Features of the discharge ignition in the trigger unit of the cold-cathode thyratron

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Abstract. The sealed-off cold-cathode thyratron TPI1-10k/50 type with a newly developed trigger unit based on auxiliary glow discharge is investigated. As distinct from the commercially produced sealed-off thyratrons, in the thyratron under investigation the high-emissivity tablet is not used. Features of ignition of the trigger discharge are considered. It has been revealed that the delay time to breakdown in the trigger unit and a jitter in the delay time decrease with an increase in working gas pressure. The delay time can be significantly decreased due to availability of the so-called parasitic current in the electrode system of trigger unit. A capability of the thyratron operation with a stability in delay time no more than 4 ns is demonstrated.

1. Introduction
Since the end of 1980s, considerable interest has been generated in a new type of low-pressure high-current switching device with a cold cathode, often named the pseudospark switch [1-7]. The principle of function of the switch and its design resembles that of a classical thyratron with a hot cathode. The main gap of the device includes in itself a plane or hollow anode and a hollow cathode, which plays a role of a grid in classical thyratron. In some methods of the switch triggering, the grid is grounded. Then the terms a cold-cathode thyratron or a grounded-grid thyratron are also used in the literature [1, 5-7].

A range of operating pressures in the thyratron corresponds to the conditions of the left branch of Paschen’s curve. Under such conditions the electron free path for ionization is much in excess of the electrode separation. For both self-breakdown in the main gap of the switch and for the external discharge triggering a considerable pre-breakdown electron current is required [5, 6]. In the case of external triggering, this current is provided due to a special trigger unit that is placed in the cathode cavity of the main gap [1-4, 8-14].

Trigger unit is intended for the generation of high-density plasma inside the main cathode cavity at a certain instant of time. This plasma is generated due to applying a trigger pulse between the main cathode cavity and one of the electrodes of the trigger unit. Due to breakdown in this electrode system, the trigger discharge with a current of about 20 A appears. Then an electron flow is extracted from the trigger discharge plasma into the main gap, so that the high-current discharge in the main gap is initiated in accordance with the mechanism described in [5].

The results of studies and applications of the cold-cathode thyratrons that use demountable experimental chambers were described, for example, in [1, 7, 8, 10-15]. By now, the sealed-off metal-ceramic devices have been developed and manufactured [3, 4, 6, 9]. The first devices have been
described in the review [6]. Currently, these devices are commercially produced in the Pulsed Technology Ltd. (Ryazan, Russia, http://www.pulsetech.ru) [6, 9, 16-19]. Different triggering methods have been employed in these devices. In particular, in the thyratrons of the TPI type, the trigger unit is based on an auxiliary glow discharge [6, 9, 16, 17].

The electrode arrangement of the trigger unit of TPI type thyratron consists of a hollow cathode and a ring anode located inside the cathode cavity. A specific feature of trigger unit is the presence of a high-emissivity tablet in the cathode cavity. The tablet is intended to assist the ignition of the auxiliary discharge and to reduce the discharge burning voltage. The tablet is placed at the bottom of the cathode cavity. It represents a 10-mm-diameter cylinder fabricated by means of hot pressing of a powder material. The influence of the tablet composition on the operating regime of the device has been previously studied in [16-19].

In particular, depending on the tablet composition the different regimes of the auxiliary glow discharge in the trigger unit can be realized. In some cases these regimes are temporary unstable, i.e. the spontaneous transitions from one regime to another may occur. In turn, the conditions of the auxiliary discharge burning influence to the delay time to breakdown in the main gap of the switch. Then the problem of nanosecond triggering for the device from pulse to pulse arises.

To overcome the problem, we have developed the novel trigger unit in which the high-emissivity tablet is absent. This unit has been incorporated in the main electrode system of the sealed-off thyratron TPI1-10k/50. Thus, the results of the investigations of discharge in the trigger unit as applied to the new version of the thyratron are presented in this paper. Data on the delay times to breakdown in the trigger system and in the main gap are discussed. The ability of the switch operation with the nanosecond stability at a high anode voltages is demonstrated.

2. Experimental setup

Figure 1 shows a schematic of the thyratron with the new trigger unit and one of the possible trigger circuits. Here, the thyratron is connected in the electric circuit for commuting the capacitance \( C_0 \) (charged to a voltage \( V_0 \)) to the load \( R_0 \). The thyratron connection corresponds to the circuit with a grounded grid.

![Figure 1. Schematic of the TPI1-10k/50 thyratron with a new trigger unit and the electric circuit for triggering. A – main anode, C – main hollow cathode, G – gradient electrode, A1 – hollow anode of the auxiliary discharge, C1 – hollow cathode of the auxiliary discharge, VH – power supply for the hydrogen reservoir, VI – power supply for the auxiliary discharge. \( R_1=26 \) kΩ, \( R_T=4.4 \) kΩ, \( R_S=60 \) Ω, \( R_0=10 \) kΩ, \( C_T=10 \) nF, \( V_0=(10–40) \) kV, \( C_0=10 \) nF, \( L_0=1.3 \) μH, \( R_0=10 \) Ω.](image-url)
The outer diameter of the thyratron ceramic case is 95 mm. The main discharge gap, to which the initial voltage $V_0$ is applied, includes in itself the anode $A$ and the grounded hollow cathode $C$. In this device, a two-section design of the main gap with the gradient electrode $G$ is used. The gap length for each section is usually 3 mm. The design of the main electrodes is the same as that in the standard version of the thyratron TPI1-10k/50. As figure 1 shows, the trigger unit electrodes are built in the grounded cavity of the main cathode.

Similar to the classical hot-cathode thyratrons, the working pressure in the device is maintained due to hydrogen reservoir. A voltage $V_H=(4-6)$ V at a current of about 2 A is applied to the heater of the hydrogen reservoir. The higher value of $V_H$, the higher gas pressure inside the thyratron. For the thyratron under investigation the operation range of the voltages $V_H$ is from 5.0 V to 5.5 V. At a voltage $V_H=5.25$ V, the static breakdown voltage of the main gap is about 45 kV. When $V_H$ increases to 5.45 V, the main gap is able to withstand without breakdown a voltage of about 30 kV.

The main discharge gap is communicated with the trigger unit via the bore holes in two baffles that are inserted in the cavity of the main electrode $C$. Inside the cathode cavity the trigger unit is located. As noted above, the trigger unit is based on auxiliary glow discharge. As distinct from the commercially produced thyratrons, the trigger unit $A_1$ and $C_1$ represent two cups, faced to each other by the open sides. Thereby discharge initiation occurs over the “long path” and acceptable discharge ignition and burning voltages are provided. The inner diameters of the cavities $A_1$ and $C_1$ are 26 mm and 30 mm correspondently. The distance between the bottoms of the cavities is 80 mm. The trigger unit communicates with the cavity $C$ via the aperture in the electrode $C_1$ whose diameter is 5 mm.

The positive DC voltage from the power supply $V_1$ through the ballast resistor $R_1$ sustains the auxiliary discharge in the trigger unit. The main fraction of the total discharge current $i_1$ flows between the electrodes $A_1$ and $C_1$. Due to the presence of an aperture in the plane part of electrode $C_1$, a certain parasitic current $i_2$ also flows to the hollow cathode $C$. Therefore, the total current of the auxiliary glow discharge is $i=i_1+i_2$. An example of the points of the current-voltage characteristics for auxiliary discharge at different pressures (different voltages $V_H$) is presented in table 1.

| $V_H$, V | 5.25 | 5.25 | 5.25 | 5.25 | 5.45 | 5.45 | 5.45 | 5.45 |
|----------|------|------|------|------|------|------|------|------|
| $V_{th}$, V | 284 | 290 | 295 | 300 | 269 | 284 | 290 | 296 |
| $i$, mA | 10 | 16 | 21 | 26 | 10 | 16 | 21 | 27 |
| $i_2$, mA | 0.135 | 0.42 | 0.62 | 0.9 | 0.52 | 0.52 | 0.76 | 1.05 |

It is seen, that the discharge burning voltage is in a vicinity of 300 V in a wide range of discharge current. Parasitic current $i_2$ monotonically increases with the increase of the total current $i$. Nevertheless, a fraction of the parasitic current in the total discharge current does not exceed 5% in the operation range of voltages $V_H$. With an increase of voltage $V_H$ from 5.25 V to 5.45 V the discharge burning voltage is slightly decreases, and the value of parasitic current increases for the same total discharge current.

The electric circuit, presented at the figure 1, corresponds to so-called grounded-grid thyratron circuit (electrode $C$ is grounded). Circuit operates by the following way. At initial conditions in the trigger unit the auxiliary discharge with the current $i=(10–30)$ mA is sustained. The high voltage $V_H$ is available at the anode $A$, and the capacitance $C_P$ inside the trigger pulse unit is charged to a voltage of 3 kV. At certain instant of time, the switch $S$ closes, and the negative trigger pulse $V_T$ is applied to the trigger resistor $R_T$ through the connecting cable whose capacitance is $C_C$. Under the action of this pulse, a trigger discharge between the electrodes $C$ and $C_1$ with a pulsed current of about 20 A develops. As a result, a high-density plasma arises in the cathode cavity $C$ so that electrons are extracted from the plasma into the main gap through the holes in the upper plane of electrode $C$. This leads to initiation of the discharge in the main gap [5].
3. Results and discussion

Let us consider the process of the trigger discharge ignition between the electrodes $C$ and $C_1$. The waveforms in figure 2 illustrate the breakdown between the electrodes $C$ and $C_1$ under the action of trigger pulse $V_T$ in the absence of auxiliary glow discharge. Beside that, the waveform $V_{RT}$ is presented. This waveform corresponds to the conditions when a voltage $V_{H}=0$, i.e. there is no discharge phenomena in the gap between the electrodes $C$ and $C_1$. The waveforms were recorded in the superimposition mode (10 pulses are superimposed) that allow us to estimate a jitter in the trigger discharge ignition.

**Figure 2.** Waveforms of the trigger pulse $V_T$ (10 pulses are superimposed) illustrating the breakdown process in the gap between the electrodes $C$ and $C_1$. $V_H=5.25$ V (a), $V_H=5.45$ V (b).

Instant $t_0=0$ corresponds to the instant when the switch $S$ closes. During 100 ns after $t_0$ the voltage $V_T$ reaches 4.3 kV and within 300 ns is decreasing to 3 kV. Such a behavior of the voltage is governed by the transient processes at the capacitance $C_P$, inductance of the connecting cable $C_C$ and resistor $R_T$. After the transient processes, the waveform $V_T$ is determined by the discharging of capacitance $C_P$ through the active resistors including the resistance of the discharge plasma.

During the time interval $t_1$ the waveforms $V_{RT}$ and $V_T$ coincide with each other. Starting from the instant $t_1$, the waveform $V_T$ goes lower $V_{RT}$. This means that a prebreakdown current begins to flow in the gap between the electrodes $C$ and $C_1$. It should be noted that prebreakdown current can also be available before the instant $t_1$, but the value of this current is too low to be defined in figure 2. The instant $t_2$ seems to be the beginning of breakdown process in the gap. In the course of breakdown development, the voltage at the gap sharply decreases. Then the time $t_2$ is the breakdown delay time $t_d$ in the trigger system.

For the case in figure 2a ($V_H=5.25$ V), the averaged delay time $t_d=t_2=2240$ ns and the jitter in the delay time is of about 320 ns. With an increase in the gas pressure, the delay time to breakdown and jitter decrease. For example, with $V_H=5.45$ V, we have $t_d=1700$ ns. It is also seen that for $V_H=5.45$ V the appearance of the prebreakdown current (time instant $t_1$) occurs earlier.

**Figure 3.** Waveforms of the pulses $V_T$, illustrating the process of the trigger discharge ignition for the case when the auxiliary glow discharge in the trigger unit is available. It is seen that the time $t_1=170$ ns is much shorter as compared to the conditions in figure 2. This means that the auxiliary glow discharge in the trigger unit and the parasitic current encourage the development of trigger discharge.

At the instant $t_2$ a sharp partial drop in voltage is observed at the waveform $V_T$. Obviously, this drop is associated with the discharging of the intrinsic capacitance of the gap between electrodes $C$ and $C_1$, through the discharge at the stage of its ignition. The availability of this drop allows us to measure the...
delay time \( t_2 \) with a high accuracy. It is evident, that in a presence of the auxiliary discharge, the delay time becomes much lower \( t_2 \approx 300 \text{ ns} \). It is also seen that the jitter in the delay time is less than 20 ns.

Figure 4 shows the waveforms of the voltage at the thyratron anode \( V_A \) and the waveforms of the trigger pulse \( V_T \). At the initial conditions auxiliary glow discharge with a current \( i = 20 \text{ mA} \) and a burning voltage \( V_d = 295 \text{ V} \) is sustained in the trigger unit, and high voltage of 31 kV is applied to the thyratron anode. At the instant \( t_0 = 0 \), the trigger pulse \( V_T \) arrives at the electrode \( C_1 \). A noticeable prebreakdown current starts flowing at instant \( t_1 = 170 \text{ ns} \). Then to the instant \( t_2 = 196 \text{ ns} \), the breakdown in the trigger system starts. Due to this breakdown, the high-current discharge in the main gap is initiated.

The delay time to breakdown in the main gap is the time interval between the instant \( t_2 \) and the beginning of a sharp decreasing in the anode voltage \( V_A \) (instant \( t_m \) at the voltage waveform). It is seen, that the delay time to breakdown is extremely small, \( (t_m - t_2) \approx 30 \text{ ns} \). Then it should be noted that the main contribution in total time \( t_m \) is provided by the delay time in the trigger system. The total jitter in the time \( t_m \) is also determined by the jitter in the time \( t_2 \). As a whole, the total jitter does not exceed 4 ns.

Thus the thyratron TPI1-10k/50 with the novel trigger unit allows obtaining the low delay time to breakdown in the main gap and the nanosecond jitter in the delay time.

4. Conclusion
The sealed-off cold-cathode thyratron TPI1-10k/50 type with the new trigger unit based on auxiliary glow discharge is developed. Electrodes of the trigger unit represent two cavities, faced to each other by open sides. Thereby discharge initiation occurs over the “long path” between the bottoms of the cavities. The voltage at which the auxiliary discharge appears in a long-distance gap is rather low (at a level of 300 V). The same voltage values are also characteristic of the discharge burning voltage \( V_d \).

The results of the preliminary testing of the switch are presented. It is shown that the total delay time to the thyratron triggering \( t_m \) consists of the delay time in the trigger system \( t_2 \) and the delay time in the main gap \( (t_m - t_2) \). The main contribution in total time \( t_m \) and in the jitter is due to delay time in the trigger system. The total jitter obtained in the experiments does not exceed 4 ns.

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References

[1] Frank K and Christiansen J 1989 IEEE Trans. Plasma Sci. 17 748
[2] Mehr T, Arentz H, Bickel P, Christiansen J, Frank K, Gortler A, Heine F, Hofmann D, Kowalewicz R, Schlaug M, Tkotz R 1995 IEEE Trans. Plasma Sci. 23 324.
[3] Bickel P, Christiansen J, Frank K, Gortler A, Hartmann W, Kowalewicz R, Linsenmeyer A, Kozlik C, Stark R, Wiesneth P 1991 IEEE Trans. Electron. Dev. 38 712
[4] Frank K, Dewald E, Bickes C, Ernst U, Iberler M, Meier J, Pruker U, Rainer A, Schlaug M, Schwab J 1999 IEEE Trans. Plasma Sci. 27 1008
[5] Korolev Y D and Frank K 1999 IEEE Trans. Plasma Sci. 27 1525
[6] Bochkov V D, Dyagilev V M, Ushich V G, Frants O B, Korolev Y D, Shemyakin I A and Frank K 2001 IEEE Trans. Plasma Sci. 29 802
[7] Bochkov V D, Kolesnikov A V, Korolev Y D, Rabotkin V G, Frants O B and Shemyakin I A 1995 IEEE Trans. Plasma Sci. 23 341
[8] Korolev Y D, Geyman V G, Frants O B, Shemyakin I A, Frank K, Bickes C, Ernst U, Iberler M, Urban J, Bochkov V D, Djagilev V M and Ushich V G 2001 IEEE Trans. Plasma Sci. 29 796
[9] Korolev Yu D, Landl N V, Geyman V G, Frants O B, Bolotov A V 2017 AIP Adv. 7 075116
[10] Zang J, Liu X 2018 Physics of Plasma 25 013533
[11] Kumar N, Lamba R P, Hossain A M, Pal U N, Phelps A D R, Prakash R 2017 Applied Physics Letters 111 213502
[12] Lamba R P, Pathania V, Meena B L, Rahaman H, Pal U N and Prakash R 2015 Rev. Sci. Instrum. 86 103508
[13] Meena D L, Rai S K, Tyagi M S, Pal U N, Kumar M and Sharma A K 2010 J. Phys. Conf. Ser. 208 012110
[14] Zhang J, Zhao J P and Zhang Q G 2014 IEEE Trans. Plasma Sci. 42 2037
[15] Hu J and Rovey J L 2012 J. Phys. D 45 465203
[16] Korolev Yu D, Landl N V, Geyman V G, Frants O B and Bolotov A V 2018 Plasma Physics Reports 44 110
[17] Korolev Yu D, Landl N V, Geyman V G, Frants O B, Shemyakin I A and Nekhoroshev V O 2016 Plasma Physics Reports 42 799
[18] Landl N V, Korolev Yu D, Geyman V G, Frants O B and Bolotov A V 2015 J. Phys. Conf. Ser. 652 012050
[19] Landl N V, Korolev Yu D, Geyman V G, Frants O B and Argunov G A 2017 Russian Physics Journal 60 1269