# *FINE STRUCTURE OF THE DISTRIBUTION FUNCTION OF ELECTRONS IN A BEAM AFTER INTERACTION WITH A PLASMA*

S. M. LEVITSKIĬ and K. Z. NURIEV

Kiev State University

Submitted December 14, 1970

Zh. Eksp. Teor. Fiz. 61, 190–197 (July, 1971)

Fine structure was observed in the distribution function of an electron beam that had interacted with a plasma by employing a high-resolution energy analyzer. The fine structure consists of a number of weak peaks appearing against the plateau background. The dependence of the fine structure on the regime and geometry of the plasma-beam system is investigated. The effect of modulation of the beam by a monochromatic signal is studied. The appearance of the fine structure is explained as being the result of beam-electron capture in potential wells of a number of discrete natural waves of the system.

ONE of the most significant results obtained to date by experimentally investigating the relaxation of an electron beam in plasma is that the initially monokinetic distribution function acquires in final analysis the form of a "plateau" that extends from zero to energies somewhat exceeding the initial energy of the beam electrons[1-3]. This result agrees fully with the conclusions of the quasilinear theory[4,5]; it was duplicated subsequently many times and confirmed by many authors.

Measurements of the distribution function were carried out in all these investigations, but by the decelerating-field method, which, as is well known, has a relatively low resolution. Using a cylindrical Hughes-Rojansky capacitor with high resolution as the energy analyzer, we succeeded in observing, against the background of the plateau, a number of individual peaks forming the fine structure of the distribution function[6]. The existence of such peaks cannot be explained from the point of view of the quasilinear theory. However, if account is taken of the electrons captured in the potential wells of the waves[7], then the existence of a fine structure can be explained naturally for spatially-bounded systems having a discrete set of natural oscillations.

In this paper we investigate the influence of the regime, geometry of the system, and modulation of the beam on the fine structure of the distribution function. The nature of the fine structure is also considered and a brief calculation is presented, which leads to certain semiquantitative estimates that admit of comparison with the measurement results.

## 1. EXPERIMENTAL SETUP

The measurements were performed with the setup shown schematically in Fig. 1. The electron beam was formed by gun 1. The beam diameter was usually 5 mm; the electron energy in the beam was determined by the potential of the second anode and could be regulated in the range from 300 to 1200 V. The beam current was controlled by the first anode of the gun in the range from 0 to 20 mA. The beam propagated along the axis of glass tube 2, with diameter 35 mm. The distance L from the gun to the collector could be adjusted from 15 to 35 cm. In most experiments it was 27 cm.

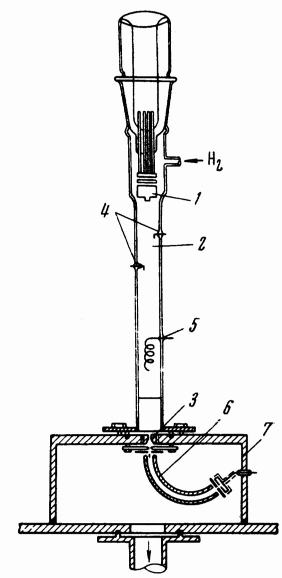


FIG. 1. Experimental setup. 1–electron gun, 2–working part of experimental tube, 3–beam collector, 4–Langmuir probes, 5–helix, 6–cylindrical capacitor, 7–cover for evacuation.

The measurements described in the present paper were performed in the absence of a constant magnetic field.

The tubes were filled with hydrogen, the pressure of which could be maintained in the range from $10^{-3}$ to $5 \times 10^{-2}$ mm Hg. On passing through the gas, the beam caused ionization and produced a plasma with which the beam itself interacted. The parameters of such a beam plasma—its concentration, electron temperature, and space potential—could be measured with several Langmuir probes 4, located in the central part of the tube at a distance 8–9 mm from the axis. The microwave oscillations were picked up by a helical segment 5 of length 40 mm and diameter 15 mm, placed inside the tube 15 cm from the gun. The longitudinal distribution of the oscillation intensity could be measured with the aid of a small capacitive electrode moving along the outer surface of the working part of the tube.

In individual cases, when it was desirable to modulate the electron beam with a monochromatic micro-

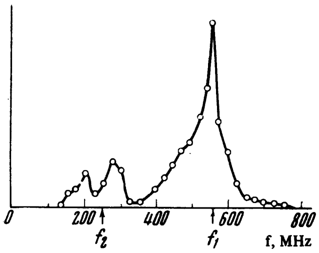


FIG. 2. Spectrum of microwave oscillations excited by the beam in the plasma. Conditions: $U_0 = 400V$, $i = 10$ mA, $p = 2.5 \times 10^{-2}$ mm Hg.

wave signal, a helical segment was placed at the output of the gun, and voltage from a microwave generator was applied to it through a coaxial lead.

The distribution function of the electrons interacting with the plasma was measured with a cylindrical capacitor 6 mounted under a cover 7, which was evacuated with a high-vacuum pump. The electrons entered the capacitor through an opening 1.5 mm in diameter drilled through the center of the collector 3. In spite of the flow of hydrogen through this opening, the gas pressure in the region of the cylindrical capacitor did not exceed $10^{-5}$ mm Hg. The energy resolution of the capacitor was about 1%. The results of the test of the capacitor and the verification of the procedure are described in[8]. The measured distribution function was plotted with an automatic recorder, the chart motion of which was synchronized with the variation of the voltage across the electrodes of the cylindrical capacitor.

The intensity of the spectrum of the microwave oscillations picked up by the helix or by the capacitive electrode was measured with a tunable resonator, a spectrum analyzer, or a measuring receiver.

## 2. MICROWAVE OSCILLATIONS EXCITED IN THE PLASMA

When the gas pressure in the working part of the tube and the beam current were sufficiently high, excitation of microwave oscillations was invariably observed. A typical spectrum of the oscillations is shown in Fig. 2. It consists of a large peak in the high-frequency region ($f_1$) and a smaller peak at a lower frequency ($f_2$). The half-width of the peak in the region $f_1$ is several dozen MHz. The frequency $f_1$ increases with the beam current and with the gas pressure. It is approximately proportional to $p^{1/2}$; no such simple power-law relation could be established for the beam current. The frequency $f_1$ agrees well with the Langmuir plasma frequency $f_p = (e^2 n_e/\pi m)^{1/2}$, which was determined from the probe measurements of the plasma-electron concentration. All this makes it possible to identify the main peak in the spectrum with the Langmuir oscillations excited in the plasma by the passing electron beam[9,10]. The second peak at the frequency $f_2$ may be the result of an interaction of the electron beam with a surface plasma-waveguide wave[10].

The distribution of the oscillation intensity along the system, measured at the frequency $f_1$, was approximately the same as described in[11,12], namely, the oscillation intensity first increased exponentially with increasing distance from the gun, reached a maximum, and then decreased again.

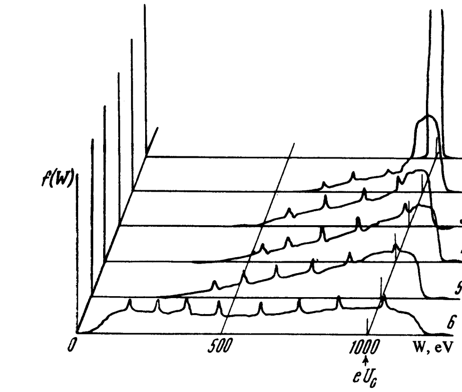


FIG. 3. Family of measured electron-beam energy distribution functions. $U_0 = 1000V$, $i = 10$ mA. The parameter of the curves is the gas pressure (in millimeter mercury): 1—$p < 10^{-3}$; 2—$1.5 \times 10^{-2}$, 3—$2 \times 10^{-2}$, 4—$2.5 \times 10^{-2}$, 5—$3 \times 10^{-2}$; 6—$3.5 \times 10^{-2}$.

The distance from the gun to the cross section where the oscillation intensity was maximal decreased with increasing accelerating voltage $U_0$. At small i and large $U_0$, the oscillation intensity could increase monotonically up to the collector itself. The region of the most intense microwave oscillations coincided with the region of the brightest glow of the plasma.

When the electron beam was modulated with a monochromatic microwave signal of sufficiently high intensity (the signal frequency was close to $f_1$), the well-known effect of suppression of the noise component of the oscillations[13] was observed. A cycle of spectrograms demonstrating this effect is shown in Fig. 7b below

## 3. BEAM-ELECTRON ENERGY DISTRIBUTION FUNCTION

The appearance of microwave oscillations is accompanied by accelerated relaxation of the electron beam. Figure 3 shows a family of measured distribution functions, in which the parameter is the gas pressure.

We see that at low gas pressures ($p \lesssim 10^{-3}$ mm Hg) the distribution function has the form of a narrow symmetrical peak. The electron energy corresponds to the accelerating voltage $U_0$. With increasing gas pressure, the peak gradually broadens. At $p > 10^{-2}$ mm Hg a gently-sloping section is formed on the low-energy side of the distribution function; the boundary of this section moves closer to zero with increasing pressure. At the same time, a certain (albeit smaller) broadening is observed on the high-energy side of the distribution function. With increasing pressure, the peak at the energy $eU_0$ vanishes, and for $p > 3.5 \times 10^{-2}$ mm Hg the distribution function acquires, in general outline, the form of a plateau, as was observed many times by many authors.

A new effect that we have been able to observe by using the high-resolution energy analyzer is the appearance of a number of small peaks, forming the fine structure of the distribution function. These peaks appear already at $p \approx 1.5 \times 10^{-2}$ mm Hg, and develop further with increasing pressure. The average interval between them is 50—100 eV and decreases somewhat with decreasing energy.

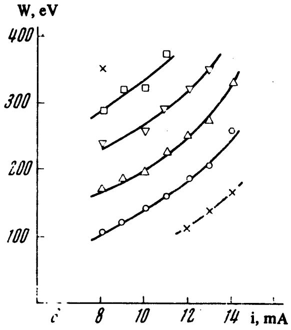


FIG. 4. Dependence of the position of the fine-structure peaks on the beam current. Conditions: p = 2.5 × $10^{-2}$ mm Hg, $U_0$ = 400V. The ordinates represent the energy of the observed peaks, and the curves show the displacement of these peaks on the energy scale with changing beam current.

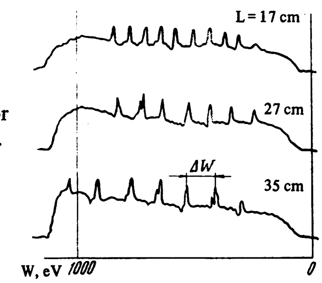


FIG. 6. Distribution functions for three different lengths of the system. $U_0$ = 1000 V, i = 10 mA, p = 3.5 × $10^{-2}$ mm Hg.

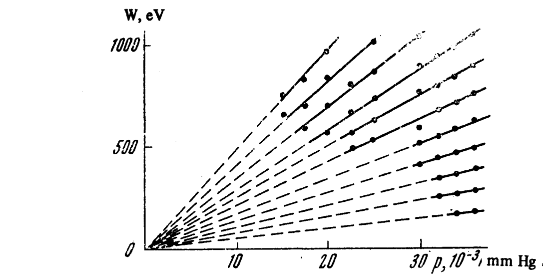


FIG. 5. Plot of the position of the fine-structure peaks on the energy scale against the gas pressure, $U_0$ = 1000V, i = 10 mA.

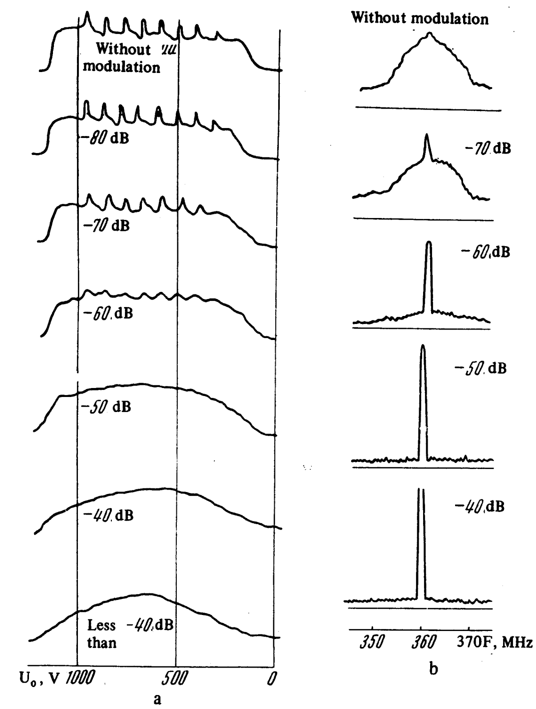


FIG. 7. Influence of beam modulation by a monochromatic signal on the distribution function (a) and on the oscillation spectrum (b). Modulating-signal frequency $f_m = f_1$ = 360 MHz; the signal level is given in dB relative to 1W. $U_0$ = 1000 V, i = 12 mA, p = 3.5 × $10^{-2}$ mm Hg.

A family plotted with the beam current as a parameter has a similar form.

The energy corresponding to the fine-structure peaks changes little with changing accelerating voltage. On the other hand, if the parameter of the family is the beam current, then the position of the peak shifts towards higher energies with increasing beam current (Fig. 4). The same thing is observed if the parameter of the family is the gas pressure (Fig. 5). In the latter case it is even possible to establish a direct proportionality of the gas pressure to the peak energy.

To study the dependence of the fine structure of the distribution function on the geometry of the system, the beam diameter was varied from 3 to 5 mm, and the diameter of the working part of the tube from 20 to 52 mm. Such variations of the beam and plasma diameter exerted no noticeable influence on the picture of the fine structure. The situation is different when the length of the system is varied. Figure 6 shows three distribution functions measured under the same conditions at different distances L from the collector to the gun. We see that with decreasing L the density of the peaks increases and the energy interval ΔW between them decreases in approximate proportion to the value of L.

The results of an investigation of the influence of the beam modulation by a monochromatic signal are shown in Fig. 7. The signal frequency $f_m$ was chosen to equal the frequency $f_1$ of the most intense oscillations excited in the plasma. Figure 7a shows a number of measured distribution functions for different levels of the modulating signal. The signal level $P_m$ is given in decibels relative to 1 W. Figure 7b alongside shows the variation of the frequency spectrum of the oscillations in the vicinity of $f_1$. We see that with increasing power of the modulating monochromatic signal the noise-oscillation level decreases. At the same time, the fine structure on the distribution function becomes smoothed out and vanishes: at $P_m$ = −60 dB it is hardly noticeable, and at $P_m$ above −50 dB it cannot be seen at all. The general outlines of the distribution function are also altered thereby: in the absence of modulation the distribution function has a clearly pronounced plateau, whereas in the case of strong modulation it acquires the form of a smooth curve with a maximum. Similar changes in the form of the distribution function were observed earlier[14].

It is natural to ask why no such fine structure was noticed before in the numerous investigations of the distribution function. We believe the reason to be the insufficient resolution of the decelerating-field method, which was used throughout by all the experimentors. On the delay-current curve, which we obtained experimentally by replacing the cylindrical capacitor with a corresponding system of electrodes, or numerically by integrating the distribution functions given above, the fine structure made a practically negligible contribution lying on the borderline of the measurement accuracy.

## 4. DISCUSSION OF RESULTS

One of the premises underlying the quasilinear theory is the assumption that the investigated system is unbounded in the longitudinal direction. Therefore when the spectrum of the oscillations is broadened with respect to k, it should form a continuum in such a system.

On the other hand, if the system is bounded in the longitudinal direction and has a length L, it should be characterized by a discrete set of eigenvalues $k_n$, determined in the simplest case by the relation

$$k_n L = n\pi, \quad n = 1, 2, 3, \ldots \tag{1}$$

If the waves under consideration are plasma waves, then their frequency is equal to $\omega_p$, regardless of the value of $k$[1)]. For a discrete set of values of $k_n$, these waves should have corresponding discrete phase velocities

$$V_{\text{phn}} = \omega_p / k_n = \omega_p L / n\pi. \tag{2}$$

When electrons with velocity $v_e$ close to one of the values of $v_{\text{phn}}$ appear during the process of plateau formation, then these electrons are trapped in the potential well of the wave and are dragged by it. The idea of such trapping of particles by the wave and its subsequent development is contained in the papers of Kadomtsev and Pogutse[7].

As applied to our case, we should expect the trapping and dragging of electrons by waves having a set of discrete phase velocities to cause singularities to appear on the velocity distribution function at the points where $v_e = v_{\text{phn}}$. Concretely, one should expect the dragging of the electrons by the wave to lead to an increase in the number of particles whose velocity is equal to the wave velocity, at the expense of depletion of the adjacent sections of the distribution function.

Going over from electron velocities to energies, we obtain the series of discrete energy values for which one should expect the appearance of singularities on the distribution function:

$$W_n = \frac{m v_{\text{phn}}^2}{2} = \frac{m}{2} \frac{\omega_p^2 L^2}{n^2 \pi^2}. \tag{3}$$

The energy interval between adjacent values turns out to be

$$\Delta W_n = W_{n-1} - W_n \approx \frac{m \omega_p^2 L^2}{n^3 \pi^2}. \tag{4}$$

In addition to explaining the very appearance of the fine structure, the foregoing expressions enable us to explain qualitatively some results of the experiment. Thus, for example, the observed shift of the fine-structure peaks with changing beam current or with changing gas pressure (Figs. 4 and 5) can be attributed to a corresponding change of $\omega_p$. Since under the conditions of our experiments $\omega_p$ was approximately proportional to $p^{1/2}$, the energy of the peaks should also be proportional to the gas pressure, as was indeed observed. The variation of $\Delta W_n$ with the length of the system is also qualitatively explained.

A quantitative estimate of $\Delta W_n$ for the experimental conditions corresponding to the middle curve of Fig. 5 ($L = 27$ cm, $f_p = 600$ MHz) gives for $W = 500$ eV a value $\Delta W = 50$ eV, which agrees satisfactorily in order of magnitude with the measured value.

The vanishing of the fine structure when the beam is modulated with a monochromatic signal can be attributed to the fact that the mechanism of plasma-beam interaction is completely altered here. Perfectly defined values of $\omega$ and $k = \omega/v_0$ are imposed on the system. On the other hand, the distribution function has in this case not the form of a plateau with a large set of electron velocities, but the form of a narrow peak that shifts over the energies with the oscillation frequency[15].

In conclusion, we are sincerely grateful to V. N. Oraevskiĭ, who induced us to undertake the research described in the present paper.

1)The dispersion dependence due to the finite temperature of the electrons does not play any role here, since $v_{\text{phn}} \gg v_{Te}$ under the conditions of our experiments.

One must not confuse the considered branch of plasma waves ($\omega = \omega_p$) with the so-called plasma-waveguide branch, for which the $k(\omega)$ dependence is significant. That branch corresponds to surface waves and lies in the frequency region below $\omega_p/\sqrt{2}$.

[1] M. D. Gabovich and L. L. Pasechnik, Zh. Eksp. Teor. Fiz. 36, 1025 (1959) [Sov. Phys.-JETP 9, 727 (1959)].

[2] I. F. Kharchenko, Ya. B. Faĭnberg, E. N. Kornilov, R. M. Nikolaev, E. I. Lutsenko, and I. S. Pedenko, Nuclear Fusion Suppl. 3, 1101 (1962).

[3] C. Etievant and M. Perulli, C.R., Paris, 255, 855 (1962).

[4] A. A. Vedenov, E. P. Velikhov, and R. Z. Sagdeev, Nuclear Fusion Suppl. 2, 465 (1962).

[5] W. E. Drummond and D. Pines, ibid. 3, 1049 (1962).

[6] S. M. Levitskiĭ and K. Z. Nuriev, ZhETF Pis. Red. 12, 172 (1970) [JETP Lett. 12, 119 (0000)].

[7] B. B. Kadomtsev and O. P. Pogutse, ICTP, Trieste preprint IC/70/45.

[8] S. M. Levitskiĭ and K. Z. Nuriev, Uch. zapiski Azerbaĭdzhanskogo universiteta, seriya fizicheskaya (Scientific Notes of Azerbaĭdzhan University, Physics Series), (in press).

[9] R. A. Demirkhanov, A. K. Gevorkov, and A. V. Popov, Zh. Tekh. Fiz. 30, 315 (1960) [Sov. Phys.-Tech. Phys. 5, 290 (1960)].

[10] G. D. Boyd, R. W. Gould, and L. M. Field, PIRE, 49, 1906 (1961).

[11] S. M. Levitskiĭ and I. P. Shashurin, Zh. Eksp. Teor. Fiz. 52, 350 (1967) [Sov. Phys.-JETP 25, 227 (1967)].

[12] S. M. Levitskiĭ and I. P. Shashurin, Nuclear Fusion 11, 111 (1971).

[13] Ya. B. Faĭnberg, Usp. Fiz. Nauk 93, 617 (1967) [Sov. Phys.-Usp. 10, 750 (1968)].

[14] S. M. Levitskiĭ and I. P. Shashurin, Trudy IX Mezhdunarodnoĭ konferentsii po yavleniyam v ionizovannykh gazakh (Trans. Ninth International Conference on Phenomena in Ionized Gases), Bucharest, 1969, p. 566.

[15] M. D. Gabovich and V. N. Kovalenko, Ukr. Fiz. Zh. 15, 1893 (1970).

Translated by J. G. Adashko
20