It is interesting to consider the case $\alpha < 0$ which corresponds to a converging electron beam. It is clear from (4) that the solution increases exponentially; i.e., if sufficiently large values of ξ are possible, the beam current must be considered suppressed for all values of $\alpha < 0$. It follows from (5) that there is no turning point of the trajectory of a beam electron. Evidently, for $\alpha < 0$ the nonlinear nature of the equation of motion has a stabilizing effect, but an exact analysis requires a numerical solution of Eq. (3).

Thus, an analysis of the motion of a test electron in a neutralized conical electron beam shows first that there is a range of values of the parameter α and the initial angular divergence of the beam for which there is no motion outside the limits initially set for the beam. In this case two types of motion are possible. The first possibility is that an initial small angular deflection is decreased as $r \to \infty$ ($\alpha < 1/2$). Evidently, this implies a certain self-focusing of the beam (with a possibility of its becoming cylindrical), which must lead to an oscillatory motion of the electrons. The second possibility ($\alpha > 1/2$) corresponds to an oscillatory motion of the electrons. This does not imply suppression of the beam current.

Finally, there is a range of values of α and θ_0 for which the beam current clearly will be suppressed. This range can be defined in the following way: $\alpha \tan(\theta_0/2) > 1$.

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LITERATURE CITED

1. H. Alfvén, "On the motion of cosmic rays in interstellar space." Phys. Rev., 55, 425 (1939).

EXPERIMENTAL VERIFICATION OF RADIATION FROM COMPTON ELECTRON CURRENTS

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§1. Theoretical investigations of the electromagnetic radiation generated by currents of Compton electrons, formed in air near an impulse γ-ray source. have been performed in many studies (for example, [1-3]). On the other hand, much less attention has been paid to comparison of theory with experimental data, evidently because at first glance such a comparison reveals significant divergence between theory and experiment as to the form and duration of the signals generated. Thus, the theoretically calculated pulse has two semiperiods with duration of several μsec, while experiment [4] has recorded a three-semiperiod pulse with duration of tens and hundreds of μsec. There is a similar discrepancy in the ratios of field amplitudes in the different semiperiods; theory predicts a ratio of the order of decades, while experiment shows ratios near unity. A new approach to comparison of theory and experiment can be achieved if we assume that the total recorded electromagnetic impulse is in fact the sum of two signals of different nature. This may be confirmed by dividing the total signal into two components, with the parameters of one being close to those predicted for Compton radiation by theory, and the parameters of the other explicable by sufficiently general physical considerations.

To reliably confirm the conclusions of Compton electron radiation theory, it is desirable to establish some general property of the signal produced which is not related to detailed characteristics of the electron current, which vary in theoretical calculations depending on the assumptions made, and also vary from experiment to experiment. The presence of such a property in the experimental signal is then the criterion of the theory validity.

Since the published quantitative results on irradiated fields (see, for example [2, 5]) have been obtained by numerical integration of the Maxwell equations, while to detect general properties of signals it is more convenient to use analytic expressions for the fields, we will consider below the question of analytic description of the radiated signal characteristics. We will consider the signal connected with the disruption of symmetry of Compton electron signals upon their reaching the surface of the earth.

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§2. We will assume that radial currents are produced, excited by a spherically symmetric γ-quantum production in air, the quantum source being located at a height h above an underlying surface of infinite conductivity, an asymmetry which ensures radiation of wave fields influenced by the underlying surface. We make the following assumptions with respect to the radiating currents: In the region above the underlying surface they are symmetric; their time dependence is that of a pulse moving with the speed of light of duration τ_0 (in reality $\tau_0 \sim 10^{-7}$–10^{-6} sec [5]), with amplitude dropping sufficiently rapidly at large distance that the convergence of the integrals considered below is ensured. As was noted above, the theoretical determination of the radiating currents is an independent problem outside the scope of the present study.

With the assumption made, the vertical component A_V of the vector potential A on the underlying surface in the wave zone may be determined by the integral over the volume V occupied by the currents [6],

$$A_V = \frac{2}{Rc} \int\limits_V j_V \left(r, t - \frac{R - (\mathbf{n}, \mathbf{r})}{c} \right) dV, \tag{2.1}$$

where R is mean distance; **n** is the unit vector directed from radiating volume to detection point; j_V is the vertical component of radial currents; the coefficient 2 reflects the contribution to radiation of currents induced in the underlying surface. If we neglect the slight deviation of the vector **n** from the horizontal direction, then in a spherical coordinate system (r, ϑ, φ) with z axis along **n** (Fig. 1, where A is the source, 0 is the source epicenter, and B is the detection point) and axial angle φ measured from the upward vertical, we have $(\mathbf{n}, \mathbf{r}) = r \cos \vartheta$, the underlying surface equation

$$r \sin \vartheta \cos (\pi - \varphi) = h$$

and, moreover (see Fig. 1),

$$j_V = j \sin \vartheta \cos \varphi,$$

where j is the absolute value of the currents. Equation (2.1) in this coordinate system is written as

$$A_V = \frac{2}{Rc} \int\limits_0^\pi \sin^2 \vartheta \left\{ \int\limits_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos \varphi d\varphi \int\limits_0^\infty r^2 j dr + \int\limits_{\frac{\pi}{2}}^{\frac{3}{2}\pi} \cos \varphi d\varphi \int\limits_0^{h/\sin\vartheta\cos(\pi-\varphi)} r^2 j dr \right\} d\vartheta. \tag{2.2}$$

Addition to the sum in curved brackets of the term

$$\int\limits_{\frac{\pi}{2}}^{\frac{3}{2}\pi} \cos \varphi d\varphi \int\limits_{h/\sin\vartheta\cos(\pi-\varphi)}^{\infty} r^2 j dr \tag{2.3}$$

[whose absence in Eq. (2.2) is due to "cutoff" of the currents by the underlying surface] leads to equality to zero of the expression for A_V. This is a result of a physically obvious fact: A spherically symmetric current system in a homogeneous medium does not radiate electromagnetic waves. Therefore, Eq. (2.2) may be written [by adding and subtracting Eq. (2.3) to the sum in curved brackets in Eq. (2.2)] in the form

$$A_V = -\frac{2}{Rc} \int\limits_0^\pi \sin^2 \vartheta d\vartheta \int\limits_{\frac{\pi}{2}}^{\frac{3}{2}\pi} \cos \varphi d\varphi \int\limits_{-h/\sin\vartheta\cos\varphi}^{\infty} j r^2 dr. \tag{2.4}$$

We note also that it is desirable to describe the current pulse moving at the speed of light by a function dependent not on r and t, but on r and t − r/c (the dependence on the first argument then describes the change in pulse amplitude and relatively slow changes in its form with distance, while the dependence on the second argument describes the pulse form). In this case the arguments of the function j in Eqs. (2.1)-(2.4) will be r and $\tau - r(1 - \cos \vartheta)/c$, where $\tau \equiv t - R/c$ is time measured from the moment of signal arrival at the detection point.

Integrating over angle φ, of which j is independent, and introducing instead of ϑ the new variable $\tau' = \tau - r(1 - \cos \vartheta)/c$, we finally obtain

$$A_V = \frac{4c}{R}\int_h^\infty dr \int_{\tau_+}^{\tau_-} d\tau' j(r, \tau')\sqrt{(\tau_- - \tau')(\tau' - \tau_+)}, \tag{2.5}$$

$$\tau_\pm = \tau - \frac{r}{c}\left(1 \pm \sqrt{1-(h/r)^2}\right).$$

The integration range on the plane (r, τ') is shown in Fig. 2, where the region with vertical lines is the integration range in Eq. (2.5) and the region with oblique lines is that in which the radiating currents are not equal to zero. Line 1—2 describes the equation $\tau' = \tau_-(r)$; line 1—3, the equation $\tau' = \tau_+(r)$. For further consideration it is significant that at significantly small τ ($\tau < \tau_0$) the upper limit in the integral of Eq. (2.5) passes through the region where the currents are nonzero. Then the time dependence of A_V and, correspondingly, the time dependence of the radiating field are determined by the time structure of the currents. At subsequent times, i.e., at $\tau > \tau_0$, the upper integration limit in Eq. (2.5) leaves the current zone and the time dependence of the radiated field is determined by the spatial dependence of the integrals over current characteristic time. We note that an analogous property is inherent to radiation of transverse currents produced by curvature of the trajectory of Compton electrons in an external magnetic field [7].

For $\tau > \tau_0$ Eq. (2.5) may be written approximately in the form

$$A_V = \frac{4\sqrt{2c\tau}}{R}\int_\rho^\infty dr I(r)\sqrt{r-\rho}, \tag{2.6}$$

where

$$I(r) \equiv \int_{-\infty}^{\infty} j(r, \tau')\, d\tau'; \quad \rho(\tau) \equiv \frac{h}{2}\left(\frac{h}{c\tau} + \frac{c\tau}{h}\right).$$

The signal described by Eq. (2.6) has the property that it is invariant with respect to spatial dependence of the radiating currents. The ratio $A_V/\sqrt{\tau}$ is of one and the same value at $\tau = \tau_1$ and $\tau = \tau_2$, if $\tau_1 \pm \tau_2$, but

$$h/c\tau_1 + c\tau_1/h = h/c\tau_2 + c\tau_2/h,$$

i.e., if $\rho(\tau_1) = \rho(\tau_2)$. The fact that the quantity $A_V/\sqrt{\tau}$ is dependent solely on ρ may be verified by experimental recording of the signal if the height of the source h is known.

In a number of cases a priori information on this height is absent. However, this parameter may be determined directly from the signal recording. The method of determining h is based on the fact that at the time $\tau = h/c$ the function $A_V/\sqrt{\tau}$ must be at a maximum. In fact, at $\tau = h/c$ the derivative

$$\frac{d}{d\tau}\left[A_V(\tau)/\sqrt{\tau}\right] = \frac{4\sqrt{2c}}{R}\frac{d\rho}{d\tau}\frac{d}{d\rho}\left\{\int_\rho^\infty dr I(r)\sqrt{r-\rho}\right\}$$

is equal to zero, since the derivative $d\rho/d\tau$ is then zero. Aside from making it possible to verify the dependence of the quantity $A_V/\sqrt{\tau}$ on $\rho(\tau)$ alone, the indicated property of the sig-

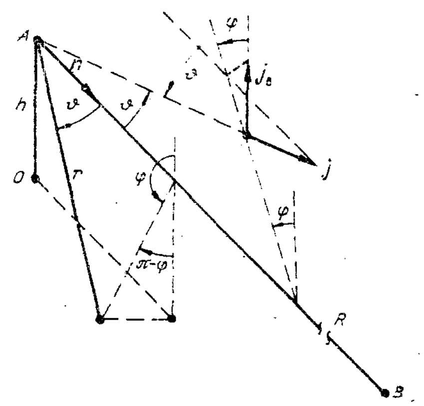

Fig. 1

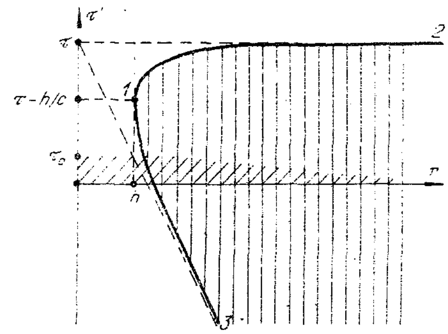

Fig. 2

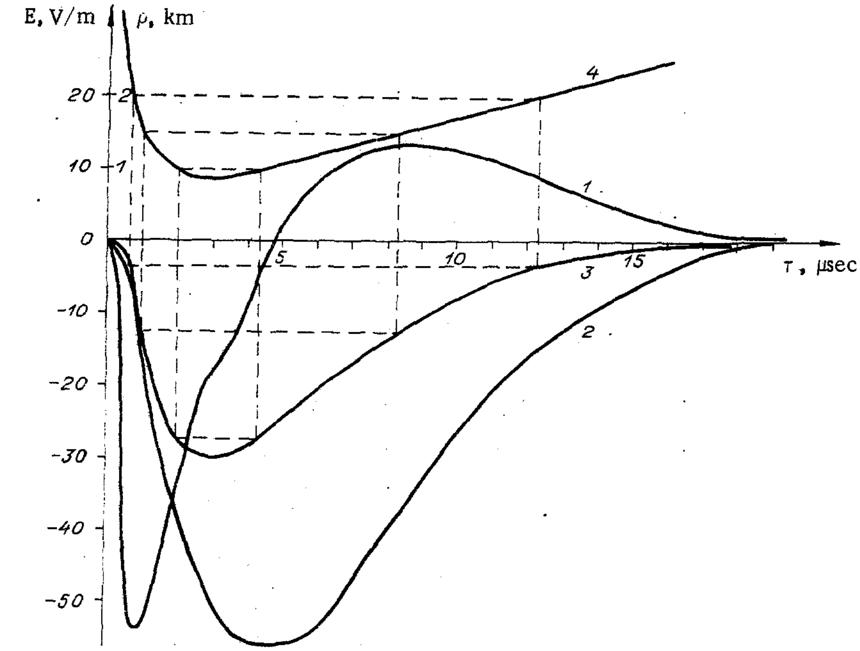

Fig. 3

nal makes it possible to determine the height of the source, which in a number of cases is of independent interest.

§3. The experimental recording of a wave signal presented in [4] was used for verification of the theory of Compton electron radiation. The separated Compton current signal is shown in Fig. 3 (curve 1). Also shown are the time dependence of the vector potential $A_V(\tau)$ (curve 2) and the function $A_V/\sqrt{\tau}$ (curve 3). As in [4], information on the height of the source is not presented, and to determine the value of h the extremality of the function $A_V/\sqrt{\tau}$ at $\tau = h/c$ was used. The h value thus obtained was equal to approximately 0.9 km. This h value was used to calculate the function $\rho(\tau)$ shown by curve 4 of Fig. 3. It is obvious from the graphs that identical values of the function $A_V/\sqrt{\tau}$ correspond to identical values of : points corresponding to ρ = 1, 1.5, and 2 km are noted in Fig. 3.

Thus, the verification performed here demonstrates the applicability of the theory of Compton electron current radiation to description of the electromagnetic effects of impulse γ-radiation in air.

LITERATURE CITED

1. S. L. Davydov, Nuclear Explosion in Space, on the Earth, and below Ground [in Russian], Voenizdat, Moscow (1974).
2. G. G. Vilenskaya, V. S. Imshennik, Yu. A. Medvedev, B. M. Stepanov, and L. P. Feoktistov, "The electromagnetic field produced in air by a transient gamma-ray source located on an ideally conductive plane," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1975).
3. H. A. Sandmeier, S. A. Dupree, and G. E. Hansen, "Electromagnetic pulse and time-dependent escape of neutrons and gamma rays from a nuclear explosion," Nucl. Sci. Eng., 48, No. 3 (1972).
4. J. R. Johler and J. C. Morgenstern, "Propagation of the ground wave electromagnetic signal with particular reference to a pulse of nuclear origin," Proc. IEEE, 53, 2043 (1965).
5. V. Gilinsky, "Kompaneets model for radio emission from a nuclear explosion," Phys. Rev., 137, No. 1A (1965).
6. L. D. Landau and E. M. Lifshits, Classical Theory of Fields, 3rd ed., Addison-Wesley (1971).
7. Yu. A. Medvedev, B. M. Stepanov, and G. V. Fedorovich, "Radio radiation by a transient gamma quantum source accompanying perturbation of the geomagnetic field," Geomagn. Aéron., 12, No. 2, 291 (1972).