Influence of transverse velocity component of a strong-current high-energy electron beam on its interaction with a plasma in a magnetic field of mirror configuration

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It is shown experimentally that when the transverse velocity component of a strong-current high-energy electron beam is increased, the effectiveness of its interaction with a plasma is greatly increased. At the same time, the power of the radiated oscillations increases appreciably and the plasma temperature rises.

It is known that the effectiveness of beam-plasma interaction is appreciably increased when the transverse velocity component of the beam is increased.[1]

We have investigated experimentally the influence of the transverse velocity component of a strong-current high-energy electron beam on the effectiveness of its interaction with a plasma confined by an open magnetic trap.

An electron beam was formed by a linear plasma betatron (LPB)[2] and had an energy 100 keV, a current 5–7 kA, and a pulse duration 1 μsec (density 10^{12} electrons/cm^3). It was injected into a magnetic trap 35 cm long. The mirror ratio was equal to two, and the magnetic field in the mirrors was 5 kG. The interaction took place with a pre-formed plasma produced by beam-plasma discharge in a glass chamber of 15 cm diameter. The plasma density in the trap ranged from 10^{12} to 10^{14} cm^{-3}. The working gas was argon or hydrogen. The LPB turned out to be very suitable for this experiment, since it was possible to obtain an electron beam with a large ratio $V_\perp/V_\parallel$ by producing magnetic-field inhomogeneities in the accelerator.

The investigations have shown that the inhomogeneity of the magnetic field and the transverse component of the beam velocity greatly increase the effectiveness of the interaction between the electron beam and the plasma. At $V_\perp/V_\parallel = 0.5$ and in the presence of a magnetic field of mirror configuration, the power of the radiated oscillations amounts to tens of megawatts, which is more than ten times the power in the case when $V_\perp/V_\parallel = 0.1$ and the magnetic field is homogeneous. The registered oscillations lie in the band $\omega_{H\,\mathrm{min}} < \omega < \omega_{0e}$ $\omega < \omega_{H\,\mathrm{max}}$ ($\omega_{H\,\mathrm{min}}$ and $\omega_{H\,\mathrm{max}}$ are the electron cyclotron frequencies in the trap and in the mirror, and ω_{0e} is the electron plasma frequency). The appearance of the oscillations may be due to excitation by the anomalous Doppler effect. The high-frequency oscillations are modulated by low frequencies on the order of ω_{0i} (ω_{0i} is the ion plasma frequency). The excitation of the oscillations is accompanied by a decrease in the beam current flowing through the trap. The maximum level of the excited oscillations is observed at $n_b/n_0 = 10^{-1}$ (n_b and n_0 are the densities of the beam and plasma, respectively).

Oscillogram *a* of Fig. 1 shows the beam current on entering the trap, while oscillogram *b* shows the beam current leaving the trap in the case of effective beam-plasma interaction ($n_b/n_0 = 10^{-1}$). A characteristic feature is the shortening of the current pulse after passing through the trap, when only 30–50% of the beam electrons are registered. This is accompanied by accumulation of space charge in the trap, with an electrostatic potential exceeding the beam energy (oscillogram *e*), and hard x-radiation is registered. This indicates that a fraction of the beam electrons is captured in the trap, and the plasma contains high-energy electrons.

The radial distribution of the longitudinal magnetic field (H_z) in the trap, measured with a miniature movable magnetic probe, has shown that a rapidly alternating magnetic field is registered in the plasma when the beam passes. Oscillogram *c* of Fig. 1 shows the variation of the magnetic field at a radius 1 cm; its intensity at the maximum is 2 kG, and it is directed opposite to the external field in the trap. Oscillogram *e* was obtained at a radius 4 cm, where the induced field had the same direction as the external field. At 8 cm from the center of the trap, the rapidly alternating field has a radial component on the trap axis, i.e., the

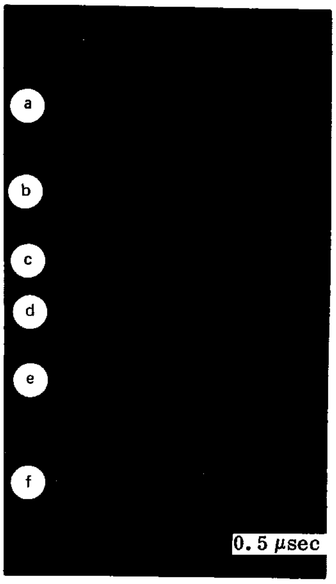

FIG. 1. a) Beam current on entering the trap; b) beam current on leaving the trap; c,d,e) rapidly alternating magnetic field H_z at distances 1, 2, and 4 cm from the axis; f) variation of plasma electric potential.

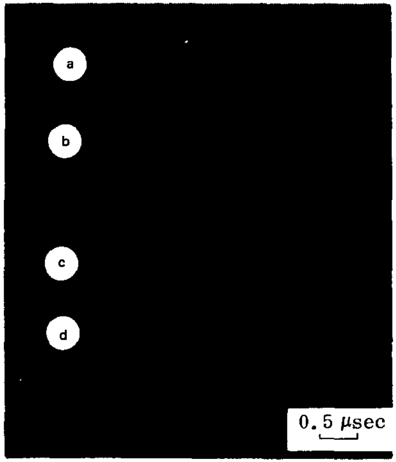

FIG. 2. Oscillograms of plasma diamagnetic signal at the center of the trap (*c*), and at 8 cm away from the trap center (*b* and *d*); oscillogram *a* shows the beam current on leaving the trap.

trapped beam electron form a closed magnetic configuration of the E-layer type.[3,4] Oscillogram d, obtained at a radius 2 cm at the center of the trap, shows that the E-layer is radially compressed.

Oscillograms b, c, and d of Fig. 2 represent the signals from the diamagnetic probe (b and d—in the mirrors, c—in the trap), with $n_0T = 2\times10^{17}$ eV/cm^3 at $n_0 = 10^{13}$ cm^{-3}; oscillogram a shows the beam current on leaving the trap.

This indicates that the plasma is effectively heated in the trap.

Thus, our experiments lead to the following conclusions:

1. Increasing the transverse velocity component of a strong-current high-energy electron beam greatly enhances the effectiveness of the beam-plasma interaction in an open magnetic trap. This leads (a) to an appreciable increase of the oscillation power radiated from the plasma and (b) to a more effective heating of the plasma by the beam. It is not excluded that the plasma heating is due to transformation of the high-frequency waves into low-frequency ones as a result of development of parametric instabilities.

2. The increase of the transverse component of the beam velocity when the beam excites oscillations in a plasma in an open magnetic trap can lead to the capture of some of the beam electrons in the plasma and to the formation of a surface of the E-layer type.

3. Individual elements of the described phenomena were observed in experiments with strong-current relativistic beams.[5,6] This gives grounds for assuming that the proper choice of magnetic-trap parameters such as $V_\perp/V_\parallel$, n_b/n_0, and H_{max}/H_{min} can greatly increase the effective plasma heating by a relativistic beam under conditions when beam instability develops.

In conclusion, we are grateful to N.S. Pedenko for supplying the experimental setup.

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