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ANOMALOUS ELECTRON SCATTERING AND THE EXCITATION OF PLASMA OSCILLATIONS

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We have studied the interaction of an electron beam with an independently formed plasma, an interaction leading to an appreciable change in the electron energy and to the excitation of plasma oscillations. The observed data can qualitatively be interpreted by assuming that the electrons form clusters and that these clusters interact coherently with the plasma.

THE phenomenon of the so-called anomalous scattering, which consists in that electrons passing through a plasma experience a strong interaction leading, in particular to the occurrence of anomalously fast electrons, was already described by Langmuir.[1] In a careful study Merrill and Webb[2] established the connection between this phenomenon and the plasma oscillations and in a number of later papers further experimental studies of this effect were made[3-6] or attempts were made to interpret Merrill and Webb's experiments.[7-10] Notwithstanding the progress made in both directions, this problem has not lost its urgency and a further elucidation of it is not only required as far as an additional analysis of the physical phenomena is concerned, but also with respect to obtaining new experimental data.

The method applied in the present research enabled us to analyze more thoroughly the electron beam which passes through the plasma. It was also more flexible since it allowed us to change independently the plasma parameters and those of the electron beam passing through the plasma. This possibility was, for instance, already present in the work of Polin and Gvozdover[11] and of Looney and Brown,[3] but was not used in the direction in which we are interested.

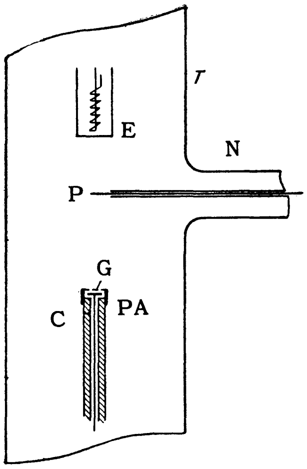


FIG. 1. Diagram of part of the experimental apparatus. E – oxide heater cathode; PA – probe analyzer; G and C – grid and collector of the probe analyzer.

THE METHOD

The apparatus studied was a glass tube T (Fig. 1) which had a lateral branching tube O. Using a liquid-mercury cathode and a system of anodes, one can form a plasma in the mercury vapors along the tube T. By changing the current I_a in the circuit of one of the anodes, we could change the concentration of charges of this plasma, usually within the range from 1×10^9 to 1.5×10^{11} cm^{-3}. We took care that that part of the apparatus which contained the liquid-mercury cathode was removed from the plasma region studied; the liquid cathode was in the coldest position and at constant temperature, so that condensation of mercury at other, hotter places was avoided; the mercury vapor pressure was $p \approx 10^{-3}$ mm Hg.

As an electron source we could use a tungsten filament, a tantalum heater cathode, or an oxide heater cathode E. In that part of our research which is described here we used mainly an oxide cathode. By applying an appropriate potential difference between the anode and the emitter E, we could introduce an electron beam into the plasma. The notation used in the following, for instance, E = 50 v, means that the cathode potential relative to the anode was – 50 v; the energy of the electrons entering the plasma was in fact less by 2 v (anode drop).

In all similar investigations[1,2,4,5,11] the analysis of the velocity of the velocity of the electrons passing through the plasma was performed by plotting the normal probe characteristics. Since in that case the division between the fast primary electrons and the "plasma electrons" is impeded and since at high energies of the primary electrons a strong distortion may arise due to the secondary emission from the probe, we employed for such an analysis a modulation of the electron beam in conjunction with use of probe-analyzer PA. The latter consisted of a collector C and a grid G (diameter 1.5 mm, wire diameter 10 μ, width of the square mesh of the grid 50 μ) which screened it from the plasma. A relatively small negative grid potential U_{ac} produces an overlap of it with the ionic film and a delay of the main flow of the plasma electrons. A sufficiently large positive collector potential (for instance +100 v relative to the grid) does not allow the positive ions from the plasma to fall upon the collector; the collector potential was so chosen that a change in it did not produce a change in the collector current. On the collector may impinge: fast primary electrons which cannot be delayed by the grid for a given potential U_{ac}, a small fraction of the plasma electrons, and some fraction of the secondary electrons knocked out of the grid. The last two components of the collector current are weakly affected by the characteristics, and even less in the case of a modulation of the electron beam. The above-mentioned low-frequency modulation was realized in such a way that the cathode E periodically, during 1/40 sec, was at a chosen negative potential, and during the next 1/40 sec at a potential close to the plasma potential. The current in the collector circuit was in that case measured by means of a narrow-band smplifier (frequency 20 cps, band width 2 cps) and all effects connected with the unmodulated plasma in the main discharge were not affected by the characteristics. In Fig. 2, curves 1 and 2 show the dependence of the collector current on the retarding grid potential PA – U_{ac} obtained for a small value of the electron beam current I_e, when there is no anomalous scattering. The fact that the collector current becomes equal to zero for a potential less than 50 v can be explained by the contact potential difference between the grid and the oxide cathode. The drop in potential between the loops of the grid was estimated, and in the most unfavorable case was not more than 1 or 2 v. For small retarding potentials of the grid ($U_{ac} < 20$ v) the behavior of the characteristic was discontinuous, for obvious reasons. The probe-analyzer with a grid of the given geometry could therefore not be used for small beam energies. In that case, and also in other cases when the PA cannot be used for different reasons, one can use a normal cylindrical probe P with simultaneous modulation of the electron beam. The modulation by itself allows us to separate the probe current of primary electrons (more exactly, the current of the primary beam and the modulated components of the plasma currents) from the probe current, which is connected with the unmodulated plasma of the main discharge.

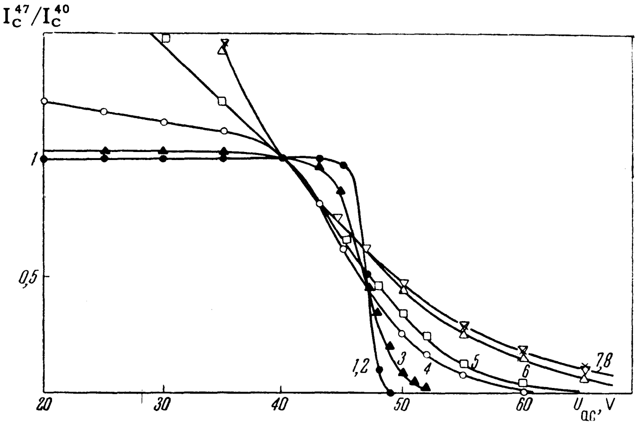


FIG. 2. Dependence of the current in the collector (PA) circuit on the potential of the grid of that probe ($I_a = 0.5$ amp, E = 50 v, l = 50 mm). 1 – $I_e = 0.05$; 2 – $I_e = 0.8$; 3 – $I_e = 1.2$; 4 – $I_e = 1.65$; 5 – $I_e = 2.25$; 6 – $I_e = 3.8$; 7 – $I_e = 6$; 8 – $I_e = 13$ ma.

To indicate the oscillations and to measure their frequency, it was most useful to use a double-wire line connected to the cylindrical probe P (length 5 mm, diameter 150 μ). The latter served also for a measurement of the plasma parameters.

In conclusion we note that both probes were movable and could be placed at any point in space, and their position could be fixed with an accuracy of 0.2 mm. By means of a small motor one could give the probe P a continuous, uniform motion and determine the spatial distribution of the intensity of the oscillations by an EPP-09 recording instrument with a synchronized moving tape.

ANOMALOUS SCATTERING. THE LIMITING CURRENT

In Fig. 2 the delay characteristics are given for different beam currents I_e (E = 50 v, $I_a = 0.5$ amp) corresponding to a particle concentration $n = 1.6 \times 10^{10}$ in the plasma. The ordinates of all curves are normalized at the point $U_{ac} = 40$ v. The probe-analyzer was at a distance $l = 50$ mm from the cathode. When the beam current is small, say $I_e = 0.05 - 0.8$ ma or less, all curves lie on one another (curves 1, 2). When, for the same beam currents, the particle concentration in the plasma of the main discharge is increased to $n \approx 1 \times 10^{11}$, the form of the characteristics is not changed.

Only beginning with the above-mentioned maximum concentration can one notice in the characteristics a small increase in loss, which can be assumed to be the result of a diffractive scattering connected with Coulomb interaction, as an estimate shows. More important effects were observed when the beam current was increased. As is clear from Fig. 2, starting from some value of the current I_e (curve 3), there appear electrons undergoing a large loss and also electrons with an energy appreciably higher than their original energy (Langmuir[1] was the first to show that these effects set in at large beam currents).

The strong interactions observed at large currents I_e are accompanied by a diffractive scattering of the beam. The particular curves of Fig. 2 were treated as follows. The dependence on the beam current of the ratio of the probe currents for a value U_{ac} near the threshold and one somewhat less [for $E = 50\,v$, the ratio I_c ($U_{ac} = 47\,v$) to I_c ($U_{ac} = 40\,v$)] was determined. Starting with some value of the beam current I_e, the value of this ratio rises steeply and the corresponding value of I_e is a limiting current I_{lim}. It is of interest to determine the dependence of the limiting current on the beam parameters and the parameters of the plasma with which the beam interacts. The data obtained are given in the table. These data correspond to an electron energy $E = 50\,v$. The most important consequence of this table is the independence of the limiting current on the charged-particle concentration in the plasma. We note that for a cathode diameter of 5 mm and $E = 50\,v$ a beam with a current $I_e = 1.0$ ma produces along its track a plasma with a concentration of charges $n \approx 5 \times 10^8$ cm^{-3}, so that the independence of I_{lim} from I_a, which we have established, corresponds to a wide range of values for the charged particle concentration in the plasma. The table discloses some dependence of the limiting current density on the cathode diameter, but since the measurements were performed only on cathodes of three different diameters, it is premature to insist on this sort of dependence. An analysis of similar curves shows that the magnitude of the limiting current increases approximately linearly with the electron energy.

The problem of the spatial location of the region where the observed anomalous scattering takes place is of interest. We cannot use the probe-analyzer in that case, since near the cathode it shows a strong perturbing action on the plasma. We therefore used the probe P simultaneously with modulation of the electron beam. By taking the probe characteristics at different distances from the cathode, we could plot $I_c(55)/I_c(40) = f(l)$, where $I_c(55)$ and $I_c(40)$ are the currents at the probe for grid potentials U_{ac} of 55 and 40 v respectively (electron energy $E = 50\,v$), and l is the distance from the cathode. Such a dependence is given in Fig. 3 for different beam currents I_e, all above the limiting current.

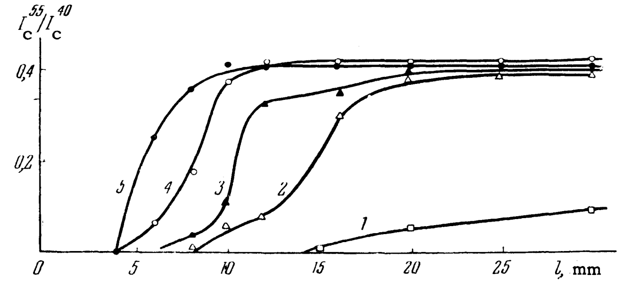


FIG. 3. Dependence of the relative number of anomalously fast electrons on the position of the probe ($I_a = 0.5$ amp, $E = 50$ v). 1 – I_e = 1.6; 2 – I_e = 3.8; 3 – I_e = 7.4; 4 – I_e = 12.4; 5 – I_e = 30 ma.

It follows from this figure that an increase of the electron energy occurs in a certain zone. When the beam current I_e is increased, this zone approaches the cathode and its width decreases. We could detect this zone by a somewhat different method and establish that it possesses a structure, for instance, it may consist of two separate zones.

The foregoing characteristics of the delay due to the observed diffractive scattering of the beam enable us to analyze the electrons only as far as the normal velocities are concerned and cannot serve to determine the total energy losses of the electrons. A specially developed method, which will be described elsewhere, made it possible to determine that for electron beam energies $E = 50$ to 125 v and for a current larger than the limiting value the average total energy loss of the electrons through the interaction with the plasma is 10 to 20%.

In conclusion we note that when the beam current is larger than the limiting value, one can observe an increase in the noise level in the plasma.

Type of cathode and its diameter, mm	$I_a = 0.05$ amp, $n = 1.6 \cdot 10^9$		$I_a = 0.5$ amp, $n = 1.6 \cdot 10^{10}$		$I_a = 5$ amp, $n = 1.6 \cdot 10^{11}$	
	I_{lim}, ma	j_{lim}, ma/cm²	I_{lim}, ma	j_{lim}, ma/cm²	I_{lim}, ma	j_{lim}, ma
Oxide, 3	0.9—1.1	12.7—15.5	0.6—0.8	8.5—11.3	0.5—0.7	7—9.9
„ 5	1—1.2	5.1—6.1	0.8—1.2	4.1—6.1	1,1—1,6	5.6—8.2
„ 10	7—9	8.9—11.5	6—8	7.6—10	5.6—6.6	7.6—10
Ta, 5	0.7—1.1	3.6—5.6	1—1.3	5.1—6.7	0,6—1,5	3.1—7.7

It was impossible to establish "monochromatic" oscillations in the general case.

EXCITATION AND QUENCHING OF PLASMA OSCILLATIONS

The occurrence of anomalously fast electrons can be explained by the production of microwave oscillations. However, in the general case one does not succeed in establishing monochromatic oscillations, as was mentioned above. To find such oscillations the condition $I_e > I_{lim}$ is necessary, but not sufficient. Only by an appropriate choice of I_e and E one can find such conditions that monochromatic oscillations are produced. In those cases one observed an easily expressed oscillation zone, the position and width of which depend both on the beam current (this was established in reference 2) and on the charged-particle concentration in the plasma of the main discharge. In Fig. 4 we show the spatial distribution of the intensity of the oscillations for different beam currents, and in Fig. 5 similar curves for different currents in the main discharge, I_a, In the legends to the figures we have also given the relative intensities of the peaks (I_{osc}). It is clear that an increase in the beam current strength as well as an increase in the current of the main discharge causes the vibration zone to come closer to the cathode and also to become narrower. A complete analogy with the influence of these parameters on the width and position of the scattering zone (see Fig. 3) was observed. It follows from Fig. 5 that an increase in the charge-particle concentration leads to a decrease in the intensity of the monochromatic oscillations produced. In Fig. 6 we have given the dependence of the intensity of the vibrations and their wavelength on the current of the main discharge I_a. This figure shows the quenching of the oscillations when the plasma is intensified and at the same time verifies the correspondence of the observed wavelengths (experimental points) with the ones calculated from the equation $\lambda = 2\pi c/\omega$, where

$$\omega = \{(4\pi e^2/m)(n_b + n_{pl})\}^{1/2}, \tag{1}$$

and $(n_b + n_{pl})$ denotes the concentration measured while the beam passed through the plasma. If we substitute in Eq. (1) the concentration of charged particles measured without the beam we

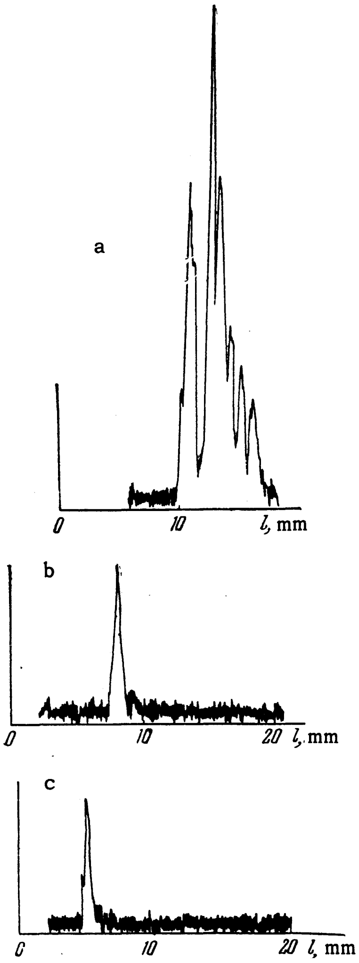


FIG. 4

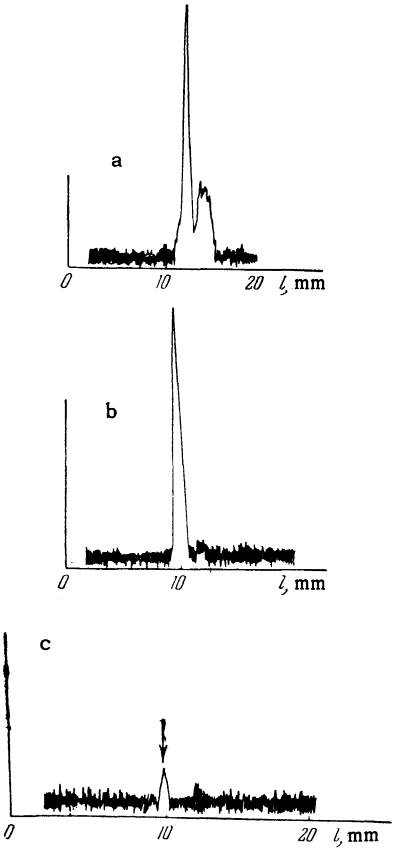


FIG. 5

FIG. 4. Spatial distribution of the oscillation intensity for different electron beam currents (I_a = 10 ma, E = 40 v). a – beam current I_e = 13.5 ma, oscillation intensity I_{osc} = 200; b – I_e = 33 ma, I_{osc} = 300; c – I_e = 68 ma, I_{osc} = 100.

FIG. 5. Spatial distribution of the oscillation intensity for different currents in the main discharge (I_e = 13.5 ma, E = 40 v). a – I_a = 100 ma, I_{osc} = 60; b – I_a = 400 ma, I_{osc} = 12; c – I_a = 600 ma, I_{osc} = 2.

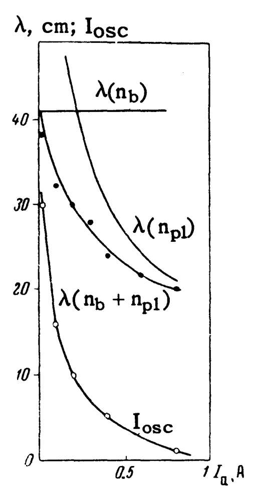


FIG. 6

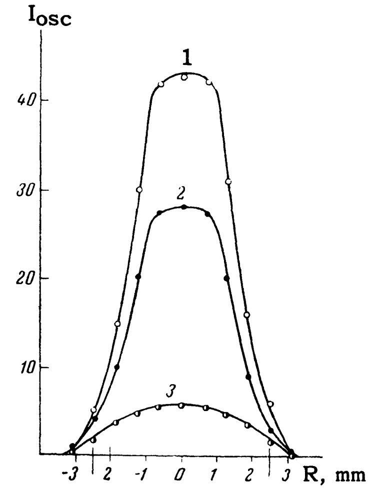


FIG. 7

FIG. 6. Dependence of the wavelength and the oscillation intensity on the current of the main discharge ($I_e = 20$ ma, $E = 28$ v).

FIG. 7. The radial distribution of the oscillation intensity in the beam passing through the plasma for different currents of the main discharge ($I_e = 20$ ma, $E = 28$ v). 1 – $I_a = 0.01$; 2 – $I_a = 0.1$; 3 – $I_a = 0.5$ amp.

obtain the curve for $\lambda(n_{pl})$. If the concentration were determined by the plasma produced by the beam itself, the line $\lambda(n_b)$ would be obtained.

In Fig. 7 we show the radial distribution of the oscillations for different currents of the main discharge. It is clear that the oscillations are strongly damped in the direction of the periphery of the beam.

INFLUENCE OF AN EXTERNAL MAGNETIC FIELD

The application of an external magnetic field parallel to the direction of the electron beam reduces somewhat the magnitude of the limiting current. For instance, at $H = 0$, $E = 75$ v, $I_{lim} = 1.4$ ma, and at $H \approx 100$ to 200 oe, $I_{lim} \approx 0.6$ ma. If prior to application of the magnetic field conditions were such that oscillations with a well defined wavelength were observed, the field causes a steep decrease in the intensity of these oscillations, until it is totally impossible to observe them for $H \approx 30-50$ oe.

DISCUSSION OF THE RESULTS

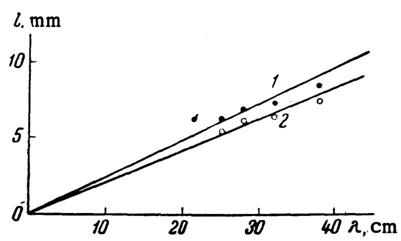
The facts stated above, together with those already known, make it possible to give the following picture of the interaction of the beam with a plasma.

In accordance with the prevalent point of view[2,5,8] we shall imagine that near the emitter E at the boundary of the plasma there is a localized modulating voltage of amplitude ΔU. According to the simplest klystron theory the velocity modulation of the electrons leads to a localization of electron clusters at the position

$$l_{osc} = mv_0^3 / e\omega\Delta U = mv_0^3\lambda / 2\pi ce\Delta U, \qquad (2)$$

where v_0 is the initial electron velocity, ω the modulation frequency, and $\lambda = 2\pi c/\omega$ the measured wavelength of the electromagnetic oscillations. To verify the applicability of Eq. (2) to our case we plotted the dependence of the position of the localization of the center of the oscillation zone l_{osc} on the wavelength λ. Such a plot is given in Fig. 8; to obtain this we varied λ by changing the main-discharge current I_a. Here is also plotted the dependence of the position of the scattering zone on λ (curve 2). As also in the experiments of Merrill and Webb,[2] the oscillation zone is slightly shifted with respect to the scattering zone. In Fig. 9 we have given the dependence $l_{osc} = f(\lambda)$; to obtain this we varied λ by changing the beam current. In all cases one could observe a linear dependence $l_{osc} = f(\lambda)$, corresponding to Eq. (2). A comparison of the slope of these curves with (2) enables us to estimate the unknown ΔU. From Fig. 8, $\Delta U = 3.9$ v ($E = 28$ v); from Fig. 9, $\Delta U = 3.7$ v ($E = 28$ v) and $\Delta U = 5.7$ v ($E = 41$ v). As we have stated, there exists a complete analogy between the behavior of the oscillation zone and the scattering zone in those experiments where no monochromatic oscillations are produced. Using our data on the anomalous scattering, one can construct the dependence of the distance from the cathode

FIG. 8. The dependence of the position of the oscillation zone (1) and of the scattering zone (2) on the wavelength of the observed electromagnetic oscillations ($I_e = 20$ ma, $E = 28$ v).



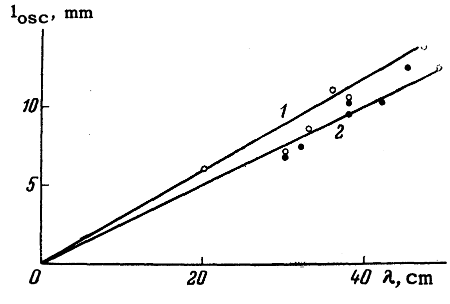


FIG. 9. The dependence of the position of the scattering zone on the wavelength for electron energies of (1) $E = 41$ v and (2) $E = 28$ v.

to the scattering zone l_1 on the quantity $\lambda_{eq} = 2\pi c/\omega$ where ω is the frequency of the plasma oscillations; the latter, and hence λ_{eq} can be evaluated using Eq. (1) from the experimentally determined particle concentration in the plasma. The result of such a treatment is given in Fig. 10. The slope of the straight line enables us to determine $\Delta U = 5.1\,v$ $(E = 50\,v)$. The value of ΔU cannot be determined in our experiments independently. We can only refer to reference 12 where, by direct measurements, the existence of a variable microwave field with an amplitude of several volts was proved. It seems to us to be incorrect to compare ΔU with the spread in the electron energy determined at large distances, as was done in reference 5.

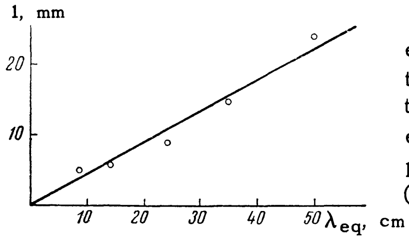


FIG. 10. The dependence of the position of the scattering zone on the wavelength which is equivalent to the given plasma concentration (I_e = 5 ma, 3 = 50 v).

From the data stated above we conclude that the ideas of the importance of phase focusing can be applied to all cases of anomalous scattering, independent of whether or not monochromatic oscillations are observed. In either case the modulation of the electron beam takes place near the cathode with a frequency equal to the natural frequency of the plasma and a consequent formation of clusters leading to a strong interaction (vide infra). The difference between them consists only in the fact that when monochromatic oscillations are observed the phase relations are satisfied and the necessary inverse coupling is maintained constantly, whereas in the other case this does not occur. The quenching of the monochromatic oscillations described above (spreading of the frequency spectrum) can be explained by a disturbance to the necessary feedback and of the phase relations occurring when a sufficiently intensive plasma is introduced.

This quenching of the oscillations occurring when an intensive plasma is introduced is, apparently, connected with the influence of the latter on the modulating layer in front of the cathode. We shall show in another paper that the separation of the region of the modulation of the beam from the region where the beam interacts with the plasma makes it possible to observe in the plasma not the quenching of the oscillations, but their amplification and plasma resonance.

The experimental data given here show that a strong interaction occurs in the region where the electrons bunch into clusters. It is well known[13] that when a particle of charge q and mass M passes through a plasma it undergoes an energy loss which can be evaluated from the formula

$$\frac{d\varepsilon}{dx} = \frac{\omega^2 q^2}{v_0^2} \ln \frac{1.23\, m v_0^3 M}{eq\omega\,(m + M)}, \tag{3}$$

where ω is the plasma eigenfrequency, v_0 the particle velocity (the formula in this form is valid for $v_0 < eq/\hbar$). If we assume, for instance, $\omega = 1 \times 10^{10}\ \mathrm{sec}^{-1}$, and $q = e = 4.8 \times 10^{-10}$ esu, $M = m$, $v_0 = 2.5 \times 10^8\ \mathrm{cm\ sec}^{-1}$, then $d\epsilon/dx = 3.5 \times 10^{-3}\ \mathrm{ev\ cm}^{-1}$. The individual interaction of the electrons with the plasma can thus not explain the experimentally observed loss.

If we assume that in these experiments a coherent interaction with the plasma occurs[4] of clusters containing a charge $q = Ne$, where N is the number of electrons in a cluster then the change in energy per electron will be described by the formula

$$\frac{d\varepsilon}{dx} = \frac{\omega^2 e^2 N}{v_0^2} \ln \frac{1.23\, m v_0^3}{N e^2 \omega}. \tag{4}$$

The number of electrons in a cluster can be estimated as $N = \pi jS/e\omega$ where j is the beam current density and S the cross section for coherently interacting particles in the cluster. If we take $jS \approx I_{\lim} \approx 1$ ma and $\omega = 1 \times 10^{10}$ then $N \approx 2 \times 10^6$, and the quantity $d\epsilon/dx$ turns out to be comparable with the experimentally observed magnitude ($d\epsilon/dx \approx 600\ \mathrm{ev\ cm}^{-1}$).

The extension of the scattering zone we shall take to be equal to the wavelength of the plasma oscillations $\Delta x \approx \lambda_{pl} \approx 2\pi v_0/\omega$. The change in the electron energy can then be estimated as follows:

$$\Delta\varepsilon \approx \frac{\omega^2 e^2 N}{v_0^2} \lambda_{pl} \ln \frac{1.23\, m v_0^3}{N e^2 \omega}. \tag{5}$$

If $S > S_c$, where S_c is the cathode surface area, the quantity $\omega^2 N \lambda_{pl} \neq f(\omega)$. The quantity $\Delta\epsilon$ turns thus out to be independent of the particle concentration in the plasma. This is in accordance with the independence of the limiting current on the plasma intensity, established by us. Expression (4) enables us to explain also the increase of the limiting current with increasing initial energy of the particles.

The numerical comparisons given here cannot, of course, pretend to give a quantitative explanation of the observed facts. Indeed, the phenomenon is very complicated and can, in particular, not be considered to be uniform; this is illustrated by our observations with a probe and visually of an angular divergence of the beam (for $I_e > I_{lim}$) behind the spot where the clusters are localized and by the splitting of the beam into separate rays.[15] However, it seems to us that the considerations given above enable us to combine a large number of experimental facts into one idea about the importance of a bunching of electrons in clusters and about the coherent interaction of the latter with the plasma.

The authors express their gratitude to N. D. Morgulis for discussions of the results of this paper.

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