Experimental determination of the slowing-down distance of a high-current beam of relativistic electrons in a dense plasma

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(Submitted 20 August 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **30**, No. 7, 435–438 (5 October 1979)

The slowing-down distance of the electron flux, which is in agreement with the idea that the electrons entering the plasma are magnetized, was determined from the measurements of the radiation of plasma produced as a result of thermal explosion of the anode foil heated by relativistic electrons from a high-current diode. A radiation anisotropy, which is attributable to the energy straggling in the incident flux, was observed.

PACS numbers: 52.40.Mj, 79.20.Kz

The use of high-power, high-current accelerators for initiating a pulsed thermonuclear reaction requires investigation of the interaction of relativistic electron beams with a density of about 10^7 A/cm^2 with metallic foils. Investigation of the properties of plasma produced by concentrating the beam energy on a thin (5–15 μm) gold foil was begun using the "Triton"[1] and "Angara-1"[2] facilities. In this paper we evaluate the results of the measurements of plasma radiation generated in the diode of the "Angara-1" accelerator in the range of 10 to 1000 Å for the purpose of determining the slowing-down efficiency of the electron beam. The results of these measurements were reported at a conference in Zvenigorod.[3] Analogous measurements were reported in a paper[4] presented at the Conference on High-Power Electron and Ion Beams in Novosibirsk (1979). In this paper we focus attention on the symmetry on the asymmetry of heating of the foil and explain this effect.

As radiation detectors we used vacuum photodiodes with an aluminum cathode that had a large photoelectronic output in the range of interest to us. The emission intensity was measured by an open detector and through filters that narrowed the range of the wavelengths. Coaxial photodiodes with plane-geometry electrodes, which had $\sim$200 A/cm^2 density of the saturation current produced by the space charge, were built; this provided a linear dependence of the detector's signal on the emission intensity. To determine the area of the emitting surface, we used vacuum cameras, which provided soft x-ray images, in addition to the conventional pinhole cameras for hard bremsstrahlung. The parameters of the experiment were as follows: voltage—0.9 MV, peak power—$(1\text{–}2)\times 10^{11}$ W, and pulse duration at half-height 35 nsec. The diode current at maximum power was 130–170 kA, and the current density at the focal point was of the order of $(3\text{–}5)\times 10^6$ A/cm^2. The experiment is shown schematically in Fig. 1. An anode foil in the shape of a spherical segment heated by an electron beam is the radiation source. The foil is attached to the massive anode which has an aperture for recording the emission. The arrangement of the of the sensors shown schematically enabled us to record the emission on both sides of the foil. A permanent

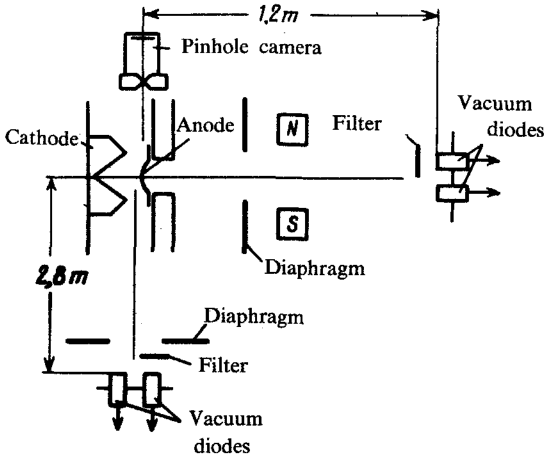

FIG. 1. Experimental setup.

magnet prevented the electrons that had passed through the foil from striking the sensor. The current and voltage oscillograms are shown in Fig. 2a.

Figure 2c shows the signals from the latteral emission detectors without a filter $J_\perp$ and with a filter $J_\perp^f$, and the signal from the end sensor without a filter $J_\parallel$, which is reduced to this distance. It can be seen that the emission intensity from the surface of the plasma directed toward the beam exceeds severalfold the emission from the opposite side of the anode foil. Figure 2b shows the curve for the power input into the foil P_i, which was calculated by taking into account the electron magnetization by the magnetic field of the current.

$$P_i = \frac{dE}{dx}\,\Delta\,\frac{I}{e}\,a \tag{1}$$

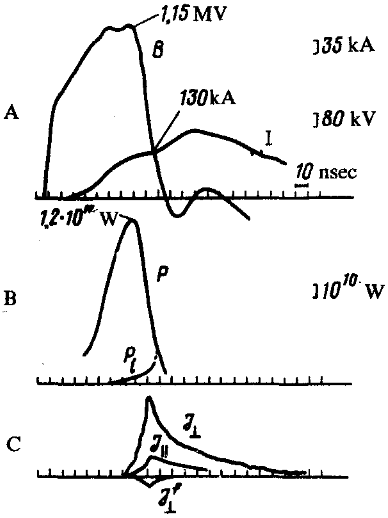

FIG. 2.(a) Current (I); voltage (V); (b) diode power (P); power input into the foil (P_i); (c) signal from the side detector without filter ($J_\perp$) and with filter ($J_\perp^f$); signal from the end detector ($J_\parallel$).

where dE/dx are the losses in the single-particle approximation, Δ is the foil thickness, and α is the coefficient of the energy input anomaly.

According to the calculations in Ref. 5

$$\alpha = 3I/2I_A, \qquad I_A = 17000\,\beta\gamma$$

For comparison, the calculated power of the diode is given. It can be seen that the principal energy input into the foil occurs during the decrease of the voltage applied to the diode, whereas the current continues to increase. The location of the emission signal peak coincides with the maximum of the curve for the energy release P_i.

The results obtained experimentally allowed us to calculate the emission power, assuming a Planck spectrum; the emission power turned out to be $(2\text{–}3)\times 10^9$ W on the side of the diode gap and $(0.6\text{–}1.2)\times 10^9$ W on the outer side of the foil. The numerical calculations and theoretical examination show that for a relatively small energy input into the foil plasma the thermal conductivity is insufficient for transferring heat from the center of the plasma to its edge, which gives rise to luminescence of its boundary layers only. Under these conditions, the measured flux from the plasma is related to the current density of relativistic electrons $j(\mathrm{A/cm^2})$ by the relation

$$q \approx 10^7\left(\int_0^t \alpha j\,dt\right)^{3/2}(\alpha j)^{1/2}, \quad (\mathrm{W/cm^2}) \quad . \tag{2}$$

We obtain α by substituting the measured $q(t)$ and $j(t)$ in Eq. (2). At the maximum the measured value of α is 10, which is close to the calculated value of $3I/2I_A$ at this point. Notice that the errors in determining q and the area of the spot S, as well as the inaccuracy of Eq. (2), have a small effect on the value of α $(\alpha \sim q^{1/2}, S^{-1/2})$.

The observed anisotropy of radiation can be accounted for if it is assumed that the electron distribution function in the incident flux has an energy straggling. Thus, instead of Eq. (1), we can write

$$\frac{dP_i}{dx} = \int_{E(z)}^{E_0(t)} \frac{dE}{dx}\, f(E)\,dE, \qquad \alpha(E) = \frac{2}{3}\,\frac{I(t)}{I_A(E)}\,, \tag{3}$$

where E_0 and $E(z)$ are, respectively, the maximum energy of the incident beam and the energy of the electron stopped in the layer $z\rho_0$. In the weakly relativistic energy region $(E \gtrsim 100$ keV$)$

$$\frac{dE}{dx}\,\frac{1}{I_A} \sim \frac{1}{\beta^3\gamma} \sim \frac{1}{E} \quad .$$

The $f(E)$ function can be reconstructed for Eqs. (2) and (3) from the ratio of the luminescence intensities $q_\perp/q_\parallel$. Thus, if we assume that $f(E) = \text{const}$, then

$$\frac{dP_i}{dx} \sim \ln E_0/E(z), \qquad q_\perp/q_\parallel \sim \left(\ln\frac{E_0}{E_1}\right)^2 \Big/ \left(\ln\frac{E_0}{E_2}\right)^2, \tag{4}$$

where E_1 and E_2 are, respectively, the energy of the electrons stopped in a thin layer, which releases radiation in the radiation in the direction of the cathode, and the energy of the electrons whose stopping distance is equal to the thickness of the foil.

The continuous functions $f(E) \sim c_1$ and $f(E) \sim c_2 E^{-1/2}$, i.e., the distributions for which the current and the energy in the electron flux incident on the foil are transported primarily by the particles from the high-energy part of the spectrum, correspond to the observed emission anisotropy.

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