Central European Science Journals
www.cesj.com

Central European Journal of Physics
Central European Science Journals
CEJP 4 (2003) 708–756

High Power Self-Controled Volume Discharge Based Molecular Lasers

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Received 17 March 2003; accepted 29 August 2003

Abstract: An investigation was made of the characteristics of the formation of a self-controled volume discharge for the pumping of CO_2 lasers, i.e. self-sustained volume discharge (SSVD), which involved a preliminary filling of a discharge gap by an electron flux from an auxiliary-discharge plasma. We have found that this method was suitable for large interelectrode gaps, that distortion of the electric field in the gap by the space charge of the electron flux played an important role in the formation of the discharge and that the electrodes could be profiled dynamically during propagation of an electron flux through the discharge gap and a SSVD could form in systems with a strongly inhomogeneous field. High power SSVD based CO2 laser systems have been created and investigated.
Another type of self-controled volume discharge without pre-ionization, i.e. a self-initiated volume discharge (SIVD), in nonchain HF lasers with SF_6-C_2H_6 mixtures was investigated as well in our review. We have established that, after the primary local electrical breakdown of the discharge gap, the SIVD spreads along the gap in directions perpendicular to that of the electric field by means of the successive formation of overlapping diffuse channels under a discharge voltage close to its quasi-steady state value. It is shown that, as new channels appear, the current flowing through the channels formed earlier decreases. The volume occupied by the SIVD increases with increase in the energy deposited in the plasma and, when the discharge volume is confined by a dielectric surface, the discharge voltage increases simultaneously with increase in the current. The possible mechanisms which explain the observed phenomena, namely the dissociation of SF_6 molecules and electron attachment SF_6 molecules, are examined. A simple analytical model, which makes it possible to describe these mechanisms at a qualitative level, was developed. High power SIVD based HF(DF) lasers have been developed and tested.

Keywords: Lasers, plasma, discharge
PACS: 42.55.Ks, 52.80.Mg

Part 1

1 Introduction

A SSVD can be established in a gas by creating primary electrons the density of which should exceed a certain minimum value n_{min} throughout the discharge gap [1, 3]. Various methods for preionization of a gas in the discharge gap have been developed for this purpose [4, 7]. Primary electrons are created by these methods directly in the discharge gap, which sometimes causes difficulties in the establishment of conditions necessary for the formation of a SSVD. For example, high voltages are needed for the formation of an initial plasma when the preionization source and the active medium are combined in the same volume [8], whereas preionization with ultraviolet radiation may be ineffective because of strong absorption of such radiation in a medium [9], and if soft x rays are used, it is necessary to ensure rigid synchronization of the x-ray and pump sources [10].

In mixtures of gases typical of CO_2 lasers, losses of electrons due to trapping are relatively small at low values of E/p, where E is the electric field intensity and p is the gas pressure. The trapping coefficient is considerably less than the absorption coefficient of ultraviolet radiation for the same mixtures [10]. It follows that, in principle, it should be possible to create primary electrons in a density needed for the formation of a self-sustained volume discharge at a considerable distance from an ionization source and then transport the electrons to the gap by drift in an electric field. A method of formation of a self-sustained volume discharge by filling the discharge gap with a flux of electrons drifting in an electric field, without preliminary ionization of the whole discharge volume, was proposed and implemented in Ref. [12]. The source of electrons was a plasma formed in an auxiliary discharge initiated under a grid cathode. This method made it possible also to establish a SSVD in a system of electrons with a strongly inhomogeneous electric field in the discharge gap. The present paper as well as Ref. [13] is a review of our earlier investigations.

2 Experimental setup

The formation of an electron flux and its characteristics were studied using a setup shown schematically in Fig. la. The source of electrons was an auxiliary discharge 1 initiated under a grid cathode 2. An electron flux was formed by the application of an electric field to the auxiliary-discharge plasma. Under the action of this field some of the electrons were driven to the discharge gap, where the electron flux was maintained by a bias voltage U_0 applied to an anode 4.

The electron flux current in the discharge gap was deduced from the voltage drop across a resistor R. The charge carried by the flux was found from the change in the voltage across a capacitor C for $R = 0$. The contribution to the gap conductance made by the photoionization of the gas in the gap by the auxiliary-discharge radiation was estimated from the charge of the positive ions formed in the gap (these measurements were carried out by applying a negative bias voltage U_0).

The following types of an auxiliary discharge were investigated.

(1) A barrier discharge [14] in which a wire insulated with polyethylene was used as the electrode.

(2) A corona discharge initiated by a multipin electrode, stabilized by limiting the current through the pins by a ballast resistor [15].

(3) A volume discharge between a grid (discharge gap cathode) and a metal cathode, initiated as described in Ref. [16].

(4) A volume discharge between a semiconductor cathode (carbon-filled rubber with a bulk resistivity [17] and a grid (discharge gap cathode) initiated without preionization [18].

(5) A multichannel discharge on the surface of a high-permittivity insulator limited by the insulator capacitance [19]

(6) A multichannel discharge on the surface of a semiconductor (carbon-filledrubbe [17]) limited by the semiconductor resistance (this auxiliary discharge was realized in the same way as a multichannel discharge on the surface of a ceramic described in Ref. [19]).

In all these auxiliary discharges, an electric field was applied to auxiliary discharge plasma. A special auxiliary electrode was not essential. The auxiliary electrode is the one used to apply the voltage pulse to ignite the auxiliary discharge.

The characteristics of the formation of a SSVD by filling the discharge gap with an electron flux were investigated using a system of electrodes with an initially homogeneous distribution of the electric field (the anode had the Chang profile [20] and the cathode was a planar grid) with a discharge gap $d = 6 - 10$ cm. In these experiments we used the configuration shown in Fig. la with values U_0 lower than the static breakdown voltage of the discharge gap, as well as a configuration with pulsed application of a voltage higher that U_{st} to the discharge gap. In the latter case the filling of the discharge gap with electrons from the auxiliary-discharge plasma occurred either by the application of a preliminary bias to the gap, by Analogy with Ref. [21], or by a deliberate increase of the duration of the leading edge of the voltage pulse applied to the discharge gap [21, 22]. The value was selected so that electrons could reach the anode before the onset of ionization processes in the discharge gap.

Investigations of the conditions for formation of a SSVD in the presence of a strong inhomogeneous initial electric field in the discharge gap were carried out using apparatus shown schematically in Fig. Ib. The electrode system ($d = 10$ cm) was formed by a planar anode 1 (representing a rectangular plate of 18 × 50 cm dimensions rounded along the perimeter to a radius of 10 mm) and a cathode 2 with sharp edges (brass grid of rectangular shape and 10 × 40 cm dimensions). The area occupied by the auxiliary discharge 3 under the grid was slightly greater than the cathode area.

The working voltages were reduced [23, 24] and the duration of SSVD was increased [25, 26] by adding easily ionizable substances (tripropylamine and triethylamine at vapor pressures of ~ 1 Torr) to the investigated mixtures.

We determined experimentally the lowest voltage needed to ignite a SSVD (this was deduced from the voltage of the pump source) and the stability limit of such a discharge considered as a function of the composition of a CO_2-N_2-He gas mixture and the input energy. The homogeneity of the SSVD was checked visually by photographs of a section of a discharge and also on the basis of the small-signal gain and its distribution over the aperture of an amplifier.

3 Model of an electron flux propagation

The process of propagation of an electron flux in the discharge gap (one-dimensional case) in the absence of ionization and multiplication is described by the following system of equations and boundary conditions for the electric field $E(x,t)_0$ electron density $n(x,t)$, and concentration of negative ions $N_t(x,t)$ (Ref. [27]):

$$\frac{\partial n}{\partial t} + \frac{\partial (n\mu E)}{\partial x} = -\alpha n\mu |E|, \tag{1}$$

$$\frac{\partial N_t}{\partial x} = \alpha n\mu |E|, \tag{2}$$

$$\frac{\partial E}{\partial x} = -\frac{(N_t + n)e}{\varepsilon_0}, \tag{3}$$

$$\int_0^d E dx = -U_0, \tag{4}$$

$$n(0,t) = const = n(0), \tag{5}$$

$$N_t(x,0) = 0, \tag{6}$$

$$n(x,0) = 0 \quad \text{for} \quad x > 0. \tag{7}$$

where a is the trapping coefficient, u is the mobility, e is the charge of electrons, and e_0 is the permittivity. The x axis is directed from the cathode to anode. The electron density at the cathode surface is assumed to be constant in time. The loss of electrons from the cathode to the region occupied by the bias field is compensated by the arrival of new electrons from the auxiliary-discharge plasma). The mobility of negative ions in Eqs. (1) - (7) is assumed to be negligible.

The system of equations (1 - 7) was solved on a computer employing an explicit difference scheme [27].

The dependences $n(x)$ and $E(x)$ calculated for different moments are plotted in Fig. 2a. We can see that in the absence of electron losses due to trapping distributions $n(x)$ and $E(x)$ are established in the discharge gap.

Space charge of the negative ions prevent the propagation of the electron flux and accumulates in the discharge gap. Calculations for different values of a and d indicate that the electron densities near the anode $n_\alpha(d)$ are related by (8)

$$n_\alpha(d) = r.(d)e^{-\alpha d}. \tag{8}$$

$$\delta = \frac{3\varepsilon_0 E_0}{4en(0)d} \ll 1 \tag{9}$$

is of the form [28]

$$E(x) = \frac{3}{2}E_0\sqrt{\frac{x}{d} + \delta^2}, \tag{10}$$

$$n(x) = \frac{3\varepsilon_0 E_0}{4ed}\sqrt{\frac{d}{x + \delta^2 d}}, \tag{11}$$

$$j = \frac{9}{8}\mu\varepsilon_0\frac{E_0^2}{d}(1 - 3\delta^2), \tag{12}$$

$$\int_0^d Edx = -\frac{U}{2}(1 - \cos\frac{\pi t}{r_t}). \tag{13}$$

In atmospheric pressure, CO_2-N_2-He mixtures usually employed in CO_2 lasers, the losses of electrons due to trapping have no significant influence on the propagation of an electron flux and the ultimate potential of the proposed discharge can be analyzed in a steady-state electron flux model.

We shall now obtain some estimates. We shall assume that $E_0 = 1$ kV/cm and $d = 50$ cm; then, Eq. (11) shows that $n(d)$ is clearly greater than n_{min} required for the formation of a self-sustained volume discharge [2]. The condition (9) is then satisfied already for $n(0) =: 10^8 - 10^9$cm [3]. We shall show that such low electron densities at the cathode can be provided by practically any type of auxiliary discharge.

These estimates therefore confirm that a primary electron density necessary for the formation of a SSVD can be established at sufficiently large distances from the cathode by filling the discharge gap with an electron flux. We shall now point out some features of this method which follow from the above simple model.

It is clear from the expression (11) that at some distance from the cathode for $E_0 = 1$ kV/cm, $d = 40$ cm, and $n(0) = 10^9$cm [3] when the condition (9) is obeyed, the value of $n(x)$ is no longer dependent on $n(0)$. Therefore, the discharge gap will be filled uniformly with electrons (in a plane perpendicular to x) even in the case of a strong inhomogeneity of the distribution $n(0)$ over the cathode area, which makes it possible to form a SSVD avoiding small-scale inhomogeneities (typical of ultraviolet preionization and due to the shadow formed in the discharge volume by the grid cathode) [29] and to increase the small-signal gain as well as the efficiency of CO_2 lasers.

It is clear from Eq. (10) that, in spite of the relatively low density of the primary electrons in the discharge region, the presence of an uncompensated negative charge of the electron flux distorts considerably the electric field in the discharge gap. Consequently, the ionization processes begin first at the anode where the electric field may be 1.5 times higher than E_0. The ionization at the cathode is hindered because the field here is close to zero as a result of the screening of the cathode by the space charge of the electron flux. Clearly, this screening of the cathode as a result of filling of the discharge gap with electrons should be manifested also in the real geometry of the discharge gap. Consequently, it would be desirable to find the conditions for the formation of a SSVD in systems with unprofiled electrodes, because this would simplify greatly the construction of electric-discharge lasers.

The distortion of the electric field in the discharge gap by the space charge of the electron flux should reduce the voltage at which a SSVD can be established and this is a clear advantage of the proposed method. However, when a preliminary bias U_0 is used to fill the discharge gap with electrons and this is followed by the application of a voltage pulse of amplitude U to the discharge gap, the degree of enhancement of the electric field at the anode (compared with U/d), may be small, because it is not always permissible to increase U_0. The degree of distortion of the field can be increased by deliberate delay of the leading edge of the voltage pulse [22]. Figure 2b gives the results of a numerical solution of the system of equations (1) - (3) and (5) - (7) for $n(x)$ and $E(x)$, obtained for the case when $a = 0$ subject to the boundary condition which corresponds to the rate of rise of the voltage in a discharge gap selected for this case. A complete filling of the discharge gap with electrons requires also that some condition to be satisfied. It is clear from Fig. 2b that in the case of a static bias across the discharge gap, the value of $E(d)$ is enhanced (factor of 1.5) and the value of $E(0)$ is reduced several-fold.

4 Discussion

Figures 3a and 3b show oscillograms of the electron charge $q(t)$ extracted from the discharge gap and of the voltage $U(t)$ between the gap cathode and the auxiliary-discharge electrode, recorded for a mixture of N_2 with tri-propylamine obtained for the case when $d = 2$ cm and the electrode area was $S = 200cm^2$. The auxiliary discharge was a multichannel discharge on the surface of a ceramic (with the permittivity -2000), limited by the capacitance of the ceramic itself [19]. The shape of $U(t)$ was set by the parameters of a special RC circuit. A comparison of the $q(t)$ oscillograms recorded for different polarities of the voltage $U(t)$ indicated that the main rise of $q(t)$ occurred in the region where $dU/dt < 0$. When a negative bias voltage was applied to the discharge gap, the form of the $q(t)$ oscillograms was independent of the sign of dU/dt. In accounting for these results one should bear in mind that the sign of the electric field in the gap between the ceramic surface and the discharge gap cathode was the same as the sign of dU/dt. Therefore, for $dU/dt < 0$ some of the electrons were expelled from the auxiliary-discharge plasma into the discharge gap across the grid cathode and drifted toward the anode in the bias field ($U_0 > 0$). For $dU/dt > 0$ or $U_0 < 0$ it was not possible to drive electrons beyond the grid and the flow of the current in the discharge gap was then entirely due to the photoionization of the gas by the auxiliary-discharge radiation.

Figure 3c shows the oscillograms of the voltage $U(t)$ and of the electron current in the discharge gap $I(t)$ for an oscillatory form of the voltage $U(t)$. It is clear from these oscillograms that a considerable current in the discharge gap was recorded only for $dU/dt < 0$, irrespective of the sign of $U(t)$.

It should be stressed that we investigated long-duration auxiliary discharges in order to identify the conditions for the formation of an electron flux from the auxiliary-discharge plasma itself. Under these conditions, in spite of the presence of an easily ionizable substance in the gas, the contribution to the discharge gap conductance of the electrons arriving from the auxiliary-discharge plasma was (for suitable signs of dU/dt and U_0) approximately ten times higher than the contribution made by the photoionization of the gas by the auxiliary-discharge radiation even when the latter was of the surface type. Under these conditions the contribution of the photoionization to the charge of the electrons crossing the gap did not exceed 10% of the contribution of the electron flux for a corona discharge and it was not greater than 1% in the case of barrier volume discharges (these values were obtained for $d = 6$ cm, $U_0 = 30$ kV, mixture of N_2 with tripropylamine, $P = 1$ atm) and the presence of an easily ionizable substance in the gas had practically no influence .

When the auxiliary discharge pulse was shortened (by reducing the inductance or the active resistance in the circuit of this discharge), the contribution of the photoionization to the discharge-gap conductance increased and, in principle, it was possible to form an electron flux from a plasma created by the ultraviolet radiation of the auxiliary discharge in the cathode region (and also from a plasma on the surface of a plasma cathode [30] or a barrier discharge plasma in systems described in Ref. [16]) As already pointed out, the homogeneity of a SSVD could be improved by selecting the auxiliary discharge characteristics in such a way as to satisfy the condition (9). Naturally, one would then have to ensure a certain minimum density of the electron current in the auxiliary gap.

Figure 4a shows oscillograms of the electron flux current and of the auxiliary discharge current (this was a volume type of discharge) obtained for a mixture of gases of the CO_2:N_2 = 1:3 composition at a pressure of $p = 0.3$ atm when the gap was $d =$cm and the applied bias voltage was $U_0 = 12$ kV. The distance between the auxiliary discharge electrodes was 1 cm and the area of the auxiliary electrode was $S = 200 cm^2$. It is clear from Fig. 4a that change in the auxiliary discharge current by an order of magnitude altered $I(t)$ by just 10%, indicating that the condition (9) was satisfied.

Both volume and corona discharges could be stabilized by utilizing electrodes made of semiconductor materials [18]. Figure 4b shows oscillograms of the volume discharge current in a mixture of gases of the CO_2:N_2:He = 8:32:60 composition with an admixture of triethylamine at $p = 1$ atm, ignited without a preliminary ionization between a semiconductor material cathode (which was a disk 5 cm in diameter and 2 cm thick) and a grid (discharge gap cathode); it also includes an oscillogram of the charge $q(t)$ of the electrons extracted from the discharge gap in the case when $U_0 = 5$ kV, $d = 8$ cm, and the distance between the auxiliary discharge electrodes was 1 cm. The density of the auxiliary discharge current obtained in this way was ~ 50 mA/cm^2 and the duration of the stable burning of the discharge in gas mixtures of various compositions exceeded 30 mksec.

In the case of a discharge of the surface of an insulator, which was limited by the capacitance of the insulator itself, our measurements indicated that the electron current in the gap between the insulator surface and the grid was an order of magnitude less than via an auxiliary electrode.

When the necessary condition was satisfied, stable long-term burning of the discharge was achieved also for a multichannel auxiliary discharge on the surface of a semiconductor material, which was limited by the resistance of the material itself, when the charging capacitor was suitably selected.

It therefore follows that when special measures were taken, all the types of the auxiliary discharge discussed above were capable of forming an electron flux with the maximum parameters specified by Eq. (12).

Figure 5a shows the dependence of the electron flux current $I(U_0)$, recorded under the same conditions as the oscillograms in Fig. 4a. Clearly, at low values of U_0 this dependence is in agreement with Eq. (12). When U_0 exceed a certain minimum value, the current rise steeply and this was accompanied by volume radiation in the discharge gap, indicating the onset of the ionization processes and the formation of a SSVD. This minimum value of U_0 amounted to (2/3) U_{at}, as expected on the basis of Eq. (11), according to which the electric field at the anode was enhanced by the space charge of the electron flux by a factor of 1.5 compared with E_0. We could assume that the possibility of igniting a SSVD at a voltage lower than £7_{st}, mentioned in Refs. [31] and [21], was also due to distortion of the electric field by the space charge of the electron flux and in Ref. [21] this flux could be formed both from an auxiliary-discharge plasma under the cathode or from the photoplasma in the cathode region, because the discharge on the surface of a ceramic used in Ref. 21 was of relatively short duration (~ 1.5 mksec).

The influence of the distortion of the electric field on the conditions of formation of a SSVD is manifested also by the results in Fig. 5b, which gives the dependence of the minimum voltage for the ignition of such a discharge (7_{min} on U_0 in a circuit with a preliminary bias of the discharge gap. The sign of this bias was opposite to the sign of U_0 in order to avoid formation of an electron flux on application of a voltage pulse to the discharge gap. In this case the auxiliary discharge was of the barrier type. Experiments were carried out on a mixture of the CO_2:N_2:He = 1:1:3 composition and the other parameters were $d = 6$ cm and/? $= 0.5$ atm. A voltage pulse was applied to the discharge gap after the delay relative to the beginning of the auxiliary discharge. It is clear from Fig. 5b that U_{min} decreased monotonically on increase in U_0 in accordance with the above model.

At low overvoltages across the discharge gap the distortion of the electric field by the space charge of the electron flux had a considerable influence on the conditions of energy deposition in the plasma of the SSVD and on the residual voltage across the gap after the end of the discharge.

Figure 6a gives oscillograms of the voltage $U(t)$ and current in a SSVD formed when the density of the electron flux current was too low for a significant distortion of the field and the condition (9) was not obeyed ($d = 6$ cm, gas mixture of the CO_2:N_2:He = 1:1:3 composition,$p = 0.5$ atm, charging voltage $U_{ch} = 45$ kV). Figure 6b shows oscillograms of $U(t)$ and $I(t)$ recorded under the same conditions as in Fig. 6a, but in this case the condition (9) was satisfied. A comparison of Figs. 6a and 6b indicated that distortion of the electric field by the space charge of the electron flux resulted in some reduction in the amplitude of the voltage pulse across the discharge gap and also increased the amplitude of the current in the SSVD; it also increased the energy deposited in the discharge by a factor of about 2. This could be important under conditions when it would be difficult to establish a high overvoltage across the discharge gap.

All the forms of the auxiliary discharge investigated by us using a system of profiled electrodes made it possible to form a SSVD when the energy deposited was up to 300 J/liter. The content of CO_2 in CO_2-N_2-He gas mixtures (with the addition of easily ionizable substances) at atmospheric pressure reached 40% when the total content of all the molecular gases was up to 70%, whereas in helium-free mixtures it was up to 30%. We also established a SSVD in atmospheric air ($p = 0.4$ atm, $d = 10$ cm) by the addition of triethylamine, which was evidence of the high efficiency of the method of formation of a SSVD by filling the discharge gap with an electron flux, and this was true also of gases characterized by strong electron trapping.

The best characteristics of a SSVD in a system of nonprofiled electrodes (Fig. la) did not differ from the characteristics of the corresponding discharge observed when the initial distribution of the electric field in the discharge gap was homogeneous. The discharge formed using such electrodes could be ignited employing any of the listed types of the auxiliary discharge, with the exception of a volume discharge utilizing metal electrodes (this type of the auxiliary discharge was difficult to realize using nonprofiled electrodes because of the inhomogeneity of the electric field in the auxiliary gap). The investigated system was characterized by a strongly inhomogeneous initial distribution of the electric field in the discharge gap, which was close to the field distribution between one of the electrodes and a plane of symmetry in a parallel-plate capacitor of limited size (as shown in cross section in Fig. 1b); the field on the anode decreased monotonically along the normal to the symmetry axis of the discharge gap, whereas the field on the cathode increased reaching its maximum at the edge. Consequently, the static breakdown voltage in the system with nonprofiled electrodes was approximately half the corresponding voltage in the quasisteady phase of a SSVD. When the discharge gap was subjected to a voltage pulse of amplitude $U > U_{si}$ (representing the regime with a deliberately delayed leading edge of the voltage pulse), a spark breakdown at the cathode edge was observed in the absence of an auxiliary discharge. When the auxiliary discharge was started and the static voltage was in the required range a spark did not appear during the period r_{ad} even when the formation of such a spark in the absence of an auxiliary discharge was less than r_t. A weak electron flux current was then observed in the discharge gap. When the amplitude of the voltage pulse exceeded required level and an auxiliary discharge was started simultaneously with the leading edge of the pulse a volume discharge appeared in the gap.

It therefore follows that the distortion of the initial distribution of the electric field by the space charge of the electron flux in the case of nonprofiled electrodes resulted, in contrast to the case of profiled electrodes, in an increase (rather than a reduction) of the pulsed breakdown voltage of the discharge gap and the breakdown was of volume nature. A strongly inhomogeneous initial distribution of the electric field in the presence of nonprofiled electrodes was corrected in the process of filling the discharge gap with electrons, i.e., a dynamic profiling of electrodes by the space charge of the electron flux took place. We shall now consider qualitatively this phenomenon.

Screening of the cathode by the negative charge of electrons reduced severalfold the electric field on the cathode surface, compared with the average field $U(t)/d$ in the discharge gap at a given moment, so that ionization processes could not develop near the sharp edges of the cathode. The field at the anode was then enhanced and the relative magnitude of the enhancement should be highest at the center of the electrode, since the electron flux spread in the course of propagation in a discharge gap as a result of the electrostatic repulsion between the electrons. Bearing in mind also the initial distribution of the field in the discharge gap, we concluded that the ionization processes began to develop simultaneously from the anode to the cathode and from the center to the edges of the discharge gap, i.e., the propagation of an ionization wave, which formed a cathode layer when it closed the discharge gap, was not governed by the initial configuration of the electric field but by that configuration which was formed with the participation of the space charge of the electron flux. This made it possible to prevent spark breakdown and to form in a system with nonprofiled electrodes a SSVD with a deposited energy distribution typical of such nonprofiled electrodes. Measurements of the small-signal gain at low pump energies, which represented the distribution of the energy deposited in the discharge in a plane perpendicular to the optic axis, demonstrated that the gain decreased away from the optic axis to the electrode edges. This provided an indirect confirmation of the above description of the formation of a SSVD. It should be stressed that a change in the voltage on the electrodes resulted in a redistribution of the electric field in the discharge gap at a finite rate governed by the electron mobility. Therefore, the condition for screening of the cathode by the space charge of the electron flux (where U/d is the instantaneous value of the field) could be disturbed if the voltage across the discharge gap rose too rapidly. In fact, it was not possible to create a SSVD using nonprofiled electrodes when the voltage was applied abruptly to the electrodes and this was true even when the application of a bias resulted in a preliminary filling of the discharge gap with electrons. Sparks were observed at the corners of the cathode, i.e., in the regions with the maximum concentration of the electric field in the absence of screening. The discharge was stable in the case when the leading edge of the voltage pulse was delayed deliberately [21, 22] so that the duration of this edge was ¿ 2 mksec. for $d = 10$ cm.

A classical example of nonprofiled electrodes with a strongly inhomogeneous initial distribution of the electric field in the discharge gap was the first transversely excited

CO_2 laser [16]. The present experiments indicated that the electron flux in such a system was formed by a barrier discharge plasma created directly on the cathode surface and this made it possible to satisfy quite readily the saturation (Eq. (9)) and screening conditions. One should stress also that an increase of the stability of a SSVD [22] in systems of the type described in Ref. [16] and considered in the present study, which was observed when easily ionizable substances were added to the gas mixtures, was not due to photoionization of these additives because in the case of regimes used to form a SSVD by filling the gap with an electron flux the contribution of the photoionization to the conductance of the discharge gap during the filling process was unimportant compared with the contribution of the electron flux from the auxiliary discharge plasma and this was true for the majority of the auxiliary discharges. Our investigations made it possible to increase the aperture of SSVD based lasers and amplifiers up to 80 cm and to obtain a radiation energy of CO2 lasers more then 5 Kj for the electric efficiency more then 10%.

Part 2.

5 Introduction

The main problem arising in the construction of powerful wide-aperture nonchain HF(DF) lasers in which a chemical reaction is initiated by a SSVD is the implementation of the SSVD itself in mixtures of SF_6 with hydrogen carriers (deuterium carriers). The possibility of applying for such purposes the usual methods based on the preliminary ionization of the gas in a homogeneous electric field with the subsequent application of a high-voltage pulse to the discharge gap [32] is limited by the high electro-negativity of the SF_6 molecules.

A new approach to the solution of the problem of increasing the volume of the active medium and the energy of the radiation emitted by nonchain HF(DF) lasers was found in our earlier studies [33, 34, 35]. In a study [34] of a nonchain HF(DF) laser with preionization by soft x-rays, it was observed that the SSVD characteristics and the laser output characteristics are independent of the presence of preionization if the cathode surface has been subjected to a treatment involving the deposition on it of small-scale inhomogeneities. In other words, if the cathode has a rough surface, preionization is not essential in order to obtain an SSVD in the mixtures of an HF(DF) laser.

The possibility of achieving an SSVD without preionization and with an energy input homogeneous throughout the volume under the conditions of a high edge inhomogeneity of the electric field in the discharge gap of an HF(DF) laser has also been demonstrated [35]. These investigations made it possible to increase the aperture of a nonchain HF(DF) laser based on SF_6 - hydrocarbon (deuterocarbon) mixtures up to 27 cm and to obtain a radiation energy of $\sim$ 400 J for an electric efficiency of approximately 4% [39].

An SSVD without preionisation in SF_6 and in mixtures containing it, i.e. a self-initiated volume discharge (SIVD) [36], has a number of properties unusual for volume discharges. The observation of a discharge of this kind opens up unique opportunities for the development of simple and effective nonchain HF(DF) lasers operating in both pulsed and repetitively pulsed regimes. Further investigations of the SIVD in order to establish the principal mechanisms determining its development is therefore of undoubted interest. To review the results of our investigations is in fact the subject of the present paper.

6 Experimental apparatus

The SIVD characteristics were investigated in discharge gaps with electrodes having different configurations (Fig. 7) with the ratio of the partial pressures of the mixture components SF_6:C_2H_6 = 10:1-10:3 and $pd = 0.02 - 0.7$ cm bar (p is the pressure of the mixture and d the interelectrode distance). The integral characteristics of the discharge and the dynamics of its development were studied by using a system of plane electrodes illustrated schematically in Fig. 7a. The SIVD was struck with $d = 2 - 6$ cm between an aluminium cathode 6 cm in diameter, rounded (1 cm radius) along the perimeter, and an aluminium anode 12 cm in diameter. The surface of the cathode, including the rounded parts, was sandblasted.

In order to investigate the SIVD dynamics, an artificial (transmission) line with a variable number of cells was discharged across this gap [37]. This made it possible to follow, by varying the duration of exposure to the voltage across the gap in the range 40-400 ns at a constant current, the development of the discharge in time and in space by photographing it for various exposures to the voltage. In the remaining SIVD studies in which the above and other electrode systems shown in Fig. 7 were used, the discharge o a capacitor was used to strike the volume discharge. The discharge gaps (Figs 7a and 7b) were additionally illuminated from the side by a low-current ($I < 3$ A) spark enclosed in a quartz envelope. This spark could not ensure the volume photoionisation of the gas, but, as a result of the initiation of electrons at the cathode, it made it possible to stabilise the scatter of the gap-breakdown delay times. The discharge gaps in the configurations shown in Figs 7c-7f were not additionally illuminated.

The dynamics of the development of the SIVD was also investigated in an electrode system with a sectioned cathode (Fig. 7b). Here, the main cathode and anode were the same as in Fig. 7a, but an earthed conductor 1.5 mm in diameter (the initiating electrode) was connected in parallel to the main cathode at a distance 5 mm in a horizontal plane extending from its edge. The vertical distance between the cathode surface and the tip of the conductor was chosen in such a way that, during the initiation of the discharge by a low-current spark, the electrical breakdown of the gap extended initially to the conductor.

A conductor with polyethylene insulation and a core diameter of 1.5 mm served as the cathode in the electrode system in Figs 7c and 7d (the discharge occurred between the rod and the plane). In these experiments, the SIVD was investigated under conditions such that not more than one cathode spot could be formed on the cathode. In the discharge gap shown in Fig. 7d, the discharge cross section on the anode was confined by a glass tube 6-8 mm in diameter (confined discharge), placed between the electrodes in such a way that its upper edge touched the surface of the anode.

In the configuration presented in Fig. 7e, the plane electrodes (the same as in Fig. 7a) were linked by a dielectric plate 2 mm thick with a transverse dimension of 5 cm. In the electrode system shown in Fig. 7f, the SIVD was struck for an interelectrode distance (the distance between two aluminium disks 3.6 cm in diameter) of 5.5 cm; the disks were placed in a quartz tube with an internal diameter of 3.8 cm, the electrodes had sharp edges, and the cathode surface was sandblasted.

The SIVD dynamics was studied in discharge gaps with different geometry. The scheme of the setup for investigating the discharge in a gap with a linear cathode geometry is shown in Fig. 7a. The SIVD with a total duration of $\sim$ 370 ns was ignited in the SF6: C2H6 = 10:1 mixture at a pressure $p = 33$ Torr and an interelectrode distance of 4 cm. The electrodes were a 0.5-mm thick copper bar 16 cm in length (a knife-edge cathode) placed edgewise and a disk anode 6 cm in diameter rounded over the perimeter with a radius of curvature of 1 cm. The breakdown was forcedly initiated at the center of the cathode with a weak-current spark limited with an $R = 900$ Q resistor. This spark could not provide an initial electron density in the gas high enough for the development of a volume discharge, but allowed fixing the position of the primary gap breakdown. The SIVD glow was recorded with a single-frame streak camera tube with a frame exposure time of 20 ns, which was triggered with a variable delay T relative to the instant of gap breakdown.

To study the SIVD dynamics in the plane gap geometry, we used the circuit with a sectioned cathode shown in Fig. 7b. In this case, the interelectrode distance, the working mixture pressure, and the electrical circuit of the setup were the same as in the previous experiment, except that the cathode was not a copper bar, but a disk 6 cm in diameter rounded over the perimeter with a radius of curvature of 1 cm and subjected to sandblast processing [33, 34, 35, 36]. Insulated conductors 1 mm in diameter were inserted into holes 2 mm in diameter drilled 4 cm apart through the cathode in its plane region. One of the conductors (1) protruded above the cathode surface by 1 mm to ensure the occurrence of the primary gap breakdown at precisely this point. By comparing the oscilloscope traces through the ignitor (7) and monitoring (2) electrodes, we could trace the SIVD spread over the gap.

The dynamics of an individual diffusion channel was investigated using the setup shown in Fig. 7c. The diffusion channel was simulated by a discharge with a rod (cathode) - plane gap geometry at a pressure $p = 16.5 - 49.5$ Torr of the SF6: C2H6 = 10:1 mixture for an interelectrode distance of 4 cm. The cathode was the end of a polyethylene-insulated wire with a core diameter of 1.5 mm, and the anode was a disk 10 cm in diameter. The SIVD development was monitored with the streak cameras, as in the experiments performed using the setup of Fig. 7a.

In the circuits shown in Figs 7a and 7b, the capacitor C discharged into the gap via inductance L upon switching spark gap. In the circuit of Fig. 7c, an artificial line discharged into the gap. The currents in the circuits of Fig. 7 were monitored with Rogowski coil R_c, the voltage across the gaps was measured with resistive dividers.

A typical photograph of an SIVD in a plane-electrode system is presented in Fig. 7a.

Fig. 7b shows the corresponding current (1) and voltage (U) oscillograms. It is seen from Fig. 8 that the SIVD does not outwardly differ from the usual SVD with preionisation. It consists of a set of diffuse channels, linked to bright cathode spots and expanding towards the anode. By overlapping, the diffuse channels generate an overall diffuse glow. Despite the appreciable strengthening of the electric field on the edge of the gap, this region is scarcely distinguishable and the cathode spots cover the entire surface of the cathode.

The SIVD voltage and current oscillograms are also typical for SSVD in electronegative gases. Energy is deposited in the SIVD plasma at a quasi-steady-state voltage The voltage in mixtures of SF_6 with hydrocarbons, when the content of the latter is not greater than 17%, depends only slightly on their partial pressure. The dependence of $f/_{qs}$ on pd for $pd = 0.05 - 2.5$ cm bar and specific energy inputs in the discharge plasma up to 0.2 J cm-^{3} is described satisfactorily by the expression [38] where p_{SF6} is the partial pressure of SF_6 in the mixture. For pure SF_6 and SF_6: C_2H_6 = 10:1, 10:2 mixtures, we have respectively $A = 0.72$, 0.79, and 1.1 kV and $B = 92.7$, 94.8, and 96.4 kV cm bar. The value of B obtained in the present experiments is close to the known [38] critical reduced electric field strength $(E/p) = 89$ kV cm bar (the difference is 8%).

The differences between SIVD and SSVD are manifested in the dynamics of their development. Fig. 9 presents the results of studies on the dynamics of the development of an SIVD in a plane-electrode system (Fig. 7a) for the discharge across the gap of an artificial line with a variable number of cells. As can be seen from Fig. 9, in contrast to SSVD, an SIVD is struck initially in the zone of the maximum amplification of the electric field on the gap edge in the form of one or several diffuse channels linked to the cathode spots. The radiation from the discharge in the remainder of the gap is not detected at this instant. The channels formed first initiate the appearance of the subsequent channels and the SIVD spreads over the gap perpendicular to the direction of the electric field at a constant voltage, gradually filling the entire gap. The total number of spots on the cathode increases from the instant of the electrical breakdown of the gap virtually in proportion to time, i.e. in proportion to the energy injected into the discharge when account is taken of the experimental conditions.

Since the SIVD develops at a constant current (with the exception of the leading and rear edges) under the experimental conditions described, the current flowing through channels formed earlier should diminish after the appearance of new ones. The characteristic features of the development of an SIVD listed above suggest the operation of current-limiting mechanisms in SF_6 and in mixtures based on it, which hinders the transfer of the entire energy through a single channel. It appears that precisely these mechanisms are in fact responsible to a large extent for the existence of the unusual form of the discharge such as the SIVD, including the possibility of achieving it in gaps with a strong edge inhomogeneity of the field.

The existence of such mechanisms is also indicated by the results of experiments in an electrode system with simulation of the first diffuse channel by the initiating electrode (Fig. 7b). Fig. 10a, which presents characteristic oscillograms of the discharge current through the initiating (curve 1) and main (curve 2) cathodes, shows that the current through the initiating cathode does indeed appear appreciably earlier than the current through the main cathode and its maximum is attained at an instant when the main current still continues to grow.

Fig. 10b illustrates the dependence of the fraction of the energy A, transmitted by the initiating cathode, relative to the total energy W injected into the discharge. The quantity A decreases monotonically with increase in W, reaching saturation, which yet again constitutes evidence in favour of the existence of mechanisms preventing the transfer of the entire SIVD energy through one channel.

However, we may note that that in the experiment under consideration, the simulation of the initial diffuse channel with the aid of a special electrode is not entirely equivalent to the real conditions, because, in order to guarantee that the discharge begins from the initiating cathode, it would be necessary to raise it by approximately 1 mm above the surface of the main cathode. For this reason, the brightness and transverse dimensions of the simulated initial diffuse channel differed appreciably from those of channels in the main gap, whereas under real conditions this was not observed (Fig. 8).

Fig. 11 presents a typical dependence of the total number of spots on the cathode N_S on the average specific energy W_{sp} injected into the plasma. It was recorded in a system of plane electrodes for different values of d and p. W_{sp} was varied during the experiments by varying the charging voltage and charging capacitance. The duration of the discharge current was also varied. Evidently, for a fixed value of p, N_S depends only slightly on d. Within the limits of error, the points fit satisfactorily on a linear dependence of N_S on W_{sp}.

Consequently, for a fixed value of p, the number of spots on the cathode is determined by W_{sp} and not the density and duration of the current, W_{sp} actually specifying the total number of spots on the cathode. For a short duration (less than 100 - 150 ns) of the current, the spots may not cover the entire surface of the cathode but only its section near the site of the primary electrical breakdown of the gap. In short discharges, the local density of spots may therefore be greater than in long discharges.

The dependence of N_S on p may be more complex: N_S increases with increase in p and the increase is nonlinear. A diminution of the transverse dimensions of the spots on the cathode and of the diffuse channels on the anode is also observed under these conditions, i.e. the volume occupied by each channel decreases simultaneously with increase in N_S. One may postulate that such influence of the growth of p on N_S is associated with the increase in the electric field strength (defined as $E_{qs} = U_{qs}/d$) for which an SIVD develops and which is known [1] to determine the probability of the formation of a cathode spot. The dependence of N_S on the parameter $W_{sp}Eqs$ plotted for different values of p and d taking into account this hypothesis, is presented in Fig. 12. It is satisfactorily fitted by the linear function $\mathrm{N}_S = a + bW_{sp}E_{qs}$, in which the constant b is in its turn a function of the state of the cathode surface and of the hydrocarbon content in the mixture [39].

A conclusion important for the further interpretation of the mechanisms of the development of an SIVD follows from Figs 11 and 12: the volume occupied by the discharge increases with increase in the amount of energy injected into the plasma and almost in proportion to the energy.

Figs 13a and 13b present photographs of an SIVD in a rod-plane electrode system (Fig. 13c) for $d = 5$ cm and $p = 34$ Torr in the SF_6: C_2H_6 = 10:1 mixture recorded for two energies W deposited in the discharge plasma. In this geometry, the SIVD consists of a diffuse plume, expanding towards the anode, with formation of a bright plasma on the cathode. Under conditions such that new spots cannot be formed on the cathode, the volume V of the glowing part of the plume (an analogue of a diffuse channel) increases with increase in W.

The dependence of V on W obtained under the same conditions as in Fig. 13 is presented in Fig. 14. A linear growth of V with increase in W can be seen. For $W = 5$ J, the volume V is ~ 20 cm^3, whereas the size of the plume on the anode is 3.6 cm. The high stability of the discharge in the gap geometry under consideration, despite the fact that the current density of the cathode is $j = 1.2 \times 10^5$ A cm-^{2}, is striking. It is noteworthy that the influence of the duration of the discharge current on V is also appreciable in this geometry. This accounts for the considerable scatter of the points in Fig. 14 because in the experiments the duration of the current varied from 50 to 300 ns.

Figs 15a and 15b present voltage (U) and current (I) oscillograms for an SIVD in the rod-plane electrode system (Fig. 7c) for current pulses of 100 and 200 ns duration with identical charging voltage and charging capacitance in the SF_6: C_2H_6 = 10:3 mixture ($p = 40$ Torr, $d = 4.4$ cm). Figs 15c and 15d show similar voltage and current oscillograms for an SIVD recorded under the same conditions but with confinement of the discharge on the anode by a tube 7 mm in diameter (Fig. 7d). As can be seen from Figs 15a and 15b, the voltage and current oscillograms in the rod - plane system do not differ in any way from typical oscillograms obtained in a plane electrode system.

Confinement of the discharge leads to an appreciable change in the type of oscillograms. For a long duration of the current pulse (Fig. 15d), after the initial fall of the voltage, one observes its increase simultaneously with increase in the current, the current maximum being attained sooner than in the case of an 'unconfined' discharge. The current amplitude also diminishes, whereas the voltage is appreciably higher at its maximum than in the case of an 'unconfined' discharge. Voltage oscillograms of a similar type are obtained when the discharge characteristics are calculated taking into account the attachment of electrons to vibrationally excited SF_6 molecules [40]. However, the calculated oscillograms in Ref. [40] do not agree with the experimental ones. We are not aware of other studies in which a similar form of the discharge voltage was observed in SF_6 and in mixtures based on it.

For $T = 200$ ns, the confined SIVD contracts after the current has reached a maximum. A decrease in the duration of the current makes it possible to obtain an uncontracted confined SIVD (Fig. 15c). In this case, there is no break in the voltage oscillogram and, following a general increase in the discharge voltage, the 'tail' becomes less tilted. We may note that the modification of the voltage pulse observed in Figs 15c and 15d following the confinement of the SIVD is associated precisely with the increase in the specific energy input in the plasma because under the conditions of the given experiment the discharge cannot expand during the energy deposition process.

Fig. 16 presents dependences of U_{qs} on the energy $W1/2$ deposited in the discharge plasma before the attainment of the current maximum, in the rod-plane electrode system for confined (curve 1) and unconfined (curve 2) SIVD; was determined at the current maximum. Evidently, with increase in W an appreciable growth is observed in the confined SIVD, significantly more notable than in the unconfined SIVD. The relative increase (compared with for the unconfined SIVD) for the same values of W is greater the smaller the value of p, i.e. the greater the energy deposited in the plasma per unit volume and per molecule.

The results presented in Figs 15 and 16 indicate an increase in the electron attachment coefficient in SF_6-based mixtures with increase in the specific energy input in the discharge plasma.

The possibility of obtaining a volume discharge in the electrode systems illustrated in Figs 7e and 7f is a consequence of the existence of mechanisms restricting the SIVD energy transmitted by an individual diffuse channel and leading to an increase in the volume occupied by the discharge with increase in the input energy. Fig. 17 presents photographs of a discharge in air and in the SF_6 :C_2H_6 = 10:1 mixture, respectively, at a pressure of 65 Torr obtained in the system comprising plane electrodes linked by a dielectric plate (Fig. 7e). As was to be expected, the discharge in air develops in the form of the electrical spark breakdown of the gap along the surface of the dielectric plate, the bulk phase being entirely absent. In a SF_6 - C_2H_6 mixture, the discharge is very much of the volume type, its external appearance and oscillograms being completely indistinguishable from an SIVD obtained in the same system in the absence of a plate (with the exception that the photograph shows a black band at the site where the plate is located).

In the system with transverse dimensions of the electrodes close to the internal diameter of the tube (Fig. 7f), the discharge is also very much of the volume type for the mixture SF_6: C_2H_6 = 10:1 and $p = 15 - 65$ Torr. When $W_{sp} > 0.05$ J cm^{-3}, the surface density of the cathode spots has a maximum in the central zone of the cathode, as in the usual gap with plane electrodes which are not linked by a dielectric surface.

In the subsequent ignitions of an SIVD without change of mixture, an appreciable increase and a decrease in the current are observed in the above electrode system. Since in the case under consideration the SIVD occupies the entire volume of the discharge chamber (Fig. 7f), this fact indicates that, in the mixture of gases formed as a result of the dissociation of the starting materials, the effective ionization coefficient is smaller than in the initial mixture. We may note that a volume discharge in a tube with an internal diameter close to the diameter of the electrodes had been obtained earlier in a SF_6 - H_2 mixture [41], but the authors [41] did not interpret this result.

7 Discussion

Thus, the following processes are characteristic of SIVD: consecutive formation of diffuse channels (with a simultaneous decrease in the current through the channels which had arisen earlier) during the development of the SIVD in a gap with planar geometry, the expansion of the diffuse-glow zone in the rod - plane gap, an increase in the discharge voltage with increase in the specific energy. As already mentioned, these processes are apparently determined to a large extent by the mechanisms of the confinement of the current in the conducting channel, which depend on the specific energy input. We shall consider two possible mechanisms leading to this state of affairs, namely the dissociation of SF_6 by electron impact and the attachment of electrons to vibrationally excited SF_6 molecules.

In the first place we note that, for the ratios E/N close to the critical value, virtually the entire energy deposited in SF_6 is consumed in dissociation [45]. According to Ref. [38, 42], the $SF_6 \twoheadrightarrow SF_4 + 2F$ channel is dominant.

The ionization potential of F atoms (17.42 eV) exceeds that for SF_6 (15.7 eV) [43], so that an appreciable contribution by the F atoms produced to the overall ionization should not be expected even at their considerable concentrations. As regards the attachment of electrons, the formation of F$\sim$ ions via any of the possible mechanisms is known to be incapable of competing, as shown by estimates [44], with the attachment of electrons to SF_6 molecules. The F excitation threshold is 12.7 eV [43] (the component of the main doublet with a threshold energy of ~ 0.05 eV may naturally be disregarded in the given instance), i.e. it is in the region of the intense excitation of the SF_6 terms by electron impact [45]. Furthermore, there are grounds for the postulate that inelastic processes with participation of SF_4 molecules also do not influence in any way significantly the energy spectrum of the electrons in the discharge.

Thus, bearing in mind the qualitative nature of the models considered and neglecting therefore the difference between the cross sections for the elastic scattering of electrons by SF_6 molecules and their decomposition products, one may postulate that the influence of the dissociation of SF_6 may only affect the decrease in the reduced field strength E/N with increase in the total concentration of neutral particles N as the specific energy input increases.

It is possible to show that allowance for additional factors will significantly complicate the description without altering fundamentally the result: the dissociation of SF_6 by electron impact and the attachment of electrons to vibrationally excited SF_6 molecules may indeed serve as the mechanisms of the limitation of the current in the conducting channel in the active media of an HF laser. At the same time, the mechanisms of current limitation in the conducting channel are not sufficient for complete understanding of the processes observed in the experiment, in particular the propagation of the discharge into the interior of the gap in the direction perpendicular to the applied field [18]. Fig. 19 shows the streak-camera images of a SIVD in the gap with a knife-edge cathode obtained at different instants of time. The corresponding oscilloscope traces of discharge current and voltage are given in Fig. 20. One can see from Fig. 19 that the gap is broken down at the center (at the region of the auxiliary spark discharge). At this instant of time, the SIVD has the form of one diffusion channel, with a cathode spot already formed. Then, new channels appear near the first channel, which have a significantly lower brightness, and are developing at a voltage close to the static breakdown voltage for SF6.

The number of new channels increases with time, they 'disperse' from the middle to the periphery of the gap, and their brightness gradually achieves that of the first channel, the channels closest to the first channel being the brightest. All the channels become equally bright with time, while the brightness of the first channel decreases significantly. Upon a further SIVD development, the brightness of the channels at the gap periphery (i.e., the channels removed from the primary breakdown region) gradually increases. However, for $T > 210$ ns the glow becomes uniform again over the cathode length, the glow in the first channel also being restored. This effect will be referred to as a current return (to the channel). Then, we observed the development of discharge instability against the background of the total diffusion glow.

Therefore, the results outlined above confirm directly the fact that the SIVD spreads over the gap at a voltage close to the static breakdown voltage in the form of a sequence of diffusion channels. In this case, the first channel, which was produced upon the gap breakdown, fades away as new channels emerge. Note also that the current return (see Fig. 19), which is manifested in the equalization of the brightness of all the channels and in the increase in the brightness of the first channel following its initial decrease, is observed only when the energy introduced into the plasma is high enough. This effect vanishes when the energy is lowered or the linear size of the cathode is increased. For high energy inputs (150-200 J/L) typical of HF (DF) lasers, the SIVD spreading over the gap is so fast that the time resolution of our streak camera is insufficient A similar pattern of SIVD development is also observed with the plane discharge gap geometry. Fig. 21 shows the oscilloscope traces from the igniter and monitoring conductors (see Fig. 18b) obtained in the experiment with the sectioned cathode. One can see from Fig. 21 that the current begins to flow through the monitoring conductor with a significant delay relative to the current through the ignitor.

By the time of onset of the current through the monitoring conductor, the amplitude of the current through the ignitor lowers by more than a factor of two, i.e., in this experiment, too, we observed quenching of the initially produced channel upon the emergence of subsequent channels. One can also see from the oscilloscope trace of the current through the ignitor (Fig. 21) that a current returns to the first channel after its almost complete quenching in the case of a plane gap as well, provided the energy input is high enough. In the rod-plane gap, the spreading of the flame, which simulated a single diffusion channel, was observed to occur in two stages. During the first 20-30 ns following the gap breakdown, the discharge volume rapidly increased, out of proportion to the energy inputted. Then, the discharge volume increased approximately linearly with the energy. For a constant total energy W introduced into the plasma, the largest volume V occupied by the SIVD by the instant of energy input termination increased with lowering the mixture pressure p. Fig. 22 shows the dependence of V on the parameter W/p obtained for different p. One can see that this dependence is satisfactorily, to within the error of experimental determination of V, described by a linear function.

The results presented above confirm assumptions that there exist mechanisms of current density limitation in the diffusion channel of a discharge in SF6 and SF6-based mixtures [32, 36, 46, 47, 48, 49] (and also in several other strongly electronegative gases [36, 49]). It would be reasonable to attempt to relate these mechanisms to the specific feature of SF6, namely, with its strong electronegativity.

Strongly electronegative gases have highly reduced electric field strengths of E/N, where E is the field strength and N is the concentration of neutral molecules, at which an electrical breakdown occurs and the energy is inputted into the plasma. They also have large electronegativity parameters X_a defined as the ratio of concentrations of negative ions and electrons. For this reason, the following features of the charge kinetics inherent in these gases should be taken into account in the study of a volume self-sustained discharge in strongly electronegative gases such as SF6 and SF6-based laser mixtures.

First, the electron-impact dissociation of SF6 molecules and other components of the mixture plays a significant role in this discharge. Indeed, for high E/N close to the critical value $(E/N)_{Cr} = 360$ Td, the average energy of plasma electrons in the quasi-stationary stage of a self-sustained discharge approaches the SF6 dissociation threshold and more than 80% of the energy inputted into the discharge is spent to the dissociation [44, 52] resulting in the production of an F atom. In the submicrosecond range typical for the discharge under study, decomposition products have no time to escape from the discharge channel, resulting in a local increase in the concentration N of particles, a decrease in E/N, and a decrease in the electric conductivity of the diffusion channel due to the increase in electron losses through attachment.

High negative ion concentrations are attained in the discharge, with the effect that the electron detachment from negative ions can make a significant contribution to the balance of charged particles. Usually the disintegration of negative ions in their collisions with neutral molecules and/or due to associative ionization is taken into account. However, for medium gas pressures ($p = 10 - 100$ Torr) and a submicrosecond discharge duration, these processes do not make any noticeable contribution to electron multiplication [53]. However, there are firm grounds to believe that the electron-impact detachment of electrons from negative ions can be an efficient channel of the delivery of secondary electrons to the discharge plasma [54].

Third, a significant influence on the parameters of an SF6-discharge plasma, including its conductivity, can be exerted by dissociative electron-ion recombination because high concentrations of positive ions are achieved in the discharge, and the energy is mainly inputted into the plasma . Ion-ion recombination must also be taken into account, because it may significantly limit the concentration of ions in the plasma.

Therefore, it follows from the above discussion that the main mechanisms of SIVD current density limitation are the dissociation of SF6 molecules by electron impact resulting in a decrease in the ionization rate and an increase in the electron attachment rate due to the local reduction of the parameter E/N in the diffusion channel, and also electron -ion recombination, which is responsible for the growth of electron losses with increasing current density in the channel. It was shown qualitatively [49] that the current density can be also limited due to the attachment of electrons to vibrationally excited SF6 molecules. However, the absence of reliable data on the rate constants for these reactions in the literature complicates a quantitative estimate of the role of this process in the balance of charged particles in the plasma.

We performed SIVD simulations to verify whether the above assumptions are consistent with the available experimental data. The channel structure of the discharge was modelled with a set of resistive elements connected in parallel. Similarly to Ref. [55], the concentrations of particles were determined by solving continuity equations for particles of each sort in combination with the Kirchhoff equations for the discharge circuit. The nonuniformity of initial conditions for the development of channels along the cathode length was simulated by prescribing different initial electron concentrations in each of the channels. In addition to the electron-impact ionization of SF6 and electron attachment to SF6 molecules, the following processes were included in the calculation.

(1) SF_6 dissociation by electron impact. The number of dissociated molecules was defined as $N_d = W/qF$, where W is the energy inputted into the discharge and $q_F - 4.5$ eV is the energy spent to produce an F atom [41].

(2) Electron detachment from negative ions by electron impact. It was assumed that $SF_6 \sim$ negative ions dominate in the plasma because the charge exchange reactions have no time to occur during the discharge period, while the cross sections for the electron-impact production of other negative ions are too small [52, 53]. The rate constant for the disruption of negative ions by electron impact should not be smaller than the rate constant for elastic electron scattering by molecules [54].

(3) Dissociative electron - ion recombination. The rate constant for this process was estimated assuming that the SF6 discharge plasma is dominated by SF_5^+ positive ions (52).

(4) Ion - ion recombination. In this case, the rate constant for the E/N values close to the critical value was taken from Ref. [53].

We simulated an SIVD with nine channels, which corresponds approximately to the conditions of the experiment performed using the setup of Fig. 18a. Fig. 23 shows the oscilloscope traces of the voltage, the total discharge current and the current through a single channel for which we prescribed the maximum initial electron concentration, calculated for the energy density inputted into the discharge plasma equal to 80 and 40 J/L. One can see from Fig. 23a that the current through a single channel has two maxima when the energy input is high. This is in qualitative agreement with the oscilloscope trace of current through the ignitor (see Fig. 21) in the plane gap geometry and in agreement with the experimentally observed redistribution of the channel glow intensity upon the SIVD development in the knife edge-plane gap (see Fig. 19). The current return vanishes when the energy input is lowered (Fig. 23b).

Calculations also show that the electron detachment by electron impact and electron -

ion recombination virtually compensate each other within the accuracy of estimates of the rate constants. The dissociation of SF_6 molecules and other components of the HF(DF)-laser mixture should therefore be considered as the principal mechanism responsible for current density limitation in the SIVD channel. However, it is reasonable to refine the magnitudes of the rate constants. Note that our model (like any zero-dimensional model which neglects the time variation of the SIVD volume) pretends only to a qualitative illustration of the current redistribution in the channels when account is taken of possible mechanisms of current density limitation.

Note also that the electron detachment from negative ions by electron impact should be taken into account in the analysis of the processes determining the instability development of the volume discharge in SF6 and other strongly electronegative gases.

Once again we draw attention to the result that follows from the investigation of the dynamics of a single diffusion channel: an SIVD develops at an approximately constant value of the energy parameter $W/(Vp)$.

Conclusions

We investigated the formation of the SSVD in CO_2-N_2-He mixtures by preliminary filling of the gap with an electron flux from an auxiliary discharge plasma. This method was suitable for large distances between the electrodes. A study was made of the characteristics of some of the discharges which could be used as auxiliary ones. It was established that the formation of a SSVD was affected significantly by the distortion of the electric field due to the presence of a space charge of the electron flux. Dynamic profiling of electrons was found to be possible and a SSVD was attained in systems with a strongly inhomogeneous initial distribution of the electric field in the gap.

The simplicity of the proposed methods is very promising for their applications in CO_2 lasers. Although the main results of the present investigation were obtained for CO_2-N_2-He gas mixtures, the methods can clearly be applied also to other gases like N2O, for example. Due to our investigations the aperture of SSVD based lasers and amplifiers had been increased up to 80 cm. for the electric efficiency of more then 10%.

At the same time the SIVD in SF_6 – hydrocarbon mixtures, used as the active media for nonchain HF lasers, has been investigated as well. The following features of the development of the SIVD have been established:

- After the primary electrical breakdown of the discharge gap, the SIVD spreads in the gap in the direction perpendicular to that of the electric field as a result of the consecutive appearance of overlapping diffuse channels. As the new channels appear, the current flowing through the channels formed earlier diminishes.
- The volume occupied by the SIVD increases almost linearly with increase in the energy deposited in the plasma and, when the discharge volume is confined by a dielectric surface, the discharge voltage increases simultaneously with increase in the current.

The hypothesis was put forward that mechanisms exist for the limitation of the current in the conducting channel. They are associated with the specific energy released in the plasma and they prevent the transfer of all the deposited energy through a separate channel. It is shown that such mechanisms may be the dissociation of SF_6 and the attachment of electrons to vibrationally excited SF_6 molecules.

Main result for SIVD based HF(DF) lasers looks very much promising and half of Kj level for energy output is very far from the natural limit for this type of the systems.

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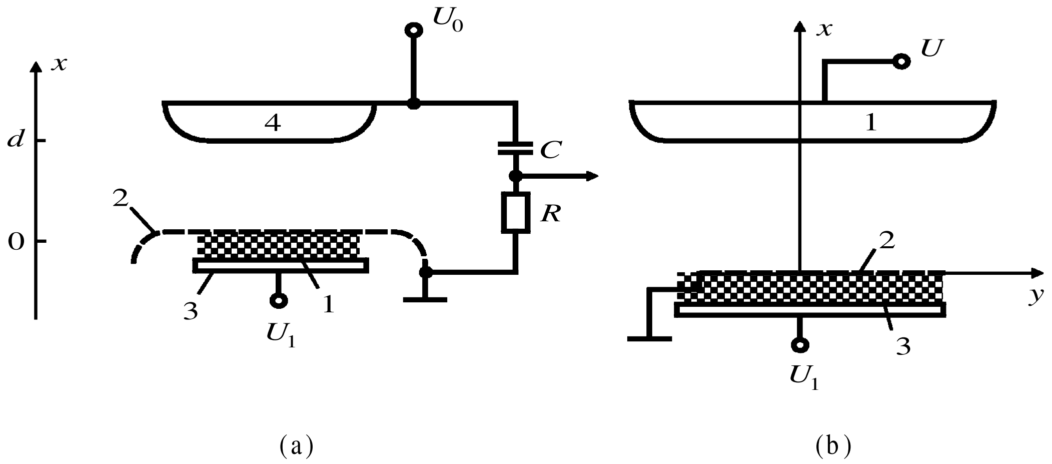


Fig. 1 Discharge systems with profiled (a) and nonprofiled (b) electrodes.

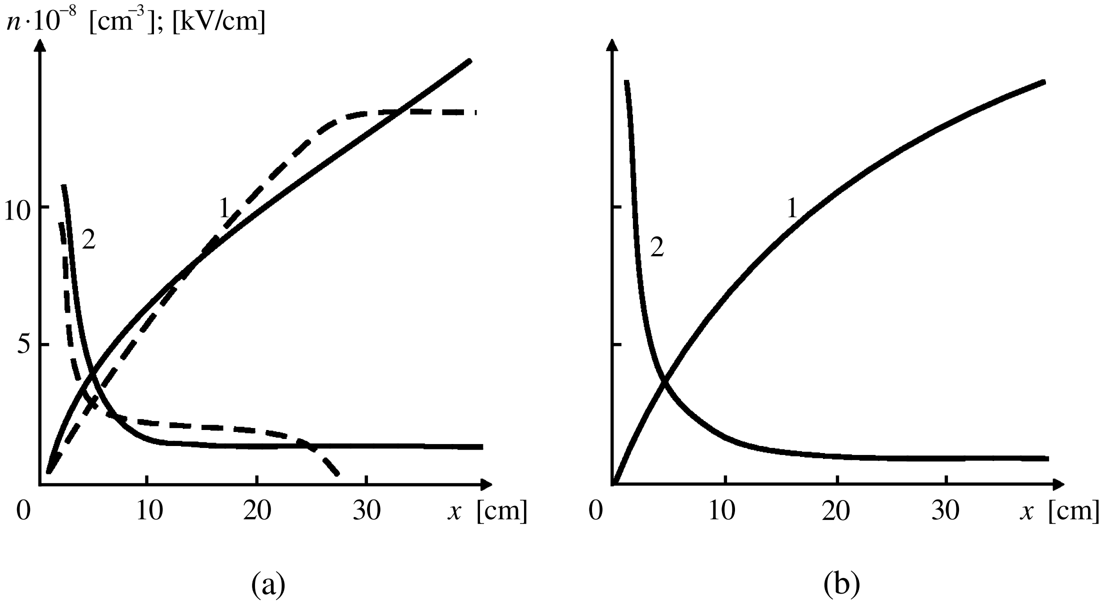


Fig. 2 Calculated dependences $E(x)$ (curves denoted by 1) and n(x) (curves denoted by 2): (a) $t = 2$ mksec (dashed curves) and 4-6 mksec (continuous curves); (b) $U = 400$ kV, $t = 8$ mksec, $n(0) = 10'^{\circ}$ cm-^{3}.

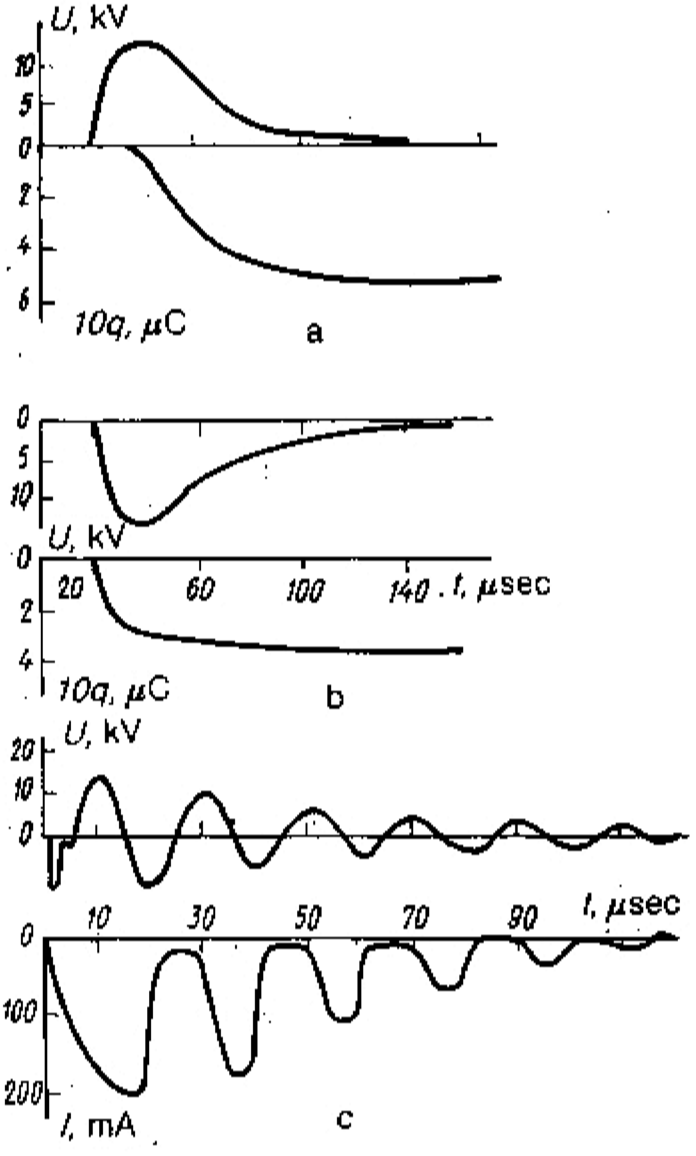


Fig. 3 Oscillograms of the voltage $U(t)$ on the auxiliary electrode, of the electron charge $q(t)$, and of the electron flux current $'l(t)$ in the case of positive (a) and negative (b) polarities, and also in the case of oscillatory nature of the voltage $U(t)$ (c).

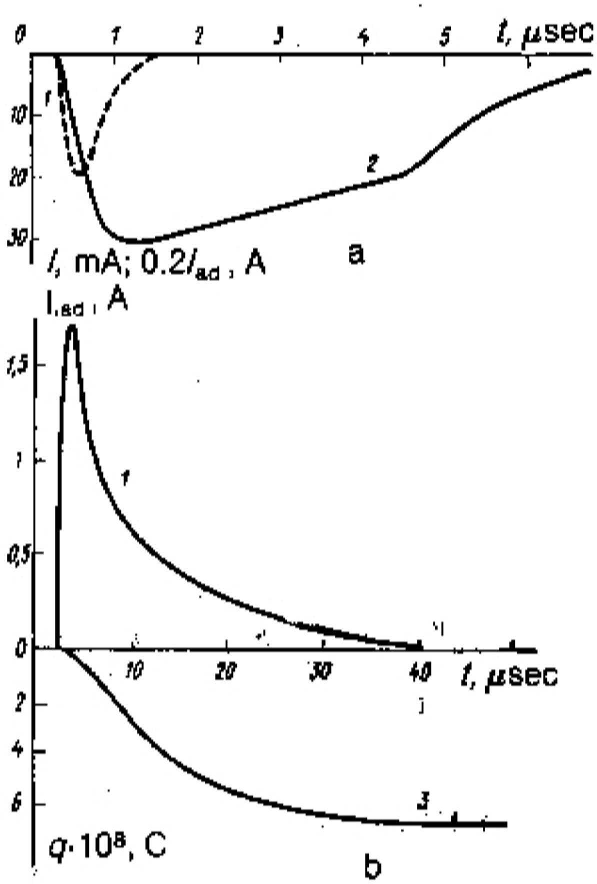


Fig. 4 Oscillograms of the volume auxiliary discharge current (1) from metal (a) and semiconductor (b) electrodes, of the electron flux current (2), and of the charge carried by this flux (3).

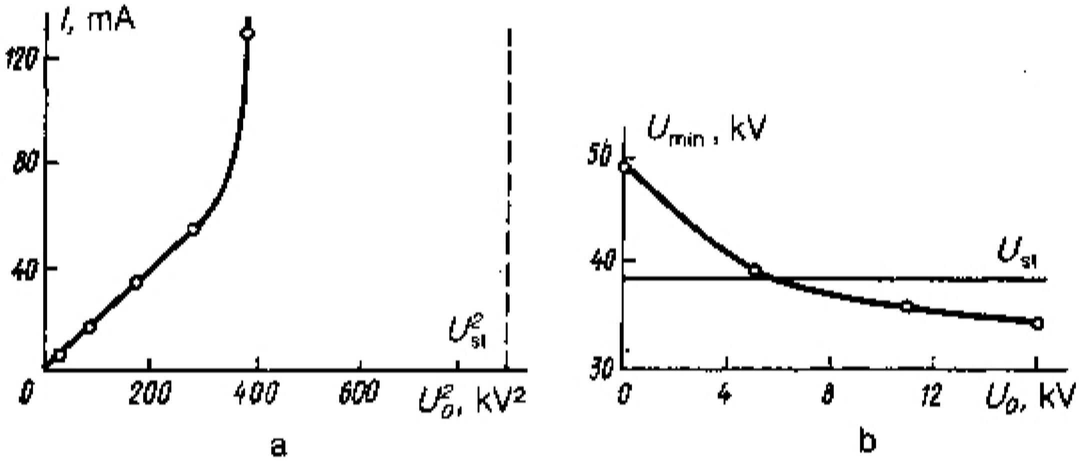


Fig. 5 Dependences of the amplitude of the electron flux current (a) and of the minimum ignition voltage of a SSVD (b) on U_0.

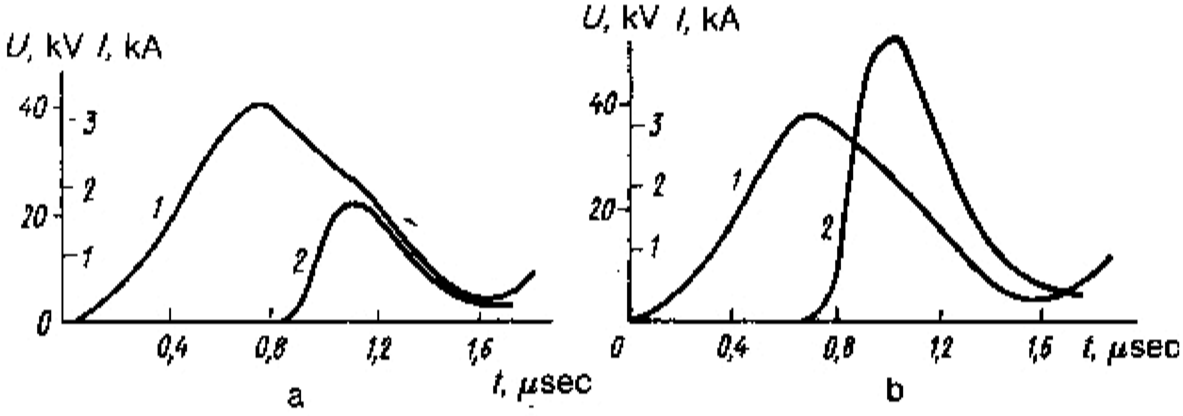


Fig. 6 Oscillograms of the voltage U (curves denoted by 1) and of the current (curves denoted by 2) for a SSVD when the condition (9) is not satisfied (a) and when it is satisfied (b)

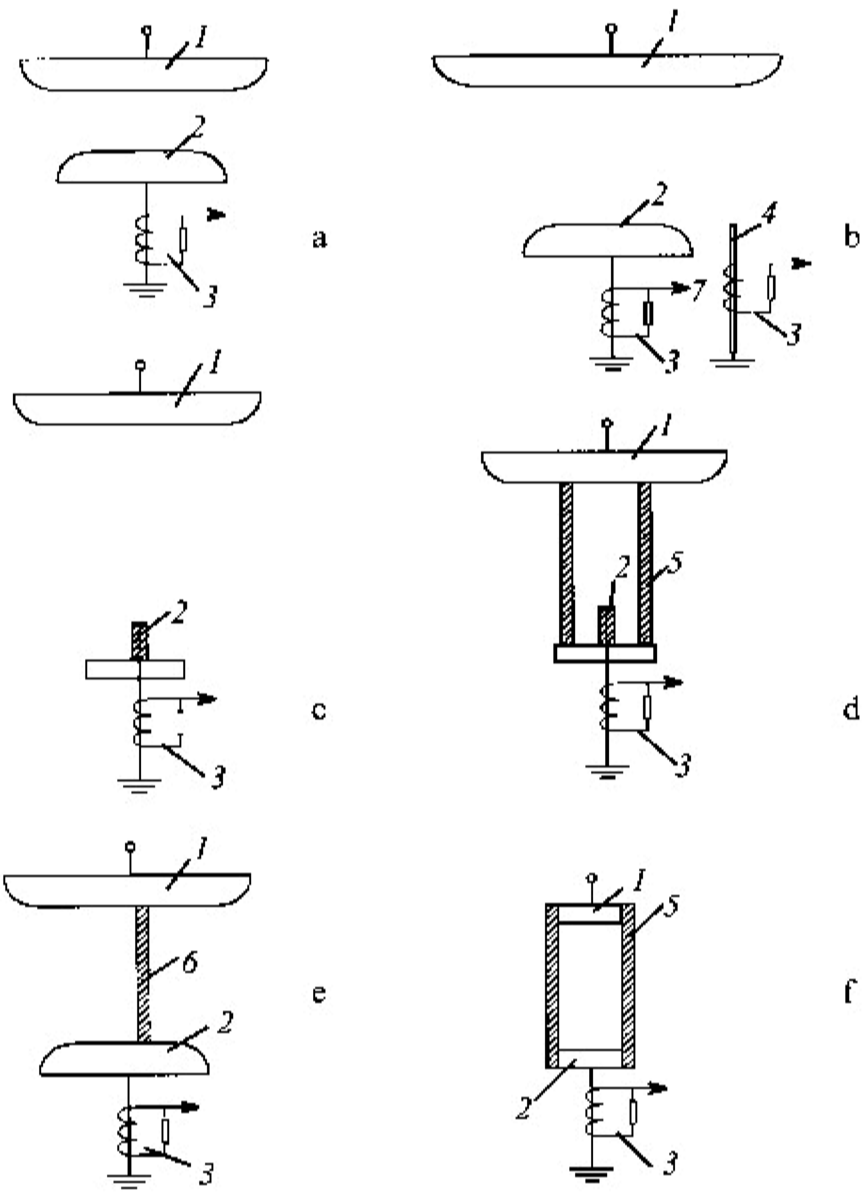
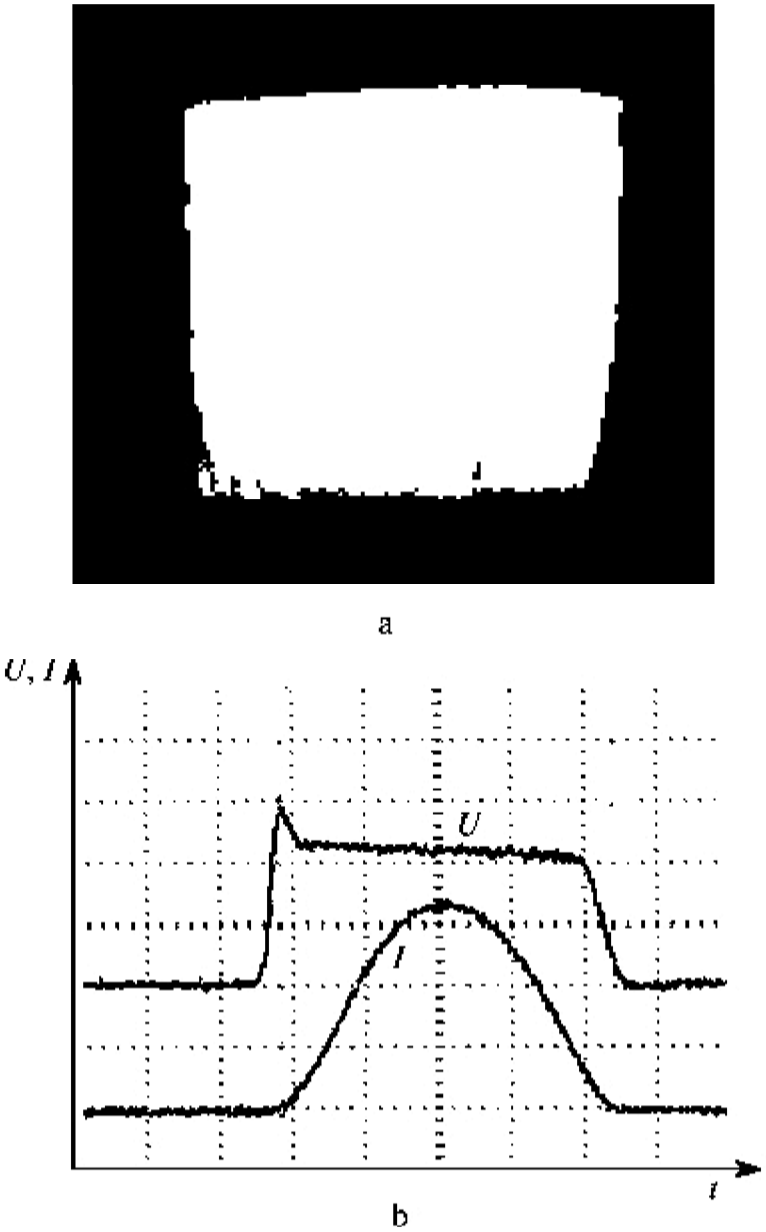


Fig. 7 Discharge gaps with electrodes having different configurations: (1) anode; (2) cathode; (3) Rogowski loop; (4) initiating electrode; (5) glass tube; (6) glass plate.



a

b

Fig. 8 Photograph of an SIVD in a system of plane electrodes (a) and typical current (I) and voltage (U) oscillograms for the SIVD; scan—100 ns division-[1] (b).

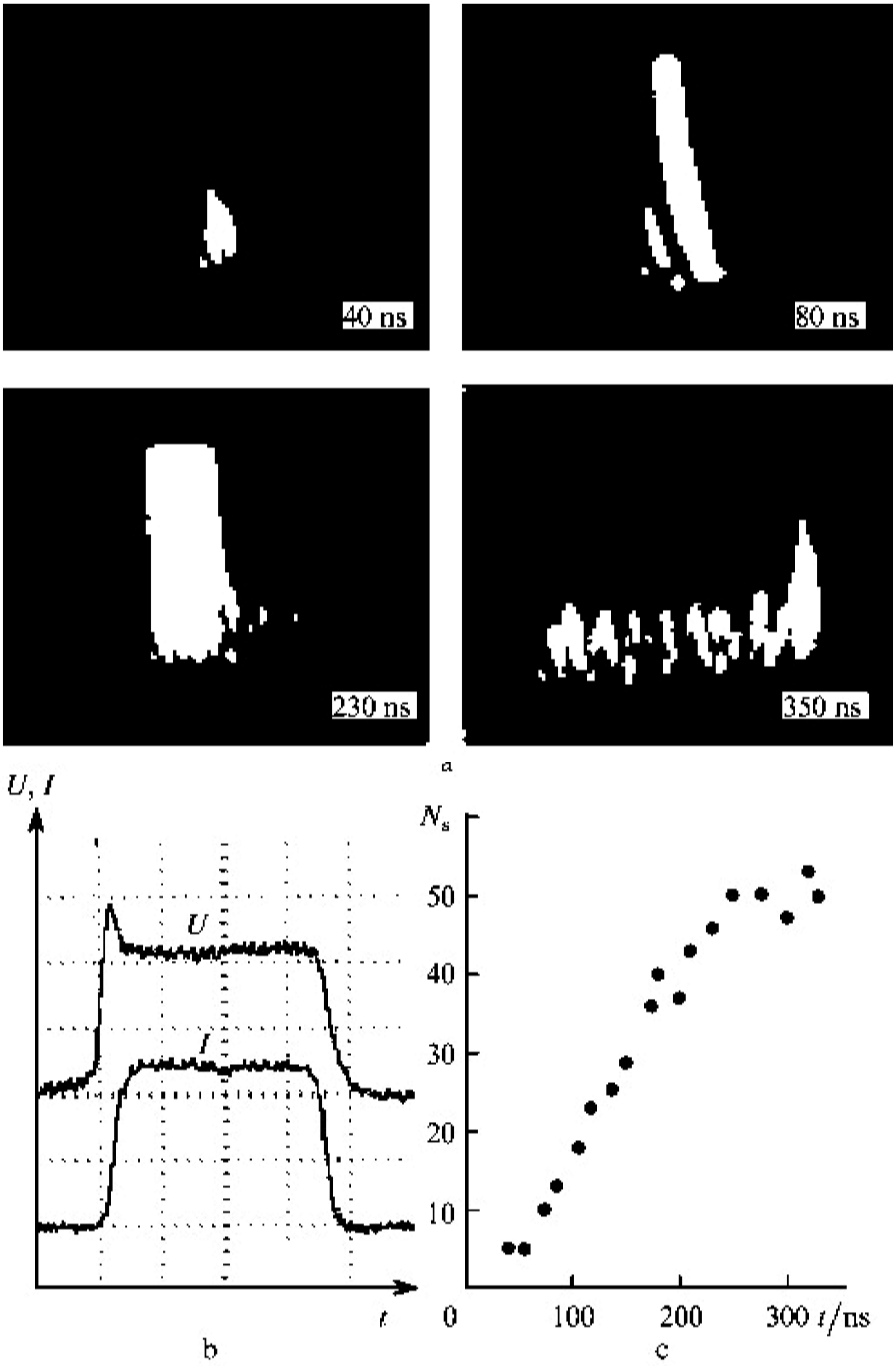


Fig. 9 Characteristics of an SIVD: photographs of an SIVD in a system of plane electrodes at different times (spark illumination from the left) (a), voltage (U) and current (I) oscillograms for the SIVD during the discharge across the gap of an artificial line consisting of 20 cells (scan — 100 ns division-[1] (b) and time dependence of the number of spots on the cathode N_s (c).

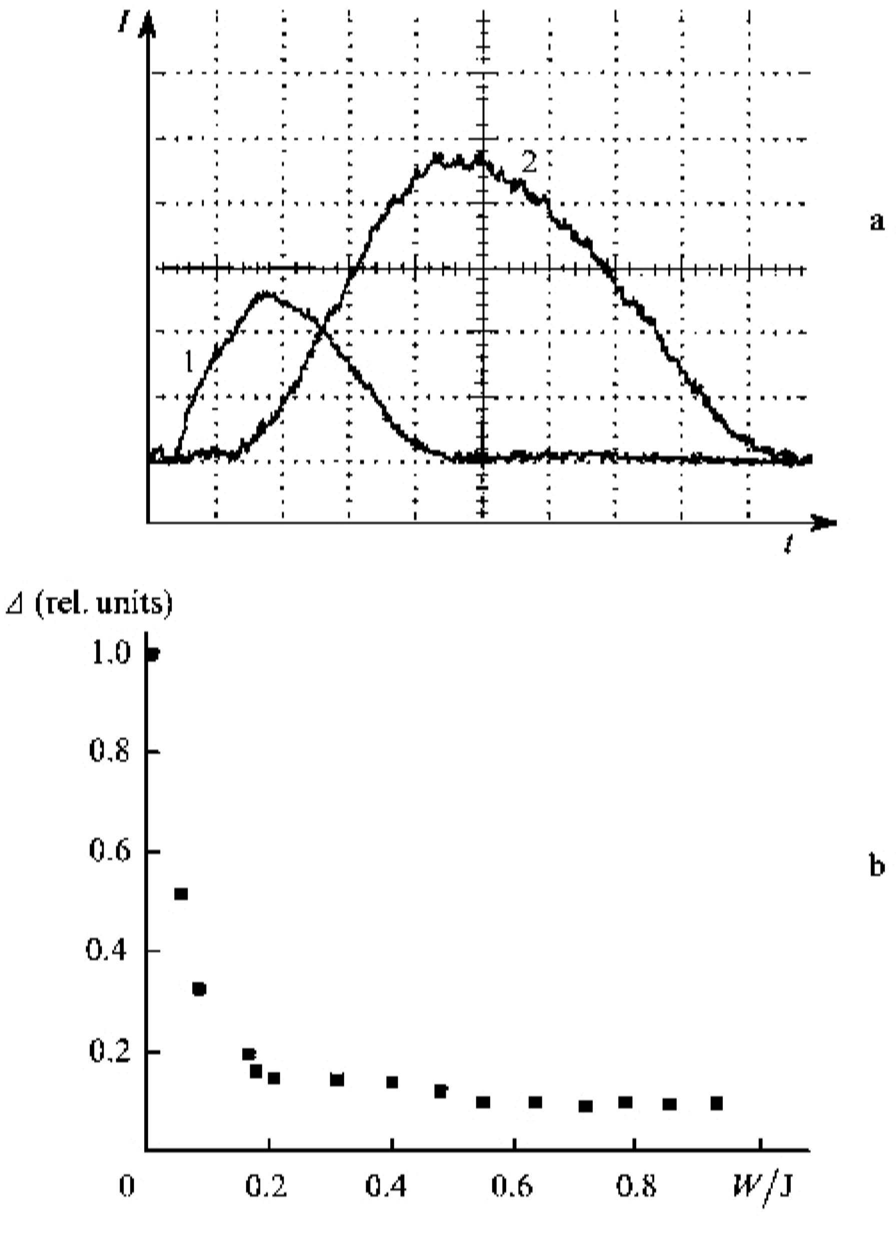


Fig. 10 Oscillograms of the current through the initiating (1) and main (2) cathodes (39.7 A division-[1], scan — 50 ns division-[1] (a) and dependence of the fraction of energy A transmitted through the initiating electrode relative to the total energy W (b).

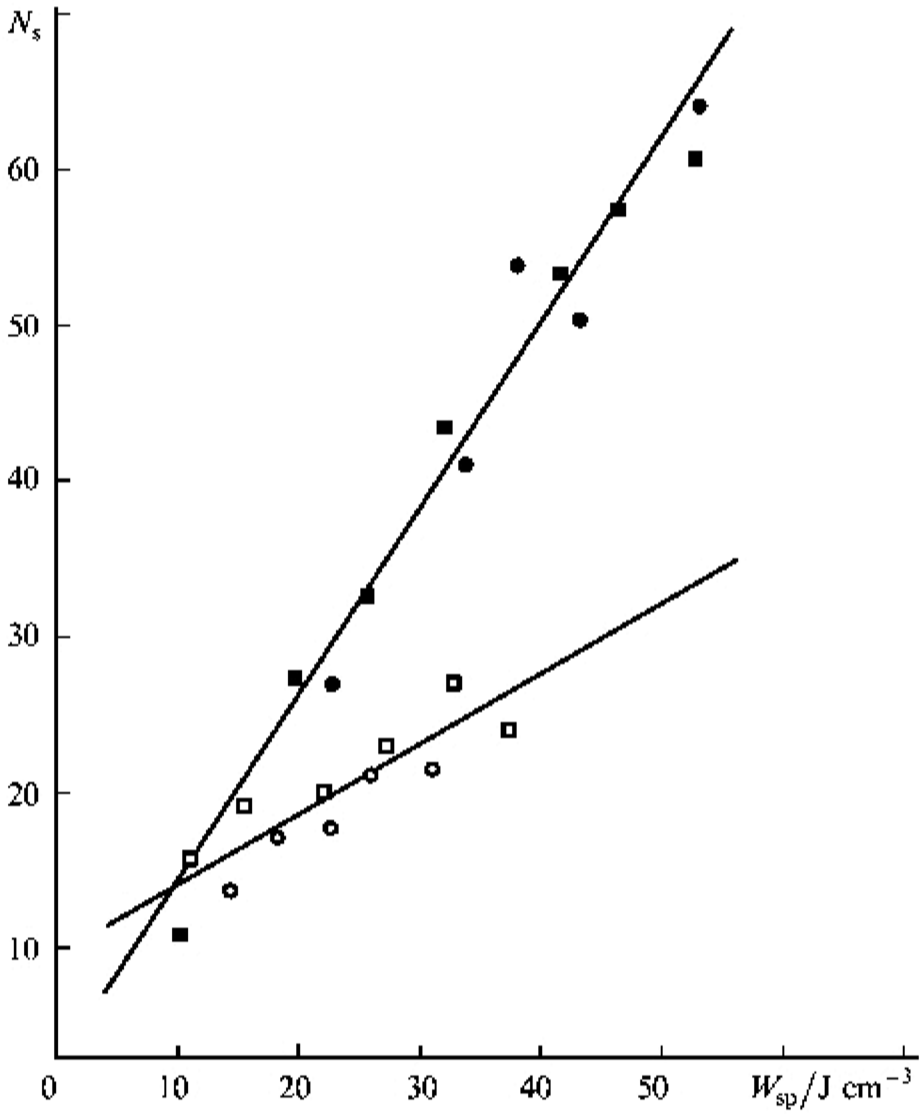


Fig. 11 Dependence of the number of cathode spots N_s on the specific input energy W_{sp} for the $SF_6 : C_2H_6 = 10{:}1$ mixture with $d = 6$ cm and $p = 33.6$ Torr (), $d = 2$ cm and $p = 33.6$ Torr (), $d = 6$ cm and $p = 16.8$ Torr(n), and $d = 2$ cm and $p = 16.8$ Torr (o).

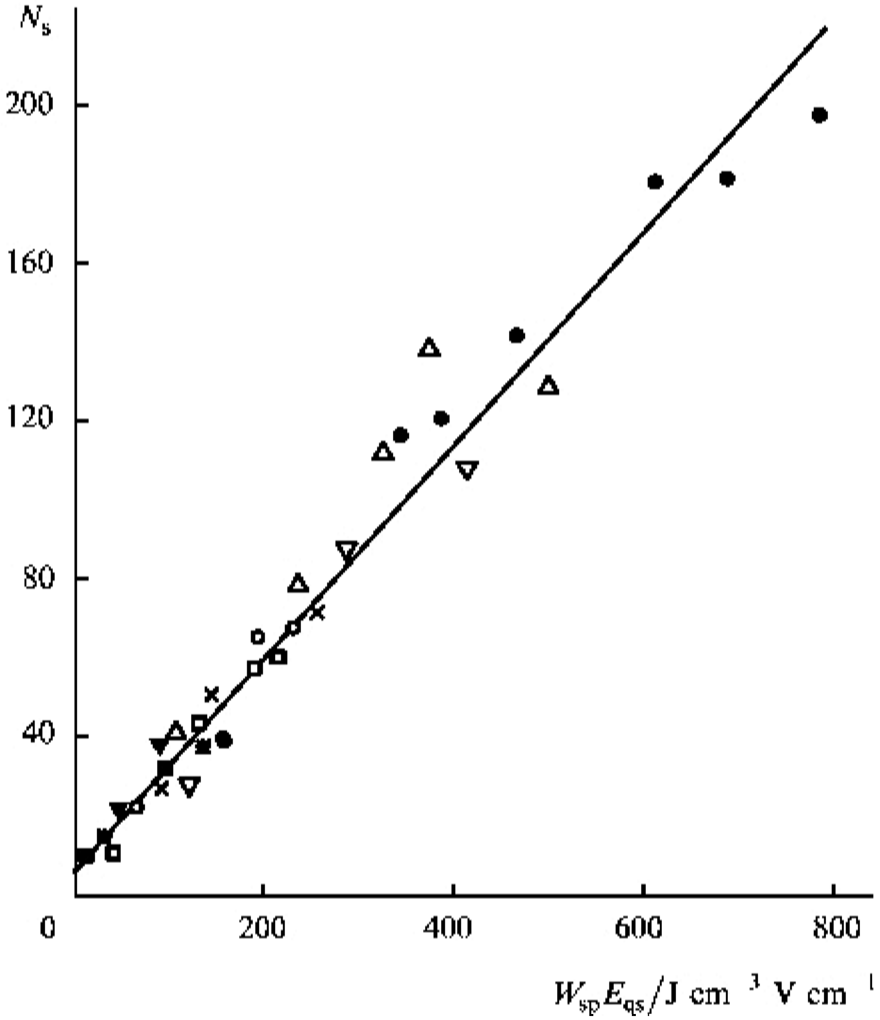


Fig. 12 Dependence of the number of cathode spots N_s on $W_{sp}E_{qs}$ for the $SF_6 : C_2H_6 = 10{:}1$ mixture with $d = 6$ cm and $p = 33.6$ Torr (n), $d = 6$ cm and $p = 16.8$ Torr (), $d = 4$ cm and $p = 23.3$ Torr (*), $d = 3$ cm and $p = 23.3$ Torr (), $d = 3$ cm and $p = 33.6$ Torr (o), $d = 3$ cm and $p = 50.4$ Torr (A), $d = 3$ cm and $p = 67.2$ Torr (), and $d = 2$ cm and $p = 33.6$ Torr (x).

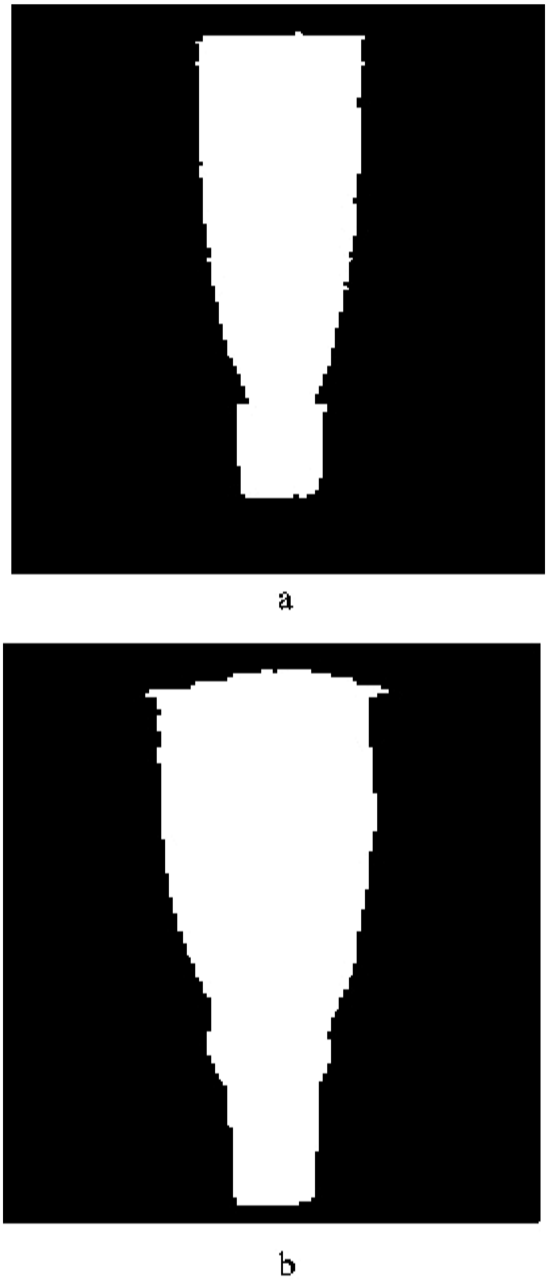


Fig. 13 Photographs of an SIVD in the rod-plane electrode system with $W = 0.73$ J (a) and 2.33 J (b).

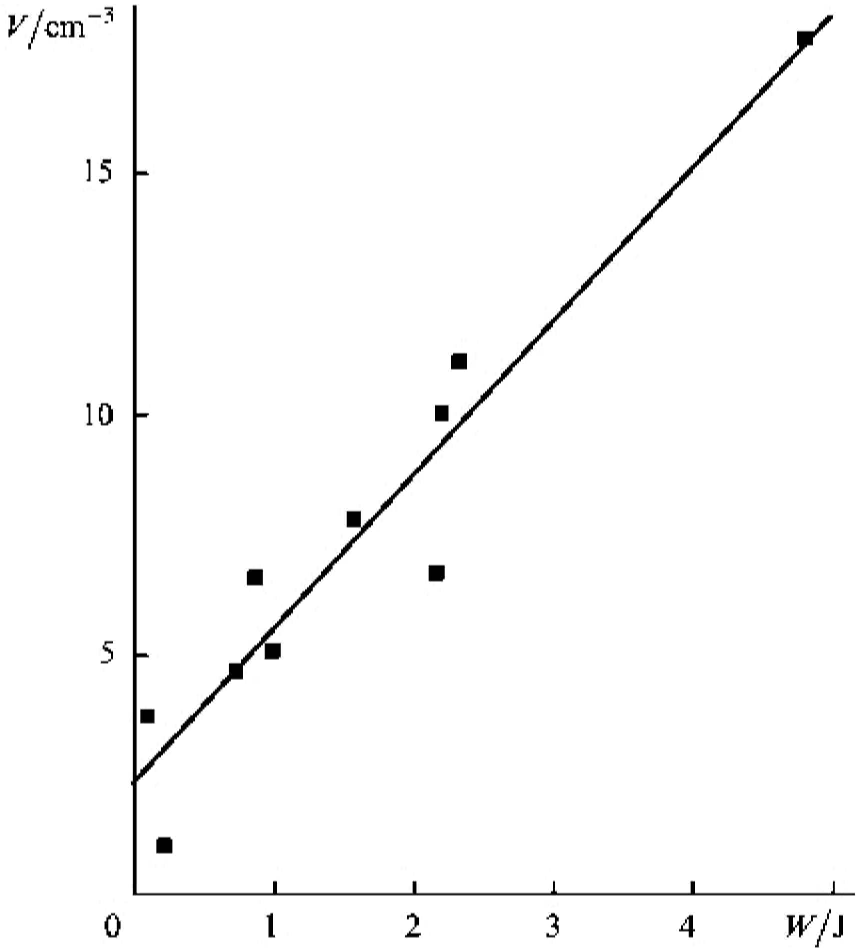


Fig. 14 Dependence of the volume V of an SIVD on the energy W in the rod - plane electrode system.

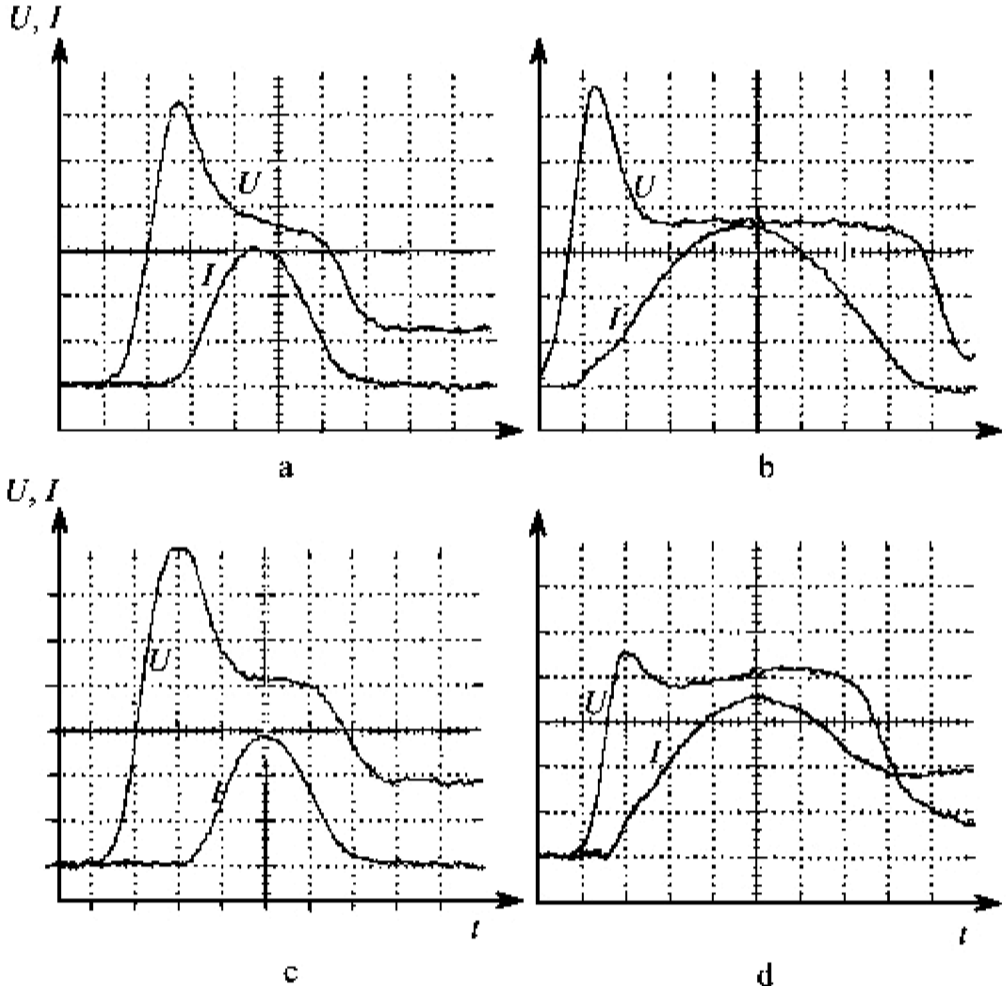


Fig. 15 Voltage (U) and current (I) oscillograms for an unconfined (a, b) and confined (c, d) SIVD in the rod-plane electrode system with $T = 100$ ns (a, c) and 200 ns (b, d). Oscillogram scales: 5.1 kV division [1] (a-d), 79.4 A division [1] (b, d), 198.5 A division [1] (a, c); time scan — 25 ns division".

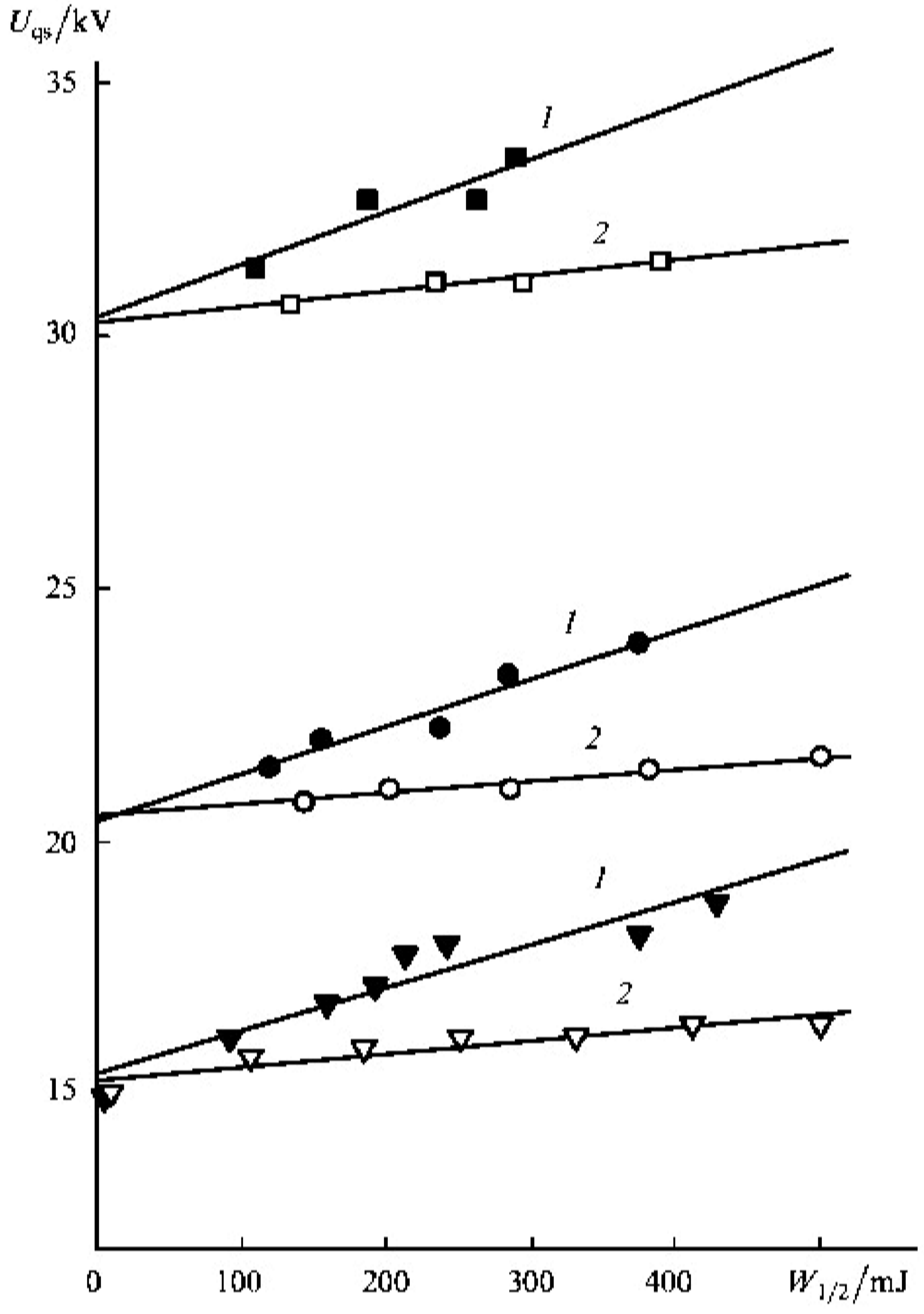


Fig. 16 Dependence of U_{qs} on the energy $W\backslash/_2$ f $^{\circ}$ ^{r} ^{a} confined (1) and unconfined (2) SIVD with $p = 33.6$ Torr (triangles), 45.8 Torr (circles), and 67.2 Torr (squares); SF_6 : C_2H_6 = 10:1 mixture, $d = 4$ cm.

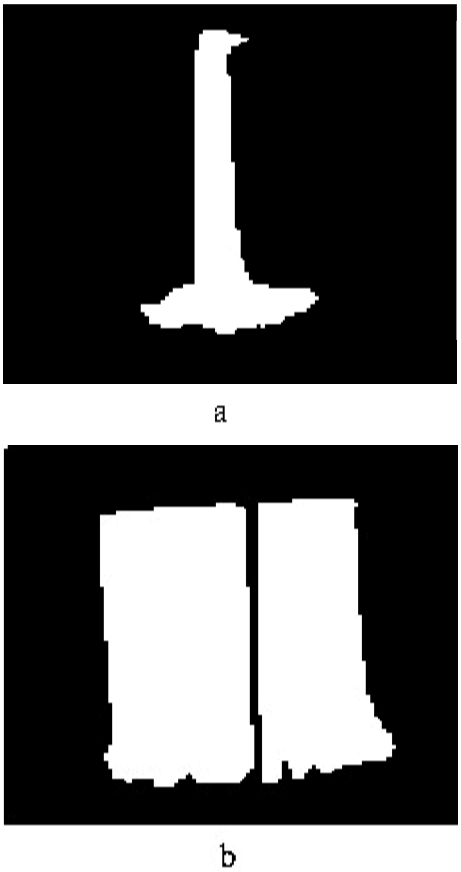


Fig. 17 Photographs of a discharge in a system of plane electrodes linked by a glass plate in air (a) and in the SF_6: C_2H_6 = 10:1 mixture (b).

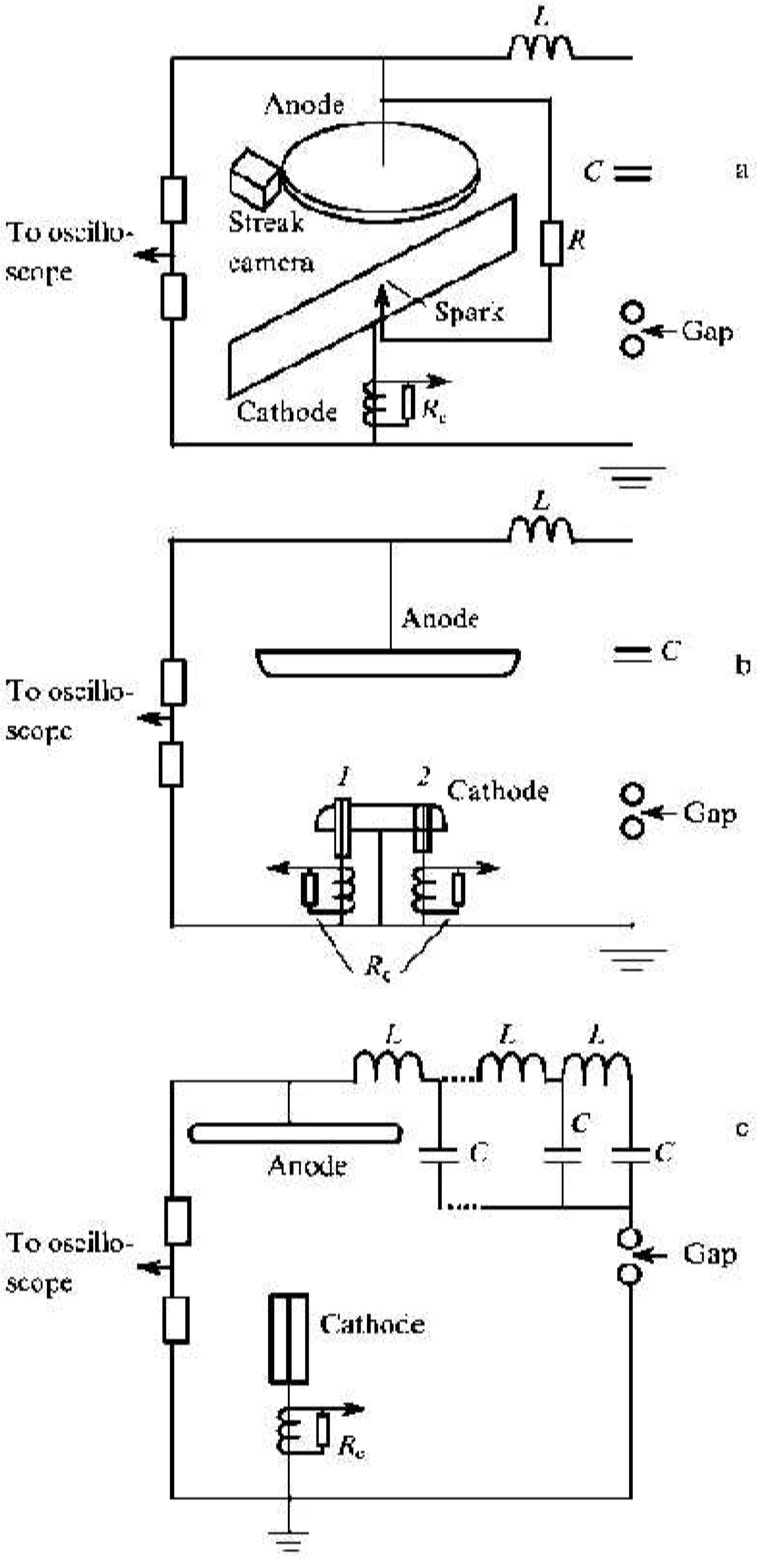
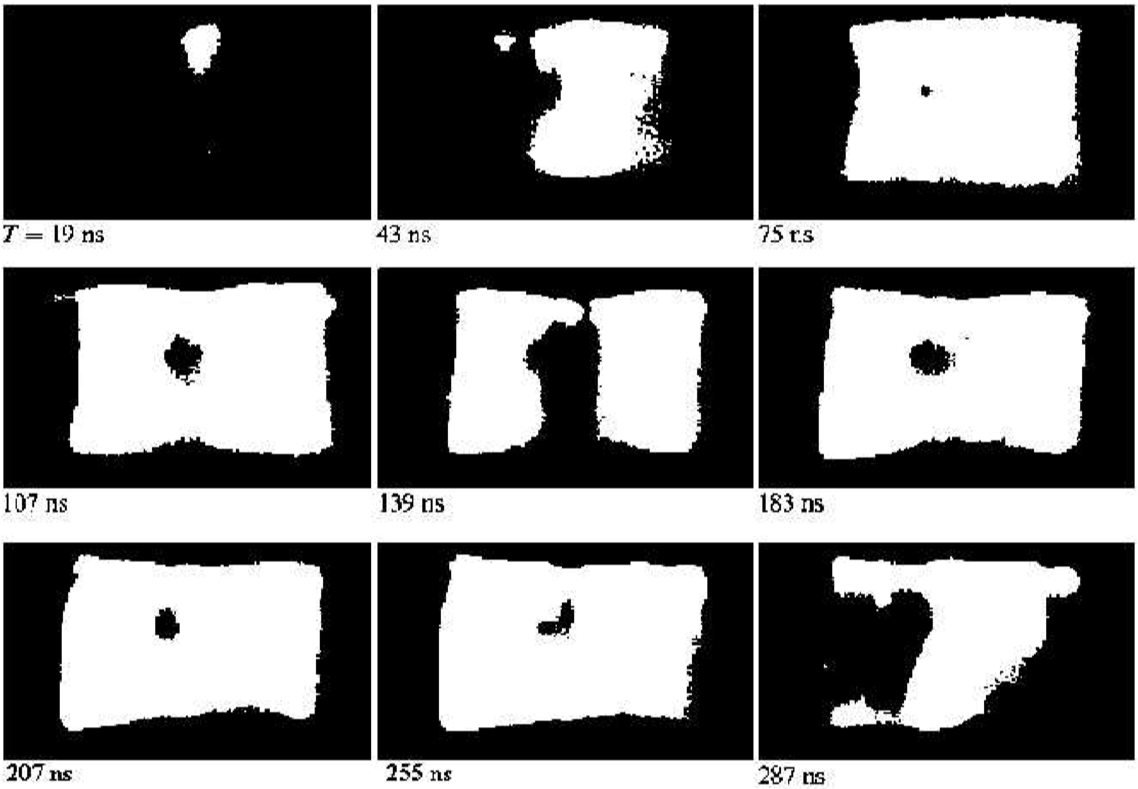


Fig. 18 Schemes of experimental setups for studying the SIVD dynamics: ignitor (7) and monitoring (2) conductors.



$T = 19$ ns, 43 ns, 75 ns, 107 ns, 139 ns, 183 ns, 207 ns, 255 ns, 287 ns

Fig. 19 Streak camera images obtained at different instants of time T.

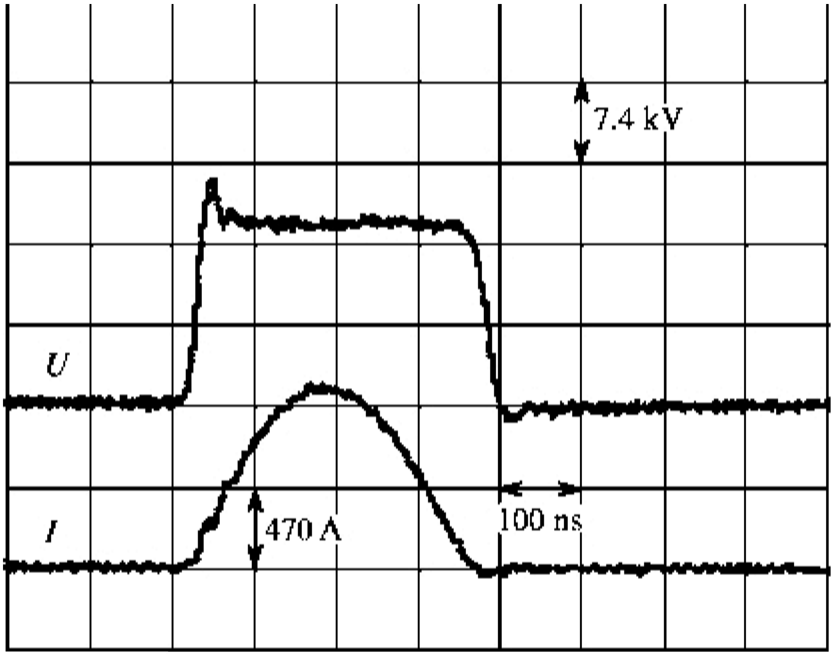


Fig. 20 Oscilloscope traces of the voltage and current of a SIVD.

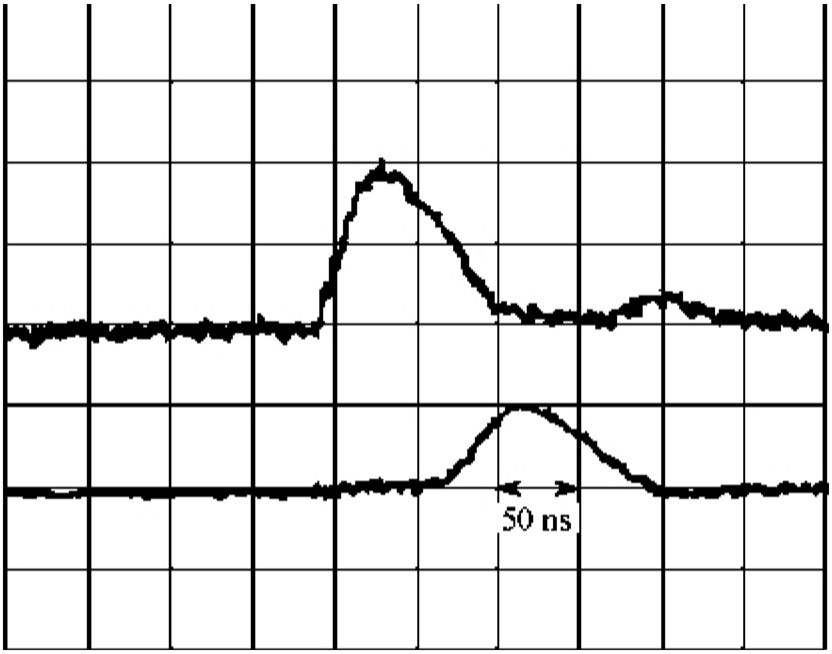


Fig. 21 Oscilloscope traces of the current through the ignitor (the upper trace) and monitoring (the lower trace) conductors.

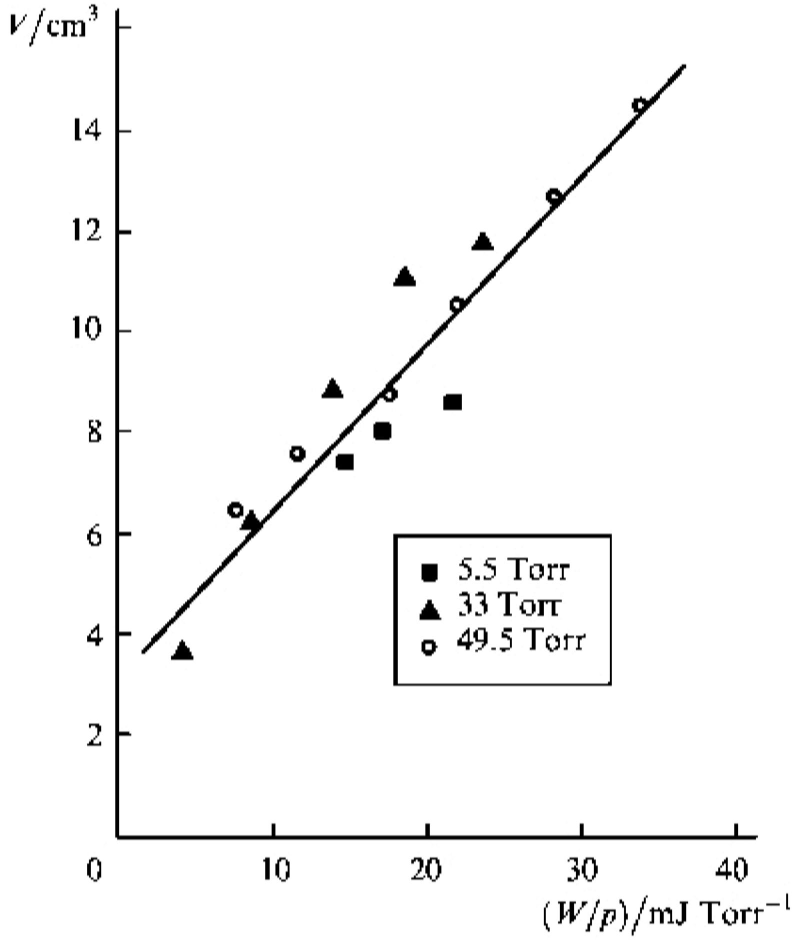
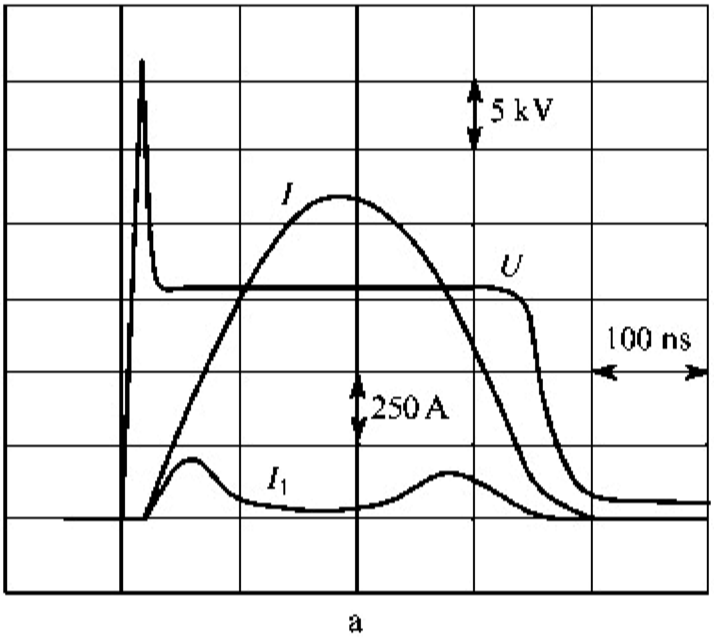


Fig. 22 Dependences of the volume *V* occupied by discharge on the parameter W/p for the SFe: C2H6 =10:1 mixture at a pressure p.



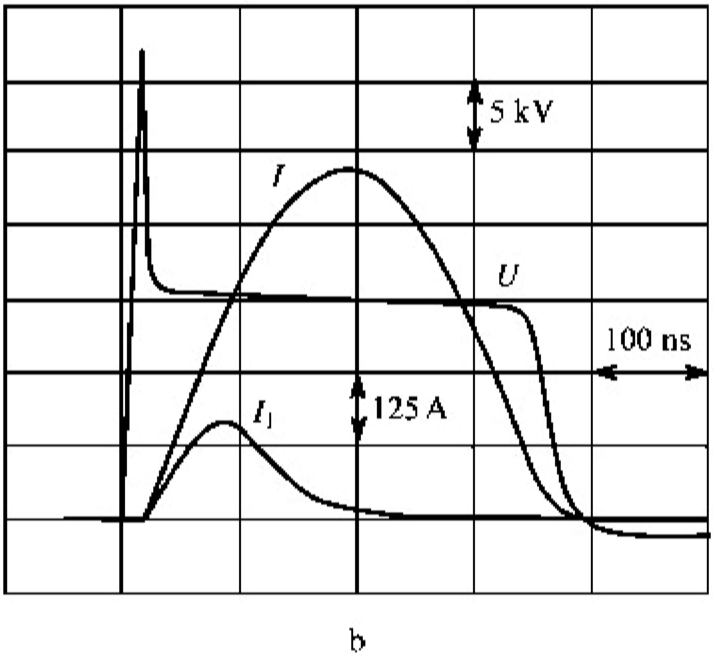


Fig. 23 Calculated oscilloscope traces of the voltage U, the total discharge current /, and the current I\ through the first channel for energy density 80 (a) and 40 J/L (b).