Stereo-photography of streamers in air

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Standard photographs of streamer discharges show a two-dimensional projection. Here, we present stereophotographic images that resolve their three-dimensional structure. We describe the stereoscopic setup and evaluation, and we present results for positive streamer discharges in air at 0.2–1 bar in a point-plane geometry with a gap distance of 14 cm and a voltage pulse of 47 kV. In this case, an approximately Gaussian distribution of branching angles of $43° \pm 12°$ is found; these angles do not significantly depend on the distance from the needle or on the gas pressure. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2894195]

A streamer is a rapidly extending discharge channel that can appear when a high voltage is applied to any ionizable medium; most studies are done in air. Streamers precede phenomena such as sparks, leaders, and lightning. The main difference is that streamers do not significantly increase the gas temperature; they are rather governed by impact ionization and space charge effects.[1] Streamers are directly observed in nature in the form of sprites,[2] which are enormous atmospheric discharges above active thunderstorms at about 40–90 km altitude. Streamers also have many technical applications in ozone generation and consecutive disinfection, in biofuel processing, plasma assisted combustion, and aviation; for a short review with references, we refer to Ref. 1,

A largely unexplored issue in streamer research is the breakup of single channels. Such branching events are commonly seen in experiments;[3–5] multiple branching actually determines the gas volume that is crossed by streamers and consecutively chemically activated for plasma processing purposes. However, up to now, only the conditions of the first branching event have been resolved in microscopic models.[6–10] On the other hand, the distribution of branching lengths and angles is an ingredient of models for the complete branching tree on larger scales.[11–13] In the present paper, we resolve these lengths and, in particular, the angles in experiments.

Imaging of streamer discharges is usually done with conventional or digital cameras.[4,8,14] This leads to two-dimensional (2D) representations of what is essentially a three-dimensional (3D) phenomenon. These 2D representations can cause problems of interpretation. For example, it is impossible to see whether an apparent loop or reconnection is really what it seems to be. It is also impossible to get a complete picture of the 3D spatial structure and to measure branching angles. For this purpose, we have implemented a stereophotography method which makes it possible to image streamer discharges in 3D. In this way, we resolve the imaging ambiguities in the fundamental physical phenomena, help in understanding which gas volumes are actually treated by the discharge, and supply experimental data for larger scale models. The stereoscopic technique that we use has been around for a very long time[15,16] and has been used for a large variety of topics. Some phenomena similar to streamers that have been studied with stereophotography are sparks,[17] flames,[18] and dusty plasmas.[19]

To generate streamers, we use the experimental setup that is discussed thoroughly in Ref. 4, and we use the electric circuit called C-supply in Ref. 4. In this setup, a capacitor is charged negatively with a dc power supply. This capacitor is then discharged by means of a spark-gap switch. This results in a positive voltage peak on the needle inside the vacuum vessel. A positive corona discharge then propagates from the needle to the grounded plate. Both needle and plate are highlighted in Fig. 1. In the present measurements, a positive voltage of 47 kV with a rise time of about 30 ns was applied to the point, 14 cm above the plate. The atmosphere in the vacuum vessel consisted of ambient air at different pressures (200, 565, and 1000 mbar).

MacAlpine *et al.*[17] have studied sparks with a camera and a prism. In this study, two images were taken using a prism to form an image at a right angle to the directly observed one. In this way, the complete 3D structure of the spark path can be reconstructed with great accuracy. Similar work was reported by Makarov.[20] However, this method only works well for structures that have very few channels (e.g., the one spark of MacAlpine). When there are many channels,

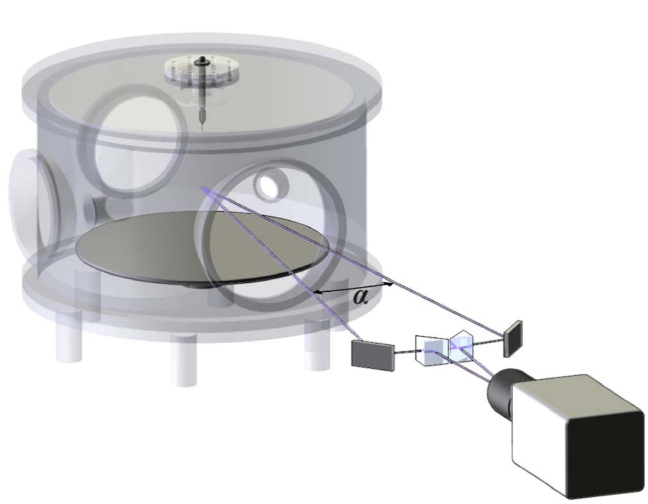

FIG. 1. (Color online) Overview of the stereoscopic measurement setup with a schematic drawing of the two image paths.

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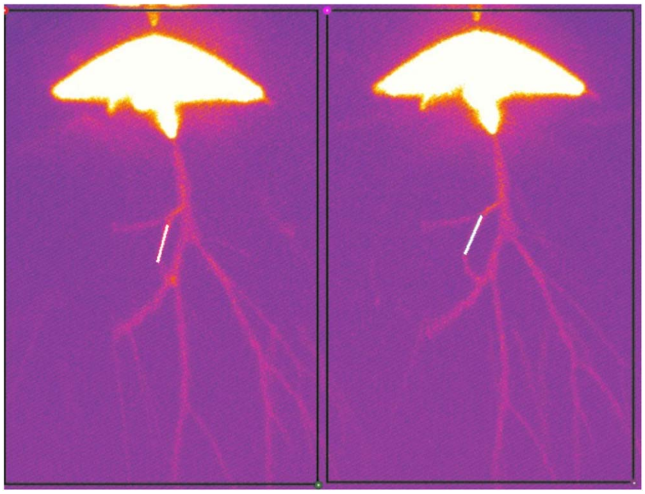

FIG. 2. (Color online) Stereoimage as recorded by camera. Settings: positive voltage on tip, $U=47$ kV, $p=200$ mbars, $\alpha=13°$, and $d=14$ cm. The intensity has been scaled so that the structure in the bottom part can be clearly seen. One streamer section has been marked with a white line in both images.

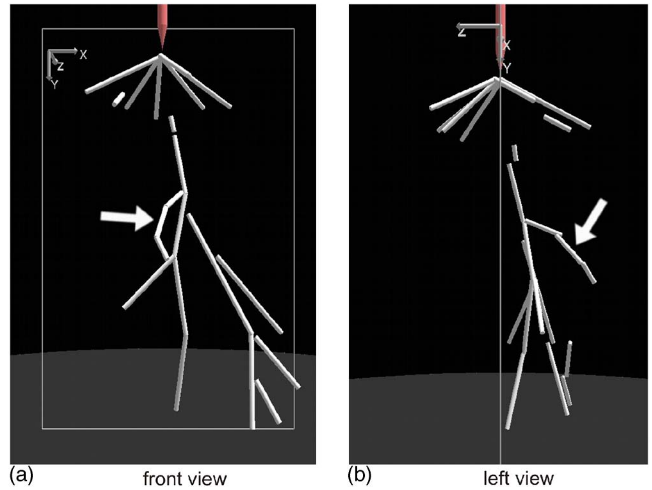

FIG. 3. (Color online) Orthogonal views of the 3D reconstruction of streamer structure shown in Fig. 2. The section originally marked with the white line is now marked with an arrow in both views.

it is very difficult to correlate them pairwise from two images taken at an angle of 90°.

In our case, we want to study streamer discharges that contain many (10–100) streamers. For this purpose, a similar method can be used but with a much smaller angle between the two image paths so that the two images of one streamer can be recognized. To achieve a smaller angle, one camera has been used in combination with two prisms and two flat mirrors, as shown in Fig. 1. With this setup, two images (from different viewing angles) are captured on one camera frame; therefore, they are temporarily perfectly synchronized. An example of such a camera frame is shown in Fig. 2.

From the two 2D images, the 3D structure of the streamer channels can be reconstructed in the following manner: a straight section of a streamer channel is selected in both images. The end points of these two lines are now translated from 2D (xy) to 3D (xyz). In principle, an exact trigonometric evaluation would supply absolute locations in space. However, as we are only interested in local observables (branching angles and lengths), we have used a simplified approach assuming that the cameras are far from the system and have a very large focal length. Indeed, the distance between camera and streamers is about 1 m, while the distances between recently splitted streamer branches never exceed 2 cm.

The two images give the 2D coordinates (x_l, y_l) and (x_r, y_r) of identical streamer parts within the left or right image, respectively, where the origins of the respective coordinate systems are chosen in the electrode tip. The depth coordinate z is then approximated as $z=(x_r-x_l)/[2\sin(\alpha/2)]$, where α is the full angle between the two optical paths (as indicated in figure 1, in the present measurements $\alpha=13°$). The 3D x and y coordinates are calculated as $x=(x_r+x_l)/2$ and $y=(y_r+y_l)/2$.

The error in streamer distances after splitting that results from this simplification is less than 0.2 mm. The dominant error comes from the visual determination of the locations of streamer section end points on the stereoscopic images. In many situations, it is difficult to locate the exact point of branching, especially where two streamers are very close to each other. The total error is approximately 1 mm for local observables and 5 mm for absolute locations.

The two 2D lines have now been translated into one 3D streamer section. This can be done for all suitable streamer sections in the image. When all these 3D streamer sections are now plotted in 3D space, we get some insight in the real structure of the streamer discharge. The 3D reconstruction of the example from Fig. 2 is shown in Fig. 3. Here, it can clearly be seen that the streamer section marked with the white lines in Fig. 2 is not part of a loop. This information cannot be derived from just one of the original 2D images. One of the measurements that can be performed now is measuring branching angles. The measured angles are the inner angles between two 3D streamer sections, represented as vectors. The technique described here has also some limitations, the most important one is that it is not possible to process discharge images that contain more than about 50 streamer channels.

Figures 4(a)–4(c) show histograms of the measured branching angles for 200, 565, and 1000 mbar and Fig. 4(d) combines the results for all pressures into one histogram. As can be seen, the distribution is roughly Gaussian, with average values between 39° and 46° and standard deviations of 11°–13°. The average branching angle shows a slight decrease as a function of pressure. However, it is not clear whether this is statistically significant due to the limited amount of data points (about 35 points per pressure setting).

The length scales of streamers are expected and observed to scale quite well with pressure. However, density fluctuations do not scale with density;[1,21] if they play a significant role in streamer branching, one would expect the branching distribution to depend on pressure. Therefore, in Fig. 5, the branching angle is plotted as function of pd, where p is the pressure and d is the vertical distance from the tip (the y coordinate) at the point of branching. If the branching behavior would differ for streamer sections close to the tip from sections close to the cathode plane, this would be seen in this plot. Also, a pressure dependence would be seen. However, only a small dependence on pd can be observed. This dependence is statistically not significant given the large

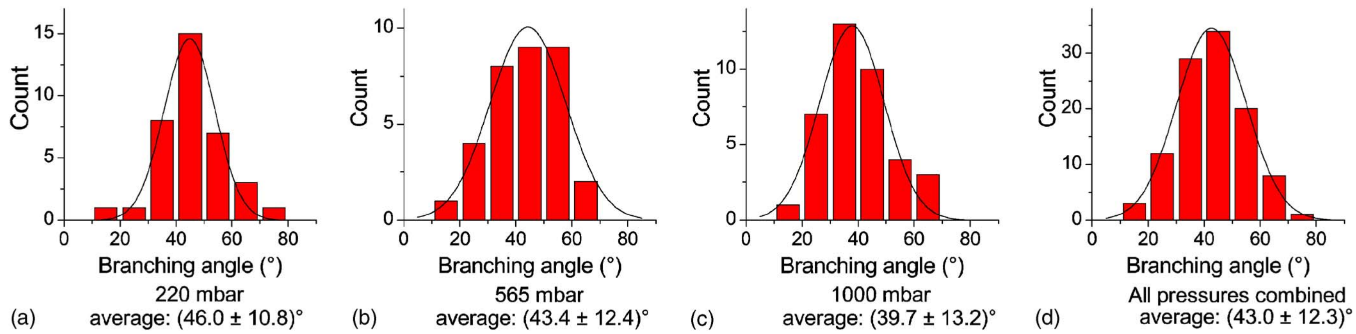

FIG. 4. (Color online) Histograms with Gaussian fits for branching angles for three different pressures and for all pressures combined.

spread and measurement error in the data set (correlation coefficient $R^2=0.15$).

The ratio of streamer length between branching events over streamer width has also been measured. This ratio is about 15 for all pressures. This is a bit higher than the ratio of 12 found by Briels *et al.*[21]

In conclusion, we have built a stereographic setup that is able to reconstruct 3D spatial structures of streamer discharges. This enables us to get more insight into what really happens in such a discharge. For example, we are now able to see if something that looks like a streamer reconnecting to another streamer is indeed what it seems. Up to now, such statements relied on multiple observations from 2D images.[4] We are also able to measure branching angles of streamers.

We have found that the branching angle for streamers in an overvolted gap of 16 cm does not significantly depend on pressure and *pd*, and is distributed normally with an average of 43° and a standard deviation of 12°.

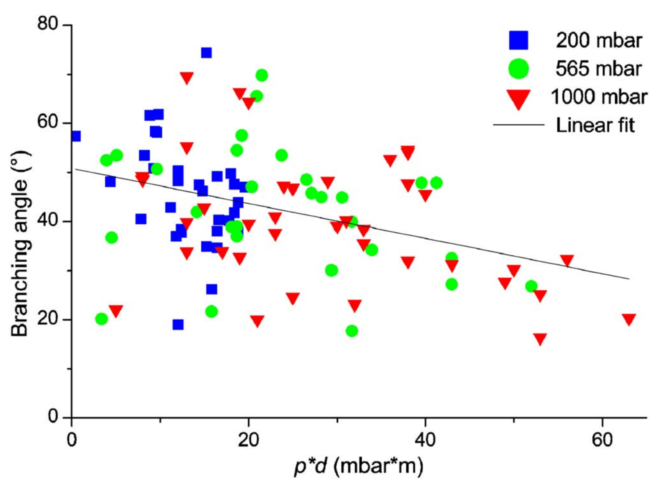

FIG. 5. (Color online) Measured branching angle as function of *pd*.

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