Laboratory experiments on the interaction of streamers

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ABSTRACT: Pictures show that streamer or sprite discharge channels emerging from the same electrode or position sometimes seem to reconnect or merge even though their heads carry electric charge of the same polarity; one might therefore suspect that reconnections are an artifact of the two-dimensional projection in the pictures. We have used stereo-photography of laboratory scale streamer discharges to investigate the full three-dimensional structure of such events. We analyze reconnection, possibly an electrostatic effect in which a late thin streamer reconnects to an earlier thick streamer channel, and merging, a suggested photo-ionization effect in which two simultaneously propagating streamer heads merge into one new streamer. We also investigate the branching lengths and angles in the 3D streamer tree structures.

1 INTRODUCTION

Streamers penetrate into undervolted gaps due to space charges and local field enhancement at their heads [Ebert et al, 2006]; frequently they break up into shapes reminding trees with many branches. Sprite streamers in transient luminous events are related to streamers at standard temperature and pressure through similarity laws [Pasko 2007; Ebert et al., 2010]. Streamer branches stretching out from the same electrode carry head charges of equal polarity and repel each other electrostatically. On the other hand, streamers and leaders emerging from oppositely charged electrodes carry opposite head charges; therefore when propagating towards the opposite electrode, they attract each other electrostatically and connect; this is seen, e.g. in the counterleaders stretching from tall structures upwards towards an approaching lightning leader.

However, there are recent observations [Briels et al., 2006; Cummer et al., 2006; Grabowski et al., 2005; Winands et al., 2006] that seem to violate this scheme: streamer or sprite channels emerging from the same polarity electrode or atmospheric region do not repel each other, but they seem to merge or reconnect. These events were imaged with normal photography, i.e. in a two-dimensional projection of the full three-dimensional event. Therefore it is impossible to determine from the figures whether two streamer branches really do join, or whether they pass behind each other, and only the statistical analysis of many pictures can lead to such a conclusion. However, the true three-dimensional event can be reconstructed from stereo photography. Here, stereo photography is applied to several situations where streamers appear to reconnect or merge.

Another largely unexplored issue in streamer research is the breakup of single channels. Up to now, only the conditions of the first branching event have been resolved in microscopic models. On the other hand, the distribution of branching lengths and angles is an ingredient of models for the branching tree on larger scales. Therefore branching lengths and angles are here investigated through stereo-photography as well.

2 EXPERIMENTAL APPROACH

All experiments presented here have been performed in ambient air with a cathode-anode gap of 40 or 140 mm. We use the electric circuit called the C-supply treated in [Briels 2006]. In this set-up a capacitor is charged negatively with a DC power supply. This capacitor is then discharged by means of a spark-gap switch which results in a voltage pulse on a pointed tip or wire with a risetime of about 20 ns, a maximum voltage between 6 and 55 kV and a decay time of a few microseconds. A positive corona discharge then propagates from the needle

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or wire to the grounded plate.

The corona discharge produced by the circuit is imaged onto an intensified CCD-camera (Stanford Computer Optics 4QuickE). We have implemented a stereo-photography 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 understanding which gas volumes are actually treated by the discharge, and supply experimental data for larger scale models [Nijdam, 2008].

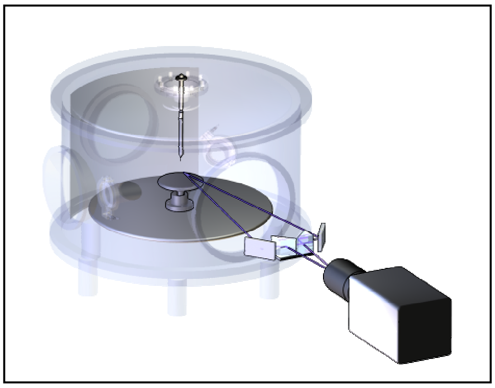

Figure 1. Schematic overview of the stereoscopic measurement set-up with the two image paths indicated.

One camera has been used in combination with two prisms and two flat mirrors as shown in figure 1. With this set-up two images from different viewing angles are captured on one camera frame; therefore they are perfectly synchronized in time. From the two images, we reconstruct the 3D structure of the original discharge. Four different anode geometries have been used: a single tip, symmetrical double tips, asymmetrical double protrusions from a plane and a wire. All experiments were done in a 40 mm gap, except for the branching angle measurements, where a 140 mm gap was used.

3 EARLIER OBSERVATIONS AND RESULTS OF 3D RECONSTRUCTION

3.1 Streamer branching

We have measured streamer branching in ambient air at different pressures (200, 565 and 1000 mbar). In these measurements, a positive voltage pulse of 47 kV with a risetime of about 30 ns was applied to the point, 14 cm above the plate. The distribution of branching angles in these discharges is roughly Gaussian, with average values between 39° and 46° and standard deviations of 11° to 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). More details can be found in [Nijdam, 2008].

3.2 Reconnection

Earlier observations: In pulsed power experiments in a needle-to-plane electrode geometry, thin and slow streamers seem to approach thick and fast early ones in an almost perpendicular direction [Briels et al., 2006]. Such an event will be called reconnection. A physical mechanism for such an event is given by Briels et al: the originally positive thick streamer channel charges negatively after connecting to the cathode and therefore attracts the late positive streamer electrostatically.

A similar event was reported by Cummer et al. [2006] in high speed images of sprite discharges above thunderclouds. Here sprite channels propagating downwards seem to connect to each other, often accompanied by a bright spot. Sprite discharges have been established to be large versions of streamers at low gas densities, related to each other by similarity laws. This phenomenon looks quite similar to the reconnection described above; however, the sprite streamers do not reach any electrodes to change the channel polarity. A possible explanation of the reconnection in sprites was recently given by Luque and Ebert [2010]. They find in simulations that charge conservation in combination with varying air density along the channel creates a negative charge in the streamer tail while the streamer head carries a growing positive charge, thereby creating a polarization along the channel. The negative charging of the tail may attract newer positive streamer heads. Similar results on streamer channel polarization have been found by Liu [2010].

Our 3D reconstruction: We define streamer reconnection in generalization of the events above as the case where one streamer channel connects in nearly perpendicular direction to another streamer channel that originates from the same electrode. We study streamer reconnection in single tip geometry and in double protrusion geometry. In our measurements we have found that reconnection in the single tip geometry does occur, confirming the interpretation of normal images by Briels et al. [2006]. When it occurs, there is always a thin late streamer channel reconnecting to a thick earlier streamer channel. This is confirmed in the 3D reconstructions.

Streamer reconnections can also be observed in the asymmetrical double protrusion anode geometry. In this geometry, the thickest and earliest streamer channels originate from the tip that protrudes farthest from the plane. An example of such a discharge event is shown in figure 2. This image shows multiple reconnections from streamer channels originating from the right tip to streamer channels originating from the left tip. All these reconnections are clearly visible in both views and are therefore interpreted as real reconnections. The width of the thick, early channels is about 1.1 mm; the width of the thin channels about 0.6 mm. We find that reconnection only occurs to thick streamer channels that have crossed the entire gap and end on the cathode plate. The shape of these reconnections is remarkably similar to the sprite images by Cummer et al. [2006].

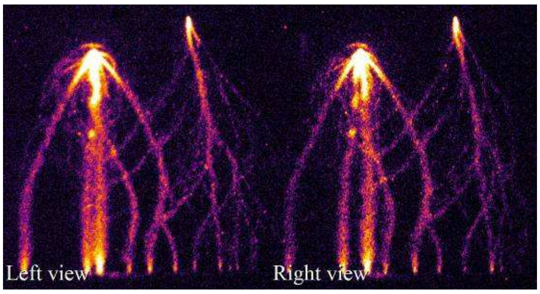

Figure 2. A stereo image of multiple streamer reconnections in the double protrusion-plane anode geometry. The horizontal distance between the two tips is 18 mm, the left tip protrudes 14 mm from the plane and the right tip protrudes 8 mm from the plane. Other experimental settings: gas fill: 1000 mbar air; V_{max} = 50 kV.

Briels et al. [2008b] have reported that thick streamer channels are always faster than thin streamer channels. In our experiments, tens to hundreds of nanoseconds after the thick channels have bridged the gap, thinner and slower streamers can connect to the conducting traces left behind by the early thick streamers. This has been confirmed by increasing the delay of the camera so that only the late streamers are visible. In this case we observe that thin channels seem to change direction instantaneously by about 90° at positions similar to the reconnection positions in the full images. This is interpreted as streamer reconnection consisting of the approaching streamer and the already existing channel. This confirms that reconnection is indeed the attraction of a late streamer channel towards an earlier streamer channel. More details can be found in [Nijdam, 2009].

3.3 Merging

Earlier observations: Another type of events was seen by Grabowski et al. [2005] and Winands et al. [2006] in pulsed power experiments: many streamers emerged from a wire electrode, and sometimes two almost parallel streamers seemed to merge into a single one while propagating away from the wire. Such an event will be called merging. A physical mechanism for such merging was proposed by Luque et al. [2008]: the non-local photo-ionization reaction could generate so much ionization in the space between the streamer heads that the heads merge despite their electrostatic repulsion.

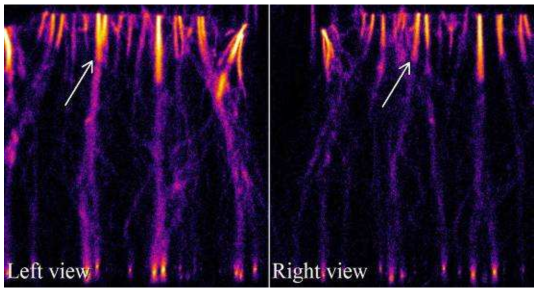

Figure 3. Stereo image of a wire-plate discharge. Possible merging in the left hand view is indicated with an arrow. However, the right hand view shows that no merging occurs. Experimental settings: gas fill: 1000 mbar air; V_{max} = 45 kV

Our 3D reconstruction: We have reproduced similar experiments with the wire-plate electrode. We have never found a definite case of merging of streamer channels in the hundreds of discharge events studied. Often channels seem to merge in one of the images, but are not merging in the other image, like shown in figure 3.

In experiments with two tips close to each other we have always found that two separate streamers emerge. Only when the tips are so close to each other (or the pressure is so low) that the streamer width is more than 10 times the tip distance, a single channel emerges from the two tips. More details can be found in [Nijdam, 2009].

4 CONCLUSIONS

We have found that the branching angle for streamers in an overvolted gap of 14 cm does not significantly depend on pressure and *p*d* and is distributed normally with an average of 43° and a standard deviation of 12°. We find that reconnections as defined above occur frequently. We attribute this to electrostatic attraction by the channel that has crossed the gap of the later channel that has not crossed the gap yet. Besides electrostatic attraction, two other interaction mechanisms between streamers can be imagined as the reason for reconnection: magnetic attraction and photo-ionization. However, magnetic attraction between current channels only occurs when these channels are more or less parallel and would not lead to the near perpendicular reconnections that are observed. Besides, the currents in these streamer channels are low and would not lead to any significant Lorentz force. Photo-ionization can also be excluded because it decays exponentially for distances larger than the photo-ionization length (about 1.6 mm at atmospheric pressure air). Therefore photo-ionization is much weaker at larger distances and cannot turn the streamer path over such distances. Merging on the other hand was only observed with a double tip electrode at a pressure of 25 mbar and a tip separation of 2 mm. In this case the full width at half maximum of the streamer channel is more than 10 times as large as the tip separation. All observations show that thinner streamer heads always do repel each other and will remain separate while propagating between anode and cathode.

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