Generation of accelerated electrons in nanosecond electrical discharges using extensive slot cathodes limited by dielectric walls

N A Ashurbekov, K O Iminov and A R Ramazanov
Dagestan State University, 43a M. Gadjieva St., Makhachkala, 367002, Russia

Email: nashurb@mail.ru

Abstract. The spatio-temporal formation dynamics and basic electrical and optical characteristics of nanosecond discharges with an extended slot cathode in helium are investigated. It is established that electrons ribbon beams are formed in such discharges with an energy of several hundred eV. It is demonstrated that the restriction of the discharge gap in dielectric walls leads to the trapping of electrons in the gap and an increase in the efficiency of excitation and ionization of atoms of beam electrons, which leads to a substantial increase in the current density and intensity of optical radiation of the limited discharge. Experimental data obtained on the relaxation of charge density on the deposited surface of the charge limiter and the value estimates of the electric potential of the dielectric surfaces, were analysed. It is demonstrated that the variation in the discharge structure restricted by the dielectric walls corresponds to the variation in the distribution of the electric field in the gap, as well as under the influence of the surface potential.

1. Introduction
One of the significant features of high-voltage nanosecond discharges is that they are developing in gas pressure gaps, which form when high-energy electrons are generated in the discharge gap [1-5]. This phenomenon is of a fundamental importance since the high-energy electrons and X-ray radiation, which are generated during deceleration of high-energy electrons on the anode and in the gap, influence the ionization process in the gas; this consequently determines the pulse discharge characteristics. The discharge properties of the generated high-energy electrons are largely determined by conditions during the discharge development phase, electrode geometry and, to some extent, by the processes on the wall of the discharge chamber. In this regard, the nanosecond discharges by means of extending the cathode slits, where almost all the applicable voltage to the discharge gap is concentrated in a narrow cathode layer interspacing between the cathode plasma discharge chamber and the cathodic surface, are of particular interest [6-9]. The main function in the systematic establishment of these categories plays a developing role, which results in secondary electron emission on the cathode surface, the electrons acquired in the cathode layer being used up as an energy for excitation and ionization of the gas resulting from subsequent oscillations in the cathode chamber. The acceleration of electrons in the cathode layer, in order to redistribute the field in the discharge with a slot cathode, enables the reception of beams of high-energy electrons at much lower values of applied voltage. Such plasma-beam discharge (PBD) enables the generation of currents up to hundreds of
amperes, as a result of medium and high gas pressures required to produce, for example, optical generation in gas lasers. In comparison with similar discharges, the advantages of PBD with a slot cathode are manifested in a significantly greater volume of discharge, low operating voltages, and the ability to control the beam properties.

The objective of the present work is an experimental study of the effect of limiting the discharge area of the dielectric walls on the generation of accelerated electrons and the main characteristics of nanosecond PBD with an extended slot cathode.

2. Experimental methods and technique
An automated experimental setup was used, the detailed description of which is given in [7]. The setup consists of a high-voltage nanosecond pulse generator (VP G), a discharge chamber (figure 1 (a)), pumping and gas pressure control systems, a system for inferring the electrical and optical characteristics of the discharge with PC registration of measurements. A Blumlein type VPG, enabling the voltage doubling, which generated the voltage pulses with a leading edge of 10–15 ns and had an amplitude regulator up to 10 kV and a pulse repetition rate of up to 100 Hz, was manufactured.

The discharge chamber consisted of a quartz tube of 5cm diameter and a length of 50 cm, into which an electrode system, consisting of two aluminium electrodes spaced by 0.6 cm, was placed. The cathode consisted of a cylindrical rod having a length of 40 cm and a diameter of 1.2 cm, along which a rectangular cavity (slit) of 0.2 cm width and a depth of 0.6 cm had been cut. The anode consisted of a flat plate with a length of 40 cm, a width of 2 cm, and a thickness of 0.5 cm (figure 1 (a)). In order to limit the discharge field, flat plates of a polished glass-bonded dielectric material were used. Limiters were installed along the electrode at a distance of 2 mm (the width of rectangular cavity in the cathode) from each other (see figure 1 (b)). The design of the discharge chamber enabled the spatial structure of the discharge to be observed, and the spatial distribution of optical radiation in the discharge gap and in the cathode chamber to be recorded.

![Figure 1. a – discharge chamber type (1 – quartz tube; 2 – anode; 3 – cathode; 4, 5 – gas inlet and outlet); b – discharge boundary schema (2 – anode, 3 – cathode; 6 – dielectric loading).](image)

The discharge formation and its development dynamic were analyzed by means of the images produced by the high-speed time-lapse photography over time, using a Princeton Instruments PI-MAX3 ICCD Camera. Following the detection on the CCD, the image matrix was read with a controller, digitized, and transmitted to a computer for processing via a broadband connection.

In order to study the changes in the dielectric properties of the discharge limiters following their interaction with nanosecond discharge, the investigated dielectric samples were placed between two plates of a parallel-plate capacitor, as a dielectric. The facings of this capacitor are connected to the digital (WK6500P) capacitance and tgδ-dielectric loss meter. Measurements were carried out both at a fixed frequency and when scanning this frequency within the range from 1 kHz to 15 MHz. In the
work, the dielectric permittivity and $\tan \delta$ of the dielectric loss of the discharge limiter were measured before and after the interaction with the nanosecond PBD.

3. Results and discussions

Systematic experiments were performed to study both the electrical and optical characteristics, and the dynamics of formation of the spatial structure of the discharge within the gap and the slot of the cathode, using helium, to measure the gas pressure variability in the chamber ($p = 1-100$ Torr), and the amplitude of the voltage applied to the electrodes ($U_0 = 0.5-5$ kV). In similar conditions, the properties of the dielectric material of the wall limiting the discharge were also examined before and after the interaction with the PBD.

Experimental investigations have shown that the oscillogram of the discharge current ($I_{br}$) and the burning voltage ($U_{br}$) differ greatly in the form, the magnitude, and the duration for unlimited and limited discharge with identical end values $U_0$ and $p$. Figure 2 shows an example of the oscillogram $U_{br}$, $I_{br}$ and the corresponding image of the spatial distribution of optical radiation filming 70 ns after the beginning of the current pulse.

![Figure 2](image-url)

**Figure 2.** Oscillograms of voltage and burning of the discharge current and the images of spatial distribution of optical radiation: a-unlimited discharge; b-limited discharge in helium ($p = 10$ Torr; $U_0 = 1$ kV)

In the figure, it is shown that the peak value of the pulse $U_{br}$ is three times higher, and $I_{br}$ is more than one order higher than a limited discharge. Limitation of the discharge gap leads to a substantial
excitation of pulses $U_{br}$ and $I_{br}$. The rate of increase of current rises, when the discharge limit reaches up to $5 \cdot 10^{10} \text{A/s}$.

The research of the spatio-temporal formation dynamics of the optical discharge radiation has enabled the characteristics of the formation and development of unlimited and limited discharges in helium gas at moderate pressures to be established. In the unlimited discharge, a glow first appears on the cathode surface at the exit of the slot. Approximately 30 ns after the start of the current pulse, a diffused glow uniformly fills the cathode chamber and the gap between the electrodes. Subsequently, there is an increase in discharge emission intensity, which reaches a maximum at 65–70 ns. Moreover, the intensity of radiation in the cathode chamber grows faster and much higher in the active phase of the nanosecond discharge than in the gap between the electrodes (figure 3 (I)). When the gas pressure is raised above 40 Torr, the structure of the unlimited discharge changes significantly. Within the cathode gap, the discharge is pressed against the walls of the chamber and the dark space is formed towards the center, which comes to the surface of the anode. The limited discharge first glow appears simultaneously on the cathode surface and in the gap between the electrodes. Further, the discharge permeates the cathode chamber and increases the intensity of the discharge radiation. In the limited discharge, the opposite holds true: the radiation intensity grows faster and earlier in the limited space between the electrodes. Under certain external conditions, a focusing of the optical radiation and discharge is observed towards the center of the anode surface (figure 3 (II)). Under gradual increase $U_0 \geq 2.5 \text{kV}$ at the focal site along the surface of the anode, an extensive bright spot appears, and the glow is filling the limited gap with maximum intensity in the center. The results of the study of the formation of optical radiation dynamics of the discharge show that the limiting of the discharge gap leads to a significant change in the spatial structure of the discharge and a redistribution of the intensity of the optical radiation in the discharge gap.

![Figure 3](image)

**Figure 3.** Optical image: I - unrestricted discharge; II - restricted discharge in helium ($p = 20 \text{Torr}$; $U_0 = 1 \text{kV}$)

A comparative analysis of the primary parameters of unlimited and limited discharges was conducted under the same external conditions. The density of the discharge current $j_0 = I_{br}/S$ was estimated from experimental values $I_{br}$ at the maximum cross-sectional area of the discharge $S$. At the moment when the gas pressure reached $p = 10 \text{Torr}$, the value, which shows that the length of the cathode potential drop (CPD) area $d_c \approx 0.01 \text{cm}$, and the length of the mean free path of electron, is $\lambda = 1/(N\sigma_0) \approx 0.08 \text{cm}$ [8]. Since $\lambda > d_c$, electrons emitted from the cathode surface pass a check point area without collisions and gain the energy $W = eU_c$, where $U_c = 3 \cdot U_{br}/5$ [9].
Oscillograms $I_{br}(t)$ and $U_{br}(t)$ can be used to estimate the electron beam current density ($j_e(t)$). It is known, the anode current density is expressed by the formula: $j_D = e n_e v_{tr}$, where $n_e$ is the number of electrons formed in the plasma beams and by means of secondary electrons when colliding with gas atoms. As it is shown in the table, the beam's electrons are accelerated and gain the energy of hundreds eV. These accelerated beam electrons lose their energy ionizing the gas atoms during collisions with them in the gap, and the total number of created secondary electrons can be evaluated by means of the ratio: $z_i \approx W / E_1$, where $E_1$ is the energy created by a pair of electron - ion (for helium $E_1 = 46$ eV). Assuming that the anode current is exclusively conditioned by secondary electrons, and proceeding from the condition of continuity of current in an electric circuit, we can then approximately evaluate $j_D \approx z_i j_e$. The evaluations show that the discharge limiting leads to an elevated efficacy of ionization of atoms by accelerated electrons; this, in turn, results in the increase of discharge current density. The most favorable conditions for the formation of accelerated electron beams are developed in an unrestricted discharge, where the magnitude of the beam current at the anode surface reaches up to 20% of the discharge current (see table 1).

Table 1. The main parameters of the discharge in helium are $p = 10$ Torr.

|                  | unlimited discharge | limited discharge |
|------------------|---------------------|-------------------|
| $U_0$, V         | 1000                | 1000              |
| $U_{br}$, V      | 390                 | 750               |
| $J_e$, A/cm²     | 2.0                 | 45.0              |
| $W$, eV          | 234                 | 450               |
| $J_e$, A/cm²     | 0.4                 | 4.6               |
| $J_e/j_D$        | 0.20                | 0.10              |

Such considerable changes in the electrical, optical characteristics and spatial structure of the unrestricted and restricted discharge patterns are caused by a change of the electric field spatial distribution in the discharge gap under discharge limitations associated with any number of surface phenomena at the dielectric-plasma boundary.

The dielectric properties of the wall material limiting the discharge dependent on the time function and the degree of interaction with the PBD were studied, in order to establish this connection. Through the interaction of PBD on the dielectric wall limiter, some quantity of dielectric charge is captured. The sign of the developing charge coincides with the sign of the particles charge bombarding the surface. The quantity of the captured charge depends on the energy current density of charged particles settling on the surface, and the duration of pulse discharge. To determine the surface charge density at a low frequency range, the ratio: $\sigma \approx \omega \varepsilon_0 \varepsilon_\infty g \delta$ can be used, correlating $\varepsilon_\infty g \delta$ with its conductivity [10].
Estimates of the captured charge density using measurements of the values $\tan\delta$ and $\varepsilon$ enabled the construction of a relaxation curve for the captured charge density material following the cessation of interaction with the PBD at a determined frequency (figure 4):

$$n \approx \frac{\omega \varepsilon \varepsilon_0 \tan\delta}{e\mu},$$

where $\mu$ - the mobility of electrons in glass-bonded dielectric material.

The estimates show that the charge density of captured dielectric material in the discharge reaches $10^9$ cm$^{-3}$, after the cessation of interaction with PBD a relaxation surface charge density occurs and the process duration lasts tens of minutes (figure 4).

The change in the electrical characteristics, while limiting the discharge, can be explained by means of the following: when limiting the discharge by dielectric walls, a portion of the line of electric force becomes isolated on the negatively charged surface of the limiter; in order to penetrate into the cathode field, a higher field value is required, which leads to an increased burning voltage value. With more efficient ionization of emitted atoms by the electron limiter surface, free electrons, and free electrons captured in the discharge gap in the case of limited discharge, the density of plasma between the electrodes is much higher. Before this dense plasma attains its respective field values, it penetrates quickly into the cathode chamber, which leads to a faster growth and higher values of the discharge current than in the case of unrestricted discharge (figure 2).

![Figure 4. Density relaxation of captured charge material after cessation of interaction with the PBD when pulses surpass a frequency of 100 Hz](image)

Changes of the discharge spatial structure located along the center of the gap with a focus on the anode surface, and similarly the redistribution of radiation while limiting the discharge are primarily due to a change in the electric field distribution in the gap. The charge is obtained due to irradiation of the dielectric surface by an electron beam. The charging time of the dielectric surface depends on the conditions of its irradiation and ends at such a time when deep traps are completely filled [11-14]. The total electric charge $Q$, resulting from capture of the accelerated electrons by traps of the dielectric, during the process of their interaction with the PBD on the dielectric surface, gives rise to the emergence of a surface potential which exhibits a significant influence on the distribution of the electric field in the limited discharge gap. The surface potential of the limiter can be evaluated by means of the following relation [11]:
where $\varepsilon_0$ and $\varepsilon$ is the dielectric penetrability of the vacuum and dielectric, and $R$ is the path depth of primary electrons. The depth of penetration of primary electrons depends on the accelerating voltage and on the element composition of the glass-bonded dielectric material, which, in our experiment, was a few microns thick. Under the experimental conditions influenced by PBD, the limiter surface charges negatively with a value of the surface potential within several hundred volts. Consequently, electrons are reflected from the negatively charged limiter wall and under the influence of the changed field distribution in the gap, are focused towards the center of the gap. This leads to a change in the spatial structure of the discharge due to its limitations. The discharge gradually contracts toward the center and is focused in a line along the anode surface (figure 2 (b)).

4. Conclusions
The experimental research and evaluations made thereon show that electron ribbon beams with an energy of several hundred eV were formed in the nanosecond discharge with the help of an extended slot cathode. It is demonstrated that the restriction of the discharge gap in the dielectric plates leads to electrons capturing in the gap and the increase of excitation and ionization efficiency of beam electron atoms, which also leads to an increase of the current density and intensity of optical radiation. The relaxation of the captured dielectric surface charge density takes tens of minutes, which affects the electric field distribution between the electrodes and causes a change in the spatial structure of the discharge.

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