The Method of Determining of Streamer Density in the Streamer Zone of Spark Discharge

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We propose a method for determining the concentration of streamers in streamer zone of leader discharge by instant digital photography with spatial resolution insufficient for registration of individual streamers. The method is based on statistical analysis of fluctuations of the brightness of the set of nearby pixels. An example of applying this method to determine the parameters of the streamer zone of the final-jump phase of the spark discharge is presented.

1. Introduction

Streamer zone is an important structural part of the spark discharge at the stage of ionized spark channel formation in the gas-discharge gap. Streamer zone consists of a number of streamers that start with the leader's head in different directions and moving at a velocity far exceeding the leader's velocity. According to modern concepts, streamers in streamer region are localized plasma formations that have no galvanic connection to the head of the leader. Each streamer has an uncompensated charge that is transferred to the space together with the streamer. A charge supplied to the leader head by the current flowing in the leader channel, is carried into space by the flow of charged streamers, forming a space charge of the leader sheath and self-consistent electric field in the streamer zone. Data on the concentration of streamers and its distribution in the streamer zone may significantly contribute to the development of a self-consistent model of a streamer zone. The spatial distribution of the streamer density in streamer zone can be determined from the distribution of images of streamers at the photos of the streamer zone using the cylindrical symmetry of the latter. Visible light of streamer is emitted only from his head, where there is a region of high electron density and high electric field strength. The streamer head size is small, less than a millimeter, so images of streamers at the photos look points. Direct counting of streamers on the picture of streamer zone of atmospheric pressure spark is only possible in that areas of streamer zone where the concentration of streamers is small, namely, on the edge of the streamer zone at the continuous leader propagation phase of discharge. In the denser parts of the streamer zone, as well as in final-jump phase when the streamer density across the streamer zone significantly increases, the spatial resolution of fast cameras is not enough to separate the individual streamers. This report is devoted to the method for determining the concentration of streamers in the streamer zone on the basis of its fast camera photo under conditions where each pixel of receiving matrix of the camera gets a lot of streamers images. The combination of this method with other measurements (image brightness and discharge current) allow us to determine some parameters of streamers. The report presents the results of applying this method to measure the absolute magnitude and spatial distribution of the volume concentration of streamers and some other parameters in the streamer zone of the final-jump phase of spark discharge in the rod-plane gap of 5.5 m length.

2. Description of the method

The method is based on statistics of fluctuation in the number of streamers images located on a given area of the streamer zone photo. The positions of images of streamers within the area, much less than the inhomogeneity scale (characteristic size) of brightness of streamer zone image, are random. It can be shown that in this case the number N of streamers images within a given area comprising a plurality (>>1) of streamers images obeys normal distribution with dispersion equal to the square root of the mean value:

$$w(x) \approx \frac{1}{\sqrt{2\pi\bar{N}}} exp\left(-\frac{x^2}{2\bar{N}}\right) \qquad x = N - \bar{N} \qquad (1)$$

where $\bar{N}$ is the mean value of N. The dispersion is

$$\sigma_N = \sqrt{\langle x^2 \rangle} = \sqrt{\bar{N}} \qquad (2)$$

If the glow intensity of all streamers are the same, the intensity I of illumination of selected part S of the streamer zone image is proportional to the number of streamers images N placed within S: $I = aN$, where a is unknown factor. The average value $\bar{I}$ and dispersion σ_I of illumination intensity I of part S of the streamer zone image are, respectively: $\bar{I} = a\bar{N}$, $\sigma_I = a\sigma_N$. A ratio of the square of illumination intensity mean value to the square of its dispersion equals to the average number of streamers images within S:

$$\frac{(\bar{I})^2}{(\sigma_I)^2} = \bar{N} \quad (3)$$

Thus, by measuring the mean value and the dispersion of the output signal of camera matrix pixels on a certain part of the image streamer zone, rather small to variation of the mean value of the output signal within it would be insignificant, but includes enough pixels to make the error of the mean value and dispersion measuring not too large, we can determine the concentration of the streamers images on site S of streamer zone photos.

3. Statistics of noise brightness fluctuations

In the complete absence of light radiation entering the camera lens, snapshot has a noise. The distribution of noise intensity is also subject to the normal law. The mean value and square of dispersion of sum of two independent random variables equal respectively the sum of their mean values and squares of their dispersions. Therefore, to determine the average value and dispersion of the image pixels brightness one must to subtract the noise parameters from that obtained by statistical analysis of the frame. Photographs of the discharge, which will be analyzed in the next section were obtained using fast camera 4Picos. We have found that the average value of the noise intensity for camera 4Picos is approximately 520 units of the digital output and the dispersion is 164 units (square of the dispersion - 26800).

4. Analysis of the streamer zone image of the final-jump phase of spark discharge

Figure 1 shows two consecutive shots of the final-jump phase of the spark discharge in air obtained in [1]. The discharge proceeded in the rod-plane gap of 5.5 m length with a positive polarity voltage pulse is applied to the rod. The exposure of each shot was 0.2 µs, the time delay between pictures was 10 µs. Current measured at the high-voltage electrode (on the rod), was as follows: at the time of the first shot - 11 A, at the time of the second frame - 34 A.

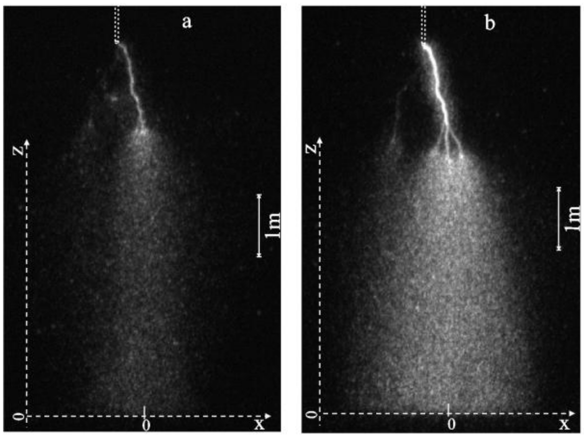

Fig.1. Two consecutive photos of one spark discharge. **a** - first frame, **b** - second frame. Exposure time is 0.2 µs. The time delay between the end of the first exposure and the start of the second is 10 µs. Gas gap length is 5.5 m. The current at the rod electrode was: at the time of the first exposure - 11 A, at the time of the second exposure - 34 A.

For statistical analysis we divided the frames into squares consisting of $K\times K$ pixels, where K is the number of pixels on the side of the square. In each of the squares the average value of the intensity of illumination of pixels and its square of dispersion were calculated, from the obtained values were subtracted the mean value and the square of dispersion of noise, and by the formula (3) the average number of images of streamers per one pixel was determined. Then, using the scale of the images 1 pixel = 1.06 cm, we found the surface density of streamers $N_{str}(x,z)$ on the projection of a streamer

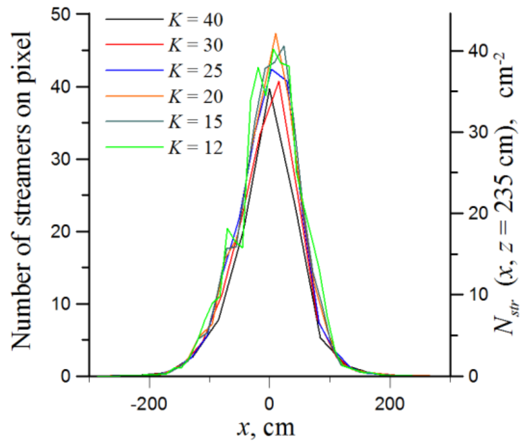

Fig.2. The surface density of streamers on the vertical projection of the streamer zone along the horizontal line located at a distance of z = 2.35 m from the plane obtained in a variety of sizes K of the statistical square.

zone on the vertical plane. Figure 2 shows the distribution of the surface density of the streamers on the vertical projection of the streamer zone along the horizontal line located at a distance of 2.35 m from the surface, resulting in different sizes of the statistical squares. As it is seen from fig.2, for small K the value N_{str} has noticeable fluctuations (fluctuations occur at K = 12) because of the smallness of the statistical sets ($K^2 \lesssim 100$), for large K values $\bar{N}$ reduces because of the influence of streamer zone image spatial inhomogeneity at the scale of the statistical square on the value of dispersion. All further analysis was carried out at a size of statistical square of 15 × 15.

The relative average luminescence intensity W_1 of a single streamer in each statistical square was calculated by dividing the average intensity of illumination of a pixel in this square on the average number of images of streamers in the pixel: $W_1 = \bar{I}\,/$

$\bar{N}$. Figure 3 shows the distributions of streamers luminescence intensity W_1 in the vertical projection plane of the streamer zone, and along a horizontal line at 235 cm from the plane, and along the vertical axis of symmetry of the streamer zone. All values are determined only in those statistical squares, where the level of intensity $\bar{I}$ exceeds the noise level in two or more times. The ratio of the brightness in the pictures 3a and 3c corresponds to the ratio of the values of W_1. As can be seen from Figure 3 the streamers luminescence intensity W_1 within the scatter ±50% remains approximately constant throughout the volume of the streamer zone, with a tendency of growth in the periphery of the zone. This fact is evidence of the proximity of parameters for all streamers in the streamer zone. Streamer parameters are highly dependent on the ambient electric field, so the similarity of streamers in the streamer zone confirms the idea of the approximate constancy of the modulus of the electric field in it [2]. The consequence of the constancy of the electric field in the streamer zone should be also the constancy of the speed of streamers. Then, since the electric field and the velocity of streamers in the

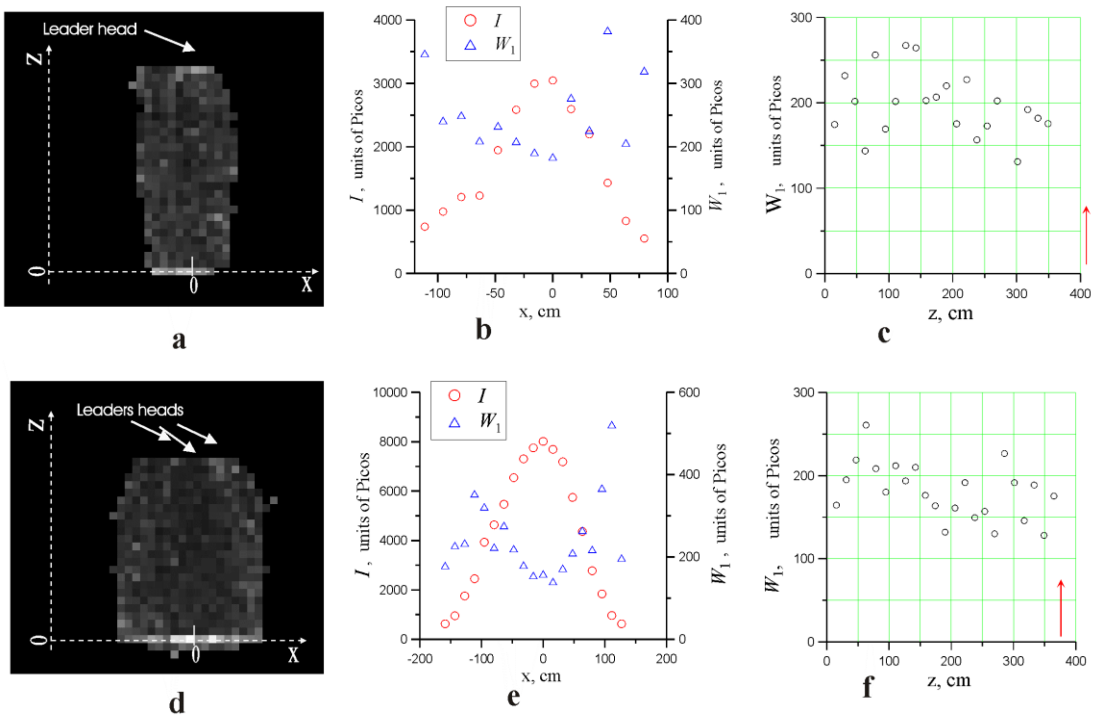

Fig.3. The distribution of the emission intensity of the streamer W_1: **a**, **d** - in the plane of the vertical projection of the streamer zone; **b**, **e** - along a horizontal line at 235 cm from the plane; **c**, **f** - along the symmetry axis of the streamer zone (x = 0). **a**, **b**, **c** - the first frame; **d**, **e**, **f** - the second frame. The value of I at **b** and **e** is the average intensity of illumination of pixels $\bar{I}$ (in units of the digital output of camera 4Picos).

streamer zone at final-jump phase of discharge is directed mainly downwards, the flow of streamers along the *z*-axis is approximately proportional to the linear density of streamers along the *z*-axis. The dependence of the linear density N_z on the coordinate *z* determined by summing the number of images of streamers on the horizontal rows of pixels is shown on Fig.4. Note that the accuracy of determination of linear density N_z is higher than that is for $\bar{N}$. As can be seen from Fig.4, the linear density of streamers in the streamer zone changes relatively weak: in the first frame it is $N_z \approx$ (1300÷2400) cm^{-1}, in the second frame - $N_z \approx$ (5500÷7500) cm^{-1}. Therefore, we can speak about the approximate conservation of streamers flow along the streamer zone. It is known [2] that the streamer velocity in the streamer zone at the leader phase of discharge is close to critical (in the air ~ 10^7 cm/s) - the minimum possible for the propagation of streamers. In a final-jump phase the streamer velocity increases with decreasing length of the streamer zone. In our case, we are dealing with the beginning of the final-jump phase, when the length of the streamer zone has decreased only slightly, so one can expect that the velocity of the streamers are close to critical, V_{str} ~ 10^7 cm/s. If we consider that the current in the streamer zone is the movement of streamer charges [2], then we can define the streamer charge by dividing of the discharge current to streamers flow: $q_{str} = current/\ N_zV_{str}$. We get from the first frame on Fig.1 that q_{str} = (8.5÷4.5)·10^{-10} C, and from the second frame - q_{str} = (6÷4.5)·10^{-10} C. These values correspond well to those obtained from measurement with a sectioned cathode [2].

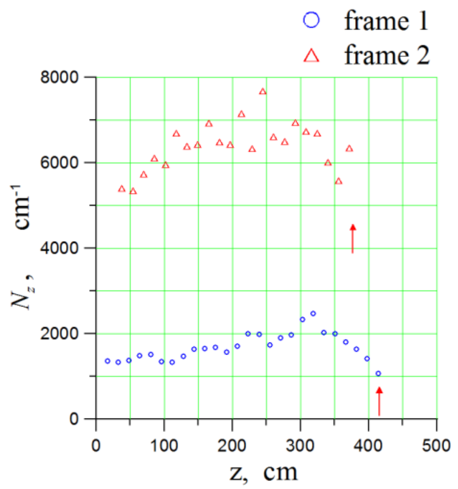

Fig.4. The linear density of streamers in the streamer zone shown on the Figure 1.

The spatial distribution of the volume concentration n_{str} of streamers in the streamer zone can be founded from the distribution of the surface concentration N_{str} of streamer projections on the vertical plane, assuming the streamer zone has axial symmetry. We approximated the dependence $N_{str}(x)$ by Gaussian curve (Fig.5):

$$N_{str}(x,z) = N_m(z) exp\left\{-\frac{x^2}{[\Delta x(z)]^2}\right\} \quad (4)$$

where $N_m(z) = N_{str}(0,z)$ is the value of surface density of streamers images on the symmetry axis of the vertical projection of the streamer zone.

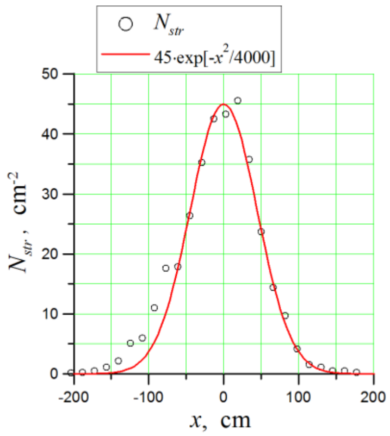

Fig.5. Approximation of the surface density of streamers images on the vertical projection of the streamer zone (second frame in Figure 1) on the transverse coordinate x at z = 235 cm.

The spatial distribution of the volume concentration of streamers $n_{str}(r,z)$ corresponding to (4) for axisymmetric streamer zone can be obtain with the use of the Abel transformation:

$$n_{str}(r,z) = \frac{N_m(z)}{\sqrt{\pi}[\Delta x(z)]} exp\left\{-\frac{r^2}{[\Delta x(z)]^2}\right\} \quad (5)$$

where r is radial coordinate. The volume concentration of streamers on the symmetry axis of the streamer zone $n_{str}(r=0,z)$ are shown in Fig. 6 (the error in determining n_{str} is about ±50%). In the lower part of the streamer zone (closer to the flat electrode) the concentration of the streamers is almost independent of z: on the first frame $n_{str}(r=0,z\approx0) \approx 0.1$ cm^{-3}, on the second frame $n_{str}(r=0,z\approx0) \approx 0.15$ cm^{-3}. Accordingly, the average distance between the streamers in the lower part of

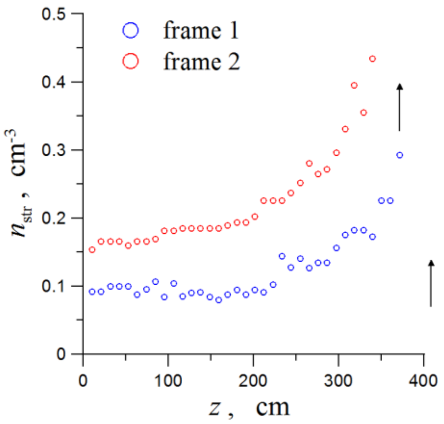

Fig.6. Concentration of streamers n_{str} on the symmetry axis of the streamer zone (r = 0). The arrows indicate the positions of the lower leader head.

the streamer zone on the first frame is 2.1 cm, and on the second frame - 1.9 cm. In [2] it is pointed that the average density of streamers in streamer zone is ~ 1 cm^{-3}, which is close to our data.

It is easy to find from our data the total number of streamers in the streamer zone: on the first frame - $4.3 \cdot 10^4$, on the second frame - $1.5 \cdot 10^5$.

5. Conclusion

Method of statistical analysis of brightness fluctuations in the image of streamer zone obtained using high-speed cameras, allows to determine the concentration of streamers and its distribution in the streamer zone under conditions of insufficient spatial resolution of camera, when the selection on photos of single streamer is impossible.

6. Acknowledgments

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7. References

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