The opposite mode of streamer-to-leader transition

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Abstract

Streamer discharge propagates in air by impulse voltage impact. It is not dangerous for high voltage devices itself. However if streamer channel closes a pair of electrodes –вЃY breakdown may occur. Barrier insulation may be used to increase breakdown voltage вЃY– solid dielectric elements are placed on the supposed path of the streamer. Elongation the shortest path through air between electrodes ("arcing length") leads to proportional increase of breakdown voltage in a first approximation. In this regard the following question occurs вЃY– what is a limitation on this method of breakdown voltage increasing.

1 Rounding breakdown mode in system with dielectric barrier

In systems of electrodes with a highly inhomogeneous distribution of electric field both without barriers and with a barrier, a streamer discharge arises from a certain voltage level [1]–[4]. If the voltage is large enough, the streamers reach the surface of the barrier and change the direction of their propagation to a tangent to the surface of the barrier. In this case they propagate first along the surface of the barrier, and then, reaching the edge of the barrier, they germinate towards the counter electrode. From a certain voltage level the length of the streamers becomes sufficient to go around the edge of the barrier and then reach the counter electrode. When streamers reach an opposite (grounded) electrode and close the interelectrode gap, a spark breakdown is possible. The spark channel in this case is located above the surface of the barrier ("envelopes" the barrier), passing mainly through air, at some distance from the surface of the solid dielectric (Fig. 1–2). Such a situation is analogous to the classical breakdown mode at small interelectrode distances without a solid dielectric: the barrier only extends the trajectory of the closing streamers and the subsequent leader, forcing them to walk through the air in order to bypass the obstacle. We will call such a breakdown mode as an "enveloping leader" or вЃЁenveloping mode of breakdownвЃ№.

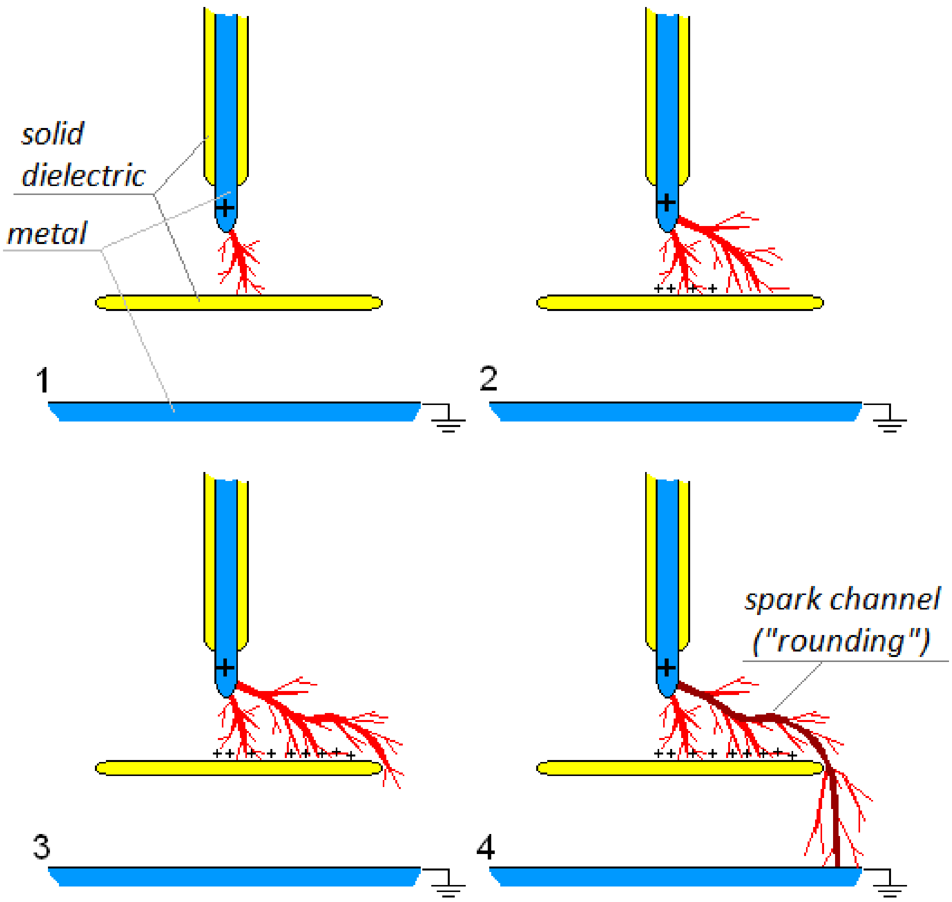

Figure 1: "Enveloping" breakdown mode outline.

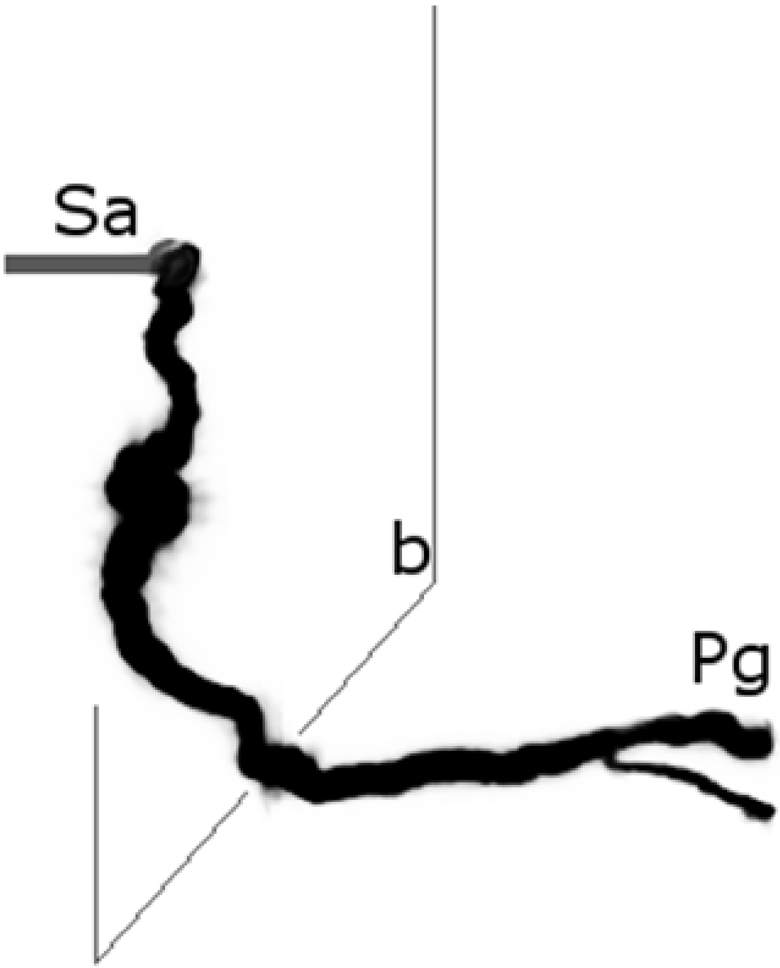

Figure 2: Negative of a photograph of spark breakdown in the sphere-plane system. "Sa" вЂ" high voltage spherical electrode, "Pg" вЂ" plane spherical electrode, "b" вЂ" dielectric barrier. The leader has an "enveloping" shape — spreads over the barrier surface and envelops the dielectric barrier through air.

2 Opposite streamers

The source of standard lightning voltage pulses is used (the duration of the leading edge is 1.5 μs, the trailing edge is 50 μs). The stand is equipped with a highly sensitive camera, which provides receiving photos of leaders and streamers. Exposure time exceeds the duration of the applied voltage pulse, therefore the resulting photographs are not instantaneous images of the glow of the discharge, but integral pictures. Visualization of the surface charge at the barriers is accomplished by applying an electrically conductive powder.

If the barrier diameter is sufficiently large, one can observe the formation of streamers on the either side of the barrier (Fig. 3). A similar situation arises both in "symmetric" systems such as sphere-sphere, cylinder-cylinder, and in systems with a flat counter electrode. Why is the formation of streamers possible not only near the high-voltage electrode, but also near the grounded one, where the field strength is lower? The reason is the distortion of electric field by the "primary streamers" (propagating between the high-voltage electrode and the barrier). The occurrence of conductive channels between the high-voltage electrode and the barrier leads to the fact that the field strength in this air gap decreases, and, in contrast, increases between the barrier and the counter electrode (potential difference between the electrodes is fixed and equals to the voltage).

Experimental evidence of electric field redistribution by streamers development is the accumulation of surface charge at the barrier. Since the barrier material has electrically insulating properties, a significant portion of electric charge remains on it after exposure to a voltage pulse, its distribution can be visualized, and the charge density can be measured.

Fig. 4 shows the distribution of the surface charge at the upper and lower sides of the barrier. As can be seen, a wider spot is observed from the side of the high-voltage electrode – this is the "imprint" of the "primary" streamers, which provide redistribution of electric field in favor of the gap between the barrier and the counter electrode. The trace of the "secondary" streamers is more concentrated – these streamers propagate directly to the center of the barrier.

Thus, streamers develop on both sides of the barrier at a sufficiently high voltage. The structure of streamers from the positive and negative electrodes corresponds to the previously described structure of positive and negative streamers in the air gap [1].

Both the "primary" and "secondary" streamers deposit surface charge on the barrier (Fig. 4). The polarity of charge on the opposite sides of the barrier differs. Thus, an electric capacitor appears on the barrier, the "plates" of which are two spots of surface charge.

3 Opposite leader formation and breakdown

Consider breakdown in systems with a large barrier size (Fig. 5). The spark channel has a complex shape. A common feature of spark channels in such systems is the pair sections of channels that run along the barrier surface on its both sides opposite each other ("2" and "3" in Fig. 4). Sometimes spark channels branching is

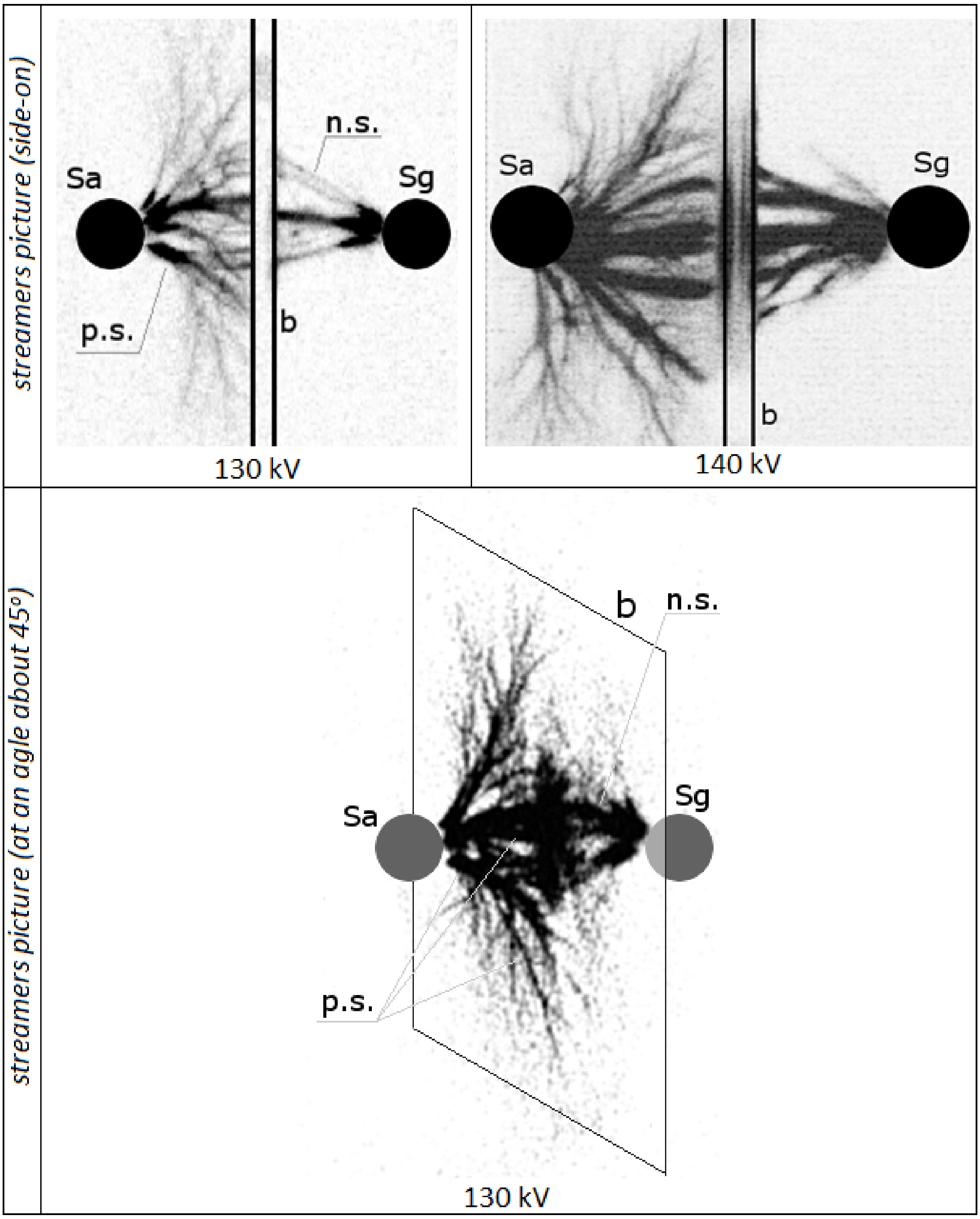

Figure 3: Photos of streamers from different angles. Negatives of photographs. "Sa" –вЃY high voltage spherical electrode, "Sg" –вЃY grounded spherical electrode, "b" –вЃY dielectric barrier. "p.s." — positive streamers, growing from the active electrode, "n.s." — negative (вЃЁoppositeвЃ№) streamers, growing from the grounded electrode. Images of electrodes and a barrier on a photo are put artificially during processing of the data.

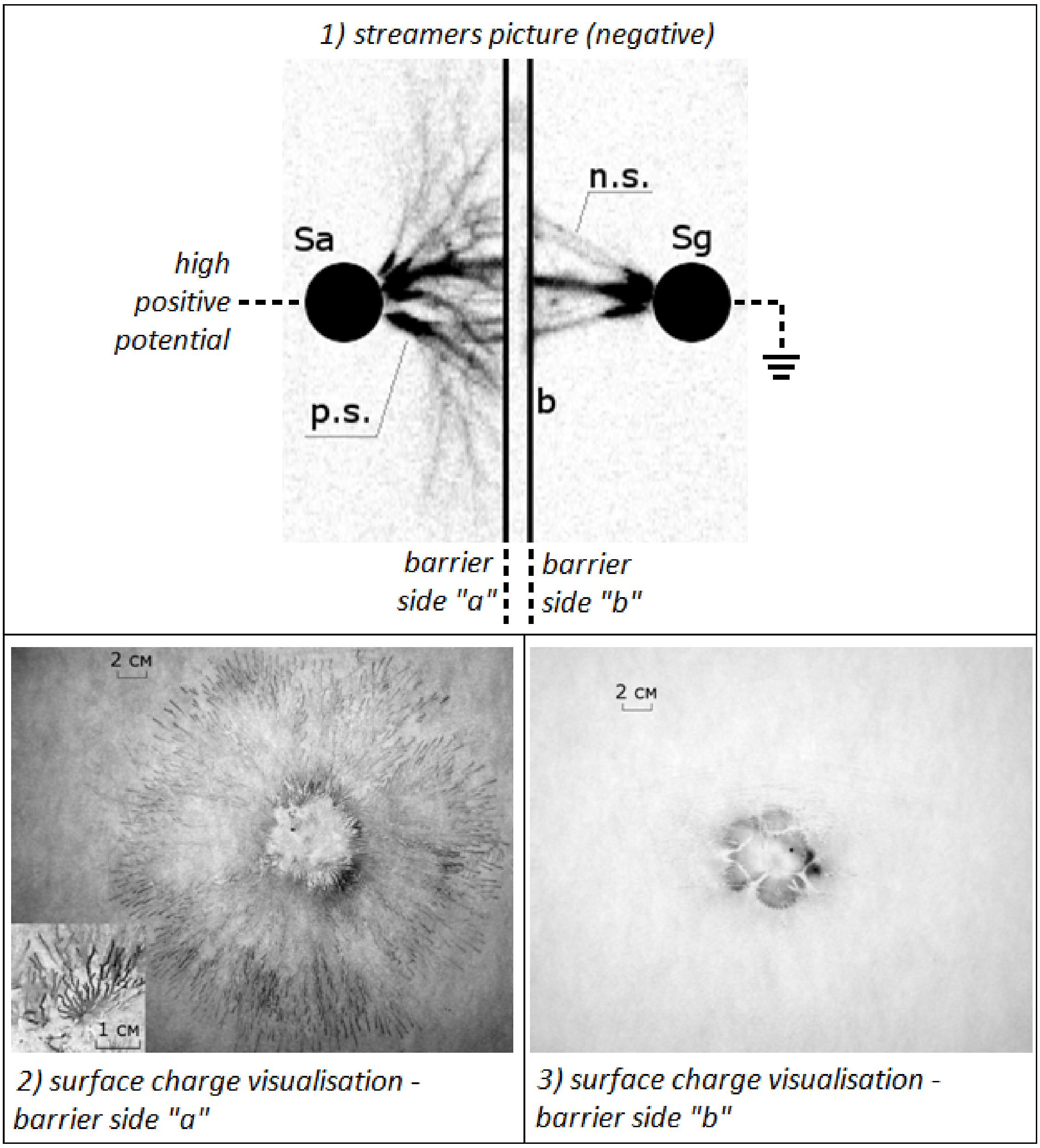

Figure 4: 1) Negative of a photograph of spark breakdown in the sphere-sphere system. "Sa" –вЃY high voltage spherical electrode, "Sg" –вЃY grounded spherical electrode, "b" –вЃY dielectric barrier. 2-3) surface charge visualization on the opposite barrier sides.

observed, which is reproduced on the other side of the barrier. It is interesting that in this situation the spark channel does not go along the shortest path between the electrodes: at the photo (Figure 5b) the spark channel does not close from the end of the barrier directly to the grounded plane — instead the channel goes along the opposite side of the barrier and closes on the plane opposite the active electrode. This property can be explained by assuming that regions "1" and "5" are first formed (in Fig. 5a) — connecting electrodes with a barrier (resulting in two unclosed leader areas), and then the resulting pair of leaders propagate along the barrier ("2" and "3" in Figure 5a), and only when they close at the edge of the barrier, there is a single spark A channel that closes the electrodes and provides a breakdown.

The described mechanism is shown schematically in Fig. 6. This scheme also explains why the breakdown of gaps in the case of a large-diameter barrier occurs with a small length of streamers, which is not enough to bend the barrier. Indeed, the leader channels originate from short streamers connecting the electrodes to a barrier, and further propagation of the discharge occurs already in the leader stage. However, it is generally assumed that at moderate voltages (up to about 400 kV [3]), the formation of a leader is possible only when the pair of electrodes close up the streamers. Otherwise, the heating of the streamer channels with Joule heat is not enough to transfer the plasma in the channels from the low-temperature (nonequilibrium) to the high-temperature (equilibrium) state. As in this case, the necessary heating is achieved, if the streamer channels do not explicitly close the air gap (Fig. 4), they are separated by a solid dielectric barrier.

The necessary heat is released as a result of the capacitance presence described above, which arises between the charge spots on the barrier. Due to the large area of the spots and the small thickness of the barrier, the capacity can be quite large. Consider in the first approximation the situation after the emergence of primary and secondary streamers as charging the RC circuit from the voltage source U, in which C is the capacity of the pair of charge spots on the barrier, R is the resistance of the streamer channels. In such a system, the energy stored in the capacitor ($CU^2/2$) is equal to the energy of Joule losses scattered by the resistance. This implies the presence of a link –вҐY increasing the capacitance C entails an increase in the thermal energy released in the streamer channels. It is due to the large capacity between the charge spots on the barrier that it becomes possible to form a pair of leaders ("opposite leaders") from unclosed streamer channels.

4 Consequences for high-voltage insulation

Since the threshold for the formation of opposite leaders in the described scheme is determined by the capacitive electric energy accumulated in the barrier between the charge spots, the breakdown voltage in such a situation does not depend on the diameter of the barrier. Indeed, experiments show that while the diameter of the barrier is small, the breakdown voltage depends linearly on the diameter. However at some point the curve suffers a break and reaches a constant (within the inaccuracy) level (Fig. 7). Analysis of the photographs of spark channels shows that in the first section of this dependence the channels have an "enveloping" shape, and on the second one — the channels stick along the surface in pair, which is characteristic for

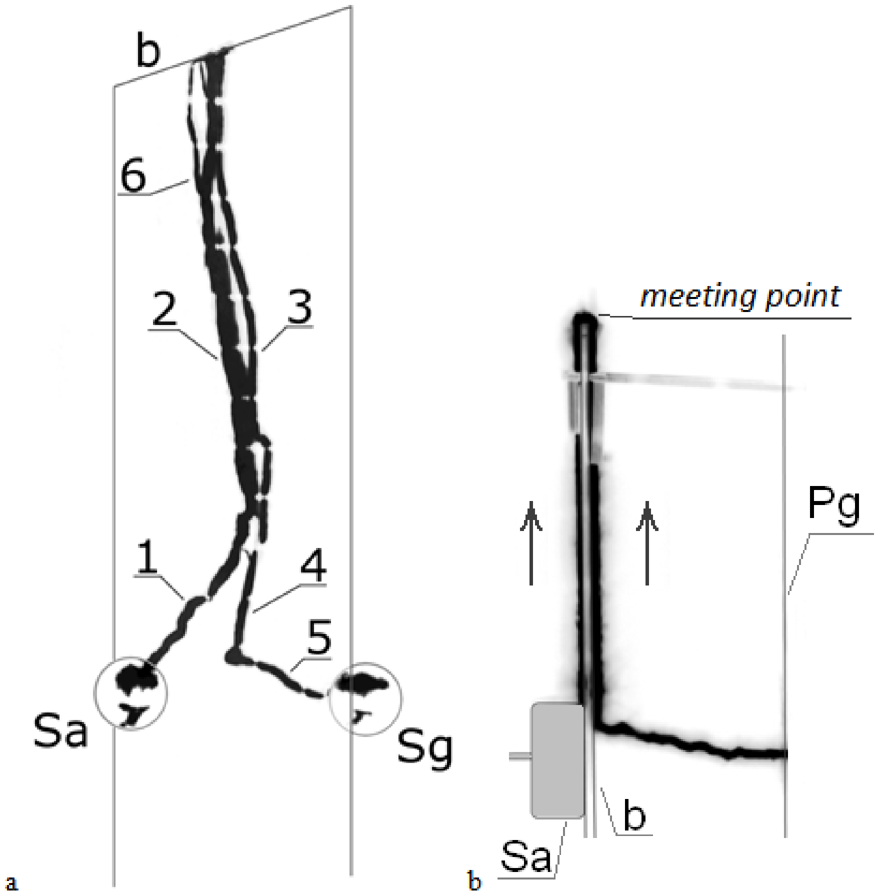

Figure 5: Breakdown by opposite leaders in the sphere-sphere electrode system (a) and in the cylinder-plane electrode system (b). Pictures negatives. "Sa" — high-voltage electrode, "Sg" вЃY grounded spherical electrode, "Pg" –вЃY grounded plane electrode, "b" вЃY dielectric barrier. "1" — the section of the positive leader channel from the active electrode to the barrier, "2", "3" — a pair of positive and negative leader channels spread along the upper and lower surfaces of the barrier: on the side of the active ("2") and grounded ("3") electrodes , "4" — the section of the negative leader channel spreads over the surface of the barrier from the side of the grounded electrode, "5" — the negative leader channel section from the grounded electrode to the barrier, "6" –вЃY the branch point of the positive leader channel. The images of the electrodes and the barrier are artificially imprinted to the photograph during the processing of the data.

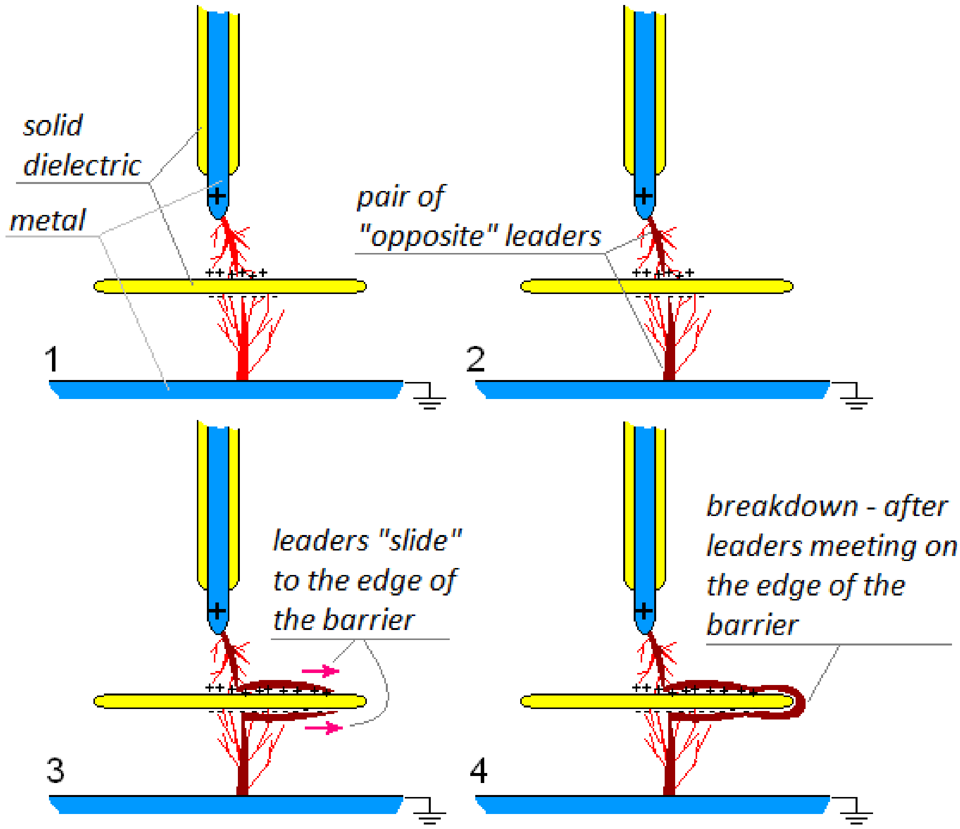

Figure 6: "Opposite leaders" formation outline.

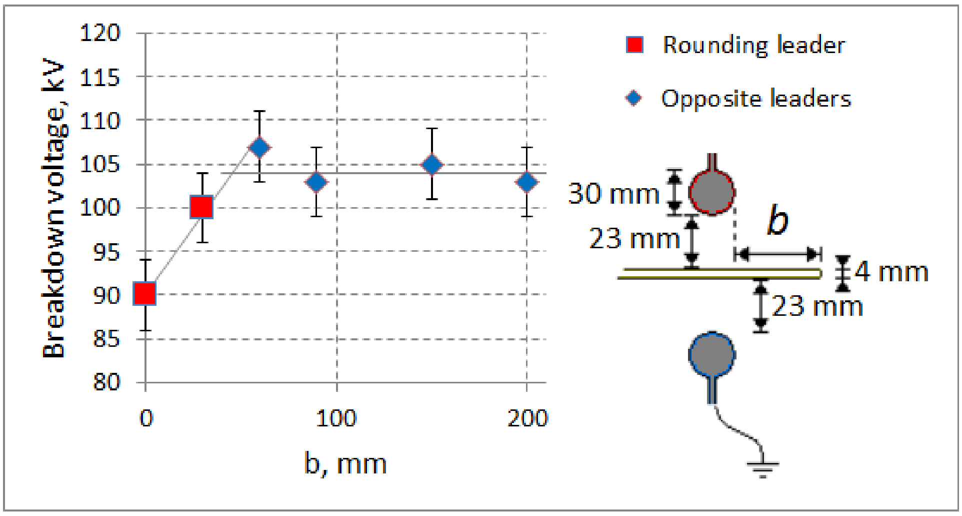

Figure 7: Dependence of breakdown voltage on the "offset" *b*.

opposite leaders.

5 Conclusions

1. A new mechanism for leadersвЃЄ formation in systems with solid dielectric barriers is identified and described — "opposite leaders". The feature of the mechanism is the formation of different polarity leaders pair, extending to the barrier from different sides.

2. In вЃЁopposite leadersвЃ№ mode the heating in streamers channels (which is necessary for streamer-to-leader transform) is due to the passage of significant charge deposited on the barrier. The accumulation of significant charge on the barrier becomes possible due to the fact that charge accumulates in the form of two large unipolar spots spaced a short distance (the thickness of the barrier). Thus, an effective large capacity is formed in which charge is accumulated.

3. The mechanism of "opposite leaders" limits the breakdown strength of systems with large-diameter dielectric barriers, in which breakdown along the trajectory "bypassing" the barrier is obstructed

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