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Recovery of the electric strength in a cold cathode thyratron

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Abstract. The paper deals with the investigations of the recovery process of electric strength in a cold cathode thyratron. Method which allows extracting the plasma of the preceding discharge not only from the cathode cavity but also from the main gap of the thyratron 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 thyratron (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 thyratron [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 thyratron 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 thyratron 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.

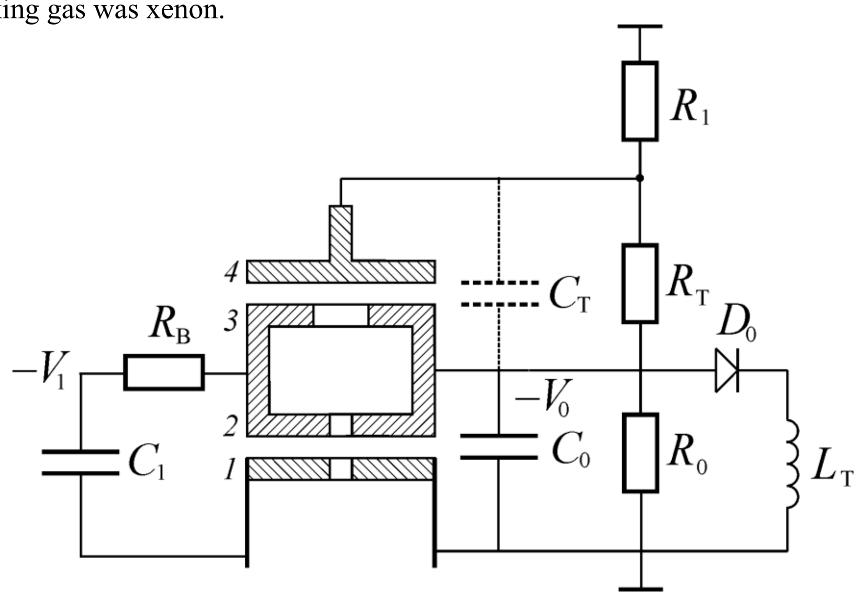

Figure 1. Design of electrode system and electric circuit. C_0 = 1 nF, R_0 = 70 kΩ, R_1 = 100 kΩ, R_T = 100 kΩ or ∞, R_B = (10 – 100) kΩ, C_T is the parasitic capacitance of the gap *3–4*.

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 μs 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.

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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 μs). 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 μs and the self-breakdown of the main gap occurs. The instant of breakdown corresponds to t = 200 μs. 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 μs is much less than the oscilloscope time scale).

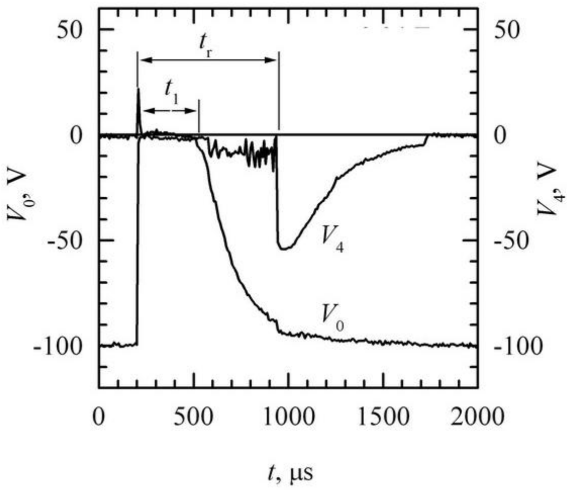

Figure 2. Voltage waveforms at electrode *4* and at the main gap. p = 0.04 Torr, V_0 = 3 kV, V_1 = 100 V, R_B = 10 kΩ, R_0 = 70 kΩ, R_1 = 100 kΩ, R_T = ∞.

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_0R_B = 100 μs. 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= ∞) 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_TR_1 = 2 μs).

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 μs 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 kΩ 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.

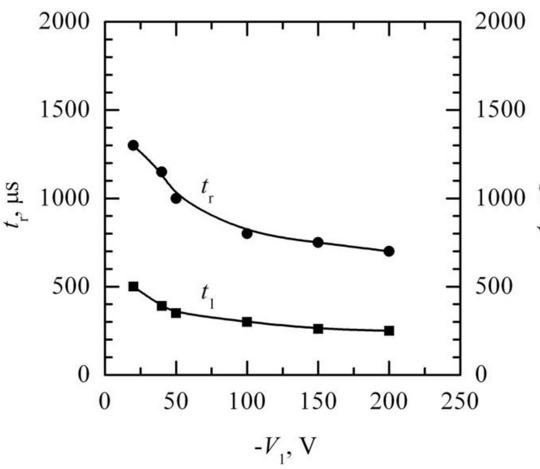

Figure 3. Recovery time t_r and time t_1 versus the voltage of power supplier V_1. R_B = 10 kΩ, R_1 = 100 kΩ, R_T = ∞, p = 0.03 Torr.

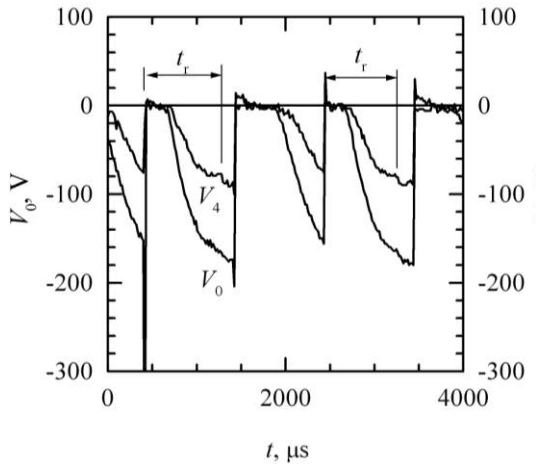

Figure 4. Voltage waveforms at electrode *4* and at the main gap. V_0 = 4 kV, V_1 = 200 V, R_B = 100 kΩ, R_1 = 100 kΩ, R_T = 100 kΩ, p = 0.04 Torr.

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 μs. 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 kΩ 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 μs, t_2 = 1400 μs, t_3 = 2400 μs, and t_4 = 3400 μs. 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 kV. After that, in the time interval ($t_3 - t_2$), the recovery time is larger than 1000 μs. As a result, at an instant t_3 we have the breakdown at low voltage ($V_{br} \approx$ 1.5 kV). Then again, in the pause ($t_4 - t_3$) the time t_r becomes less than 1000 μs, 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 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 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 nF) and correspondingly for a high pulsed discharge current.

Experimental arrangement is shown in figure 5. Here the intermediate capacitor bank C_{ch} = 35 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 μs 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 V is attached to the main gap in the pause between the pulses.

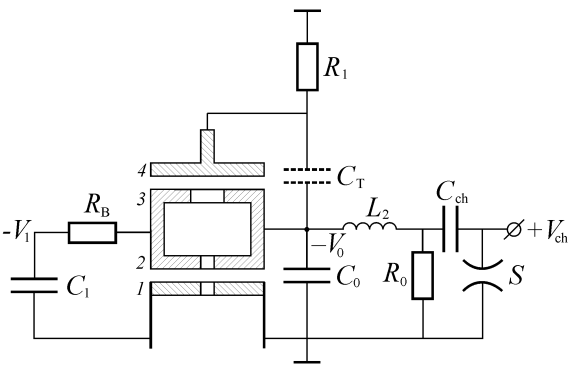

Figure 5. Design of electrode system and electric circuit for investigation of the recovery of the main gap at a high value of C_0. C_T is the parasitic capacitance of the gap *3 – 4*; C_0 = 35 nF, C_{ch} = 35 nF, R_0 = 50 kΩ, R_1 = 100 kΩ, R_B = 1 kΩ.

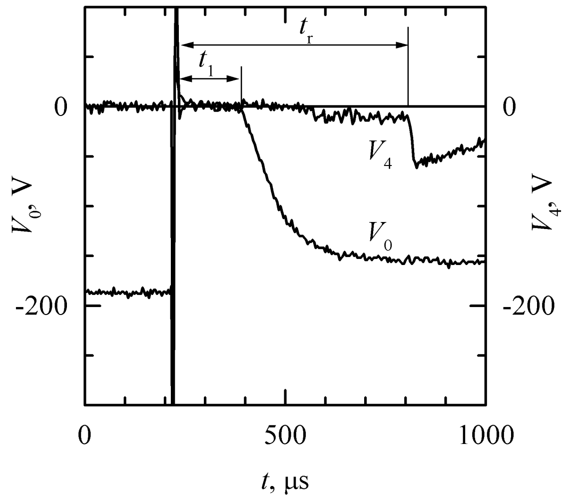

Figure 6.Voltage waveforms for the electric circuit shown in figure 5. V_1 = 200 V, R_B = 1 kΩ, R_1 = 100 kΩ, $R_T = \infty$, V_0 = 4 kV, p = 0.05 Torr.

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

Acknowledgments
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