SINGLE-MODE INTERACTION IN A TURBULENT PLASMA-BEAM DISCHARGE

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Numerous experiments have shown that excitation of noise-like oscillation with a broad continuous frequency spectrum and the formation of a plateau on the distribution function characterize the development of two-stream instability in a plasma.

These results patently contradict both the conclusion of the linear theory of coherent particle wave interaction, which predicts the "monochromatization" of the wave packet with increasing wave [1, 2], and the recently developed nonlinear interaction theory, in which account is taken of particle capture and electron-bunch ("macroparticle") formation in the field of the excited wave [3, 4].

It was shown earlier [5] that measurements of the electron distribution function under conditions in which the time-averaging of the measured quantities can be excluded result in an f(v) curve that has many peaks and agrees with the conclusions of the nonlinear theory of particle interaction with a quasimonochromatic wave.

We present here an analysis of the "instantaneous" characteristics of the HF field excited in the system; these characteristics were measured in a time interval much shorter than the characteristic time of variation of the discharge

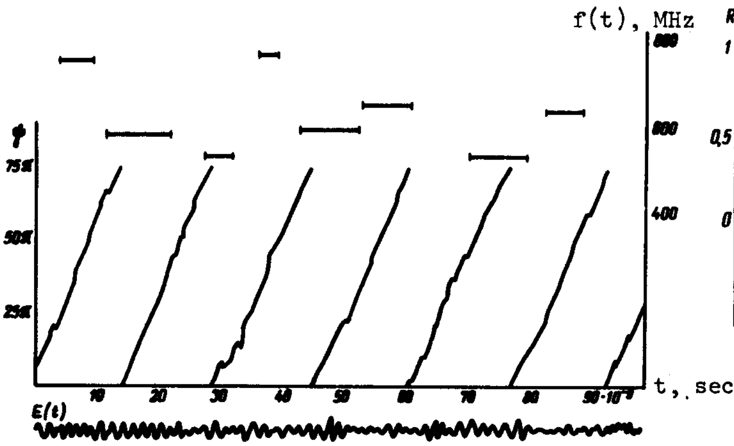

Fig. 1

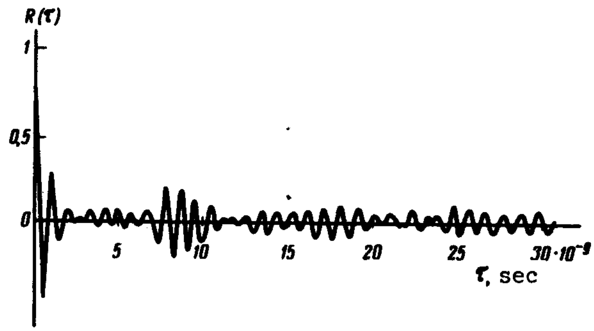

Fig. 2

Fig. 1. Typical oscillogram of HF field E(t), the running phase Ψ(t) of the oscillations, and the instantaneous frequency f(t) of the quasi-harmonic inclusions.

Fig. 2. Autocorrelation function of the oscillation shown in Fig. 1.

parameter. This analysis has confirmed the applicability of the nonlinear theory of "single-mode" interaction to the plasma-beam discharge, in spite of the fact that the averaged characteristics of the process indicate it to have a stochastic character.

The measurements were performed in a plasma-beam discharge in hydrogen with continuous injection of an electron beam of energy 1 keV and current 20 - 40 mA [6]. As is well known, in such a system, under the conditions of the plateau of the distribution function, intense high-frequency oscillations are excited, with a broad continuous spectrum near the electron plasma frequency. We measured under the same conditions the distribution function following application of a sawtooth voltage of duration 2.5×10^{-7} sec to an analyzer with retarding potential, and determined the time structure of the HF oscillations over a time interval equal to 10^{-7} sec. The measuring system was operated under conditions of one-shot triggering at random instants of time, while the electron beam injection was continuous.

Figure 1 shows a typical oscillogram of E(t). The oscillograms were statistically analyzed with the aid of a computer.

The shape of the autocorrelation function of the investigated oscillatory process (Fig. 2) corresponds to oscillations having periodic components. The correlation time of the random part of the process is of the order of several nanoseconds. The relative intensity of the periodic component was determined from the maximum amplitudes of the function $R(\tau)$ at $\tau > \tau_{cor}$ and equals 0.1 - 0.15.

The frequency spectrum (Fig. 3) is narrower than the averaged spectrum measured with a wave meter (dashed curve). The frequency spectra of individual realizations are uneven, and individual spectral components of appreciable amplitude are separated. The average oscillation frequency in the maximum-intensity region varies from realization to realization. The average over the ensemble of such spectra spans the frequency range from 250 to 1500 MHz, which agrees with the frequency characteristic obtained from measurements over large time intervals (dashed curve).

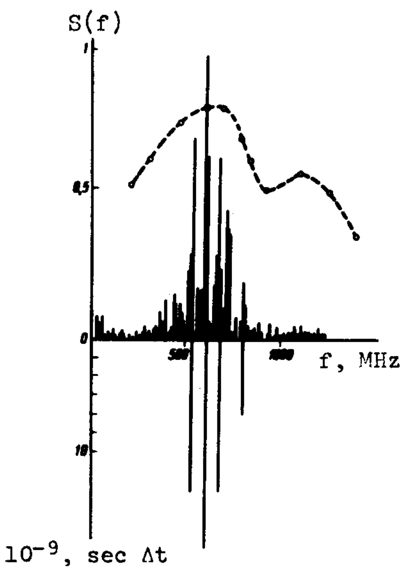

Fig. 3. Fourier transform of the E(t) oscillogram compared with the averaged spectrum (dashed curve) and with the probability distribution of the quasiharmonic inclusions $\Delta t(f)$.

The time dynamics of the running frequency of the oscillatory process enable us to trace the applicability of the phase-frequency analysis [7]. The gist of the method is to represent the oscillatory process in the form $E(t) = A(t) \cos \Psi(t)$ and to determine the amplitude and phase characteristics on the basis of Hilbert transforms [8].

This method enables us, in particular, to reveal in a random process quasiharmonic inclusions that are locally stationary in frequency, and to determine their characteristic frequency $\omega = d\Psi/dt$. Such inclusions appear on the $\Psi(t)$ curve as linear sections.

The results of the analysis are shown in Fig. 1 in the form of the $\Psi(t)$ curve and the time dependence of the running frequency $f = \omega/2\pi = f(t)$. The $\Psi(t)$ shows the presence of quasiharmonic inclusions and abrupt changes in the oscillation phase. It is seen from the f(t) plot that the oscillations exist mainly in four frequency regions (530, 580 - 590, 630 - 640, and 750 - 760 MHz), which apparently alternate in time in random fashion. The lifetimes of such quasi-harmonic inclusions are (5 - 10) × 10^{-9} sec, i.e., several cycles. As a rule, the frequency changes are accompanied by phase shifts of 70 - 180°. By summing the lifetimes of the individual frequency components, we obtain quantities that characterize the probability distributions of the excitation of these frequencies. It turns out that the components of this distribution correspond to the most intense components in the spectral resolution S(f) of the investigated realization (Fig. 3). Thus, the results of the investigation of the temporal structure of the oscillatory process following development of instability in a plasma-beam system indicate that the interaction of the electron beam with the plasma is in the main coherent, in spite of the fact that the averaged spectra point to a stochastic character of the process.

This conclusion is confirmed also by measurements of the electron distribution function [5]. As follows from the nonlinear theory of beam interaction with a quasimonochromatic wave in a plasma, the distribution function measured over a time 10^{-7} sec which is short in comparison with the period of the low-frequency fluctuations in the discharge has the shape of a curve with many peaks.

The distribution function measured under the same conditions over a prolonged time has the form of a plateau, this being the result of averaging the time-varying distribution function.

Thus, the averaged characteristics of both the HF oscillations and of the state of the beam mask the true character of the interaction.

The causes of the rapid change in the oscillation frequencies, which cause the averaged characteristics of the system to be stochastic (continuous noise-like frequency spectrum and plateau-like distribution function) may be the instability of the oscillations at individual frequencies, caused by the low-frequency oscillations, by the coupling of different natural modes [9], or by excitation of satellites in the spectrum as a result of periodic oscillations of plasmoids in the potential well of the excited wave [4]. The development of methods for the analysis of the instantaneous characteristics of two-stream instability uncovers a possibility of identifying these effects.

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