# ELECTRIC FIELD DISTRIBUTION IN A VOLUME GAS DISCHARGE CONTROLLED BY AN ELECTRON BEAM

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UDC 53

The production of powerful laser radiation fluxes with high spatial homogeneity and little divergence is necessary to the successful solution of a whole series of physical and applied problems. As is known [1], inhomogeneity of the amplification of the active medium can significantly degrade the optical characteristics of powerful laser systems. In this connection, a more detailed investigation of the possibility of uniform excitation of gases in large volumes acquires substantial value.

However, insofar as we know, an investigation of the spatial distribution of the electrical parameters in the volume discharge of pulsed $CO_2$ lasers has clearly been performed inadequately, especially in experimental aspects.

Preliminary experimental results of measuring the electric field distribution in a volume discharge excited by an electron beam in air at a pressure of $p=1$ atm are presented in this paper.

## 1. DESCRIPTION OF THE APPARATUS AND METHODS OF MEASUREMENT

The investigations were performed on a powerful pulsed $CO_2$ laser whose detailed description was expounded in [2, 3]. The gas discharge was ignited in a volume of $10 \times 10 \times 100$ cm. The discharge was initiated by an electron beam with the mean current density $j_B \simeq 0.8$ A/cm$^2$. The scheme, in principle, is presented in Fig. 1. Investigations of the homogeneity of the beam current density over the section by a selective "Faraday cylinder" showed (to the accuracy of the oscilloscope recording method) that inhomogeneity of $j_B$ over the length of the beam cross section is practically nonexistent, while a diminution of ~20% at the volume discharge boundary was observed across the width. The parameters of the voltage pulse generator used to supply the electron accelerator were the following: initial working voltage $U_B \simeq 200$ kV, stored energy ~1.25 kJ, wave impedance ~3 Ω. Typical oscillograms of the voltage $U_B$ and the electron beam current $j_B$ are represented in Figs. 2a and b. In our case the beam current duration was determined by the diminution in voltage at the cathode, and therefore, by the essential reduction in the capacity of the ~80-μm-thick aluminum foil through which the electrons were injected into the gas.

The energy source for the main discharge was a low-resistance voltage pulse generator with the parameters: working voltage $U_d \simeq 70$-250 kV, capacitance $C = 0.45$ μF, wave impedance $\rho \simeq 1.5$ Ω. Typical oscillograms of the discharge current $I_d$ and the potential at different spacings from the cathode: 1) $l = 10$ cm (anode); 2) $l = 7$ cm; 3) $l = 5$ cm; 4) $l = 3$ cm, are represented in Figs. 2c and d.

The potential distribution at different points of the discharge were monitored by an electric probe, for which a metal wire stretched along the discharge gap parallel to the electrodes was used (see Fig. 1). A high-resistance voltage divider $R_1$, $R_2$ ($r \ll R_1$, $R_2$) was connected directly to the energy source and supplied a positive potential to the probe, prior to initiation of the discharge, which corresponded to a linear electric field distribution in the interelectrode space.

The probe potential in the discharge was measured by using the ohmic divider $R_2$, r (see Fig. 1). As the probe diameter $\phi \simeq 0.2$-0.5 mm and the total resistance $R_1 + R_2 \simeq 50 + 80$ kΩ varied, agreement between the measurement results was observed within the ~10% limits of error of the oscilloscope method of recording.

The voltage was supplied to the discharge gap 0.7 μsec before the accelerator was switched on. Ionization of the gas by the initial powerful high-energy electron pulse resulted, as is seen from Fig. 2, in an abrupt diminution in the discharge resistance $R_d$ to a quantity less than $\rho$ (the wave impedance of the storage) and to a corresponding redistribution of the voltage between $R_d$ and $\rho$. The diminution in the intensity of external ionization during the time $\tau \lesssim 300$ nsec caused a growth of $R_d$, and therefore, an increase in the voltage across

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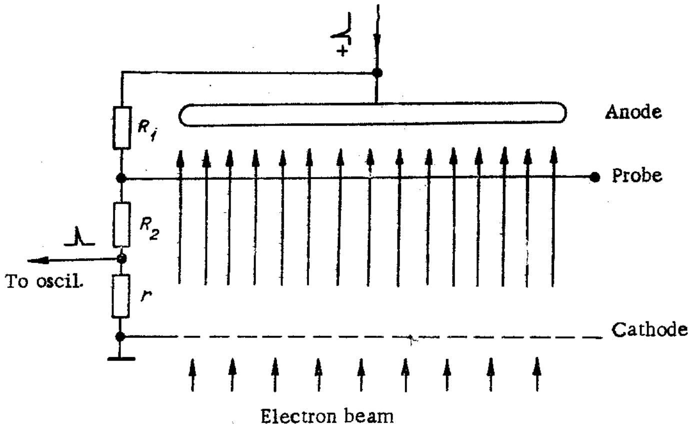

Fig. 1

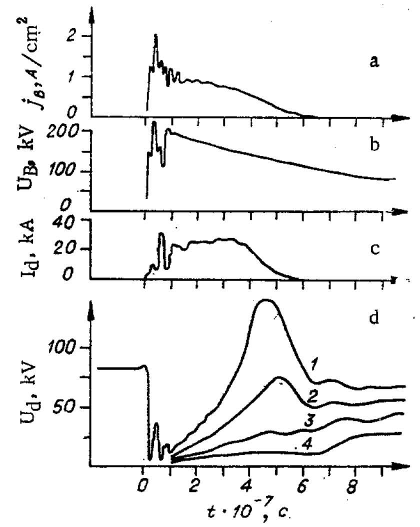

Fig. 2

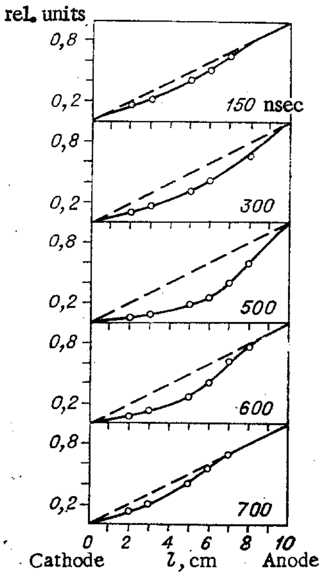

Fig. 3

the discharge gap. The significant decrease in the current $j_B$ and the beam electron energy at $\tau > 300$ nsec specified a sharp reduction in the discharge current. In addition, this process caused an increase in the voltage at the discharge because of the inductive component of the internal impedance of the energy source.

## 2. RESULTS OF THE EXPERIMENT

The potential distributions along the length of the discharge gap, as measured at different times, are represented in Fig. 3. The dashed lines correspond to a linear dependence of the quantity $U_d(x)$ on the spacing. It follows from the data presented in Fig. 3 that a substantial deviation of $U_d(x)$ from the linear law is observed in the discharge under investigation, where growth of the potential gradient occurs in the direction of electron beam motion from the cathode to the anode in the discharge gap.

In order to estimate the degree of influence of the various factors specifying such a strong distortion of the field distribution of the volume discharge controlled by an electron beam, we performed an approximate computation of the change in time of the following most important parameters: the magnitude of the electric field E, the electron concentration $n_e$, the intensity of external ionization $\psi$, and the rate of electron capture $\eta$.

The magnitude of the field E was determined by differentiating the dependence of the potential on the spacing to the cathode, which was measured in the experiment. The error in determining E did not exceed 30%. The electric field distribution along the length of the discharge gap is represented in Fig. 4 for different times. The numbers 1-7 denote the times 150, 200, 300, 400, 500, 600, 700 nsec from the beginning of the discharge. The cathode and anode potential drop, whose total magnitude can be several percent of the total voltage in the discharge gap according to data presented in [4], was not taken into account in performing the computations.

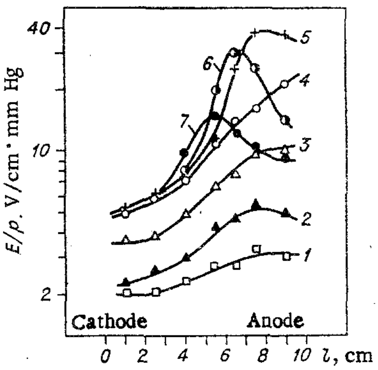

Fig. 4

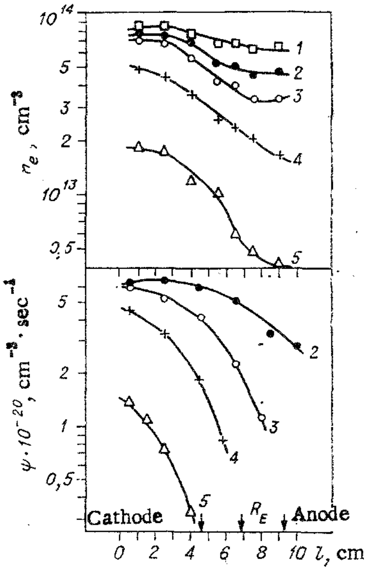

Fig. 5

It can be shown that the volume discharge current $I_d$ is determined, under the condition of our experiment, mainly by the electron mobility in the electric field. Hence, the mean value of $n_e$ over the cross section is determined by the expression

$$n_e \simeq \frac{I_p}{eA(E/p)S},$$

where ε is the electron charge, S is the discharge section, and A is the coefficient of electron mobility whose dependence on E/p for air is presented in [5].

By using the electric field distribution in the discharge gap obtained in the experiment E/p, the electron concentration $n_e$ could be obtained at different points of the volume discharge. The distribution of the electron concentration $n_e$ at different times 150, 200, 300, 400, 500 nsec after the beginning of the discharge is represented in Fig. 5. The data presented in Figs. 4 and 5 show that the nonuniformity in the distribution of the quantities $n_e(x)$ and the electric field E/p(x) is quite weak in the initial stage of the discharge. However, if the electron concentration at the cathode changes negligibly in the time $\tau \lesssim 400$ nsec, a sharp diminution in $n_e$ is observed near the anode. The field intensity in this domain is magnified almost ten times, reaching the value $E/p \simeq 25$-35 V/cm · mm Hg. Such high values of the parameter E/p occurring up to termination of the injection of the electron beam can contribute to the development of ionization processes in the main discharge field.

Indeed, as is seen from Fig. 4, after the discharge current ceases ($\tau \simeq 600$ nsec) a weak ionization wave moves from the anode resulting in equilibration of the field distribution in the discharge gap.

The rate of electron–ion pair generation $\psi$ for a beam of electrons with energies of 100-200 keV can be estimated by using the following relations [4, 6]:

$$\psi(x, t) \simeq \frac{j_B}{e\omega}\frac{dU_B}{dx}; \tag{2.1}$$

$$\frac{dU_B}{dx} \simeq 0.3 \cdot 10^6 \rho\,(Z/A)\,\beta^{-2} \ln \frac{1{,}16 U_B}{I_0}, \tag{2.2}$$

where $j_B$ is the beam current density, ω is the energy of electron–ion pair formation, $dU_B/dx$ (eV/cm) is the ionization loss of the fast electrons with energy $U_B$, A is the atomic weight of the material decelerating the beam, Z is the charge on the nucleus, ρ is the density, g/cm³, $I_0$ is the mean ionization potential, and $\beta = V_e/c$. The quantity ω is independent of $U_B$ and is ~34 eV for air [6].

The distributions of the ionization losses $\psi(x, t)$ [7] at the times 150, 200, 300, 400, 500 nsec after the beginning of the discharge (see Fig. 5) were computed by using (2.1) and (2.2) and taking account of attenuation of the beam current density $j_B$ as it passed through the gas gap.

As follows from the results obtained, as represented in Fig. 5, ionization of the gas by the external beam apparently occurred, substantially nonuniformly along the direction of its motion, under the conditions of the experiment being described. The dependences $n_e(x, t)$ and $\psi(x, t)$ show that the electron concentration in the

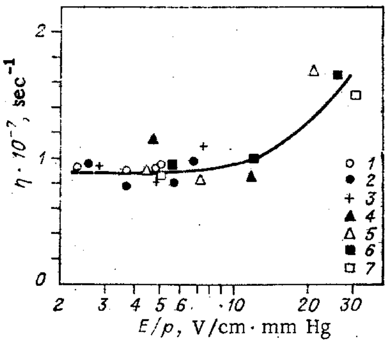

Fig. 6

discharge is controlled by the external ionizer during practically the whole current pulse in just the domain adjoining the cathode.

It is seen from Fig. 5 that extrapolation of the calculated values of the ionization losses $\psi(x, t)$ to zero at $t = \text{const}$ results in values of x close to the computed values of the average transit of the fast electrons $R_E$ with initial energies $U_B(0, t)$ which are represented in [6].

It follows from the data obtained that a sufficiently uniform ionization of the gas is observed in the volume discharge in a domain whose characteristic dimension is close to the value $l \lessdot R_E/2$.

This result shows that in contrast to the results of the numerical simulation presented in [8], under the conditions of our experiment the intrinsic electric field of the discharge apparently exerts no noticeable influence on the distribution of the ionization losses in the discharge gap.

Moreover, it can be assumed that destruction of electrons because of trapping must be taken into account in order to explain the dynamics of the discharge under investigation.

By using the expression

$$\eta = \frac{\psi}{n_e} - \frac{1}{n_e}\frac{\partial n_e}{\partial t},$$

which describes the behavior of the electron concentration in the volume discharge, values of the trapping coefficient $\eta$ were calculated for the times 200, 300, 400 and 500 nsec from the beginning of the current pulse at different spacings from the cathode (Fig. 6).

Sufficiently close values of the quantity $\eta$, obtained for essentially distinct changes in both the magnitude and nature of the parameters $n_e(x, t)$ and $\psi(x, t)$ of the discharge domains (see Fig. 6), permit making the deduction that the computed rate of external ionization $\psi(x, t)$ shown in Fig. 5 and the trapping process describe the volume discharge behavior sufficiently completely. Here if the behavior of $n_e(x, t)$ near the cathode is determined mainly by the change in $\psi(x, t)$, i.e.,

$$n_e(x, t) \simeq \psi(x, t)/\eta,$$

then at the anode the external ionizer acts only during the time $\tau \lessdot 200$ nsec. The electron concentration in this domain later diminishes according to the law

$$\partial n_e/\partial t \simeq -\eta n_e,$$

where the quantity $\eta$ grows as the parameter $E/p$ increases.

Under conditions when the initial beam energy $U_B(0, t)$ does not assure homogeneous ionization of the gas in the discharge gap, i.e., $d \gtrdot R_E/2$, the growth of the electric field near the anode apparently results in an increase in the rate of electron destruction because of trapping. Because of this effect the possible increase in the ionization losses in the domain $x > R_E/2$ because of the intrinsic discharge field is weakened substantially.

Therefore, the investigations performed showed that for a mean discharge electric field intensity of $E/p \simeq 10$ V/cm · mm Hg uniform ionization of a gas by an electron beam in air is accomplished within the spacing $x \lesssim R_E/2$, i.e., at half the length of the extrapolated fast electron transit. A diminution in the voltage at the accelerator diode (see Fig. 2b) because of the discharge of the capacitive storage will specify a reduction in the mean energy, and therefore, in the length of the fast electron transit also. Hence, the dimension of the volume discharge domain in which the conductivity is controlled by the external ionizer will become less than the spacing between the electrodes, which governs the inhomogeneity of energy absorption in the gas. Taking account of the substantial influence of the trapping, it should be noted that to produce a uniform volume discharge it is necessary to select the voltage at the accelerator diode so that the transit of the high-energy electrons in the working gas $R_E$ would exceed the discharge dimension during the whole progress of the current pulse. Let us note the prospects of using electric lines as energy storage for the electron accelerator for these purposes.

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# CONDITIONS FOR THE MAINTENANCE OF THE CURRENT IN THE CATHODE LAYER OF A SEMI-SELF-MAINTAINING VOLUMETRIC DISCHARGE EXCITED BY AN ELECTRON BEAM

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The distribution of an electric field in a gas gap with the flow of a semi-self-maintaining discharge through the gap is characterized by the presence of preelectrode regions with an increased intensity of the field and the column of the discharge, where the field is approximately homogeneous [1]. With a small rate of generation of electron–ion pairs $\psi$ and small applied voltages $U_0$, there are strong screening conditions. Under these conditions shock ionization, as a rule, is insignificant [1]. With high values of $\psi$ and $U_0$, the electrical field in the cathode region rises so much that the principal mechanism of the generation of charged particles can become shock ionization. Then, the processes in the cathode layer of a discharge excited by a beam and of a glow discharge are similar in many respects. Therefore, the use of methods of calculation developed for the investigation of a glow discharge has made it possible (see, e.g., [2-4]) to obtain certain evaluations for the case of large currents.

In the present work, on the basis of a numerical solution of the balance of charged particles and the Poisson equation, an investigation is made of intermediate conditions of the passage of a current in the cathode layer. The transformations of the cathode layer after the beam has been switched off are also discussed.

The system of equations for determining the parameters of the precathode layer has the form

$$(1)\ -dj_+/dx = dj_-/dx = e\psi + \alpha j_- - \beta j_-(j - j_-)/v_+v_-, \tag{1}$$

$$dE/dx = [(1 + v_+/v_-)j_- - j]/\varepsilon v_+, \quad j_-(0) = \gamma j/(1+\gamma), \quad j_-(d) = j, \int_0^d E(x)\,dx = U_0,$$

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