BEADED STRUCTURE OF DISCHARGE DURING BREAKDOWN IN A NONUNIFORM FIELD

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UDC 553.09+551.594

The phenomenon described in the literature as beaded lightning is an intermittent glow which remains along the trajectory of ordinary streak lightning for a time ranging from a few tenths of a second to 2 sec [1]. The discharge channel of streak lightning breaks up, as it were into separate glowing breadlike regions so that the glow of some parts persists for a longer time than that of others. The beads are estimated to range in size from several centimeters to several meters [1, 2]. The dark gaps may have a size of several diameters of a bright segment.

Beaded lightning differs from ordinary streak lightning by the following features: the main feature is that it resembles a "dotted line"; its dotted line is sinusoidal in many other cases, but not always; and its trace is not branched. The number of reports, published photographs, and discussions pertaining to beaded lightning is substantially smaller than the number of studies devoted to another anomalous phenomenon, ball lightning. Most frequently a picture of beaded lightning is obtained in photographs taken with simple cameras in a "waiting" mode. In these cases the observer was either not present or did not visually distinguish the beaded lightning.

Discharges with the structure of the beaded lightning type were obtained with a system of induction coils [1]. The phenomenon of beaded lightning was not observed by experimenters but was discovered on cine film after the experiments. The beaded structure was the remainder of the high-voltage discharge channel and existed for about 0.16 sec.

It was of interest to find the conditions for observing phenomena similar to bead lightning, in a discharge in an extremely nonuniform field such as a creepage spark, since breakdown occurs in a creepage spark and in lightning by similar processes. Photoscans of lightning and creepage sparks have a longitudinal glow nonuniformity both in the breakdown stage and the stage of current decrease and afterglow. This was the initial premise for the search for beaded-lightning-like phenomena in creepage sparks.

We studied both controlled and uncontrolled creepage sparks in air at atmospheric pressure. The control method and the experimental procedure were described in [3]. Photographs were taken with an SFR-2M light-beam recorder. Only controlled creepage sparks were studied in the photoscan mode. Replacement of the entrance lens of the SFR-2M with a faster lens and measures to enhance the photosensitivity of the film increases the sensitivity of the light-beam recording by an order of magnitude.

The beaded structure in the incomplete stage of the creepage spark was recorded in the high-speed slow-motion mode in the uncontrolled discharges. Figure 1 shows film frames with a beaded structure.

If a cosinusoidal alternating voltage with a negative first half-period is applied to the spark gap, the dielectric surface in incomplete creepage sparks displays a beaded structure in the form of a series of glowing points 1-4 mm long, separated by dark intervals of 3-20 mm. The most typical length of the dark intervals is 10-15 mm. The beads are linked together by a weakly glowing filament. With time the beads grow longer and the filament becomes brighter. The beads glow for no longer than 10 μsec.

All of the films were taken with an 85-cm discharge gap. The dielectric (polyethylene terephthalate) was 0.1 cm thick. The voltage breakdown of the gap was 80 kV. The amplitude value of the voltage was 70 kV for the others. The amplitude value of the current was 100 A for Fig. 1 and 2 kA for Figs. 2 and 3. A voltage pulse was obtained the secondary winding of a cable transformer with a transformation ratio of six. The capacitance of the capacitor in the primary circuit was 6 μF. The period of the cosinusoid was 10 μsec. The film in

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Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 16-21, January-February, 1990. Original article submitted April 4, 1988; revision submitted August 30, 1988.

0021-8944/90/3101-0016$12.50

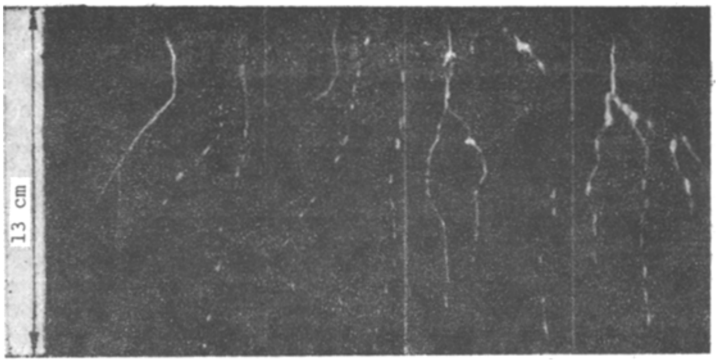

Fig. 1

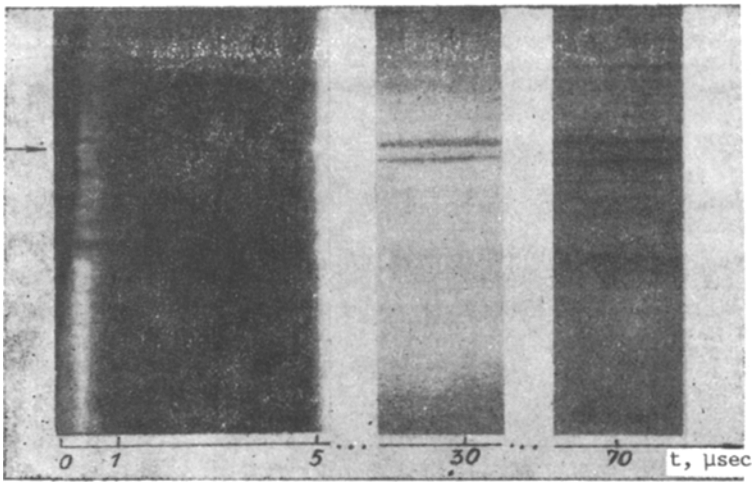

Fig. 2

Fig. 4 was taken with a grounded variable-inductance ferrite-core electrode introduced into the circuit. The first half-period of the cosinusoidal alternating voltage was negative. A beaded structure in the incomplete stage of discharge could not be recorded when the first half-period of the cosinusoidal alternating voltage was positive.

The longitudinal nonuniformity of the glow in the photoscan of a controlled creepage spark, which under our conditions is a stable law regardless of the sign of the voltage applied, up until breakdown has the form of narrow dark bands of width 1-4 mm, which alternate every 10-15 mm as a rule (Fig. 2). Upon completion of the high-current stage the glow time of individual segments in some scans is an order of magnitude rather than that of neighboring segments. Segments with a longer afterglow are often linked to dark bands which arise in the breakdown stage.

Comparison of the photoscans of the breakdown process, films with beaded structures, as well as the mechanism of breakdown in a long spark under negative voltage pulses [4] permits the following assumption to be made about the mechanism giving rise to a beaded structure in the incomplete stage of the discharge. Breakdown produces primary and secondary streamers directed toward the anode and another counter streamer in the opposite direction, toward the cathode. The counter streamer is due to the volume positive charge formed during the separation of charges, which probably already begins in the fast, wave stages of the breakdown [5].

The time resolution of the SFR-2m recorder is insufficent for observation of the initial stages of breakdown, but at times, when the applied voltage is roughly equal to half the breakdown voltage for the given discharge gap and the breakdown process is slowed down in various segments of the gap, we observe a process which can be interpreted as a counter streamer. In the photoscan (Fig. 2) the interval from 0 to 1 µsec is the breakdown stage, the high-current stage begins at 5 µsec, the current drop begins at 30 µsec, the current flows for ~ 40 µsec, and afterglow is at 70 µsec. The photoscan was carried out on a 38-cm segment

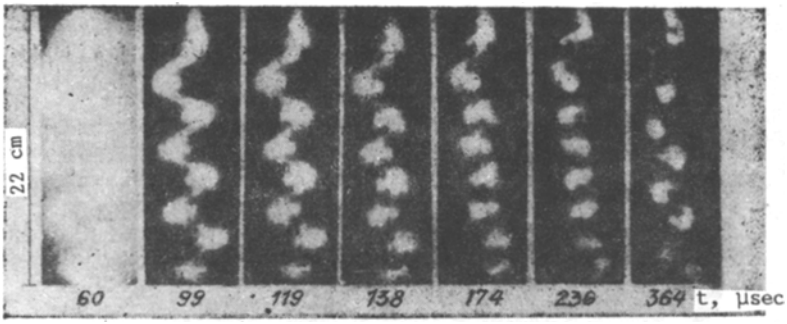

Fig. 3

adjacent to the high-voltage electrode. The glow zone with reverse slope is indicated with an arrow. Thus, the breakdown when the high-voltage electrode has an overvoltage appears over time as the formation of bright points, whose glow propagates in both directions for 0.01-0.1 μsec. If the breakdown stops or slows down, the bulk charge is insufficient to form a counter streamer, breakdown ceases and neutralization of the zones of concentration of bulk charge occurs much more slowly than when the breakdown front moves, which makes it possible to observe a beaded structure on a cine film of the discharge.

Breakdown caused by positive voltage pulses also gives rise to zones of concentration of charge of opposite sign, i.e., points of concentration of electron avalanches and primary streamers (stem and nodes of the corona [6]), but charge neutralization occurs without recombination radiation and, therefore, a beaded structure could not be recorded in this case.

A beaded structure thus is formed when the successive development of breakdown in the given channel or a side branch of it slows down or stops. Moreover, we can say that the films of Fig. 1 do not reflect the process of breakdown development but rather reflect the afterglow, i.e., the process of recombination of the bulk positive charge formed in the breakdown stage.

Analysis of photographs of beaded lightning revealed that the bright beads remain unperturbed and stable even in the case of close successive discharges [1]. This indicates that the beads are not the result of current flowing in the bead-lightning channel since such a current should be perturbed by the effect of the current of the neighboring discharge. This accords with the conclusion that a best structure is an incomplete creepage spark when there is a halt in the breakdown process. The complete absence of current after the formation of a bead structure is improbable because of the neutralization of the excess charge of the beads, as indicated by the weakly glowing filament linking the beads, but this current should be substantially lower than that from the moving breakdown front.

If the beaded structure is taken to be the unrealized direction of breakdown and the formation of beads is assumed to be a necessary stage of the breakdown of long discharge gaps in the realized direction of breakdown, we can explain the appearance of dark bands in the photoscans of the creepage spark. The local zones of charge concentration (beads) probably have a low resistance in comparison with the average resistance of the discharge channel. In the transition to the bulk phase of current flow in the given segment, i.e., behind the breakdown front, the energy release in the channel is proportional to the resistance of the channel segment. Less energy is released in the segment with a lower resistance and the radiation of this segment is weaker; this gives rise to dark bands, corresponding to zones of charge concentration. The side branches in the photoscans of creepage spark, as a rule, are adjacent to dark bands. Similarly, in lightning the intensity of the radiation decreases abruptly at branch points [7].

A beaded structure lifetime of the order of 10 μsec, obtained in an incomplete creepage spark, is substantially shorter than the lifetime of beaded lightning, which lasts for up to 2 sec. In order to obtain a beaded structure with a lifetime of the order of 1 msec we tried to obtain it in the completed stage of a creepage spark. We proceeded on the basis of the following facts.

A beaded structure was also recorded when lightning was artificially stimulated with a grounded wire, trailing behind a rocket [1]. The lightning channel was observed to be rectilinear initially but then became sinuous. The brightest beads appear at points of maximum channel compression. This accords with the assumption [7] of an interrelationship

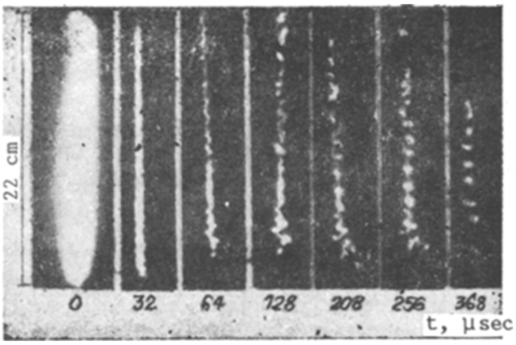

Fig. 4

between the beads and the points of channel deformation. It is also known [2, 8] that after the current flow ends the lightning discharge channel has local regions with stable glow, whose duration is roughly an order of magnitude longer than that of the glow of the main channel. Such a phenomenon often occurs at kinks in the channel [2]. When this effect is modeled in a controlled creepage spark, where the shape of the channel was predetermined, one zone of longer glow corresponds to each kink of the channel; these zones are initially arranged in a zigzag, much like the Tepler pattern reproduced in [1], and after 200-250 μsec they extend into a straight line similar to beaded lightning (see Fig. 3).

A study of the sinuosity of lightning channels [7] shows that the average absolute change in the direction is approximately constant from flash to flash and amounts to 16°. For a creepage spark it is 5-10° at the high-voltage electrode and up to 45° at the grounded electrode when the voltage is roughly equal to the breakdown value. The sinuosity substantially decreases when there is an overvoltage. Since the sinuosity of the lightning channel is most probably caused by the radial component of the electric field strength, the sinuosity of the discharge channel should increase at the opposite electrode both in a creepage spark and in lightning, where the relative value of the radial component of the field strength increases. On the basis of this we can formulate the premises for the appearance of beaded lightning by analogy with the beaded structure of a creepage discharge.

Beaded lightning can arise in the complete and incomplete stages of the discharge. The photographs in [1], which were obtained when the observer did not see beaded lightning, can probably be attributed to the incomplete stage. In this case the condition for bead lightning to appear in a segment of the discharge gap is that the breakdown field strength has a limited effect, sufficient to form local zones of bulk charge but insufficient to form a channel with good conduction. This condition can be satisfied both in a side branch, i.e., an alternative discharge trajectory, and at the breakdown front if the field strength is insufficient for a bulk-conduction channel to form.

If beaded lightning is to appear in the complete stage, the breakdown must occur at a voltage roughly equal to the breakdown voltage, i.e., the condition of maximum sinuosity must be satisfied, at least at the ground. The second condition is that the discharge have a low energy, sufficient to form local regions of longer glow but insufficient to form a channel with a high discharge current. This is primarily the condition for observing beaded lightning with the unaided eye, since a longitudinal nonuniformity can be recorded virtually always in a breakdown in a nonuniform field.

Extremely nonuniform fields with large potential gradients can arise if a positive leader counter to the negative leader from the ground is formed [7]. When these conditions are modeled in a creepage spark a beaded structure can be formed even in the rectilinear part of the channel (see Fig. 4). These conditions probably also arise during the artificial stimulation of lightning [1]. A beaded structure can be obtained here in a limited segment of the channel, in the zone of interaction of the two leaders, with the above-mentioned condition of a limit on the energy.

For any quantitative evaluations of such a phenomenon it is necessary to know why the plasma formations have an anomalously long lifetime. The most probable cause is that the plasma is nonideal in the zones of local charge concentration [9]. The intensity of the radiation from the nonideal plasma is reduced because part of the upper levels are not realized and the ionization potential is decreased [10]. For this reason the decay of the nonideal plasma can be appreciably slower [11] and this apparently explains the appearance of dark bands in the photoscans of a creepage spark (see Fig. 2).

Recording of a beaded structure makes it possible to consider the breakdown process in a long discharge gap from a slightly different viewpoint: not as the motion of a charge-bearing streamer but as the formation of a chain of local charges (in the entire ionization zone at the breakdown front) as a result of the action of breakdown waves [5] and corona processes [6]. The successive inclusion of local charges in the conducting channel of the leader during photographic recording looks like the stepped propagation of the leader local charges if the realized leader trajectory are compensated in a time of the order of $1 \cdot 10^{-8}$ sec; such compensation does not occur when the breakdown front stops in alternative trajectories of the leader. Here the local charges decay with radiative recombination, because of which it becomes possible to record the beaded structure both in the incomplete stage of a creepage spark or in lightning.

In kinds of the discharge channel (see Fig. 3) the ionization zone increases and here, too, the local charges formed are not compensated in the high-current stage. On the contrary, they can apparently continue to form and grow, especially in the decaying plasma of the high-current discharge. The problems of charge localization, structure of local charges, and recombination time are as yet unclear and require further study.

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