

ELECTRIC BREAKDOWN IN LARGE NEON GAPS UNDER CONDITIONS OF PRELIMINARY IONIZATION

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Submitted March 1, 1972

Zh. Eksp. Teor. Fiz. 63, 491-497 (August, 1972)

Results of investigation of the formation of a spark channel in neon along a preliminary ionized path in a spark chamber are presented which are obtained by means of an electro-optical shutter in the nanosecond range and a light amplifier. Space-time and radiance-time characteristics of processes of formation of inclined sparks are obtained for various values of the electric field strength in the chamber and angle of inclination of the preliminary ionization path to the direction of the electric field. These characteristics indicate that the spark is formed as the result of merging of a chain of streamers polarized in the direction of the initial ionization path as a result of the external field being distributed along the streamers as along quasiconductors.

INTRODUCTION

ONE of the types of breakdown of greatest practical interest is electric breakdown in pre-ionized path. Such a phenomenon is observed in spark chambers operating in the tracking regime^[1]. This regime is of interest because the chain of initial electrons is disposed in the chamber from electrode to electrode in the direction of the field or at a certain angle to this direction. Depending on the angle between the pre-ionization track and the electric field direction in the chamber, the discharge develops in the form of a spark that preserves the track direction (at small angles), or breaks up into a large number of sparks that develop along the direction of the electric field.

The mechanism that produces a spark making a certain angle with the electric field direction is still unclear and has been the subject of a number of discussions^[2-4]. For a complete understanding of the mechanism whereby such sparks are produced, it is necessary to study the space-time characteristics of the pre-breakdown stages of this phenomenon. The experiments performed at CERN^[5,6] were perhaps the first attempts in this direction. The lack of the spatial characteristics of the processes, however, has not enabled these workers to obtain the concrete scheme of inclined-channel formation scheme.

We present here the results of a study of the formation of an inclined spark along the track of a cosmic-ray particle, performed by high-speed photography using a nanosecond-range electron-optical shutter and a light amplifier. The preliminary results of the investigations were performed in^[7] and are reported completely in a dissertation by one of the authors^[8].

EXPERIMENTAL PROCEDURE

We used a frame-by-frame photography procedure described in^[9]. A high-voltage pulse was applied to the electrodes of the discharge chamber, with a delay not exceeding 500 nsec; this delay was the sum of the operating time of the logic elements and the starting time

of the high-voltage nanosecond-pulse generator. The angle at which the cosmic-ray particle traversed the discharge-chamber volume was varied by rotating the chamber relative to the axis of a scintillation-counter telescope that selected particles moving in only one direction. The angle θ between the cosmic-ray particle track and the direction of the electric field in the chamber was measured accurate to 1° . Specially purified neon was constantly drawn through the chamber. The particle tracks were photographed at definite instants of time, starting with the stage of development of the individual electron avalanches up to their coalescence and formation of an inclined spark channel^[1]. During each stage of the investigated process, we obtained and processed 80-100 image-converter photographs. Typical photographs of the inclined spark, obtained at successive instants of time, are shown in Fig. 1.

SPACE-TIME CHARACTERISTICS OF FORMATION OF AN INCLINED SPARK CHANNEL

The results of the study of the spatial evolution of the processes that occur on the track of an ionizing particle during the early stages of discharge development reduce to the following:

1. At the initial instant (the start of the observation) there exist on the particle track a number of ionization fronts that develop from the anode side. The density distribution of the electron avalanches per unit length of the particle track in the observation plane is shown in Fig. 2. The number of maxima on the density plots in Fig. 2b corresponds to the average avalanche density registered in the experiments.

2. During the later stages of spark-channel development, the direction of ionization-front motion from the anode side tends to coincide with the direction of the particle track. At a discharge-chamber field intensity $E_0 < 10$ kV/cm and at inclination angles $\theta > 20^\circ$ one observes motion of an ionization front also from the cathode side of the ionized regions.

¹⁾Henceforth, $t = 0$ will mean the instant at which the high-voltage pulse front appears on the spark-chamber electrodes.

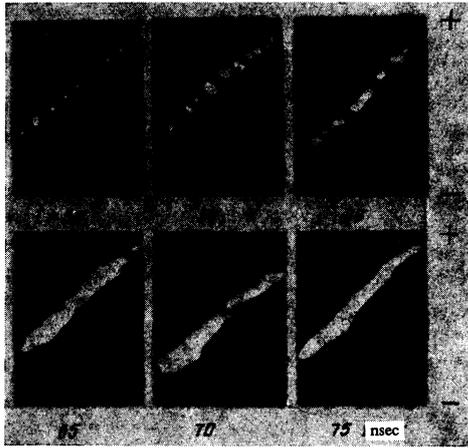


FIG. 1. Successive stages of discharge development along the track of an ionizing particle (time is reckoned from $t = 0$); $E_0 = 7.5$ kV/cm, $\theta = 45^\circ$.

3. The ionization front velocity remains practically constant at $\sim 1 \times 10^8$ cm/sec over the entire observation interval.

4. When the delay in the application of the high-voltage pulse was increased, the density of the avalanches (streamers) on the ionizing-particle track decreased to 2 cm $^{-1}$. The streamers interact at distances much larger than their transverse dimension.

5. At angles $\theta \geq 60^\circ$ of pre-ionization track inclination, an inclined spark channel was produced in only 10% of the cases. The image-converter pictures show, besides the inclined channels, also several (usually two or three) channels that develop from electrode to electrode in the direction of the electric field. The brightness of the inclined channel is much lower than that of the channels parallel to the field.

TIME OF INCLINED-CHANNEL FORMATION

The spark-channel formation time determines the complete picture of the discharge process in the inter-electrode gap. In the experiments we determined the channel formation time at electric field intensities from 4 to 16 kV/cm and at pre-ionization track angles $\theta = 0-60^\circ$. The time of formation of the inclined channel was taken to be the instant of complete coalescence of individual streamers to form a channel. To exclude errors connected with the finite spatial resolution of the optical system, the instant of complete coalescence of the streamers on the track was determined with allowance for the data obtained by measuring the densities of the optical images of the tracks (see Fig. 2b). The density distribution of Fig. 2b at $t = 40$ nsec corresponds to the instant of complete coalescence of the streamers, since the optical density corresponding to the minima in this figure is equal to the maximum density registered in Fig. 2b at $t = 36$ nsec. The minimal densities in this upper figure correspond to the density of the fogging of the photographic film.

The measured time t_f of formation of an inclined spark channel is plotted in Fig. 3 against the electric field intensity for the angles 0, 30° , and 45° . The results reduce to the following:

1. The formation time of an inclined spark de-

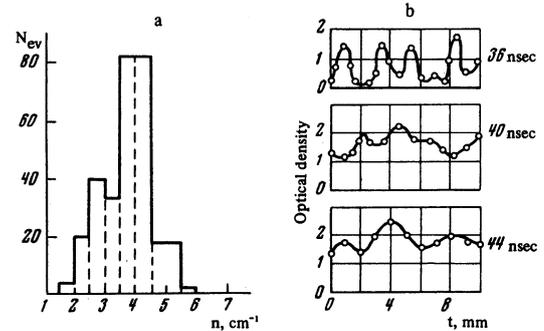


FIG. 2. a—Distribution of avalanche density on the track of an ionizing particle in the observation plane, $\tau_d = 500$ nsec (N_{ev} —number of events). b—Density plots of 1 cm of track, obtained in successive instants of time.

creases successively with increasing electric-field intensity, and increases with increasing angle θ if the field intensity is fixed.

2. The dependence of the spark-channel formation time on the angle θ increases with decreasing field intensity in the discharge chamber.

3. The formation time of an inclined spark channel, at angles $\theta > 0$ and at all values of the electric field intensity, exceeds the time of avalanche-streamer transition in neon. Curve 4 of Fig. 3 corresponds to the time of avalanche-streamer transition in neon, determined in earlier independent investigations of streamer breakdown of neon^[9]. It should be noted, however, that in the inclined spark one does not observe the accelerated ionization observed in the case of streamer breakdown. Thus, when streamers are independently developed, their length, at a time equal to the inclined-spark formation time, turns out to be much larger than the length of the interacting streamers in the inclined spark channel. The table lists the values of the total length that would be possessed by the streamers were they to be independently developed in a 40 mm gap.

LIGHT EMISSION FROM SPARK CHANNEL

The light emission could be determined under the conditions of our experiment simultaneously with the determination of the spatial evolution of the process, so that the connection between the changes in the brightness characteristics and in the structure of the process could be determined directly. The brightness characteristics were obtained in the following manner. The relative apertures of the input and intermediate objectives were chosen such that the brightness of the images in the spark channel on the output screen of the light amplifier remained practically constant, and the photographic material was used in the linear part of its characteristic curve. The densities of the photographed processes on the film were measured with a DFE-10 densitometer. They were then recalculated into object brightnesses with allowance for the values of the relative apertures and of the image scales.

The results of the measurement of the brightness characteristics are shown in Fig. 4 for three values of the angle θ and for three values of the electric field intensity. The character of the time variation of the brightness agrees well with the measurement data of Caris et al.^[6] The intensity of the light from the spark

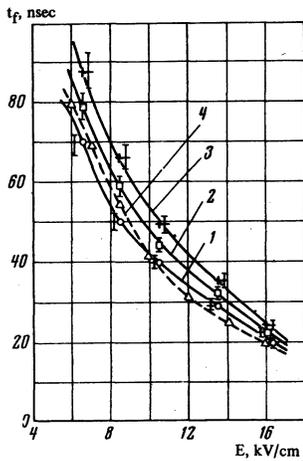


FIG. 3. Spark formation time as a function of the electric field intensity and of the pre-ionization track angle. 1— $\theta = 0^\circ$; 2— $\theta = 30^\circ$; 3— $\theta = 45^\circ$; 4—critical time of development of an electron avalanche in neon [9].

channel increases with increasing rate of evolution of the process, the latter depending both on the initial electric-field intensity and on the inclination of the pre-ionization track. The instants of time at which the rate of change of the light intensity begins to depend on the ionizing-particle track angle, at fixed values of the intensity (points of intersection of the curves in Fig. 4) are very close to the instants when the electron avalanches go over into the quasiconducting state^[9]. However, the visually observed streamer interaction (change of ionization-front propagation direction) sets in at later instants of time (marked by arrows in Fig. 4). It should be noted that at the instant that the ionized channel is formed its brightness is approximately the same for all angles and all intensities. The experimentally observed^[10] dependence of the spark-channel brightness on the spark inclination sets in during the stage after the coalescence of the streamers. This dependence is due mainly to two factors. First, after the ionized channel is produced, the voltage is distributed over its length, and the field intensity in the channel depends on the angle in accordance with the expression

$$E_c = U \cos \theta / d, \tag{1}$$

where U is the pulse amplitude and d is the width of the spark gap. Second, the time of channel formation (streamer coalescence) decreases with decreasing angle. Therefore at a fixed duration of the applied pulse the source energy is released in the formed channel for a time that increases with decreasing angle.

DISCUSSION OF RESULTS

The data obtained in our experiments as well as by others^[5,6] corroborate the point of view that the mech-

		Total streamer length (mm)					
		$E_0, \text{ kV/cm}$					
θ		6,6	7,5	8,6	10,4	14,5	16
45°	≥ 40*	≥ 40*	> 40*	20	5	3.0	3.0
30°	15	10	8	5.0	3.0	2.5	2.5
0	2.5	2.5	2.5	2.5	2.5	1.5	1.5

*Overlap

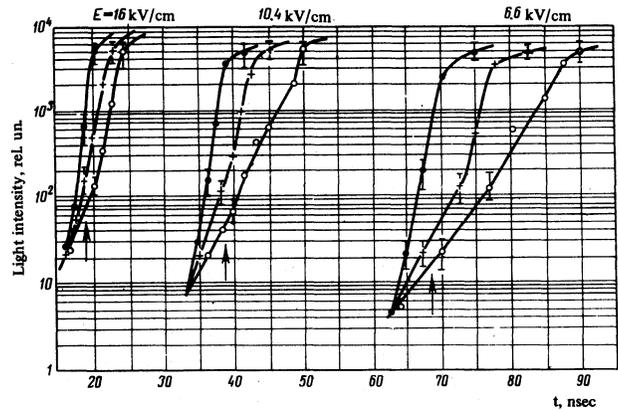


FIG. 4. Time variation of the light intensity from the spark channel (time reckoned from $t = 0$): ●— $\theta = 0^\circ$; +— $\theta = 30^\circ$; ○— $\theta = 45^\circ$.

anism whereby the inclined spark is produced incorporates the production of a space-charge field that causes the electrons to move along the pre-ionization track. Such a field can result either from the interaction of the space charges of the electron avalanches^[11], or as a result of formation of a homogeneous charge front^[6], or finally through distortion of the external field by a chain of conducting streamers^[4,12].

Static photographs of the processes show that the production of a homogeneous charge front by diffusion of the avalanches during their earlier stage of development is impossible, since a definite number of streamers, interacting at large distances, develop on the track of the ionizing particle.

If it is assumed that the mutual diffusion is not due to the effect of space-charge interaction, and the production of a homogeneous charge front is due to free diffusion, then the time of formation of the homogeneous charge front is given by

$$t_{hr} = \sin^2 \theta / 16m^2D, \tag{2}$$

where m is the avalanche density in the track of the ionizing particle and D is the diffusion coefficient. If the time of formation of the homogeneous front amounts to an appreciable fraction of the total spark formation time then, in accord with (2), the time of spark formation is independent of the electric field intensity, which patently contradicts the experimental results and the operating experience with spark chambers. In addition, the calculated time of formation of the homogeneous front greatly exceeds the time of coalescence of ionized regions, observed in experiment in the entire range of intensities and angles.

The measured times of the processes have shown that the formation of a continuous ionized channel occurs during the streamer stage, and not at an instant when the charges in the avalanche are still separated. The scheme of formation of the spark channel, based on the separation of the charges in the electron avalanches^[11], is therefore likewise not confirmed. The streamer interaction sets in only after they reach a definite degree of conductivity over a certain length. The streamers can interact after a long path, and not a short one as stipulated in^[13].

Thus, the process of formation of an inclined spark channel reduces to the following. The discharge is formed out of a series of clearly pronounced avalanches

that change into streamers. When the streamers attain a definite conductivity, the external field becomes distributed over a certain length along a chain of conducting streamers, and this polarizes them further in the direction of the pre-ionization track. When a large number of streamers develops, the external field becomes distributed along a chain of them, remaining uniform in the space between the streamers, because the dimensions of the conducting regions are commensurate with the distance between them. Therefore the field intensity on the ionization front cannot increase strongly, and the ionization processes evolve much more slowly than in the case when independent streamers develop, where the increase of the intensity is due to strong distortion of the external field by a conducting channel located against the plane of the chamber electrode.

The subsequent development of the streamer takes place in the modified field along the pre-ionization track, at practically constant velocity. The experiments have shown that at the instant when the interaction starts the number of carriers in the head of each streamer is $\sim 10^{10}$, producing a field of the same order as the external field at the location of the neighboring streamer. The presence of a space charge of opposite sign, stipulated in^[11], is not obligatory in this case, since it will be produced by polarization of the neighboring streamer by this field. As a result, all the streamers will be polarized along the pre-ionization track. Coalescence of the streamers produces an ionized channel that preserves the direction of the pre-ionization track.

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Translated by J. G. Adashko