Injection emission from volume-charged electrodes

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The paper presents description and phenomenology of a new type of the charged particle emission from electrodes due to the electromagnetic field penetration inside the emitter surface layer and formation there of the excess density of charged particles (volume charge). Such type of emission is termed injection emission (IE). Based on the IE mechanism, the generation of the abnormally high-energy electrons in a high-voltage discharge is explained.

In electro-vacuum and gas-discharge devices, as well as in accelerators of charged particles, gas-discharge lasers, and lasers pumped by the electron beam, the current is initiated and supported due to charged particle emission from electrodes (emitters). The emission mechanism can be of one or several types simultaneously.

At present, the following types of emission are known and taken into account: thermoelectronic, thermoionic, autoelectronic, photoelectric, secondary, and their various combinations.

In the context of a search for simple and cheap methods of producing electron beams, processes (including emissive) in the vacuum and gas discharges excited by high-voltage impulses with an amplitude of 10^5–10^6 V and leading edge time of 10^{-8}–10^{-11} s are of a special interest. Pulse discharges in the above-stated amplitude–time range were investigated experimentally and theoretically.[1–6,9] Electron beams were obtained at discharges in gases and atmospheric air.

In the gas-discharge plasma, the electrons with abnormally high energy were recorded, several times exceeding the energy of eU_{max} (Refs. 3 and 6) (e is the electron charge, U_{max} is the electrode voltage amplitude). To explain the experimental results, the theories of runaway of electrons and their stochastic acceleration in plasma, including the ionization wave fronts, were developed and applied. [2,3,6,9]

Based on experimental results on nanosecond high-voltage discharges under various initial conditions in the discharge medium,[2–6,9] a conclusion about injection nature of the electron emission from electrodes at the initial discharge stage has been made.[4,5] The reason of such emission can be in formation of a volume charge inside the cathode surface layer on penetrating into it of the electromagnetic field.

A physical explanation of the new emission type in more detail is given in this paper. It is underlined that a volume charge is formed in the surface layer of the emitting electrode, corresponding in sign and size to the electrode potential and capacity, or, respectively, to difference of potential and interelectrode capacity of the discharge gap. In this case, the cathode work function can be considerably reduced and the current of electron emission from cathode increased due to the bending of energy zones and the increase in the Fermi level energy of the cathode material, i.e., when the electron density in the volume of the cathode material near its emitting surface increases.

Actually, in the absence of the external field, the cathode work function is determined by the difference between energies of the lowest emission level and the Fermi level E_F.

It is well-known that

$$E_F = (3n/8\pi)^{2/3}(h^2/2m_e), \quad (1)$$

where n is the electron density in the uncharged cathode metal; h is the Planck's constant; m_e is the electron mass.

If the alternating voltage of U_{max} amplitude is applied to the interelectrode gap, then an excess charge appears in the cathode skin-layer

$$q = CU_{max}. \quad (2)$$

Here C is the capacitance of the interelectrode gap or of a single electrode (cathode).

For an alternating field of ω frequency, the skin-layer depth is

$$\delta = \sqrt{2/\pi\sigma\mu\omega}, \quad (3)$$

in which σ is the electrical conductivity of the cathode material; μ is its permeability. For the pulse field, the pulse rise time can be expressed as

$$\tau_p = T/4 = \pi/2\omega, \quad (4)$$

where T is the equivalent frequency period of the alternating field.

It follows from Eqs. (3) and (4) that

$$\delta = (2/\pi)\sqrt{\tau_p/\sigma\mu}. \quad (5)$$

If the distribution of the excess charge density in the skin-layer is uniform, then at $\delta \ll d$ the excess electron density in the cathode skin-layer for the plane–parallel diode can be found as

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$$\Delta n = \frac{CU_{\max}}{eV_\delta} = \frac{\varepsilon_0 \varepsilon \pi U_{\max}}{2de}\sqrt{\frac{\sigma\mu}{\tau_p}} = k_1 \frac{U_{\max}}{\sqrt{\tau_p}}; \qquad (6)$$

$$k_1 = \frac{\varepsilon_0 \varepsilon \pi \sqrt{\sigma\mu}}{2de}, \qquad (7)$$

where d is the interelectrode gap; ε is the dielectric permittivity of the interelectrode medium, ε_0 is the electric constant; V_δ is the cathode skin-layer volume.

For a tip cathode of $U_{\max}$ potential and the curvature radius $r \cong \delta$ [Eq. (5)], Δn can be found in a spherical approximation as

$$\Delta n = \frac{3\varepsilon_0 \varepsilon U_{\max} \pi^2 \sigma\mu}{4e\tau_p} = k_2 \frac{U_{\max}}{\tau_p}; \qquad (8)$$

$$k_2 = \frac{3\varepsilon_0 \varepsilon \pi^2 \sigma\mu}{4e}. \qquad (9)$$

Given Δn, it is possible to find the energy ΔE_F, by which the above work function further decreases due to increase in electron density of the cathode material

$$\Delta E_F = E_F(n + \Delta n) - E_F(n). \qquad (10)$$

It is also well known that to escape the cathode surface, the electron must overcome the mirror reflection force. This process consumes the energy, thus increasing the work function. At the same time, in the presence of the excess electron charge in the volume V_δ of the skin-layer the electron on the emitter surface and in its proximity experiences the force of electrostatic repulsion. This force is subtracted from the force attracting the electron to the cathode, thus reducing the work function. As a result, such a reduction of the work function can be attained that the decisive role in the process of electron emission from the cathode surface will play forces of electrostatic repulsion between electrons in the negatively charged cathode surface layer. In this case, the electron emission has an injection character (injection emission).

In the experiment, we used the discharge conditions close to conditions described in Ref. 2 (Fig. 1).

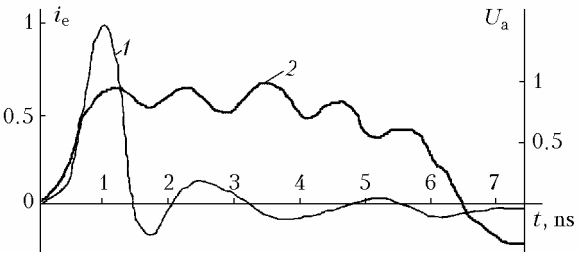


Fig. 1. Typical oscillograms of the electron beam current i_e (*1*) and voltage U_a (*2*) on the anode at discharge in free air (P = 1 atm).

Figures 2*a–f* demonstrate the pulse high-voltage discharge glow from a single cone cathode in free air ($U \sim 10^5$ V, $\tau_p \sim 0.3$ ns, $\tau_U \sim 1$ ns). The glow in the near-cathode area has a nature of the radially extending cloud (Figs. 2*a–d*) irrespective of the position of one or two anodes (Figs. 2*e* and *f*). The same glow character in the near-cathode area is also observed in the absence of anode. It may be concluded that this near-cathode zone is created by a non-compensated negative charge of electrons moving along the field force lines from cathode to the near-cathode area.[4,5] Note that two well-defined zones of the extending glow are formed when discharging from the cone cathode in the presence of anode (Fig. 2*a–e*). However, if two or several parallel cathodes (Fig. 2*g–f*) are available, including a wide-aperture noncircular configuration of the multitip cathode (Fig. 3), the separation into two well-defined extending zones is practically not observed even in the presence of anode. This points to a significant role of the space–time parameters of intrinsic electric and magnetic fields of the adjacent discharges initiated by several emissive centers on the cathode and anode.

By means of the IE mechanism, it is possible to explain the appearance of escaping electrons of abnormal energy (AEE), generated at the initial stage of the discharge, as well as in dense gases. Their energy exceeds the value of $eU_{\max}$ corresponding to the maximal value of $U_{\max}$ on electrodes in the process of discharge.[3,6]

Simple computations show that in case of emission from the volume-charged spherical cathode under the potential $U_{\max}$ without a significant energy attenuation of electrons escaping the sphere center of any radius, the speed V_0 and kinetic energy E_0 of electrons according to laws of electrostatics already on the cathode surface (without accounting for relativistic effects) are

$$V_0 = \sqrt{eU_{\max}/m_e}; \qquad (11)$$

$$E_0 = eU_{\max}/2. \qquad (12)$$

At an infinite distance from the cathode in the absence of anode or at a sufficiently removed anode at $r \ll d$, V_∞ and E_∞ (disregarding the relativistic effects) are

$$V_\infty = \sqrt{6eU_{\max}/m_e}; \qquad (13)$$

$$E_\infty = 3eU_{\max} > eU_{\max}. \qquad (14)$$

Such conditions for subnanosecond ($\sim 10^{-9}$ s) high-voltage ($\sim 10^5$ V) discharges are realized at cathode peak curvature radii of $\sim 10^{-6}$ m. In this case, (for example, for aluminum) according to the Thomson and Viddington's law[7] (the law of electron energy attenuation in a matter), the attenuation does not exceed 10%. The same conclusion follows from the fact that in a crystalline conductor free of defects in the crystal, the length of free electron path can attain great values. Taking into account that in real crystalline conductors the concentration of defects makes shares of percent of the total atom concentration in the crystal (solid body), the length of free electron path attains $\sim 10^{-6}$ m (Ref. 8).

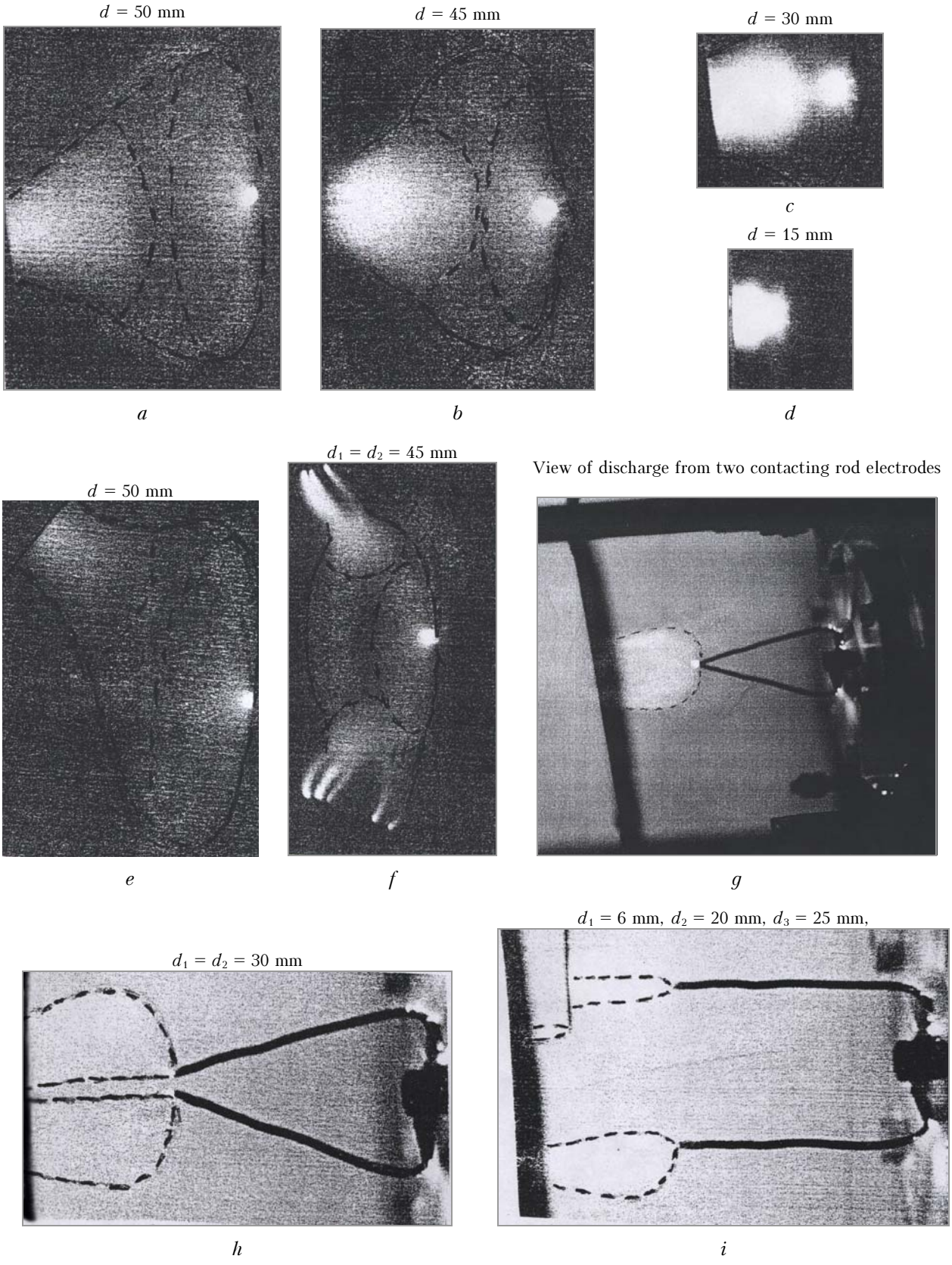
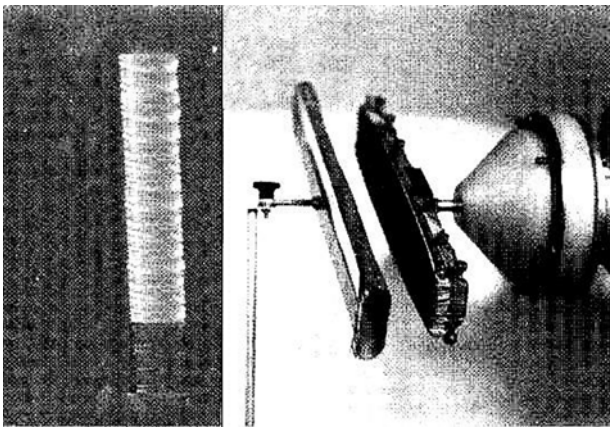


Fig. 2. The view of a high-voltage nanosecond discharge in air (P = 1 atm) at various configurations of the interelectrode gaps. Dash line denotes the boundaries of the discharge glow. Cathodes are to the right; anodes are to the left.



a *b*

Fig. 3. Discharge glow in free air; current amplitude of the beam with aperture of 180 cm^2 is ~ 3 kA (*a*); the multitip cathode of a 6 cm width is to the right, the mesh anode is to the left, interelectrode gap is ~ 40 mm (*b*).

In agreement with solid body physics, monocrystalline inclusions of the cathode material with small or even zero defect concentration, sizes of ~ 10^{-6} m, and also minimal or null resistance, are always present and spontaneously appear on the emitter surface and inside its surface layer. In other words, there are emission centers of metal monocrystals on the emitter surface, in which the electrons being in the field of a volume charge inside the emitter surface layer, are practically free of collisions and, hence, energy losses.

In view of the channeling effect of charged particles in crystals, it is possible to term such emission centers (EC) the centers of abnormal superconductivity (ASC). Electrons practically do not collide with the ionic shell of the crystal in such EC. Therefore, under the "ejecting" action of a negative volume charge the electrons already near the emitter surface are accelerated up to high speeds ($V_0 \sim 10^8$ m/s) and attain energy E_0 of ~ 10^5 eV that is sufficient for electron runaway conditions in a gas. The cross section of electron interaction with the gas in the near-cathode area is also considerably reduced and their free path length increases. This favors the increase in the electron energy in the accelerating field up to abnormally high values.

Thus, even on ignoring the distribution of the initial electron energy in cathode, in the discharge gap the electron energy can reach abnormal values. The essence of this paradox is in the fact that in the experiments, U_{max} is measured on the electrode surface, because the field potential gradient and the resulting charge inside the electrode material are taken zero. Actually, the potential gradient is also propagated inside the emitter volume, because it is volume-charged under the above-stated conditions. The heating of electrons inside the cathode by the internal field leads to additional increase in the energy of electron emitted into the discharge as compared to the energy computed by relations (11)–(14).

Finally, it is possible to state that the discharge development is mainly conditioned by the process of the injection emission of charged particles from the volume-charged electrodes, i.e., not by acting of the external field, but by acting of the field formed inside the emitter surface layer. It can be supposed that the discharge between the cathode and anode is accompanied by the injection emission of both electrons (from the cathode) and ions (from the anode). The experimental fact of similarity of discharge glow configurations in the interelectrode gap at a change of the potential electrode polarity proves this supposition.[9]

The injection emission can manifest itself both in pulse and in frequency modes. To compute the frequency mode, it is sufficient to substitute in the above-stated relations $\tau_p = 1/4f$, where f is the frequency of alternating voltage at electrodes.

The described new type of emission can be termed the injection skin-emission in accordance with conditions of its formation. The skin mechanism of the field penetration into the emitter surface layer is underlined by the fact that development of the electron beam current (see Fig. 1, curve *1*) takes place only in the section of increasing voltage on the cathode (see Fig. 1, curve *2*), i.e., at $dU/dt > 0$. At $dU/dt \le 0$, the surface skin-layer disappears (the skin-effect property). As a consequence, the volume charge in the cathode surface layer disappears, as well as the "ejecting" field and the injection emission, although the cathode voltage in this moment still is close to its peak value (see Fig. 1, curve *2*).

At the same time, the injection emission can take place at other mechanisms of field penetration into the emitter surface layer as well, including the constant voltage mode, when a sufficiently high gradient of the electric field in the emitter is attained due to the voltage drop in a high-resistance or semiconductive material of the emitter when passing the discharge current.

Both narrow and wide-aperture electron beams in gas diodes (including free air) were obtained. This shows an opportunity of pumping lasers by the electron beam generated immediately in the active laser medium.

Note that the wide-aperture beam was obtained with the help of the combined distributed electrode[10] allowing an increase of the discharge uniformity (see Fig. 3*a*). The essence of the combined distributed electrode consists in the fact that the multitip rectangular cathode composed of a pack of multitip strips, is connected to the negative lead of the high-voltage pulse generator (VPG) in the point of the pack geometrical center (the pack periphery is not connected to the generator); and the mesh rectangular anode is connected to the VPG positive lead only by its peripheral parts.

Summarizing the above-said, the following conclusions can be drawn:

1. Penetration of electromagnetic field into the emitter surface layer creates conditions for formation

there of an excess volume charge, which, in turn, initiates the injection emission from the electrode.

2. Both in vacuum and gas discharges, the injection emission is a component of resulting emission from electrodes.

3. Relatively large monocrystalline formations of the emitter material can appear on the emitter surface, in the volume of which charged particles can be accelerated practically without energy losses under the action of the field penetrating into them. Such formations (injection emission centers) possess abnormally high conductivity.

4. In the injection emission mode, there appear high-energy charged particles in the emission centers, which, leaving the emitter, pick up speed in the accelerating field of the near-electrode area up to abnormally high energy values [Eqs. (13) and (14)].

5. In the discharge conditions considered in this work, electrons already near the emitter surface (cathode) attain the energy and speed magnitudes exceeding critical values necessary for transition into the runaway mode [Eqs. (11) and (12)].

6. The work function of electrons and emissive capacity of the emitter, depending on the Fermi level position in the emitter material, are determined by the speed of voltage rise on electrodes rather than by the amplitude value and the pulse leading edge time [Eqs. (6) and (8)].

7. On the basis of the injection emission mechanism, it is possible to design lasers pumped by the beam of charged particles generated immediately in the laser medium adjacent to the emitter.

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