H = 1000$ Oe).

The observed wave exhibits the following characteristics: the wave propagates in the azimuthal direction in the direction of the electron Larmor drift and has a longitudinal component; the oscillation frequency is inversely proportional to the magnetic field and the frequency of the fundamental is close to the drift frequency

$$\omega_* = k_y \frac{cT}{eH} \frac{dn/dr}{n}$$

(k_y is the azimuthal component of the wave vector). We note that in computing ω_* the quantities $k_y = 2\pi/\lambda_y$ and dn/dr are determined at the radi radius at which the oscillation amplitude is a maximum. In this case the experimental values of the frequency are somewhat larger than the calculated values (but not more than a factor of 1.5). The observed frequency is smaller than the ion-cyclotron frequency ω_{Hi}. The wavelength of the aximuthal (fundamental) and longitudinal components are $\lambda_y = 2\pi R$ and $\lambda_z = 2L$; the longitudinal phase velocity is $v_i < \omega/k_z < v_e$ (v_e and v_i are the electron and ion thermal velocities). Thus, $k_y/k_z \gg 1$, $k_y\rho_i < 1$ (~0.15—0.37 when $H = 1000$ Oe), that is to say, $\lambda_y = 2\pi\rho_i$ and $\lambda_y > a$. It should be noted that the electron collision frequency $\nu_{ei} > \omega$ but that $k_z\lambda_{ei} \gtrsim 1$ so that collisions can be neglected.

The drift instability in a collisionless plasma has been investigated theoretically by Kadomtsev[18,19], (in[19], p. 277). The theory is derived for the plane case under the assumption that $\lambda \ll a$, $\rho_i \ll a$ and $\omega < \omega_{Hi}$. It is found that perturbations of the form $\exp[i(-\omega t + k_y y + k_z z)]$ propagate in the electron drift direction with a longitudinal phase velocity $v_i < \omega/k_z < v_e$ and that these are unstable when $k_y/k_z \gg 1$. In the case being considered

$$\omega = \omega_* \frac{\beta_s}{1-\beta_s}, \quad \gamma = 2\sqrt{\pi}\frac{\omega_*^2}{k_z v_e}\frac{\beta_s(1-\beta_s)}{(2-\beta_s)^2}$$

where $\beta_s = e^{-s} I_0(s)$, $s = k_y^2 \rho_i^2$ and I_0 is the Bessel function of imaginary argument. When s is small, $\omega \sim \omega_*$.

The case being considered here differs from the case considered theoretically in that the plasma is in the form of a cylinder which is bounded at the ends; furthermore, it is found that the excited waves are characterized by $\lambda > a$. Nonetheless, the nature of the wave, the direction of propagation, the frequencies, and the phase velocities are in good agreement with the theory, indicating that the observed instability is the drift instability.

A disagreement with the theory appears in the fact that the estimates of the growth rate are not in agreement with the theoretical estimates. According to[18] the growth rate is a maximum for $s = 1$ ($\lambda_y = 2\pi\rho_i$) and diminishes as s diminishes. For the present parameters γ should be a quantity of approximately $10^{-3}\omega_*$. Thus, the computed growth rate is small in absolute value and should be a maximum at approximately the third to fifth harmonic. However, in the present experiment, as well as in similar experiments[20,21], the maximum amplitude is exhibited by the fundamental. Evidently it is reasonable to assume that in a cylindrical system the growth rate can be a maximum at the fundamental frequency. As we have indicated, it should be noted that in the present case the growth rate is large: $\gamma \sim \omega_*$, that is to say it is several orders of magnitude greater than the theoretical value. This result can not be explained at the present time.

In the transition from an electron sheath to an ion sheath the instability develops as is manifiest in the growth of fluctuations over a wide spectral range. As the amplitude increases the noise level between the harmonics is reduced and in the fully developed instability, in which case $\tilde{n}/n \sim 1$, the noise level is small compared with the amplitudes of the harmonics. The correlation analysis indicates that when $\tilde{n}/n \sim 1$ the phase correlation for the oscillations is maintained over approximately 10 periods. Under these conditions each frequency corresponds to its own wave number. This may be called the weakly turbulent state in accordance with the definition given above; however, it should be emphasized that in the usual theory the idea of weak and strong turbulence implies total randomization of the oscillation phases. We note that this assumption is not in accordance with the results of a number of experiments [1,2,22,23] in which phase correlations are observed over several periods. Apparently this assumption is not a valid one for long-wave oscillations in bounded systems. It is probable that in this case it is more correct to discuss highly nonlinear oscillations rather than the turbulent state.

2. An investigation of the diffusion shows that the diffusion coefficient increases with oscillation amplitude in proportion to $(\tilde{n}/n)^2$ and that when $\tilde{n}/n \sim 1$ the diffusion coefficient reaches a value 10^3 cm^2/sec (H = 1000 Oe) which is some three orders of magnitude greater than the classical value. We note that the diffusion coefficient is several orders of magnitude greater than the classical value as observed in a system similar to the present one but with low plasma density.[24] Unfortunately oscillations were not investigated in that experiment.

When $\tilde{n}/n \sim 1$ in the region of magnetic fields where damping of the instability is not important, we find $D \propto H^{-2}$. However, in the region in which the damping of the fundamental is important we find that D diminishes more rapidly: $D \propto H^{-4}$. From this result we draw the conclusion that the basic contribution to the diffusion is due to the interaction with the fundamental.

The plasma flux across the magnetic field is in the form of tongues, that is to say, the diffusion exhibits a convective character. This is in agreement with theoretical ideas concerning diffusion in the drift instability ([19], pp. 296, 299). Tongues of this type have also been observed in instabilities in a highly inhomogeneous plasma.[25] They have the same nature as the tongues observed in instabilities in a hot-cathode discharge [26–28] one of which has been identified with the drift-dissipative instability.[28] Evidently this is a characteristic feature of a loss of plasma across a magnetic field in longwave electrostatic oscillations that propagate across a magnetic field. The loss mechanism is essentially the drift of the electrons and ions in the electric field of the wave, this drift being perpendicular to the magnetic field.

Attention is directed to the fact that the diffusion is not related to the turbulent state of the plasma since the tongues are observed to be in phase with the oscillations of the density even in those cases in which they are essentially coherent (small amplitudes), that is to say the tongues are not related to randomization of the oscillations.

Thus, the earlier conclusion that the diffusion is due to random noise oscillations between the harmonics [6] is evidently incorrect. The experiment reported in [6] appears to lead only to the conclusion that pure sinusoidal coherent oscillations produced by a generator do not cause diffusion.

It should be noted, however, that since the loss of plasma across the magnetic field is not of a random nature, strictly speaking the term "diffusion" is not properly applied here. The diffusion coefficient is purely formal in character and is defined as the ratio of the time averaged flux to the density gradient.

A mechanism for plasma loss across a magnetic field similar to that observed in the present work has been considered by Chen [29] for the drift-dissipative instability.

In recent years a number of papers have appeared [30,32] in which attempts were made to estimate the diffusion coefficient from the Spitzer formula [33] on the basis of measurements of density fluctuations. It should be noted that for the "tongue" plasma loss mechanism these estimates are evidently incorrect.

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Note added in proof (February 28, 1967). We note that the behavior of the amplitude of the harmonics as a function of magnetic field described in the text can be given another explanation. It is known that a plasma bounded in length by a hot ionizing plate and a cold plate moves toward the latter with a velocity $\sim v_i$ [34]. Evidently in this case the perturbation can not grow if the period of azimuthal rotation is comparable with the transport time of the perturbation $\tau_s \sim L/v_i$ from the ionizer to the cold plate. In the present experiments it is found that $\tau_s \sim 2T$ ($T = 1/f$ where f is a frequency of the fundamental at which damping occurs). Thus, the quenching of the oscillations due to variation of the magnetic field could be due to the effect described here as well as to Landau damping.

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