NEW MATERIALS ON THE DEVELOPMENT OF THE CHANNEL OF A LONG SPARK

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NEW MATERIALS ON THE DEVELOPMENT OF THE CHANNEL OF A LONG SPARK

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Although the development of a long spark under various types of voltage has been studied for a long time, a number of important aspects of the process still remain unclear. Using an electron-optical converter (EOC) (^{1}) and a high-speed electron-beam oscilloscope (^{2}), the authors have obtained new materials on the development of the spark channel under impulse voltage in a rod–plane gap ($+r-p$), of length S_0 from 3.0 to 5.75 m.

The basic experimental arrangement is shown in Fig. 1. The impulse-voltage source was the generator GIN 1. To record the current, cylindrical shunts 5 (^{3}) were used; the voltage from them was fed through a coaxial cable 6 of length 15 m, terminated in the surge impedance 7, and through damping resistances 8 to the oscilloscope 9. With the electron-optical converter (EOC) 11 equipped with a "Jupiter-3" objective, the optical picture of the spark development was recorded; for decoding it, the discharge was simultaneously photographed on stationary film by camera 12. Synchronism of the recording by the EOC and the oscilloscope was ensured by connecting their time plates to one common source of sweep voltage 13, which was triggered through control unit 14 by the voltage on current shunt 5. The errors in oscillographing the current in circuit A are negligibly small, while in circuit B the recorded current pulses in reality have a somewhat smaller front and an approximately 15% larger amplitude*.

The sweep of the EOC is produced by an electric field, and therefore various parasitic influences on the voltage on the deflecting plates lead to distortion of the true picture of the development of optical phenomena in the discharge gap. This circumstance makes it necessary to carry out very carefully all the working circuits of the arrangement as a whole.

Figure 2 shows a photograph of the image, swept in time, of the development of the spark (A) in the $+r-p$ gap at $S_0 = 5.3$ m, its static photograph (B), and the synchronous oscillogram of the current (V). The switching-on of the time sweep began at the moment t_0, when the leader length had reached 3.8 m (point a). In Fig. 2A, of the entire leader length, only a small lower section ak is visible at this moment. From the moment t_0, the elongating leader channel was swept until its head came into contact with the plane. From a to b there occurs, on the whole, a smooth elongation of the leader channel, although here, especially on the negatives, small steps, amounting in kind to 1-3 cm, can be distinguished, which follow one another at short time intervals. At the same time the recorded current increases smoothly. In Fig. 2A an unusual phenomenon attracts attention—the jump-like elongation of the leader channel in the section *bc*, considerably exceeding the average elongation of the channel in the preceding — existing path. The leader channel almost instantaneously (the greatest possible time for formation of the leader channel over the section *bc* can be estimated as 10^{-8} sec) increases its length by 30 cm. From this moment t_{bc}, on the photographic sweep one can observe a somewhat greater intensity of the glow of the previously formed leader channel, while on the oscillogram a rather sharp increase in the recorded current is noted. A peculiar pulse with a duration of the order of 10^{-7} sec is superposed on the smooth curve of the leader current.

Fig. 1. Schematic diagram of the experiments.
1—HIVG ($U_0 = 3.5 \cdot 10^5$ V, C_0 = 18,000 pF, $R_0 = 3$ kΩ), 2—cylindrical barrier made of pressboard, 3—grounded plane 8×8 m^2, 4*A*—measuring plane 1.2 m in diameter, 4*B*—measuring plane 3×3 m^2, 5—current shunt, 0.29 or 0.62 ohm, 6 —RK-3 coaxial cable, 7—wave resistance 75 ohm, 8—75 ohm, 9—oscillograph, 10 —metal cabin, 11—EOP, 12—camera, 13—sweep unit, 14—control unit, 15—360 ohm, 16—20 ohm, 17—walls of the room

Further, the leader from *c* to *d* usually develops as, for example, in the section from *a* to *b*. From point *d* there again occurs a jump-like elongation *dc*, 50 cm long, up to the plane itself, after which the main stage follows. In what follows we shall call the process of jump-like elongation of the leader channel by a length $\geqslant$ 5—10 cm in a time $\leqslant 10^{-8}$ sec a **jump**. It is not necessarily accompanied by a light flash along the previously formed leader channel, thereby differing from the "steps" associated with the development of a "stepped" lightning leader. The jump completing the leader stage (*dc* in Fig. 2) will be called **final**; its formation in a spark in the gap +*c*—p at $S_0 = 100 \div 150$ cm was discovered in 1958 by E. N. Brago and I. S. Stekolnikov. In the gaps +*c*—p that we investigated, at $S_0 = 3$ m we recorded jumps from 10 to 28 cm long, and final ones from 15 to 56 cm; and at $S_0 \simeq 5$ m, respectively, 10-60 cm and 15-125 cm.

The length of the final jump substantially affects the amplitude of the current pulse of the main stage (^{6}), by which is meant the process of change in the physical state of the leader channel, propagating in the form of a head of brighter glow along the channel in the direction opposite to the development of the leader. In this connection the question arises of the role of the current caused by the final jump in the total current of the main stage. Some conclusions about this can be drawn by considering the development of the spark in Fig. 3. In addition to the jump in the section *bc*, after some time in the section *de*, at the moment

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* In relating the recorded current to the current in the discharge gap, one should bear in mind Schokley' s theorem (^{4},^{5}).

Figure 2

Figure 1: Figure 2

Figure 3

Figure 2: Figure 3

t_{de}, another jump occurs, causing the current i_{1-2}. Approximately after 0.1 μsec, at the moment t_{fg}, the final jump occurs in the section fg. The current i_{2-3} caused by it is smaller than that from the preceding jump de. According to previous ideas (6,7), on current oscillogram B the current pulse $i_{1-2-3-4}$ from the time t_{de} should have been taken as the current of the main stage. Taking into account that the jump causes a definite current pulse and that the main stage begins only after formation of the final jump fg, at the moment t_{fg}, on the basis of Fig. 3 one may conclude that the share of the current associated with the final jump in the recorded pulse is significant. We also note that on the optical sweeps no motion of the luminous head of the main channel was recorded. Usually the glow of the leader channel that exists by the moment of the final jump remains approximately constant at subsequent times as well, and only sometimes, from the moment of formation of the final jump, was an increase in the glow of the channel observed. The propagation of the glow in time, as was established with the aid of an electro-optical shut-

Fig. 2. Optical image of the spark in the $+c-p$ gap at $S_0 = 5.3$ m, $R_0 = 3$ kΩ, and $k = U/U_{\min} = 1.1$. **A** –time sweep, –static photograph, –corresponding current oscillogram.

Fig. 3. Same as in Fig. **2**, but at $S_0 = 5.2$ m.

of the leader (8), can often not be observed; apparently this is connected with the optical properties of the apparatus.

In Fig. 4 A the dependence (1) of the amplitude of the current I_{S_f}, caused by the final jump, on its length S_f is plotted, independently of S_0 and k. Assuming that the current is only a function of S_f, by differentiating $I_{S_f}(S_f)$ with respect to S_f one can establish the role in the recorded current of unit elements ΔS of the length of the jump S_f according to their height above the measuring plane. This dependence $i_S(h_S)$ is shown in Fig. 4 A by curve 2. Fig. 4 B gives the dependence 3 of the current $i_S = I_S/l_S$ (where I_S is the amplitude of the current pulse caused by the jump, l_S is the jump length) on the height h_S of the jump, equal to

Figure 4

Figure 3: Figure 4

Fig. 4. A. 1—dependence $I_{S_f}(S_f)$ of the amplitude of the recorded current of the main stage on the length of the final jump; 2—dependence $i_S(h_S)$ of the current falling on a unit element of the length of the final jump on the height h_S of this element above the measuring plane. B. 3—dependence $i_S(h_S) = I_S/l_S$ of the ratios of the amplitudes of current pulses accompanying jumps of length l_S at height h_S from the measuring plane to l_S

the distance between the middle of the jump and the measuring plane. Curve 2, obtained for the final jumps, is also shown here. The agreement in the course of both curves confirms the common physical nature of the leader jumps in the middle of the discharge gap with the final ones and, on the other hand, that the current pulse of the main stage in the oscillograms is caused mainly by the final jump. It is important to emphasize that the duration of the current caused by the jumps is, in order of magnitude, greater than the time of optical formation of the jump. This means that changes of the current in the main stage are due to physical processes in the already formed leader channel, including in the region of the final jump.

In considering the causes that produce the jumps, one should bear in mind the work (^{9}), where, by analysis of current oscillograms, it was shown that when the field in the discharge gap is equalized, simultaneous ionization occurs along the entire length. Subsequently this was confirmed by optical sweeps made by E. N. Brago with the aid of an image converter for a sphere—sphere gap.

In connection with this it may be assumed that the leader jumps are associated with equalization of the field and strengthening of the mean potential gradient by space charges, whose concentration in the gap depends on the preceding development of the process. Therefore the distinctive character of spark development is one of the causes of the irregularity of the jumps.

On the basis of the available data, an attempt has been made to give a calculation formula for determining the length of the final jump S_f. At a certain moment of time the voltage U_{S_0} across the gap being broken down S_0 is equal to the discharge voltage $U_p = E_{\text{cp}} \cdot S_0$, where E_{cp} is the mean discharge gradient in the gap. As the leader propagates toward the plane, the quantity U_{S_0} decreases,

is due to the voltage loss ΔU_{i_p} in the external circuit from the leader current i_l, i.e.,

$$U_p = E_{\text{av}} \cdot S_0 = U_{S_0} + \Delta U_{i_p}. \tag{1}$$

Before the moment at which the final jump arises, the leader has length $S_0 - S_f$ and an average longitudinal gradient E_l. Let us denote the average gradient in the section S_f by E_f. Then

$$U_{S_0} = E_l(S_0 - S_f) + E_f S_f. \tag{2}$$

Substituting (2) into (1) and determining, in the first approximation, ΔU_{i_p} only through the ohmic losses in the damping resistance at the maximum leader current i_{lm}, which, according to data[7], for minimum impulse voltages and $R_0 = 1.0 \div 20$ k can be expressed by the empirical formula $i_{lm} = 1.3\,R_0 l^{-0.12R_0} S_0$, we find

$$S_f = \frac{E_{\text{av}} - E_l - 1.3R_0 l^{-0.12R_0}}{E_f - E_l} \cdot S_0 \text{ (cm)}. \tag{3}$$

Here E_{av}, E_l, E_f are expressed in kV/cm, R_0 in kΩ, and S_0 in cm.

In calculations by (3), E_f may, on the one hand, be estimated as a quantity equal to the discharge gradient in a weakly nonuniform field, 23 kV/cm[9]. On the other hand, taking into account that the section S_f is subjected to ionization by the impulse corona, E_f may have smaller values. For each spark the degree of ionization of this section is probably different, which apparently is one of the reasons for the irregularity of the jump length. For minimum impulse voltages in the $+c$—p gap $E_{\text{av}} = 5.4$ kV/cm. E_l is taken, according to the laboratory data for the indicated values of R_0, within the limits $E_l = 0.3 \div 1.0$ kV/cm. In the $+c$—p gap at $S_0 = 500$ cm and $R_0 = 3.0$ k , for E_l within the limits $0.3 \div 1.0$ kV/cm and E_f within the limits $23 \div 10$ kV/cm, S_f calculated from (3) is within the limits $40 \div 125$ cm; under the same conditions, but at $S_0 = 300$ cm, $S_f \approx 15 \div 50$ cm. The calculated values obtained for S_f are in good agreement with the experimental results.

The phenomena discovered are of great importance for the theory of the long spark and of lightning.

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Note: Figure translations are in progress. See original paper for figures.