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3D properties of pulsed corona streamers

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Abstract. Properties of pulsed corona streamers are measured and simulated in full three spatial dimensions (3D). Stereo photography is used to measure branching angles and to investigate whether apparent streamers reconnections are real. 3D simulations of two parallel streamers show that they can repel each other electrostatically, but that they also can merge due to photoionization. The electrostatic interaction of several streamers becomes evident through theoretical investigations of a periodic array of streamers.

PACS. 52.70.Kz Optical (ultraviolet, visible, infrared) measurements – 52.80.Hc Glow; corona – 07.68.+m Photography, photographic instruments; xerography

1 Introduction

Pulsed corona discharges can form very complex patterns [1,2]. Figure 1a shows a photo of a discharge in quite pure nitrogen where the electrodes are a needle above and a plate below, i.e., the electrode geometry is cylindrically symmetric around the needle axis. Therefore the figure shows a two-dimensional projection of a three-dimensional event. From the needle a number of streamers emerge that branch repeatedly until more than 100 streamers have formed in the middle between the electrodes. Streamers branch after a characteristic length and with a characteristic distribution of angles, they probably repel each other, but there are also events where they seem to reconnect. Figure 1b shows streamers emerging from a wire on the right (shown as a white line) and propagating to a plane at the left edge of the figure. The figure shows reconnections as well. Photos of streamers emerging from a row of pins [3,4] inserted into a planar electrode resemble those of wire-to-plane configurations [5,6].

It is clear that branching and interaction of streamers are intrinsically three-dimensional events. However, photographs as Figure 1 show only a two-dimensional projection and most simulations are constrained to the cylindrical symmetry of a single streamer [7–10] and cannot handle full branching or interaction of streamers. 3D simulations of streamer branching are presented in [11–13] and in forthcoming work by the authors. We here report experimental and theoretical investigations of the three-dimensional aspects, in particular, stereoscopic imaging, simulations of the interaction of two streamers and a first comparison with experiments, and the analysis of an array of streamers.

2 Stereographic imaging in experiments

The apparent reconnections in Figure 1 require further investigation. Streamer discharges are usually (as in Fig. 1) imaged with conventional or digital cameras [1–7]. This leads to a 2D projection of an essentially 3D phenomenon. These 2D projections can be difficult to interpret. For example, it is impossible to see whether an apparent 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. To resolve these questions, we have implemented stereo photography which makes it possible to image streamer discharges in 3D. The stereoscopic technique that we use has been around for a long time [15,16] and has been used for many phenomena. Stereo photography has also been used to study phenomena similar to streamers, e.g., sparks [17], flames [18] and dusty plasmas [19]. For precise timing and when only one camera is available, two images at different angles have to be taken with one camera. Figure 2 shows how this is done. The details on how the 3D image is reconstructed from these two images can be found in the recent papers [20,21]. In short, a straight section of a streamer channel is selected in both images, and the end points of these two lines are reconstructed from two images in 2D (xy) to 3D (xyz).

3 Theory and simulations

The interaction of streamers is theoretically largely unexplored. We present two different studies. On the one hand, a fully 3D code is developed and the interaction

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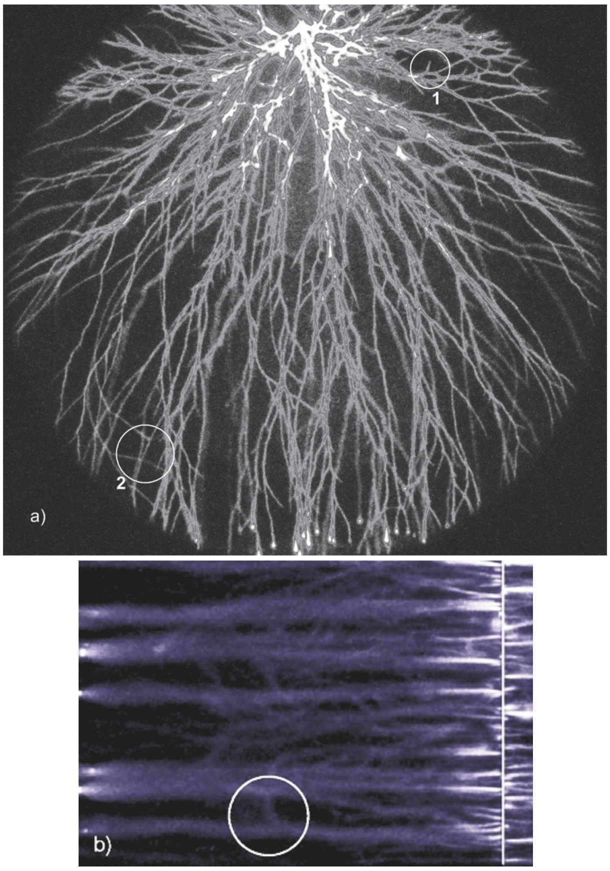

Fig. 1. (Color online) (a) ICCD image of a point-to-plane corona discharge in a 16 cm gap at 400 mbar in nitrogen with about 0.2% oxygen [14]. The streamers are thinner than in air, form very short branches, e.g., in circle 1, and possibly reconnect, see circle 2. (b) Streamers in a 5 cm wire-to-plane discharge in air also show reconnections [6]. Furthermore only a small fraction of the streamers that initiate at the wire reach the cathode.

of two streamers studied [22], on the other hand, an array of identical streamers can be represented within a 2D simulation based on symmetry arguments [23].

A three-dimensional simulation for streamers has been developed in [22] based on cylindrical coordinates (r, z, φ). The coordinates r and z are represented on adaptively refined grids, allowing a fine resolution of the space-charge layer. The angular coordinate φ is discretized uniformly, and a Fourier transform is performed over φ. Each Fourier mode now can be solved on a different processor, taking advantage of multiprocessor machines. This discretization is quite accurate close to the axis, and we constrain evaluations to this case.

In another paper [23], we analyze a periodic array of parallel and identical streamers in a homogeneous high field. In this case, it actually suffices to simulate a single streamer, and to take the symmetry plane between two streamers as the boundary with appropriate boundary conditions implemented. We assume that either the external circuit is high-Ohmic or that the gap is sufficiently long; in this case the streamers can approach uniform translation, in contrast to a single streamer. We allow the streamer shape to adjust dynamically. Such an array of streamers with fixed period can be created experimentally by an array of needle electrodes inserted into a plate [3]. Here and in [23], we study the two-dimensional version of this problem, because we expect it to be qualitatively similar, but easier to study in this first analysis, and because the two-dimensional problem actually exhibits very interesting similarities with Saffman-Taylor fingers in two fluid flow in Hele-Shaw cells that casts a new light on this classical selection problem.

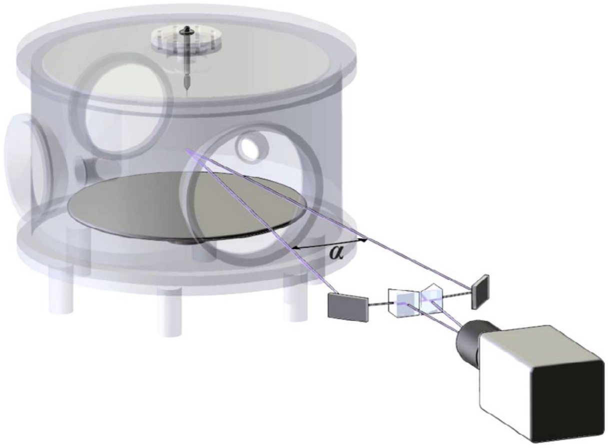

Fig. 2. (Color online) A stainless steel vessel of 50 cm diameter and 30 cm height is used to create a 16 cm gap in a controlled gas composition. The large side window offers the possibility to view the streamer under two angles. Details on the set-up and its pulsed power supply can be found elsewhere [1,14].

4 Results

4.1 Stereo photography

Stereo photography allows one to analyze whether apparent reconnections as in Figure 1 are real. Figure 3 shows one example where an apparent reconnection is shown to be fake. On the other hand, in our recent preprint [21], we present examples of real reconnections.

Stereo photography also allows one to investigate the branching angle that can not be obtained from 2D projections. We have determined histograms of the measured branching angles for 200, 565 and 1000 mbar and combined the results for all pressures into one histogram in [20]. The distribution of the angles 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).

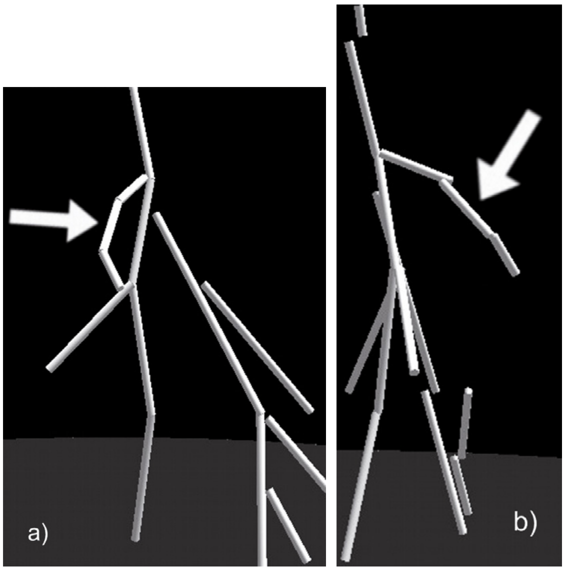

Fig. 3. (a) The front view of a streamer that appears to reconnect. (b) The reconstructed side view that clearly indicates that reconnection does not occur. This measurement is performed with a positive voltage of 47 kV and a rise-time of about 30 ns in a point-plane gap of 14 cm. The atmosphere in the vacuum vessel consisted of ambient air at a pressure of 200 mbar. Figures taken from [20].

4.2 3D simulations

In all simulations discussed here, the pressure is 1 bar; other pressures are discussed in [22]. We use two identical Gaussian seeds of 70 μm and amplitude 1.4×10^{10} cm^{-3} separated by a distance of 230 μm as an initial condition. They are exposed to a homogeneous and constant background electric field $E_b = 80$ kV/cm in the positive z direction. The streamers plotted on reduced length, time and density scales are similar to each other if photo-ionization is neglected. The simulations were performed with an angular resolution of $\theta = 2\pi/64$, but we also checked that the results are stable when we double the number of angular grid cells. Figure 4a shows the electron density for negative streamers in nitrogen at normal pressure and temperature at time $t = 1.56$ ns. Figure 5 shows the space charge layers at the streamer heads (more precisely, the half maximum line at the respective time is shown) in the plane intersecting the two streamer axes in time steps of 0.12 ns. The calculations are performed in nitrogen with oxygen concentrations varying from 10% to 100 ppm. Experiments with the same variation in oxygen content are in preparation.

Figure 5a is quite close to ambient air and Figure 5c is approximately the mixture used in the experiments reported in [2,14]. The calculations show that the streamer diameter becomes smaller with decreasing oxygen content, which agrees with the measurements [14]. The experiments also observe streamer merging, but only for a shorter distance between the streamers, for details see [21].

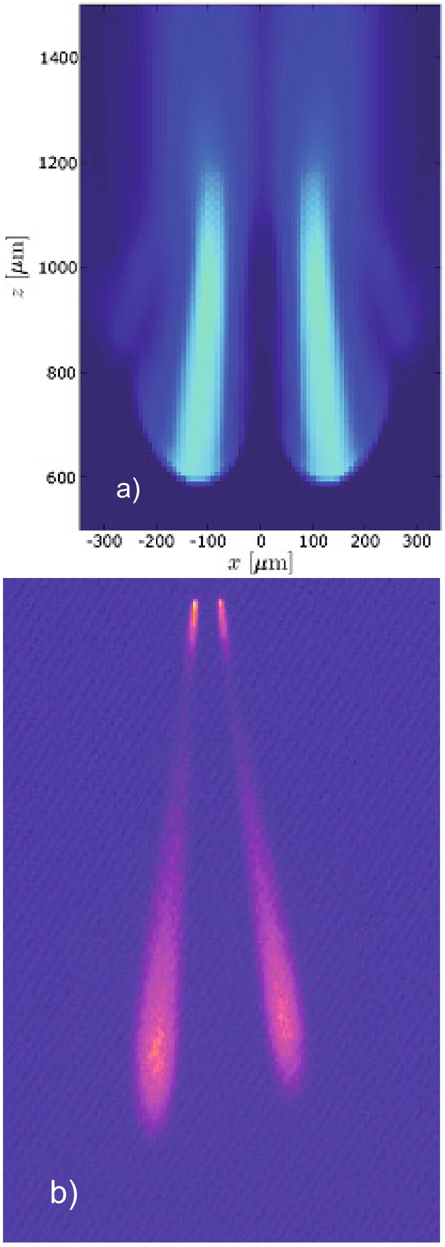

Fig. 4. (Color online) (a) Two negative streamers in nitrogen at atmospheric pressure advancing downwards and repelling each other; shown are surfaces of constant electron density in an advanced state of evolution within a constant background field. (b) Experimental observation of positive streamers emerging from two anode pins [21] in air at 400 mbar and 48 kV in a 10 cm gap. The distance between the needle tips is 0.2 cm. A further comparison of experiments and simulations can be found in [21].

4.3 Periodic array of streamers

The simulations [23] show that after initial transients, the streamers in the array will either branch in a similar way as a single streamer [24–26], if the distance L between the streamers is large, else they will approach a mode of uniform translation that does not occur for single

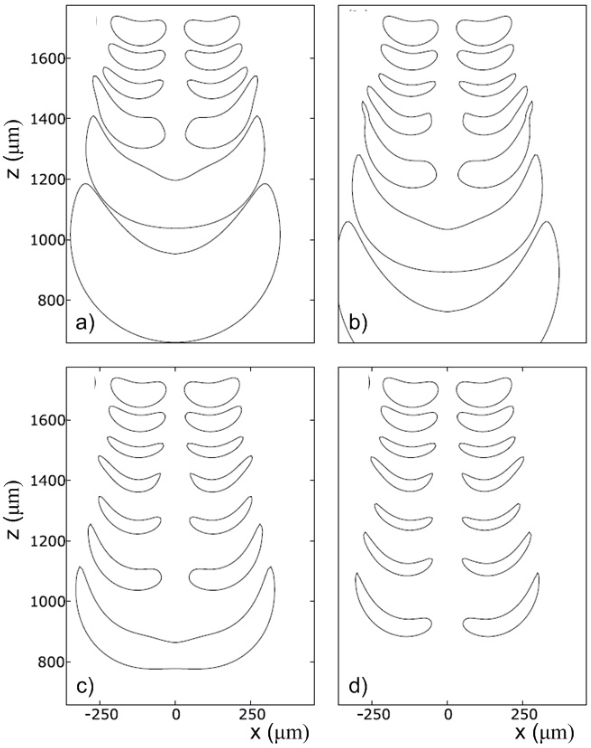

Fig. 5. Evolution of the space charge layers of two adjacent streamers at atmospheric pressure, but for different concentrations of O$_2$: $p_{O_2} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$ in panels (a)–(d). The figure is taken from [22].

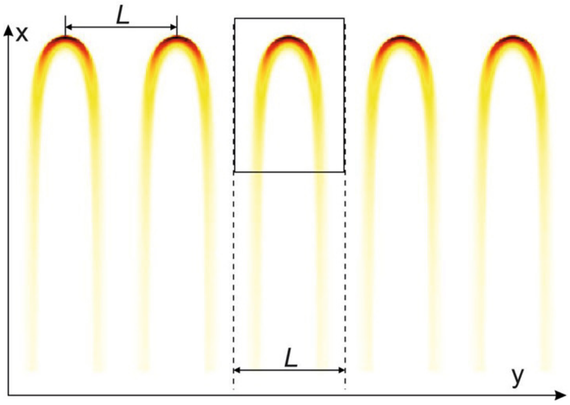

Fig. 6. (Color online) Simulation of an array of identical streamers. In 2D, the streamer diameter is half of the streamer separation, and the electric field inside the streamers vanishes due to collective screening. The figure is taken from [23].

streamers; an example is shown in Figure 6. In this mode, the streamer heads together carry so much charge that the electric field in the streamer channels and between them is completely screened. What fixes the streamer channel width w, is a classical mathematical question in a similar problem in two-fluid flow. It is found that similarly to this Saffman-Taylor finger problem, the streamer width w always approaches 1/2 of the period L, and that the field at the tip is enhanced by approximately a factor of 2. For details, we refer to [23].

5 Conclusions

- We show how pulsed corona streamer propagation can be analyzed in simulations and experiments in full three dimensions.
- Stereo photography shows aspects of streamers that cannot be obtained from 2D images. It allows one to determine clearly whether streamer reconnections are real or an artifact of the 2D photographic projection. Furthermore, branching angles are determined. Their values are $43° \pm 13°$, so there is a considerable statistical spread, but the angle seems to be independent of pressure and may slightly vary with the distance from the electrode.
- Full 3D simulations of positive and negative streamers are now possible based on a multiprocessor, pseudo-spectral method. The results show that streamers can repel each other due to electrostatic interaction or they can merge due to photoionization. First pictures show a qualitative similarity with experiments, but more work is required.
- An array of identical parallel streamers has been simulated using a periodic boundary condition.

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