Effectiveness of interaction between an electron beam having large ν/γ and a preheated flat target

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It is shown that the absorption of a relativistic electron beam of density 10^{13} W/cm^2 exceeds the classical absorption when the beam interacts with a preheated plasma.

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Babykin *et al.*[1] and Gribkov *et al.*[2] considered the possibility of increasing the energy delivered by a relativistic electron beam to a dense plasma.

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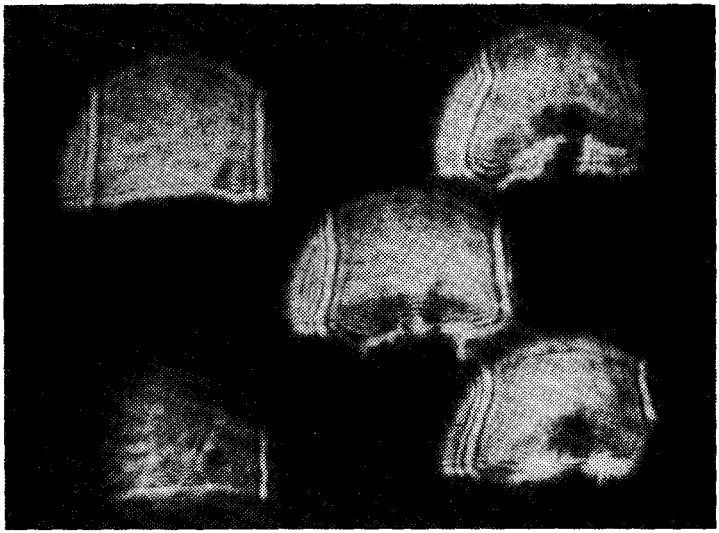

FIG. 1.

We show in this paper that preheating a solid target increases the coefficient of absorption of a beam of relativistic electrons.

1. The investigations were made with the "plasma focus" (PF) installation[3]1) with a battery energy 50 kJ, a charging voltage 27 kV, filled with deuterium at 0.5 Torr pressure. Besides the standard methods of measuring the plasma parameters, we used shadow and interferometry five-frame photography of the plasma with the aid of a ruby laser (pulse duration 1 nsec, distance between frame on the order of 20 nsec), and also single-frame Schlieren photography.[4]

2. The shadow patterns and the interferometry have shown that as the current sheath cumulates towards to chamber axis at a velocity on the order of 3×10^7 cm/sec, the pinch diameter decreases to a value on the order of 1—1.5 cm. The pinch then expands slightly, cools down, and maintains without further pulsation a constant diameter 2—2.5 cm and a density $(2-3)\times10^{18}$ cm^{-3} during a time on the order of 50—70 nsec, until the current sheath breaks.[5] An estimate of the plasma temperature during that time follows from the balance of the magnetic and gas kinetic pressures yields $T\approx150$ eV. The kinetic energy of the cumulating plasma sheath and the energy stored in the magnetic field turn out to be $E_{\rm kin}\approx E_H\approx10$ kJ.

3. After the interruption of the current in the PF,[5] an intense electron beam is produced with average electron energy $\mathcal{E}_e\approx100$ keV. Figure 1 shows a five-frame shadow pattern demonstrating the self-focusing of the beam.[1,8] The shadow pattern shows clearly also that prior to the final focusing of this beam (first and second frames), a plasma moves from the copper anode in the interior of the current sheath of the pinch. This plasma was produced when the anode was evaporated by heating with current or by the electron and radiant heat conduction from the pinch plasma, and in the classical interaction of

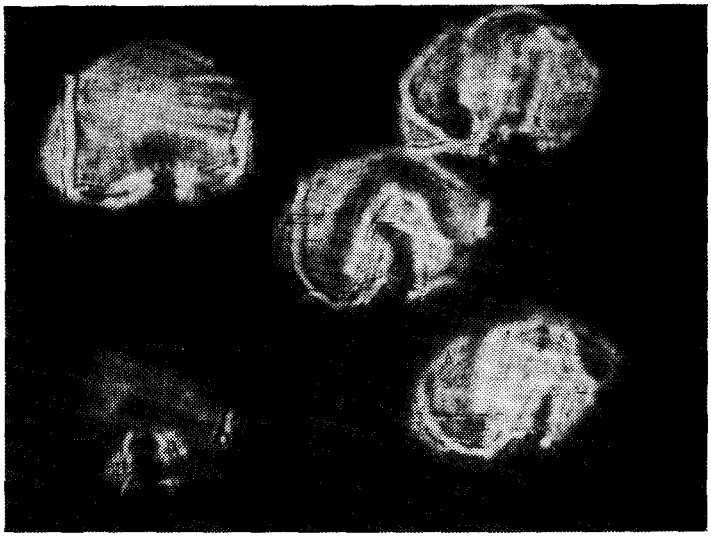

FIG. 2.

the beam and of the return current with the anode during the self-focusing process. It is easy to calculate from the shadow pattern the velocity of the plasma (of the opacity region), which is equal to 2×10^6 cm/sec. Since the velocity near the surface of the anode is close to that of sound, an estimate of the temperature of this plasma yields $T_k \lesssim 100$ eV. By measuring the coefficient of absorption of ruby-laser radiation in this plasma we can determine the plasma density, namely $N_e \sim 10^{19}$ cm^{-3}, which is lower than the pinch density by one order of magnitude.

4. From an electotechnical calculation of the transient in an inductive storage element having a fast switch and loaded by an active resistance (in our case, the electron beam) it is easy, knowing the total energy stored in the magnetic field, to estimate the energy of this beam, [7] namely $E_{r\,eb} \approx 6$—8 kJ. In our case the electron-beam current $I_{r\,eb}$ is of the order of the total current I_{pinch} through the pinch at this instant of time, as is demonstrated by Schlieren-photography measurements of the focusing length as well as of the growth rate and the wave number of the hose instability, the values of which coincide with the theoretical ones[1] only under the condition $I_{r\,eb} \approx I_{pinch}$. We note that in our case the hose instability did not cause the beam to break, and the focusing point did not shift from its initial position on the anode.

An estimate of the total energy of the electron beam from absolute measurements of the hard x-rays, both by the nuclear-emulsion method and with photomultipliers, yields a value of the order of 2—4 kJ. The minimal diameter of the focused electron beam near the anode was $\lesssim 1$ mm, corresponding to a flux density 5×10^{12}—10^{13} W/cm^2. An important fact is that by the instant when the self-focusing of the beam terminates, the amplitude of the hard x-ray pulse decreases almost to zero, whereas the magnetic channel of the relativistic electron beam can still be seen for 20—50 nsec after the vanishing of the hard x-ray pulse.

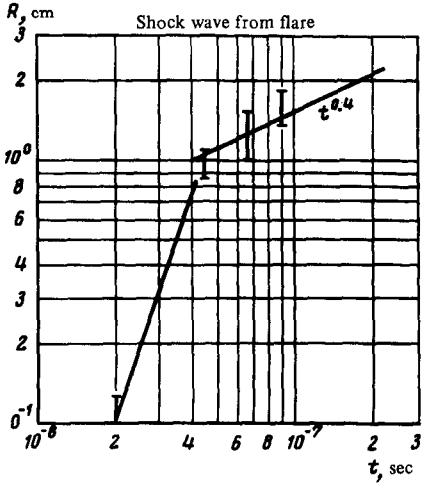

FIG. 3.

5. Figure 2 shows a five-frame shadow pattern obtained during the period of time following the termination of the self-focusing of the relativistic electron beam. One can clearly see in the deuterium plasma of the pinch a shock wave propelled by the "flare" produced when the focused relativistic beam interacts with the heated plasma of the copper anode. Figure 3 shows an R-t diagram of the shock-wave (SW) front. The errors are due mainly to refraction of the light on the SW front.

It follows from the foregoing (see Sec. 2) that this SW is strong (Mach number 3—4). It is seen from the R-t diagram that the shock-wave goes into a nearly self-similar regime ($R \sim t^{0.4}$)[8] at $R \gtrsim 1$ cm. An estimate of the relativistic-electron-beam energy absorbed in this flare, based on the theory of a point-source explosion, [8] yields the value

$$E_{\text{abs}} = \left(\frac{R_2 - R_1}{\xi_0}\right)^5 \frac{\rho_0}{(t_2^{2/5} - t_1^{2/5})^5} \approx 2 \text{ kJ}; \quad \left[\xi_0 = \xi_0(\gamma_0);\ \gamma_0 = \frac{5}{3}\right].$$

A check on this value against the parameters of the expansion at the initial instant ($R < 1$ cm), and also against measurements of the kinetic energy of a deuterium plasma behind the shock wave at $R > 1$ cm, leads to the same value of E_{abs}.

Knowing the SW velocity in the deuterium plasma at $R < 1$ cm, we can easily calculate the velocity of the "piston," i.e., the mass velocity of the copper flare[8]: $v_p \approx 3 \times 10^7$ cm/sec. The total evaporated mass of the copper flare is determined by estimating the mass of the deuterium plasma enveloped by the shock wave up to $R = 1$ cm ("upper bound" estimate). It turns out to be of the order of $(6-7) \times 10^{-6}$ g.

The evaporated mass estimated from the classical mean free path of the electron ($\mathcal{E}_e \approx 10^5$ eV) in copper yields a value larger by at least one order of

magnitude ("lower-bound" estimate—$M_i \gtrsim 10^{-4}$ g). If this mass were to be ejected from the PF anode in 100 discharges, an appreciable opening would be produced in the anode (as is the case when the PF operates in the pinchless regime, i.e., without heating the anode). In our case, however, the damage to the anode insert was negligible. Thus, the aggregate of the experimental data (see Table I) as well as the abrupt-decrease of the intensity of the hard x-rays during the period of the main heating, and the absence of strong damage to the target, all offer evidence that the bulk of the relativistic electron beam energy is delivered to the preheated near-anode plasma as a result of collective processes that take place over a length shorter than or of the order of 1 mm.

TABLE I.

E_{kin} of shell	$\lesssim 10$ kJ
E_H	≈ 10 kJ
$I_{r\,eb}$	700 kA
$\dot{I}_{r\,eb}$	$\gtrsim 10^{14}$ A/sec
$\mathcal{E}_{e\,r\,eb}$	~ 100 keV
$E_{r\,eb}$	6 - 8 kJ
$j_{r\,eb}$	100 mA/cm²
ν/γ	~ 50
$P_{r\,eb}$	$\sim 10^{13}$ W/cm²
$E_{r\,eb}$ abs.	$\gtrsim 2$ kJ
M_i of heated copper	$\lesssim 7 \times 10^{-6}$ g
v_P	3×10^7 cm/sec
$\mathcal{E}_i$ of copper	~ 100 keV/particle
T_i of copper	~ 1 keV

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[1]M. V. Babykin, E. K. Zavoĭskiĭ, A. A. Ivanov, and L. I. Rudakov, Paper at 4th Internat. Conf. on Plasma Physics and Controlled Thermonuclear Fusion, Madison, Wis., 1971.
[2]V. A. Gribkov, O. N. Krokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova, Pis'ma Zh. Eksp. Teor. Fiz. 18, 541 (1973) [JETP Lett. 18, 319 (1973)].
[3]N. V. Filippov, T. I. Filippova, and V. P. Vinogradov, Nuclear Fusion, Appendix, Part 2, 577 (1962).
[4]N. G. Basov, V. A. Gribkov, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz. 54, 1073 (1968) [Sov. Phys. JETP 27, 575].
[5]V. A. Gribkov, O. N. Korokhin, G. V. Sklizkov, N. V. Filippov, and T. I. Filippova, 6th European Conf. on Controlled Fusion and Plasma Phys., p. 375, 1973, Moscow.

[6]V. A. Gribkov, Energy Storage, Compr., and Switching, ed. by W. H. Bostick, V. Hardy, and O. S. F. Zucker, Plenum Press, 1976.
[7]M. V. Babykin and A. V. Bartov, Preprint, Atom. Energy Inst., 2253, Moscow, 1972.
[8]K. P. Stanyukovich, Neustanovivshiesya dvizheniya sploshnoĭ sredy (Unsteady Motion of a Continuous Medium) Moscow, 1971.