Interaction of a relativistic monochromatic electron beam with plasma produced in the atmosphere

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This paper is devoted to the study of transmission and interaction of a relativistic monochromatic electron beam with the atmosphere. It is shown that such a beam interacts collectively with the produced plasma ($n_p \sim 10^{13}$ cm^{-3}). This is indicated by the large loss of energy in the beam and by the observed electromagnetic radiation and x-rays.

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Kiselev *et al.*[1] and Berezin *et al.*[2] investigated the interaction of a relativistic electron beam with an independently produced plasma of density 10^{15}–10^{17} cm^{-3} and showed that in the case of monochromatic beams the efficiency of the interaction, which has a collective nature, increases with increasing plasma density.

Lately, much attention has been devoted to the study of transmission of electron beams through high-density gases.[3–6] In view of this, it is of interest to study the transmission of monoenergetic relativistic electron beams through such a gas, the possibility of producing plasma by such a beam in a dense gas and the collective interaction of the beam with the plasma.

The experiments were carried out using a setup described in Ref. 1. An electron beam with energy of 2 MeV and a current $I_b \sim 1$ A and duration $\tau \approx 2$ μsec was brought out through a 0.2-mm-thick copper foil into the atmosphere.

The mean free path of the high-energy electrons in the air[1)] was determined as $R = 0.57$ and $E = 0.16$, where E is the electron energy in MeV and R is the mean free path in g/cm^2, which for the given beam is ~8 meters.[7] In our experiments we discovered that, in entering the atmosphere, the beam produces a plasma in the shape of a cone 5 cm in diameter near the foil and 10 to 15 cm in diameter at a distance of 10 cm from the foil. The overall length of the plasma column was 50 to 60 cm. The plasma density was determined by the cut-off of the hf signal with a 3-cm wavelength. Such a signal was blanked 4- to 20-cm from the output foil i.e., the plasma density at such a distance was $\geqslant 10^{12}$ cm^{-3}.

Taking into account the ionizing capacity of this beam, we can estimate the density from the expression:

$$n_p \approx n_b c \tau m ,$$

where n_b is the beam density and m is the number of electron-ion pairs produced by the fast electron along a 1-cm trajectory in the air at $P = 760$ mm Hg, c is the speed of light in a vacuum, and τ is the pulse duration. For our case taking into account the angular distribution of the beam ($n_b \sim 10^7$ cm^{-3} and $\gamma = 5$ for the 2-MeV electrons) at a distance of 5 cm from the foil, $n_p \sim 10^{13}$ cm^{-3}.

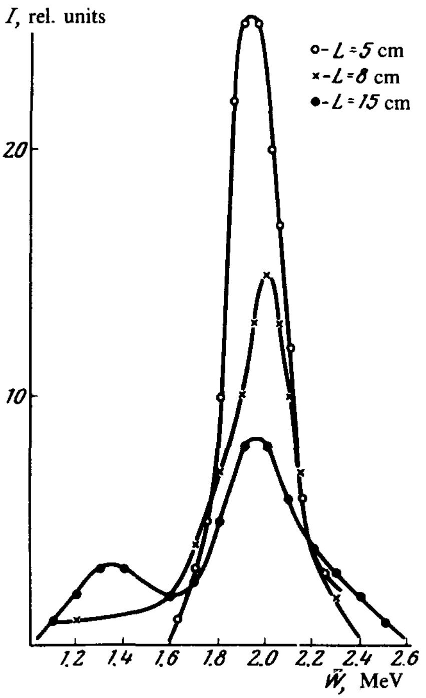

FIG. 1. Energy spectra of the beam electrons at different distances from the exit foil.

The measurements of the energy spectra of the electron beam at different distances from the foil using a magnetic analyzer showed that at a distance of 5 cm from the foil the energy spectrum of the beam remains practically the same compared to that of the beam in a vacuum (Fig. 1). At a distance of 8 cm from the foil the energy spectrum expands in the direction of the energy decrease and at a distance of 15 cm we can observe electrons with energy of <1 MeV. These effects cannot be attributed to inelastic pair collisions, since the total losses in the beam, which consist of ionization and radiation losses, at such distances do not exceed 100 keV for individual electrons. A sharp increase of the scattering angles at a beam current $I_b \sim 1$A indicates that the energy loss of the beam is large (Fig. 2). A large increase of the scattering angle of the

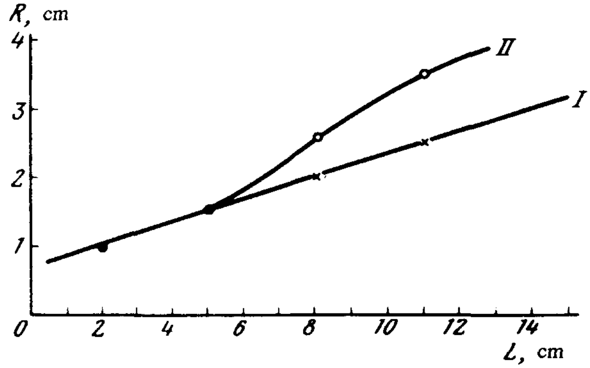

FIG. 2. Angular distribution of the beam electrons: 1, $I_b \sim 100$ mA; 2, $I_b \sim 1$ A.

electrons at a distance of 5 cm from the foil at a full current of 1 A is attributable to the fact that the beam electrons lose their energy due to collective intraction with the plasma.

The observed electromagnetic radiation from the plasma at 10.3- and 0.8-cm wavelengths indicates that the interaction of the relativistic monochromatic beam with the plasma is collective in nature (Fig. 3). The radiation at 3- and 0.8-cm wavelengths is concentrated in a region located 5 to 10 cm from the foil. The radiation intensity depends on the current and the width of the energy spectrum of the beam electrons. An increase of the width of the energy spectrum of the beam from 8 to 17% decreases the amplitude of the radiation signals at 10- and 3-cm wavelengths and changes the shape of the pulse (Fig. 4). A radiation with a wavelength $\lambda = 8$ mm was not observed in the last case.

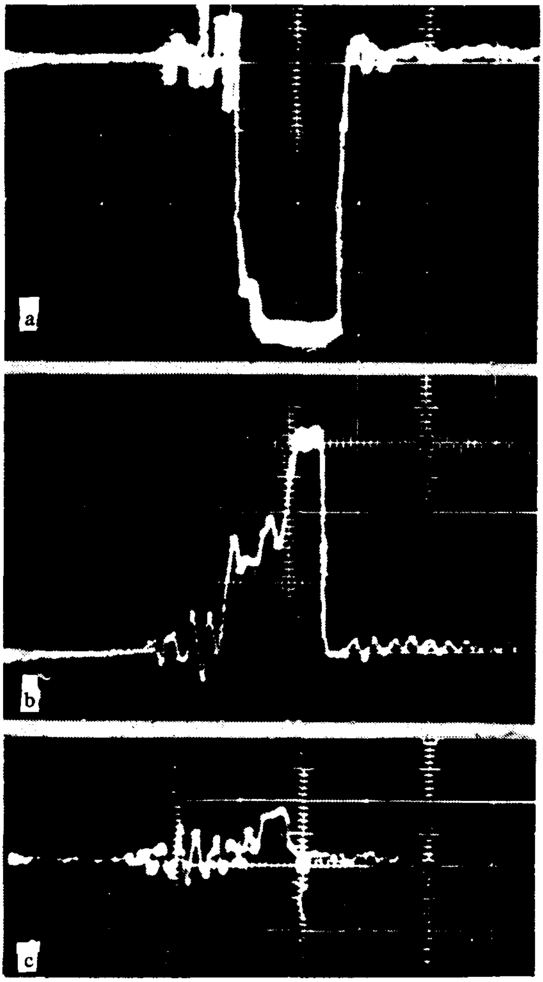

FIG. 3. Oscillograms of the electromagnetic-radiation signals: a, $\lambda = 10$ cm; b, $\lambda = 3$ cm; c, $\lambda = 8$ mm ($\Delta W/W = 8\%$).

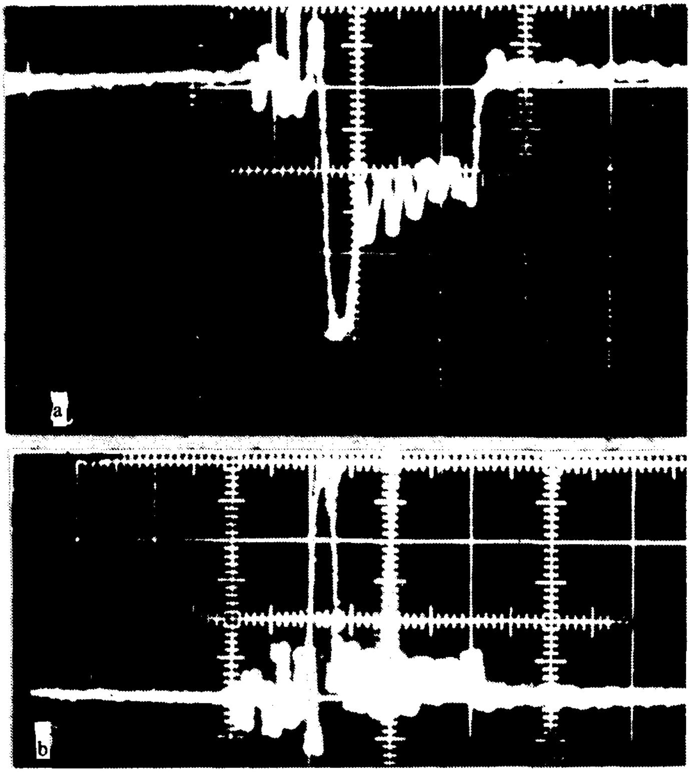

FIG. 4. Oscillograms of the electromagnetic-radiation signals: a—$\lambda = 10$ cm; b—$\lambda = 3$ cm ($\Delta W/W = 17\%$).

Using a pinhole camera we noticed that soft x-rays were emitted from the region located 5 cm from the output foil. By moving the camera along the axis of the system we were able to show that the radiation is localized in this region. The diameter of the obtained x-ray spot was $\leqslant$4–5 cm.

Thus, a highly dense plasma (up to 10^{13} cm^{-3}) can be produced by introducing into the atmosphere a relativistic monochromatic electron beam which effectively interacts with the produced plasma. This is indicated by the large energy loss of the beam, by the electromagnetic radiation with 10-, 3-, and 0.8-cm wavelengths and by the soft x-rays localized in the neighborhood of the interaction, which indicate that the plasma is heated in this region. The onset of 8-mm radiation at the end of the current pulse (Fig. 3), which is attributed to additional ionization by the hf field, evidently increases the plasma density.

The collective nature of such an interaction is indicated by a decrease in the efficiency of the interaction with a decrease of the electron-beam current and an increase in the width of the energy spectrum of the electrons.

[1)] The mean free path of a particle in this case is defined as the path leading to a total loss of ionizing capacity.

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