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EFFECT OF THE SELF-ELECTRIC FIELD OF HEB ON ENERGY RELEASE IN TARGETS

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By using the Monte Carlo method we study the effect of the self-electric field of a beam on the distribution of the energy release of HEB electrons in conductors and dielectrics.

The development of accelerating facilities has given great importance to works dealing with the study of the passage of high-current beams of charged particles through matter. This problem cannot be solved exactly using only the linear theory of radiation transfer in view of the fact that charged particles of high-current (in contrast to low-current) beams interact with each other through self-electromagnetic fields [1].

When high-current relativistic electron beams (HEB) pass through metal targets, the self-magnetic field has a significant effect on the distribution of energy losses by the fast electrons of the beam [2–4]. In [5] it is shown that at a certain power of such a beam passing through conductors it is also necessary to take into account the current of the thermalized electrons of the HEB. The effect of an external electric field on the passage of HEB through dielectrics was investigated in [6, 7].

Here we study the effect of the self-electric field of a high-current electron beam on the distribution of energy losses by fast electrons in conductors and dielectrics. Just as in [5], the problem is solved in the quasisteady approximation. It is likewise assumed that the transient terms and the absence of external electromagnetic fields in the corresponding Maxwell equations can be disregarded. The distributions of energy losses by fast electrons of HEB in passing through matter were calculated for constant parameters of the medium (density, conductivity, interaction cross sections). The problem was solved for the case of axial symmetry in a cylindrical coordinate system. The calculations were performed for a high-current electron beam of radius $r_0 = 1-2\cdot 10^{-3}$ m with current $I = 10^3-10^6$ A and electron energy $E_0 = 1$ MeV for normal incidence of the beam on a semi-infinite target made of aluminum, paraffin, polyethylene, and a dielectric with $z = 6$ and $A = 12$.

The paths of the electrons of the beam were calculated by the Monte Carlo method according to the scheme of continuous energy losses and scattering on a segment using the Goudsmit–Saunderson formulas [8, 9]. Moreover, in passing through matter the fast electrons of HEB interact with each other by means of the self-electromagnetic field. The field exerts an effect on the path of the electrons. To determine the additional change in the path of an electron due to the effect of the self-electromagnetic field of the high-current beam, it is necessary to solve the relativistic equation of electron motion

$$m\frac{d}{dt}(\gamma\beta) = -\frac{1}{c}(e\mathbf{E} + e\,[\beta\mathbf{H}])\,. \qquad (1)$$

The first term on the right-hand side of Eq. (1) determines the effect of the self-electric field of HEB on the electron path and the second term determines the effect of the self-magnetic field of the beam.

The self-electric field of a high-current beam depends on the rate of thermalization of fast electrons N ($\nabla \mathbf{j}_b = -eN$) [3] and on the space charge induced by the fast electrons of the HEB in the target. Under the assumptions made, the resulting strength of the self-electric field of the beam is equal to

$$\mathbf{E}(r,\ z) = -\operatorname{grad}\varphi_t - \operatorname{grad}\varphi_\rho\,. \qquad (2)$$

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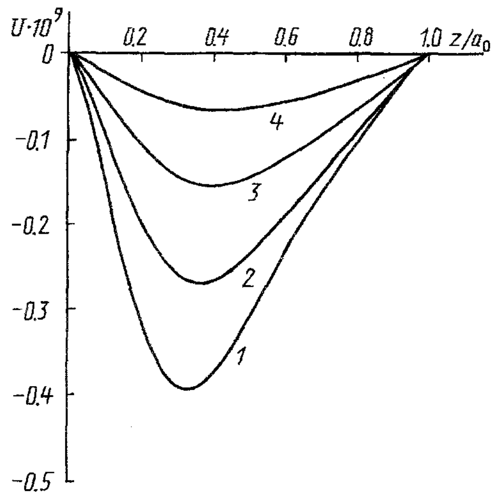
TABLE 1. Distribution of Energy Losses over the Depth of an Aluminum Target ($r = 0.2 \cdot 10^{-3}$ m, $I = 5 \cdot 10^4$ A, $\rho(z)_1$ with allowance for the self-electric field, $\rho(z)_2$ is taken from [5])

z/a_0	0.0	0.1	0.2	0.3	0.4	0.5	0.6
$\rho(z)_1$	0.369	0.364	0.225	0.157	0.100	0.096	0.081
$\rho(z)_2$	0.365	0.348	0.218	0.156	0.098	0.096	0.084



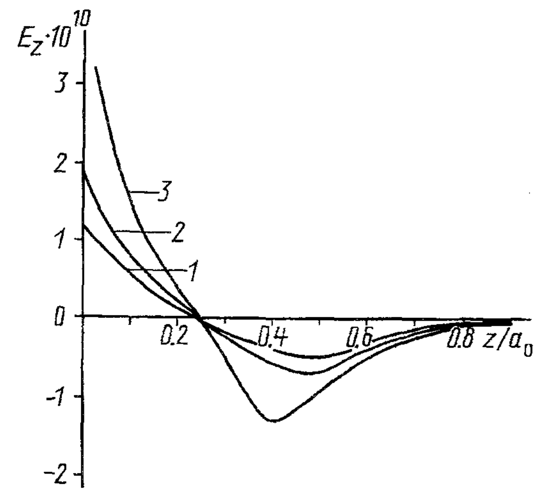
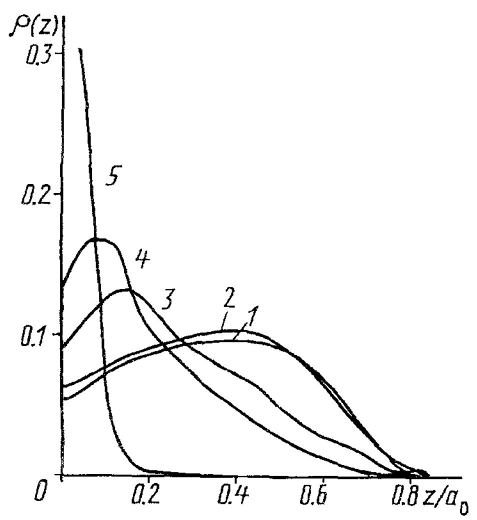


Fig. 1. Distribution of the electrostatic potential in a dielectric with $z = 6$ and $A = 12$ ($E_0 = 1$ MeV, $I = 5 \cdot 10^4$ A, $r_0 = 2 \cdot 10^{-3}$ m); r/a_0: 1) 0.0; 2) 0.25; 3) 0.5; 4) 0.7. U, V.

Fig. 2. Distribution of the longitudinal component of the self-electric field strength over the thickness of a dielectric target with $z = 6$ and $A = 12$ in the near-axial region: 1) $I = 5 \cdot 10^4$ A; 2) 10^5; 3) 10^6 (at $z/a_0 = 0.0$, $E_z = 9.4 \cdot 10^{10}$ V·cm^2/g).



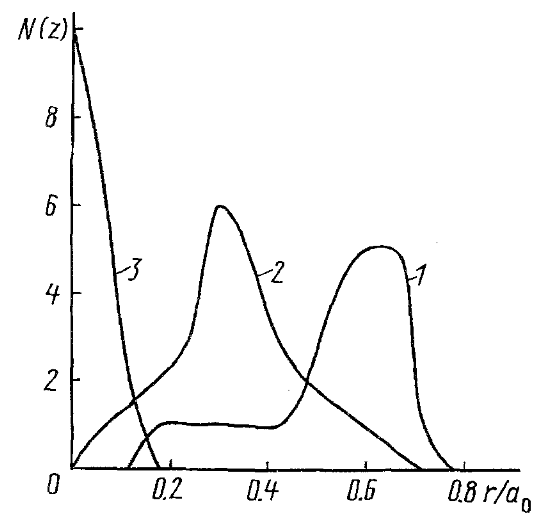


Fig. 3. Distribution of the energy losses of a beam over the thickness of a dielectric target with $z = 6$ and $A = 12$ ($E_0 = 1$ MeV, $r = 2 \cdot 10^{-3}$ m): 1) $I = 10^3$ A; 2) 10^4; 3) $5 \cdot 10^4$; 4) 10^5; 5) $I = 10^6$ A ($\rho(z) = 0.671$ at $z/a_0 = 0.0$).

Fig. 4. Distribution of thermalized electrons in a dielectric with $z = 6$ and $A = 12$ ($E_0 = 1$ MeV, $r = 2 \cdot 10^{-3}$ m) at a depth of $z/a_0 = 0.3$: 1) $I = 10^3$ A; 2) $5 \cdot 10^4$; 3) 10^6.

Proceeding from the equation for the potentials, the electrostatic potentials of the thermalized electrons φ_t and the space charge of the beam φ_ρ have the form

$$\Delta\varphi_t = -\frac{eN(r, z)}{\sigma}, \tag{3}$$

$$\Delta\varphi_\rho = 4\pi\rho(r, z). \tag{4}$$

As is seen from Eqs. (2) and (3), the strength of the self-electric field of the beam is inversely proportional to the conductivity of the target material. Thus, we may conclude that in targets with a high conductivity, for example in conductors, the self-electric field of HEB will have a lesser effect than in targets with a low conductivity (for example, in dielectrics and semiconductors exposed to irradiation).

In view of the assumptions made, we may conclude that the electrostatic potentials of thermalized electrons and the space charge on the surface of the target at the instant of irradiation are equal to zero. Thus, it is possible to solve Eqs. (3) and (4) using the method of variable directions [5].

When a high-current beam of relativistic electrons passes through conductors, the self-magnetic field of the HEB exerts a great effect on the distribution of energy losses [2–4]. Table 1 presents the distribution of energy losses over the depth of an aluminum target with allowance for the effect of the self-electromagnetic field of the HEB and the current of the thermalized electrons ρ_1, as well as the distribution of energy losses ρ_2 given in [5] for the case where the effect of the self-electric field of the beam was ignored. Comparing the distributions of ρ_1 and ρ_2, we see that during the passage of the HEB through conductors the energy losses of the fast electrons of the beam remain unaffected by the self-electric field of the beam.

Figure 1 shows the distribution of the electrostatic potential of the thermalized electrons over the depth of a dielectric target with $z = 6$, $A = 12$, $\rho_0 = 2.265$ g/cm, and $\sigma = 10^{-5}$ $(\mathrm{W \cdot cm})^{-1}$. From Eq. (3) it is evident that the absolute value of the electrostatic potential depends strongly on the conductivity of the target material. This trend is confirmed by comparing the obtained results with the distribution of the electrostatic potential in conductors [3]. The general form of the distribution of the potential of thermalized electrons is independent of the nature of the target.

It is seen from Fig. 1 that at a depth of $\sim 0.2-0.3\alpha_0$ (α_0 is the electron range) the electrostatic potential reaches its extremum. This results in the fact that at small depths ($< 0.2-0.3\alpha_0$) the longitudinal component of the strength vector of the self-electric field of the HEB $E_z > 0$, and hence the initial part of the electron paths lies in the retarding field. At larger depths ($> 0.3\alpha_0$) the self-electric field becomes accelerating ($E_z < 0$) and its strength decreases (Fig. 2).

It is known [7] that when the Coulomb force eE is comparable with the dissipative force, which is numerically equal to the specific losses $B(T)$, the electric field exerts a substantial effect on the passage of electrons through matter. The results of calculations of energy losses as a function of the magnitude of the beam current are presented in Fig. 3. Distributions over the thickness of a dielectric target are given. We can see from the figure that at a beam current $I > 10^4$ A the effect of the self-electric field of the HEB during the passage through dielectrics cannot be ignored. All the changes in the distribution of energy losses by fast electrons of a high-current beam compared to the distribution of energy losses by electrons of a low-current beam ($I \leq 10^3$ A) are caused by the effect of the self-electric field of the HEB. With a further increase in the beam current the region of vigorous energy release contracts toward the target surface. This is associated with growth of the self-electric field strength of the HEB (see Fig. 2) which further hinders the penetration of fast electrons into the target. With an increase in the beam current, more and more electrons are thermalized in the region adjacent to the boundary (Fig. 4).

Thus, during the passage of a high-current electron beam through conductors the effect of the self-electric field on the energy losses by fast electrons can be disregarded. However, when an HEB passes through dielectrics, the self-electric field of the beam has a substantial effect on the distribution of energy losses by electrons.

NOTATION

a_0, electron range; A, atomic weight; β, relative electron velocity; $\gamma = (1 - \beta^2)^{-1/2}$; e, electron charge; **E** and E_z, strength of the electric field and its longitudinal component; E_0, initial electron energy; N, thermalization rate of fast electrons; I, beam current; c, velocity of light; m, electron mass; **H**, magnetic field strength; r_0, beam radius; $\mathbf{j}_b$, current-density vector of the fast electrons of the beam; φ_t, electrostatic potential of thermalized electrons; φ_ρ, electrostatic potential of the space charge of the beam; δ, conductivity of the target material; ρ_0, densityof the target material; $\rho(z)$, relative density of energy release; $\rho(z) = (r/P_0)(\partial P/\partial z)$ ($P = I \cdot U$, where U is the acceleration voltage (MV), which is numerically equal to the electron energy (MeV)).

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