DISCHARGE CHANNEL STRUCTURE IN BREAKDOWN IN AN INHOMOGENEOUS FIELD

M. F. Borisov, M. F. Danilov, E. A. Zobov,
I. G. Litvinova, and A. N. Sidorov

UDC 537.521+533.09

Electrical breakdown of long discharge gaps in a gas manifests a number of qualitative differences from breakdown of short gaps [1-3]. Foremost of these such breakdowns occurs under very inhomogeneous field conditions so that space charge plays a significant role. The overall picture of the phenomenon thus becomes much more complicated. The breakdown takes on a discontinuous or so-called stepped character [1-3], and longitudinal inhomogeneity of luminosity, branching of the discharge channel, etc. are observed.

Detailed studies of a spark channel [4-7] have considered mainly the fully developed phase of the breakdown and have described discharges in gaps up to 10 cm long. In the majority of studies of discharge development [1-3, 8-11] the mechanisms underlying avalanche, avalanche-streamer, and streamer-leader development have been dealt with, with little attention given to questions involving the effect of these processes on the discharge development after a conduction current bridges the discharge gap.

The goal of the present study is to investigate the structure and dynamics of a long spark under conditions where processes in the initial stage of breakdown, controlled by electrical parameters of individual segments of the channel, become significant. The known similarity of the latter to the glancing spark [1] stimulated our choice of the glancing spark as the object of study.

A spark 0.4-1 m in length was developed in air on the surface of a thin film dielectric, lying upon a metal tube 80 mm in diameter. The dielectric consisted of several dozen layers of Lavsan film with a total thickness Δ = 0.25-1 mm with a specific surface capacitance C_{sp} = 3-12 pF/cm². Pulses were applied to the surface electrode either from a coaxial cable transformer [12] in the form of a damping cosinusoid with amplitude up to 100 kV and risetime of ~10^{11} V/sec, period T ≈ 10 µsec, and logarithmic decrement 0.3, or from a Marx generator with impact capacitance of 0.03-0.1 µF. The energy supplied to the incompleted discharge comprised 50-100 mJ/cm at a current of 0.5 kA, with 1-2 J/cm at currents up to 2.5 kA to the completed discharge. A control line was placed on the dielectric surface when it was necessary to record the discharge path [13].

Scintillation in various portions of the spectrum and shadow images of the channel in end, side, and front views were recorded by SFR-2M and BFU-1 cameras operating in high-speed cine and chronography modes. Use of a spark control method and high-quality wide-aperture optics permitted improved spatial resolution and reproduction of a number of previously unknown details of the glancing spark channel.

Cine photography of the incompleted stage recorded a beaded channel structure with a spatial period of 1-2 cm. The size of the glowing portions increased with time, while the filaments joining these became noticeable (Fig. 1), but complete equalization of the luminosity did not occur.

Longitudinal inhomogeneity of channel luminosity recorded by chronography [14] appears in the earliest stages of the discharge in the form of glowing segments 1-2 cm long separated by dark zones 1-3 mm long. This can be seen clearly in chronograms such as that of Fig. 2. Apparently in both cases this modulation is of the same nature, being a consequence of streamer-leader breakdown processes.

Comparison of the chronograms with photographs of the discharge shows that the position of the end of a leader step coincides with a strong lateral branch, with the luminosity of the step, ~10^{-7} sec, coinciding with the duration of luminosity from this branch. Stepped leader-type luminosity was reproduced artificially by connecting lumped 1.5 nF capacitors between the grounded metallic substrate and the discharge channel and by

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 29-32, November-December, 1988. Original article submitted July 30, 1987.

0021-8944/88/2906-0785 $12.50

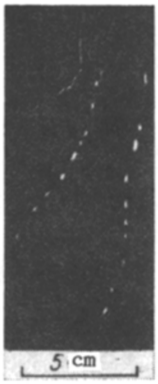

Fig. 1

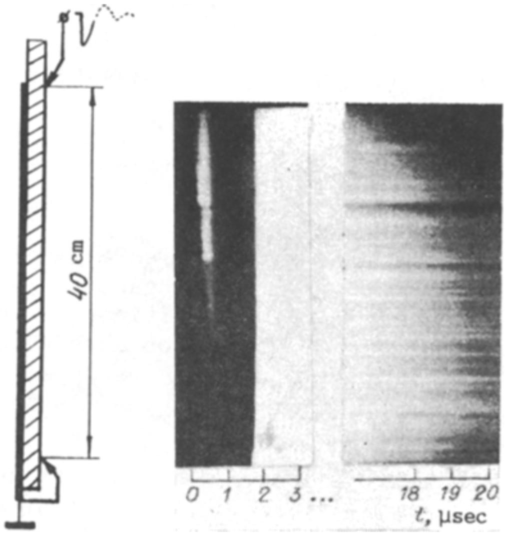

Fig. 2

controlling initiation of lateral branches. Thus a lateral branch with a system of fine branches and streamers acts like a capacitor connected to the channel. An instantaneous flare in luminosity along the entire length of the step is caused by its charging current. Weak branches may remain invisible.

The shadowgram of Fig. 3 clearly illustrates the process of glancing spark channel development upon transition from the incomplete to the high-current or complete stage, which sets in 2-5 μsec after application of the voltage pulse. A thin (diameter less than 0.1 mm) channel which develops on the dielectric surface is heated by each half cycle of the current and expands intermittently, forming semicylindrical plasma layers. The initial channel expansion rate is 1-2 km/sec. Expansion then slows and shock waves with a velocity of 350-500 m/sec depart from the channel surface. The charging currents of the dielectric's distributed capacitance produce weaker waves which depart directly from the surface. Discharge shadowgrams [15] and Fig. 3 show an inhomogeneous radial channel structure, consisting of several coaxial semicylindrical layers.

Recording of luminosity from the channel face in cine and chronograph modes revealed that the energy in the channel is liberated nonuniformly. By the time t ≃ 30 μsec (Fig. 4) one can clearly see the axial channel on the dielectric surface and an external layer with r ≃ 4 mm.

The longitudinal inhomogeneity of the channel luminosity which develops in the initial phase of the breakdown (see Fig. 2) also appears in the completed stage, when the current amplitude decreases from 2.5 to 1 kA, and is maintained until completion of the discharge. In some cases there are segments with luminosity duration almost an order of magnitude greater than in the remaining portion of the channel. Photography using filters to attenuate the radiation from the discharge showed no marked inhomogeneity of the luminosity near the through current maximum.

The shadowgrams of Fig. 5, taken at 22 μsec intervals, show that channel expansion is accompanied by development of instability. Wavelike perturbations appear on the surface of the initially smooth channel. Initially these are localized about centers related to lateral branch formation, but then develop over the entire visible surface of the semicylindrical layer. The amplitude and spatial period of these perturbations are ~1 mm. With passage of time they become more intense.

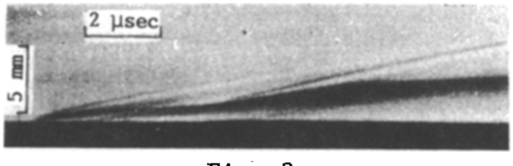

Fig. 3

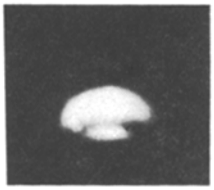

Fig. 4

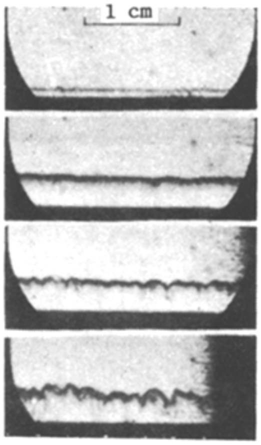

Fig. 5

High-speed photography of the spark lumonisity from the side (Fig. 6) revealed the following details of its development. In the high-current stage the boundary of the channel luminosity takes on a wavy outline. The perturbations then continue to grow, taking on the form of necks, kinks, and screws, finally leading to discontinuities in the channel luminosity, which explains the inhomogeneity of the luminosity recorded photographically in the completed stage of the discharge.

Thus the structural features of the channel in the axial and radial directions permit us to speak of the presence of a longitudinal and transverse structure with several spatial and time scales. One must distinguish the channel structures in the various stages defined by changes in the character of the discharge current: the uncompleted stage where a through conduction current from the high-voltage electrode to the grounded one is absent; the high-current stage when through current flows; the completed stage, when the decreased through current cannot maintain the channel temperature.

In the incompleted stage the conduction current in the formed portion of the channel is complemented by a displacement current through the dielectric. In long discharge gaps this is accompanied by intense branching of the channel. The basic structural elements in this stage are a streamer zone, which is a cluster of weakly glowing equally bright streamer channels, and a segment where one can clearly distinguish a brighter leader channel [1, 2].

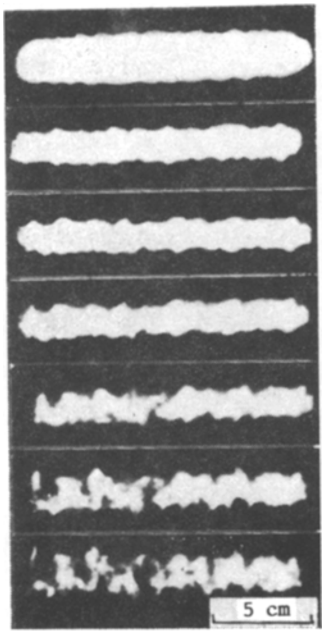

Fig. 6

For the discharge gap length under consideration l = 1 m and dielectric thickness Δ = 0.25 mm 90% of the voltage drop and ~20% of the liberated energy is expended in such segments. The channel brightness and diameter increase from the streamer zone toward the high-voltage electrode and for a sufficiently long discharge length become comparable to the parameters of the high-current (spark) stage of the breakdown.

On the basis of [12] it can be proposed that the spark portion of the channel has a length $l_s = l - 1.8 \cdot C_{sp}^{0.5}$ m if C_{sp} is measured in pF/cm², and can be characterized by a mean electric field intensity E ~ 10^2 V/cm. For a dielectric thickness Δ = 0.25 mm and C_{sp} = 11 pF/cm² a spark segment is found at l > 0.5 m.

In the completed stage the spatial distributions of the current, energy, luminosity brightness, and channel diameter are practically constant over length.

The results obtained supplement the data on radial structure of a spark channel presented in [2, 4, 5]. The differences between a long and short spark manifest themselves upon an increase in the role of the capacitive current, which is comparable to the through conduction current. The differences are caused by the large dimensions of the perturbation zone which develops around the central long spark channel and the large fraction of the energy liberated in this segment in the uncompleted stage. This, as well as the fact that perturbations of the high-current channel surface are most intense near the centers from which they are generated, i.e., the points of channel branching and bending, on the boundaries of leader steps, and components of the bead structure, explain the relationship between the bright long-term luminosity channel segments and the luminosity structure observed in the incompleted phase.

LITERATURE CITED

1. I. S. Stekol'nikov, The Nature of the Long Spark [in Russian], Akad. Nauk SSSR, Moscow (1960).
2. J. Mick and J. Crags, Electrical Breakdown in Gases [Russian translation], IL, Moscow (1960).
3. M. Uman, Lightning, McGraw-Hill, New York (1969).
4. I. S. Marshak, Impulsive Light Sources [in Russian], Gosenérgoizdat, Moscow—Leningrad (1963).
5. K. Volrat, "Spark light sources and high-frequency spark cinematography," in: Physics of High Speed Processes [Russian translation], Mir, Moscow (1971).
6. S. I. Drabkina, "On the theory of development of a spark discharge channel," Zh. Éksp. Teor. Fiz., 21, No. 4 (1951).
7. S. I. Braginskii, "On the theory of spark channel development," Zh. Éksp. Teor. Fiz., 34, No. 6 (1958).
8. G. Reter, Electron Avalanches and Breakdown in Gases [Russian translation], Mir, Moscow (1971).
9. E. D. Lozanskii and O. B. Firsov, Spark Theory [in Russian], Atomizdat, Moscow (1975).
10. P. N. Dashuk, V. A. Dement'ev, and M. D. Yarysheva, "Electrooptical studies of development of a glancing discharge and formation of a reverse leader," Pis'ma Zh. Tekh. Fiz., 9, No. 2 (1983).
11. E. M. Bazelyan and A. Yu. Goryunov, "The mechanism of streamer development in a strongly inhomogeneous electric field," Élektrichestvo, No. 11 (1986).
12. S. I. Andreev, E. A. Zobov, and A. N. Sidorov, "Study of a glancing spark in air," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1978).
13. S. I. Andreev, E. A. Zobov, and A. N. Sidorov, "Method for controlling development and formation of a system of parallel glancing spark channels in air at atmospheric pressure," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1976).
14. M. F. Borisov, M. F. Danilov, E. A. Zobov, et al., "Features of the space—time structure of glancing spark channel radiation," in: Reports to the 3rd All-Union Conference on Gas Discharge Physics, Part 1 [in Russian], Kiev (1986).
15. E. A. Zobov, A. N. Sidorov, and I. G. Litvinova, "Study of a glancing spark by the shadow method," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1986).