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EXCITATION OF LOW-FREQUENCY OSCILLATIONS AND CONTROL OF TWO-STREAM INSTABILITY SPECTRA

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This paper is devoted to a study of the mechanism of excitation of low-frequency (LF) oscillations in two-stream instability, and also to the possibility of controlling their spectrum by using high-frequency (HF) modulation of the electron beam at several frequencies. From our earlier results [1 - 3] it was to be expected beforehand that the use of HF modulation of the electron beam at two frequencies from the HF spectrum would make it possible to excite a narrow LF section as a result of nonlinear interaction of two oscillations that are coupled externally [4]. This makes it possible to study in detail not only individual sections of the LF spectrum and their interaction, but also to identify the oscillations, to determine the mechanism of their excitation, and to assess the possibility of their use to heat the plasma ions.

The experiments were performed with the setup described in detail in [1]. An electron beam (current 50 - 100 mA, energy 5 keV) produced a plasma of density 10^{10} - 5 x 10^{11} cm^{-3} in a constant uniform 1 - 2 kG magnetic field. The electron beam was modulated with the aid of a resonator at the TM_{010} mode. The resonator was fed from two 10-cm generators through ferrite decouplers. The oscillations were registered with the aid of the IV-46 and S4-8 analyzers, and received with movable Langmuir probes and magnetic dipoles. The LF oscillations were also registered with a collector in the beam current.

The experiments on two-frequency modulation of the electron beam were carried out under conditions when one of the monochromatic signals, of low power level, was fed to the modulation system at a frequency corresponding to the conditions for the suppression of the LF and HF spectrum [1]. Application of a second monochromatic signal in the region of the LF signal produces a signal at a difference frequency. Within the limits of measurement accuracy, the frequency of the LF difference oscillation always equals the difference between the frequencies of the two HF monochromats. By continuously varying the frequency of one of the modulating monochromats, it is possible to scan smoothly the entire LF spectrum with the excited LF monochromat. It must be specially emphasized that the amplitude distribution of the difference monochromator always duplicates the amplitude distribution of the excited LF spectrum. Figure 1 shows one of the oscillograms taken from the screen of the S4-8 analyzer. The solid broad white bands represent the part of the LF spectrum excited ina beam-plasma discharge in the absence of beam modulation. The thin white lines correspond to the amplitude distribution of the difference monochromat when the latter moves continuously over the spectrum. This oscillogram indicates that the difference monochromat is of the same origin as the corresponding section of the LF spectrum.

A study of the wave characteristics of the difference monochromat and measurement of the

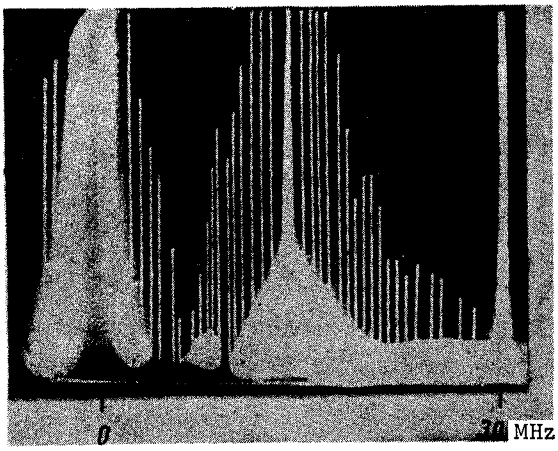

Fig. 1. Reconstruction of LF spectrum by difference monochromat

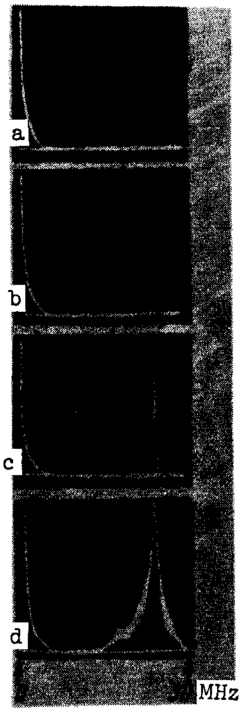

Fig. 2. Dependence of width of spectrum on the amplitude of the difference monochromat: a - beam modulated at 3010 MHz; b, c, d - beam modulated at 3010 and 3034 MHz.

dependence of the frequencies of the excited oscillations on the gas mass, the interaction length, and the magnitude of the magnetic field show that the LF spectrum can be divided into three regions: 1) the region of ion-acoustic waves ($K_z \gg K_\perp$); the region of drift waves connected with the plasma-density inhomogeneity ($K_\perp \gg K_z$); the region of the waves connected with the nonequilibrium character of the plasma ($K_z \gg K_\perp$) [5].

Thus, the LF oscillations are the direct consequence of two-stream instability. They are the result of either nonlinear interactions of the HF oscillations or of the inhomogeneity and non-equilibrium character of the plasma, caused by the HF fields.

Increasing the amplitude of the difference monochromat in the region of ion-acoustic waves, by increasing the amplitude of one of the HF monochromats, causes the narrow line to degenerate into a broad spectrum. By smoothly varying the frequency differences and the amplitudes of the monochromats it is possible to set the required spectral energy density in any section of the LF spectrum. Thus, by external HF modulation of the beam at two frequencies, it is possible to control, in the broad sense of the word, the spectra of both the HF and LF oscillations. Figure 2 shows the dependence of the spectrum width on the amplitude of the difference monochromat. A strong increase of the amplitude of the differ-

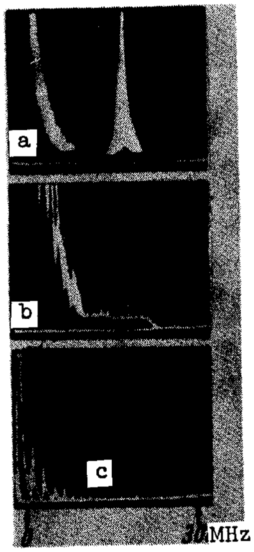

Fig. 3. Nonlinear interaction of the band of LF oscillations with the LF monochromat: a - beam modulated at frequencies 3010 and 3027 MHz, with the amplitude of the 3027 MHz monochromat being 50 times larger than that of the 3010 MHz monochromat; b - beam modulated at 3008, 3010, and 3027 MHz; c - amplitude of 3008 MHz monochromat 50 times larger than in the case b.

ence monochromat leads to the breakup of the broad spectrum into narro non-overlapping regions. A reaction of the LF oscillations on the HF oscillations is observed in this case. The HF oscillations are excited in the form of temporal packets. The probably corresponds to the conditions when the dispersion properties of the plasma change as a result of the sharp increase in the LF oscillation amplitude. The cause of the breakup of the broad LF spectrum into narrow bands may be already the nonlinear interaction of the low-frequency waves. To verify this assumption, we employed three-frequency HF modulation of the electron beam, making it possible to set in the LF oscillation spectrum two difference frequencies with a smooth variation over the LF spectrum. By changing the amplitudes of the LF monochromats, it is possible to trace their nonlinear interaction. When the amplitude of one of the LF monochromats is insufficient, only two monochromats are observed in the LF spectrum. With increasing amplitude of the lower-frequency monochromat, combination frequencies appear in the spectrum. Further increase of the amplitude can lead to total absorption of the main monochromat, with energy transfer to the combination frequencies. Figure 3 shows the interaction of a broad line with a monochromat. When the amplitude of the low-frequency monochromat a increases, the broad line breaks up into combination frequencies, b. Further increase of the amplitude leads to a total absorption of the broad line and to transfer of energy into spectral region of lower frequency.

Thus, the nonlinear interaction of LF waves makes it possible to redistribute the energy in the LF spectrum. Consequently, external multi-frequency modulation of the electron beam uncovers extensive possibilities for the control of the oscillation spectrum of two-stream instability.

Experiments on multi-frequency beam modulation revealed the presence of high-energy ions, and therefore by controlling the width of the LF oscillation spectrum and the spectral density of its energy it is possible to produce the required conditions for effective ion heating and by the same token solve the problem of effective energy transfer from the electron beam to the plasma electrons and ions.

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