Interaction Between a Plasma and an Electron Beam Modulated by Low-Frequency Oscillations

G. P. Berezina, Ya. B. Faĭnberg, A. K. Berezin, and V. P. Zeĭdlits
Physico-technical Institute, Ukrainian Academy of Sciences
Submitted November 15, 1971
Zh. Eksp. Teor. Fiz. 62, 2115–2120 (June, 1972)

The possibility of regulating the low-frequency oscillation spectra in a plasma-beam discharge by means of external, low frequency modulation of the electron beam is studied. The high efficiency of this modulation technique is demonstrated. Low-frequency oscillations can be introduced into the beam-plasma system by deep modulation of the beam. When the modulation frequency is the same as that of the natural low-frequency plasma oscillations, the latter are excited in a resonant manner and suppression takes place of those oscillations, including drift oscillations, whose frequencies differ from the modulation frequency. Moreover, the degree of turbulence of these oscillations in the low-frequency region decreases.

THE possibility of regulating the spectra of oscilla- 1
tions excited in a plasma by means of a modulated beam has been shown previously.[1] The high sensitivity of the spectra to external variable fields leads to the result that an external signal, even of small amplitude in comparison with the amplitude of the oscillations, can significantly change the character of the oscillations in the plasma. In the work of Haas and Dandl[2], low-frequency modulation of the beam density was used for the purpose of excitation of intense ionic cyclotron oscillations in the plasma. Here, the possibility of heating of the ions of the plasma was studied. A study of the mechanism of excitation of low-frequency oscillations in two-stream instability, and of the possibility of control of their spectrum by use of high-frequency modulation of the electron beam at several frequencies was carried out by Krivoruchko and Kornilov.[3]

In the present work, the possibility of controlling the spectra of low-frequency oscillations by supposition of external modulation on the beam at the frequency of ion-sound oscillations has been studied in the present research.

The experiments were carried out with the following parameters of the beam and plasma: beam current 2–4 A, energy 6–10 keV, duration of the current pulse 110 μsec, repetition rate 3 Hz, electron density produced by the plasma beam 5×10^{12}–2×10^{13} cm^{-3}, intensity of the longitudinal magnetic field 2 kOe, length of the interaction region ~ 70 cm, working gas hydrogen. A description of the setup was given in[4], a block diagram is shown in Fig. 1.

A study was made of various methods of low-frequency modulation of the electron beam in the cathode-anode, grid-anode and grid-cathode spaces. The experimental results showed that the most effective method is modulation in the grid-cathode gap. The modulation of the electron beam was performed at the frequencies 150, 300, and 500 kHz (f ~ 500 kHz is the frequency of the ion-sound oscillations).

Figures 2a, b show the current pulse of the electron beam from a Faraday cylinder, in the absence of plasma, without modulation and in the presence of a modulation of the beam. The beam current was 4 A, sweep time 20 μsec/div, modulation frequency 150 kHz, amplitude of the modulating signal 160 V. An increase in the current of the electron beam was noted during its modulation.

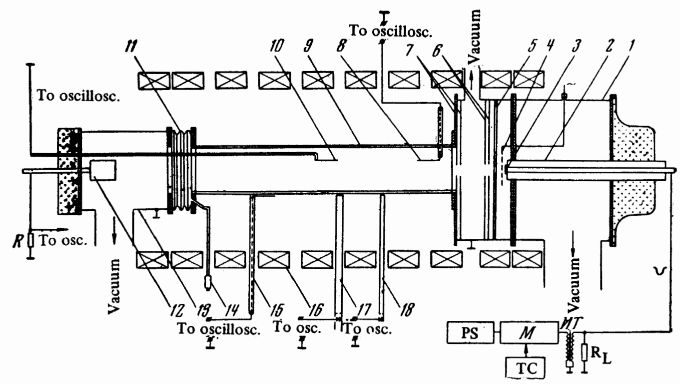

FIG. 1. Block diagram of apparatus: 1—electron gun chamber; 2—electron gun; 3—cathode; 4—grid; 5—anode; 6 and 7—two pairs of diaphragms; 8 and 10—internal probes; 9—plasma chamber; 11—sylphon bellows; 12—Faraday cylinder; 13—experimental chamber; 14—leak valve; 15—external probes; 16—magnetic field coil; 17 and 18—ten- and three-centimeter waveguides; PS—power supply; M—modulator; TC—trigger circuit.

With increase in the pressure in the plasma chamber and with the formation of a dense plasma, intense radiation from the discharge of low-frequency oscillations has been observed over a wide range of frequencies,[4] and was recorded with a 5-beam oscillograph S1-33 with a bandwidth 8 MHz. The oscillations were picked up from the discharge by probe-type antennas oriented along the longitudinal or transverse component of the electric field and located both inside and outside the plasma chamber, and by waveguides (10 and 3 cm), the location of which near the glass tube corresponded to reception of the E_z components of the field.

Figure 3a shows oscillograms of the following signals: trace I—sum oscillations in the region of the resolution frequency of the oscillograph, taken by a probe located inside the plasma chamber. Trace II represents the ion current, recorded at the end of the interaction region, where the decrease in the magnetic field makes possible the separation of the electron and ion currents flowing along the axis of the system. Traces III and IV record the amplitudes of the detected signals from the ten- and three-centimeter waveguides in a band of frequencies limited by their critical dimension. Trace V gives the oscillations in the ten-meter frequency range, determined by a resonant wavemeter

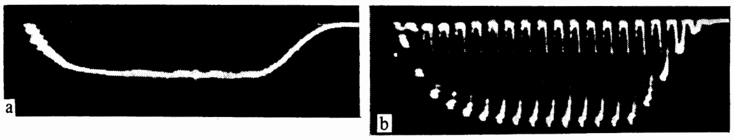

FIG. 2. Oscillograms of the current of the unmodulated (a) and modulated (b) electron beam.

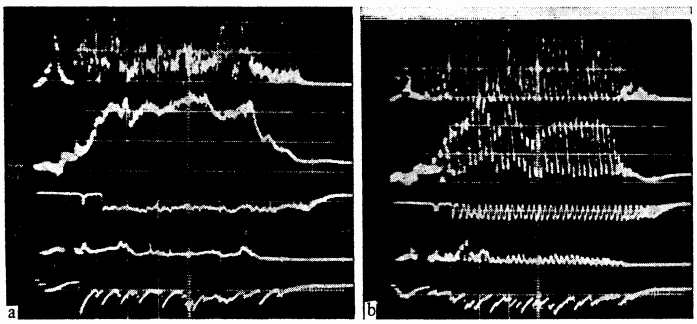

FIG. 3. Oscillograms of the discharge in the absence of modulation of the electron beam (a) and in its presence (f ~ 500 kHz) (b). The y-axis scales of trace II are 0.75 A/div in Fig. a and 1.5 A/div in Fig. 2.

(600–2000 MHz) and picked up from the discharge by the external probe.

For comparison, similar signals are shown in Fig. 3b, taken from the discharge in the presence of modulation. It is seen from Figs. 2 and 3 that, with the aid of a very weak, external regular low-frequency signal of power ~ 2 W, 80–100% modulation of the electron beam can be had with power up to 40 kW. In the plasma-beam discharge, oscillations at Langmuir and electron-cyclotron frequencies and at the emission frequencies of in the decimeter band are modulated at the frequency of the given signal (amplitude modulation).

Intense excitation of low-frequency oscillations occurs at frequencies of the modulation of the beam (~ 500 kHz). A modulated ion current is observed, recorded by a Faraday cylinder at the end of the system. Thanks to the initial modulation, the value of the ion current rises to 3 A (approximately twice as large in comparison with the case of an unmodulated electron beam), while the energy, corresponding to the maximum of the intensity of the spectrum of the ions, is practically unchanged (~ 2 keV).[5,6] Thus the power of the ion beam amounts to ~ 6 kW for a power of the electron beam ~ 30 kW (beam current 4 A).

As a result of the modulation of the electron beam, an effective narrowing of the frequency spectrum S_{xx} takes place in the region of low frequencies ($\Delta\omega/\omega \sim 0.13$ in comparison with $\Delta\omega/\omega \sim 0.5$ in the absence of modulation) (see Fig. 4), for which reason it is possible to have a cutoff in the generation of drift oscillations.[6]

A calculation has been carried out of the curve of the spectral energy density of the oscillations $S_k(\omega)$ for k = 0.1, similar to that described earlier.[6] As follows from the shape of this curve, $\Delta\omega/\omega \sim 0.4$. A similar calculation for the case of the unmodulated electron beam gives $\Delta\omega/\omega \sim 0.8$. A comparison of the half-widths of these curves ($\Delta\omega$), which represent the reciprocal of the correlation times of the low-frequency oscillations τ_{cor} for a given k, indicates a decrease in the degree of turbulence of the oscillations in the region of low frequencies upon modulation of the electron beam ($\tau_{cor} \sim 2.5\ \mu$sec in comparison with $\tau_{cor} \sim 4\ \mu$sec).

Oscillograms similar to those shown in Fig. 3b, were obtained for various values of the pressure of the

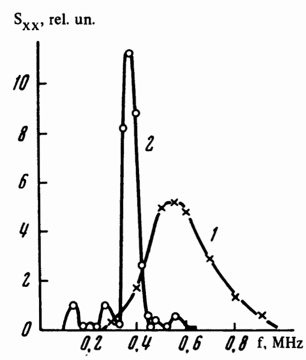

FIG. 4

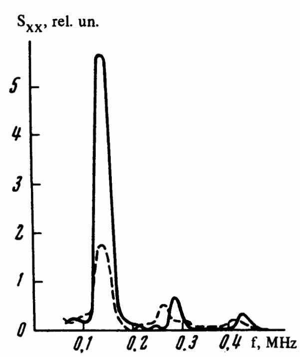

FIG. 5

FIG. 4. Frequency spectrum of the oscillations generated by a plasma beam discharge in the absence of modulation of the electron beam (curve 1) and in its presence (curve 2).

FIG. 5. Dependence of the amplitudes of the generated oscillations on the value of the modulation signal: continuous curve–150 V, dashed curve–50 V (frequency of modulation 150 kHz).

residual gas in the plasma chamber, magnetic field intensity, and output voltage of the modulating generator. With increase in pressure (from the instant of formation of the dense plasma at $p \sim 2 \times 10^{-4}$ Torr) a decrease is observed in the amplitude of the generated oscillations, independent of the method and location of their reception (along the length of the discharge) and a simultaneous decrease in the ion current. Similar effects are observed when the magnetic field intensity decreases from 2000 to 1000 Oe.

Figure 5 shows the dependence of the amplitude of the low-frequency spectrum of the oscillations on the value of the output voltage of the modulation generator. Upon decrease in the modulation voltage across the grid-cathode gap (beginning with 50 V), the external modulation ceases to have an effect on the frequency spectrum of the oscillations. The coefficient of correlation between the oscillations, taken out of the system by the ion beam and the direct signal from the output of the modulation generator is shown in Fig. 6 as a function of the output voltage of the modulating generator.

The modulation of the electron beam quenches the drift oscillations observed in the absence of modulation

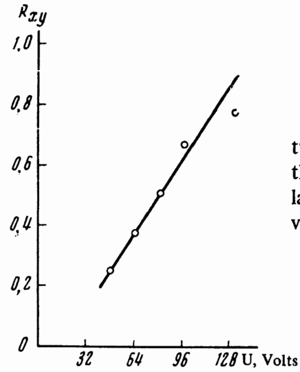

FIG. 6. Correlation coefficient between oscillations of the ion current and the signal from the output of the modulation generator as a function of the voltage of the latter.

and generated in the plasma-beam discharge at high pressures ($p \gtrsim 5 \times 10^{-4}$ Torr). Similar effects were observed following modulation of electron beam at frequencies of 150 and 300 kHz.

Proceeding to the explanation of the obtained results, we recall that only high-frequency waves are excited directly by the beam under conditions of the given discharge (in the absence of modulation). This process occurs most effectively under conditions of excitation of Langmuir waves, with frequencies close to the electron plasma frequency. The high-frequency waves excited by the beam interact with one another and also with the low-frequency oscillations of the plasma, which are not excited directly by the beam. Strong modulation of the beam allows us to introduce low-frequency oscillations into the beam-plasma system. Resonance excitation takes place when the modulation frequency coincides with the characteristic low-frequency oscillations of the plasma.

We also point out another possible mechanism of excitation of low-frequency oscillations in the beam-plasma system, consisting of changes in the increment of the high-frequency oscillations due to low-frequency modulation of the density of the electron beam.[7]

Thus, it has been shown experimentally that the modulation of an electron beam by a low-frequency regular signal leads to intensive excitation of low-frequency oscillations in the beam-plasma system, to a narrowing of the spectra generated by the oscillations, which is accompanied by the simultaneous collapse of the generation of drift oscillations over a wide range of frequencies, and to a decrease in the degree of turbulence of the oscillations in the low-frequency range.

The nearly 100% modulation of the ion current observed indicates the great effectiveness of the suggested method of modulation, which allows the effective transfer of energy from the electron ions to the plasma-beam discharge, as the result of the collective interaction of waves with particles and nonlinear processes of interaction of the waves among themselves.

It is shown that, because of the initial modulation of the electron beam, not less than 20% of its energy goes toward acceleration of the plasma ions.

[1]Ya. B. Fainberg, Intern. Symposium on Beam-Plasma Interaction, Prague, 1967; Czech. J. Phys. **18,** 649 (1968).
[2]G. M. Haas and R. A. Dandl, Phys. Fluids **10,** 678 (1967).
[3]S. M. Krivoruchko and E. A. Kornilov, Zh. Eksp. Teor. Fiz. Pis'ma Red. **10,** 465 (1969) [JETP Lett. **10,** 299 (1969)].
[4]A. K. Berezin, Ya. B. Faĭnberg, L. I. Bolotin, G. P. Berezina, I. A. Bez'yazychnyĭ, Yu. M. Lyapkalo, and E. V. Lifshitz, Plasma Phys. and Controlled Nuclear Fusion Research 1, Vienna, 1966, p. 515.
[5]A. K. Berezin, G. P. Berezina, L. I. Bolotin, and Ya. B. Faĭnberg, VIII Intern. Conference on Phenomena in Ionized Gases, IAEA, Vienna, 1967, p. 370.
[6]G. P. Berezina, A. K. Berezin, and V. P. Zeĭdlits, Zh. Eksp. Teor. Fiz. Pis'ma Red. **14,** 13 (1971) [JETP Lett. **14,** 8 (1971)].
[7]A. S. Bakaĭ, A. I. Ermakov, and N. I. Nazarov, Ukr. Fiz. Zh. **16,** 12 (1971).

Translated by R. T. Beyer
245