DIFFUSION IN HIGH-FREQUENCY PLASMA STABILIZATION

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The diffusion coefficient for charged particles has been measured experimentally in experiments on rf stabilization of the current-convective Kadomtsev–Nedospasov instability in an electron-hole plasma in a germanium semiconductor. The value of the diffusion coefficient is determined from the spatial distribution of particles in the plasma. This measurement is made on the basis of the absorption of the infrared radiation of a He-Ne laser, the absorption being due to free carriers. It is shown that rf stabilization leads to a reduction of the anomalous diffusion coefficient, the latter being reduced to values approximately the same as those measured for a stable plasma.

It was shown in 1958 by Ho and Lehnert[1] that under certain conditions the plasma in the positive column of gas discharge can exhibit anomalous values of the diffusion coefficient; these values are much greater than the value computed on the basis of a theory which only considers binary collisions between particles. In the same experiments it was shown that when the anomalous diffusion appears the discharge is always characterized by strong fluctuations of the current and local values of the particle density. A theory developed in 1960 by Kadomtsev and Nedospasov regarding the stability of the positive column of a gas discharge in a magnetic field[2] showed that the anomalously high plasma diffusion observed in [1] was due to the development of helical convective perturbations in the plasma. This theory[2] establishes a unique relation between the anomalous diffusion and the fluctuations of the electromagnetic fields in the plasma that are associated with the instabilities.

A similar effect was discovered simultaneously with [1] in the electron-hole plasma in a semiconductor by Ivanov and Ryvkin.[3] Modifications of the theory in [2], taking account of the specific features of the semiconductor plasma, were given in a paper by Glicksman[4] who showed that the effect observed in [3] is completely analogous to the Kadomtsev–Nedospasov instability in a gas plasma.

In 1965 Dubovoĭ and Shanskiĭ[5] observed that rf modulation of the current causing the instability in the semiconductor plasma could lead to a sharp reduction of the fluctuation level; the conclusion was drawn that the Kadomtsev–Nedospasov instability could be stabilized by rf stabilization. Using the results of the experiments[5] Kadomtsev and Vladimirov developed a theory[6] with which it was possible to explain the basic features of the effect reported in [5]. In [7], satisfactory agreement was obtained between the results of the calculations and experiments and it appears that one can now properly say that the theory and experiment explain both the excitation of the instability as well as the high-frequency stabilization of the instability.

However, as has been shown by measurements of diffusion in magnetic traps that have been carried out in recent years,[8] a reduction in the level of the local fluctuations in density and electromagnetic fields that characterize the turbulent state of the plasma does not always lead to corresponding reduction in the value of the anomalous diffusion coefficient. Furthermore, as has been observed in experiments on rf stabilization of the Shafranov–Kruskal instability[9] in experiments with theta-pinches and in a number of other papers,[10] the rapidly varying currents used for the rf stabilization can, themselves, excite a number of characteristic current-driven and drift instabilities.

If the frequency of the new instability excited by the rf current falls in a region which is far from that being monitored in the experiment, the transition of the plasma from one turbulent state, stabilized by the rf field, to another, induced by the rf stabilization current, may not be noticed. In situations of this kind it is more convenient to investigate transport effects in the plasma, for example, any anomalous nature of the diffusion process in an experiment is generally the most reliable indication of the turbulent state of the plasma, regardless of the type of perturbation that has been excited.

In this connection, an attempt has been made here to measure directly the plasma diffusion coefficients in experiments on rf stabilization of the Kadomtsev–Nedospasov instability in an electron-hole plasma in a semiconductor.

The excitation of the instability and its stabilization by rf fields are shown in the oscillogram in Fig. 1. The lower beam of the oscillogram shows the fluctuations of the current in the semiconductor circuit while the upper trace shows the amplitude of the current applied along the sample $I = I_0 = \text{const}$ and $I = I_0 + I_1 \cos(\omega t)$. It will be evident that when $I_1 = 0$ and $I_0 \neq 0$ the plasma exhibits oscillations at a characteristic frequency $f_0 \sim 5\text{–}10 \times 10^4$ Hz indicating the presence of the current-convective instability. When $I_1 \gtrsim 2I_0$ and $\omega \gg 2\pi f_0$ (in the present case $\omega = 1 \times 10^7\ \text{sec}^{-1}$) the oscillations are suppressed. The effect exhibits a threshold nature so that the boundaries of the region corresponding to excitation of the instability are described by the relation $B_C E_C = F \approx \text{const}$ where B_C and E_C the minimum critical values of the magnetic field and the electric field below which the plasma is always stable and the constant F depends on the boundary conditions at the surface of the plasma in the semiconductor and on the particle diffusion coefficient.[4]

As in the earlier experiments[5,7] the work here is carried out in the electron-hole plasma in n-type ger-

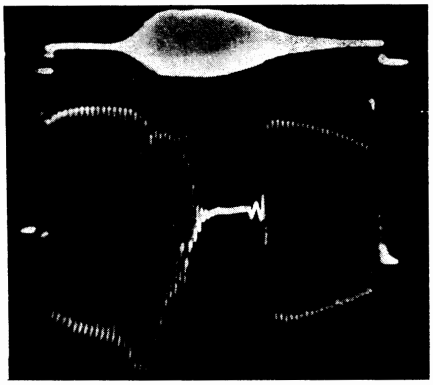

FIG. 1. Oscillogram showing the effect of rf stabilization. $B = 1.2 B_C$, $I_0 \approx 30$ mA, sample $2 \times 2 \times 5$ mm.

manium with a specific resistance $\rho = 45$ ohm-cm. The semiconductor samples are slabs of rectangular cross section with dimensions $2 \times 2 \times 5$ mm and $1.5 \times 1.5 \times 5$ mm. The volume recombination time for these samples $\tau_0 = 3 \times 10^{-4}$ sec, the equilibrium electron density is $n_0 = 2.47 \times 10^{13}$ cm^{-3} and the drift mobility μ 125 cm^2 sec^{-1} V^{-1}. By etching and polishing the samples it is possible to obtain a surface recombination rate $s \sim 800-1600$ sec^{-1}. At one of the faces at the point $x = 0$ there is an injection contact and at the other ($x = l = 5$ mm) there is an ohmic contact.

A block diagram of the experiment is shown in Fig. 2. The source of probing radiation in the experiments is a He-Ne laser operated at $\lambda = 3.39\ \mu$. Through the use of a special manipulator the samples can be moved smoothly in the transverse (y coordinate) and longitudinal (x coordinate) directions. The transverse dimensions of the light spot in the region of the semiconductor rod are smaller than 0.1 mm. In these experiments the ratio $\Delta\Phi/\Phi$ is measured, where Φ is the intensity of the light that is transmitted through the sample before injection, and $\Delta\Phi$ is the change of Φ associated with the injection of an excess density of current carriers δp. The quantity Φ is used for normalization of $\Delta\Phi$. In order to eliminate effects associated with the intensity of the light generated by the laser the light transmitted through a sample Φ and that corresponding to the primary flux Φ_1 are balanced by means of a bridge arrangement 7. After passing through a balanced amplifier the signal, which is proportional to $\Delta\Phi/\Phi$, goes to the oscilloscope 8.

In order to avoid heating of the samples the experiment are carried out in the pulsed mode. The peak current $I_0 = 30$ mA; the field in the sample of $2 \times 2 \times 5$ mm is approximately 30 V cm^{-1} and the length of the pulse I_0 is 10^{-3} sec; $I_1 \gtrsim 2I_0$.

In order to reduce the loss of light due to reflections from the boundaries of the sample the surfaces are carefully polished. In these experiments the reflection loss is smaller than 50–70%.

Following [11], we now consider the basic expressions that characterize the relation between the quantity $\Delta\Phi/\Phi$ measured in the experiments, the plasma parameters, and the diffusion process. In the present case the equation continuity can be written conveniently in the form

$$\frac{\partial \delta p}{\partial t} = -\frac{\delta p}{\tau} + D\nabla^2 \delta p - \mu E \nabla\, \delta p. \tag{1}$$

In Eq. (1) τ is the lifetime of the plasma in the sample, D is the ambipolar diffusion coefficient:

$$D = (n+p)\left(\frac{n}{D_p} + \frac{p}{D_n}\right)^{-1}, \tag{2}$$

μ is the ambipolar mobility

$$\mu = (n-p)\left(\frac{n}{\mu_p} + \frac{p}{\mu_n}\right)^{-1}. \tag{3}$$

$\mu_p = 1900$ cm^2 sec^{-1}, $\mu_n = 3900$ cm^2 sec^{-1} V^{-1}, $D_p = 50$ cm^2 sec^{-1}, $D_n = 100$ cm^2 sec^{-1} are the semiconductor constants. In the present case $D \approx 65$ cm^2 sec^{-1} and $\mu = 125$ cm^2 sec^{-1} V^{-1}. We now introduce the dimensionless coordinates $Y = y/a$ and $Z = z/a$. We take x along the axis of the sample while the axes Y and Z are perpendicular to the side faces. The latter are bounded by the planes $Y, Z = \pm 1$ so that the thickness of the rod is 2a.

Under steady-state conditions (the measurements are carried out under steady-state conditions with $\partial\delta p/\partial t = 0$) the general solution of Eq. (1) is

$$\delta p(x, Y, Z) = \delta p(0)\, e^{-x/L} \cos(kY) \cos(mZ). \tag{4}$$

In Eq. (4) we have neglected all solutions corresponding to higher spatial harmonics since these can be neglected at the termination of the transient process that follows the injection pulse.[12] The calculation then gives

$$\frac{1}{L} = \frac{-\mu E + [(\mu E)^2 + 4D/\tau]^{1/2}}{2D}. \tag{5}$$

If $(\mu E)^2 \ll 4D/\tau$ then $L = (D\tau)^{1/2}$ and all the transport processes are determined by diffusion alone. If $(\mu E)^2 \gg 4D/\tau$ is large, $L = \mu E \tau$ and the longitudinal distribution of the plasma density depends on E. The relation giving the transverse distribution of the plasma density can be obtained from the equation

$$\Delta\Phi/\Phi \sim \delta p(Y)/\delta p(0) = \cos(kY) = \eta(Y) \tag{6}$$

and the boundary conditions at the point $Y = 1$:

$$D\nabla\delta p(1) = \delta p(1) s. \tag{7}$$

Making use of Eqs. (6) and (7) we have

$$as = Dk \operatorname{tg} k, \tag{8}$$

where $k = \arccos \eta(1)$. When $\Delta\Phi/\Phi \ll 1$ (in the present case $10^{-4} \le \Delta\Phi/\Phi \le 10^{-2}$)

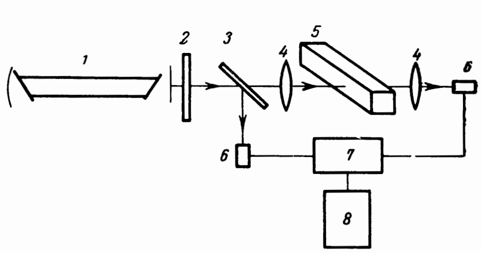

FIG. 2. Block diagram of the apparatus: 1) He-Ne laser, 2) filter, 3) semitransparent mirror, 4) long-focus lens, 5) semiconductor sample, 6) radiation detector, 7) differential amplifier, 8) oscilloscope.

$$\Delta\Phi/\Phi \sim \delta p(0) e^{-x/L} \cos(kY), \quad (9)$$

whence it follows that the transverse distribution $\Delta\Phi/\Phi \sim \cos(kY)$ while the longitudinal distribution $\sim \exp(-x/L)$. To measure the longitudinal distribution of $\Delta\Phi/\Phi$ the laser ray must be moved along x for $Y = 0$, in which case $\cos(kY) = 1$.

Although the experiments on diffusion are carried out in a magnetic field B = 5–10 kG the plasma can be regarded as being unmagnetized[4] since $\mu B \ll 1$, and D can be regarded as independent of B to a high degree of accuracy. The presence of B only leads to the excitation of the instability if $B > B_c$.

Returning to the discussion of the measurements carried out in the work we note that the solutions obtained for D and τ only take account of ordinary binary collisions between particles. However, the relations that have been derived for D and τ have a much greater generality. Thus the quantities D and τ, which are obtained formally from the spatial distribution of plasma density, can describe any diffusion process including anomalous diffusion. Collisions of particles need not only be binary collisions, but can be any other scattering process which can change the momentum of the electrons and holes. In particular, such a process might be fluctuations of the electromagnetic field caused by instabilities in the plasma. In this case the quantities D and τ as measured from $\delta p(x, Y)$ give the mean effective values of D_{eff} and τ_{eff} that characterize the particle loss associated with a given kind of instability. From general considerations for a turbulent plasma we find

$$D_{eff} \geqslant D, \tau_{eff} \leqslant \tau.$$

In Fig. 3 we show the functional dependence $\Delta\Phi/\Phi = f(x)$ obtained in experiments with the sample $2 \times 2 \times 5$ mm for the cases $B = 0.9\ B_c$; $B = 1.2\ B_c$, $I_1 = 0$ and $B = 1.2 B_c$, $I_1 = 2 I_0$. A characteristic feature of these curves is the break at the point $x = x_c = 1.8$ mm. Estimating $\Delta\Phi/\Phi$ from the absolute values and from the change in the total resistance of the sample at the time of injection for $\delta p(0)$, we find that the break at the point $x = x_c$ corresponds to the approximate relation $\delta p(x_c)/p_0 \approx 1$. When $x > x_c$ we have $\delta p(x) < p_0 \approx n_0$, $E = 30$ V cm^{-1} and D and μ are independent of δp. In this region the longitudinal distribution $\delta p(x)$ is due to the radial diffusion of the particles and ambipolar drift in the field **E**. When plotted in semi-logarithmic coordinates the relation that has been obtained gives a good approximation to a straight line, whence it follows that for $x < x_c$ and for $x > x_c$ the diffusion length L for each of the plasma states is a constant. Using the notation 0, 1, 2 to denote quantities obtained from the density distribution for the stable state of the plasma, the unstable state, and the state stabilized by the rf current, from the curves in Fig. 3 we find that $L_{0,1,2} = 0.62$ mm for $x < x_c$ and $L_0 = L_2 = 2.12$ mm, $L_1 = 1.2$ mm $< L_{0,2}$ for $x > x_c$. It should be pointed out here that the analysis of the curves $\Delta\Phi/\Phi$ in the region $x < x_c$ is not of special interest; because of the inequality $\delta p > p_0$, which is satisfied here, $E < E_c = 30$ V cm^{-1} and the criterion for the excitation of the instability is not satisfied; hence the plasma is stable and there is no difference between L_0, L_1 and L_2. In this connection greatest interest attaches to the behavior of the curves $\Delta\Phi/\Phi = f(x, Y)$ in the region $x > x_c$. Foregoing further detailed discussion of the curves shown in Fig. 3 we now wish to analyze the results that have been obtained concerning the data on measurements of the transverse distribution of the density $\delta p(Y)$. In Fig. 4 we show the functional relations $\eta(Y) = \delta p(Y)/\delta p(0)$ for two samples with different surface recombination rates: No. 1, $2 \times 2 \times 5$ mm, $s = 1600$ cm sec^{-1}, No. 2, $1.5 \times 1.5 \times 5$ mm, $s = 800$ cm sec^{-1}. These measurements are carried out for $x = 3$ mm $> x_c$. As in Fig. 3, $E = 30$ V cm^{-1} and $\delta p < p_0$. It will be evident that, as in the data of Fig. 3, the curves of the distribution of $\delta p_{0,2}$ are essentially the same for the stable plasma and for the stabilized plasma while the curves $\delta p_1(Y)$ for the plasma in the turbulent states are sharply different from $\delta p_{0,2}(Y)$. In order to obtain quantitative data, on each of the figures we have plotted the calculated relation $\eta = \cos(kY)$, where the values of k have been chosen to give the best agreement with the measured curves. For sample No. 1, $k_{0,2} = 1.15$, $k_1 = 0.64$, $D_{0,2} = 62$ cm^2 sec^{-1}, $D_1 = 330$ cm^2 sec^{-1}. For sample No. 2 $k_{0,2} = 0.83$, $k_1 = 0.35$, $D_{0,2} = 66$ cm^2 sec^{-1}, $D_1 = 460$ cm^2 sec^{-1}. The measured values of $D_{0,2}$ are in good agreement with the calculated value $D = 65$ cm^2 sec^{-1} for the case of ordinary collisional diffusion of electrons and holes with the crystal lattice

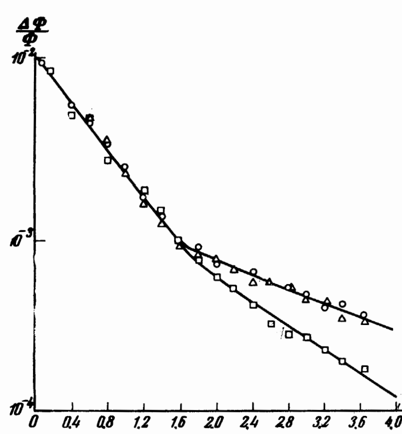

FIG. 3. Absorption curve of light along the axis of the semiconductor sample with dimensions $2 \times 2 \times 5$ mm ($s = 1600$ sec^{-1} cm): ○) $B = 0.9\ B_c$; □) $B = 1.2\ B_c$, $I_2 = 0$; △) $B = 1.2\ B_c$, $I_1 = 2I_0$.

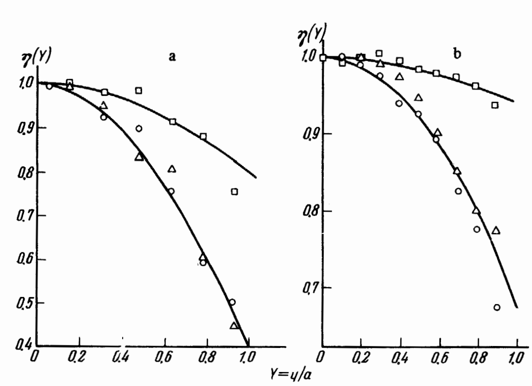

FIG. 4. Curve showing the absorption of light in the direction transverse to the sample: a) Sample with dimensions a) $2 \times 2 \times 5$ mm, $s = 1600$ cm sec^{-1}, b) $1.5 \times 1.5 \times 5$ mm, $s = 800$ cm sec^{-1}. The notation on the experimental points is as in Fig. 3.

while $D_{0,2} < D_1$, which verifies the anomalous value of the diffusion coefficient of the plasma in the unstable turbulent state as expected from theory and from experiments with gas plasmas.

We return now to the data obtained from the functional relation $\delta p(x)$, comparing these with the results of the measurements of $\delta p(Y)$. As we have already noted, $L = \mu E\tau$. In the case of the sample with the square cross section the quantity τ can be found from the general relation

$$\frac{1}{\tau}=\frac{1}{\tau_0}+\frac{2k^2}{a^2}D. \tag{10}$$

Substituting in Eq. (10) the data obtained from the analysis of the measurements of $\delta p(Y)$ we find the computed values $\tau_{0,2} = 0.52\times10^{-4}$ sec, $\tau_1 = 0.32\times10^{-4}$ sec. From the values $\tau_{0,1,2}$ we can compute the corresponding values for D and τ from $\delta p(Y)$, obtaining the diffusion lengths $L_{0,2} = 0.2$ cm and $L_1 \approx 0.12$ cm. Comparing the values of $L_{0,1,2}$ obtained from $\delta p(Y)$ with those obtained from $\delta p(x)$, the values $L_{0,2} = 0.21$ cm and $L_1 = 0.12$ cm, we find that the data obtained in the measurements of $\delta p(x)$ and $\delta p(Y)$ are in satisfactory agreement.

Thus, in these experiments we have found a relation between the anomalous increase of the diffusion coefficient in the plasma and the instabilities. In fields $B > B_c$ the quantity D has been found to increase by a factor of 5 or 6. It is also shown that in the stable state, in which $B < B_c$, and in the state in which $B > B_c$, but in which the instability is suppressed by means of rf currents, the diffusion processes are described by the usual collisional theory, that is to say, the turbulence of the plasma does not play a role in the transport processes. This result is a direct demonstration of the high efficiency of stabilization of the Kadomtsev-Nedospasov instability by means of rf fields in a semiconductor plasma. The absence of any instability caused by the rf currents is due to the fact that under the present experimental conditions the plasma is characterized by high dissipative losses so that current-driven instabilities are quenched.

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