Beam-plasma discharge occurring during the nonlinear interaction of a fast ion beam with the electronic oscillations of a plasma

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A beam-plasma discharge occurring during the collective interaction of a fast ion beam with the electronic oscillations of a plasma has been observed. The main distinctive features of this type of discharge, which are due to the specific character of the nonlinear stage of the ion–electron interaction, at which the major role is played by the capture of the nonresonance electrons of the plasma by the wave field, are elucidated. It is shown that the discharge occurs only when the beam energy is sufficiently high, and that it is relatively homogeneous along the axis of the system.

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It is well known[1–7] that under certain conditions there occurs during the passage of an electron beam through a gas a beam-plasma discharge in which the gas is ionized largely by the plasma electrons accelerated in the fields of the unstable oscillations. In the present paper we investigate the possibility of the induction of a beam-plasma discharge during the collective interaction of an ion beam with the electronic oscillations of a plasma in the absence of a magnetic field. As follows from previous investigations,[8,9] such a discharge should have distinctive features connected with the fact that the nonlinear ion-electron interaction has a character that is fundamentally different from that of the nonlinear electron-electron interaction. If in the case of the electron beam the dominant nonlinear mechanism is phase focusing[5] followed by the capture of the beam electrons by the wave field,[10] in the case of the ion beam the dominant role is played by the capture of the nonresonance electrons of the plasma by the wave field.[8,9] In the first case the field amplitude is proportional to the degree of bunching of the beam electrons, and, consequently, attains its maximum value in the region of the phase focus.[5] In the second case the plasma electrons are captured when the depth of the wave's potential well $e\tilde{\varphi} \gtrsim \frac{1}{2} m v_+^2$ (v_+ is the beam velocity and m is the electron mass), which leads to a partial neutralization of the space charge of the resulting ion bunch, with the result that further bunching of the ions does not lead to an increase in the potential.[8,9] On the basis of the foregoing, we can predict the following characteristics for the beam-plasma discharge in an ion-electron system:

1) The discharge should be triggered in an ion beam of fairly high energy, i.e., with

$$ {}^1/_2 m v_+^2 \gg e\varphi_i, \tag{1}$$

where φ_i is the ionization potential of the residual gas.

2) In contrast to the electron-electron system in zero magnetic field, in which the discharge blazes primarily in a narrow zone—meniscus—located in the region of the phase focus, in the ion-electron system the discharge should be relatively homogeneous over the entire length of the system, starting from some critical distances.

The efficiency with which the gas is ionized by the accelerated plasma electrons can be derived by considering the balance equation for, for example, the plasma ions. If we assume that the particles are uniformly distributed within the limits of the beam, then from this equation we can easily derive the following expression for the ion flux toward the side walls of the chamber:

$$\frac{I_i}{I_+} = n_a \sigma_i L \left(1 + \frac{\langle \sigma_e v_e \rangle}{\sigma_i v_+}\right) \Big/ \left(1 - \frac{n_a \langle \sigma_e v_e \rangle R}{2\bar{v}_i}\right), \tag{2}$$

where I_+ is the beam current; n_a is the concentration of the neutrals; σ_e and σ_i are the cross sections for ion production through ionization of the gas by the gas electrons and the beam ions; v_e and $\bar{v}_i$ are the velocities of the plasma electrons and ions; R is the beam radius; and L is the length of a side wall.

It can be seen from (2) that, in the absence of electron-induced ionization of the gas (i.e., for $\sigma_e \to 0$),

$$ I_i / I_+ = n_a \sigma_i L \tag{3}$$

and that the electron-induced ionization becomes important if the electrons' characteristic ionization time is of the order of the time characterizing the removal of plasma ions from the system.

The experiments were performed with a beam of positive helium ions of energy 120 keV and current strength 10 mA, passing through the xenon atmosphere. Located at the entrance through which the beam passed into the chamber was a three-grid modulator, with the aid of which monochromatic oscillations of frequency 38 MHz were excited in the system. The length of the interaction chamber was 200 cm, and the xenon pressure in the chamber was varied within the range from 4×10^{-3} Pa to 4×10^{-2} Pa. The variable potential of the wave was measured with the aid of a capacitive probe; the variable current in the beam, with the aid of a screened grounded collector grid.[11] The plasma-ion current toward a wall was measured with a cylindrical collector that concentrically enveloped the beam. To separate the charges of the plasma, the collector was supplied with a small negative potential relative to a

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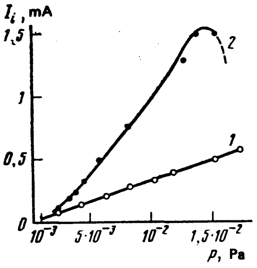

FIG. 1. Dependence of the plasma-ion current to the boundary collector on the xenon pressure: the curve 1) $U_1 = 0$, $z = 200$ cm; the curve 2) $U_1 = 1500$ V, $z = 200$ cm.

grounded grid mounted in front of the collector.

In the absence of an external signal on the modulator, there were excited in the system electronic oscillations that grew exponentially along the beam. The magnitude of the spatial increment was determined by the damping arising as a result of the thermal velocity spread of the electrons, and was equal to $(1-2)\times10^{-2}$ cm^{-1} (Ref. 12). The oscillation frequency ranged from 40 to 100 MHz. The amplitude of these spontaneously-excited potential oscillations did not exceed several volts, and was not high enough to trigger a beam-plasma discharge. The ion current toward a wall in this case was proportional to the pressure, and corresponded to the expression (3) (the curve 1 in Fig. 1).

Upon the supply of a modulating voltage, the spectrum of the oscillation narrowed down, while the amplitude initially increased with increasing U_1, and then saturated (the curve 1 in Fig. 2). The quantity $\tilde{\varphi}$ in the saturation region corresponded to the equilibrium potential $\tilde{\varphi}\sim mv_+^2/2e$, established as a result of the capture of the electrons by the wave. When the potential attained a fairly high value, we observed an increase in the ion current toward the wall, which was the result of additional ionization of the gas by the electrons (the curves 2 and 3 in Fig. 2). As was to be expected, the magnitude of the additional increases with increasing gas pressure (Fig. 1). The dependence $I_i = I_i(p)$ is close to (2) if we take into account the fact that the mean electron velocity $\bar{v}_e \approx v_+$ and $\bar{\sigma}_e \approx 2\times10^{-16}$ cm^2. The maximum increase in the plasma-ion current was attained at $p \approx (1.33-2.66)\times10^{-2}$ Pa. Further increase of the pressure led to appreciable beam-current losses on account of charge transfer by the ions. The variable potential in the beam and, accordingly, the addition to the plasma-ion current due to the ionization by the electrons then decreased.

The increase in the ion current toward the walls was accompanied by an appreciable increase in the intensity of the luminescence of the gas not only within, but also outside, the beam. The discharge was practically homogeneous along the beam axis at fairly high generator amplitudes. When gases with a higher ionization potential (hydrogen, air, argon) were used, no luminescence occurred outside the beam, and the increase, due to the ionization by the electrons, in the ion current toward the walls did not exceed 10–20%.

The totality of the above-presented facts shows conclusively that we have observed in the system for the first time the induction of a beam-plasma discharge during the nonlinear interaction of a fast ion beam with the electronic oscillations of a plasma. The observed phenomenon may play a significant role during the passage of quasi-stationary beams through an overcharged stream of the vapor of a metal with a low ionization potential, as well as during the transportation of pulsed, high-current light-ion beams. Let us note in connection with the latter observation that Kiyashko et al.[13] have obtained data indicating the possibility of the induction of a beam-plasma discharge during the passage of a fast high-current ion beam through a gas. The authors, however, think that the beam-plasma discharge occurs during the interaction of a beam with the ion oscillations of a plasma.

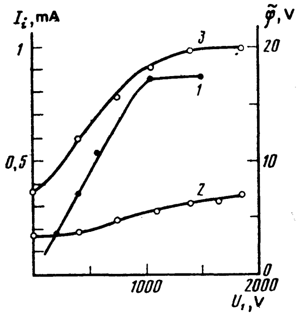

FIG. 2. Dependence of the doubled amplitude to the potential oscillations (the curve 1) and the plasma-ion current to the boundary collector (the curves 2 and 3) on the modulation amplitude. The distance from the modulator to the collector z = 200 cm; the xenon pressure $p = 4.66\times10^{-3}$ Pa (the curves 1 and 2) and $p = 1.33\times10^{-2}$ Pa (the curve 3).

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