1. Introduction

Interest in self-sustained volume discharge (SSVD) was largely provoked by the development of electric-discharge lasers that operate at sub-atmospheric and super atmospheric pressure. A necessary condition for obtaining SSVD is the presence of preionization and the homogeneity of the electric field in the discharge gap (DG). This ensures the homogenization of ionization processes in the active volume [1,2]. However, this condition is not sufficient due to the instability of the discharge. Powerful electrophysical devices require stable operation with a pulse repetition rate of 1 kHz or with the discharge volume of nearly 100 liters. Self-sustained discharge in such cases should be quasi-continuous or it should have a burning duration of 10 μs. For these purposes the fundamental problem is the complete suppression of plasma inhomogeneities in volume self-sustained discharge. Unlike conventional SSVD it can be called a extremely homogeneous self-sustained discharge. In this paper we propose a new approach to the suppression of plasma inhomogeneities and instabilities in SSVD [3,4].

2. Main types of inhomogeneities and instabilities in SSVD

Let’s consider the most distinctive types of local inhomogeneities.

A) The stage of discharge formation is a stage of discharge development from the moment of applying voltage pulses to the electrodes up to appearance of the cathode potential drop. At this stage the ionization multiplication of initial electrons and removal of electrons through the anode take place. These processes have wave character mainly. Due to electrons removing from the cathode region their concentration may become essentially less, than concentration of initial electrons $n_0$. Therefore, even at performance of a condition for overlapping primary avalanches, in this area streamers are able to emerge from not overlapping secondary avalanches. Also ionization waves lead to large-scale cross-section irregularities. Cathode wave moves most quickly in the discharge center, creating more dense plasma also in the center [5].

In [6] there was described the discharge model which considered that the velocity of electrons motion along the field lines is more than velocities in other directions. Therefore the electron reproduction occurs in the form of chains of the avalanches trailing each other. As a result, the plasma
column appears non-homogenous and consists of plasma micro strings extended in a direction of a field.

The effect of noted negative phenomena decreases with growth of \( n_0 \) and becomes not essential at \( n_0 = 10^8 - 10^9 \) cm\(^{-3} \). But even in these conditions, development of cathode instability occurs as follows [7]. At the initial stage of discharge plasma column removes from the cathode, forming electron-poor region. In this region filamental distribution of current occurs. As a result there are local places with raised electron emission on cathode, where cathode spots appear.

B) Discharge burning stage starts from occurrence of cathode layer, which provides effective electron emission due to bombardment of cathode by ions. The inhomogeneities, arisen at the stage of SSVD formation, grow quickly under the action following energy input. Cathode spots turn into unfinished spark channels. As a result, the duration of sustained discharge burning decreases with increasing pump power density [3,4].

Also on the burning stage of SSVD different types of volume instabilities may occur. They are ionizing-overheating instability, ionizing instability, stability caused by stepwise particle ionization. The condition of volume instabilities is usually certain threshold energy density released in the positive column. For example, in mixtures of CO\(_2\)-lasers at atmospheric pressure with 50 % content of molecular components threshold value of specific energy input is \( w_{th} = 0.4 - 0.5 \) J/cm\(^3\) [3,4].

Thus, at the stage of SSVD formation the initial irregularities occur in the form of streamers, nonuniform distribution of plasma density across the discharge, or cathode spots. At burning stage of the discharge these inhomogeneities cause the growth of spark channels, what reduces duration of steady discharge burning. Therefore, if we exclude the formation stage from discharge development and do not exceed threshold value of energy input, it is possible to eliminate the occurrence of inhomogeneities and instabilities considered above and to ignite extremely homogeneous SSVD with maximum possible duration of burning.

3. Critical conditions for ignition of extremely homogeneous self-sustained discharge

Let’s consider a mechanism and ignition conditions, when discharge arises right from the burning stage without formation stage. Figure 1 shows general view for distribution of electric field in the discharge gap (DG) filled by initial plasma with electron concentration \( n_0 \). After applying to DG the field \( E_0 \) a charge separation takes place and near the cathode surface a layer with ion extra charge \( \Delta \). The field distribution at \( x \) distance from left column edge is given by:

\[
E_x = E + 4\pi en_0(\Delta - x) = E + 4\pi en_0(\Delta - x) \quad (0 < x < \Delta)
\]  

Figure 1. General view for distribution of electric field \( E(x) \) and charged particles before ionization processes in discharge gap with width \( d \) between cathode (C) and anode (A). \( E_0 \) is an external electric field; \( E_C \) is a cathode field; \( \Delta \leq x \leq d \) is a plasma column formed by preionization; \( 0 \leq x \leq \Delta \) is a cathode layer.

The burning stage of SSVD begins with the formation of cathode layer and corresponding cathode drop. It means that conditions for cathode layer formation must precede the occurrence of impact ionization in the plasma column. Thus, it is necessary to fulfill a condition

\[
\Delta < \alpha^{-1},
\]
where $\alpha$ is a coefficient of impact ionization in plasma column depending on $E$.

Townsend discharge is a process providing the current in cathode layer. A dependence of cathode layer thickness on discharge current density is falling, which limits the size of the border $\Delta$ separating the charges by the value corresponding to the condition of the Townsend breakdown in this layer. The condition for occurrence of Townsend breakdown in the cathode layer has the following form [2,8]:

$$\int_0^\Delta \alpha_c(E_x)dx = \ln \left(\frac{1}{\gamma} + 1\right).$$

(3)

where $\alpha_c(E_x)$ is a coefficient of impact ionization in cathode layer depending on $E_x$. If we replace the linear distribution of the field in the cathode layer with a step with value of the field at the cathode $E_c$ and use an empirical formula for $\alpha = pAe^{-Bp/E}$ ($A$, $B$, $\gamma$ are constants [2,8]), than from the (1), (2), (3) we obtain the connection between $n_0$ and $E$

$$n_0 > \frac{1}{4\pi e} \frac{pAe^{-Bp}}{E} \frac{C' E^2}{(Bp - C' E)}.$$

(4)

Figure 2 shows the dependence of $n_0$ on $E$ for ignition border right from the burning stage of SSVD in gas mixture of CO$_2$:N$_2$:He = 1:2:3 at $p = 760$ torr, $A = 5.3$ (cm·torr)$^{-1}$, $B = 135$ V/(cm·torr), $\gamma = 10^{-2}$, $C' = \ln \left(\frac{1}{\gamma} + 1\right) = 1.53$. It is calculated by (4). This mixture has value of field equal $E_{qs} = 12.5$ kV/cm for the phase of quasi-stable discharge burning. Suggesting the field value for ignition of extremely homogenous self-sustained discharge in mixture of CO$_2$-laser belongs to interval of $E_1 = E_{qs} \leq E \leq 2E_{qs} = E_2$, from (4) we have $n_1 = 1.7 \times 10^9 \leq n_0 \leq n_2 = 5.5 \times 10^{11}$ cm$^{-3}$.

![Figure 2](image-url)

**Figure 2.** Calculated dependence of boundary concentration of initial electrons $n_0$ on the field strength $E$ in the DG for producing extremely homogeneous SSVD in the mix of CO$_2$:N$_2$:He = 1:2:3 at $p = 1$ atm.

4. **Upper limit for $n_0$**

SSVD with the optimal mode of the energy input, when all the electrical energy is dissipated in the plasma over the first half-period of the discharge current, represents the greatest practical interest. This mode is executed under the condition $U = 2U_{qs} = 2E_{qs}d$ with calculated for it value of $n_0 = 5.5 \times 10^{11}$ cm$^{-3}$. If we increase $n_0$ from its minimal value $n_0_{\text{min}} = 5.5 \times 10^{11}$ cm$^{-3}$, then at some value of $n_0_{\text{max}}$ during the initial period of development stage the volume unsustained discharge (VUD) occurs. To minimize
the stage of VUD it is necessary to restrict the $n_0$ of the top. To estimate this value we assume that $U_0$ is an output voltage of pump generator, $Z$ is a wave impedance of discharge circuit, $U_p$ is a plasma voltage, $I$ is a current in discharge circuit. Therefore, plasma voltage is given by:

$$U_p = U_0 - IZ.$$ 

The discharge will be self-sustained under the condition $U_p \geq U_{qs}$, where from it is easy to find

$$n_0^{\max} \leq \frac{d(U_0/U_p-1)(\varepsilon \mu_e S)}{l^2},$$

$S$ is a discharge square. Then, considering that $\mu_e = 7 \times 10^{-2}\text{cm}^2/(\text{V} \cdot \text{s})$; $S = l \cdot h = l \cdot d$, where $l$ is a discharge length, $h$ is a discharge height, $l = 100-200$ cm, $Z = 5-3$ Ohm, for the mode of optimal energy input ($U_0 = 2U_{qs}$) we have $n_0^{\max} \leq 10^{13}$ cm$^{-3}$.

Thus, for producing extremely homogeneous volume self-sustained discharge in the mode of optimal energy input it is necessary that:

$$n_0^{\min} < n_0 < n_0^{\max}, \quad U_0 = 2U_{qs}, \quad w < w_{th}.$$ 

5. Experimental researches of conditions for initiation of extremely homogeneous SSVD in gas mixes CO$_2$: N$_2$: He

The considered theoretical model corresponds to the experimental results received earlier at initiation of SSVD by a low-current electron beam. The voltage on electron gun and beam current density were change in the following ranges

$$U_e = 160-220 \text{kV}, \quad j_e = 2-20 \text{mA/cm}^2 (n_0 = 10^7-10^{13}).$$

The duration of electron current $T_e$ was less than 1 $\mu$s. The pressure of gas mixtures was changed from 1 to 2 atm [3,4].

Figure 3 shows photographs of glowing SSVD ($w = 0.3 \text{J/cm}^3$ atm), the duration of discharge current was about 4 $\mu$s in gas mixture of CO$_2$:N$_2$:He = 1:2:3 at $p = 760$ torr with different values of plasma concentration $n_0$ forming by low-current electron beam in a gap with distance between electrodes $d = 9$ cm (cathode on the right). At relatively low preionization level ($n_0 = 5 \times 10^7$ cm$^{-3}$) a typical pattern of a discharge inherent to the exciting systems with an UV irradiation is observed. There were clearly visible inhomogeneities in the form of unfinished spark channels sprouting from the cathode by almost a third length of the electrode gap. A cathode directed channel starts growing from the anode. Even at $n_0 = 2 \times 10^{10}$ cm$^{-3}$ there is still a large number of channels regularly distributed over the cathode surface. They are likely to originate from cathode spots. And only at $n_0 = 5 \times 10^{11}$ cm$^{-3}$ the discharge takes on the shape of a completely uniform positive column with an evenly glowing narrow cathode sheath.

![Figure 3. Photographs of SSVD glowing in mixture CO$_2$:N$_2$:He = 1:2:3. a) $n_0 = 5 \times 10^7$ cm$^{-3}$; b) $n_0 = 2 \times 10^{10}$ cm$^{-3}$; c) $n_0 = 5 \times 10^{11}$ cm$^{-3}$. Anode is on the left side, cathode is on the right side. (Two dark vertical stripes do not apply to the discharge, they form due to support grid placed in front of discharge chamber window).](image)

An experiment was conducted to determine the duration of the stable burning of extremely homogeneous SSVD in the discharge volume $V \sim 60$ l with $d = 18.5$ cm and a total energy input of about 10 kJ. The current was elongated by incorporating of inductors into the discharge circuit. When the inductance $L = 30$ $\mu$H the total duration of the discharge current was $T = 10$ $\mu$s for mixture CO$_2$:N$_2$:He = 1:2:3 at atmospheric pressure.
6. Conclusions

The new approach for suppression of plasma inhomogeneities and instabilities in the self-sustained volume discharge is offered. It consists in two special aspects. The first aspect is in excluding the formation stage, at which main types of inhomogeneities arise, from development of the discharge. And the second one is not to exceed a threshold on a specific energy input at which the volume instabilities occur.

We offer the physical model and calculate the dependence of boundary concentration of initial electrons $n_0$ on the intensity of an electric field $E$ demanded for ignition of the self-sustained discharge at burning stage without the stage of discharge formation.

There were defined the conditions of obtaining extremely homogeneous self-sustained volume discharge (with full suppression of plasma inhomogeneities and instabilities) in the mode of an optimal energy input.

In the mixture CO$_2$:N$_2$:He = 1:2:3 of atmospheric pressure the self-sustained discharge in the volume of 60 litres with burning duration of 10 µs and total energy input of near 10 kJ is received. These values were limited by setup parameters and could be exceeded.

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