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# *NONLINEAR STABILIZATION OF TWO-STREAM INSTABILITY*

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Partial stabilization of two-stream instability during interaction between an electron beam and performed decaying plasma is demonstrated experimentally.

WHEN an electron beam interacts with plasma, there may be factors which stabilize the two-stream instability. These may be due to two-body collisions and nonlinear effects.[1] It was shown earlier[2] that the interaction between an electron beam and performed decaying plasma will, under certain conditions, lead to strong attenuation of the high-frequency Langmuir oscillations.

In this research we have investigated the degree of stabilization of two-stream instability and the distribution function for the beam electrons in the course of the attenuation of the high-frequency oscillations.

The installation which we have employed was described in detail in[2].

A beam of 10-keV electrons carrying a current of 4 A was introduced into a glass plasma chamber 40 cm long and 3.7 cm in diameter. The chamber was placed in a constant uniform magnetic field of 2500 Oe. The beam diameter was 1 cm and the current pulse length was 7.5 $\mu$sec. The density of the preformed plasma, produced by a high-frequency field, could be varied between 0 and $10^{12}$ cm$^{-3}$. The plasma density was measured with a double probe and by the space-charge wave method. The plasma electron temperature $T_e$ was measured with a double probe. The longitudinal energy spectra of the beam electrons were recorded with a grid analyzer. The electron current passing through an aperture of 1 mm in diameter in the collector was analyzed. High-frequency oscillations excited in the beam-plasma system were received by dipole antennas and after detection were exhibited on an oscillograph screen.

Figure 1 shows the intensity of the high-frequency oscillations as a function of the density of the preformed plasma for a 4 A electron beam. The amplitude of the integrated high-frequency signal after detection was measured with apparatus of a higher sensitivity than in[2], so that more detailed information was obtained on the attenuation of the oscillations.

It is clear from Fig. 1 that the oscillation intensity decreases after the density of the preformed plasma reaches the value $N = 5 \times 10^{11}$ cm$^{-3}$. The oscillations are attenuated by 35 dB when $N = 5 \times 10^{11}$ cm$^{-3}$. Further increase in density has little effect on the attenuation. Similar results are obtained for other values of the beam current, but as the current is reduced the attenuation of the oscillations occurs at lower densities of the preformed plasma.

Let us consider the plasma parameters during the attenuation of the high-frequency oscillations. At the beginning of this process the plasma density n in the beam-plasma discharge exceeds the density of the preformed plasma by a moderate factor. The plasma electron temperature amounts to ~100 000°K. This is only an order-of-magnitude estimate because the probe method of measuring the plasma parameters in the presence of high-intensity high-frequency fields is subject to considerable errors. When the high-frequency oscillations are highly attenuated the electron temperature and plasma density are 4000°K and $5 \times 10^{11}$ cm$^{-3}$, respectively. The low value of $T_e$ is due to the fact that the parameters of this plasma are largely determined by the parameters of the preformed decaying plasma, and the contributions of the remaining high-frequency oscillations to the density and tempera-

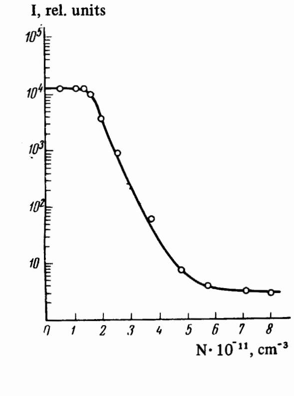


FIG. 1. Intensity of oscillations as a function of the preformed-plasma density.

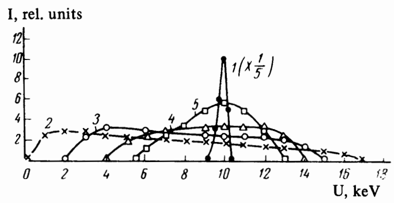


FIG. 2. Energy spectra of beam electrons for different values of the attenuation of the oscillations: curve 1—without plasma; 2—0 dB; 3—7 dB; 4—15 dB; 5—35 dB.

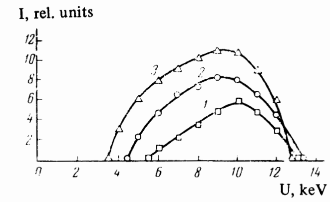


FIG. 3. Electron energy spectra in the case of strong attenuation of the oscillations. Curve 1—I = 0.8 Å; 2—I = 1.6 Å; 3—I = 2.4 Å.

ture parameters of the plasma are small. In fact, measurements have shown that these values are almost identical with the parameters of the preformed plasma.

We have also measured the energy spectra of beam electrons during the attenuation of the high-frequency oscillations. Figure 2 shows the beam-electron distribution functions for a current of 0.8 A for different degrees of attenuation of the oscillations. The density range of the preformed plasma in which the attenuation of the oscillations was observed for a beam current of 0.8 A was $4 \times 10^{10}$—$8 \times 10^{10}$ cm$^{-3}$. The beam-electron distribution function in the absence of the plasma is shown by curve 1. Curve 2 was obtained at the beginning of the attenuation process and is practically indistinguishable from the distribution function in the absence of the preformed plasma.

The characteristic feature of the distribution function is the presence of the region with negative slope (instead of the plateau) which may be due to the quasilinear transformation of high-frequency oscillations into low-frequency oscillations, or to relaxation processes connected with the instability of the plateau against the excitation of oscillations through the anomalous Doppler effect.[3,4] Curves 3, 4, and 5 were recorded with the oscillations attenuated by 7, 15, and 35 dB, respectively. Attenuation by 7 dB leads only to a contraction of the energy range corresponding to the distribution function, whilst at larger values of the attenuation the distribution function is deformed and assumes a double-hump shape. Further increase in the density of the preformed plasma has practically no effect on the distribution function, and this can be explained by the small change in the intensity of the remaining oscillations.

We have also recorded the beam-electron distribution functions in the case of strong attenuation of the oscillations for different values of the beam current (Fig. 3). The broadening of the distribution functions toward lower energies as the beam current increases is due to the increase in intensity of the remaining oscillations. Anomalous scattering of beam electrons to energies greater than the initial beam energy during the attenuation of the high-frequency oscillations is substantially reduced. However, its relative magnitude remains considerable, which is particularly noticeable at low beam currents.

The curves in Figs. 1-3 were obtained with air as the working gas ($p = 7 \times 10^{-4}$ mm Hg). Similar results were obtained in the case of hydrogen. The distribution function for the beam electrons in the case of high attenuation (curve 5, Fig. 2; curves 1-3, Fig. 3) thus shows the presence of partial stabilization of the two-stream instability. The remaining oscillations still have an appreciable effect on the shape of the beam-electron distribution function.

It was noted in[2] that Coulomb collisions and nonlinear effects may be responsible for the suppression of the high-intensity oscillations. Measurements of the temperature of plasma electrons during the attenuation of the high-frequency oscillations enable us to obtain more detailed information about the processes that stabilize the two-stream instability.

Comparison of the electron-ion collision frequency $\nu_{ei} \approx 8 \times 10^7$ sec$^{-1}$ with the quasilinear oscillation growth rate $\gamma_{qs} \approx 4 \times 10^8$ sec$^{-1}$, calculated for the curve in Fig. 1 at $N = 5 \times 10^{11}$ cm$^{-3}$ which corresponds to $T_e = 4000°$K, shows that Coulomb collisions may have an appreciable effect on the attenuation of the oscillations. The reduction in the oscillation intensity during the subsequent increase in the density of the preformed plasma may be wholly determined by the Coulomb interaction.

It is also known that, during the development of the high-intensity oscillations in the plasma-beam system, the attenuation of these oscillations may be determined by nonlinear effects (induced scattering by charged particles and decay processes). The theory of induced scattering of the oscillations by plasma electrons shows that, in our case, for the curve shown in Fig. 1 the attenuation of oscillations above $N = 1.5 \times 10^{11}$ and Te $\sim 100\,000°$K is, to a considerable extent, due to scattering of the oscillations by plasma electrons in which the polarization of the plasma is important ions (the effect of two-body collisions on the attenuation is negligible in this case).

The above scattering process may occur when

$$(m_i / m_e)^{1/3} < v_{\rm ph} / v_{Te} < (m_i / m_e)^{1/2},$$

where $m_i$ and $m_e$ are the ion and electron masses, $v_{ph}$ is the phase velocity of the wave, and $v_{Te}$ is the thermal velocity of plasma electrons. This condition is adequately satisfied when $v_{ph} = 6 \times 10^9$ cm/sec for plasma with $T_e = 10^4$—$10^5$°K. At the point where the attenuation of the oscillations begins for a beam current of 4 A, the attenuation rate calculated from the formula

$$\gamma_e \approx \omega \frac{n_0}{n} \frac{v_{\rm ph}}{v_{Te}},$$

is $2 \times 10^{10}$ sec$^{-1}$, which is much greater than the quasilinear growth rate ($\omega$ is the plasma frequency, $n_0$ is the electron density in the beam, and $n$ is the density of the beam-plasma discharge). Since the effectiveness of the nonlinear interaction may substantially increase with increasing role of the Coulomb collisions[5], this nonlinear effect may explain almost the entire fall on the curve in Fig. 1.

Another possible nonlinear mechanism is provided by stimulated scattering of the oscillations by plasma ions with "cascaded" transfer of the oscillations from the resonance region into the nonresonance region. If we take two-body collisions into account the condition under which this process is possible can be written in the form

$$\left(\frac{v_{\mathrm{ph}}}{v_{Te}}\right)^4 > \frac{27}{\pi}\left(1-\frac{\nu_{ei}}{\gamma_{\mathrm{KB}}}\right)\frac{m_i}{m_e}\left(1+\frac{T_e}{T_i}\right)^2.$$

This is adequately satisfied for $T_e \leq 10^4$°K, and for $T_e = 4 \times 10^3$°K and $n \approx N = 5 \times 10^{11}\ \mathrm{cm}^{-3}$ the rate of attenuation calculated from the formula

$$\gamma_i \approx \omega \frac{n_0}{n}\frac{v_{\mathrm{ph}}}{v_{Ti}}\frac{T_e/T_i}{(1+T_e/T_i)^2},$$

is $2 \times 10\ \mathrm{sec}^{-1}$, where $v_{Ti}$ if the thermal velocity of the plasma ions.

The condition for the decay process

$$3v_{Te}(m_i/m_e)^{3/10} < v_{\mathrm{ph}} < 3v_{Te}(m_i/m_e)^{1/2}$$

is also adequately satisfied for $T_e = 1000-6000$°K. Here, the quantity

$$\gamma_{\mathrm{elec}} \approx \omega \frac{n_0}{n}\left(\frac{v_{\mathrm{ph}}}{v_{Te}}\right)^3 \sqrt{\frac{m_e}{m_i}}$$

is of the order of $10^{12}\ \mathrm{sec}^{-1}$.

We may thus conclude that the attenuation of the oscillations and the observed stabilization of the two-stream instability (Figs. 2 and 3) can be explained within the framework of the existing theory in terms of two-body collisions and nonlinear effects. However, a direct confirmation of the nonlinear interaction between the waves in the system will require the experimental verification of the conditions $\omega_1 - \omega_2 \leq |\mathbf{k}_1 - \mathbf{k}_2| v_{Ti}$ for induced scattering by plasma ions and $\omega_1 - \omega_2 \ll |\mathbf{k}_1 - \mathbf{k}_2| v_{Te}$ for induced scattering by plasma electrons with allowance for ion polarization ($\omega_{1,2}$ and $\mathbf{k}_{1,2}$ are, respectively, the Langmuir frequencies and wave vectors). To establish this it will be necessary to perform experimental determinations of wave-number and frequency spectra, and to show that the above relations are satisfied for them.

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[1] V. N. Tsytovich, Nelineinye effekty v plazme (Nonlinear Effects in Plasma), Izd. Nauka, 1967.

[2] N. I. Leont'ev, A. P. Timoshenko, and Yu. K. Udovichenko, Zh. Tekh. Fiz. 40, 942 (1970) [Sov. Phys.-Tech. Phys. 15, 728 (1970)].

[3] E. O. Shustin, V. P. Popovitch, and I. F. Kharchenko, Proc. Eighth Intern. Conf. on Phenomena in Ionized Gases, Vienna, 1967, p. 376.

[4] V. D. Shapiro and V. I. Shevchenko, Zh. Eksp. Teor. Fiz. 54, 1187 (1968) [Sov. Phys.-JETP **27**, 634 (1968)].

[5] V. G. Makhan'kov and V. N. Tsytovich, Zh. Eksp. Teor. Fiz. 53, 1788 (1967) [Sov. Phys.-JETP 26, 1023 (1968)].

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