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Mechanism of initiating the process of switching a short vacuum gap by an auxiliary spark discharge

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The results and analysis of experiments are presented, the purpose of which is to study the mechanism of ignition of a high-voltage arc discharge in a vacuum gap. The results indicate that the development of an arc discharge under the presented conditions is occurs mainly due to the ionization of the residual gas by a flow of overheated electrons with an energy of $\sim 100-500$ eV from an auxiliary spark discharge.

Keywords: vacuum arc, spark discharge, plasma, magnetic field.

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The interest in spark and arc discharges in vacuum is fuelled, on the one hand, by the existence of certain unexplained phenomena and, on the other hand, by their successful application in high-current and high-voltage electronics (e.g., switching and circuit opening devices [1]).

The aim of the present study is to demonstrate experimentally that a flow of electrons emitted by an auxiliary spark discharge along a dielectric surface may be used efficiently to ionize residual gas under a pressure of $0.1-1$ Pa in a short switched vacuum gap. Similar experiments have been performed in the conditions of self-breakdown of a vacuum gap [2], but their results are inapplicable to the regimes discussed here. The results of experiments with laser ignition suggest that the electron temperature of plasma of micropinches forming in a cathode flare may reach 100 eV and go even higher [3].

The diagram of the experiment is shown in Fig. 1. Two 1 mm vacuum gaps, which are meant to be used for switching a circuit with a $0.5\,\mu$F high-voltage capacitor acting as a current source, were the key elements of the setup. The anodes of gaps were then under a constant potential of $+3$ kV, and their cathodes were under zero potential after charging of the capacitor. A spark discharge along a dielectric surface with a duration of $\sim 30-50$ ns and a current amplitude of ~ 10 A was ignited by a positive (relative to the cathode) voltage pulse applied to the auxiliary gap 0.2 mm in width. A high-voltage generator was the source of this voltage pulse with an amplitude of 5 kV and a steepness of $\sim 10^9$ V/s [4]. The voltage pulse parameters and the moment of breakdown of the auxiliary gap were determined using a low-inductance ohmic voltage divider. Three low-inductance resistors $R_7 = R_8 = R_{10} = 0.1\,\Omega$ were introduced into the switched circuit for the purpose of current measurement. Special attention was paid in experiments to maintaining the geometric equivalence (and, consequently, the equivalence of inductances) of electric circuit branches leading to two switched gaps.

Measurement resistance $R_9 = 10\,\Omega$ was also introduced into the auxiliary spark discharge loop. The discharge device was positioned in a vacuum chamber evacuated to a pressure of $0.1-1$ Pa by oil-free pumps. A near-uniform magnetic field with its induction vector perpendicular to the direction of current flow in switched gaps was produced by a set of permanent magnets. Changing the number of magnets in the set and their spatial orientation, one could alter the magnitude of the induction vector and select one of two possible directions of it.

The vacuum chamber had an observation window that was used to take photographs of discharges in the discharge device. Optical images of discharges (integral with respect to the discharge time; the frame exposure was $60\,\mu$s) were provided by a camera based on an OPHIR Spiricon BGS-USB-SP928-OSI CCD array. The camera was synchronized with the generator of high-voltage pulses in order to suppress the influence of background illumination.

The oscilloscope records of current in the switched circuit (through resistor R_{10}) and voltage across the auxiliary gap along the dielectric surface are presented in Fig. 2, *a*. The inductance, wave impedance, and ohmic resistance of the circuit determined at the stage of a steady-state periodic discharge were $3 \cdot 10^{-7}$ H, $0.8\,\Omega$, and $\sim 0.5\,\Omega$, respectively.

Let us estimate ohmic resistance R^* of plasma of a switching discharge at different points in time using the oscilloscope record of current in the switched circuit (Fig. 2, *a*) and relations

$$R + R^* = \left(\frac{1}{I}\right)\left(L\frac{dI}{d} - \frac{q_0 - \Delta q}{C}\right),$$

$$q_0 = CU_0,$$

$$\Delta q = \int_0^t I dt.$$

The notation is as follows: U_0 is the charging voltage of the capacitor, $R + R^*$ and L are the ohmic resistance and the

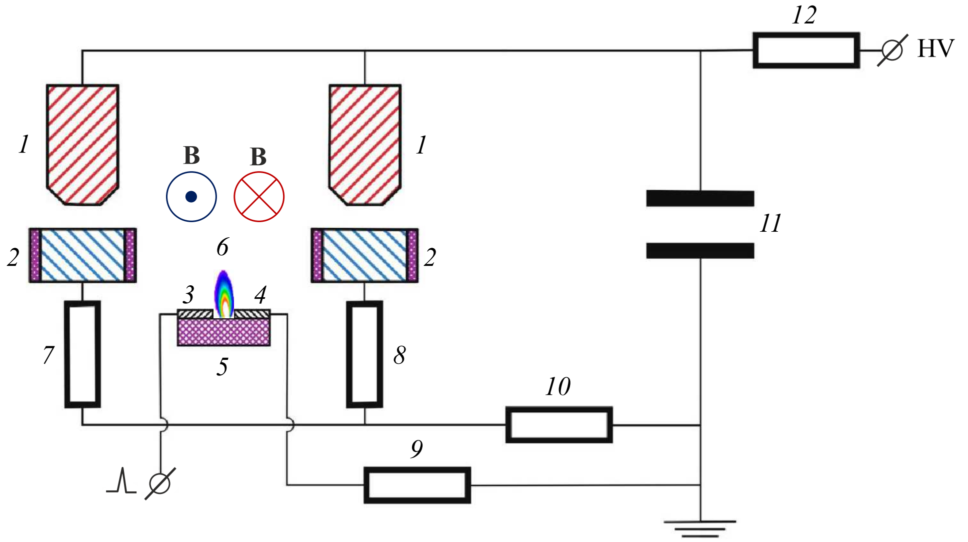

Figure 1. Schematic diagram of the experiment. *1* and *2* — Anodes and cathodes of the primary discharge (switched) gaps, respectively; *3* and *4* — ignitor electrode and cathode of the auxiliary discharge gap, respectively; *5* — dielectric; *6* — auxiliary spark discharge along the dielectric surface; *7*, *8*, and *10* — measurement resistances ($R_7 = R_8 = R_{10} = 0.1\,\Omega$); *9* — measurement resistance ($R_9 = 10\,\Omega$); *11* — high-voltage capacitor ($C = 0.5\,\mu$F); and *12* — ballast resistance ($R_{12} = 2\,\mathrm{M}\Omega$).

inductance of the circuit, and I is the strength of current in the circuit. At the onset of transition to the arc discharge stage (~ 250 ns from the start), resistance R^* is $\sim 20\,\Omega$; at the end of the most pronounced current surge (~ 250 ns from the start), it is $\sim 3\,\Omega$; at the first current maximum, the resistance is $\sim 1\,\Omega$. At later points in time, it remains at the level of several tenths of Ω. Note that the characteristic ohmic resistance of an arc discharge is $\sim 0.1{-}1\,\Omega$ [5,6]. Thus, in the initial phase (within ~ 250 ns from the start), the discharge in the switched gap differs clearly from an arc one. It is likely to be a glow-type discharge. Presumably, it is initiated as a result of ionization of residual gas by a flow of superthermal electrons from an auxiliary spark discharge along the dielectric surface at the boundary of the switched gap. Later on, the development of instability of a volume discharge leads to its contraction and transformation into an arc [5]. The time of development of the cathode layer instability in the conditions of our experiments, which leads to contraction of the current channel and emergence of a cathode spot, is estimated at around $10^{-8}{-}10^{-7}$ s [5,7].

Examining the oscilloscope record of current in the switched circuit, one finds that the front is very steep (within the first quarter of a period) and diverges from the primary oscillatory process frequency. This is apparently attributable to the following. The ohmic resistance of discharge plasma decreases by more than an order of magnitude within the interval between the onset of transition to the arc discharge stage and a point just short of the first maximum (i.e., within $50{-}100$ ns). An aperiodic current flow regime with the ohmic resistance in the circuit being dominant undergoes a transformation into a periodic regime dominated by the wave impedance. The change in the discharge plasma resistance is associated with the emergence of a cathode spot and the propagation of a cathode flare in the switched gap. This sharp drop of ohmic resistance in the aperiodic regime is what causes the rapid growth of current in the circuit.

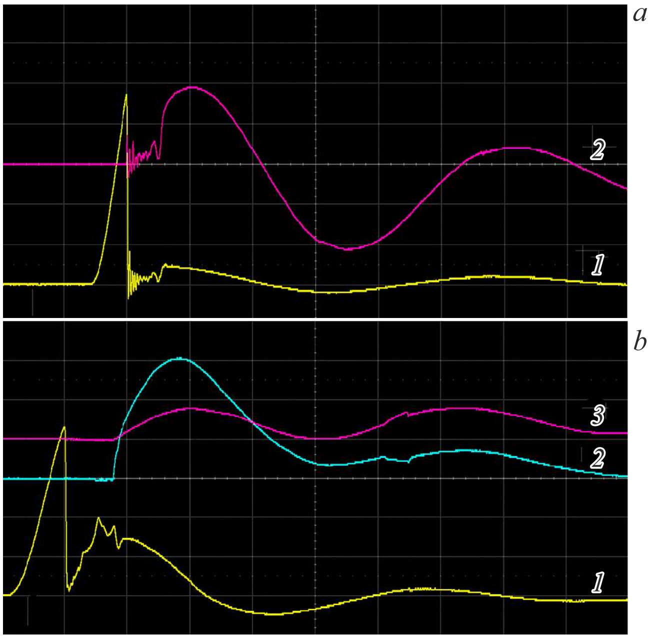

Figure 2. Experimental oscilloscope records. *a* — Voltage across the auxiliary gap along the dielectric surface (trace *1*) and current in the switched gap (trace *2*). Sensitivity: trace *1* — 1 kV/div; trace *2* — 1 kA/div. The sweep speed is 500 ns/div. *b* — Voltage across the auxiliary gap along the dielectric surface (trace *1*) and current in each switched gap in a 30 mT magnetic field (traces *2* and *3*). Sensitivity: trace *1* — 1 kV/div; trace *2* — 0.5 kA/div; trace *3* — 0.5 kA/div. The sweep speed is 500 ns/div.

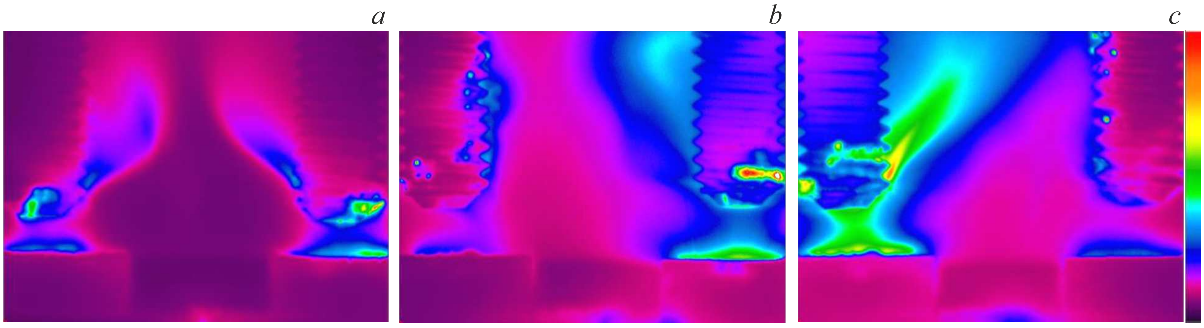

Figure 3. Images of discharges in switched gaps. *a* — Zero external magnetic field; *b* — the external magnetic field is 30 mT, and the magnetic induction vector is directed normally to the picture plane away from the observer; *c* — the external magnetic field is 30 mT, and the magnetic induction vector is directed normally to the picture plane toward the observer. The intensity scale is shown on the right (the glow intensity increases from bottom to top).

The oscilloscope records of currents in each switched gap (currents through resistors R_7 and R_8) and voltage across the auxiliary gap along the dielectric surface are presented in Fig. 2, *b*. The following features are worth noting. First, the sum of indicated currents is somewhat smaller in magnitude than the total measured current in the switched circuit; second, these currents are unipolar. The first fact suggests that a fraction of the total current in the switched circuit ($\sim 5\%$) flows between the anodes of switched gaps and metal walls of the grounded vacuum chamber. The second feature provides an opportunity to identify reliably the type of discharge in each switched gap (i.e., determine the presence of cathode and anode spots). The amplitudes of currents measured in two switched gaps differ by approximately 10% in zero external magnetic field. In a 30 mT external magnetic field, the current amplitudes differ by a factor of around 4 (Fig. 2, *b*). The current amplitude in an applied magnetic field reaches its maximum in the switched gap corresponding to the direction of displacement of electrons emitted from the auxiliary discharge along the dielectric surface. The observed delay of current flow in switched gaps is probably attributable to the existence of initial unstable low-current discharges that transform later (e.g., as a result of development of current instability) into a high-current discharge.

Figure 3 presents the images of discharges observed in different experimental conditions. It can be seen that an arc discharge is maintained in both switched gaps in zero magnetic field (Fig. 3, *a*). Magnetic fields of different polarities (Figs. 3, *b* and *c*) induce similar changes in the glow pattern: the discharge glow intensity increases in one switched gap and decreases in the other. This enhancement of the discharge glow intensity in a certain switched gap is aligned with the direction of displacement of electrons emitted from the auxiliary discharge along the dielectric surface in the applied magnetic field. At a magnetic field strength of ~ 20 mT or more (Figs. 3, *b* and *c*), a spatial structure typical of an arc discharge (with cathode and anode spots and a current channel in the form of a plasma column) is established in one of the switched gaps. The discharge in the other gap has a spatial structure similar to the one of a glow discharge (with anode spots of a characteristic shape, no cathode spots, and no plasma column). A similar spatial discharge structure at currents typical of an arc has already been observed in our earlier experiments [8].

The obtained results suggest that electrons emitted from an auxiliary spark discharge play a leading part in the production of a conductive medium and development of a discharge in a switched gap. The emission of electrons with energies of 300–500 eV, which (presumably, in combination with short-wave radiation) ionize residual gas efficiently and turn it into plasma within less than 10 ns, has already been reported in [9]. At the same time, it is believed that the temperature of plasma emitted from a cathode spot of a spark is on the order of 1–5 eV [9,10]. Note that when a vacuum chamber is evacuated to residual gas pressures within the range of 0.1–1 Pa, the residual gas is expected to consist mostly of O_2, N_2, and H_2O molecules [11] with the highest electron-impact ionization cross sections falling within the range of electron energies of 30–500 eV (the maximum ionization cross section corresponds to an electron energy of ~ 100 eV [12]).

The results obtained in [13] in experiments with a discharge device of a somewhat different geometry provide an opportunity to determine more accurately the lower boundary of energies of superthermal electrons inducing the transformation of residual gas into a conductive medium. Electrons emitted from an auxiliary spark discharge toward a switched gap were effectively accelerated and decelerated in an electric field. An arc discharge in the switched gap was always ignited at an accelerating potential difference of 100 V. At a decelerating potential difference of 100 V, this discharge was not observed in most cases. This suggests that the lower boundary of energies of electrons ionizing the residual gas is close to 100 eV.

In order to gain a better understanding of the observed effects, the motion of electrons emitted from spark discharge plasma was simulated in the one-particle approximation at different magnitudes of the applied electrostatic field. It was found that, regardless of the presence of a magnetic field, both thermal (~ 5 eV) and superthermal (~ 100–500 eV) electrons reach only the boundary of a switched gap at a cathode–anode gap voltage of 1–3 kV. However, a magnetic field of ~ 20 mT may prevent them from entering one of the gaps. The penetration of electrons with energies of $\sim 100-500$ eV from an auxiliary spark discharge into a switched gap is feasible only at voltages $\leqslant 300$ V and only under the influence of a magnetic field.

It should be taken into account that the potential difference between the auxiliary cathode and the ignitor electrode drops almost to zero within ~ 10 ns [4]. In the primary discharge, the potential difference in the cathode–anode gap also drops almost to zero within 10 ns. The observed duration of electron emission from the auxiliary discharge is on the order of 30 ns [4] (i.e., this emission is maintained for a significantly longer interval of time than an electric field that has the capacity to alter noticeably the trajectories of electrons moving in a magnetic field). Under a weak influence of an electric field and a magnetic field strength of ~ 20 mT, emitted electrons do not reach a switched gap, and their Larmor radius is ~ 4 mm. This allows one to estimate the maximum energy of emitted electrons at ~ 500 eV.

Our findings suggest the following conclusions. The process of switching a short vacuum gap (~ 1 mm) under a residual gas pressure of 0.1–1 Pa by an auxiliary spark discharge along the dielectric surface is initiated by the ionization of residual gas. This ionization is performed by a flow of superthermal electrons with an energy of $\sim 100-500$ eV injected into the switched gap from the auxiliary spark. The initially emerging low-current discharge is unstable and transforms into an arc one.

Conflict of interest

The authors declare that they have no conflict of interest.

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