Increase of the effectiveness of the interaction between a strong-current relativistic electron beam and a plasma

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Experimental results are presented, which indicate that the effectiveness of interaction of a strong-current of a relativistic electron beam with a plasma is greatly increased when the beam angular divergence is decreased and when the external magnetic field is increased.

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It is known that the effectiveness of energy transfer when a strong-current relativistic electron beam passes through a plasma pinch is 5–7% per meter at a plasma density $n \approx 5\times 10^{13}$ cm^{-3} and at the typical values of the beam current density ~ 1 kA/cm^2 and of the energy ~ 1 MeV (see, e.g.,[1]). When the density of the initial plasma is increased, the effectiveness of the interaction decreases, as observed in a number of experiments.[1–4] It becomes urgent therefore, especially from the point of view of thermonuclear applications, to search for methods of increasing the beam-energy fraction transferred to the denser plasma.

It is known from the theory (see, e.g.,[5]) that the growth-rate of the beam instability increases with decreasing beam divergence, and accordingly the relaxation length of the beam in the plasma can decrease. The electron angle spread of a strong-current relativistic electron beam is determined to a considerable degree by the thickness and material of the anode foil through which the beam is injected into the plasma. In addition, a contribution can be made to this quantity by the angle divergence caused by the noncollinarity of the electric field and the external longitudinal magnetic field in the diode of the accelerator, and also by the influence of the beam's own magnetic field. It is therefore advisable, in experiments aimed at plasma heating with the aid of relativistic electron beams, to inject the beam through as thin a foil as possible and in a maximum possible longitudinal magnetic field.

The experiments were performed with the "INAR" installation, whose diagram and measurement procedures are described in[1,6,7]. In the present series of experiments the parameters of the relativistic electron beam were the following: energy 0.8 MeV, maximum beam current 20 kA, duration 50 nsec, beam diameter at entry 4 cm. The measurements were performed at a preliminary plasma density $n=(3\text{–}5)\times 10^{14}$ cm^{-3}, the magnetic field on the homogeneous section could vary in the range $H_0 = 5\text{–}25$ kOe, and the mirror ratio was 1.7 (the field in the diode region reached 42 kOe). The thickness d of the anode foil ranged from 50 to 6 μm.

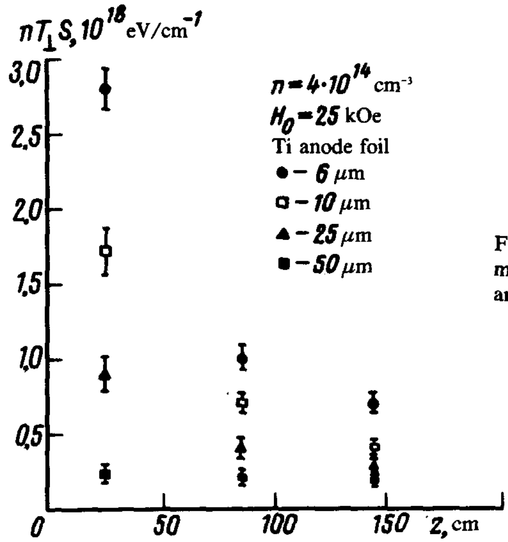

FIG. 1. Distribution of transverse energy of the plasma over the length of the plasma pinch at different anode-foil thicknesses.

Diamagnetic measurements have shown that a decrease of the beam divergence $(\overline{\theta^2})^{1/2}$ (by decreasing the thickness of the anode foil) leads both to a substantial increase of the total energy released in the plasma and to the appearance of a strong non-uniformity of the energy release over the length of the plasma pinch (see Fig. 1). It is seen that the signal from the diamagnetic pickup closest to the anode foil ($z=25$ cm) increases by more than 10 times when d is decreased from 50 to 6 μm [$(\overline{\theta^2})^{1/2}$ decreases in this case from 24° to 7°]. Signals from pickups farther from the entrance of the beam also increase, although to a lesser degree.[1)]

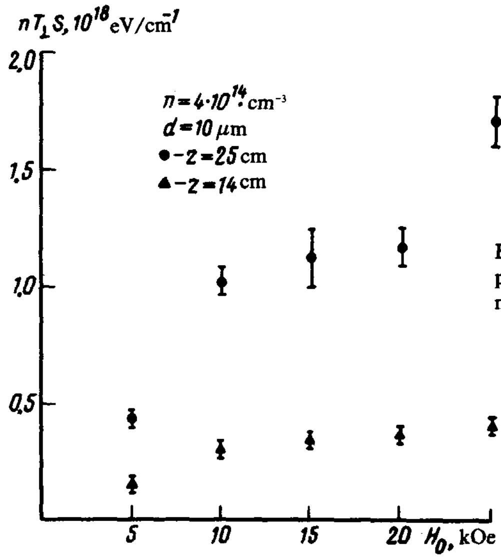

FIG. 2. Dependence of the transverse energy of the plasma pinch on the intensity of the longitudinal magnetic field.

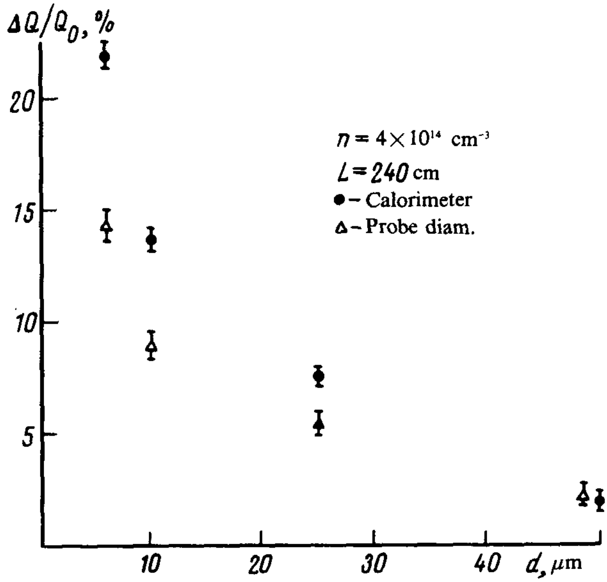

FIG. 3. Dependence of the effectiveness of the interaction of the relativistic electron beam with the plasma on the anode-foil thickness.

Figure 2 shows a plot of the transverse plasma energy $nT_{\perp}S$ against the intensity of the longitudinal magnetic field. It is seen that with increasing magnetic field the transverse energy of the plasma increases, and near the entrance of the beam ($z=25$ cm) it increases more rapidly than at a larger distance ($z=145$ cm). On the whole, a change of H_0 from 5 to 25 kOe leads to an increase of the total energy transferred to the plasma by approximately 3 times. This increase of the energy transfer can be the result of an improvement of the angular characteristics of the beam with increasing longitudinal magnetic field, a particularly important factor in the case of thin entry foils. At the same time, a direct influence of the magnetic field on the intensity of the interaction of the relativistic electron beam with the plasma is also possible.

The plots of the energy released by a relativistic electron beam in the plasma against d and H_0, obtained with the aid of diamagnetic measurements, agree with the results of calorimetric measurements of the losses of the total energy of the beam. Figure 3 shows plots of the beam energy losses and of the energy transferred to the plasma, referred to the total energy of the beam at the entrance, against the thickness of the anode foil. The energy losses were determined by measuring in succession, with one and the same calorimeter, the beam entrance and exit energies. In the investigated regime, the beam passing through the plasma retained its entire charge, so that the energy losses registered by the calorimeter were due to the deceleration of the relativistic electron beam. As seen from Fig. 3, the beam energy loss increases rapidly with decreasing d and reaches 22% at $d=6\ \mu$m (at a total initial beam energy $Q_0=500$ J). It follows from the diamagnetic measurements that under the same conditions the energy stored in the plasma column is $\Delta Q \approx 75$ J (assuming a uniform distribution of the kinetic energy of the plasma particles over the degrees of freedom), which amounts to approximately 15% of the initial energy reserve of the beam. Some difference, especially with thin foils, between the values of $\Delta Q/Q_0$ determined from calorimetric and diamagnetic measurements can be attributed to the presence of energy losses from the plasma in the course of heating, and also to the fact that the heating is not isotropic.

As shown earlier[8], at a plasma density $\gtrsim 2\times 10^{14}$ cm^{-3}, complete compensation of the beam is observed not only with respect to current and charge, but also with respect to current density. In the described experiments we also monitored the cancellation of the beam current, which was always compelte. Therefore the observed transfer of energy from the beam to the plasma cannot be due to dissipation of the energy of the return current. The strong dependence of the energy release in the plasma on the angle spread of the beam, and also the nonuniformity of the release over the length of the apparatus, indicate that in this case the principal role is played by beam instability.

Thus, at a plasma density $n=4\times 10^{14}$ cm^{-3}, we have attained an effectiveness $\Delta Q/Q_0 \approx 20\%$ of energy transfer from a strong-current relativistic electron beam to a plasma, over a plasma-pinch length $L=240$ cm.

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[1)]Generally speaking, the change of the thickness of the entrance foil from 50 to 6 μm leads to an increase of the amplitude of the injected current by several percent, and of the total beam energy by almost 20%. These changes of the entry parameters of the relativistic electron beam were measured in the experiment and were taken into account in the reduction of the results.

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