EFFECT OF STRONG ELECTRIC FIELD ON LIGHT FLASH EXCITED BY A GAMMA-RAY SOURCE IN AIR

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In considering the luminosity excited in air by a γ-ray pulse, it is usually assumed [1-4] that the light energy emitted by an elementary volume is proportional to the γ-ray energy absorbed in that volume. However, the energy losses of Compton electrons in work done against the forces of the created electric field effectively decrease the absorbed γ-ray energy [5]. Actually, the retarding field E can reach values of the order of 10^5 V/m in air of normal density [6] with the parameter $g = eEl/\varepsilon_e$ (l and ε_e are the range and kinetic energy of a Compton electron, $\varepsilon_e \simeq 1$ MeV, $l = 2$ m [7]), which characterizes the electric field, reaching a value of 0.2; i.e., the effect is already noticeable. At lower air densities ($\sim 10^{-4}$ g/cm^3), the parameter g reaches values on the order of 10 [8] and the energy losses of electrons in the field become a controlling factor. Thus the problem of a light flash excited by a γ-ray pulse must be considered in conjunction with the problem of the electric field. For proper evaluation of the electric-field amplitudes excited in a γ-ray flux, it is necessary to consider the reduction in the current of Compton electrons and in the conductivity current because of the retarding effect of the field [5] and also the heating of secondary electrons by the field, which leads to a change in conductivity [9]. In addition, it is necessary to consider the self-absorption of light through photodetachment of electrons from negative oxygen ions formed during ionization of air by γ rays [1, 4] in order to formulate the time characteristics of a light flash properly. This paper presents a study of the effect of a strong electric field on the characteristics of a light flash excited in air by a pulsed γ-ray source. The γ-ray source is assumed to be a monochromatic point isotropic source emitting $\dot{N}(t)$ γ rays per unit time ($\dot{N} = 0$ for $t \leq 0$).

The light flash excited by a γ-ray pulse in air is determined from the summation of all the flashes from elementary volumes of air with allowance for the self-absorption of light in air excited by γ rays. The luminosity of an elementary volume of air is determined by the energy $\dot{E}(r, t)$ absorbed per unit volume and by the law governing the luminescence $K_\delta(t)$ of an elementary volume under the influence of a short pulse (δ pulse) of γ rays. An effective reduction of the absorbed γ-ray energy proportional to the quantity $(1+g)^{-1}$ occurs because of the retardation of Compton electrons by the field [5]. The electric field is determined by the system of equations for electron–ion balance in air subject to the action of γ rays:

$$\frac{dg}{dt} = 4\pi\left\{\frac{e^2l^2}{\varepsilon_e}\frac{\mu f_\gamma}{1+g} - eK[E(\varepsilon)]\,n_e g\right\}, \tag{1}$$

$$\frac{dn_e}{dt} = \frac{\nu\mu f_\gamma}{1+g} - \gamma[E(\varepsilon)]\,n_e - \alpha_e[E(\varepsilon)]\,n_e(n_e + N_-), \tag{2}$$

$$\frac{dN_-}{dt} = \gamma[E(\varepsilon)]\,n_e - \alpha_i N_-(n_e + N_-) \tag{3}$$

with zero initial conditions. Together with electron attachment, electron–ion, and ion–ion recombination, Eqs. (1)-(3) take into account the retarding effect of the electric field by the introduction of the factor $(1+g)^{-1}$ in Eqs. (1) and (2) [5] and the heating of secondary electrons by the field leading to a change in the coefficients γ, α_e, and K (as in [5, 9], we assume that the conductivity of air results from the secondary electrons created by the Compton electrons). In the system (1)-(3), $g = eEl/\varepsilon_e$ is the dimensionless electric field; n_e is the electron density; N_- is the density of negative oxygen ions; $\gamma(\varepsilon)$ is the attachment coefficient for secondary electrons: $K(\varepsilon) = (e/m)\nu(\varepsilon)$ is the mobility of secondary electrons [10]; e and m are the charge and mass of the electron; $\nu(\varepsilon)$ is the effective electron collision frequency; α_i and α_e are the ion–ion and electron–ion recombination coefficients; $\alpha_e = 3\cdot 10^{-7}\,(\varepsilon_0/\varepsilon)^{3/2}$ cm^2/sec [11]; μ^{-1} is the effective γ-ray range; $\nu = 3\cdot 10^4$ is the number of secondary electrons formed by the absorption of 1 MeV of energy in a weak field; f_γ is the γ-ray flux; ε is the mean energy of secondary electrons, which is connected with the electric field E by the relation [10]

$$\varepsilon - \varepsilon_0 = e^2E^2/m\delta(\varepsilon)\nu^2(\varepsilon),$$

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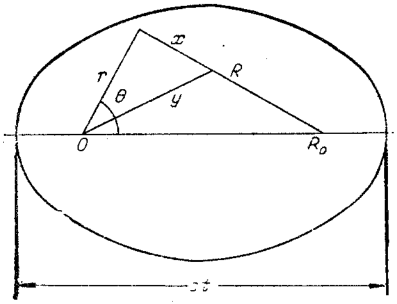

Fig. 1

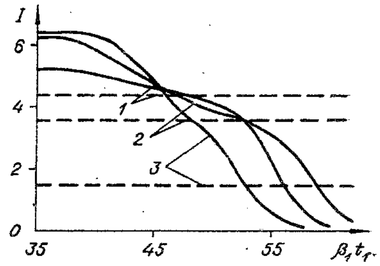

Fig. 2

$\varepsilon_0 = 0.025$ eV; $\delta(\varepsilon)$ is the relative energy loss by an electron in a collision. Note that the quantities μ, α_i, and l^{-1} are proportional to the air density and for normal density are $\mu^{-1} = 300$ m, $l = 2$ m [7], and $\alpha_i = 2 \cdot 10^{-6}$ cm^3/sec. The results of experimental measurements of the quantities $\nu(\varepsilon)$, $\delta(\varepsilon)$, and $\gamma(\varepsilon)$ were interpolated by means of the analytic relations given in [12].

The quantity $K_\delta(t)$ is determined from the radiative decay time α^{-1} for excited molecular states (several units per 10^{-8} sec [13]),

$$K_\delta(t) = \alpha \exp(-\alpha t),$$

and the absorbed energy is

$$\dot{E}(r, t) = \frac{\mu \varepsilon_\gamma \dot{N}(t - r/c)}{1 + g(r, t)} \exp(-\mu r)/4\pi r^2, \tag{4}$$

where $\varepsilon_\gamma = 1$ MeV is the γ-ray energy. In contrast to [1], the quantity $g(r, t)$ appears in Eq. (4), which takes into account the reduction in absorbed γ-ray energy because of the retarding effect of the electric field and which is determined by the system (1)-(3). Note that the quantities $g(r, t)$ and $\dot{E}(r, t)$ differ from zero when $t > r/c$, which reflects the effects of retardation.

After consideration of the differential characteristics $K_\delta(t)$ and $\dot{E}(r, t)$ of the luminosity, we discuss the integral (over volume) characteristics of the luminosity of air excited by an γ-ray pulse at distances R_0 less than, or comparable with, the mean range of a light quantum in unperturbed air, which is 10-20 km at normal density [1].

An elementary volume of air at a distance r from the source (Fig. 1) luminesces under the action of γ rays in accordance with the law

$$i(r, t) = \eta \int\limits_{r/c}^{t} K_\delta(t - t') E(r, t')\, dt',$$

where η is the luminescence efficiency (ratio between the energy released in the optical range and the absorbed γ-ray energy). Assuming that the light is emitted isotropically by an elementary volume of air, the intensity of the light flux produced by an elementary volume of air at a distance R_0 from a γ-ray source without allowance for light absorption is given by the expression

$$i(R_0, t) = \frac{\eta}{4\pi R^2} \int\limits_{r/c}^{t - R/c} K_\delta\left(t - t' - \frac{R}{c}\right) \dot{E}(r, t')\, dt'. \tag{5}$$

For proper consideration of the effects of self-absorption of light, it is necessary to introduce in Eq. (5) a factor describing the reduction in light flux because of photodetachment of electrons from negative oxygen ions, which is determined by an integral over the space and time distribution of the density of negative oxygen ions along the trajectory of a light quantum:

$$\exp\left\{-\sigma \int\limits_0^R N_-\left(y, t - \frac{R - x}{c}\right) dx\right\}, \tag{6}$$

where $\sigma = 2.8 \cdot 10^{-18}$ cm^2 is the photodetachment cross section [1] and the density $N_-(r, t)$ of negative ions is determined from the equation system (1)-(3). Allowing for (5) and (6), the time dependence of the intensity of the light flux at a distance R_0 from a γ-ray source including the self-absorption of light and retardation effects is determined at the time t by the summation of flashes from elements dv of the volume V_t bounded by the surface of the ellipsoid $r + R = ct$:

$$I(t)=\frac{\eta}{4\pi}\int\limits_{V_t}\frac{dv}{R^2}\exp\left\{-\sigma\int\limits_0^R N_-\left(y,t-\frac{R-x}{c}\right)dx\right\}\int\limits_{r/c}^{t-R/c}K_\delta\left(t-t'-\frac{R}{c}\right)\dot{E}(r,t')\,dt'. \tag{7}$$

We investigate Eq. (7) for a γ-ray source with the time dependence

$$\dot{N}(t)=\begin{cases}\beta_1\exp(\beta_1 t), & t<T,\\ \beta_1\exp\{\beta_1 T-\beta_2(t-T)\}, & t>T,\end{cases} \tag{8}$$

at large distances from the source. The constants in Eq. (8) have typical values $\beta_1\approx 10^8\ \mathrm{sec}^{-1}$, $\beta_2\simeq 0.02\beta_1$, $\beta_1 T\sim 50$–60 [6].

We consider the leading edge ($t<T$) of the luminosity. The γ-ray flux f_γ in the system (1)–(3) is

$$f_\gamma=\beta_1\exp(-\mu r+\beta_1 t)/4\pi r^2.$$

A numerical calculation of the system (1)–(3) shows that the quantities g and N_- at large $\beta_1 t$ depend strongly on the single parameter $\tau=\exp(-\mu r+\beta_1 t)/r^2$ alone, while the dependence on the other parameters is extremely weak. This simplifies the numerical analysis of Eq. (7) considerably. Note also that because of strong heating of secondary electrons by the field (for example, the ratio $\varepsilon/\varepsilon_0$ is on the order of 50–100 for times $\beta_1 t\sim 50$), electron–ion recombination will be suppressed in comparison with electron attachment since the electron–ion recombination coefficient $\alpha_e\sim(\varepsilon_0/\varepsilon)^{3/2}$ [11].

At short times, the quantity g(t) repeats the functional time dependence (8) of the γ source, but the values of g(t) themselves are small in comparison with unity. At long times ($\beta_1 t \gtrsim 40$), the quantity g(t) reaches values of the order of unity and above but then goes to saturation and changes little in comparison with $\exp(\beta_1 t)$ for changes in t of the order of $1/\beta_1$. Numerical calculation of the system (1)–(3) also shows that in the intermediate region, the quantity $1+g(t)$ changes little. This circumstance simplifies the calculation of the integral over t' in Eq. (7); the quantity $1+g(r,t')$ can be taken out of the integration over t' by assuming $t'=t-R/c$ in it. At large distances ($R_0\gg\mu^{-1}$), the approximate equality $r\cos\theta+R\simeq R_0$ can be used. After integration of Eq. (7) over t', we obtain

$$I(t_1)=\frac{\eta\mu\varepsilon_\gamma}{8\pi R_0^2}\frac{\alpha\beta_1}{\alpha+\beta_1}e^{\beta_1 t_1}\int\limits_0^\infty dr\int\limits_{-1}^{1}d\xi\,\frac{\exp\left\{-\sigma\int\limits_0^R N_-(\tau)\,dx-\mu r+\frac{\beta_1 r}{c}(\xi-1)\right\}}{1+g(\tau)}, \tag{9}$$

where $t_1\equiv t-R_0/c$.

It is immediately clear from Eq. (9) that the light flash repeats the functional time dependence (8) of the source if the field and self-absorption effects are small. Numerical evaluation shows that the quantity $\exp\left\{-\sigma\int\limits_0^R N_-(\tau)\,dx\right\}\Big/[1+g(\tau)]$ changes little in comparison with $\exp(\beta_1 r\xi/c)$ for changes in ξ of the order of $c/\beta_1 r$ so that it can be taken out of the integration over ξ by setting $\xi=1$ in it. After integration over ξ, we have

$$I(t_1)=\eta\frac{\mu c\varepsilon_\gamma}{8\pi R_0^2}\frac{\alpha}{\alpha+\beta_1}e^{\beta_1 t_1}\int\limits_0^\infty dr\,\frac{\exp\left\{-\sigma\int\limits_0^R N_-(\tau)\,dx-\mu r\right\}}{1+g(\tau)}\,\frac{1-\exp\left(-2\frac{\beta_1 r}{c}\right)}{r}.$$

Figure 2 gives the results of numerical calculations of the quantity $I(t_1)$ in units of $\eta(\mu c\varepsilon_\gamma/8\pi R_0^2)[\alpha/(\alpha+\beta_1)]\exp(\beta_1 t_1)$ [1) p = 1; 2) p = 0.3; 3) p = 0.1; p is the air density in units of normal density]. Calculations show that a deviation from an exponential law begins at times $\beta_1 t_1\gtrsim 40$ and is produced by the retarding effect of the electric field. At normal pressure, the electric field reduces the luminous energy relatively little (by roughly 20%), but at low pressures, the reduction of the light signal is quite significant (by a factor of four, for example, at p = 0.1). At times $\beta_1 t_1\gtrsim 50$, the effects of self-absorption begin to be felt, leading to a still greater reduction in the light signal.

The electric field has relatively little effect on the γ-ray absorbed energy in calculating the time characteristics of the trailing edge of the luminosity ($t_1>T$). Indeed, at times $t_1>T$, the γ-ray flux (8) begins to fall exponentially in time and rapid relaxation of the electric field occurs as a result. The relaxation time can be estimated from the expression $t_r\approx(4\pi eKn_e)^{-1}$ [see Eq. (1)], which yields $t_r\sim 10^{-9}$ sec for typical values of the secondary-electron density $n_e\sim 10^{12}\ \mathrm{cm}^{-3}$.

The electric field, heating the secondary electrons [9], changes the coefficients for elementary processes in air under the influence of γ rays and thereby influences the self-absorption effect [see Eqs. (1)–(3)]. However, an exact calculation of the time characteristics of a light flash is made extremely complicated because of marked computational difficulties (numerical solution of the system (1)-(3) for a γ-ray flux varying in space and time). For times of the order of T, it is generally necessary to consider the time dependence of β_1 and β_2 [14]. The influence of self-absorption on the time characteristics of a light flash excited by a γ-ray source decaying exponentially in time was evaluated in [4] but secondary-electron heating by the electric field was neglected.

We consider the possibility of experimental observation of the effect of the intrinsic electric field on the luminosity excited in air of normal density at the beam exit of an electron accelerator [15]. We assume the electrons traverse a path l, producing uniform ionization over the range. Let the time dependence of the electron beam be represented by a rectangular pulse of length Δt. The electron energy $\varepsilon_e \simeq 1$ MeV. The equations for the field and the conductivity have the form

$$\frac{dg}{dt} = 4\pi\left\{\frac{e^2 l}{\varepsilon_e} i - eKn_e g\right\}; \tag{10}$$

$$\frac{dn_e}{dt} = \frac{\nu i}{l} - \gamma n_e, \tag{11}$$

where i is the current density. At values of Δt and i, where $g \leq 0.5$, the quantity g in Eqs. (10), (11) is neglected in comparison with unity. The secondary-electron density n_e increases linearly with time for times $t < \gamma^{-1} \simeq 10^{-8}$ sec. Considering this, we obtain for the field g

$$g = b \int_0^t \exp\{a(x^2 - t^2)\}\, dx, \tag{12}$$

where $a = 4\pi eKi/l$, $b = 4\pi e^2 li/\varepsilon_e$. Using the equality $x^2 - t^2 = \beta t(x - t)$, where $1 < \beta < 2$, we obtain for Eq. (12)

$$g = \frac{b}{\beta at}[1 - \exp(-\beta at^2)]. \tag{13}$$

Equation (13) has a maximum at $t \sim 1/\sqrt{a}$. Hence, we obtain an estimate for $\Delta t \lesssim 1/\sqrt{a}$. The value $g_m \sim b/\sqrt{a}$ is reached at these times. Substituting the numerical values of the constants and expressing the current density i in A/cm^2 and Δt in units of 10^{-8} sec, we obtain an estimate for the pulse duration Δt and the electric field g_m attained:

$$\Delta t \lesssim 1/\sqrt{10i}, \quad g_m \sim 10\sqrt{i}.$$

The effect can be observed for short pulses with $\Delta t \lesssim 10^{-8}$ sec and current densities $i \sim 0.1-1$ A/cm^2, which are completely achievable in modern electron accelerators. With constant pulse length Δt, an increase in accelerator current will lead to a reduction in the ratio of luminous energy to total energy in the electron beam. It is advisable to measure the ratio of light signal to accelerator current integrated over a pulse in order to avoid random fluctuations in accelerator current or electron energy.

Thus the effect of a strong electric field at low pressures markedly decreases the luminous energy and changes the time behavior of the luminescence. The effect of strong electric fields on the luminosity of air excited by fast electrons can be observed under laboratory conditions.

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ELECTROPHYSICAL PROPERTIES OF A DETONATION PLASMA; HIGH-SPEED EXPLOSIVE CIRCUIT BREAKERS

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A plasma with an electrical conductivity of $\sim 1\ \Omega^{-1}\cdot \mathrm{cm}^{-1}$ forms behind the detonation front (DF) of condensed explosive materials (EM) [1]. The conducting region is divided into two parts [2, 3]: nonequilibrium (the chemical-reaction zone with a width of ~1 mm) and equilibrium. The equilibrium electrical conductivity can be on the order of the nonequilibrium value or much lower and it declines rapidly in the expansion waves.

The motion of the conducting zone behind a DF with a velocity of 5-8 km/sec can be used to break a high-current circuit in a time of $\leqslant 1\ \mu$sec. Such circuit breakers can find application in powerful energy sources. The speed of the existing methods of explosive circuit breaking (~10 μsec [1]) is limited by the formation of arcs during the breaking of the circuit.

In the proposed method the conducting zone moves behind a DF between two electrodes. The current flows through the plasma and ceases when the EM between the electrodes has reacted and the electrical conductivity declines. The considerable electric strength of the detonation products [5] prevents the breakdown of the gap and the formation of an arc. Therefore, the breaking time is determined by the decline in electrical conductivity behind the DF, and with a minumum conducting zone (the reaction zone) it comprises ~0.1 μsec. The volt–ampere characteristics of the plasma at high current densities are required for the application of the new method of circuit breaking. These data can also be useful in clarifying the mechanism of plasma conduction.

Experiments. The voltage source was a capacitor battery (25 μF, 30 kV). The midpoint of the battery was grounded and the two halves were charged to voltages of opposite polarity. Such a scheme made it possible to reduce the demands on the voltage leads to the explosive chamber.

A cross section of the charge is shown in Fig. 1. The explosive material 1 (3 × 5 mm, length 12-15 cm) lay between copper electrodes 2 with a length of 10 cm. The voltage on the charge and the current were oscillographed with compensation of the inductive leads [6, 7]. Photographic recording was carried out with a high-speed photographic sweep through the plastic wall.

The charge was connected to the battery by arresters following the contact of the electrodes with the conducting zone behind the DF. The electrodes were protected from breakdown ahead of the DF by two to four layers of Dacron film 25 μ thick. Under the action of the high pressure the resistance of the film became low behind the DF in comparison with the resistance R of the plasma.

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