

## Recovery of the electric strength in a cold cathode thyatron

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**Abstract.** The paper deals with the investigations of the recovery process of electric strength in a cold cathode thyatron. Method which allows extracting the plasma of the preceding discharge not only from the cathode cavity but also from the main gap of the thyatron is proposed. Method is based on the usage of a low-current nonsteady state discharge in the pause between the pulses.

### 1. Introduction

The cold cathode thyatron (or the pseudospark switch) is considered as an advanced alternative to ignitrons and vacuum switches in the facilities that require an extremely high current [1–9]. The triggering with a small jitter makes it possible to use the pseudospark switch instead of the classical thyratrons in the electric circuits with a fast current rise. In general, the principle of operation of the pseudospark switch resembles that for the classical thyatron [4]. On the one hand, a usage of the cold cathode is quite definite advantage from the viewpoint of increasing the switching current [3–5]. On the other hand, the problem of increasing the pulse repetition rate in the pseudospark switch is more severe than that in the thyatron with hot cathode [4, 10, 11].

The upper level of the pulse repetition rate in the switch is determined by the conditions when a characteristic recombination time for plasma in the gap becomes comparable with the time interval between the pulses [11–15]. In these conditions, a residual plasma from a preceding discharge remains in the gap to the instant when a successive pulse arrives to the electrodes thereby the pulsed breakdown voltage for the switch decreases.

One of the methods to enhance a limited value of the pulse repetition rate is based on the idea to extract the products of the preceding breakdown from the cathode cavity in the pause between the pulses. For this purpose a so-called blocking electrodes can be applicable [2, 11]. These electrodes are intended to extract the electrons from the cathode cavity and to suppress the prebreakdown electron current in the main gap.

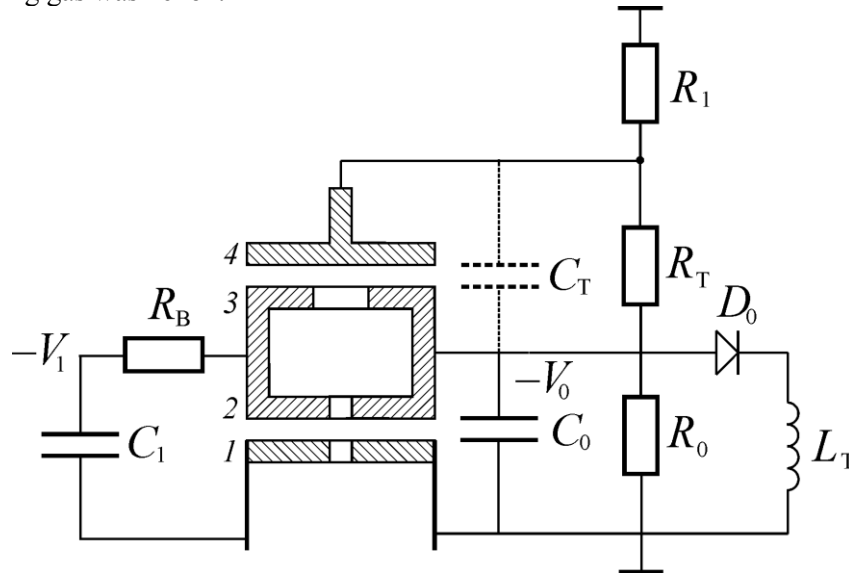
In this paper we investigate the method which allows extracting the plasma of the preceding discharge not only from the cathode cavity but also from the main gap of the switch. This method also allows us to obtain the information on the process of deionization in the main gap.

### 2. Experimental setup and principle of operation of the electric circuit

To investigate the recovery process of the main gap we used the electric circuit shown in figure 1. The main electrode system of the thyatron is formed by grounded anode 1 and hollow cathode 2. The main gap distance, the borehole diameters, and the thickness of the flat part of electrodes 1 and 2 are



equal to each other and amount to 4 mm. A thickness of the upper flat part of electrode 3 is 1 mm and an aperture diameter is 12 mm. A height of the cathode cavity  $h = 16$  mm and its diameter  $D_c = 30$  mm. The working gas was xenon.



**Figure 1.** Design of electrode system and electric circuit.  $C_0 = 1$  nF,  $R_0 = 70$  k $\Omega$ ,  $R_1 = 100$  k $\Omega$ ,  $R_T = 100$  k $\Omega$  or  $\infty$ ,  $R_B = (10 - 100)$  k $\Omega$ ,  $C_T$  is the parasitic capacitance of the gap 3–4.

The principle of operation of the electric circuit can be described as follows. The main gap 1–2 is powered by means of a low-inductance circuit from a capacitor bank  $C_0$ , which is charged to a voltage  $V_0$  from the pulsed transformer  $L_T$  during a typical time of about 5  $\mu$ s and larger. Some fraction of the voltage  $V_0$  is derived to electrode 4 due to the active divider  $R_T - R_1$  or due to divider  $C_T - R_1$  (when  $R_T = \infty$ ). Electrode 4 can be considered as the blocking electrode [11]. The essence of the blocking effect seems to be as follows. With respect to the main cathode cavity 2, the potential  $V_4$  of the electrode 4 is positive, and electrons can be extracted from the main cathode cavity 2 to electrode 4 via the aperture in electrode 3. Then, the process of discharge initiation in the main gap is suppressed that allows operating the switch with an enhanced pulsed breakdown voltage.

Enhancing in efficiency of the blocking effect is achieved when the additional DC power supply  $V_1$  is used. A low voltage of about 200 V and less is applied to the main gap. This voltage is not sufficient for appearing a self-sustained discharge [11–13, 16]. However, due to this voltage a certain nonself-sustained current is available in the main gap not only in the time interval during the charging of the capacitor  $C_0$  but also in the pause between the pulses.

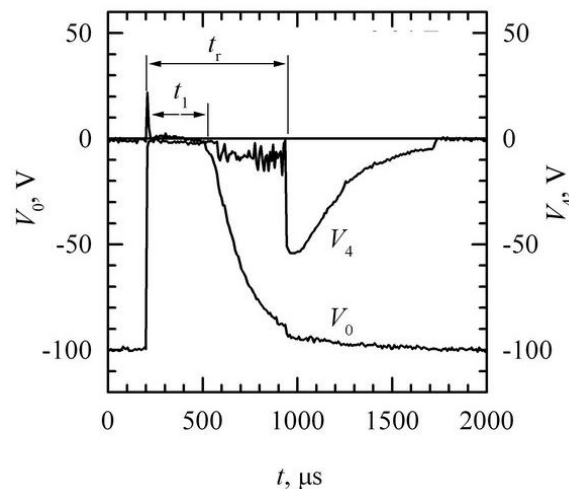
In the experiments we measured the voltage  $V_0$  between the electrodes 2 and 1 (i. e., the potential of electrode 3 with respect to the ground) and the potential  $V_4$  of electrode 4 with respect to the ground. In the initial conditions the main capacitor  $C_0$  is charged to the voltage  $V_1$  ( $R_0 \gg R_B$ ). When the high-voltage pulse appears at the capacitor  $C_0$  the self-breakdown in the main gap can occur. Typical breakdown current is about 1 kA and period of the current oscillations is 60 ns.

As a result of the breakdown the discharge plasma appears in the main gap and in the main cathode cavity 2 so that the current from power supply  $V_1$  flows in the gap in the pause between the pulses. This current is determined by the voltage  $V_1$ , the ballast resistor  $R_B$ , and by the properties of the plasma in the main gap. The voltage  $V_1$  and the resistance  $R_B$  are selected from the condition of preventing the self-sustained discharge in the gap 1–2 (the voltage  $V_1$  is lower than the discharge burning voltage for a glow type of discharge [12, 16]). Correspondingly, measurements of the potential  $V_0$  during breakdown and in the pause between the pulses offer a possibility to investigate the process of recovering the electric strength for the main gap.

### 3. Results and discussion

Typical voltage waveforms are shown in figure 2. On the basis of these waveforms we can envision the following interpretation of the processes in the main gap and in the cathode cavity.

In the initial conditions the capacitance  $C_0$  is under a voltage  $V_1 = 100$  V (the time interval before  $t = 200$   $\mu$ s). When the high voltage pulse is formed by the pulsed transformer  $L_T$  the capacitance  $C_0$  is charged to a voltage  $V_0 = 3$  kV for a time of about 5  $\mu$ s and the self-breakdown of the main gap occurs. The instant of breakdown corresponds to  $t = 200$   $\mu$ s. Then the capacitor bank  $C_0$  is completely discharged via the main gap. (Note that the voltage pulse of 3 kV is not visible in figure 2 since the pulse duration of 5  $\mu$ s is much less than the oscilloscope time scale).



**Figure 2.** Voltage waveforms at electrode 4 and at the main gap.  $p = 0.04$  Torr,  $V_0 = 3$  kV,  $V_1 = 100$  V,  $R_B = 10$  k $\Omega$ ,  $R_0 = 70$  k $\Omega$ ,  $R_1 = 100$  k $\Omega$ ,  $R_T = \infty$ .

As a result of the breakdown the gas discharge plasma of a high density is generated in the main gap and in the cavity 2 so that the current from the power supply  $V_1$  starts flowing through this plasma. During the time interval  $t_1$  we can speak of a low-current discharge with extremely low discharge burning voltage. The gas discharge plasma seems to be a short-circuiting bridge for power supplier  $V_1$ . Correspondingly, the potentials  $V_0$  and  $V_4$  are close to zero. At this stage the plasma density in the main gap decreases mainly due to volume recombination processes and due ambipolar diffusion to the surface of the electrodes.

After the time interval  $t_1$  the plasma density decreases in such extent that the total resistance of the gap 1–2 becomes comparable with the resistance of  $R_B$  and  $R_0$ . It means that the capacitor  $C_0$  becomes to charge from the power supplier  $V_1$ . However the charging time is still larger than  $C_0 R_B = 100$   $\mu$ s. In other words, the resistance of the main gap gradually increases with time, which leads to increasing the voltage  $V_0$ . As applied to this stage we can say that the charge carriers are extracted from the main gap due to the voltage  $V_0$ . In succeeding description for the sake of definiteness we will use the term "extracting current" for the current between the electrodes 1 and 2 and the term "blocking current" for the current to electrode 4.

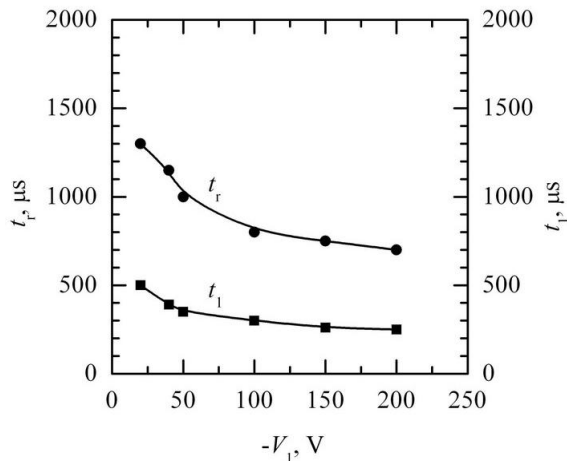
A special case is the behavior of the voltage  $V_4$  at the stage under discussion. Note that for the conditions in figure 2 the resistor  $R_T$  is absent ( $R_T = \infty$ ) and the voltage  $V_4$  is determined by the spurious capacitance  $C_T$ , by the resistor  $R_1$ , and by the properties of the discharge between the hollow cathode 2 and electrode 4. If the voltage  $V_4$  was equal to zero, we would definitely say that the residual gas discharge plasma in the gap 2–4 is absent. In these conditions the capacitor  $C_T$  would be charged to a voltage  $V_0$  at each instant of time (a characteristic charging time for this capacitor is extremely small,  $C_T R_1 = 2$   $\mu$ s).

If the gap 2–4 was filled with high-density plasma, than the voltage  $V_4$  would be equal to  $V_0$ . For our particular case we observe the chaotic oscillations in the voltage  $V_4$  at the stage  $(t_r - t_1)$ . It means that a low-density plasma is available in the gap 2–4. A blocking current through this plasma is responsible for the voltage behavior at the resistor  $R_1$ .

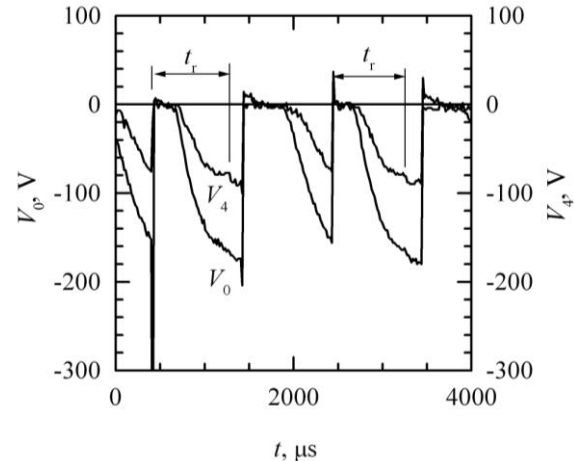
At the instant  $t_r$  the abrupt increase in the voltage  $V_0$  is observed. We interpret it as a complete de-ionization of the main gap (the charge carriers have been extracted from the main gap to the instant  $t_r$ ). As a result, the charging time for the capacitance  $C_0$  becomes to determine by the resistor  $R_B$  which is accompanied by the fast rise in the voltage  $V_0$ . Simultaneously, the abrupt increase in the voltage  $V_4$  takes place. According to the above interpretation we can say that the current from power supply  $V_1$  is intercepted by the blocking discharge which burns in the gap 2–4. The initial current of this discharge is equal to  $V_4/R_1 = 0.55$  mA. After the time  $t_r$  the charge carriers continue to be extracted from the gap 2–4. Correspondingly, the voltage drop at the gap 2–4 increases and potential  $V_4$  decreases. To a time  $t = 1600$   $\mu$ s the non-self sustained blocking discharge in the gap 2–4 is stopped.

The time interval  $t_r$  corresponds to complete recovering of the electric strength of the main gap. After the time  $t_r$  a small current is still available in the gap 2–4. This current can be considered as a blocking current, which is useful from the viewpoint of preventing an occasional breakdown in the main gap when a successive voltage pulse arrives [11].

The summary of experimental data on measuring the time  $t_r$  is presented in figure 3. We fixed the value  $R_B = 10$  k $\Omega$  and changed the voltage  $V_1$ . It should be stressed that the voltage  $V_1$  cannot be increased unlimitedly. With a high voltage  $V_1$  the situation is possible when the voltage drop at the main gap achieves of about 250 V. Then a steady state self-sustained glow discharge appears in the main gap. It is evident that the electric strength of the gap decreases dramatically in this case. With taking this fact into account we normally use the voltage  $V_1$  at a level of 200 V and less.



**Figure 3.** Recovery time  $t_r$  and time  $t_1$  versus the voltage of power supplier  $V_1$ .  $R_B = 10$  k $\Omega$ ,  $R_1 = 100$  k $\Omega$ ,  $R_T = \infty$ ,  $p = 0.03$  Torr.



**Figure 4.** Voltage waveforms at electrode 4 and at the main gap.  $V_0 = 4$  kV,  $V_1 = 200$  V,  $R_B = 100$  k $\Omega$ ,  $R_1 = 100$  k $\Omega$ ,  $R_T = 100$  k $\Omega$ ,  $p = 0.04$  Torr.

Due to an increase in the extracting current the time  $t_r$  can be decreased approximately by two times. However, the curve saturates and we obtain a minimal  $t_r \approx 800$   $\mu$ s. Note that a decrease in the time  $t_r$  is mainly due to reduction of the first stage of recovering (the time  $t_1$ ).

The recovery time  $t_r$  is influenced both the extracting current between the electrodes 1 and 2 the blocking current between the electrodes 3 and 4. As for the latter, we can vary this current by means of variation of the voltage  $(V_0 - V_4)$  across the gap 3 - 4. A convenient method to do it is to insert the

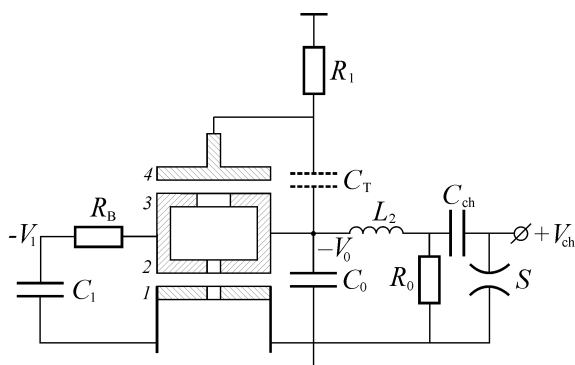
resistor  $R_T$  in the circuit. Then the relation between  $R_T$  and  $R_1$  determines the potential difference ( $V_0 - V_4$ ).

Figure 4 shows voltage waveforms at the electrode 4 and at the main gap for the conditions of figure 2, but a resistor  $R_T = 100 \text{ k}\Omega$  is available in the circuit. The time scale is chosen from the consideration to demonstrate four pulses at the main gap, which follow one after another at the times:  $t_1 = 400 \text{ }\mu\text{s}$ ,  $t_2 = 1400 \text{ }\mu\text{s}$ ,  $t_3 = 2400 \text{ }\mu\text{s}$ , and  $t_4 = 3400 \text{ }\mu\text{s}$ . We can see that in the time interval ( $t_2 - t_1$ ) the gap is completely recovered its electric strength. Then at an instant  $t_2$  breakdown in the main gap occurs, and breakdown voltage  $V_{br} = V_0 = 4 \text{ kV}$ . After that, in the time interval ( $t_3 - t_2$ ), the recovery time is larger than  $1000 \text{ }\mu\text{s}$ . As a result, at an instant  $t_3$  we have the breakdown at low voltage ( $V_{br} \approx 1.5 \text{ kV}$ ). Then again, in the pause ( $t_4 - t_3$ ) the time  $t_r$  becomes less than  $1000 \text{ }\mu\text{s}$ , and the breakdown occurs at a high voltage and so on.

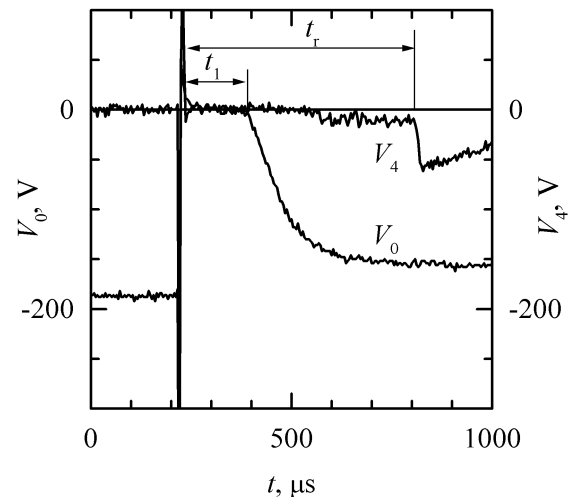
A characteristic feature of the above described experiments is that we used the main capacitor bank  $C_0 = 1 \text{ nF}$ . In this case we can obtain a high pulse repetition rate but a value of the main discharge current is rather small for these conditions (less then  $500 \text{ A}$ ). It could be expected that the discharge current in the main gap would influence to its recovery process. However with the electric circuits that we currently have we are not able to provide simultaneously both a large value of  $C_0$  and a high pulse repetition rate.

On the other hand the method of measurements that we have proposed allows us to obtain direct information on recovery time for the main gap. The experiments presented below are the investigation of the recovery process in the main gap for a high value of capacitor bank ( $C_0 = 35 \text{ nF}$ ) and correspondingly for a high pulsed discharge current.

Experimental arrangement is shown in figure 5. Here the intermediate capacitor bank  $C_{ch} = 35 \text{ nF}$  is charged by a positive voltage from the power supply  $V_{ch}$ . After closing the pseudospark switch  $S$  the resonant charging of the main capacitor bank  $C_0$  occurs and the voltage pulse with a voltage rise time of  $5 \text{ }\mu\text{s}$  forms at the main gap. The main gap operates in self-breakdown mode. Due to the power supply  $V_1$  an extracting voltage up to  $200 \text{ V}$  is attached to the main gap in the pause between the pulses.



**Figure 5.** Design of electrode system and electric circuit for investigation of the recovery of the main gap at a high value of  $C_0$ .  $C_T$  is the parasitic capacitance of the gap 3 – 4;  $C_0 = 35 \text{ nF}$ ,  $C_{ch} = 35 \text{ nF}$ ,  $R_0 = 50 \text{ k}\Omega$ ,  $R_1 = 100 \text{ k}\Omega$ ,  $R_B = 1 \text{ k}\Omega$ .



**Figure 6.** Voltage waveforms for the electric circuit shown in figure 5.  $V_1 = 200 \text{ V}$ ,  $R_B = 1 \text{ k}\Omega$ ,  $R_1 = 100 \text{ k}\Omega$ ,  $R_T = \infty$ ,  $V_0 = 4 \text{ kV}$ ,  $p = 0.05 \text{ Torr}$ .

Typical voltage waveforms are shown in figure 6. The maximum current in this case is about  $4 \text{ kA}$ . The presented data allows us to estimate the recovery time for the main gap as  $t_r \approx 600 \text{ }\mu\text{s}$ . It means

that an essential increase in the discharge current does not lead to increasing the recovery time. The pulse repetition rate for the pseudospark gap in similar regime can be at a level of 1000 Hz.

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