On the relaxation of an electron beam in a high-density, slightly ionized gas

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The relaxation of an electron beam in a high-density, slightly ionized molecular gas is examined. The relaxation length of the beam is found, with account of the dependence of the electron density and the instability increment of the energy of the Langmuir vibrations.

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In studying the relaxation process of an electron beam one usually considers a completely ionized collisionless plasma. In this case the intensity of the Langmuir vibrations, in resonance with the beam electrons, can be determined by various nonlinear transfer mechanisms of the waves over the spectrum.[1] On the other hand, when an electron beam is injected into a slightly ionized, high-density gas, where the electron density n is determined by the energy W_0 of the Langmuir vibrations, the beam instability stabilization effect can be related to the dependence of the instability increment $\gamma \sim 1/\sqrt{n}$ on W_0.

For a sufficiently high density N of the neutral gas, when electron diffusion plays no significant role, the electron density is determined by the local value of W_0 and can be found from the kinetic equation[2]:

$$\frac{\partial f_e}{\partial t} = \frac{W_0}{n} \hat{D}_\epsilon (f_e) - \hat{St}(f_e) - \hat{D}(f_e), \tag{1}$$

where $f_e(\epsilon)$ is the plasma electron energy distribution function; the first term on the right side of (1) describes the heating of the electrons in the field of the Langmuir vibrations for collision with particles of the weakly ionized gas; the second term describes the elastic and inelastic interaction of electrons with the weakly ionized gas; the third—electron destruction processes.

In the case of a molecular gas, however, when most of the electron energy goes into the excitation of vibrational degrees of freedom, the dependence of the electron density on W_0 has a simpler form[3]:

$$W_0 \nu_{en} = n \hbar \omega \nu_{ev} , \tag{2}$$

where ν_{en}, ν_{ev} are the frequencies of elastic collision and vibrational excitation of the molecules, respectively; $\hbar\omega$ is the vibrational quantum of the molecule.

Since ν_{en} and ν_{ev} have only a slight dependence on the average electron energy, we shall ignore this dependence below.

Thus, as follows from (2), the beam instability in a slightly ionized, high-density gas may be due to a decrease of the increment $\gamma \sim 1/\sqrt{n}$. Assuming the relaxation to be one-dimensional, consider the following system of quasilinear equations:

$$v_g \frac{\partial W_k}{\partial x} - \frac{\partial \omega_{pe}}{\partial x} \frac{\partial W_k}{\partial k} = 2\gamma_k W_k - \nu_{en} W_k , \tag{3}$$

$$v \frac{\partial f_b}{\partial x} = 4\pi^2 \left(\frac{e}{m}\right)^2 \frac{\partial}{\partial v} \frac{W_k}{v} \frac{\partial f_b}{\partial v} , \tag{4}$$

where $f_b(v)$ is the velocity distribution function of the beam electrons; W_k is the energy spectral density of the Langmuir vibrations; k is the wave number; $v_g \equiv \partial\omega_k/\partial k; \omega_{pe} = (4\pi n e^2/m)^{1/2}$; e, m are the electron charge and mass; γ_k is the instability increment for wave number k. Since the group velocity v_g of the Langmuir vibrations is small, then if the intensity W_0 of the Langmuir vibrations is calculated under the assumption that $2\gamma_k > \nu_{ev}$, it turns out to be so large for beam electron densities of practical interest that the condition $2\gamma_k > \nu_{en}$ is drastically violated in light of relation (2). Then, ignoring the left side in (3) and finding the function $f_b(v)$

$$f_b(v) = 2\frac{v_0}{v} \frac{(v - v_m)}{(v_0 - v_m)} , \tag{5}$$

where v_m: $f_b(v_m) = 0$, $v_m < v_0$; after its substitution into (4) with (2) taken into account we obtain the equation for the relaxation rate

$$\frac{du_m}{d\xi} = \frac{u_m^2}{(1 - u_m)^4} \frac{2}{(1 + u_m)} , \tag{6}$$

where $u_m = \dfrac{v_m}{v_0}$, $\xi = 6\pi^2 \dfrac{\hbar\omega}{1/2mv_0^2} \dfrac{\nu_{ev}}{\nu_{en}} \dfrac{\omega_{pb}^2}{\nu_{en} v_0} x$.

In the case $\Delta v/v_0 \lesssim 1$ we have an estimate of the relaxation length

$$L_{\Delta v} \approx \frac{1}{30\pi^2} \frac{1/2\, mv_0^2}{\hbar\omega} \frac{\nu_{en} v_0}{\omega_{pb}^2} \frac{\nu_{en}}{\nu_{ev}} \left(\frac{\Delta v}{v}\right)^5 . \tag{7}$$

For typical beam energy values of ~ 3 keV, a beam electron density $n_b = 2 \times 10^9$ and a neutral gas pressure of the order of 0.1 Torr the relaxation length is equal to about 10 cm, which agrees well with experimental results.[4] It should be noted that the dependence of $L_{\Delta v}$ on v_0 and n_b also agrees well with experimental data.

Equation (7) was obtained for the relaxation length by ignoring the left side of Eq. (3)—consideration of spectral transfer because of plasma inhomogeneity does not significantly influence the relaxation process if the condition

$$\frac{1}{6\pi^2}\;\frac{\nu_{en}^3}{\nu_{ev}\,\omega_{pb}^2}\;\frac{1/2\; m v_o^2}{\hbar\omega} >> 1 \;. \qquad (8)$$

is satisfied.

[1]A. A. Galeev, R. Z. Sagdeev, V. D. Shapiro, and V. I. Shevchenko, Zh. Eksp. Teor. Fiz. **72**, 507 (1977) [Sov. Phys. JETP **45**, 266 (1977)].

[2]A. A. Ivanov, T. K. Soboleva, and P. N. Yushmanov, Fiz. Plazmy **3**, 152 (1977) [Sov. J. Plasma Phys. **3**, 87 (1977)].

[3]A. A. Ivanov, S. I. Krasheninnikov, V. V. Starykh, V. V. Phylushkin, I. Wilhelm, and R. Winkler, 4th International Symposium on Plasma Chemistry, Zurich, August 27 - September 1, 1979, Proceedings, p. 421.

[4]A. M. Alekseev, V. M. Atamanov, E. M. Erastov, A. A. Ivanov, S. I. Krasheninnikov, G. B. Levadny, Yu. F. Nasedkin, V. A. Nickiforov, Yu. M. Pustovoit, V. V. Shapkin, T. K. Soboleva, and E. P. Tsvetkov, 4th ISPC, p. 427.