External Triggering of the Pseudospark Discharge in a Source of EUV Radiation[1]

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Abstract – One of the widely used systems for external triggering of the pseudospark discharge is based on a trigger unit with an auxiliary glow discharge. In most cases the trigger unit is mounted at the grounded cathode. However, in some cases a specific requirement for triggering is demanded, namely, a trigger unit has to be located at potential cathode electrode. Direct application of the previous experience as applied to these cases leads to a rather intricate design for both mechanical parts of the trigger unit and electric circuit. This paper proposes a simple trigger method for such conditions. The trigger system combines both the function of triggering and the function of blocking (*i.e.* suppressing of an accident breakdown in the main gap).

1. Introduction

The pseudospark switch is a device that depends on a low-pressure gas discharge with hollow cathode [1]. In most cases the electrode system of the switch consists of two cavities that communicate through axial bore holes. In the cavity of one of the electrodes (typically, the grounded cathode) a trigger unit is placed intended to initiate breakdown in the main gap.

The pseudospark switches are capable of operating in extremely wide range of current. In a regime of high current (more than 10 kA) and short pulse duration (of about 100 ns) the high-temperature multicharged plasma is generated in the area of the cathode bore hole [2]. In this connection considerable interest has recently been displayed in application of the pseudospark discharge plasma as a source of extreme UV radiation. The promising results in this direction for the discharge in oxygen and xenon have been demonstrated in [3]. In particular, for radiation of beryllium and lithium like ions in a range from 10 to 18 nm an efficiency of 0.1% has been obtained in a pulse repetition rate regime.

In the installations for generation of EUV radiation the grounded anode cavity is used for different diagnostics, so that the trigger unit has to be placed in the cathode cavity under high potential. This paper describes a simple trigger system that is suitable for a usage in the cases when the discharge has to be triggered from the side of potential electrode. The proposed design of the trigger system is based on an auxiliary glow discharge. Simultaneously with the function of external triggering, the system provides so-called blocking effect (*i.e.* increasing a pulsed breakdown voltage and preventing the accident breakdowns in the regime of high pulse repetition rate).

2. Experimental Arrangement

Principle of operation for the trigger system is illustrated in Fig. 1.

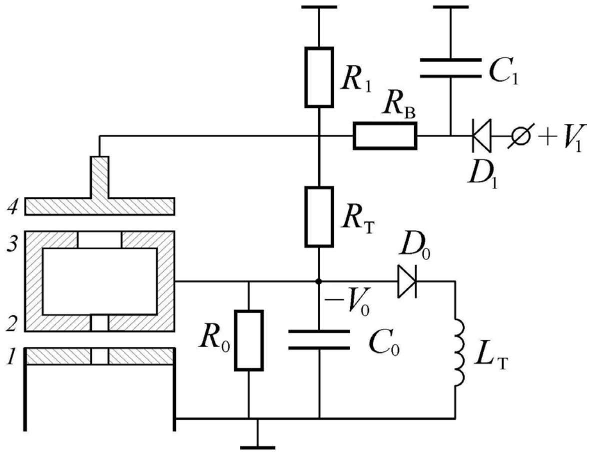

Fig. 1. Design of electrode system and electric circuit for experiments on suppressing the prebreakdown current and increasing the pulsed breakdown voltage. C_0 = 1 nF, R_0 = 70 kΩ, R_T = 100 kΩ, R_1 = 2 MΩ, R_B = 1 MΩ

The main electrode system of the switch forms by grounded anode *1* and cathode *2*. The main gap distance, the bore hole diameters, and the thickness of the flat part of the electrodes are equal to each other and amount 4 mm. This gap is powered through a low inductance circuit from a capacitor bank C_0 that is charged to a voltage V_0 during a typical time of 5 μs and larger.

The simplest regime of operation of the system corresponds to the conditions when the additional power supply V_1 is absent. The trigger unit includes in itself electrodes *3* and *4*. To simplify the electric circuit we propose the idea to use the voltage V_0 for powering of the auxiliary glow discharge. According to Fig. 1, a minor part of the energy stored in the capacitor bank C_0 is derived to the active divider $R_T - R_1$. The static breakdown voltage in the trigger chamber (between the electrodes *3* and *4*) has to be

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much less than that for the main gap (between the electrodes *1* and *2*). In such conditions, the ignition of the low-current auxiliary glow discharge occurs in the gap *3 – 4* essentially earlier than in the gap *1 – 2*. The current of auxiliary glow discharge is limited by the resistor R_1.

External triggering of the main gap implies that at a prescribed instant of time (when the voltage at the main gap reaches a maximum value) a trigger pulsed voltage of about 3 kV is applied between the electrodes *3* and *4*. Under the effect of the trigger pulse the breakdown in the gap *3 – 4* occurs, the trigger discharge plasma is generated in the main cathode cavity *2*, and the switch is triggered. The condition that the auxiliary glow discharge already burns in the gap *3 – 4* facilitates the triggering of the switch.

In accordance with the above description electrode *4* serves as one of the electrodes of the trigger chamber. On the other hand, if we properly chose the current of auxiliary glow discharge (this current has to be about 1 mA and less) electrode *4* will simultaneously play a role of so-called blocking electrode [4].

The essence of the blocking effect seems to be as follows. With respect to auxiliary glow discharge cavity *2* plays a role of a hollow cathode. The electron flux from the cavity to the main gap is suppressed. Correspondingly, the prebreakdown current in the main gap and the process of discharge initiation is suppressed which allows operating the switch with an enhanced pulsed breakdown voltage.

An increase in efficiency of the blocking effect is achieved when the additional power supplier V_1 is used (Fig. 1). Here we have the conditions in which a positive voltage V_4 is permanently applied to electrode *4*. Then after the breakdown in the main gap the discharge plasma appears in the cathode cavity *2* and in the pause between the pulses a low current is sustained between the electrodes *4* and *2*. On the one hand this current can be referred to as the blocking current. On the other hand the conditions when this current flows in the pause between the pulses are favorable from the viewpoint of de-ionization of the main gap. The charged particles are extracted from the main cathode cavity *2*, which leads to faster recovering of the dielectric strength of the main gap. Below we demonstrate that the above system offers a possibility to increase the pulsed breakdown voltage of the switch and to operate with a high pulse repetition rate.

2. Static and Pulsed Breakdown Voltages for the Gap

The external conditions, in which the experiments have been carried out, can be characterized by the static breakdown voltage of the main gap. This voltage has been measured in absence of power supply V_1 and in the case when the electrodes *3* and *4* are connected with each other. The corresponding data are presented in the Table below.

p, 10^{-2} Torr (Xe)	1.7	2.0	2.5	3.0	4.0
V_{br}, kV	7.0	3.4	2.0	1.2	1.0

At a pulsed charging of the capacitor bank C_0 the voltage that the gap withstand without breakdown is higher than the static breakdown voltage. Delay time to breakdown depends on the pulse repetition rate. This is illustrated in Fig. 2.

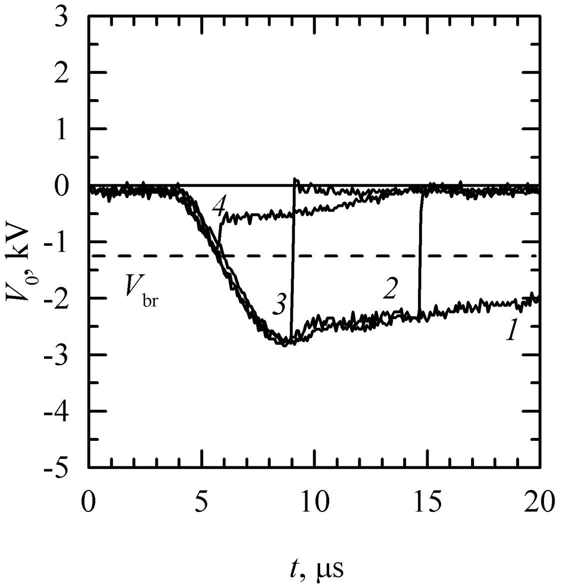


Fig. 2. The voltage waveforms illustrating a delay time to breakdown in the main gap in xenon at different pulse repetition rates. $p = 0.03$ Torr, $C_0 = 1$ nF, $V_0 = 3$ kV. *1* – $f = 1$ Hz; *2* – $f = 100$ Hz; *3* – $f = 200$ Hz; *4* – $f \geq 500$ Hz

In general the features of the breakdown in the conditions of a high pulse repetition rate are reduced to the following. When we apply a pulsed voltage to the gap, then during a number of pulses the gap withstands a high pulsed voltage without breakdown. However, in the case of an occasional breakdown, the residual plasma from this breakdown influences on the breakdown formation process in the succeeding pulse.

At a pulse repetition rate $f = 1$ Hz the breakdown does not occur (Fig. 2). In these conditions the applied pulsed voltage exceeds the static breakdown voltage of the gap more than two times.

With the pulse repetition rate $f = 100$ Hz, an occasional breakdown is possible after several seconds. After that the delay time to breakdown is stabilized at a level of 15 μs.

For moderate values of f the delay time smoothly decreases with an increase in f. However when the pulse repetition rate reaches a critical value, the delay time to breakdown becomes not stable. For example, at $f \approx 500$ Hz from pulse to pulse we can observe both the voltage waveforms of type *3* and the voltage waveforms of type *4*. A further minor increase in f leads to appearing the waveforms of type *4* only. In the other words achieving the critical pulse repetition rate $f \approx 500$ Hz results in a sudden decrease in the breakdown delay time to a value of $t_d = 1.5$ μs. The pulsed breakdown voltage in this case becomes even lower than the static breakdown voltage.

As a whole for the particular conditions under discussion the pulse repetition rate of the switch is limited by a value of 500 Hz. As it will be seen below, a forced extraction of the charged particles from the main cathode cavity allows us to enhance the pulsed breakdown voltage and to increase the limited pulse repetition rate.

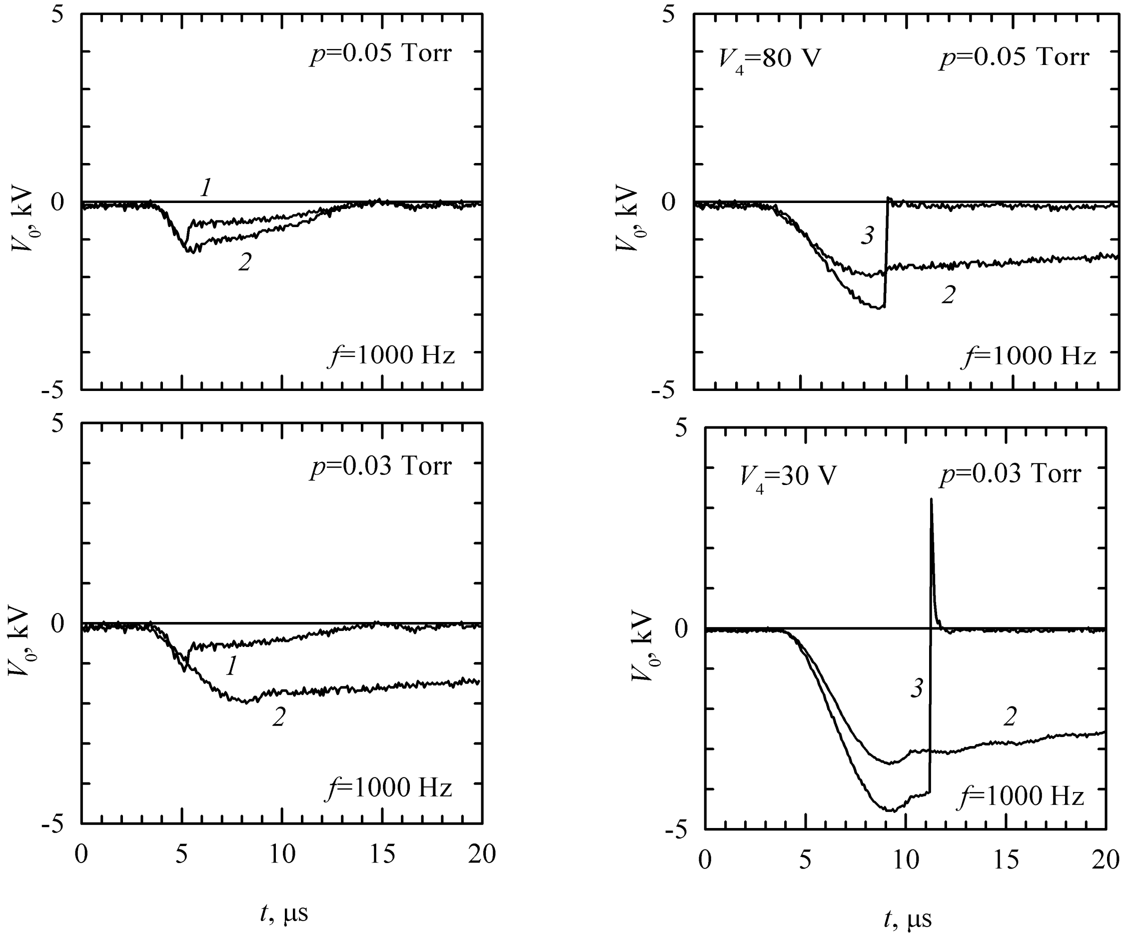
3. Investigation of the Blocking Effect

The circuit shown in Fig. 1 can operate in two modes: in the regime when the additional power supply V_1 is absent (so-called regime of auto-blocking) and in the regime when the power supply V_1 is available (auto-blocking in combination with the external blocking). Operation of the blocking system for both regimes is illustrated by the waveforms in Fig. 3. Let initially consider the case when the power supply V_1 is absent.

In the pause between the pulses all electrodes of the system are at the same potential (potential of earth). When the voltage pulse appears at the secondary coil of the pulsed transformer L_T the main capacitor bank C_0 starts charging with a voltage rise time of about 5 µs. Simultaneously the voltage V_0 is distributed between the resistors R_T and R_1 so that the potential difference $V_{34} = V_0 - V_4$ appears between the electrodes *3* and *4*. The voltage V_{34} is so-called blocking voltage. Due to this voltage a low-current glow type discharge arises in the electrode system *3 – 4*. However, this discharge does not initiate the breakdown in the main gap as far as the discharge current is limited by the resistor R_1.

Thus, for the circuit under consideration we have the blocking effect only after applying the voltage pulse V_0 to the main gap.

The auto-blocking regime (power supply V_1 is absent) is illustrated by the waveforms in Fig. 3,*a*. The voltage waveforms *1* correspond to the case when the resistor R_T is shortened (electrodes *3* and *4* are connected with each other by conductor). We can see the same voltage waveforms as the waveforms of type *4* in Fig. 2. It is understandable that the time interval between the pulses is not large enough to provide for complete de-ionization of the gap.



a *b*

Fig. 3. Typical voltage waveforms at the main gap in the conditions of Fig. 1: *a* – the case when potential V_1 is absent; *b* – the case when potential V_1 is available

If, during the operation of the circuit with the pulse repetition rate of 1000 Hz, we remove the conductor (insert the resistor R_T instead of the conductor), the voltage waveforms immediately transform to type *2* (Fig. 3,*a*), *i.e.* as a result of blocking effect the pulsed breakdown voltage increases. Remind that in this case the blocking effect starts working only after arrival the voltage V_0 at the gap since a potential difference V_{34} appears only after applying the voltage V_0. Nevertheless the voltage V_{34} (or strictly to say the blocking current) results in two important consequence. First, this current encourages the removal of plasma from preceding discharge; and second, due to the blocking current the effect of the suppression of the prebreakdown current in the main gap takes place.

Typical voltage waveforms for the case when the power supply V_1 is available is shown in Fig. 3,*b*. The circuit operates by the following way. The voltage $+V_1$ is attached in such a manner that the current from power supply V_1 flows via resistor R_B, resistor R_T, diode D_0, and the secondary coil of the pulse transformer L_T. As a result, a positive (with respect to electrode *3*) voltage V_4 is available in the pause between the pulses V_0. This is the blocking voltage, which works in the pause between the pulses.

When the voltage V_0 appears at the capacitor bank C_0 the potential distribution over the electrodes *3* and *4* becomes to determine by this voltage (role of the power supply V_1 becomes negligibly small). It is important however that electrode *4* continues to be positive with respect to electrode *3*, and the blocking current is limited by the resistors R_1 and R_B. Hence, after applying the voltage pulse we have the regime of auto-blocking and in the pause between the pulses the blocking is provided by the power supply V_1.

Let consider for definiteness the data in Fig. 3,*b* for $p = 0.05$ Torr. Experiment is carried out as follows. Initially we apply to the gap a voltage pulse $V_0 = 1.75$ kV and keep the voltage $V_1 = 0$. After the very first breakdown the voltage at the gap corresponds to waveform *2* (Fig. 3,*a*). It means that in the regime of the auto-blocking the gap is not able to withstand the voltage $V_0 = 1.75$ kV without breakdown.

Then we gradually increase the voltage V_1 *i.e.* we increase the potential V_4. At a threshold value $V_4 = 80$ V the waveform *2* (Fig. 3,*a*) abruptly transforms in the waveform *2* (Fig. 3,*b*). The physical meaning of this effect is that due to a non-self sustained current in the gap *2 – 4* the charge carriers are extracted from the main cathode cavity in the pause between the pulses. Then the main gap withstands a higher pulsed voltage without breakdown. For the example under consideration the potential $V_4 = 80$ V is a minimal voltage which provides the blocking effect.

When the blocking effect works we can increase the voltage V_0 without breakdown. As applied to Fig. 3,*b* ($p = 0.05$ Torr) the breakdown appears again when $V_0 = 2.8$ kV (see voltage waveform *3*).

The experimental data obtained by the same method are also shown for the pressure $p = 0.03$ Torr. For example, it is quite illustrative to compare the data in Fig. 2 and the data in Fig. 3,*b* for $p = 0.03$ Torr. We can see that due to the blocking effect the gap withstand a voltage $V_0 = 3$ kV even with a high pulse repetition rate $f = 1000$ Hz.

The voltage V_4 can not be increased unlimitedly. In a range of V_4 larger than 100 V the pulsed breakdown voltage sharply decreases again. Presumably the current in the electrode system *2 – 4* becomes so high that instead of the blocking effect this current encourages the ignition of the gas discharge in the main gap. However, the range of voltages V_4 in which the suppressing the prebreakdown current in the main gap is provided is rather wide. This offers a possibility to use the blocking effect in the systems with external discharge triggering.

The above-discussed data are related to the pulse repetition rate of 1000 Hz. The higher f the lower voltage V_0 which the gap is able to withstand without breakdown. However, even for $f = 2500$ Hz the pulsed voltage V_0 is still higher than the static breakdown voltage of the main gap. Such a situation is achieved due to blocking effect.

As a whole, due to application of the blocking effect in the range of the above-described condition the source of EUV radiation with external triggering is able operate at a pulse repetition rate up to 1000 Hz.

References

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