[3] M.A. Leontovich and V. Khait, ZhETF Pis. Red. 13, 579 (1971) [JETP Lett. 13, 414 (1971)].

EXPERIMENTAL OBSERVATION OF OSCILLATIONS ON THE ELECTRON DISTRIBUTION FUNCTION FOLLOWING PLASMA-BEAM INTERACTION

V.A. Lavrovskii, E.G. Shustin, and I.F. Kharchenko
Radio and Electronics Institute, USSR Academy of Sciences
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It follows from the recently developed nonlinear theory of plasma-beam interaction [1 - 3], in which account is taken of the bunching of the beam electrons (formation of "macroparticles") and of capture of the beam electrons by the field of the wave, that the beam velocity distribution function should have a complicated multiple-peak form that varies during the course of the electron-beam relaxation. In many experiments, however, the observed distribution function was smooth and tends in the limit to the plateau predicted by the quasilinear theory.

It was shown earlier experimentally that even under conditions of stationary injection of the beam into the plasma the interaction has a nonstationary character manifested by rapid variations of the amplitude, of the frequency spectrum, and of the structure of the excited oscillations, and due, in particular, to the excitation of different modes of low-frequency oscillations [4, 5]. One should expect the distribution-function oscillations predicted by the nonlinear theory likewise to reveal in the experiments a nonstationary character, since their character is determined by the amplitude and by the frequency spectrum of the field. Such a nonstationary behavior should lead at a large measurement time constant to averaging of the experimentally-observed distribution function.

Even if the beam interacts with a monochromatic wave of given amplitude, the time averaging, as shown by our calculation1), leads to a smoothing of the oscillations on the distribution function and ultimately, with a sufficiently long averaging interval, to formation of a plateau.

It should be noted that in the experiments performed to date the time measurement of the distribution function was always larger than the characteristic period of the nonstationarity, and this inevitably led to averaging of the measured quantity and to smoothing of the observed distribution function.

To ensure experimental observation of the fine structure of the distribution function, it is thus necessary to make the measurement times short compared with the nonstationarity period. We present below the results of such an experiment.

The experiment was performed with a plasma-beam discharge in hydrogen in a longitudinal magnetic field of 0.2 Tl with initial electron-beam energy 1 keV at a current of 20 - 40 mA [6]. The electrons were velocity-analyzed with a grid analyzer in coaxial form, which make it possible to record the delay-current curve within a time on the order of several dozen nanoseconds. The decelerating voltage was a sawtooth pulse of 1.5 kV amplitude with a growth rate of 6×10^9 V/sec. The upper limit of the bandwidth of the measuring circuits was not lower than 200 MHz. The measurement system operated in a single-triggering regime with stationary beam injection.

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1) This calculation will be published in a detailed article.

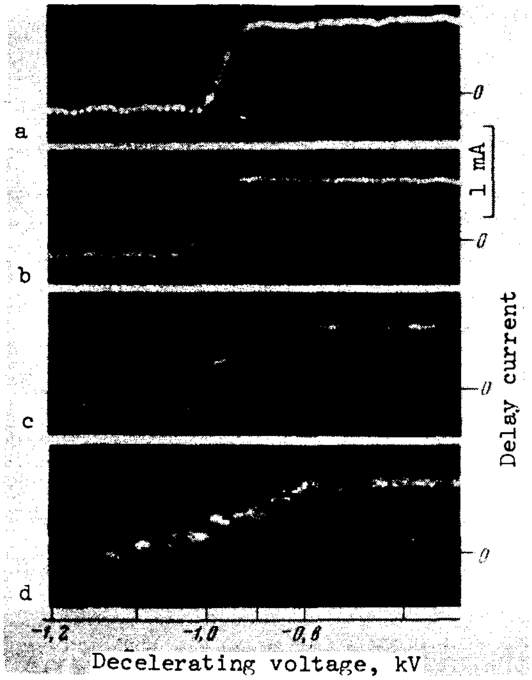

Fig. 1

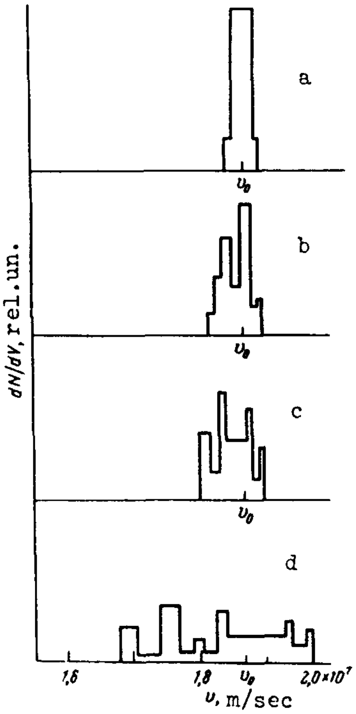

Fig. 2

Fig. 1. Oscillograms of the delay current. Sweep duration 2×10^{-7} sec. a) $p = 5 \times 10^{-6}$ mm Hg, b) $p = 1.3 \times 10^{-3}$ mm Hg, c) $p = 2 \times 10^{-3}$ mm Hg; d) $p = 2.7 \times 10^{-3}$ mm Hg.

Fig. 2. Electron velocity distribution corresponding to Fig. 1.

We observed in such a system excitation of HF oscillations in the 1000 MHz band and LF oscillations with frequencies up to 600 kHz. The chosen analysis time was thus much shorter than the period of the LF oscillations.

As is well known, the effectiveness of the interaction of the electron beam with the plasma in a plasma-beam discharge depends on the pressure of the neutral gas in the interaction region. At sufficiently low pressure ($p = 5 \times 10^{-6}$ mm Hg), the delay curve (Fig. 1a) has the form of a steplike pulse, and its differentiation yields a bell-shaped electron-beam distribution function with an initial scatter of 40 eV. When the pressure is decreased to $p = (1 - 3) \times 10^{-3}$ mm Hg, the shape of the delay curve changes (Figs. 1b, 1c, 1d) and HF and LF oscillations are excited. The decrease of the average slope of the curve indicates a spreading of the velocity distribution function. At the same time, HF oscillations are observed in the beam current, and their frequency band and envelope shape correspond to those observed for the HF fields excited in such a system [4].

The most important fact is the nonmonotonic change of the slope of the delay curve with changing decelerating voltage, indicating that the electron distribution function has multiple peaks (Fig. 2). Individual electron groups have energy scatters ranging from 20 to 100 eV. Several such groups are observed simultaneously. With further increase of pressure in the system, the distribution remains multiple-peaked, but the curve shifts as a whole towards lower velocities, and particles with velocities higher than v_0 appear.

The character of the transformation of the distribution function with increasing plasma density (corresponding to growth of γ or t in the model of

[1 - 3]) agrees qualitatively with the predictions of the theory. Indeed, the number of peaks on the distribution function increases with increasing plasma density. Processing of the delay curves that correspond to a sufficiently large smearing of the distribution function yields, as a rule, a "shelf" in the vicinity of v_0, where one can most readily expect a manifestation of the Coulomb collisions that cause diffusion in velocity space and smoothing of the peaks on the distribution function [3].

If the time constant of the recording apparatus in the same system is large ($\tau \simeq 10$ msec), smoothing of the distribution function is observed, with formation of a plateau in the regimes where the most intense HF oscillations are excited.

It should be noted that the distribution functions have different structures for one and the same regime and for a constant total width of the spectrum. As indicated above, this is obviously connected with the nonstationary time behavior of the plasma-beam discharge. The "instantaneous" form of the distribution function does not coincide with its average form, and has a more complicated structure that varies in time. Analogously, the instantaneous spectra of the excited oscillations contain discrete narrow frequency bands, and the averaged spectra have a uniform structure in a broad frequency band [4].

Thus, a velocity analysis of the electron-beam distribution function has revealed the formation of a multiple-peaked electron distribution upon relaxation of the electron beam in the plasma, confirming the prediction of the nonlinear theory, namely that individual electron bunches ("marcoparticles") are produced in velocity space as a result of capture of the beam electrons by the field of the excited wave.

[1] L.M. Al'tshul' and V.I. Karpman, Zh. Eksp. Teor. Fiz. 49, 515 (1965) [Sov. Phys.-JETP 22, 361 (1966)].
[2] O'Neil, Phys. Fluids 8, 2255 (1965).
[3] B.B. Kadomtsev and O.P. Pogutse, Phys. Rev. Lett. 25, 1155 (1970).
[4] V.A. Lavrovskii, I.F. Kharchenko, et al., Zh. Tekh. Fiz. 39, 1586 (1969) [Sov. Phys.-Tech. Phys. 14, 1190 (1970)].
[5] R.V. Neidich, I. Alexeff et al., Plasma Phys. a Contr. Nucl. Fus. Research, Proc. Conf., Vienna, 1969, II, p. 693.
[6] E.G. Shustin, V.P. Popovich, and I.F. Kharchenko, Zh. Tekh. Fiz. 39, 993 (1969) [Sov. Phys.-Tech. Phys. 14, 745 (1969)].

STUDY OF TWO-DIMENSIONAL MIXED STATE OF TYPE-I SUPERCONDUCTORS

I.L. Landau and Yu.V. Sharvin
Institute of Physics Problems, USSR Academy of Sciences
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As already reported [1], when the superconductivity of a hollow cylindrical sample is destroyed by current flowing through it, a thin layer of the "mixed" state predicted by L.D. Landau is produced in its surface; the current flowing in this state has a density greatly exceeding the current density in the normal phase of the sample. In the experiments described below we realized conditions under which a cylindrical layer of such a state could be produced not only on the inner or outer surface of the cylindrical sample, but also inside the sample at an arbitrary distance from the axis. Inasmuch as the mixed state of a type-I superconductor apparently always takes the form of thin layers, we shall use here the term "two-dimensional mixed state" (t.m. state), to distinguish it from the mixed state of a type-II superconductor.