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Experiments on the diameter of positive streamers in air

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ABSTRACT
Streamer propagation and branching depends on several factors like the electrode geometry or the pressure. The influence of four different parameters (external series resistance, electrode gap length, pressure and voltage) on the streamer diameter is investigated. Streamer images are determined from images of an intensified CCD-camera.

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Experiments on the diameter of positive streamers in air

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Streamer propagation and branching depends on several factors like the electrode geometry or the pressure. The influence of four different parameters on the streamer diameter (external series-resistance, electrode gap length, pressure and voltage) is investigated. Streamer diameters are determined from images of an intensified CCD-camera. The addition of a series-resistance or a change in electrode gap length does not influence the diameter. The diameter increases with increasing voltage. Pressure and diameter are approximately inversely proportional as expected from theoretical arguments.

1. Introduction

When a high voltage is applied to a non-conducting medium, narrow ionised channels can form. These channels are called streamers. In case of a point-plane electrode configuration, streamers start at the sharp tip, where the electric field is enhanced. Streamers create large amounts of free radicals that can be used for gas and water cleaning [1]. In nature, streamers are found in high-altitude discharges (sprites) [2] or as precursors of sparks and lightning [3].

In a first attempt to generalise streamer behaviour, we performed measurements on the streamer diameter d. In literature some diameter values can be found. However, they correspond to experimental setups with fixed parameters. In [4] positive streamers in a fixed 25 mm gap in air are reported to have diameters in the range of 0.2 to 0.8 mm. Their diameter is dependent on the resistance and inductance in the circuit. In [5] an increase in diameter from approximately 0.3 mm to 2.75 mm is reported for a pressure p decrease of 1000 to 467 mbar for a cathode-directed streamer in a fixed 30 mm gap at a fixed voltage V of 24 kV.

In an ideal experiment, one could rescale all lengths and the complete geometry with $1/p$ while keeping V fixed. If furthermore current injection through the electrode does not play a role (e.g. because the streamer emerges in free space from an avalanche), scaling of d with $1/p$ is expected. This is based on scaling laws for the fast two-particle processes in the bulk of the gas, as elaborated, e.g., in [6,7]. This scaling with pressure is the basis for the interpretation of sprite discharges as an up-scaled version of streamers.

In this paper we show results of the streamer diameter as a function of variable pressure, electrode gap and voltage. Also the influence of an external resistance, added to the discharge circuit, is investigated.

2. Experimental setup

In Figure 1 the electric circuit of the setup is shown. The high-voltage power supply charges capacitor C (250 pF) via resistor R_1 (25 MΩ). When the high-voltage switch is closed, the capacitor discharges over the needle (anode) and plane (cathode). The charge, remaining on the capacitor after a pulse, can flow to earth via resistor R_2 (25 MΩ). The series-resistor R_3 can be varied; it prevents the HV-switch from damage in case of a spark. The voltage is measured close to the anode in Figure 1 with a high-voltage probe and the current is collected on a disk with a radius larger than the gap spacing. This current flows to ground across R_4 (2.75 Ω). The voltage of the HV-probe and the voltage across R_4 are measured with a fast oscilloscope (LeCroy Waverunner 6100A) [8].

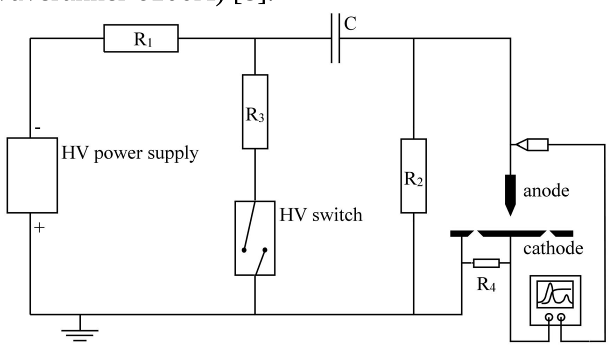

Figure 1: Schematic view of the experimental setup.

Three different HV-switches are used, which are a sparkgap and two semiconductor switches (Behlke HTS301 and HTS361). The used electrode configuration is point-plane and the distance between the electrodes is adjustable. The tip is made of thoriated tungsten and has a radius of ~15 μm. The measurements are performed on positive (cathode-directed) streamers in air at different pressures.

The photographs are made with an intensified CCD-camera. The pictures are time-integrated (20 µs) to show the complete streamer pattern.

3. Measurement of the streamer diameter

The streamer diameter is determined from photographs. While measuring the diameter, care is taken that measurements are only done on a single streamer, at a place without return stroke, multiple streamer, anode glow or “out-of-focus”-effect. Typically the measurement is done in the lower half of the picture.

The + in Figure 2a, indicates the place where a horizontal and vertical cross-section are made, which are shown in the profile bars below and beside the picture. Each peak in the spectrum corresponds to a streamer. The streamer diameter is measured as the full width at half maximum of such a peak. Each point in the Figures 3, 5, 6 and 7 below represents one such measurement. The distribution of the streamer widths is within a range of a factor 3-4. This is also directly evident in the pictures.

4. Results and discussion

4.1. Influence of the series resistor R_3

In [4] it is shown that adding or removing components from the electric circuit affects the streamer pattern at voltages close to the breakdown voltage: an extra resistance creates thin streamers with more branches whereas inductance leads to thicker and more diffuse streamers with less branching. Figure 2 shows photographs with a resistance R_3 of 0, 500 or 1000 Ω in the circuit. These photographs are comparable to the results in [4].

The broad streamers can be the result of a return stroke, which arises after the streamers have bridged the electrode gap. However, when only diameters of streamers are determined that have no visible return stroke, the measured widths lie within the same diameter range, as shown in Figure 3. Hence, a small series-resistor has not much influence on the primary streamer diameter. Therefore, photographs with exposure times that are in the range of the typical streamer propagation time (~100 ns) will be taken in the future. Then the return stroke will not be visible and the streamer diameter can be measured more accurately.

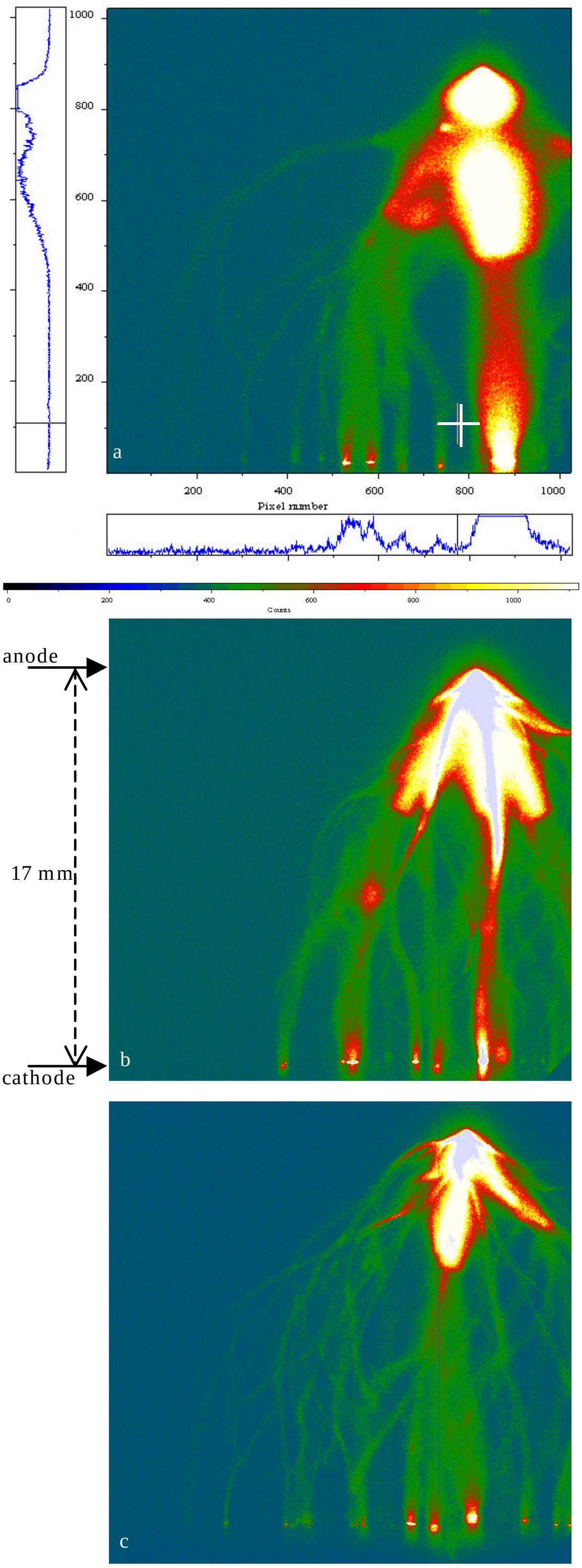

Figure 2: Photographs of streamers in a 17 mm gap at 25 kV at 1 bar, switched by the sparkgap, with (a) R_3 = 0 W, (b) R_3 = 500 W and (c) R_3 = 1000 W. The pictures are scaled to the same intensities as indicated by the colour bar.

We remark that with a power source that delivers a much higher current, streamers do become much thicker at the same voltage even before any return stroke appears [9].

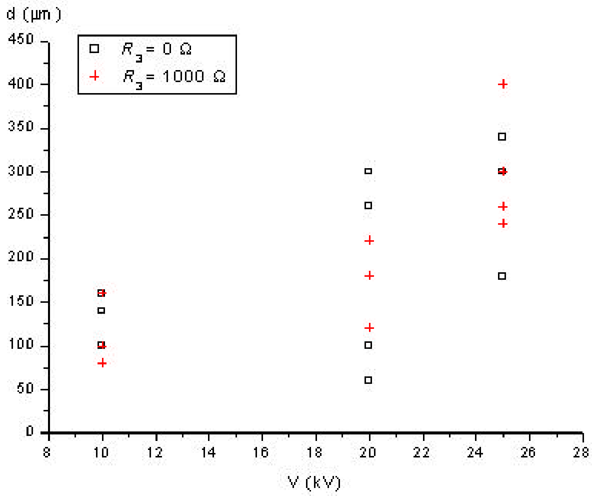

Figure 3: The streamer diameter as a function of the voltage for a 17 mm gap, switched by the sparkgap, with resistor R_3 =0 or 1000 W in the circuit at 1 bar.

Current and voltage are also measured (Figure 4). The corona current I_{corona} is given by the subtraction of the capacitive current I_{cap} = C_g*dV/dt (where C_g is the capacitance of the gap) from the measured current I_{meas}. It is in both cases ~1.1 A at a voltage of 25 kV. Therefore, the minimum gap resistance is ~23 kΩ. Hence the effect of a series-resistor of 1 kΩ on the energy of the pulse is negligible. This is also found in the energy per pulse, which is calculated from

$$E = \int V * I_{corona} * dt\,. \qquad (1)$$

At a voltage of 25 kV, an energy of 3.6 ± 0.3 mJ and 3.7 ± 0.2 mJ is found when R_3 = 0 or 1000 Ω, respectively.

4.2. Influence of the electrode gap

Figure 5 shows the streamer diameter as a function of voltage and electrode gap length (10, 17, 25 and 40 mm) at 1 bar. The measured diameters at a fixed voltage, e.g. 15 kV, and variable gap length fall within the same diameter range. Therefore, it can be concluded that the gap length does not influence the diameter. This can be expected, as the local electric field in the neighbourhood of the anode is mainly determined by the needle geometry and the voltage and not by the gap length.

The diameter increases with increasing voltage at a fixed gap length.

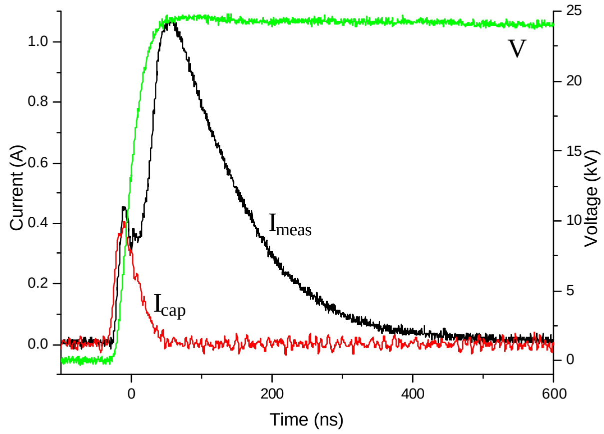

Figure 4: Current-voltage characteristic of positive streamers in a 17 mm gap at 25 kV with R_3 = 1000 W. The sparkgap switch is used.

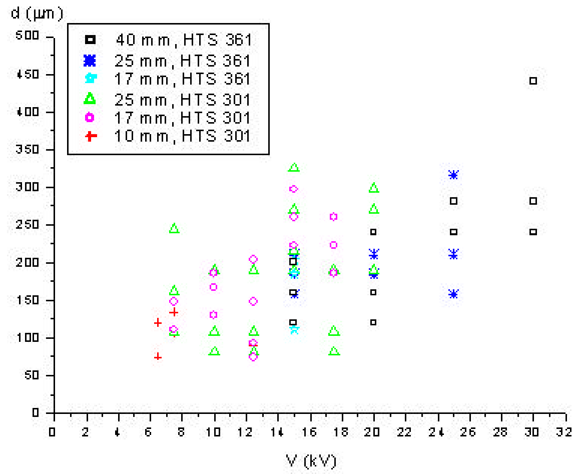

Figure 5: The streamer diameter as a function of the applied voltage for different gap lengths and two semiconductor switches in air at 1 bar. The Behlke HTS361 is used with resistor R_3 = 1000 W in the circuit, the Behlke HTS301 is used with resistor R_3 = 0 W.

4.3. Influence of pressure

When the pressure decreases from 1 to 0.1 bar, the streamer diameters increase. This was already observed in [5] and [10]. Here, in Figure 6, we give precise data of the streamer diameters for different voltages and pressures. The streamer diameter increases with increasing voltage and also with decreasing pressure.

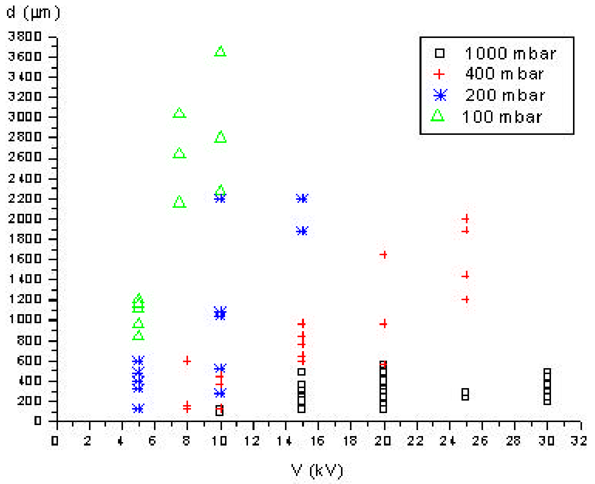

Figure 6: The streamer diameter as a function of the applied voltage and pressure in a 40 mm electrode gap. The Behlke HTS361-switch is used with resistor R_3 = 1000 W.

Theoretical arguments [6,7] suggest that the diameter *d* for fixed *V* should scale like 1/*p*. Therefore, the data for *p*d* for fixed *V* should coincide. Hence, in Figure 7 this data collapse is tried. Within the scatter of the data, this plot indicates the same trend for all pressures. Considering the large experimental scatter, better data is required for a quantitative test of the hypothesis. In particular, we here present data with an exposure time of 20 μs while shorter exposures will give a clearer indication of the initial streamer width. Deviations from the *d* ~ 1/*p* relation can also be due to electrode and/or electric circuit effects.

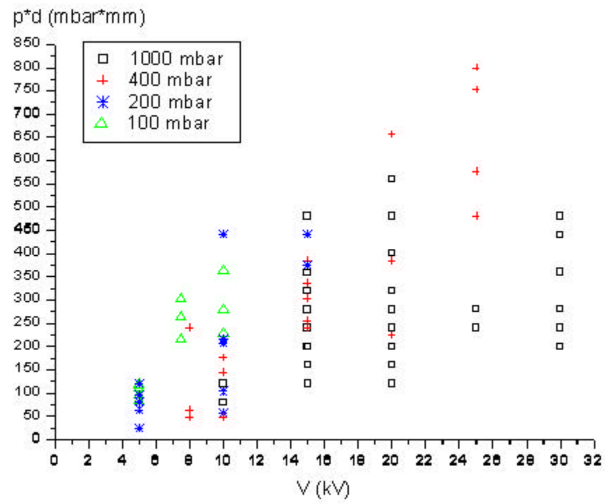

*Figure 7: Data collapse of Figure 6 with p*d.*

5. Conclusions

The pattern and the diameter of pulsed positive streamers are quite reproducible at certain parameter settings. Therefore, the influence of one parameter can be studied while the others are unchanged. The statistical scatter is, however, quite large (factor 3-4).

Earlier photographs show that streamers are narrower when a series-resistor is added to the circuit. The overall shape of Figure 2 supports this conclusion, but the measured diameters of streamers without return stroke presented here, do not show this narrowing when a resistor is added. Current measurements show that the extra series-resistor of 1000 Ω has no influence on the discharge energy. Probably a larger resistor will have an influence, in agreement with [4].

It can be concluded that the electrode gap length does not influence the streamer diameter.

The pressure has a large influence on the streamer width. The measurements show that the pressure and the diameter are roughly inversely proportional.

6. Acknowledgement

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