Multi-dimensional experimental studies on streamers

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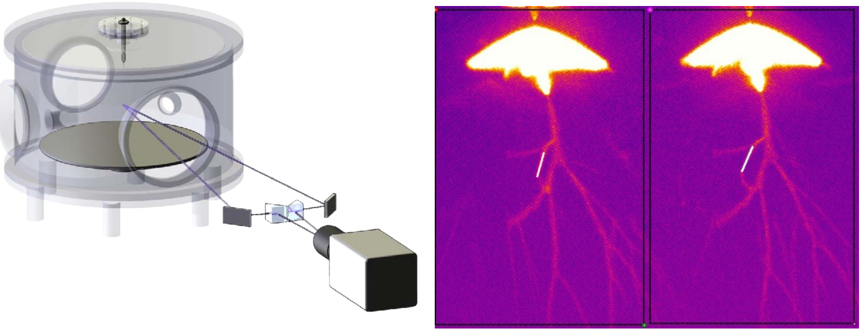
Abstract

Precise space and time resolved imaging of propagating streamers can be very challenging due their stochastic nature and high propagation velocities. I will discuss two techniques to improve streamer imaging above what can be achieved with the ubiquitous standard ICCD method. The first of these techniques is stereo imaging with one ICCD-camera. This method can image the three-dimensional path of streamers in great detail. The second technique that I will discuss is stroboscopic imaging where the gate of an ICCD camera is repeatedly opened and closed with a frequency up to 110 MHz. Together these techniques can give a complete insight in the time-dependent position of a propagating streamer head. This is a valuable tool to understand the physics governing the propagation of streamers and their interaction with each other, background ionization density or dielectric surfaces.

In nearly all streamer discharges the streamers are following complex paths, while the duration of propagation is generally in the order of a few hundred nanoseconds or less. Advanced diagnostic methods are required to capture all details of such fast three-dimensional phenomena. One of these methods is stereo-photography with one ICCD-camera. This technique was first employed by us to measure the branching angle of streamers in air [1]. Recently this technique has been used by others as well [2, 3].



(a) (b)

Figure 1: (a) Stereo photography set-up as used in [1]. It contains, from left to right, the vacuum vessel with pointed tip above the plate, the stereo-photography set-up and the ICCD camera. The approximate center lines of both optical paths are also shown. (b) Stereo image of a streamer discharge as imaged by this set-up. Settings: positive voltage on tip, $V_{max} = +47$ kV, $p = 200$ mbar, point-plane gap of 140 mm. Images from [1].

The stereo-photography set-up used by us is shown in figure 1a. With it, streamer discharges in air at pressures between 200 and 1000 mbar were imaged. This was achieved by placing a combination of two prisms and two mirrors between the discharge and the ICCD camera. This allowed us to capture two images from slightly different directions at once, as is shown in figure 1b. This image shows two near identical views from which we can reconstruct the full three-dimensional structure of the discharge. An example of such a reconstructed image is given in figure 2.

Stereo-photography can also be used to check if phenomena that are observed in 2D streamer images actually occur or are artefacts caused by the projection. An example of this is visible in figures 1b and 2. In figure 1b two streamer sections are marked with a white line. It appears that this section is makes a curve and then reconnects with the 'main branch' of the discharge. However, the reconstruction shown in

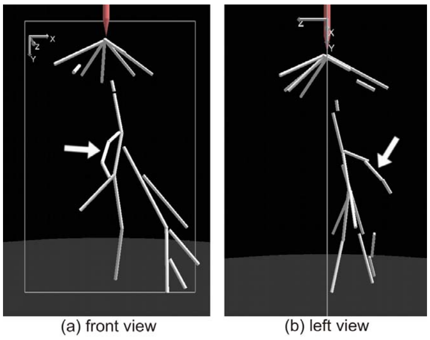


Figure 2: Orthogonal views of the 3D reconstruction of streamer structure shown in figure 1. The section originally marked with the white line is now marked with an arrow in both views. Image from [1].

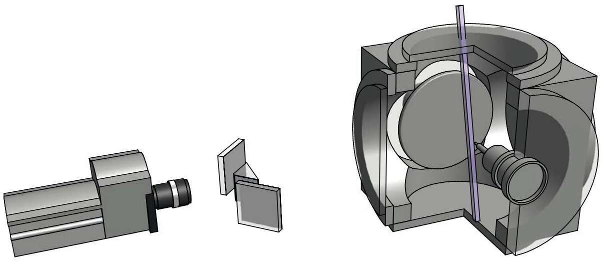


Figure 3: Schematic overview of the set-up including, from left to right, the ICCD camera, stereoscopic set-up and vacuum vessel with indication of laser beam path. In the presented images the recorded images are rotated anti-clockwise by 90° so that the electrode tip is shown on top.

figure 2 reveals that this apparent reconnection is caused by the image projection and in fact is a streamer moving almost perpendicular to the image plane.

Recently we have used stereo-photography to test the effects of low levels of pre-ionization on the propagation of streamers [4]. Here we have used a KrF excimer laser to create a trail of increased background ionization in oxygen-nitrogen mixtures. The estimated density of background ionization produced by the laser is about $8 \cdot 10^8\,\mathrm{cm}^{-3}$ in 133 mbar pure nitrogen. The size of the trail is approximately 9 by $10\,\mathrm{mm}^2$.

For this experiment we have used a similar stereo-photography set-up as is described above, but now rotated 90° with respect to the point-plane geometry (see figure 3). This allows us to accurately determine the position of streamers that run horizontally (i.e., parallel to the plane) in contrast to the original set-up which can better determine the positions of streamers that roughly run in the vertical direction.

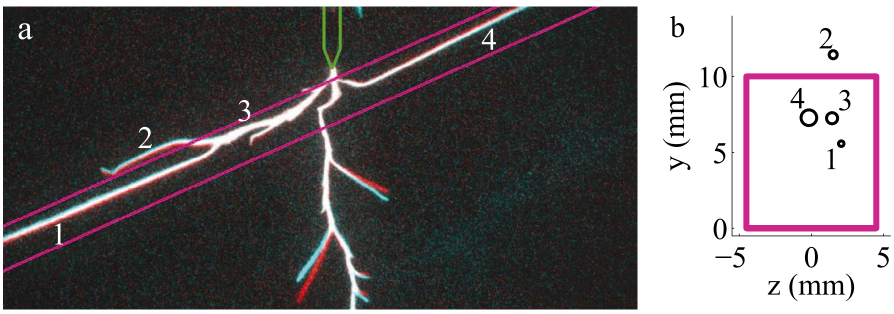


Figure 4: (a) Example of stereo-photography image with the laser trail indicated by the purple lines and the anode tip indicated in green. Experimental settings: gas fill: 133 mbar pure nitrogen; 103 mm point plane geometry; $V_{max} = +5.9\,\mathrm{kV}$. Measured parts of the streamer trails are indicated by numbers. b) Plot of the position of the numbered streamer trails with respect to the laser beam position (marked by the purple rectangle). The marker size indicates their x-position.

An example of a streamer of which the path is deflected by the laser beam is shown in figure 4a. This image is a composite of the two original image parts (looking slightly from above and below) which are represented in red and cyan respectively. Streamers that appear at the same position in both images are represented in white and move in the plane of the image. The figure shows that the streamers are indeed affected by the pre-ionization trail left by the laser. In fact, many of the channels follow this trail instead of taking a more direct route towards the plane electrode below. The position of the numbered sections with respect to the laser beam in figure 4a is plotted in figure 4b. Together, these two figures show the strength of stereo-photography by clearly proving that the numbered streamer sections are actually guided by the laser pre-ionization.

Even though all experiments discussed above do give the exact positions of streamer trails, they give no information about the development of streamer velocity or other time-resolved properties. Unfortunately, no practical and affordable camera is fast enough to shoot multiple frames during the propagation of a streamer as this would require a frame-rate of at least 20 million frames per second (and preferably more). This can be partly remedied by using multiple image paths [5, section 2.3.3] or multiple cameras. Both methods have the disadvantage that only a very small number of frames ($\lesssim 4$) can be used. Alternatively, it is possible to measure the development by acquiring many images of different discharge events. This method was recently employed by Clevis et al. [6] and improved by Heijmans et al. [7]. However, it only works for very reproducible discharges or to investigate reproducible phenomena in more stochastic discharges.

A technique that can give direct insight into the time and space resolved velocity distribution of propagating streamers is stroboscopic imaging. This can be achieved with an ICCD camera of which the gate can be opened and closed at high repetition rates. This technique has been first used by Pancheshnyi et al. [8] and has recently been used more extensively by us [9]. We use a LaVision PicoStar HR12 camera that can be gated with a maximum frequency of 110 MHz. Because the propagating streamers in air and other nitrogen-oxygen mixtures only emit radiation from the streamer head and decay times are short, images made in this way will look like a string of beads. An example of such an image is shown in figure 5.

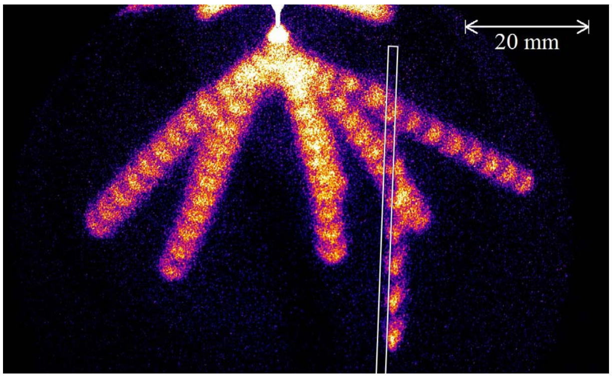


Figure 5: Stroboscopic image of streamer discharge with a surface component in 60 mbar ambient air with a 10 kV positive voltage pulse imaged with a gating frequency of 50 MHz at a 50 % duty cycle. The anode tip and the dielectric rod are shown in white. Image from [9].

Here a streamer discharge in the vicinity of an epoxy rod is imaged. The relative velocity of each streamer section can be easily deduced from this image. This shows that the streamers propagate faster along the dielectric rod than through the bulk gas.

The present stroboscopic images are made without a stereo-photography set-up. Therefore velocities of streamers which are propagating out of the image plane will be underestimated. This can be remedied by combining stroboscopic imaging with stereo-photography. Together this can give a full three-dimensional, time-resolved image of streamer propagation in a single discharge.

Figure 6 contains such a combined stereoscopic stroboscopic image. In this experiment a dielectric plate with dimensions $150 \times 30 \times 2\,\mathrm{mm}^3$ is placed nearly vertical below and to the side of the tip. The left part of the stereoscopic image is directed at the side of the plate while the right part is looking slanted onto the surface of the plate. The angle between both views is approximately 20°.

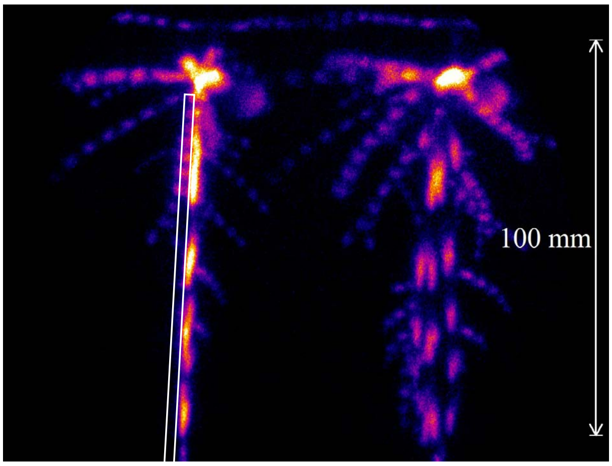


Figure 6: Stroboscopic stereo image of streamer discharge with a surface component in 200 mbar ambient air with about 21 kV positive voltage pulse imaged with a gating frequency of 50 MHz at a 50 % duty cycle. A dielectric plate with dimensions $150 \times 30 \times 2\,\mathrm{mm}^3$ is placed below and to the side of the tip. The approximate location of this plate is shown in white in the left side view. Image from [9].

In this figure some of the most prominent streamers propagate over the surface of the dielectric plate. These streamers show branching with some of the branches continuing on the surface itself while other, shorter, branches propagate away from the surface. Again the streamers on the surface have a higher propagation velocity than the bulk gas streamers.

Even without detailed three-dimensional reconstruction or exact velocity measurements this image shows the potential of the combination of imaging techniques.

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