DRIFT INSTABILITY IN A PLASMA

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ABSTRACT: Drift instability is examined for the transition from a low-density plasma ($\lambda_{ei} \geqslant L$) to a high-density one ($\lambda_{ei} < L$). The oscillation amplitude and diffusion coefficient are found to be independent of the density; diffusion and the character of D(H) are dependent of the density. The diffusion is classical in the absence of instability. The damping of instability harmonics is examined as a function of magnetic field, which is related to loss of perturbations by drift in a system with a cold end. The damping of the second harmonic increases as the field decreases on account of stabilization by ion-ion collision.

There have recently been many theoretical [1,2] and experimental [3-11] studies of drift instability, which occurs as the excitation of oblique waves of the type $A(x) \exp i(\omega t + k_y y + k_z z)$ for $k_y \gg k_z$, which propagate in the direction of electron diamagnetic drift. The frequency of these oscillations is close to the drift frequency:

$$\omega_* \approx k_y \frac{cT}{eH} \frac{n'}{n}.$$

Here k_z is the component of the wave vector parallel to the magnetic field H, k_y is the perpendicular component, T is electron temperature, n is plasma density, and n' is the gradient in that density.

Many of the experimental studies [3-7] are concerned with drift instability in a dense plasma, when λ_{ei} (mean free path for electron-ion collisions) is much less than the size L of the system (L was around 100 cm and n was 10^{11} to 10^{12} cm^{-3}). Detailed comparison [9] gave good agreement between experiment and the theory of drift-dissipative instability.

Some experiments [8-11] have been made on low-density (collision-free) plasmas with $\lambda_{ei} \geqslant L$ ($L \approx 40$ cm, n of $10^9 - 10^{10}$ cm^{-3}). Here the instability was examined, as was the turbulent state of the plasma with the fully developed instability; measurements were made of the oscillation amplitude A and diffusion coefficient D, and A(H) and D(H) were recorded. It has been shown [8,10] that the instability retains the same character when $\lambda_{ei} < L$ ($L \approx 40$ cm, n up to $5 \cdot 10^{11}$ cm^{-3}), i.e., a dense plasma.

In fact, there is no change in the oscillation frequency, wave type, or direction of propagation. However, A(n) and D(n) were not examined with sufficient care, and no study was made of the reasons for field-dependent damping of the instability harmonics.

The experiments were done with an apparatus [12] in which the plasma was produced by thermal ionization of potassium on a tungsten plate of radius R = 2 cm at about 2000° K; L = 36 cm (distance between the hot plate and the cold plate) and n was $3 \cdot 10^8$ to $5 \cdot 10^{11}$ cm^{-3}, while H was 600-3000 Oe.

We measured n and A with a Langmuir probe from the dc and ac components of the saturation ion current, respectively [10].

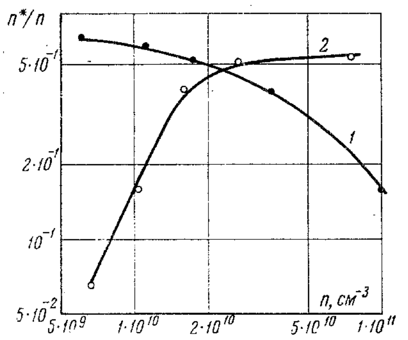

Fig. 1

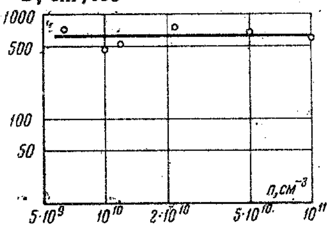

Fig. 2

The oscillation spectrum was examined with an S5-3 harmonic analyzer (passband about 200 Hz), which recorded the effective amplitude.

The coefficient D for diffusion across the magnetic field was measured with an instrument [10] that recorded the transverse plasma flux.

Thermal ionization can produce near the ionizer an ion or electron layer, which is determined by the flux of neutral atoms (which determines the ion flux) and the ionizer temperature (which determines the electron flux). Drift instability occurred only when there was an ion layer in the system with a cold plate at the end; with an electron layer, the azimuthal perturbations were balanced by the Simon effect and instability did not develop. The amplitude of the drift oscillations increased on going from an electron layer to an ion one. It has been shown [11] that A rises to $n^*/n \approx 1$ when there is a sufficiently deep ion layer (n^* is the alternating component of the density), and it was also found that D is proportional to A^2. The dependence of A on the character of the layer made it difficult to determine the dependence of A and D on n; in fact, it has been found [8-10] that n^*/n and D begin to fall at high n, but it remains unclear whether this is due to damping by increasing ion-ion collisions [13,14] or to change in the character of the layer.

This aspect has been investigated in two experiments. In the first, n was increased by raising the ionizer temperature T at constant flux $(nv)_0$, so that transition to an electron layer could occur; in the second, T was kept constant, but the flux was increased, and so the ion layer became thicker. Figure 1 shows A(n) for constant H (about 1000 Oe), where curve 1 is for T = const and curve 2 is for $(nv)_0$ = const. Curve 1 falls increasingly rapidly [8-10], whereas curve 2 rises to a steady value. Both curves should fall if A was much affected by collisions in this range of n, e.g., from damping due to ion-ion collisions.

The instability is damped at all n in the electron-layer state, and choice of the layer thickness d can give $n^*/n \approx 1$ for any n, so we can conclude that A is independent of n in the range 10^8 to $5 \cdot 10^{11}$. Damping previously reported [8-10] was due to change in the character of the layer.

We recorded D(H) at $n = 5 \cdot 10^{11}$ cm^{-3}. Figure 3 shows the result for the electron-layer state, where there is no instability ($n^*/n \approx 5 \cdot 10^{-2}$). D varies as $1/H^2$, and its absolute magnitude is close to the classical value [10], so diffusion is governed by electron-ion collisions in the absence of instability. If $n^*/n \approx 1$, $D \approx 10^3$ cm^2/sec for $H \approx 1000$ Oe, i.e., it is larger than the classical value by an order of magnitude. Figure 4 shows D and the amplitude of the fundamental as functions of H for $n \approx 2 \cdot 10^{11}$ cm^{-3} ($n^*/n \approx 1$); $D \propto 1/H^2$ for H < 1100 Oe, while $D \propto 1/H^4$ at higher fields. These results agree with published ones [11] for low-density plasma. The change in D(H) is due to the fall in the amplitude of the fundamental for H > 1000-1100 Oe (Fig. 4), as has also been observed [11].

The diffusion is of the same character as at low densities [11]; the flow of plasma across the magnetic field occurs in bursts correlated with the density fluctuations in the wave, i.e., the diffusion is convective.

Consider now the cause of harmonic damping as H increases. The amplitude of the fundamental begins to fall in a low-density plasma as H increases above $H_c \approx 1100-1200$ Oe, and it is damped for $H \geqslant 2000$ Oe. The amplitude of the second harmonic increases for $H \geqslant H_c$ but it is also damped for $H \geqslant 2500$ Oe. Similar effects have been observed [5] on increasing H or reducing the length of the plasma column; the tests were done at $n \leq 7 \cdot 10^{10}$ cm^{-3}. Landau damping was the explanation offered for successive damping of the harmonics. In fact, the frequency of the drift oscillations decreases as H increases, and the longitudinal phase velocity ω/k_z falls; Landau damping can play a part in a collision-free plasma when this becomes about $3v_i$ (in which v_i is the thermal velocity of the ions). As k_z is determined by the length of the system, the same effect should be observed on reducing the length.

Doubt is cast on this explanation by the fact that the density in [15] was fairly high, so the frequency ν_{ii} of ion-ion collisions was comparable with ω; in fact $\nu_{ii} \approx 4 \cdot 10^4$ sec^{-1} (Cs, $n \approx 10^{11}$ cm^{-3}), while ω (fundamental) was about $6 \cdot 10^4$ sec^{-1}. Landau damping exists in the presence of collisions only if $\nu_{ii} < \delta$ (Landau damping decrement). The instability begins to be damped when δ becomes comparable with the growth rate γ. Even in the case $\gamma \approx \omega$, Landau damping is possible only for $\nu_{ii} \ll \omega$, so it should not have played a part in the case of [15] for the fundamental.

In our case, with n of 10^9-10^{10} cm^{-3}, ν_{ii} was somewhat less than ω for the fundamental, but larger for $n \approx 10^{11}$ cm^{-3}; in fact, ω was about $6 \cdot 10^4$ sec^{-1}, while ν_{ii} was 10^3-10^4 sec^{-1} for n of 10^9-10^{10} cm^{-3} and about 10^5 sec^{-1} for $n \approx 10^{11}$ cm^{-3}, so $\nu_{ii} \ll \delta$ was certainly not met for higher n, and it could not be met for lower n if $\gamma < \omega$. We should therefore check the assumption that the damping observed with increasing H is related to Landau damping and not to any other mechanism.

We can suppose that the instability damping with increasing H is due to reduction in the Larmor radius, which has a stabilizing effect [2,6].

The following mechanism can also be proposed. The plasma moves from the ionizer to the cold plate with a speed of about v_i [16,17]; if the oscillation frequency is such that the period of oscillation is greater than or comparable with the time to travel the length, $t \approx L/v_i$, any perturbation cannot grow to an appreciable amplitude; this effect should thus reduce the amplitude as ω decreases, and ultimately the oscillation is damped out. The same effect should be observed on reducing the length of the system. Of course, the second and higher harmonics should be damped at higher H. The less the γ, the earlier (i.e., the larger the ω) at which this mechanism should make itself felt.

The following experiment determines which of the three mechanisms applies in our case. The quantity A(H) is measured at: 1) low n with one cold plate (plasma drift at about v_i), 2) the same low n with the plate heated (plasma drift rate much less than in the previous case), 3) at high n with the plate cold. If Landau damping is effective, it should give the same pattern in cases 1) and 2), while damping related to reduction in the Larmor radius should be virtually the same in all three cases [13]. The transport mechanism should produce similar effects in cases 1) and 3) but a substantially different effect in case 2), since the field for onset of damping should be higher, owing to the reduction in drift velocity.

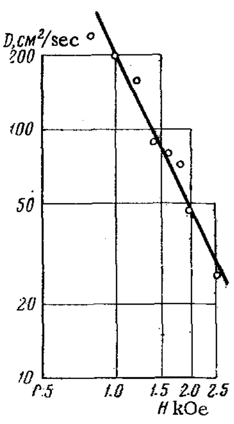

Fig. 3

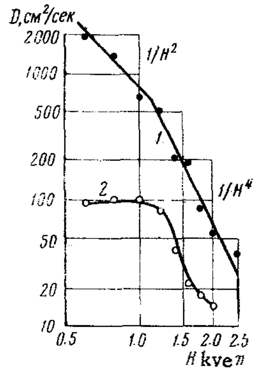

Fig. 4

Figure 5 shows A(H) in relative terms, where points 1–3 correspond to the fundamental for n of $5 \cdot 10^9$, $5 \cdot 10^{11}$, and $4 \cdot 10^9$ cm^{-3}, while points 4 correspond to the second harmonic for n of $5 \cdot 10^9$ cm^{-3}. Curves 1 and 3 almost coincide for the fundamental, while H_c for curve 2 lies much higher. This indicates that the transport mechanism is responsible for damping of the fundamental harmonic. If the wavelength of the second harmonic is also of the order of 2L, the H at which it dies out should be about twice as great; but γ is less than that for the fundamental, so the damping can occur earlier. The damping observed for the second harmonic with increasing H can thus be explained by the proposed mechanism. The observed [15] sequential damping of the harmonics as H increases or L decreases was very probably due to the same mechanism, not to Landau damping.

Consider now the damping of the second harmonic as H decreases. The H at which A starts to fall is almost the same in cases 1–3. Drift-dissipative instability has been examined in detail [6], and it was shown that damping with decreasing H is due to stabilization via ion-ion collisions, with the critical H defined by a formula in close agreement with experiment:

$$\frac{H_*}{k_\perp} = \left(\frac{mM^2c^4T\nu_{ei}\nu_{ii}}{4e^4k_z^2}\right)^{1/4}, \quad k_\perp^2 = k_x^2 + k_y^2.$$

Here M is ion mass and m is electron mass. This formula gives H_* for the second harmonic at n of $5 \cdot 10^{10}$ to $5 \cdot 10^{11}$ (the range common to our case and [6]) as about 800 Oe (with allowance for the differences in R and L, which determine $k_\perp$ and k_z). The observed H_* of about 1000 Oe agrees satisfactorily with this estimate, so the experimental results and [6] are in satisfactory agreement. The apparent independence of H_* from n [6] is due to the change in $k_\perp$ as n varies; in fact, it was shown [6] that $H_*/k_\perp \backsim n^{1/2}$, in accordance with the formula.

We thus can say that the damping of the second harmonic as H decreases is due to stabilization by ion-ion collisions. Since the instability in our case is of the same type as that in [6], we can assume that the observed instability in a dense plasma is of the drift-dissipative type.

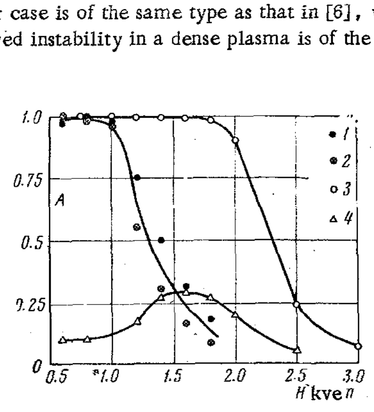

Fig. 5

The instability remains of the same type on going to lower n, and the second-harmonic damping remains as here. Then, the damping is dependent on ion-ion collisions although $\lambda_{ei}k_z > 1$ and $\lambda_{ii}k_z > 1$ for low n, and the instability excitation mechanism is collision-free [2] (p. 294). This frequency is low for n small n($v_{ii}/\omega \sim 0.02-0.2$ for n of 10^9-10^{10} cm^{-3}), but these collisions continue to damp the harmonics as H decreases [13] and may lead to absence of Landau damping.

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REFERENCES

1. A. B. Mikhailovskii, "Oscillations in an inhomogeneous plasma," collection: Plasma Theory, vol. 3 [in Russian], Gosatomizdat, Moscow, pp. 141-202, 1963.

2. B. B. Kadomtsev, "Plasma turbulence," collection: Plasma Theory, vol. 4 [in Russian], Gosatomizdat, Moscow, pp. 188-339, 1964.

3. N. D'Angelo and R. W. Motley, "Low-frequency oscillations in a potassium plasma," Phys. Fluids, vol. 6, no. 3, 1963.

4. H. Lashinsky, "Universal instability in a fully ionized inhomogeneous plasma,"Phys. Rev. Lett., vol. 12, no. 5, 1964.

5. H. Lashinsky, "Universal instability in a thermal plasma device (Q-machine)," Proc. Conf. Plasma Physics and Controlled Nuclear Fusion Research, International Atomic Energy Agency, Vienna, vol. 1, pp. 499-500, 1966.

6. H. W. Hendel and P. A. Politzer, "Collisional drift instability in nonisothermal plasmas," Proc. Conf. Physics of Quiescent Plasmas, Frascati, vol. 1, pp. 181-199, 1967.

B. Coppy, H. W. Hendel, F. Perkins, and P. A. Politzer, "Interpretation of experiments on collisional drift modes," Proc. Conf. Physics of Quiescent Plasmas, Frascati, vol. 1, pp. 201-211, 1967.

7. F. F. Chen, "Oscillations and diffusion in a shear stabilized Q-machine," Proc. Conf. Physics of Quiescent Plasmas, Frascati, vol. 1, p. 145-172, 1967.

8. N. S. Buchel'nikova, "Universal instability in a potassium plasma," Yadernyi sintez, 4, no. 3, 1964.

9. N. S. Buchel'nikova, "Drift instability in a potassium plasma," Proc. 7-th Internat. Conf. on Phenomena in Ionized Gases (Beograd, 1965), Beograd, Gradevinska Knjiga, vol. 2, pp. 671-675, 1966.

10. N. S. Buchel'nikova, "Diffusion across a magnetic field in universal instability," Yadernyi sintez, 6, no. 2, 1966.

11. N. S. Buchel'nikova, R. A. Salimov, and Yu. I. Eidel'man, "The turbulent state of a plasma in drift instability," ZhETF, 52, no. 4, 1967.

12. N. S. Buchel'nikova, "An apparatus for research on alkali plasmas," Teplofizika vysokikh temperature, 2, no. 3, 1964.

13. A. B. Mikhailovskii and O. P. Pogutse, "Effects of collisions on the drift instability of a plasma with a finite Larmor radius for the ions," Dokl. AN SSSR, 156, no. 1, 1964.

14. G. M. Zaslavskii and S. S. Moiseev, "Anomalous diffusion of a plasma in a magnetic field," ZhTF, 34, no. 3, 1964.

15. H. Lashinsky, "Landau damping and finite-length effects in universal plasma instabilities," Phys. Rev. Lett. vol. 13, no. 2, 1964.

16. A. Y. Wong, R. W. Motley, and N. D'Angelo, "Landau damping of ion acoustic waves in highly ionized plasmas," Phys. Rev., vol. 133, no. 2A, 1964.

17. N. S. Buchel'nikova and R. A. Samilov, "Excitation of ion-acoustic waves in potassium and cesium plasmas," Teplofizika vysokikh temperature, 4, no. 1, 1966.

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