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Measurement of the positive streamer charge

L Gao†, M Akyuz†, A Larsson‡, V Cooray† and V Scuka†

† Institute of High Voltage Research, Uppsala University, Husbyborg, S-752 28 Uppsala, Sweden
‡ Division of Atomic Physics and Division of Combustion Physics, Lund Institute of Technology, Box 118, S-221 00 Lund, Sweden

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Abstract. A measurement of the positive streamer charge has been performed at atmospheric conditions in a quasi-uniform electric field where the discharge was electrically triggered. By applying a square impulse voltage to the trigger electrode, which was close to, but electrically isolated from, the anode, a positive streamer discharge with one discharge event was produced. The voltage, current and luminosity associated with the streamer discharge were measured simultaneously. By placing a photographic film at the cathode, the number of individual streamers hitting the cathode was estimated within one discharge event. The amount of net charges in streamer discharges has been evaluated for different background electric fields. From the results, it has been deduced that each individual streamer channel contains a charge represented by an excess of 1.1–2.0 $\times$ 10^{11} positive ions m^{-1}. The lower value corresponds to a background field of 400 kV m^{-1} and the higher one to 600 kV m^{-1}. The streamer has also been simulated using a simplified streamer model. The results of the measurement and the calculation are compared and discussed.

1. Introduction

Parameters relevant to the propagation of streamer discharges in air and over insulator surfaces are of importance for understanding the way in which the streamer characteristics could be influenced so that the behaviour of discharges and their interactions with outdoor insulators can be predicted, and eventually streamer propagation and development can be inhibited. It has been observed that the amplitude of the current of the streamer discharge can differ by orders of magnitude, even when the atmospheric conditions are similar [1]. This results in a large difference in electrical charges involved in streamer discharges. In our previous studies [1], it was suggested that each 'streamer discharge event' contains a number of individual streamers crossing the electrode gap simultaneously and the different number of streamers in each discharge event causes the difference in current amplitudes. The modelling of streamer discharges has always been based on the simulation of the development of a single streamer where the charge distribution in the streamer is an important parameter. It is thus of great interest to measure the charge in a single streamer to justify theoretical studies. In another of our earlier studies [2], a still picture taken of streamer discharges in a 35 mm quasi-uniform electrode gap indicated that a number of individual streamers were present in each discharge event (figure 1). The total amount of charge involved in the streamer discharge can be estimated by measuring the current during the discharge. However, since the number of individual streamers is difficult to estimate from the still photographs, we do not know how much charge is in each individual streamer. In this paper, we present an experimental study, in which the number of individual streamers is estimated by placing a photographic film at the electrode at which the charges are arriving. Streamer simulations are also performed assuming a charge distribution in the streamer channel. The results from the simulations and measurements are compared and discussed.

2. Experimental arrangement

A three-electrode gap system was constructed for the experiment, consisting of two parallel plane copper electrodes with a sharp needle made of steel located at the centre of the anode, but insulated from it, as shown in figure 2. A dc voltage U_n was applied across the two plane electrodes, providing a background electric field E_b. To trigger streamer discharges, the needle was subjected to a voltage U_i from an independent voltage source. The gap distance was 35 mm, the length of the needle in the gap (i.e. from the tip to the surface of the anode) was 2 mm, and the diameter of the needle was 0.35 mm. The needle, clad in a PVC insulator, was positioned in a 16 mm diameter hole on the earthed electrode. The two parallel electrodes were 90 mm in diameter with a Rogowski profile. In this way a quasi-uniform electric field distribution was provided between the parallel electrodes: on the central axis of the gap, the derivation in the field magnitudes 5 mm away from the needle tip and at the cathode is less that 5% [2]. Current probes with 2 ns rise time and optical fibres connected to photomultipliers were used to detect streamer current and luminosity. A four-channel digital oscilloscope was used to record the measurements. The oscilloscope and its power supply, a UPS, were placed in an earthed metallic

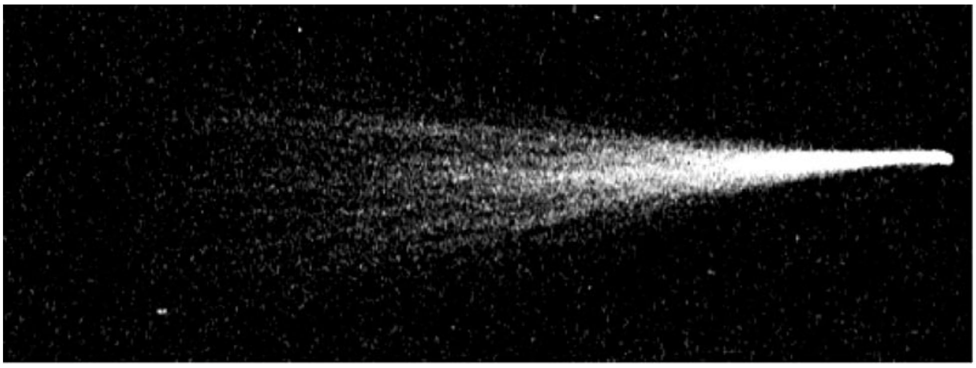

Figure 1. Still picture of a streamer discharge in a 35 mm gap. Streamers are initiated from a needle on the anode (right), then propagate to the cathode (left) in a quasi-uniform field (550 kV m^{-1}).

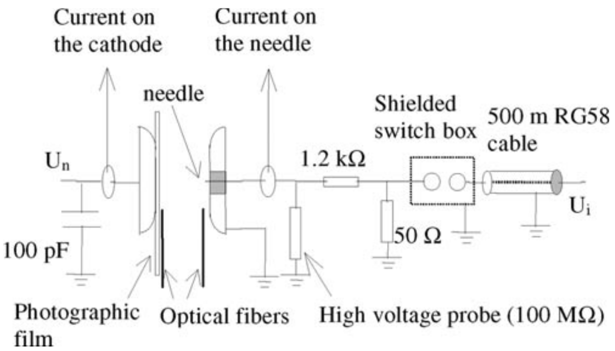

Figure 2. Schematic diagram of the experimental arrangement.

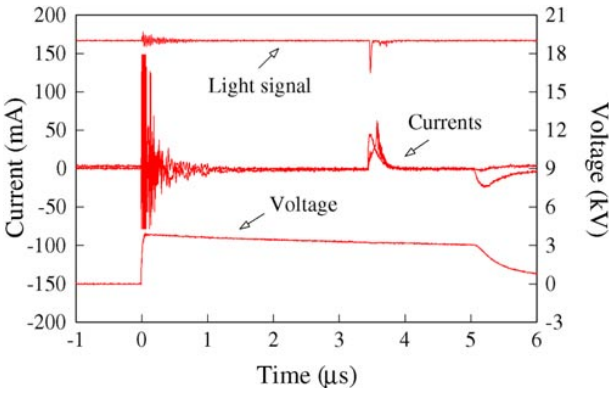

Figure 3. Typical diagrams of simultaneous measurement of the square impulse voltage applied to the needle, currents at the needle and the cathode, and the luminosity of the streamer discharge. No photographic film was placed at the cathode in this case.

cabin. The connections between the current probes and the oscilloscope were made with RG-58 coaxial cables with an extra layer of outer shielding.

It has been shown that when the gap is pre-stressed with a dc voltage above a certain magnitude, the consequence of applying a voltage to the needle is that a streamer discharge starts in the gap. Streamers can propagate from the needle tip to the cathode if the background field in the gap is high enough [2]. The difference between this experiment and our previous one is that, to ensure only one discharge event occurs during each measurement, a square impulse voltage with a predetermined duration was used as the triggering source. For this purpose, a cable generator was constructed with 500 m of RG-58 cable terminated with a 50 Ω resistor, as shown in figure 2. A square impulse voltage of about 5 μs duration was produced by discharging the cable. The dc voltage was not high enough to produce any corona at the needle tip before the application of the needle voltage. When the impulse voltage was applied to the needle, streamers could be initiated at the needle tip only within the 5 μs period. During this period, the current and luminosity associated with the streamer discharge were measured. When the background field was in the range of 400–600 kV m^{-1}, a single event of streamer discharge was always produced.

To estimate the number of individual streamers, a photographic film (Kodak professional industrex AA400 x-ray film) was placed at the cathode. The arrival of each individual streamer produced a dot on the film [3]. The measurements were performed in air under the following atmospheric conditions: temperature, 23 °C; pressure, 993 hPa; and absolute humidity, 12 g m^{-3}.

3. Measurements

Simultaneous measurements of the impulse voltage, the streamer current and the streamer luminosity are essential for the purpose of this experiment. Typical diagrams illustrating the measurements obtained for these properties are shown in figure 3. The magnitude of the square impulse voltage applied to the needle is 4 kV. Because of the resistive loss in the cable, it drops to 3 kV at the end of the square impulse. The light emitted from the streamers is used to identify the streamer discharge. A discharge event is present only when a luminosity impulse is recorded. The initial transients occurring right in the current signals after the application of the trigger impulse are not produced by a discharge event in the gap; but rather, by the capacitive current and electromagnetic noise [4]. The single luminosity impulse indicates that there is only one discharge event during the time that the impulse voltage is applied to the needle.

It is worth noting that in addition to the currents measured at the needle and the cathode, there is a third current component in the three-electrode system required to complete the current in the circuit: the current on the anode (i.e. the earthed electrode in figure 2) [5]. Figure 4 shows a measurement of the three branch currents. With the definitions of positive current direction used here, the sum of the needle and anode currents is equal to the value of the

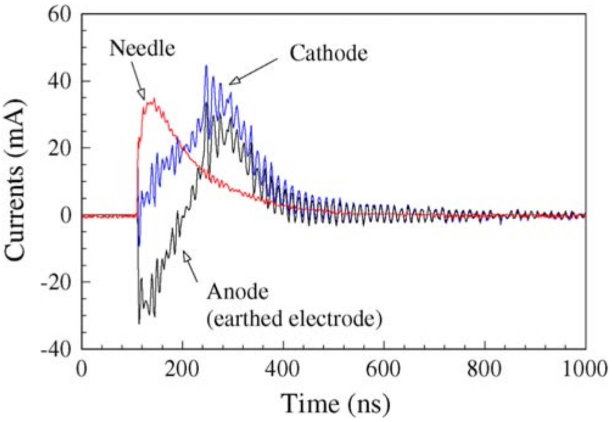

Figure 4. The currents associated with the streamer discharge measured at the needle, the cathode and the anode simultaneously.

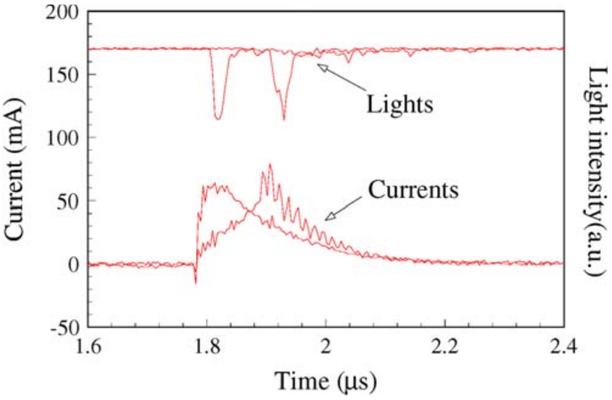

Figure 5. Typical measurements of simultaneously measured currents at the needle and the cathode, and the luminosity of the streamer discharge obtained at the needle and the cathode, respectively, when there was no photographic film placed at the cathode. The background field was 500 kV m^{-1}.

cathode current. A detailed analysis of the measurement of the three currents is presented in [5].

An enlargement of current and luminosity measurements presented in figure 3 is shown in figure 5. The luminosity signals were obtained by putting one optical fibre close to the needle tip and the other one close to the cathode surface. The current measured at the needle is the result of electrons flowing into the needle. The current measured at the cathode has two phases: the slow rising period corresponds to streamer propagation in the gap and the sudden rise indicates the streamer head arrival at the cathode [2, 4]. This interpretation is supported by the two luminosity impulses detected by the optical fibres.

The time-shift between the light and current signals is attributable to an internal delay of 22 ns in the photomultiplier. It should also be noted that the diagrams shown in figures 3 and 5 were obtained from the measurements for different discharge events. The streamer discharge may statistically occur at any time instant during the application of the square impulse voltage (between 0 and 5 μs if the recording is triggered by the rising front of the impulse voltage). Therefore, the current signals displayed in figures 3 and 5 do not necessarily occur at the same time instant. This is also the case for the diagram shown later in figure 6.

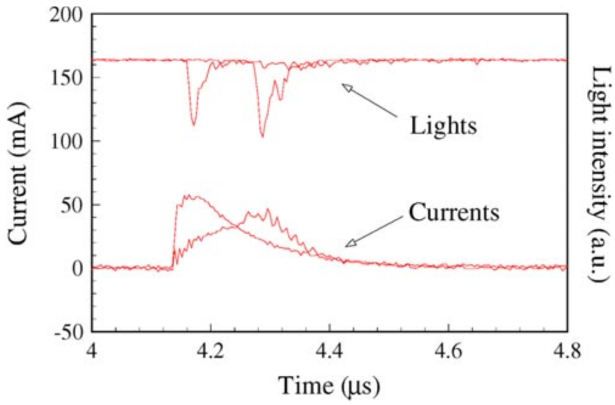

Figure 6. Typical measurements showing the currents and the luminosity of the streamer discharge at the needle and the cathode, respectively. A photographic film was placed at the cathode. The background field was 500 kV m^{-1}.

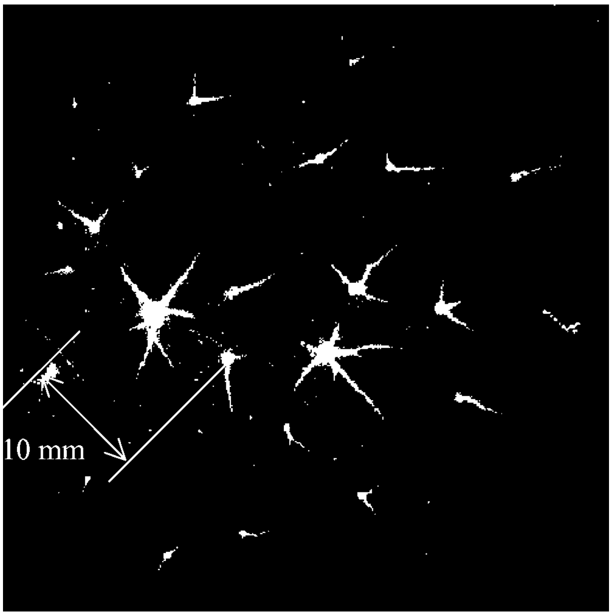

Figure 7. Star-shape dots created by positive streamers hitting the photographic film. The background field was 500 kV m^{-1}.

When a photographic film was placed at the cathode, the sudden rise in the cathode current disappeared, as shown in figure 6, indicating that streamers arriving at the cathode could not make contact with it. Instead, they hit the photographic film leaving star-shape dots on it, as shown in figure 7. The star-shape is caused by surface discharges since the charge in the streamer tip cannot be neutralized by electrons from the cathode because of the photographic film acting as an insulator.

The number of individual streamers can be obtained by counting the number of star-shape dots on the photographic film. There were always a few 'noise dots' on the film created by small protrusions on the cathode surface since the film was in contact with the cathode when the measurement was performed. To identify the dots that were created by streamers, a photographic film was placed in the middle of the gap (parallel to the electrodes) so that effects from the cathode could be eliminated. These 'noise dots' were easily

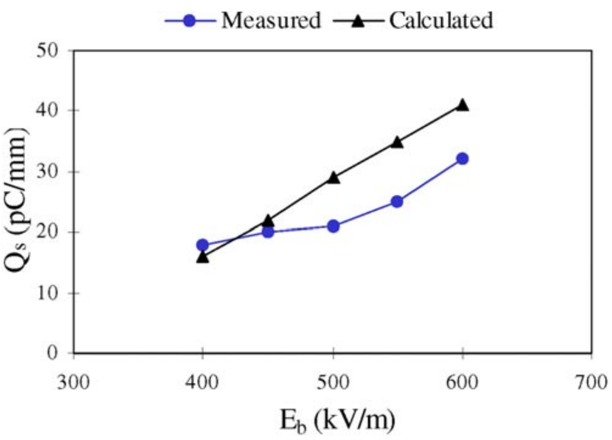

Figure 8. The charge per unit length (Q_s) of a single streamer as a function of the background electric field (E_b). The calculated results are made under the assumption that there is a voltage gradient along the streamer of 500 kV m^{-1}.

identified since they were found to be circular rather than star shaped.

4. Results of the measurement

The total net charge of the streamers is obtained by integrating the current measured at the needle, since the charge of the electrons flowing into the needle should be equal to the amount of the positive charge left in the streamer channel. The charge of an individual streamer is obtained by dividing the total charge by the number of dots on the photographic film for the relevant discharge event. However, the size of dots differs (those 'noise dots' are excluded), especially when the background field is higher than 500 kV m^{-1}. We presume that the charge carried by a 'big dot streamer' is higher than that carried by a 'small dot streamer' and a hypothesis is made as follows. For the humidity condition in the experiment (12 g m^{-3}), the electric field for the stable streamer propagation is about 500 kV m^{-1} [6, 7]. This was also verified by the observation that the peak amplitude of the current at the needle was equal to that of the current at the cathode for this background field, and the field calculation which showed a constant field strength in front of the streamer head [2]. When the background field is lower than the stable propagation field, the charge in the streamer head decreases and, when it is higher, the charge in the streamer head increases whilst the streamer propagates [2]. We assume that when it is lower than 500 kV m^{-1}, the dots on the photographic film are all created by the streamers originated in the vicinity of the needle tip. When it is higher than 500 kV m^{-1}, only the big dots on the photographic film are created by the streamers initiated in the vicinity of the needle tip, whilst the small dots are caused by streamer branching during the streamer propagation. Under this hypothesis, the average charge per unit length of a single streamer (Q_s) is estimated for different background fields, as shown in figure 8. Q_s is obtained by dividing the total positive charge by the number of dots obtained in the discharge event and the streamer length (33 mm).

The measured results displayed in figure 8 correspond to an excess of 1.1–2.0 × 10^{11} positive ions m^{-1}. The streamer charge was measured by Suzuki in a 20 mm rod–plane gap as the applied voltage was changed from 7.9 to 28 kV [8]. On the assumption of a single streamer branch, he obtained 0.6–3.0 × 10^{11} positive ions m^{-1} for primary streamers. Although our measurement was performed in a uniform background field and Suzuki's was made in a non-uniform field, good agreement is found in the results.

5. Discussion

The net positive charge distributed in the streamer channel should result in potential differences in the channel. In our earlier studies, we have presented a simplified streamer model, in which the streamer was assumed to be a cylindrical channel with a constant potential gradient (E_g) along it [2]. The discharge gap configuration in the simulation was assumed to be the same as in the experimental set-up. The streamer was simulated with one end connected to the needle and the other end, a hemispherical tip, extending into the gap. A potential gradient was assigned to the surface of the streamer channel. The potential gradient along the streamer channel was assumed to be equal to the stable streamer propagation field, i.e. $E_g = 500$ kV m^{-1}. The radius of the streamer channel was assumed to be 50 µm. The simulations have been performed with a two-dimensional field calculation program that uses the finite element method [9]. The axisymmetric (r–z) coordinate system was used in the simulation so that the solutions were solved for three-dimensional configuration. The calculated streamer charge is show in figure 8.

The measured and calculated values of the charge for a single streamer have given the same order of magnitude. However, when the background field is equal to or larger than 500 kV m^{-1}, the measured charge is always smaller than the calculated value. The discrepancy might be attributable in part to both the experiment and the calculation. In the experiment, the counting of the number of individual streamers is less accurate when $E_b \geqslant$ 500 kV m^{-1}. Following the hypothesis described earlier, when the background field is higher than the field for stable streamer propagation, increasing the charge in the streamer head makes the streamer head split. Thus, the number of individual streamers resolved by the photographic film at the cathode is more than the number of streamers which travel the whole gap length (from the needle to the cathode). Furthermore, the potential gradient and the radius were assumed to be constant for the streamer channel in the calculation. However, the charge distribution in the streamer channel may not be simply represented by a constant potential gradient in the streamer channel, since the net positive charge in the streamer channel can be reduced by the electrons created at the streamer head flowing towards the needle.

Calculations of induced charges on the anode and the cathode based on the experimental data obtained from the same experimental set-up have been presented in [5], where possible charge distributions in the streamer channel have been analysed. The analysis indicates that the net positive charge should be localized to the front part of the streamer. We infer that this may be caused by the streamer branching effect. In the calculation of the simplified model in which the streamer is assumed to be a single channel, streamer branching is not considered, and therefore, the variation in the amount of charge distributed along the streamer channel is moderate owing to the constant potential gradient [2]. If we consider the branching effect while keeping the potential gradient the same in each section of the branches, the positive charge will increase in the section with more branches, and eventually, more charge will be distributed in the front part of the streamer as a result of having more branches. Obviously, there is plenty of scope for the continuation of our studies to gain a more accurate understanding of the streamer discharge.

6. Conclusions

The streamer current has been measured for a single event of positive streamer discharge in a quasi-uniform electric field. The number of individual streamers has been estimated for the same event and the amount of net charges in streamer discharges have been evaluated under different background electric fields. It has been calculated that each individual streamer channel contains a charge represented by an excess of 1.1–2.0×10^{11} positive ions m^{-1}. The lower value corresponds to a background field of 400 kV m^{-1} and the higher value to a field of 600 kV m^{-1}. Reasonable agreement has been found between the measurement and the result of the calculation, made with the assumption that the streamer is a finitely conducting channel with a given potential gradient.

Acknowledgments

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