Heating of thin foils by a large-current electron beam

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Bombardment of thin anode foils (gold 10–30 μ thick) by a focused beam of relativistic electrons caused anomalously large heating of the foils, larger by one order of magnitude than the energy input calculated in the single-particle approximation. This effect is attributed to the increased time that the electrons stay in the foil plasma as a result of the action of the magnetic field of the strong-current diode.

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A study of the acceleration of foils by a beam of electrons focused in the diode of the "Triton" installation[1,2] has shown that the energy input to the foil had only a weak dependence on the thickness d, even at $d \ll r_0$ (r_0 is the classical electron mean free path in the foil material). The beam current in the cited experiments was 120 kA, the electron energy was 500 keV, the pulse duration at half-height was 30 nsec, and the current density was 2 mA/cm^2. The investigated vaccum-tight foil of gold or platinum, from 5 to 30 μ thick, covered an opening (3 mm dia) in the massive diode. The experimental setup is shown in Fig. 1.

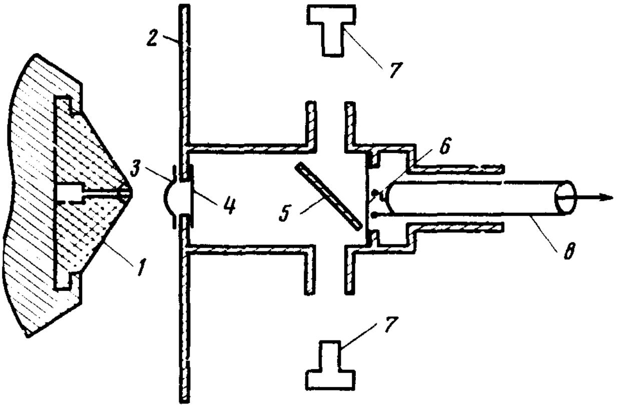

FIG. 1. Experimental setup: 1—polyethylene cathode of accelerator, 2—anode plate, 3—gold foil, 4—polyethylene foil, 5—removable foil cover, 6—moving piston of ballistic calorimeter, 7—recording photomultipliers, 8—electric double probe.

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Heating caused the foil to explode and the gold plasma entered into a ballistic calorimeter located behind the anode. The calorimeter was cylindrical in shape with a movable end cover that was displaced by the plasma pressure and short-circuited the electric probe. It was established that the calorimeter walls were not evaporated by the beam moving past the foil, and the pressure in the calorimeter was determined only by the energy content of the gold plasma.

The energy absorbed by the foil was determined from the relation

$$\epsilon = \frac{2MV_0}{S(\gamma_{eff} - 1)t_{eff}^2} l_{tr} ,$$

where V_0 is the calorimeter volume, M and S is the mass and area of the piston, γ_{eff} is the adiabatic exponent, t_{eff} is the effective action time of the pressure, and l_{tr} is the distance between the piston and the probe.

The energy, estimated from a typical oscillogram in Fig. 2a, was 600 J or 50% of the total beam energy. This is more than 10 times the energy obtained as a result of a calculation by the Monte Carlo method with allowance for the angle scatter of the velocities in the focused beams.

The foil heat rise determined also from the plasma expansion velocity, measured with the aid of light-flux recorders (moving image cameras, photomultipliers, coaxial photocells) and double electric probes. The emission of the plasma moving past the slit or colliding with an aluminum-foil partition was investigated. In the case of thin foils, the radiation could be seen past the partition after the latter was ruptured by the plasma stream. The arrival of the plasma that caused short circuiting of the electrodes was registered by the electric probes. To eliminate the optical-measurement uncertainty due to the unknown distribution of the emission of the expanding plasma, a polyethylene film of thickness $d_{(CH_2)_n} = 10 - 60\ \mu$ was placed 1 mm away from the anode foil in the majority of the experiments. The bulk of the experiments were performed at $d_{(CH_2)_n} = 10$ and $30\ \mu$. Typical oscillograms of the probe and optical signals are shown in Fig. 2. The velocity of the gold reached 7.5×10^5 and $(5.5 - 6.0) \times 10^5$ cm/sec respectively for $d_{Au} = 10\ \mu$ and $d_{(CH_2)_n} = 30\ \mu$ and $(5.5 - 6.0) \cdot 10^5$ cm/sec for $d_{Au} = 5\ \mu$ and $d_{(CH_2)} = 30\ \mu$. When the gold expanded freely, the velocity increased to $(1.2 - 1.6) \times 10^6$ cm/sec and depended little on the foil thickness.

To determine the connection between the velocity and the energy input to the foil, these experiments were numerically simulated within the framework of the system of one-dimensional nonstationary gasdynamics equations with allowance for the radiant thermal conductivity. For the experiments with $10\ \mu$ of gold and $30\ \mu$ of $(CH_2)_n$ separated by 1 mm, we obtained the dependences of the gold and polyethylene foils on the energy input to the gold foil (Fig. 3). It can be concluded from a comparison with experiment that the absorbed energy is 300 J.

The discrepancy between the measured energy and the losses calculated by the Monte Carlo method for pair collisions (4.6% of the beam energy at $d_{Au} = 10\ \mu$) can be attributed to the increase of the effective time that the electrons stay in the foil plasma as a result of the electric and magnetic self-fields of

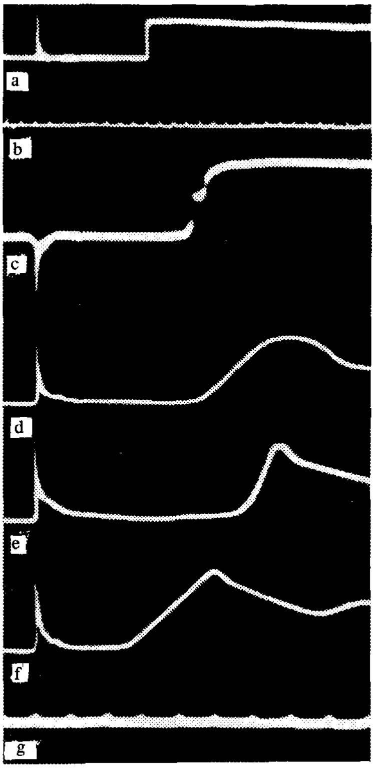

FIG. 2. Typical oscillograms of probe and optical signals: a—signal from ballistic calorimeter, b—1-sec markers, c—signal from electric probe ($d_{\mathrm{Au}}=10$ μ, $d_{(\mathrm{CH}_2)_n}$, $d_{(\mathrm{CH}_2)_n}=30$ μ), d—signal from photomultiplier ($d_{\mathrm{Au}}=10$ μ, $d_{(\mathrm{CH}_2)_n}=30$ μ) e—signal from photomultiplier ($d_{\mathrm{Au}}=5$ μ, $d_{(\mathrm{CH}_2)_n}=30$ μ), f—photomultiplier signal of freely expanding plasma ($d_{\mathrm{Au}}=10$ μ), g—0.5-μ sec markers.

the beam. In a strong-current diode, the electrons converge towards the anode and form a cloud of relativistic electrons.[3] The magnetic field of the diode penetrates into the plasma of the exploding foil, since it follows from the numerical simulation that by the instant the main energy has been absorbed the plasma parameters are $T=20$ eV and $Z_{\mathrm{eff}}=5$, and the plasma expands to $d=0.5-1$ mm. The skin-layer thickness turns out to be comparable with d.

On entering the plasma, the electrons are either reflected into the accelerating gap towards the cathode, or else pass through the foil are stopped in it. The reflected electrons are returned to the foil by the electric and magnetic

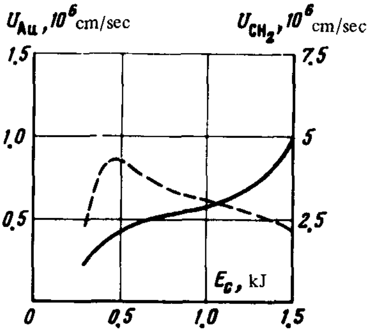

FIG. 3. Calculated dependence of the velocities of the gold and polyethylene films on the energy input to the gold foil.

fields of the diode. There is no electric field of the diode in the foil plasma. The transport of the relativistic electrons can therefore be effected by diffusion in the elastic scattering, as well as by magnetic drift. The latter can be expressed in the form

$$\frac{\gamma mc^2}{eH^2}\,|\nabla H| \approx C\frac{I_A}{21}, \qquad I_A = 17000\,\beta\gamma.$$

In our experiments the diode current was 4—5 times larger than I_A. The time of stay of the electrons in the plasma foil, and therefore also the losses, should increase by one order of magnitude. This explains, in our opinion, the observed effect. The role of the electric field behind the anode foil[4] is apparently insignificant. This is indicated by the independence of the foil heating of the gas pressure in the drift gap.

The observed anomalously large beam-energy absorption in thin films makes possible an energy input up to 80 eV per gold atom, and makes it possible to simulate the heating of thermonuclear targets.

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