

Current interruption in a low-pressure high-current pulsed discharge with hollow cathode

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Abstract. This paper deals with the investigation of current interruption in the hollow-cathode discharge as applied to the electrode configuration of pseudospark switch. The phenomenon of interruption manifests itself at currents of several kiloamperes or higher and at a low gas pressure. It is demonstrated that the region of the hollow cathode is able to pass a high current density. The region that is responsible for the current interruption is the main gap of the switch, i.e., the positive column of discharge. The theoretical model of the positive column is proposed. The model implies that the gas ionization in the column is provided by the fast electrons which are accelerated in a double electric layer at the exit of cathode cavity. The estimates with a usage of the model are in agreement with the experimental data.

1. Introduction

This paper relates to investigations of the low-pressure pulsed glow discharges with hollow cathode. When we speak of the low pressure we imply that a neutral particle density is extremely small and electron free path for ionization exceeds a characteristic size of electrode system [1–4]. On the other hand, the neutral particles still play an essential role in forming gas-discharge plasma. Thus, the discharge regime keeps an intermediate position between the classical low-pressure discharge whose behavior is determined by electron avalanche ionization and the vacuum discharge that burns in cathode metal vapor [5–7].

There is a great variety of the gas-discharge devices functioning in the aforementioned regime. An illustrative example is the so-called pseudospark switch [1, 2, 8–13]. The electrode system of the switch typically consists of two cavities that communicate through axial bore holes. A bore hole diameter and a thickness of flat part of the cathode are comparable to the main gap spacing and amount to several millimeters. At a low gas pressure, the single electrons are not able to initiate the breakdown process in electrode system. A considerable prebreakdown electron flow is required for this purpose. Then a trigger unit, which is placed in the cathode cavity, is intended to provide a sufficient electron flow through the bore hole into the main gap.

In some applications, the current densities in the pseudospark electrode geometry reach incredibly high values and a space of bore hole plays a role of hollow cathode [2, 14, 15]. A total discharge current from the cathode cavity can reach of several kiloamperes and higher. One of the phenomena, characteristic of the discharge with a high current and a decreased pressure, is the so-called current



interruption or current quenching [15, 16]. This paper describes a model of current passage in the main gap of pseudospark switch that has been developed. Based on this model an interpretation of current interruption phenomenon is proposed.

2. Experimental arrangement and summary of experimental data

A schematic of experimental arrangement is shown in figure 1. The main interelectrode gap $d = 4$ mm is formed by the electrodes 1 and 2 with a diameter of central bore hole $D = 4$ mm. A thickness of the flat part of electrode 2 is $h = 4$ mm. The discharge is initiated due to the trigger system based on flashover [15, 16]. For instant of triggering a capacitor bank C_0 is charged to a voltage V_0 . A discharge burning voltage V_d (i.e., the voltage between electrodes 1 and 2) and the discharge current were recorded with a usage of resistive voltage dividers and a current shunt. Current measurements for the fast electron beam are provided by the Faraday cup FC located in the anode cavity.

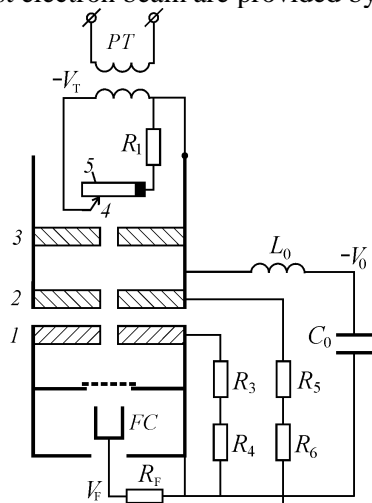


Figure 1. Schematic arrangement for investigations of the current interruption and generation of electron beam at the discharge axis in the pseudospark electrode system.

1—hollow anode, 2—hollow cathode with the bore hole at the axis, 3—baffle to separate the hollow cathode cavity from trigger system, 4—pointer contact to provide a surface breakdown over semiconductor cylinder 5. R_5/R_6 and R_3/R_4 are the resistive dividers for measuring a potential with respect to the ground. FC —Faraday cup for measuring electron beam current. $R_F = 25 \Omega$, $C_0 = 130$ nF, $L_0 = (27\text{--}300)$ nH.

Typical waveforms for different gas pressures are shown in figure 2. At the stage of lag time to breakdown, the voltage at the gap corresponds to V_0 . Increase in the discharge current during development of breakdown is accompanied by the sharp decreasing in the discharge burning voltage. As shown in [2, 14–16], in the high-current stages the discharge burns in the regimes of the so-called dense glow and superdense glow.

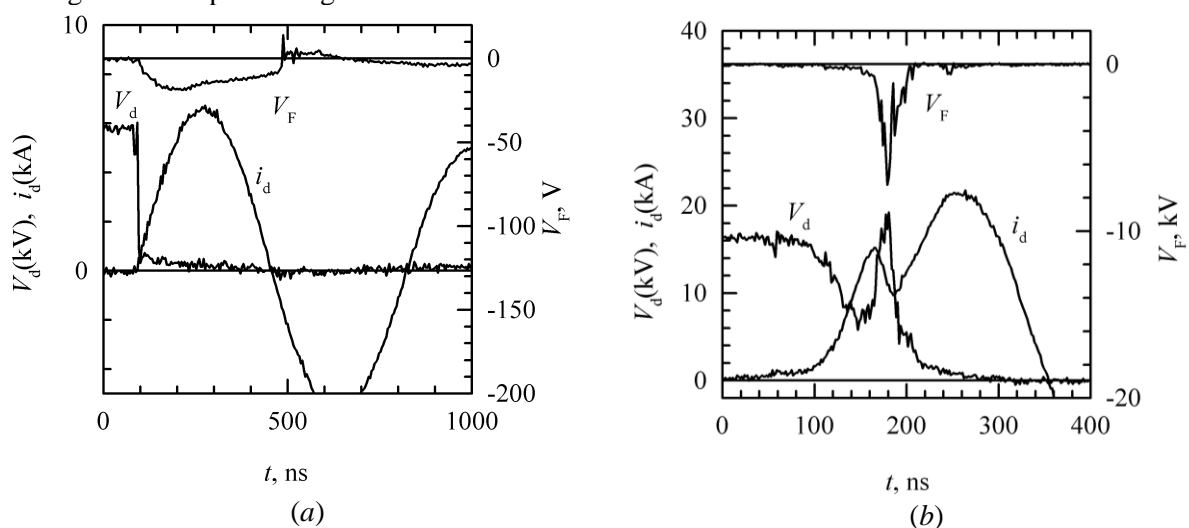


Figure 2. Current and voltage waveforms for discharge in xenon. $C_0 = 130$ nF. Current interruption is (a) absent and (b) available. (a) $L_0 = 100$ nH, $p \approx 2 \cdot 10^{-2}$ Torr. (b) $L_0 = 27$ nH, $p \approx 2 \cdot 10^{-3}$ Torr.

We can see that for a pressure $p \approx 2 \cdot 10^{-2}$ Torr the current waveform has a smooth shape, while decreasing a pressure to $p \approx 2 \cdot 10^{-3}$ Torr results in a sharp current interruption starting an instant $t = 170$ ns. Simultaneously, the inductive voltage kick is applied to interelectrode gap. A general tendency is that the current interruption manifests itself at a low pressure, for an enhanced discharge current and for short pulse duration.

In some papers, the effect of current interruption is associated with the processes inside the bore hole [17]. However, it seems [3, 15, 16] that the main physical processes responsible for the effect occur in the plasma column of the main gap. Then the description of the model of plasma column is presented below.

3. Description of the model and interpretations

Schematic of the discharge regions and the potential distributions for the temporal stage of the dense glow discharge is shown in figure 3. The space inside the hollow cathode C is filled with the negative glow plasma NG . Note that as applied to the pseudospark discharge a space of bore hole can play a role of the hollow cathode. The plasma is sustained due to gas ionization by the fast electrons which are emitted from a surface of hollow cathode and are accelerated in the cathode voltage drop region l_c .

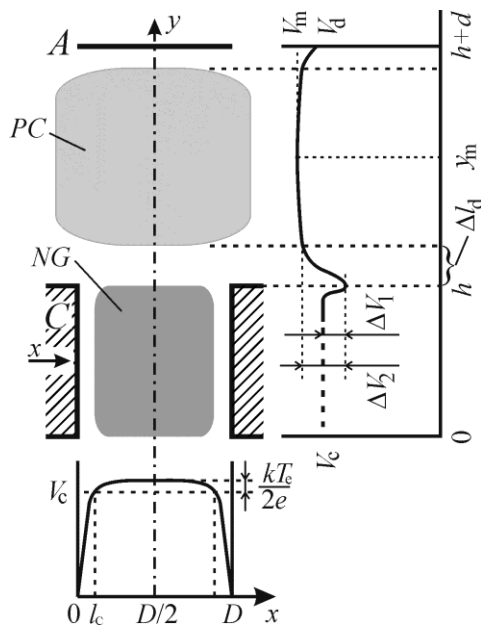


Figure 3. Schematic of the discharge regions and the potential distributions for electrode geometry of pseudospark discharge.

At the exit of hollow cathode, a negative potential barrier ΔV_1 is available. The role of the barrier is to restrict an electron current emitted from the negative glow plasma in anode direction. The emission current has to be approximately equal to a total discharge current so that the height of potential barrier is established self consistently to satisfy this condition. The negative glow region represents a potential trap for the fast electrons, and an efficient plasma generation in this region is provided due to the hollow-cathode effect.

The main gap d is filled with the positive column plasma PC . The column is separated from the negative glow by a double electric layer Δl_d [15]. The electrons those are able to overcome the potential barrier ΔV_1 are accelerated by the voltage ΔV_2 and provide the gas ionization in the positive column. Due to a balance between the rate of ionization and the rate of losses of the charged particles, a steady state plasma density in the column is established ($n_i \approx n_e$). Conceptually, a role of potential

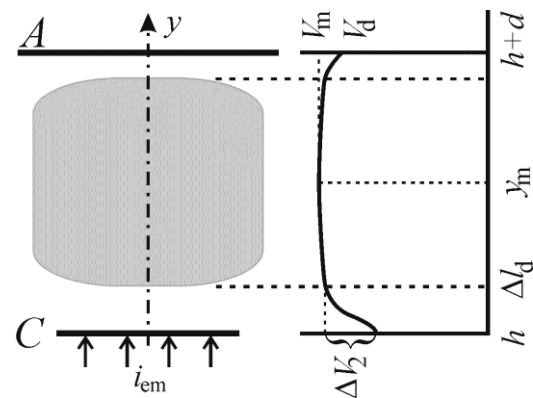


Figure 4. Schematic of the discharge regions and the potential distribution illustrating the model of current sustaining in the main gap.

drop ΔV_2 is the same as a role of the cathode voltage drop V_c in the hollow cathode. An electron current flows to the anode A from the positive column plasma. This current is controlled by a value of negative anode potential drop $\Delta V = (V_m - V_d)$.

To simplify the description of the positive column plasma we suppose that a certain emission current i_{em} enters into the column from a virtual cathode which is located in the plane $y = h$ (see figure 4). This current can be considered as an external current with respect to the main gap d .

Formally, the region of positive column also represents a potential trap for the plasma electrons. However, the effect of electron oscillations is expressed not so distinctively as that in the hollow cathode. A gas pressure in the discharge under consideration is rather low and some of the electrons, accelerated in the layer Δl_d , will go to the anode without ionizing collisions. These electrons, jointly with the plasma electrons, contribute to the total electron current at the anode. On the other hand, as shown in [2, 3], the plasma in the main gap can be generated if only a neutral particle density exceeds a certain critical value $n_a = n_{cr}$. Otherwise, the region between the cathode C and anode A will represent not a plasma gap with a high conductivity but a vacuum diode with low ion neutralization. Such a diode has a high resistance and is able to withstand a voltage of several tens of kilovolts without plasma generation. Similar regime is used in the sources of electron beams with plasma cathode [6].

For the stage of lag time to breakdown, n_{cr} is determined by the relation [3]:

$$n_{cr} \sigma_i d \left(\frac{M}{3m} \right)^{1/2} = \frac{d}{\lambda_i} \left(\frac{M}{3m} \right)^{1/2} = 1, \quad (1)$$

where σ_i is the average cross for ionization of the neutral particles by the electrons accelerated in the layer Δl_d , λ_i is the electron free path for ionization, M/m is the ratio of the ion mass to the mass of electron.

According to the model, in order that the positive column plasma be sustained, the neutral particle density has to exceed the critical value. On the other hand, as distinct to classical glow discharge or a high-pressure pulsed volume discharge [18–20], the neutral particle density is still rather low so that the number of ionizations produced by a single electron at the length of column $d/\lambda_i < 1$.

Establishing of a steady state plasma density in the column is provided as a result of balance between the rate of gas ionization and the rate of outflow of the charged particles to electrodes. The ions originated to the left of the point of potential maximum y_m travel to the cathode under the effect of potential difference $kT_e/2e$, thus providing the ion current i_{ic} . The ions originated to the right of the point y_m provide the ion current i_{ia} at the anode.

Ignoring the secondary processes at the cathode surface, we can write an expression for a total current at the cathode:

$$i = i(h) = i_{em} + i_{ic}. \quad (2)$$

The same current value should be provided at the anode. This current is added from the components entering to the following equation:

$$i = i_{eb} + i_{ep} - i_{ia} = i_{em} \left(1 - \frac{d}{\lambda_i} \right) + S \frac{1}{4} e n_e v_e \exp \left(\frac{e \Delta V}{k T_e} \right) - i_{ia}, \quad (3)$$

where i_{eb} is the current of a fast electron beam (i.e., the current of the electrons which did not collide with the atoms while going to anode), i_{ep} is the current of the electrons from plasma that are able to overcome the potential barrier $e \Delta V$, S is the discharge area at the anode, $v_e = (8kT_e/\pi m)^{1/2}$ is the average thermal velocity of electrons.

In the further consideration we suppose that $i_{ia} \approx 0$ that is the point y_m is located near the anode. The positive column contains the plasma electrons and ions ($n_e \approx n_i$) and also the fast electrons of the electron beam whose density is n_{eb} . The rate of ionization can be written as

$$\Psi = \frac{1}{e} \frac{j_{em}}{S} n_a \sigma_i = \frac{j_{em}}{e} n_a \sigma_i. \quad (4)$$

Taking into account that an average time of ion outflow from the gap $T_i = d(M/kT_e)^{1/2}$, we readily obtain the equation for plasma density in the positive column:

$$n_e = n_i = \Psi T_i = \frac{1}{e} \frac{j_{em}}{S} n_a \sigma_i d \left(\frac{M}{kT_e} \right)^{1/2}. \quad (5)$$

The region of positive column can be treated as an ionization chamber in which the originated ions go to the cathode. The same value of electron current has to flow to the anode via the potential barrier ΔV . Beside that, the fast electrons which appear in the column due to thermalization also have to leave the plasma column. Then for the current to the anode from plasma we obtain

$$i_{ep} = 2i_{em} n_a \sigma_i d. \quad (6)$$

A maximum possible current from plasma essentially exceeds i_{ep} . Then it would be concluded that the plasma is always able to carry the necessary electron current to anode. However, this situation holds true if only the gap d actually represents a plasma filled diode with the cathode layer Δl_d , but not a vacuum diode with a low ion neutralization. In other words, the plasma has to play important additional role that is to neutralize the excess space charge of electron beam. It means that the condition $n_e \gg n_{eb}$ has to be fulfilled.

At the exit of the double electric layer, the fast electrons has a velocity $v_{eb} = (2e\Delta V_2/m)^{1/2}$, and then

$$n_{eb} = \frac{j_{eb}}{ev_{eb}} = \frac{1}{e} \frac{j_{em}(1 - n_a \sigma_i d)}{S} \left(\frac{m}{2e\Delta V_2} \right)^{1/2}. \quad (7)$$

To compare n_e and n_{eb} we can use the relation that allows interpreting different current regimes and the conditions of current interruption

$$\frac{n_e}{n_{eb}} = \frac{n_a \sigma_i d}{1 - n_a \sigma_i d} \left(\frac{M}{3m} \right)^{1/2} \left(\frac{6e\Delta V_2}{kT_e} \right)^{1/2}. \quad (8)$$

It is seen that with the condition $n_a \approx n_{cr}$ the ratio $n_e/n_{eb} \approx (6e\Delta V_2/kT_e)^{1/2}$ essentially exceeds unity only for high values of voltage $\Delta V_2 = (10-20)$ kV. Such conditions are characteristic of the stage of lag time to breakdown. Transition to a high-current stage and low voltage ΔV_2 is inevitably accompanied by the current interruption. Note that the regime with a high voltage at the double electric layer is used in the electron sources with plasma cathode [6] where $n_a \leq n_{cr}$. To provide the high-current discharge at a voltage ΔV_2 less than several hundred volts it is necessary to have $n_a \gg n_{cr}$.

The regimes in which the current interruption is absent are determined not only by neutral particle density but also by total discharge current and current risetime, i.e., by the pulse duration. Figure 2a shows that for discharge in xenon at a pressure $p = 2 \cdot 10^{-2}$ Torr ($n_a/n_{cr} \approx 50$) the current waveform has a smooth shape. However, a decrease in pulse duration and an increase in current due to decreasing the inductance of electric lead to unstable regime of the current sustaining.

The illustrative example of current interruption is shown in figure 2b. Here, besides decreasing the pressure, the total discharge current has been increased to 20 kA. With such a current we have extremely high current density via bore hole, so that inside the hole the multicharged plasma is generated. Due to hollow cathode effect the plasma is able to be sustained and the bore hole region is able to pass the current. The effect of electron oscillations in the positive column is expressed not so distinctively as that in the cathode cavity. Correspondingly, a possibility of production of the multicharged ions in the positive column formally means that the ionization cross section in equation

(8) becomes much lower as compared to the regime of low current. In other words this is one more physical reason which encourages an increase in voltage ΔV_2 that is the current interruption.

Acknowledgments

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