ELECTRON OSCILLATIONS IN A PLASMA

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The conditions for periodicity of the spatial distribution of plasma oscillation intensity upon excitation by an electron beam are investigated.

It is established that periodicity is observed in the presence of a boundary reflecting primary or emitting secondary electrons which form a reflected wave. If there is no such boundary, then the oscillations build up in accordance with the principles of the theory of convective plasma instability.

Merrill and Webb [1] first discovered that in gas discharge tubes at low pressure, regions of intense plasma oscillation and regions scattering of primary electrons emitted from the cathode have a spatially periodic structure. A theory to account for these results was developed in [2] on the basis of the notion of velocity modulation of primary electrons on passage through an oscillating double layer at the boundary of the plasma and bunching near the focal plane (in much the same way as in a klystron). Later [3, 4] it was noted that periodicity of oscillation intensity distribution is observed in some cases, but not in others.

In [5] it was shown that the presence of a second boundary electrode affects the nature of intensity distribution (the first boundary is the cathode) if it reflects primary electrons or emits secondary electrons and thus leads to the formation of reflected waves. When the interelectrode distance exceeded the mean free path of beam electrons in the gas, the oscillation distribution had the form of a smooth curve with a maximum somewhere in the central region between the electrodes. However, when the distance between electrodes is less than the mean free path, periodicity appears, as described in [1]. Theory [2] does not reflect this aspect of the phenomenon, since it assumes that the medium is bounded only on one side (semi-bounded) in the direction of motion of the beam.

It is of great interest from the theoretical viewpoint to have information on the spatial distribution of the oscillations, since this makes it possible to draw conclusions concerning the nature of plasma instability as a result of which the oscillations are excited. In this article, experiments are described that confirm the role of reflected electrons in the formation of a periodic oscillation intensity. Moreover, data on the buildup of oscillations are presented and a comparison is made with the conclusions of convective instability theory.

Experimental. The plasma was produced in discharge tubes of three types filled with argon at a pressure of 2-8 microns. Tubes of types 1 and 2 had a plane oxide or pressed cathode 3 mm in diameter and a plane anode 30 mm in diameter. The diameter of the glass vessel was 70 mm. Oscillations were excited by primary electrons accelerated in the region of the cathode drop in an almost uniform stream. Electrons from the cathode initially moved in a parallel beam and subsequently, at a distance of several mm, underwent strong scattering in a narrow gas layer. Sometimes in front of the scattering zone, the beam was observed to converge to a node.

In the type 1 tube, the electrodes were located parallel to each other and 15 cm apart. At the pressures used this distance was three times greater than the mean free path for beam electrons with energies of several tens of eV.

In the type 2 tube, the anode was located in a side branch. At a distance of 200 mm from the cathode surface a plane electrode was placed in the path of the primary electrons; this electrode took the form of an aluminum reflector, which could be oriented at different angles to the direction of the initial trajectory of these electrons.

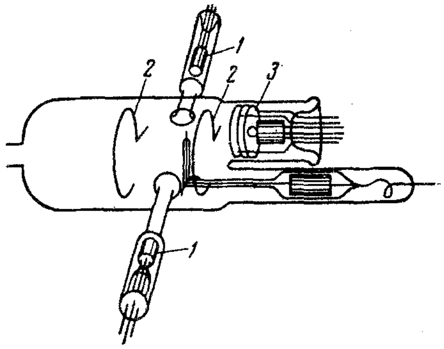

Fig. 1

A type 3 tube is shown schematically in Fig. 1. It was used for studying the oscillations associated with passage of an auxiliary beam of electrons from an external source through the plasma. The basic plasma was produced in a tube 75 mm in diameter using two oxide cathodes 1 and two anodes made in the form of a wire ring 2; the electron beam is formed with the aid of an electron gun 3 located in a branch of the tube. In contrast to experiments [6], the path of the beam electrons was not bounded by surface ion layers.

All three types of tube were equipped with a moving probe. Oscillations were recorded by means of the probe and investigated using a superheterodyne receiver.

Measurements. (a) Role of reflected wave in producing periodicity. In [5], to clarify the role of reflected primary electrons or secondary emission electrons in the formation of peaks in the oscillation intensity distribution curve, the authors used either a reflector to throw the incident electrons back into the plasma or a grid placed in front of the anode. Different potentials relative to the plasma could be applied to these electrodes.

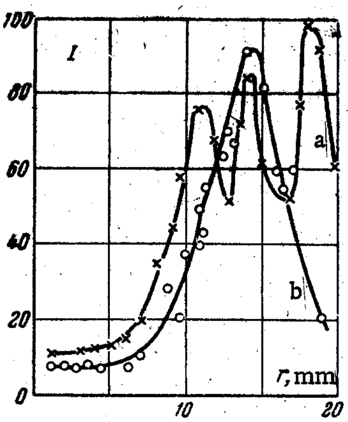

Fig. 2

In the present study, in investigating tube 2, the countercurrent formed by reflected and secondary electrons was led off to one side of the axis of rotation of the reflector. The reflector was either at a floating potential or at a potential negative by a few volts relative to the cathode. A change in reflector potential has no effect on the oscillation frequency. The oscillation intensity distribution along the discharge axis for two different cases, a) when the reflector plane is perpendicular to the direction of the primary beam and b) when the reflector forms a 45° angle with the direction of the primary beam, is shown in Fig. 2, where f = 1000 Mc, i = 58 ma, p = 5 microns. It is clear that whereas in the first case there is a distinct periodicity of intensity distribution, in the second case there is not.

Analysis showed that the length of the spatial period measured under different conditions agrees quite well with that computed from the formula

$$l = v_0 / f. \qquad (1)$$

Here v_0 is the beam electron velocity, f is the observed oscillation frequency.

The corresponding data are presented in the table.

p, μ	i, ma	V, volts	v_0, cm/sec	f, Mc	l^*, mm	l_r, mm
2.0	59	25	$3.0 \cdot 10^8$	500	6.2	6.0
5.0	61	44	4.0	1000	3.0	4.0
5.0	58	63	4.8	1000	4.5	4.8
8.0	12.9	22	2.8	480	4.5	5.6
8.0	15	220	8.8	770	9.5	11.4

Here l^* are the experimental values of the spatial period, l_r are values computed from formula (1).

If the wave phase velocity is computed from these data according to the formula v = $2lf$, it proves to be roughly twice as great as the beam velocity. In this connection, we recall that in Kofoid's experiments [7] with counter beams the phase velocity was also found to be greater than the beam velocity. At the same time, under other experimental conditions* he found that for argon these velocities approximately coincide, while for xenon the ratio of the phase velocity to the beam velocity was 0.58.

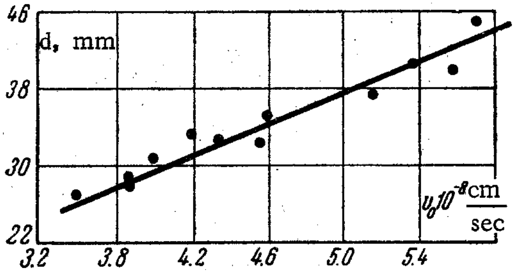

Fig. 3

(b) Distance from cathode of zone of maximum oscillation intensity. According to [2], the distance from the beam modulation zone to the focusing zone, which is identified with the region of maximum oscillation intensity, depends on the beam and plasma parameters in accordance with the relation

$$d = mv_0^3 / \omega_0 k T_e \qquad (2)$$

Here T_e is the plasma electron temperature, ω_0 is the Langmuir frequency of the plasma electrons, and k is Boltzmann's constant.

In [8], where experiments were carried out with a beam and an independently produced plasma, the relationship between d and ω_0 was verified; the results obtained agree qualitatively with formula (2).

For a plasma produced in tube 1, the oscillation intensity distribution given by curve b in Fig. 2 is typical; at a certain distance

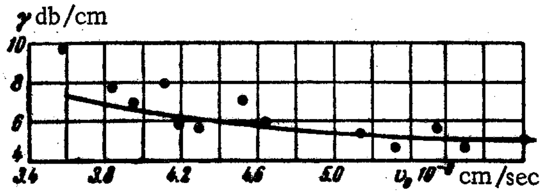

Fig. 4

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*M. J. Kofoid, "Plasma oscillations," Preprint, 1963.

from the cathode, the intensity begins to increase rapidly, reaching a maximum at some point and subsequently decreasing again.

According to klystron theory, the length d must coincide with the distance from the edge of the cathode space-charge sheath to the point of maximum intensity.

The distance from the cathode to the oscillation maximum is shown as a function of the beam electron velocity for tube 1 by the curve in Fig. 3, where f = 500 Mc, i = 22 ma, p = 5 microns. Clearly. the observed relationship is much less strongly expressed than would follow from formula (2).

The initial sections of the distribution curves correspond to an exponential increase in oscillation intensity. The coefficient γ is determined from thes sections for several values of the beam electron velocity v_0. Variation of v_0 at constant current is obtained by varying the cathode heater current*. The corresponding results are plotted in Fig. 4, where f = 500 Mc, i = 22 ma, p = 5 microns.

If the intensified oscillation is a result of convective instability of the medium, then the coefficient γ is expressed by the formula [9]:

$$\gamma = \frac{3^{1/2}}{2^{4/3}} \frac{\omega_0}{v_T} \left(\frac{v_T}{v_0} \right)^{1/3} \left(1 - \frac{v_T^2}{v_0^2} \right)^{1/6} \left(\frac{\Omega}{\omega_0} \right)^{2/3}, \qquad (3)$$

Here v_T is the mean thermal velocity of the plasma electrons, Ω is the Langmuir frequency of the beam electrons.

In our experiments, the velocity v_0 exceeded the thermal velocity v_T by a factor of 3-6. The curve in Fig. 4 shows the dependence of γ on the beam electron velocity as given by formula (3); the points correspond to measured data. The calculated curve is tied to the experimental results at the point $v_0 = 6 \cdot 10^8$ cm/ /sec. Clearly, at high velocities formula (3) accurately expresses the observed relationship, at least qualitatively. At near-thermal velocities, however, the theoretical curve and the experimental data tend to diverge. This may be because formula (3) was derived for beam velocities much greater than the mean thermal velocity.

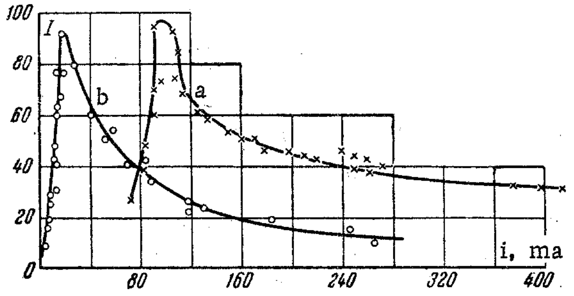

Fig. 5

(c) Experimental results using tube 3. Whereas in tubes 1 and 2 the plasma was produced and controlled by an electron beam, in tube 3 the basic plasma was produced by an independent method. Here it was possible to observe two forms of plasma interaction: a) oscillations in the auxiliary beam before passage through the plasma; and b) no oscillations in beam or plasma; they result from beam-plasma interaction. In both cases we investigated the relationship between oscillation intensity at fixed frequency and current in the basic plasma (the charge carrier density in the plasma was almost linearly dependent upon the current). The results are given in Fig. 5. Curve a in this figure was obtained from measurements at a beam oscillation frequency f = 785 Mc and pressure p = 6 microns; curve b was obtained at f = 460 Mc and p = 10 microns, for the case of no oscillations in the beam before interaction with the plasma. It is clear from Fig. 5 that the nature of the relationship is the same for both forms of interaction. The intensity at a given frequency reaches a maximum at a perfectly definite current. Plasma frequency calculations from electron concentration measurements made with a Langmuir probe showed that the intensity maximum is reached at a frequency close to the plasma electron oscillation frequency.

Experimental data obtained for interaction between plasma and a modulated beam agree with the results of the theoretical analysis [10] for an unbounded plasma.

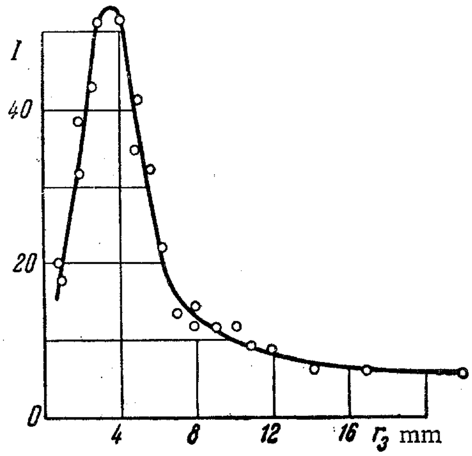

Fig. 6

Figure 6 shows a typical oscillation intensity distribution curve for case b. Case a has the same kind of distribution, but the position of the maximum on the curve is shifted in the direction of the point at which the beam enters the plasma. This may be because in case a the initial level of the amplified signal is higher.

Thus, in experiments with tube 3 amplification of perturbation waves by a mechanism associated with convective

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*The beam electrons acquire energy in the cathode drop. If the cathode operates in the so-called forced regime, the cathode drop necessary for maintaining a constant discharge current increases with decrease in the cathode heater current.

plasma instability was observed in both cases of beam-plasma interaction [11-13]. In tubes 1 and 3, the length of the beam-plasma interaction space was quite great. In these tubes there was no counter electron current capable of producing feedback. Therefore absolute instability did not arise.

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