APPLICABILITY OF LANGMUIR'S PROBE THEORY FOR MEASURING AN ION-ION PLASMA

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On the basis of published works devoted to probe measurements in an ion-ion plasma, we consider the possibility of using the theory of orbital motion to find the parameters of a low-temperature ion-ion plasma. We discuss the problem of overestimating the temperature of the ions, which is determined by the method of taking logarithms of the second derivative of the volt-ampere characteristic. A comparison is made with results of measurements performed by the theory of orbital motion for cylindrical probes.

As is known, the theory of orbital motion (OLM) was developed by Langmuir and Mott-Smith early in the 20th century [1]. It rather adequately described the behavior of currents of particles drawn to a probe in the case of a thick layer. Such a layer appears at low concentrations of charged particles, when the condition $h >> a$ is satisfied. In the case of an electron-ion plasma the OLM theory for probes of different geometrical shapes gives the following functional relations for saturation currents:

$I(U) \sim$ const for a plane probe;

$I(U) \sim (kT + eU)^{1/2}$ for a cylindrical probe;

$I(U) \sim eU$ for a spherical probe.

In fact, in a wide range of plasma parameters the above relations correspond to experimental curves. In particular, for the most widely used cylindrical probes the function $I^2(U)$ is a straight line, and its intersection with the axis of the potential gives the value of the temperature of the corresponding species of particles.

The "unpleasantnesses" of the OLM theory begin when probe measurements are made in an ion-ion plasma that appears in stationary discharges of gases that have a high degree of electronegativity $\alpha >> 1$ [2] or in the afterglow of a pulse discharge [3-5]. For example, in [2] a stationary discharge in iodine at a pressure of $P = 0.24$ torr and a discharge current of 1.2 mA was investigated. Plasma was produced in a spherical volume 15 cm in diameter, and its diagnostics was made by plane and spherical probes that had an area of 0.071 and 0.031 cm^2, respectively. Using these probes, volt-ampere characteristics (VAC) and the second derivatives with respect to the potential of the probe ($I''(U)$) were obtained. Figure 1a presents VACs taken from [2]; they were used to construct the functions $I^2(U)$ (Fig. 1b). The symmetric form of the VACs allowed the author of [2] to make the conclusion of the absence of electrons in the discharge. The temperature of the ions was determined from the slope of the logarithm of $I''(U)$ [6]:

$$\frac{kT}{e} = \frac{U_2 - U_1}{\ln (I_1''(U)/I_2''(U))},$$

and it was equal to 0.05–0.06 eV. As is known, there cannot be separation of temperature between the neutral component and the ions because of the large cross section for recharging reactions. According to estimates, the gas temperature does not exceed 0.04 eV even if all the energy put into the discharge is spent exclusively on heating the gas. The value 0.06 eV corresponds to 700 K, which is substantially in excess of the estimate.

In [2] the approximate value of the concentration of the ions $n = 8.5 \cdot 10^8$ cm^{-3} is also given, but the method by which this value was obtained is not mentioned. Most probably, the density was determined by integration of $I''(U)$, but this means that the author identifies $I''(U)$ with the energy distribution function (DF) of

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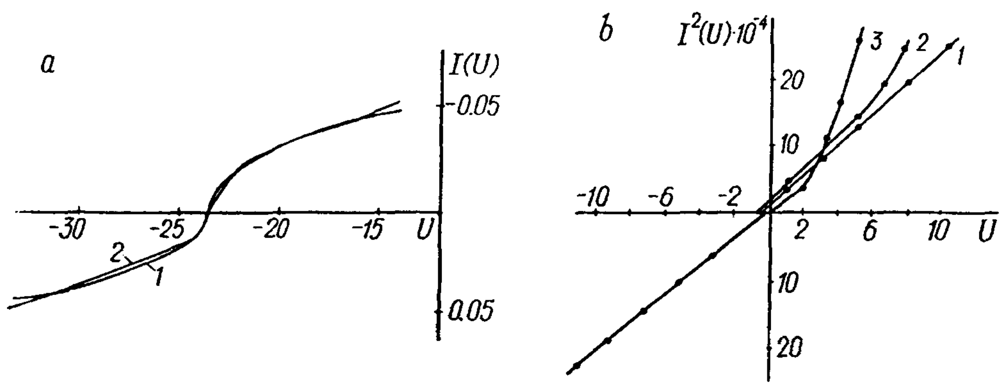


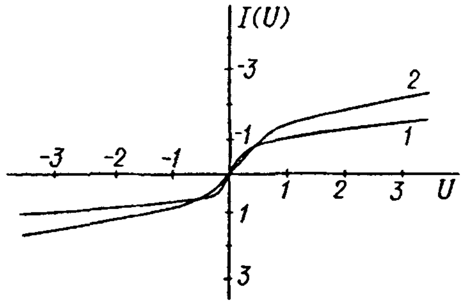
Fig. 1. Volt-ampere characteristics measured in iodine (a) and the dependence $I^2(U$ (b): 1) plane probe, 2) spherical probe, 3) $I^2(U) = U^2$. I, μA; U, V.

the ions. In fact, the second derivative of the current consists of a number of terms and only one of the components is proportional to the DF. In each specific measurement care should be taken to see that all the remaining components are substantially smaller than the DF. Since the current of attracted particles is not saturated (see Fig. 1), one must not neglect the contribution of its second derivative to the total $I''(U)$. Otherwise the magnitude of the density determined by the method of integration can be overestimated severalfold.

Let us make some elementary estimates that characterize the near-probe layer. Under the conditions given in [2] the Debye radius is 0.004 cm, the maximum of the thickness of the volumetric-discharge layer is $h = 0.023$ cm when $eU >> kT$, and the radius of the spherical probe is 0.05 cm. In the classification adopted $h < a$ and the VAC of the probe must have a region of saturation. We arrive at a contradiction: according to estimates, the near-probe layer is plane, whereas the layer of saturation is not (see Fig. 1a). According to the theory, at comparatively high concentrations of the charged particles, the case of a thin layer is realized, and the VACs of probes have a distinct region of saturation. A study of the problem of the shape of the characteristics of probes of various geometries [6] showed that even in the case of OLM the VAC of a plane probe must have a region of saturation. The current of attraction to a spherical probe in the mode of orbital motion on condition that $eU >> kT$ must have the asymptote $I(U) \sim U$. In processing experimental VACs taken from [2] it was found that for a plane probe the dependence $I(U) \sim U^{1/2}$ holds, i.e., $I^2(U)$ is a straight line. Results of processing curves by the $I^2(U)$ method for plane and spherical probes are given in Fig. 1b. For the sphere, $I^2(U)$ coincides in a wide range of values of eU with the corresponding function of the plane probe; the difference in the squares of the VACs becomes substantial when $eU > 200kT$. The figure also contains a graph of $I^2(U) \sim U^2$, which must be the case for the current of a spherical probe according to the OLM theory. A strong difference between the experimental and theoretical curves can be noted. The density of particles found by the $I^2(U)$ procedure [6] was equal to $3.2\cdot 10^8$ cm^{-3} for the spherical probe, and it was assumed that molecular ions of I_2 are the main charged particles. The value obtained is 2.5 times smaller than the estimate given in [2]. At this magnitude of the density the layer thickness exceeds the radius of the spherical probe by a factor of 1.5–2, i.e., the motion of particles to the probe is described by the OLM theory without any provisos. Processing of the VAC of the plane probe by the same procedure showed that the concentration of ions was $1.5\cdot 10^8$ cm^{-3}, i.e., the layer becomes thicker still and the motion of the charged particles becomes more "orbital." But the problem of the shape of the probe characteristics has not received its resolution from this.

On the other hand, it is reasonable to dwell on experimentally obtained VACs in the afterglow of an oxygen plasma [7, 8]. We shall give several experimental curves that also testify to the deficiency of the probe theory. We shall give a brief description of the experimental apparatus. A pulse-discharge plasma with a frequency of 1.5 kHz was produced in a cylindrical tube of length 40 cm and radius 1.75 cm. The oxygen pressure was varied from 0.04 to 0.07 torr, the discharge current was varied from 10 to 400 mA, and the pulse repetition rate was equal to 10. Several mobile probes made of molybdenum were fused into the discharge tube.

Figure 2 presents VACs taken from cylindrical probes of different radii: a "thick" one of length 0.25 cm and radius 0.04 cm and a "thin" one with $l = 1.5$ cm and $a = 0.005$ cm. The oxygen pressure was 0.04 torr, the current in a pulse was 180 mA, and the delay time was 250 μsec. At these parameters, an ion-ion plasma was



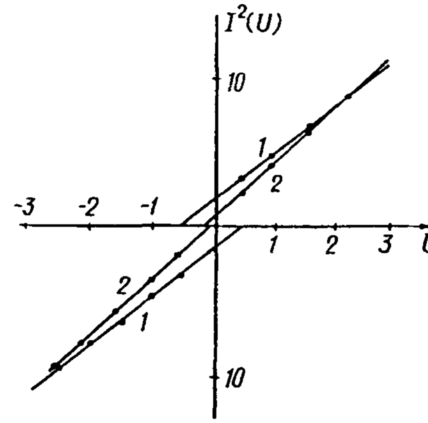
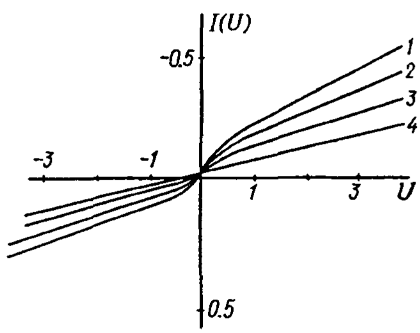


Fig. 2. Volt-ampere characteristics measured on the axis of a tube in the afterglow of an oxygen plasma: 1) "thick" probe, 2) "thin" probe.

Fig. 3. The function $I^2(U)$: 1) "thick" probe 2) "thin" probe. I^2, rel. units.



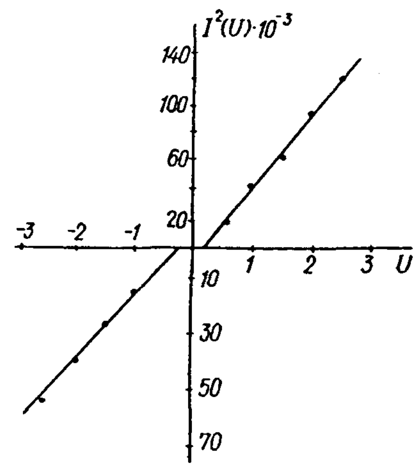


Fig. 4. Radial distribution of the volt-ampere characteristics in the afterglow of an oxygen plasma: 1) $r = 0$, 2) 0.5, 3) 1, 4) 1.5 cm.

Fig. 5. The function $I^2(U)$ for the volt-ampere characteristic measured on the tube axis.

formed in the afterglow of the oxygen plasma as a result of predominant destruction of electrons [5]. The characteristic values of the concentrations of the ions determined for these probes by the $I^2(U)$ method turned out to lie in the range of $(1.8-4.4) \cdot 10^9$ cm^{-3}. The maximum thickness of the layer is 0.015 cm; then for the "thin" probe $h/a = 3$ and the motion of ions in the layer is described by the OLM theory, and for the "thick" probe $h/a = 0.375$, i.e., the layer becomes thin. A tendemcy of the VAC to saturation of the current with increase in the radius of the probe is noticeable, which to a certain extent corresponds to the theory. Nevertheless, when $eU >> kT$, the function $I^2(U)$ lies on a straight line for both VACs (see Fig. 3). The matter of determination of the temperature of the particles is more difficult. It is seen from the figure that for the "thin" probe the temperature of the ions is rather close to room temperature, which cannot be said about the intersection of $I^2(U)$ with the abscissa for the "thick" probe. For it the doubled temperature amounts to about 1 eV. But this result can easily be explained: at a ratio $h/a = 0.375$ the OLM theory is not applicable, and therefore the temperature of the particles must be determined by a different method.

Still another paradoxical result, from our point of view, is obtained when VACs are processed in the case of low densities of the ions. Thus, in Fig. 4 radial probe characteristics are presented that were measured at a pressure of 0.07 torr, a pulse current of 10 mA, and a delay of 300 μsec [9]. The molybdenum probe had a length of 0.35 cm and a radius of 0.005 cm. The function $I^2(U)$ for the VAC of a probe located on the axis of the tube is presented in Fig. 5. It is seen that when $eU >> kT$, $I^2(U)$ lies on a straight line. The concentration of ions determined from the slope of $I^2(U)$ turned out to be equal to 10^9 cm, the thickness of the layer was of the order of 0.04 cm, and correspondingly $h/a = 8$. One might think that there is no better condition for orbital motion, but again a problem arises with determination of the temperature: it not only turns out to be substantially overestimated, namely, 0.25 eV (by a factor of 10!), but also the intersection of $I^2(U)$ with the abscissa is the reverse in comparison with Figs. 1 and 3. Systematic measurements of the VAC in the afterglow of weak-current discharges with subsequent processing by the $I^2(U)$ method confirmed the result found earlier. Moreover, such a picture can be obtained if the VAC given in Fig. 7 in [8] is processed by the $I^2(U)$ method.

Thus, the most reliable values of the parameters of an ion-ion plasma are obtained in processing the VAC by the theory of orbital motion. Here the difference in the determination of the values of the temperature of the ions and their densities is explained exclusively by the geometry of the near-probe layer, namely, the ratio h/a. Processing of probe curves shows that the OLM theory can be used for determining the concentration of the ions when $h/a > 1$, and values of the temperature close to the actual ones are obtained when $1 < h/a < 3$. However, the contradictions indicated in this work between the theory and experimental data underline the need for further development of the theory of probe measurements.

NOTATION

a, radius of the probe; e, charge of an electron; I_2, iodine molecule; $I(U)$, current onto the probe; $I''(U)$, second derivative of the current with respect to the potential of the probe; h, thickness of the layer of volumetric charge; k, Boltzmann constant; l, length of the probe; n_e, concentration of electrons; n, concentration of negative ions; p, concentration of positive ions; r, instantaneous radius of the tube; S, area of the probe; T, temperature of the ions; U, potential applied to the probe; α, degree of electronegativity, $\alpha = n/n_e$.

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