Explosive emission of electrons

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A review of papers devoted to study and use of the emission of electrons from a metal in contact with plasma clusters formed on explosion of micropoints on a cathode under the influence of thermionic field emission current of high density. A systematic discussion is given of questions of thermionic field emission of electrons from the metal, energy dissipation in cathode micropoints, explosive evaporation of the points, and formation of localized plasmas—cathode flares, which stimulate a rapid increase in electron emission from the cathode. A discussion is given of questions associated with study of the removal of cathode material in the operation of cathode flares and also with the investigation of the parameters of the plasma and the kinetics of its dispersion. The laws governing the removal of electrons from the cathode flare plasma are discussed, as well as the mechanism of electron emission from the metal to the cathode flare plasma. A separate section is devoted to the use of explosive emission in high-current electron accelerators and pulsed x-ray sources. The role of this phenomenon in initiation of electrical discharges in vacuum and gas is also discussed.

CONTENTS

1. INTRODUCTION

Conduction electrons cannot leave a metal under ordinary conditions because of the presence of a potential barrier. To overcome this barrier the electrons must acquire additional energy. For example, in thermionic emission this is accomplished by an increase of the electron's kinetic energy by heating, and in the photoelectric effect it is accomplished by transfer of the photon's energy to an electron.

There is, however, one type of emission which does not require the expenditure of additional energy—field emission.[1] In this case the emission occurs in the presence at the metal surface of a strong electric field. The potential barrier formed has a finite width and there is a nonzero probability of quantum-mechanical departure of electrons from the metal.

The various forms of emission have found wide use in practice. However, until recently it was not possible to produce high-current cathodes whose operation was based on one of the forms of electron emission mentioned above. The current density of thermionic emission is limited by the melting temperature of the cathode material. An increase of the current density of photoelectric emission requires use of such powerful radiation sources that destruction of the cathode surface results. The current density of field emission depends very strongly on the electric field strength at the cathode, and in principle high current densities (10^6–10^8 A/cm^2) are possible. However, to obtain such current densities it is necessary to prepare cathodes in the form of points with micron radii of curvature. Here it should be noted that micropoints are always present on any surface, even an optically polished one. Therefore field-emission cathodes are always pointlike. To obtain large electron currents it is necessary to prepare a tremendous quantity of points of identical geometry, which is impossible in practice. In addition, increase of the current density to 10^8 A/cm^2 leads to explosive destruction of the emitter.

A systematic study of the destruction of the stability of operation of a field-emission cathode at high current densities was made for the first time by Dyke and his colleagues.[2] It was established that destruction of the emission stability is accompanied by the transition of field emission to an arc. The nature of this process of the transition to an arc has been unambiguously explained in the study of pulsed breakdown in vacuum.[3-5] It turns out that on application of voltage to a gap the explosion of micropoints on the cathode surface occurs under the action of thermionic field emission with formation of

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local plasma bursts—cathode flares. Electrons reach the anode from the surface of the plasma of the flares, which expands with a velocity $\sim 10^6$ cm/sec. Electron emission from the cathode in the process of transition of the metal into a plasma determines the rise of the electron current in the gap. This phenomenon as a whole received the name explosive electron emission.[6] In recent years explosive electron emission has come to be widely used in high-current generators of relativistic electron beams[7,8] and high-power x-ray bursts.[9] This phenomenon also has independent value in the physics of electrical discharges, mainly discharges in vacuum.[10]

In the second section of our review we describe the processes at the cathode which directly precede explosive emission, and we then describe the results of investigations of cathode erosion, the main characteristics of the cathode flare plasma, and of the explosive emission process itself. At the end of the article we discuss the role of explosive emission in electrical discharges and also some questions of the practical utilization of this phenomenon.

2. PROCESSES AT THE CATHODE IN THE PRESENCE OF INTENSE THERMIONIC FIELD EMISSION

In the presence of an electric field the potential barrier for electrons near the boundary between the metallic cathode and the vacuum has the form[1] shown in Fig. 1. The main characteristic of the emission process is the current density

$$j_e = e \int d\mathbf{p}\, \nabla_p \varepsilon D(p_\perp, E) f(\mathbf{p}, T_e); \qquad (1)$$

here e is the elementary charge, $D(p_\perp, E)$ is the barrier penetration coefficient which depends on the component $p_\perp$ of the electron momentum normal to the emission boundary and the electric field strength E at the cathode, f is the distribution function of the cathode conduction electrons in momentum, T_e is the electron temperature, and ϵ is the electron energy. The problem of determining the current density consists of finding the transmission coefficient D and calculation of the integral (1). We will not dwell in detail on the methods used in the calculations. A sufficiently complete presentation of the current state of the theory of thermionic field emission can be found in several monographs.[1,11,12] For the further discussion we will need the dependence of the current density $j_e(T_e, E)$ on temperature and electric field strength E. Murphy and Good[13] have obtained relatively simple formulas which have a wide range of applicability. The transmission coefficient D was calculated in the quasiclassical approximation. Analytical formulas for j_e have been obtained in two main limiting cases: for high fields and relatively low temperatures (E—T emission) and also for weak fields and high temperatures (T—E emission). The corresponding expressions appear as follows: for E—T emission,

$$j_e = \frac{E^2}{16\pi^2 q t^2(y)} \frac{\pi T_e/2T_i}{\sin(\pi T_e/2T_i)} \exp\left(-\frac{4\sqrt{2}\varphi^{3/2}v(y)}{3E}\right), \qquad (2)$$

and for T—E emission,

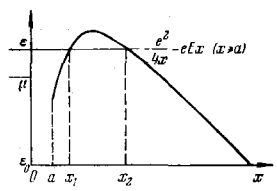

FIG. 1. Form of potential barrier at metal-vacuum boundary.

$$j_e = \frac{T_e^2}{2\pi^2} \frac{E^{3/4} T_e^{-1}}{\sin(E^{3/4} T_e^{-1})} \exp\left(-\frac{\varphi - \sqrt{E}}{T_e}\right); \qquad (3)$$

here $y = \sqrt{E}/\varphi$, φ is the work function, $T_i = E/4\sqrt{2}\varphi t(y)$, $t(y) = \nu(y) - (2/3)y(d\nu/dy)$. The Nordheim function $\nu(y)$ for $0 \le y \le 1$ has been tabulated in ref. 1. The current density j_e is given in units $m_e^3 e^9 \hbar^{-7} = 2.37 \times 10^{14}$ A/cm^2 (m_e is the electron mass, $\hbar = h/2\pi$ is Planck's constant), and the field E in units of $m_e^2 e^5 \hbar^{-4} = 5.15 \times 10^9$ V/cm, the temperature T_e and the work function φ in units of $m_e e^4 \hbar^{-2} = 27.1$ eV. In Fig. 2 we have shown the region of values of the temperature and electric field for which Eqs. (2) and (3) are valid for the work function of tungsten, which is 4.5 eV.

As $T_e \to 0$, Eq. (2) goes over to the Fowler-Nordheim equation for the field emission current density.[1] The argument of the exponential in Eq. (3) corresponds to the decrease in the work function in the presence of an electric field (the Schottky effect) (see Fig. 1). For $E \to 0$ Eq. (3) goes over to the well known Richardson-Dushman equation.[12]

As will be shown below, an important role in the cathode energy balance is played by the surface emission energy associated with an energy flux density j_ϵ through the emission surface

$$j_\epsilon = \int d\mathbf{p} \varepsilon \nabla_p \varepsilon D(p_\perp, E) f(\mathbf{p}, T_e). \qquad (4)$$

It is well known that in thermionic emission, which can be interpreted as the evaporation of electrons, a cooling effect arises. Attempts have been made to observe a similar phenomenon in field emission, but a negative result has been obtained.[1] Nottingham[14] first showed that in field emission both heating and cooling of the cathode occur. Using approximations similar to Eqs. (2) and (3), we obtain for the energy density j_ϵ in the case of E—T emission

$$j_\epsilon = j_e\left(-\varphi - \pi T_e \operatorname{ctg}\frac{\pi T_e}{2T_i}\right); \qquad (5)$$

and for T—E emission

$$j_\epsilon = j_e\left(T_e + E^{3/4}\operatorname{ctg}\frac{E^{3/4}}{T_e} - \sqrt{E}\right); \qquad (6)$$

here the quantity j_ϵ is expressed in units of $m_e^4 e^{12} \hbar^{-9} = 4.02 \times 10^{34}$ eV/cm^2-sec. The second term in the parentheses in Eq. (5) changes its sign at $T_e = T_i$, which corresponds to the transition from a heating effect to a cooling effect. The quantity T_i has therefore received the name inversion temperature. This mechanism can easily be understood if we turn to Fig. 1. The conduction electrons carry to the emission surface from the depth of the metal an average energy coinciding with the Fermi energy. For small T_e the electrons are mainly in low-lying energy levels from which they are emitted into the vacuum in field emission. Near the emission surface hot electrons are accumulated and the cathode is heated. As T_e increases, more and more hot electrons leave the

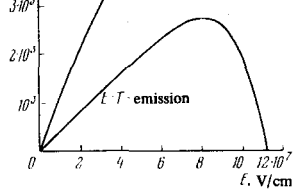

FIG. 2. Region of values of temperature and electric field for tungsten for which Eqs. (2), (3), (5), and (6) are valid.

cathode, and finally the cathode ceases to be heated and then begins to be cooled.

In addition to the surface source of heat on flow of emission current, a volume source arises in the cathode body, associated with Joule dissipation. Both of these effects lead to intense dissipation of heat at high emission currents, which brings about destruction of the cathode.

A systematic study of the thermal situation in field emission cathodes was carried out for the first time by Dyke and co-workers.[2] Between a cathode and anode separated by a vacuum gap they applied a high-voltage pulse of duration about 10^{-6} sec. They were able to obtain a maximum emission current density $j_e \approx 6 \times 10^7$ A/cm^2, at which the cathode was not yet destroyed during the time of action of the voltage pulse. Mesyats[3] has discussed the heat balance of a point cathode. Only the Joule heating mechanism was invoked as a source of heat, and the excess of heat was carried away to the cathode base as the result of thermal conduction. The condition of destruction was assumed to be equality of the maximum temperature at the emitter tip to the melting temperature of the cathode material. On this basis he made estimates of the maximum emission current density at which the emitter is preserved. He obtained qualitative agreement with the experimental results of Dyke et al.[2].

Subsequently many workers have supplemented and refined the results of Dyke and Mesyats.[2,3] For example, Gor'kov et al.[15] studied the dependence of the prebreakdown current (the maximum current preceding destruction of the point) on the opening angle of the cone of the point. A more careful numerical solution was carried out of the cathode heat-balance equation, the formulation of the problem being similar to that of Dyke.[2]

Behavior of a field emitter in the limiting current-density regime is described in ref. 16. For example, as in the results obtained by Dyke[2] in a field-emission projection tube of the Mueller type[1], several rings were observed, the current in the rings appearing with a delay relative to the time of application of the voltage pulse and depending on the initial temperature of the point. The presence of such rings was associated with thermionic field emission from the side portion of the tip on heating of the cathode. It should be noted that the field emission current goes mainly through the tip of the point, since the greatest electric field intensity E occurs at the tip.

Studies of the field emission of tungsten in the nanosecond region of pulse lengths are described in refs. 17 and 18. For a pulse length $\sim 5 \times 10^{-9}$ sec with a point emitter of tungsten it has been possible to obtain without destruction a current density of $\sim 5 \times 10^9$ A/cm^2. There are no rings in the emission pattern for such durations. This is evidently due to the fact that there has been no heating of the side surface of the cathode and corresponding increase of its emission capability from thermionic emission. Kartsev et al.[17] established a sharply expressed dependence between the delay time (relative to the time of application of the voltage pulse) of the explosion of the tip of the point t_d and the field strength E at the tip. It was also observed that the product $j_e^2 t_d$ remains constant over a wide range of current density and delay time and is equal to $\sim 4 \times 10^9$ A^{2}sec/cm^4 for W (Fig. 3).

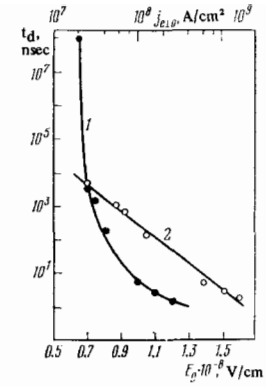

FIG. 3. Delay time of explosion of field emitter of tungsten, as a function of electric field strength (1) and of the logarithm of current density (2).

Several workers[19-22] have studied the temperature behavior of a thermionic field emission cathode, taking into account both Joule heating and the Nottingham effect. However, the calculations were made only for a stationary case, on the assumption that it was possible to establish a static temperature field in the body of the cathode. It is hard to suppose that such conditions are satisfied for the pulse lengths used in refs. 17 and 18, and therefore the results of the calculations carried out in refs. 19–22 cannot explain the experimental data in the nanosecond region of pulse length. This circumstance has led to the need for discussing the problem of increase of the temperature of a field emitter in a more general formulation.

We note first of all that the Nottingham effect and the Joule dissipation lead directly to a change in the electron temperature T_e. The lattice temperature T_p changes as the result of electron-phonon interaction. This situation can be described by the following system of equations:

$$\left.\begin{aligned} &c_e \frac{\partial T_e}{\partial t} = \lambda_e \Delta T_e + \frac{j_e c_e}{e n_e} \nabla T_e + j_e^2 \varkappa_0 T_p - \dot{\varepsilon}, \\ &c_p \frac{\partial T_p}{\partial t} = \dot{\varepsilon}, \quad T_e = T_p\,|_{t=0} = T_0, \\ &\lambda_e \nabla T_e\,|_{\substack{\text{emission}\\ \text{surface}}} = -\frac{2kT_i j_e}{e}\left(\frac{\pi k T_e}{\mu}\frac{\pi T_e}{2T_i} + \frac{\pi T_e}{2T_i}\operatorname{ctg}\frac{\pi T_e}{2T_i}\right); \end{aligned}\right\} \qquad (7)$$

here c_e and c_p are the heat capacities per unit volume of the electron gas and the lattice, respectively, n_e is the conduction electron concentration, μ is the Fermi level, and k is Boltzmann's constant. The system of equations presented is valid in the temperature range 10^2–10^4 °K, where the phonon thermal conduction can be neglected ($\lambda_e \nabla T_e \gg \lambda_p \nabla T_p$) and the resistivity can be assumed linearly dependent on the lattice temperature ($\kappa = \kappa_0 T_p$), and the electron-phonon interaction can be represented in the form given in refs. 23–26:

$$\dot{\varepsilon} = AT_D\left[\left(\frac{T_e}{T_D}\right)^5 \int_0^{T_D/T_e} \frac{x^4\,dx}{e^x - 1} - \left(\frac{T_p}{T_D}\right)^5 \int_0^{T_D/T_p} \frac{x^4\,dx}{e^x - 1}\right], \qquad (8)$$

where T_D is the Debye temperature, $A = \pi^2 v_{so}^2 n_e^2 e^2 \kappa_0 / 6$, and v_{so} is the velocity of sound in the metal. Estimates made by Anisimov et al.[26] give $A \approx 2 \times 10^{11}$ J/cm^3-sec-deg.

The problem was solved numerically for a tungsten cathode in the form of truncated cone with a radius of curvature of the emitting tip $r_e = 3 \times 10^{-5}$ cm and an opening angle $\theta = 10°$. The results of the calculation are shown in Figs. 4–6. For fields $E \geq 10^8$ V/cm the electron temperature rapidly overtakes the phonon temperature. At the initial moment of time the electron temperature increases mainly as a result of the Nottingham effect, and later the Joule heat source becomes dominant.

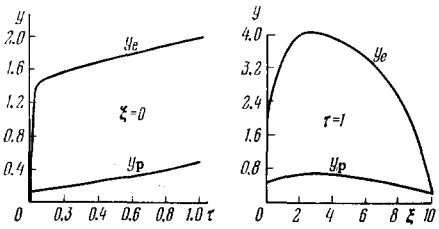

FIG. 4. Dimensionless temperature $y = \pi T/2T_i$ as a function of the time $\tau = j_{e_0}^2 \pi_0 / c_p t$ and the distance from the emitter tip $\xi = \sqrt{j_{e_0}^2 \kappa_0 / \lambda_e} \times (r - r_e)/\sin(\theta/2)$. Electric field strength at cathode tip $E = 1.2 \times 10^8$ V/cm, $j_{e_0} = 1.25 \times 10^9$ A/cm^2, $(r - r_e)/\sin(\theta/2) = 4 \times 10^{-6}\ \xi$ cm, $t = 1.3 \times 10^{-11}\ \tau$ sec, $T = 2 \times 10^3\ y$ °K.

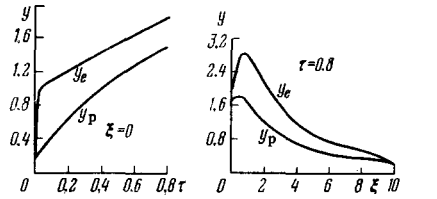

FIG. 5. Temperature y as a function of time τ and distance ξ. Field $E = 10^8$ V/cm, $j_{e_0} = 6.8 \times 10^8$ A/cm^2, $(r - r_e)/\sin(\theta/2) = 1.5 \times 10^{-5}\ \xi$ cm, $t = 1.7 \times 10^{-10}\ \tau$ sec, $T = 1.7 \times 10^3 y$ °K.

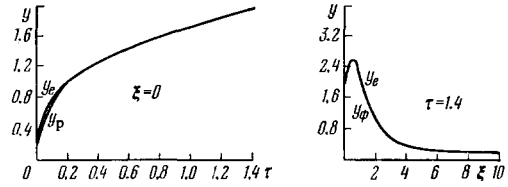

FIG. 6. Temperature y as a function of time τ and distance ξ. Field $E = 0.8 \times 10^8$ V/cm, $j_{e_0} = 10^8$ A/cm^2, $(r - r_e)/\sin(\theta/2) = 10^{-4}\ \xi$ cm, $t = 8 \times 10^{-9}\ \tau$ sec, $T = 1.4 \times 10^3 y$ °K.

For $T_e \geq T_i$ the rate of rise of T_e drops rapidly, which corresponds to strong emission cooling. The time t_d is determined by the rate of transmission of energy from the electron subsystem to the lattice ($t_d = 4c_p/A \approx 10^{-11}$—$10^{-10}$ sec). These circumstances open the possibility of obtaining short-duration pulses ($t \leq 10^{-10}$ sec) of emission current without destruction of the cathode with current density $j_e \geq 10^{10}$ A/cm^2. For $E \leq 0.8 \times 10^8$ V/cm the lattice temperature is practically identical to the electron temperature. The time t_d is related to the field-emission current density $j_{e_0} = j_e(T_e = 0)$ from the condition $c_p \partial T/\partial t \approx j_e^2 \kappa_0 T$, i.e., $j_{e0}^2 t_d \approx c_p/\kappa_0$ (for the Nottingham effect on taking into account the Wiedemann-Franz law we similarly have $c_p \partial T/\partial t \approx kT_i j_e/e\sqrt{\lambda_e t/c_p}$ and $j_e^2 t_d \approx e^2 c_p \lambda_e / 4k^2 \approx c_p/\kappa_0$. More detailed numerical calculations[27] give

$$j_{e_0}^2 t_3 = \gamma \frac{c_p}{\kappa_0}, \qquad (9)$$

where $0.75 \leq \gamma \leq 2.35$ as a function of the height of the point and the angle of the cone near the vertex. Equation (9) is in good agreement with the experimental data of ref. 17.

At the end of this section we note the following. The study of field emission from a cathode cooled to the superconducting state may present definite interest. Under such conditions there is no heating of the field emitter associated with Joule dissipation, but the influence of the Nottingham effects remains an open question. The magnetic field produced by the emission current, which will destroy the superconducting state, may prevent large currents from being obtained from a superconducting field emitter. These limitations are described by the well known Silsbee relation $i = 2\pi r_e H_{cr}$, where H_{cr} is the critical field of the superconductor, i is the current, and r_e is the radius of the field emitter. Usually $H_{cr} \approx 10^3$ Oe and we can hope to obtain from a superconducting field emitter under stationary conditions small currents in the range from a fraction of an ampere to amperes.

3. REMOVAL OF CATHODE MATERIAL

Overloading of the emitter by electron current leads to heating of the tip, to its destruction, and to formation of a plasma adjacent to the cathode, which we will subsequently call a cathode flare. One of the characteristics of this process is the intensity of destruction of the cathode. The special measurements of the mass of metal lost by a point cathode during the functioning of a flare have been made by several workers.[18,28-31] According to the data of Fursei' et al.,[29] the electrotransport coefficient for points of Mo is $(2—6) \times 10^{-5}$ g/Coulomb. The Tomsk group[32-34] have studied the nature of the destruction of point cathodes (Mo, W, Cu, Al, Ni) by comparison of photographs of the points before and after an experiment, obtained in optical or electron microscopes (Fig. 7). On first turning on and for current-pulse durations $t_p \leq 4 \times 10^{-8}$ sec, the metal was carried away only from the tip of the point. This situation is satisfactorily described by a Joule heating model on the assumption that the entire emission current passes through the tip.[32] The expression for the mass carried away during a pulse has the following form:

$$M = \left(6\sqrt{\pi}\sin\frac{\theta}{4}\right)^{-1}\left[\frac{\sqrt[3]{\rho}\,\kappa_0}{c\ln(T_{cr}/T_0)}\int_0^{t_p} i^2(t)\,dt\right]^{3/4}, \qquad (10)$$

where the heat capacity $c = c_p/\rho$, ρ is the cathode material density, and T_{cr} is some critical temperature usually taken as the melting point. We have given a comparison of the theoretical and experimental results in Fig. 7.

For pulse lengths $t_p = 8 \times 10^{-8}$ sec, erosion of the side surface of the point is observed. Here the experimentally determined amount of mass carried away from the tip is significantly less than that calculated with Eq. (10). A preliminary analysis shows that these deviations can be explained by the decrease in the current density through the tip as a result of the increase in area of the cathode emission on explosion of micropoints on the side surface of the emitter.[35]

In refs. 32—34 it was established that on repeated turning on of the current (10^4—10^6 times), in spite of an increase in the radius of the tip of the point and a decrease in the macroscopic field at the tip, the delay time in appearance of the flare remains within the limits 10^{-9} sec. This is explained by the strengthening of the field at cathode micropoints arising as the result of previous explosions[36] and as a result of the effect of adsorbed gases.[37] Emission from copper points turned out to be most stable (up to 10^6 turn-ons). Within the spread of the experimental data, the removed mass M can be expressed as a function of the number of turn-ons N (Fig. 8) by the expression $M(N) = BN^{\alpha}$, where $B \approx (10^{-9}$—$10^{-10})$ g and $\alpha = 0.65$—0.85. The decrease in the mass of metal removed during one current turn-on

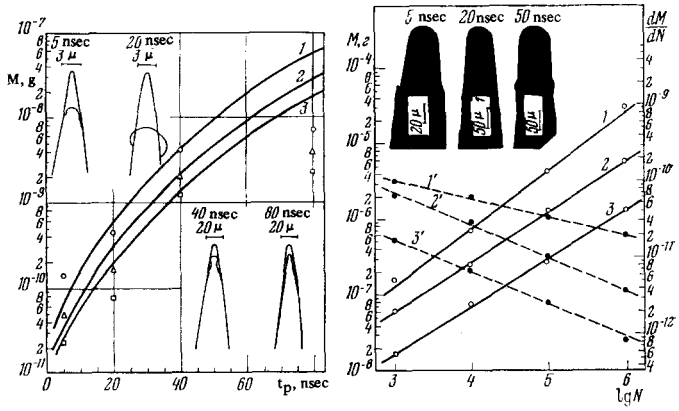

FIG. 7. Mass of metal M removed from tip of a molybdenum point, as a function of current-pulse duration on first current turn-on. 1—$\theta = 8°$, 2—$\theta = 10°$, 3—$\theta = 24°$. The curves are plotted from Eq. (10). The figure also shows the profiles of the points before and after current turn-on. U = 20 kV, d = 0.2 cm.

FIG. 8. Loss of mass by copper tips on repeated current turn-ons. U = 30 kV, d = 0.3 cm, $\theta = 6°$. Curves 1–3) M(N); 1′–3′) dM/dN; 1, 1′) $t_p = 5 \times 10^{-8}$ sec; 2, 2′) $t_p = 2 \times 10^{-8}$ sec; 3, 3′) $t_p = 5 \times 10^{-9}$ sec. The figure also shows the profiles of the tips after 10^6 current turn-ons.

dM/dN with increasing N can be explained from Eq. (10) by the increase in the radius at the point ($\theta \to 180°$), and also by the increase in the number of simultaneously exploded micropoints.

The existence of a large number of micropoints on the surface of cathodes operating in the explosive-emission mode has been confirmed by a number of direct[28-30,34] and indirect[38] measurements. Interesting data on the microgeometry of the surface of the point have been obtained by the method of the interrupted vacuum arc.[36,39-41] The appearance of micropoints is usually associated with the action of ponderomotive electrical forces which pull the micropoints out of the liquid phase.[36,38-40] However, there are as yet no reliable measurements of the electric fields at the boundary between the plasma and the cathode.

It must also be noted that in some experiments the operation of the cathode flare led to appearance of microparticles.[34,42] However, except for their existence, there is no other information on them.

4. CATHODE FLARE

a) Rate of expansion of flare. This was determined by several methods: by measurement of the rate of movement of the cathode flare luminescence boundary,[4,43,44] from the increase in the intensity of luminescence of the flare at various distances from the cathode tip,[45] from the rate of movement of the boundary of electron emission from the plasma of the flare in accordance with a three-halves law[46] (see also Sec. 5), from determination of the rate of crossing by the flare plasma of the gap between the cathode and a grid anode, which is fixed by the cutoff of current to the collector located beyond the grid.[47,48] All of these methods have shown that the rate of expansion of the cathode flare plasma is essentially constant with time, depends weakly on the applied voltage, and amounts to $\sim 3 \times 10^6$ cm/sec for Al, $\sim 2 \times 10^6$ cm/sec for W, Mo, and Cu, and $\sim 1 \times 10^6$ cm/sec for Pb.

Mesyats and co-workers[49,50] have proposed a hydrodynamical model of an expanding cathode flare. A two-component plasma was considered (electrons and ions with an average charge number $\bar{Z}$). In the scaling limit when the size of the flare becomes much greater than the initial volume of metal removed, we can write for the separation velocity of the flare v

$$v = \int_0^{n_{i_0}} \sqrt{\frac{\partial (P_i + P_e)}{\partial n_i}} \frac{d \ln n_i}{\sqrt{m_i}}, \qquad (11)$$

where n_i is the ion concentration, $n_{i_0} = n_i(t = 0)$, m_i is the ion mass, and P_i and P_e are the ion and electron pressure, respectively. Assuming that the conditions of expansion of the flare are close to adiabatic, i.e., $P_i = n_{i_0} k T_{i_0} (n_i / n_{i_0})^\gamma$, $P_e = n_{e_0} k T_{e_0} (n_e / n_{e_0})^\gamma$ (γ is the exponent of the adiabat, k is Boltzmann's constant, and T_0 is the initial temperature), we obtain from Eq. (11)

$$v = \sqrt{\frac{4\gamma}{\gamma - 1} (\varepsilon_{i_0} + \bar{Z} \varepsilon_{e_0})}, \qquad (12)$$

where ϵ_0 is the initial specific energy. If ϵ_{i_0} is set equal to the specific energy of sublimation of the cathode material and ϵ_{e_0} is the Fermi energy divided by the ion mass, $\bar{Z} = 3$, and $\gamma \simeq 5/3$, then the velocity v calculated from Eq. (12) agree satisfactorily with the experimental data of refs. 4 and 43–50.

The distribution of the concentration of particles in the flare is determined by the relation

$$n_i = \frac{M_0 \lambda (vt - r)^{\lambda - 1}}{4\pi m_i v^\lambda r^2} \qquad (\lambda \approx 2), \qquad (13)$$

which satisfies the condition of mass balance

$$M = M_0 t^2 = 4\pi m_i \int_0^{v_i} n_i r^2 \, dr. \qquad (14)$$

b) Composition of the cathode flare plasma. This has been studied by Baksht et al.[45] by the method of determining the spectral characteristics of the radiation of the plasma with a photoelectric spectrometer. An aluminum cathode was used. It was found that doubly charged Al ions appear simultaneously with the beginning of the rise of electron current. The time of appearance of the radiation from singly-charged Al ions is appreciably shifted relative to the beginning of the current rise. This is explained by the smaller concentration of Al II in the plasma of the flare in comparison with the concentration of Al III. No neutral atoms of aluminum were observed. After termination of the current pulse, the intensity of radiative transitions of singly and doubly charged Al ions continued to rise and reached a maximum after 15–20 nsec for the Al III lines (4529 Å) and after 20–30 nsec for the Al II lines (4666 Å). This nature of the luminescence is typical of the recombination afterglow of a plasma and indicates the presence in the plasma of ions of Al IV, whose radiative transitions lie in the ultraviolet region.

Analysis of the elementary processes in a cathode flare plasma which can lead to excitation and ionization of atoms has shown[45] that the main role is played by ionization by electron impact. Here it is necessary that the mean free path of the electrons be small in comparison with the dimensions of the cathode flare. According to the estimates, Al ions up to Al IV should be present in the flare plasma, which is consistent with the experimental data described above.

The electron temperature in the cathode flare plasma, determined from the ratio of intensities of the Al III lines 4529 and 4479 Å, turned out[45] to be 4.5 ± 0.8 eV.

5. ELECTRON EMISSION FROM THE CATHODE FLARE PLASMA

a) Stable emission regime. It was shown above that the cathode flare expands with a velocity v which is prac-

tically independent of the applied voltage and does not change with the passage of time. The expansion of the flare is accompanied by intense electron emission. It is natural to suppose that the space charge of the emitted electrons will in effect screen the flare plasma from external influences.[49] Gurevich et al.[51] have shown that in free expansion of the plasma into vacuum, acceleration of ions occurs. This is due to the fact that for comparable electron and ion temperatures the electrons have a significantly higher velocity and can leave the plasma. The electric field formed as the result of separation of the charges accelerates the ions and slows down the electrons. In our case where there is no acceleration of the plasma boundary of the flare, we should evidently expect the Langmuir-Child law[52] to be satisfied, i.e., $i = PU^{3/2}$, where I is the emitted electron current, P is the electron flow perveance, and U is the potential difference between the plasma front and the anode. The electrons leave the cathode flare, cross the vacuum gap, and hit the anode, their space charge being distributed in such a way that the electric field strength at the emission boundary of the flare plasma is zero.

The value of the perveance P is determined by the geometry of the vacuum gap between the plasma front and the anode. It is possible to calculate P by the method of equating specific capacitances.[53] Calculations were carried out for the case in which the emission takes place from a flare formed on explosion of the tip of a point emitter.[53] These calculations showed that, in agreement with experiment,[6] the perveance is

$$P = 37 \cdot 10^{-6} \frac{vt}{d - vt} \frac{a}{b^{3/2}}. \qquad (15)$$

Here d is the interelectrode gap and vt is the radius of the plasma cluster formed on explosion of the emitter tip.

b) Unstable emission regime. The regularities established above are characteristic of the stable emission regime which occurs in the early stage of expansion of the cathode flare and is distinguished by a constant shape and current during many pulses. With the passage of some time from the moment of appearance of the cathode flare, when the current exceeds a definite limit, this regularity is destroyed, and the current flow from the plasma becomes unstable, which is noted by the appearance of chaotic spikes in the current oscillograms (Fig. 9).[55-58] Similar oscillations of current are observed also in study of pulsed breakdown in vacuum[59,60] and in x-ray tubes with ignition.[61]

Several studies[55-58,62] have been devoted to the unstable regime of explosive electron emission. It has been established that the height of the current spikes is 1.5–3 times the current value corresponding to the 3/2-power law. Simultaneously with the current spikes, an increase by a factor of five or more is observed in the current density along the axis of the point. The duration of the bursts of current and current density does not exceed 10^{-8} sec.

The average time $\bar{t}_{cr}$ up to the appearance of bursts along the beam axis increases with increasing gap length d and decreasing voltage on the diode. Proskurovskiĭ et al.[62] have found a dependence of the average time $\bar{t}_{cr}$ on the current density along the beam axis at the moment preceding the bursts (Fig. 10). With increasing distance from the beam axis, bursts in oscillograms of the current density arise with greater delay and smaller amplitude. It was established[62] that the bursts in the

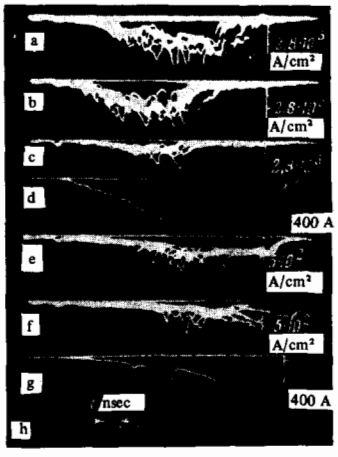

FIG. 9. Oscillograms of current and current density in which the stable and unstable stages of explosive electron emission are visible. a–c) Current density oscillograms taken from a collector located beyond an opening in the anode; a) the opening is located on the electron-beam axis; b, c) increasing displacement from the beam axis; d) oscillogram of total current; a–d) for d = 0.1 cm, U = 30 kV; e–g) for d = 0.2 cm, U = 30 kV.

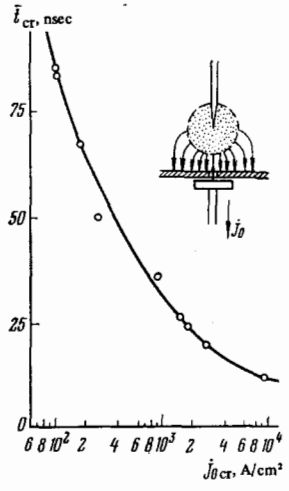

FIG. 10. Time of onset of unstable stage of explosive emission t_{cr} as a function of current density along the beam axis.

current-density oscillograms are due to formation in the near-cathode region of dense thin electron streams (of diameter 10^{-2} cm). The formation of these streams is evidently due to the multiplication and shifting of local emission centers on the cathode.

Positive ions of the near-cathode plasma accelerated toward the anode are observed at the times of the current spikes.[55,56] The energy spectrum of these ions is extremely broad; their maximum energy does not depend on the charge multiplicity and reaches 300–400 keV for a diode voltage U = 80 kV and 10–15 MeV for U = 300 kV. It should be noted that a similar effect was observed earlier in emission of electrons in spark sources,[63] which indicates an identical nature of the ion acceleration process. In the unstable emission regime, electrons with energies several times the voltage applied to the diode are also observed.[64,65]

The cause of appearance of current instability in explosive emission is related to the increase of the potential of the near-cathode plasma.[57] In the opinion of Plyutto et al.,[57] the plasma potential begins to rise at the moment when its emission capability becomes less than the transmission ability of the gap between the flare and the anode. On increase of the cathode flare potential, strong electric fields arise in the plasma, which leads to formation of a discontinuity with a high potential drop in it. At the discontinuity there is formed an electron beam which passes through the gap plasma, which compensates its space charge. Before the front of the gap plasma there is formed a region with a significant negative

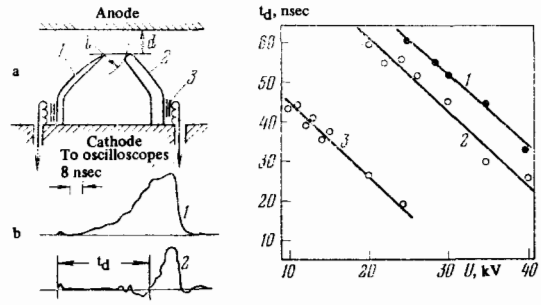

FIG. 11. Explosive emission stimulated by plasma of neighboring cathode flare. a) Electrodes: 1–point, 2–wide electrode, 3–Rogowski coil; b) oscillograms of current from point (1) and wide electrode (2); c) dependence of time t_d on voltage in gap: 1–d = 0.091 cm, l = 0.035 cm; 2–d = 0.097 cm, l = 0.029 cm; 3–d = 0.038 cm, l = 0.025 cm.

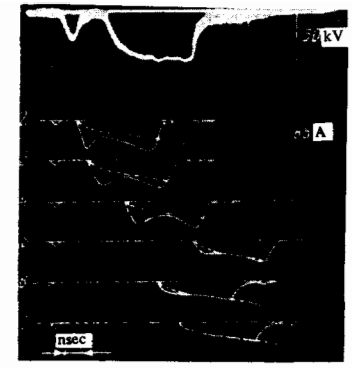

FIG. 12. Effect of duration of pause t_{ps} between auxiliary and main voltage pulses, applied to a diode with a point cathode, on the current in the main pulse. Top curve: oscillogram of voltage; 2–7) oscillograms of current, corresponding to increasing pause: 6) t_{ps} = 120 nsec, 7) t_{ps} = 180 nsec; the dashed line shows oscillograms of current in thediode without a prepulse; d = 0.4 cm.

space charge. Ions can be captured in the potential well arising here and can be drawn to the anode. Proskurovskiĭ et al.[62] have also attempted to explain the conditions of the transition to the regime of unstable current flow by the limitation of the emission capability of the cathode flare. It should be mentioned that considerable attention has been devoted recently to problems of the collective acceleration of ions in high-current vacuum diodes.

c) **Explosive emission of electrons stimulated by the plasma.** A plasma at the cathode surface can be obtained by a discharge in the ignition circuit, by the action of a high-power laser on the cathode, and also by injection from an auxiliary source. However, independently of the means of creating the plasma, maintaining of its high emission capability is possible only if good conduction exists between the cathode and the plasma. Experiments[69,70] have shown that this contact is accomplished as the result of explosive emission of electrons, which is stimulated by a plasma from an external source. The arrangement of the electrodes and typical oscillograms are shown in Fig. 11. On arrival at the anode of the high-voltage pulse, a flare appeared at the cathode 1 and the rise of current in the diode began. After a time t_d, simultaneously with one of the bursts in the oscillogram of the current from cathode 1, the current from cathode 2 rose sharply. Here several local luminescence centers arose on the cathode surface covered by the incident plasma; in the spectrum of these centers there were lines from multiply charged ions of the cathode 2 material. With increasing anode voltage and plasma concentration, the time t_d decreased.

Experiments have been carried out with double voltage pulses.[6,71-73] A high-voltage pulse was supplied to a vacuum diode, and explosive electron emission developed. Then there was a pulse during which there was no voltage on the diode, and after this a high-voltage pulse was again supplied. Typical oscillograms of voltage and current[72] are shown in Fig. 12. A characteristic feature is the fact that the repeated current pulse is appreciably greater than that which would occur if there were no pause.

d) **The mechanism of unstable explosive emission.** Analysis of the experimental data described above leads to the conclusion that at the moment of development of the instabilities the electron current extracted from the flare plasma exceeds the current injected into the flare from the cathode. The plasma is impoverished of electrons, uncompensated positive charge is formed, and the flare plasma potential rises. There arises a near-cathode layer of ion space charge, in which the potential drop is compensated and which is characterized by the presence of a strong electric field at the cathode. Being accelerated in the near-cathode layer, electrons reach the gap between the plasma front and the anode with high initial velocities. This increases the transmission capability of the vacuum gap between the flare and the anode. In other words, the cathode flare plays in effect the role of the grid in a triode. These concepts permit explanation of the current bursts at the moment of instability and in experiments with repeated voltage pulses. As the near-cathode drop increases, the electric field strength at the cathode also increases, which eventually leads to a renewed initiation of explosive emission. In this way it is possible to understand the appearance of explosive emission stimulated by the plasma. The appearance of a new portion of plasma with high concentration increases the electron current from the cathode, the potential of the flare is reduced, and the entire process reverts to the stable stage.

6. ELECTRICAL DISCHARGE IN VACUUM AND GAS

a) **Initiation and development of vacuum breakdown.** In study of the mechanism of vacuum breakdown, the main problem lies in understanding the nature of the formation of the conducting medium in the gap.[5,10,37] The phenomenon of explosive electron emission enables us to provide an unambiguous explanation of these processes.[10,74] In the case of pulsed breakdown the main features are as follows. 1) A high criticality of the breakdown delay time to the average electric field intensity is observed.[10,75] 2) The beginning of the rise of current in the gap (the transition to the spark stage) is due to the appearance of cathode flares.[10,75] 3) The rise time of the current to a maximum value limited by the resistance in the circuit (the commutation time) is directly proportional to the gap length and is almost independent of the voltage.[10,75] 4) During the rise of the current, strong x radiation and anode erosion are observed.[75-78]

From the point of view of explosive emission, the delay time of the discharge is determined by the delay in the explosion of the micropoints. From Eq. (9) it follows from $t_d \propto j_e^{-2}$, which explains the rapid decrease of the time t_d with increasing field. In the nanosecond time region where high current densities are drawn from the micropoints and there is an effect of electron space charge, we have[49] $t_d \propto E_0^{-3}$. The current rise in the gap is due to emission from the plasma of expanding cathode flares. From calculations of the behavior of the current rise, carried out in ref. 79, it follows that there

is a direct proportionality of the commutation time t_c to the gap length d and a weak dependence of t_c on voltage. The appearance of the x-ray pulse, the cathode flare, and also the destruction of the anode and the transport of anode material to the cathode are explained by the action on the anode of the intense electron beams emitted by the flares in the spark stage of the discharge.

The breakdown mechanism of vacuum gaps with a constant voltage has not yet been interpreted unambiguously.[37] However, recently performed experiments with apparatus[76] whose time resolution is 10^{-9} sec indicates that the irreversible destruction of vacuum insulation under these conditions is also due to the appearance of cathode flares.

b) Explosive emission and the cathode spot of a vacuum arc. Investigation of the explosive emission of electrons from a metal has a direct relation to the problem of the nature of the processes in the cathode spot of a vacuum arc.[5,10] On comparing the results of the studies described above with the data on cathode processes in an arc discharge,[80,81] it is easy to see that these two phenomena have many features in common. Among these are: the existence of a dense ($n \approx 10^{18}$ cm^{-3}) plasma at the cathode; a high (10^7—10^8 A/cm^2) current density in the region of the metal-plasma phase transition; a periodic increase of the potential of the near-cathode plasma, which increases the emission of electrons from the cathode; the appearance of new emission centers stimulated by the plasma; similar values of the rate of removal of metal; similar values of the rate of expansion of the cathode flare plasma and the plasma streams of the spot; the presence of multiply charged ions in the near-cathode plasma; the presence of ions accelerated from the cathode to the anode. This comparison permits the statement[5,10] that a cathode flare is the initial phase of an arc cathode spot which is being formed. Analysis of the results of recent studies of cathode spots with high time resolution[82] provides a basis for the assumption that the explosion of a micropoint and the appearance of a cathode flare are the elementary event in the functioning of cathode spots. An important role in the process of maintaining a cathode spot is played by explosive electron emission stimulated by the plasma of previous flares.

c) Discharge along a dielectric in vacuum. The initiation of this discharge always occurs in the region of contact of the cathode with insulators.[83] Because of the existence of microscopic roughness on the surface of the metal and dielectric, there are gaps in the vicinity of the contact in which the electric field can be enhanced[84,85] by a factor ϵ, where ϵ is the dielectric permittivity of the insulator. For dielectrics with $\epsilon = 10^1$—10^3 the magnitude of the field at the cathode with allowance for its enhancement at micropoints may reach 10^7 V/cm or higher, and here it is natural to expect a substantial emission of electrons from the metal and the occurrence of phenomena characteristic of vacuum discharge initiation.

The results of spectral investigations of the composition of the plasma in the initial stages of a discharge (up to 10 nsec)[86] show that at the moment of initiation, two processes occur: 1) heating of a portion of the dielectric as the result of electron bombardment, desorption of adsorbed gases, and evaporation of ceramic material with subsequent ionization of this vapor; 2) Joule heating of micropoints as a result of the flow of emission current, and their explosion with formation of a plasma.

The plasma in the dielectric is propagated with a velocity of 10^7 cm/sec under the influence of the tangential component of the electric field. Insulators with a high dielectric permittivity are characterized by a very low value of breakdown electric strength (10^2—10^3 V/cm). A reduction in the field strength at which the discharge occurs is also made possible by explosive emission from the cathode, stimulated by the plasma formed at the surface of the dielectric.

d) Discharges in a gas. In some types of gas discharges the electric field strength in the gap approaches 10^6 V/cm. Such discharges include discharges in highly compressed common gases (nitrogen, air, and so forth, for $P \leq 100$ atm.)[87] discharges at pressures of several atmospheres in gases with high breakdown strengths (SF_6, Freon, and so forth)[87] discharges in micron gas-filled gaps under ordinary conditions,[88] discharges in compressed or rarified gases under the influence of nanosecond pulses,[89] and also discharges in a gas along the surface of dielectrics with large ϵ.[90] Since the field strength at the cathode under these conditions is comparable to the breakdown strength in vacuum, there have long been attempts to explain certain characteristics of gas discharges on the basis of field emission.[89] It is logical to suggest that the initiation of a discharge in the gas can occur as the result of explosive electron emission. The existence of microsteps on the cathode increases the local field strength by one hundred times or more. For field strengths $\sim 10^8$ V/cm the explosion of micropoints is possible up to the point where the number of electrons in the shower reaches a critical value and it is converted to a streamer. For example, in a centimeter air gap with a plane tungsten cathode on overvoltage by tens of percent a discharge in the pressure region of the order of 10^2 atm will be due to explosion of points, and not to a streamer. It is possible that the departure of the dependence of breakdown voltage on pressure in compressed gases from Paschen's curve is due to the existence of the explosive emission process.

Direct proofs exist of the influence of the cathode surface on the delay time of breakdown and the value of the breakdown field strength in the action of nanosecond pulses on a gas-filled gap. Careful polishing and use of a single-crystal cathode can increase by several times the electrical breakdown strength of an air gap of length of the order of 1 mm, and can raise it to $(1.0—3) \times 10^6$ V/cm with a delay time[89] of about 10^{-9} sec. It is possible that the x rays from the anode, recorded for a discharge in air at atmospheric pressure in the region $E = 10^6$ V/cm under the action of nanosecond voltage pulses,[4] are due to electrons produced by explosive emission.

In gas-filled microgaps whose length is comparable with or smaller than the electron mean free path, the discharge is usually close to a vacuum discharge and in that case the role of explosive emission is dominant.

7. GENERATORS OF HIGH POWER ELECTRON BEAMS AND X-RAY PULSES

a) High-current vacuum diodes. One of the most important applications of explosive electron emission is in generators of high-power pulsed electron beams with durations of the order 10^{-8} sec and powers from 10^8 to 10^{13} watts.[7,8] Such electron beams have found wide appli-

cation in nuclear fusion studies, radiation physics, production of microwaves and x rays, and so forth. The main element of a generator is a diode consisting of a cathode, insulator, and a thin anode for escape of the electrons. Two types of diodes are used: the first is for production of dense beams of 10^4—10^7 A/cm^2 of duration 10^{-8}—10^{-7} sec, and the second is for beams of density 1—10 A/cm^2 of area 10^2—10^4 cm^2 and duration up to 10^{-6} sec for pumping CO_2 lasers and for technological purposes. Study of the phenomena in diodes with currents up to 2000 kA has shown[91,92] that the velocity of cathode flares is $(2-5)\times 10^6$ cm/sec, and the current in the diode is described by a 3/2-power law up to the pinching of the beam.

In the use of high-current electron beams, the structure of the beam is very important. We can mention several factors affecting the beam structure in a diode. These are the intrinsic magnetic field of the beam, the unstable region of explosive emission, the electric field configuration near the cathode, and also the interaction of closely spaced emission centers. Nonuniformities in the distribution of the current density at the anode in the form of striations extended perpendicular to the plane of a razor-blade cathode have been observed by several workers.[42,93,94] In the opinion of Toepfer and Bradley,[93] these striations arise as the result of instability in the current-carrying plasma (a discontinuity in the current layer) which is formed at the edge of the blade. Other workers[95,96] who used plane cathodes have observed beam nonuniformities in the anode plane consisting of extended erosion spots located perpendicular to a line joining cathode flares. This pattern, in the opinion of these authors,[95,96] is due to interaction of closely spaced cathode flares. Special experiments with two point cathodes[95,96] have confirmed this assumption. Calculations show that this structure of the electron flow in a diode with explosive emission is due to the electric field configuration in the near-cathode region.[96]

The limiting duration of the pulse of electron current is limited by the time in which the crossing of the gap by the plasma occurs. In most of the known beam generators this quantity does not exceed 10^{-7} sec. We can point out several means of increasing the duration of the electron current pulses. These are increasing the gap length in the diode,[97] elimination of the anode flare, and slowing down the velocity of the cathode flare by application of a transverse magnetic field.[98-100] Removal of the anode flare is achieved by use of an anode with an opening which transmits a shaped beam,[98-100] or by reduction of the electron-beam density at the anode.[97]

b) **X-ray pulse generators.** While the electrons in electron-beam generators are ordinarily extracted outside the diode, in pulsed x-ray tubes they are directed to a target mounted on the anode.[101,102] If we know the regularities of explosive electron emission, we can estimate the parameters of the x-ray pulses.[102]

For example, if the energy necessary for the x-ray pulse is stored in a capacitor with capacitance C, then in the case of a tube with a plane anode and cathode with N individual emitting centers, simultaneous solution of Eq. (15) and the Kirchhoff equation for the discharge circuit permits the following relation to be obtained for the duration of the x-ray pulse:[101,102]

$$t_{xp} \sim [cd/(Nvu_0^{1/2})]^{1/2}, \qquad (16)$$

where u_0 is the voltage to which the capacitor is charged, v is the velocity of the cathode flare plasma, and d is the distance between cathode and anode.

In the case where a line is discharged into a diode with a point cathode, the x-ray pulse duration, in agreement with experiment,[54,103] will be proportional to d/v and will be determined by the time of crossing of the gap by the plasma.

8. CONCLUSION

Explosive electron emission is the basis of a number of practical pulsed generators of high-power electron beams and x rays which have been developed. This is the only form of emission which at the present time permits electron fluxes with a power up to 10^{13} watts to be obtained.

Maintenance of the explosive emission process is provided by the plasma formed as the result of evaporation of cathode material under the action of the emitted electron current. The explosive emission process also involves continuous regeneration of micropoints whose explosion provides the repeatability of the phenomenon. Automation of this phenomenon will permit extremely simple extraction of large electron currents from the cathode.

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