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Double streamer phenomena in atmospheric pressure low frequency corona plasma

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Time-resolved images of an atmospheric pressure corona discharge, generated at 50 kHz in a single pin electrode source, show unique positive and negative corona discharge features: a streamer for the positive period and a glow for the negative period. However, unlike in previous reports of dc pulse and low frequency corona discharges, multistreamers were observed at the initial time stage of the positive corona. A possible physical mechanism for the multistreamers is suggested. © *2010 American Institute of Physics*. [doi:10.1063/1.3456522]

I. INTRODUCTION

Over several decades, corona discharges have been applied widely to various industrial fields such as toxic compound destruction, ozone generation, and recently bio-/medical material treatments.[1–3] Despite this industrial importance, understanding of the basic physical and chemical properties of the corona discharge remains incomplete. Because of its characteristics, streamer mode of the corona discharge is a research topic that demands further study. The fast moving streamer mode is known to be more efficient than other corona modes for surface treatments due to its highly energetic electrons and ions.[4] The streamer mode has also recently garnered attention as a key discharge mode for coronas generated in the coaxial and the pin to plane systems that are widely employed in bio/medical application researches.[5,6] Hence, a thorough study of the streamer mode would provide a pivotal contribution to the understanding of plasma interactions with biological objects including biomaterials, micro-organisms, cells, tissues, animals, etc. Furthermore, such study may yield a means of controlling the plasma for enhanced application efficiency.

Thus far, it has been suggested that the streamer mode is initiated by photoionization at the streamer head and sustained by collisional ionization. Although many theoretical models have been offered to fit the streamer propagation properties obtained experimentally,[7–9] none have furnished a full explanation of the experimental observations and the measured results. Even experimentally, the streamer mode has been difficult to investigate due to its fast moving speed, which easily exceeds 10^5 m/s. However, recent technological developments have made a diagnostic of the streamers possible. For instance, fast time-resolved images now allow detailed visualization of such streamers.

In this work, a single pin electrode discharge system was employed, and the corona discharge mode for each electrode polarity was clearly seen through time-resolved plasma images: a positive streamer and a negative glow. In a departure from previous reports, double streamer phenomena were observed at the initial time stage of the discharge. The experimental results regarding the double streamer and possible mechanisms for the double streamer are presented. It is thought that this double streamer observation may be used to find the streamer initiation condition.

II. EXPERIMENTS

A schematic of the plasma source is shown in Fig. 1(a), and details of the plasma source can be found in our previous reports.[10–12] The powered electrode is a copper pin with a radius of 360 μm, and helium gas was introduced axially at a constant flow rate of 3 SLM (SLM denotes standard liters per minute) through the Pyrex tube. The low frequency power (20–80 kHz) was used. The time-resolved plasma image was taken using an intensified charge coupled device (ICCD) camera (Princeton Instrument-MAX2) for one period of the input frequency. The time period corresponding to the input frequency of 50 kHz for plasma generation is 20 μs, and 40 images were captured with a time interval of 0.5 μs. The gate width or the exposure time was 0.1 μs. Also, the time-resolved (wavelength unresolved) plasma light emission signal was separately obtained using a photomultiplier tube (PMT) detector (Hamamatsu R928). The discharge voltage and current were measured using probes (Tektronix P6015A, Pearson 4100).

III. RESULTS AND DISCUSSIONS

The generated plasma appeared different for the positive and negative half periods. During the positive period, the plasma was generated at the pin electrode tip and then moved away from the electrode afterwards. During the negative period, the plasma was generated at the electrode and stayed nearby. Such behavior is consistent with the conventional corona discharge mode of positive streamer and negative glow, and results from the asymmetric source geometry and the difference in the space charge mobility. The positive streamers are known to be generated and sustained by photoionization and collisional ionization, with their propagation speeds ranging from 10^4 to 10^6 m/s.[7–9] In our experiments,

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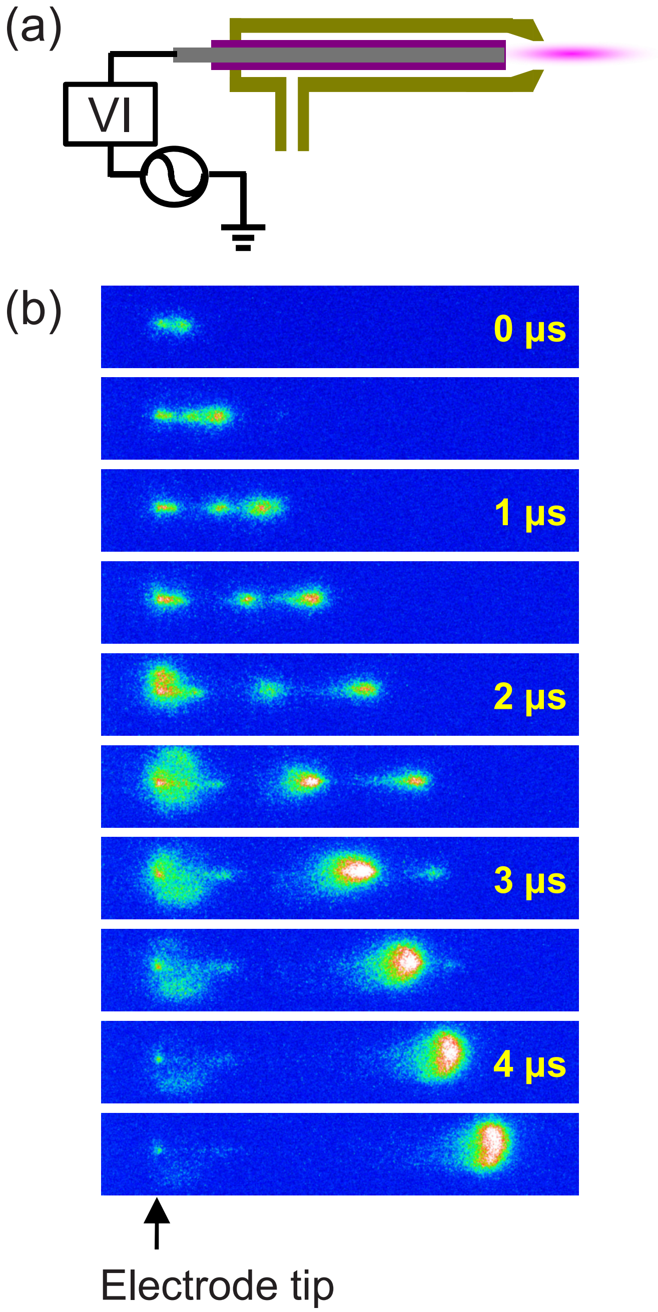

FIG. 1. (Color online) (a) Schematic of the plasma source and (b) time-resolved images of the positive streamer at $V_{in}=1300$ V.

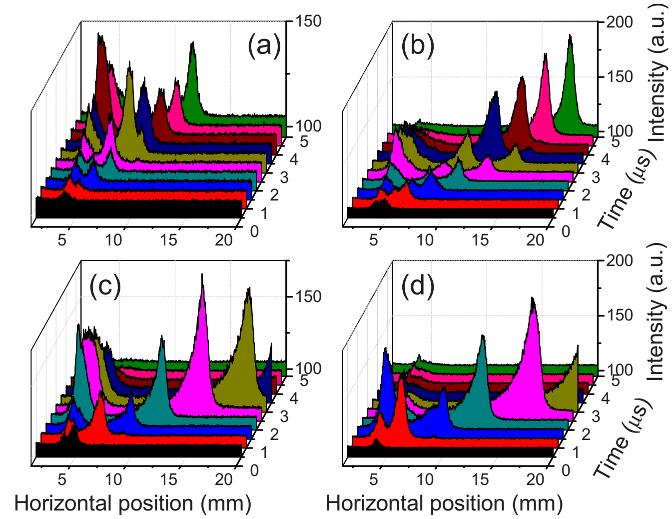

FIG. 2. (Color online) Time evolution of the positive streamer at (a) $V_{in}=1100$ V, (b) 1300 V, (c) 1500 V, and (d) 1700 V. The pin electrode was positioned at about 4.5 mm.

the positive streamer propagation speed was between 1.6×10^3 and 1.0×10^4 m/s. The speed increased as the input voltage was increased, as has also been observed by others.[13,14] The size of the speed was smaller in our case because the input voltage was lower by about one-tenth.

Unlike in previous reports,[5,6] however, there appeared two streamer heads instead of one, as shown in Fig. 1(b), a phenomenon first reported in this study. The double heads did not seem to be a result of the secondary streamer generation, as the bias voltage corresponding to the first streamer appearance time was as low as 0 V. The first streamer head was smaller in size and weaker in its intensity and faded out more quickly than the second streamer head. Hence, it would be more appropriate to designate the first streamer as an initial streamer appearing before the main positive streamer.

Figure 2 presents ICCD images converted to three-dimensional plots for various input voltages of root mean square values (V_{in}). Here, the x-axis represents the horizontal position parallel to the electrode. The y- and z-axes correspond to time and intensity of the plasma image, respectively. The positive period starts at 0 μs and ends at 10 μs. In these plots, only the initial time stage is shown since it is the temporal regime where the double streamer phenomenon occurs. It can be seen from the plots that the initial streamer head becomes prominent as the input voltage is increased to 1300 V. Then, as the input voltage reaches 1700 V, the initial and the main streamers cannot be clearly distinguished from each other as the main streamer appears earlier in time. In other words, multistreamers are only seen in a certain voltage range, which is 1000–1400 V in our experiment.

In order to confirm the analysis of the ICCD image, the plasma light emission and the discharge voltage and current were measured. Figure 3(a) presents the voltage waveform and the emission signal measured by a PMT at the pin electrode. The preceding discharge signs are seen through the multiple peaks in the PMT signal when the electrode polarity is changed from negative to positive and vice versa. The first peak becomes clearer as the input voltage increases and then disappears at 1700 V (merged with the main peak) as the main peak shifts to the left (earlier in time), consistent with the ICCD measurements. Similar observations can be made from the conduction current, as shown in Fig. 3(b). The conduction current has a small nonzero value at the end of the negative half period or just before the positive half period. The current peak appears at a certain time at which the discharge voltage reaches about 1250 V; thus, its peak time shifts to the left (earlier in time) as the input voltage increases. Therefore, it becomes difficult for initial streamer to appear at high input voltages because the main streamer occurs too early, resulting in the overlap of the two streamers.

To further support the argument, the input frequency was

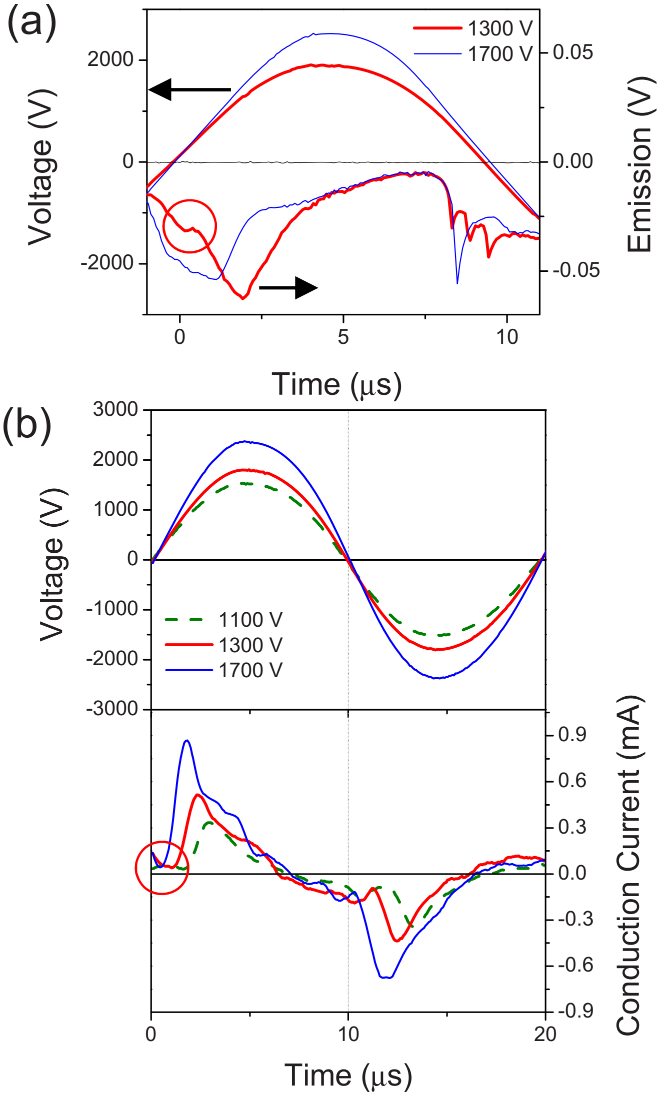

FIG. 3. (Color online) (a) Voltage and plasma light emission (by PMT) at $V_{in}=1300$ V and (b) discharge voltage and conduction current waveforms at various V_{in}.

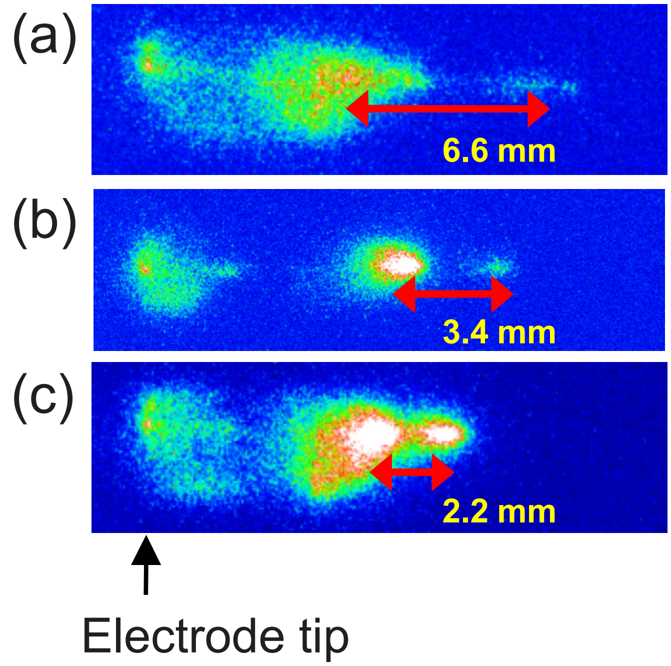

FIG. 4. (Color online) Distance between the two streamer heads for the input frequencies of (a) 40 kHz, (b) 50 kHz, and (c) 60 kHz.

varied to check whether the same phenomena could be seen. As shown in Fig. 4, the distance between the two streamer heads decreased as the input frequency was increased, i.e., the time lag between the two streamers was decreased. It is expected that as the input frequency is raised, the time taken for its voltage to reach a certain level would be decreased. Then, the time lag between the initial and the main streamers would be decreased as if the input voltage had been increased. Hence, the frequency increment gave the similar results with the voltage increment.

We suggest that the initial streamer stems from the previous discharge during the negative period. The initial streamer cannot be generated by the external field because the input voltage is as low as 0 V when it appears. The ICCD image, the PMT signal, and the conduction current all exhibit signatures of the initial streamer right after the voltage changes its polarity or when the input voltage reaches 0 V. Hence, we believe that the space charge accumulated during the previous discharge results in the appearance of the initial streamer. In other words, for the positive discharge, the positive ions produced at and remaining near the electrode during the previous negative discharge transform into the first positive streamer right at the moment when the polarity of the pin electrode is reversed by creating the polarization field. Then, afterward, as the input voltage becomes high enough, the main positive streamer is generated. Such relevance of the space charge to the streamer generation could be seen by adding a plane electrode in front of the pin electrode then changing its grounding and material. The streamer was generated earlier in time with the floating and the dielectric plane electrodes in which cases the space charges are able to last longer.

IV. SUMMARY

In summary, there was a regime of input frequency and voltage where a double streamer was observed. When the input frequency and voltage were increased to certain threshold values, the initial streamer could not be distinguished from the main streamer. The two streamers became indistinguishable because the main streamer was generated earlier in time. The initial streamer was suspected to be coming from the space charge accumulated during the previous negative discharge, and it was confirmed by changing the space charge accumulation condition. This study may contribute to determining the streamer generation conditions and to understanding the streamer dynamics including the temporal and spatial behavior of the plasma. Then, it would yield a means of controlling the plasma for enhanced application efficiency and analyzing the application results.

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