RADIAL DIFFUSION OF CHARGED PARTICLES IN A HIGH-FREQUENCY DISCHARGE IN A MAGNETIC FIELD

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The effect of an axial magnetic on radial diffusion of charged particles has been investigated. A comparison is made of the experimental diffusion coefficients with those computed from diffusion theory and those computed on the basis of the theory of ion-acoustic waves.

INTRODUCTION

IN recent years[1-8] a great deal of evidence has been accumulated to show anomalous radial diffusion of charged particles in the plasma produced in a high-frequency discharge in the presence of an axial magnetic field of sufficient strength. As a rule, the nature of the diffusion has been inferred from the dependence of a number of internal and external parameters of the discharge on the strength of the magnetic field. Such parameters are those which are related to the balance of charged particles, for instance the voltage across the tube, the power applied to the tube, the electron temperature, the transverse electric field, the ionization rate due to electrons, and the amplitude of the plasma noise. However, direct measurements of the transverse diffusion coefficients have not been carried out.

In the present work we present the results of measurements of the radial diffusion coefficient for charged particles as a function of the magnetic field in high-frequency discharges in helium and neon. A comparison is made of the experimental diffusion coefficients with those computed on the basis of classical diffusion theory and those computed on the basis of ion-acoustic waves. A preliminary report concerning certain results was given in [8].

EXPERIMENTAL APPARATUS AND METHOD OF MEASUREMENT

In Fig. 1 we show schematically a part of the experimental arrangement. The inner diameter of the discharge tube is 28 mm. Two movable cylindrical probes (length 2 mm, radius 0.1 mm) and two plane grid probes (diameter 4 mm) are sealed into the central region of the discharge tube. The criterion for the validity of conventional probe methods is the condition that the mean value of the electron Larmor radius must be larger than the dimensions of the probe in the direction of the magnetic field.[9] In order to satisfy this requirement the cylindrical probes are oriented perpendicularly to the magnetic field.

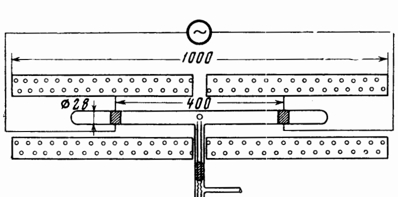

FIG. 1. Diagram of the discharge tube.

The high-frequency generator is coupled inductively to the external electrodes of the tube and has a balanced output. The current through the tube is measured by means of a shielded high-frequency current transformer wound directly on the central portion of the tube. The high-frequency signal is rectified and measured with a dc instrument. The measurement system is calibrated at the operating frequency. The voltage applied to the tube electrodes is measured with an electrostatic voltmeter. The magnetic field is produced by two solenoids that provide fields up to 600 Oe.

The measurements are carried out in the pressure range 0.03–0.20 mm Hg in helium, and 0.02–0.20 mm Hg in neon. The basic measurements are carried out at a frequency of 4.2 MHz. Certain of the measurements in helium were carried out at 28 MHz. The radial distribution of the electron temperature and charged particle density are determined by means of the two movable cylindrical probes.

The data are analyzed by the usual formulas for the double-probe method.[10] The ion current density at the wall is determined by the double-probe characteristics for two plane probes located flush with the wall. In order to find the radial distribution of potential the potential difference between the floating potentials of the cylindrical probe at a given point and the plane probe at the wall is measured. To this difference is added the difference between the space potential and the floating potential of the cylindrical probe. This quantity is computed from the results of probe measurements. The relative values of the noise amplitude in the plasma is determined in the range 1–500 kHz with a tunable amplifier or a spectrum analyzer coupled to the probe circuit.

The radial ambipolar diffusion coefficients D_{exp} and the mean ionization rate Z due to the electrons are determined from the results of the probe measurements through the use of the following expressions:

$$j_p = -eD_{exp}\left(\frac{dn}{dr}\right)_R, \quad (1)$$

$$Z = \frac{2\pi R j_p}{eN_e}, \quad (2)$$

where j_p is the ion current density at the wall, $(dn/dr)_R$ is the electron density gradient at the wall, e is the charge of the electron, $N_e = \int_0^R n(r) 2\pi r dr$ is the number of electrons per unit length of the column, n(r) is the radial density distribution of charged particles and R is the radius of the tube. Equation (2) is obtained under the assumption that the chief mechanism for the loss of charged particles is loss at the walls of the tube.

The density gradient is determined by dividing the value of the electron density at a distance of 2 mm from the wall by this distance. The electron density at the wall is thus assumed to be equal to zero. This extrapolation is in agreement with the measured radial electron distribution and evidently does not introduce errors since the values of the diffusion coefficient determined at points close to the axis agree with the values at the walls (within the limits of the allowable error).

Special investigations were made to determine the effect of misalignment of the tube with respect to the magnetic field. These measurements show that the misalignments that are possible in the experimental apparatus used here have essentially no effect on the measured results. This finding is in agreement with the criteria obtained in [11]. The intensity of the radial electric field is determined by the radial distribution of the potential at a distance 10 mm from the axis of the tube.

RESULTS OF THE MEASUREMENTS

In most of the work on high-frequency discharges the measurements are carried out with a fixed effective value of the high-frequency voltage. However, if the magnetic field is changed, maintaining a fixed value of the high-frequency voltage means a significant change in the discharge current. In the present work most of the measurements have been carried out with a fixed value of the discharge current. In most cases the measured radial distribution of charged particles is in good agreement with a Bessel distribution (Fig. 2).

When a magnetic field is applied at pressures of 0.02–0.05 mm Hg a tendency towards a less steep decay of the electron density in the radial coordinate is observed at the central region of the discharge tube. At a pressure of 0.2 mm Hg the application of a magnetic field has essentially no effect on the radial electron distribution.

In Table I we show the experimental results for the radial diffusion coefficient D_{exp}, the mean ionization rate due to electrons Z and the intensity of the radial electric field E_{exp} for a discharge in helium. As is evident from this table, at low pressures these discharge parameters are reduced as the magnetic field H is increased; this process continues up to some critical value and then, at magnetic fields of the order of several hundred Oersteds, these parameters increase or remain unchanged. The minimum values for the diffusion coefficient and the mean ionization frequency are not clearly defined. The dip in the electric field is sharper.

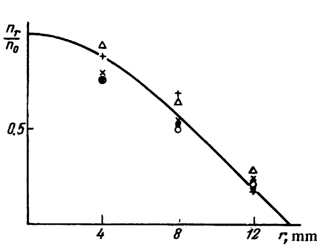

FIG. 2. Radial distribution of charged particle density in helium (p = 0.5 mm Hg, i = 25 m A): ●) H = 0, X) H = 10 Oe, O) H = 100 Oe, Δ) H = 300 Oe, +) H = 500 Oe.

In the table we show the values of the radial ambipolar diffusion coefficient D_a and the radial electric field E_a as computed from the classical diffusion formulas

$$D_a(H) = \frac{D_a(0)}{1 + b_{e0} b_{p0} H^2/c^2}, \tag{3}$$

$$E_a(H) = -\frac{\nabla n}{n} \frac{D_{eH} - D_{pH}}{b_{eH} + b_{pH}}, \tag{4}$$

$$b_{eH} = \frac{b_{e0}}{1 + (b_{e0} H/c)^2}, \tag{5}$$

$$D_{eH} = \frac{D_{e0}}{1 + (b_{e0} H/c)^2} \tag{6}$$

where b_{e0}, b_{p0}, D_{e0}, D_{p0}, and $D_a(0)$ are the values of the mobility and diffusion coefficients for the electrons and ions and the ambipolar diffusion coefficient in the absence of a magnetic field. The quantities b_{pH} and D_{pH} are determined from expressions similar to Eqs. (5) and (6) and c is the velocity of light.

In order to compute the ion mobility we have used the charge-exchange cross section[12] and to compute the electron mobility we have computed the total electron cross section. The ion temperature is taken to be 300°K.

A comparison of the computed and measured results of these parameters shows that at low pressures with no magnetic fields and at magnetic fields of several tens of Oersteds the agreement is quite good. At higher magnetic fields the experimental values are much higher than the theoretical values. These differences can be as high as an order of magnitude. At a pressure of 0.2 mm Hg the effect of the magnetic field is less pronounced.

In the table we also show the values of the diffusion coefficient computed from the mean ionization rate computed from the Schottky diffusion theory:

$$D_{sch} = Z \frac{R^2}{(2.405)^2}. \tag{7}$$

The agreement between these values and the experi-

Table I. Results of the measurements in helium

p, mm Hg	i, mA	V, V	H, Oe	$D_{exp} \cdot 10^{-5}$, cm²sec	$D_{sch} \cdot 10^{-5}$, cm²/sec	$D_a \cdot 10^{-5}$, cm²/sec	$Z \cdot 10^{-5}$, sec⁻¹	E_{exp} V/cm	E_a, V/cm
0.2	80		0	4.5	5	1.5	15	20	10
			100	4	4	1.5	12	20	9
			300	2.5	3	0.6	9	18	5.5
			500	2	2	0.3	7	15	3.5
0.05	25		0	6	7.5	8.5	22	16	15
			10	5	6.5	8	20	16	15
			100	4.5	5.5	2.5	16	16	5
			300	4.5	6	0.4	17	25	1
			500	7.5	7	0.2	20	30	0.5
0.05		1200	0	8.5	10	10	30	15	15
			10	7	10	8	30	12	15
			100	6	7.5	3	22	16	5
			300	5.5	7.5	0.5	22	30	1
			500	7	9.5	0.2	23	30	0.5
0.03	25		0	9.5	9	10	27	16	15
			60	6	6.5	6	18	12	6
			100	7	6.5	2.5	19	12	3
			500	7.5	7	0.2	21	29	0.3

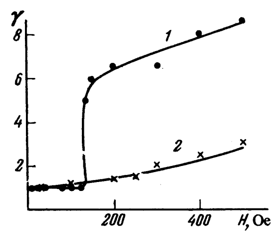

FIG. 3

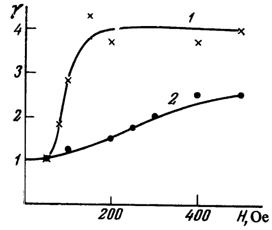

FIG. 4

FIG. 3. The relative noise level as a function of magnetic field in helium: 1) p = 0.05 mm Hg, 2) p = 0.2 mm Hg.

FIG. 4. The relative noise level as a function of magnetic field in neon: 1) p = 0.04 mm Hg, 2) p = 0.2 mm Hg.

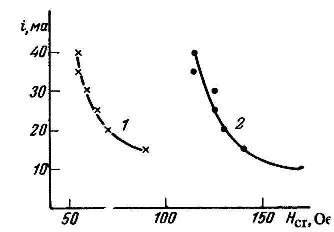

FIG. 5

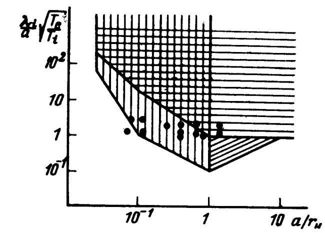

FIG. 6

FIG. 5. The critical magnetic field as a function of discharge current: 1) helium, p = 0.05 mm Hg, 2) neon, p = 0.04 mm Hg.

FIG. 6. The region of the ion-acoustic instability (vertical hatching) and the drift instability (horizontal hatching).

mental values is satisfactory. This result means that the motion of the charged particles in the magnetic field can be regarded formally as being due to diffusion, although the diffusion coefficient is anomalously large.

The anomalous dependence of the plasma parameters on magnetic field might be explained by the existence of instabilities in the plasma. Support for this suggestion is given by the nature of the change in the noise level at increased magnetic field that has been noted by a number of authors.[2-8] In the present work at first no change in the noise level is noted as the magnetic field is increased although the diffusion coefficient and the mean ionization rate are reduced. A sharp increase in the noise level is observed when the indicated parameters reach their minimum values. A detailed analysis carried out with a spectrum analyzer shows that up to 500 kHz the detected oscillations are of a white-noise nature. The dependence of the relative noise level γ (at a frequency of 80 kHz) on magnetic field for different pressures is shown in Fig. 3 and Fig. 4. It is evident that the nature of the noise level at a pressure of 0.2 mm Hg, for which one observes a monotonic drop in the diffusion coefficient, is different from that observed at lower pressures. We note that a pressure 0.2 mm Hg the configuration of the discharge is different from that which is observed at pressures of 0.03 and 0.05 mm Hg. It corresponds to the configuration which has been called the strong-current configuration;[1] on the other hand the configurations that are observed at lower pressures correspond to a weak discharge.

In Table II we show the results of the measurements and calculations for neon. In general the behavior of these parameters with increasing magnetic field is similar to that observed in helium. However, the anomalous diffusion appears at somewhat lower values of the magnetic field. This effect is evident in the curve in Fig. 5 in which we show the dependence of the critical magnetic field on discharge current as determined from the sharp rise in the noise level.

Table II. Results of the measurements in neon

p, mm Hg	i, mA	H, V	$D_{exp}\cdot 10^{-5}$, cm²/sec	$D_{sch}\cdot 10^{-5}$, cm²/sec	$D_a\cdot 10^{-5}$, cm²/sec	$Z\cdot 10^{-5}$, cm²/sec	E_{exp}, V/cm	E_a, V/cm
		0	1.5	1.5	0.6	5	15	10
		10	1.5	1.5	0.6	5	15	10
0.2	100	100	1.5	1.5	0.6	4.5	10	10
		300	1	1	0.4	3.5	5	7.5
		500	1	1	0.3	3	1	4
		0	3.5	3.5	5	10	15	20
		10	3.5	3	5	9	15	20
0.04	25	100	3	2.5	1.5	7	9	5
		300	3	3.5	0.2	10	10	0.5
		500	2.5	3.5	0.06	10	15	0.2
		0	5.5	5.5	10	15	20	20
		10	5.5	5.5	10	15	20	20
0.02	30	100	3.5	3	0.8	9	5	1.5
		300	3.5	4	0.1	12	10	0.1
		500	3.5	4	0.03	12	15	0.01

It has been suggested in [4,5] that the observed anomaly in the behavior of high-frequency plasma in a magnetic field is due to the drift-dissipative instability associated with the excitation of ion-acoustic oscillations. Timofeev[13] and Kadomtsev[14] have indicated a region of plasma parameters in which the drift-dissipative instability arises. This region is shown schematically in Fig. 6 following the results of [14]. In the figure we have plotted points that correspond to the conditions of the plasma in the high-frequency discharge for which an anomalous diffusion is observed together with a significant increase in the noise level. It is evident that these conditions correspond to the excitation of ion-acoustic waves.

In the discharge the electrons and ions drift to the wall at a rate given by $D_a \nabla n/n$. In order that the ion-acoustic perturbation develop before the corresponding element of the plasma is lost to the walls of the tube this rate must be smaller than the velocity of propagation of the ion-acoustic wave $C_s = \sqrt{kT_e/M}$ where T_e is the electron temperature, M is the ion mass and k is the Boltzmann constant. Thus, the condition

$$D_a \frac{\nabla n}{n} = C_s \qquad (8)$$

provides an estimate of the critical magnetic field H_{cr} above which the excitation of ion-acoustic waves can lead to an anomalous diffusion.

The condition in (8) can be written in more convenient form if we assume $b_{e0} b_{b0} H^2 c^{-2} \gg 1$ and write $\nabla n/n \approx 2/R$ in order to carry out estimates:

$$\frac{H_{кр}}{p\sqrt{T_e}} = \sqrt{\frac{2c^2k(mM)^{1/2}}{e^2\lambda_{0e}}}\,(pR)^{-1/2}, \qquad (9)$$

where m is the electron mass, p is the pressure of the gas and λ_{0e} is the mean free path for the electrons at 1 mm Hg. In Fig. 7 and Fig. 8 the solid lines show the functional relation (9) while the vertical segments show the experimental data for the critical field. The length of these segments is determined by the dependence of the critical field on current (Fig. 5). Both the value of the critical field and the variation with pressure are in agreement with the predictions of the theory of the ion-acoustic instability.

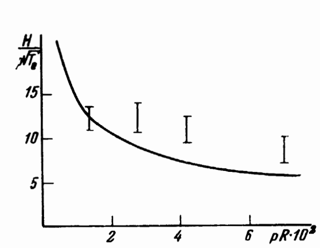

FIG. 7

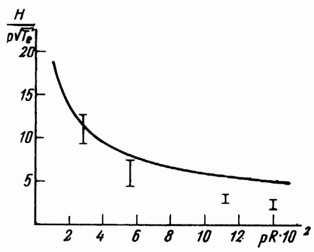

FIG. 8

FIG. 7. Comparison of the experimental values of the critical magnetic field with those computed from Eq. (9) for helium.

FIG. 8. Comparison of the experimental values of the critical magnetic field with those computed from Eq. (9) for neon.

Kadomtsev[14] has given an estimate for the diffusion coefficient in a turbulent plasma in the presence of the ion-acoustic instability:

$$D_t \approx \frac{C_s}{\nabla n/n}. \quad (10)$$

For the critical magnetic field Eq. (10) gives a value of the diffusion coefficient that coincides with the critical value. For a field higher than the critical value the diffusion coefficient computed from Eq. (10) shows essentially no change with magnetic field. The values of the diffusion coefficient computed from Eq. (10) are in good agreement with the experimental values of the radial diffusion coefficient (Table III).

Table III. Comparison of the diffusion coefficient D obtained from the experimental data (E) and computed from Eq. (10) (T)

p, mm Hg	$H = 100$ Oe		$H = 300$ Oe		$H = 500$ Oe	
	E	T	E	T	E	T
helium						
0.05	6	8	5.5	8	7	10
0.03	7	10	—	—	7.5	10
neon						
0.04	3	4	3	3.5	2.5	3.5
0.02	3.5	4	3,5	3.5	3.5	3.5

Thus, direct measurements of the dependence of the ambipolar diffusion coefficient on the magnetic field in a high-frequency discharge verify the anomalous nature of the diffusion at high magnetic fields. Anomalous diffusion, under the present conditions, is evidently related to the appearance of ion-acoustic waves.

In conclusion, we wish to thank Yu. M. Kagan for discussions.

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