Comparison of Two-Dimensional Electron Density Distribution between Positive Primary and Secondary Streamer Discharge in Atmospheric-Pressure Air

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Abstract: Comparison of two-dimensional electron density distributions was conducted between pulsed positive primary and secondary streamers in atmospheric-pressure air, by using two types of laser wavefront sensors. The electron density distribution in the primary streamer was inhomogeneous along the propagation direction, due to the rapid electron consumption caused by the dissociative recombination reaction of electrons with cluster ions. The secondary streamer propagated while maintaining an almost uniform electron density of 0.7-1 × 10^{15} cm^{-3} along the propagation direction. Such temporally stable electron density evolution suggested that the reduced electric field inside the propagating secondary streamer was about 120 Td.

Keywords: electron density, streamer in atmospheric-pressure air, laser wavefront sensor.

1. Introduction

Although the electron density is an essential factor of the radical production processes, the electron density measurement of the streamer discharge in atmospheric-pressure air has been a challenging task over many years [1]. This determination difficulty arises mainly from the spatiotemporal non-reproducibility of the streamer discharge in atmospheric-pressure air. Recently, the electron density distribution over the primary streamer discharge was successfully measured by the use of Shack-Hartmann type laser wavefront sensors capable of visualizing a two-dimensional electron density distribution from a single-shot recording [2]. However, the application of the Shack-Hartmann sensors was limited to the primary streamer, which had an electron density above 5 × 10^{14} cm^{-3}. The electron density in the secondary streamer was locally reduced below 5 × 10^{14} cm^{-3}; therefore, it was impossible for the Shack-Hartmann sensors to detect the low electron density in the secondary streamer. In order to resolve the problem, the Talbot effect was applied to the laser wavefornt sensors, which improved the measurement sensitivity. In this paper, two-dimensional electron density distributions of pulsed positive primary and secondary streamers in atmospheric-pressure air are compared with each other. From the spatial profiles and decaying time constants of the electron density, the electron consumption processes for the primary and secondary streamers is discussed.

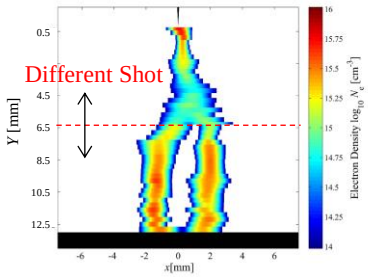
2. Experiment

A detailed description of electron density measurement using Shack-Hartmann [2] and Talbot sensors [3] was previously reported. Both sensors measure the optical spot shifts caused by the laser wavefront gradients, which reflects the electron density gradients in the plasmas. As an alternative to the micro-lens arrays installed in the Shack-Hartmann sensor, the Talbot sensor utilises the pinhole arrays, whose Talbot effect creates optical spots at 4-times longer lengths away than the Shack-Hartmann sensor. Therefore, the Talbot sensors are capable of amplifying the optical spot shifts and realising a superior sensitivity than the Shack-Hartmann sensors by a factor of 4, which allowed us to measure the electron density over the secondary streamer as low as 1 × 10^{14} cm^{-3} [3].

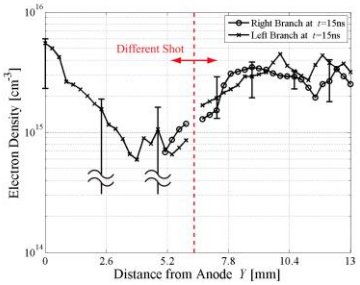
The temporal resolution of both sensors corresponded to the exposure time of the installed ICCD cameras, which was set to 5 ns. The spatial resolution was equal to the pitch of the micro-lens and pinhole arrays, which was 300 μm. Pulsed positive streamer discharges were generated in a 13-mm gap installed in open air where the H_2O concentration was about 1%. The gap was composed of a plate cathode and a pin anode, whose tip radius was 80 μm. The applied voltage to the anode rose from zero to a peak of 35 kV in 70 ns, and the voltage rise-rate was 0.83 kV/ns. In this paper, t = 0 ns corresponds to the initiation timing of the primary streamer.

3. Result and Discussion

Figure 1 shows typical electron density distributions observed by the Shack-Hartmann sensors at t = 15 ns, when the primary streamer reached the cathode [2]. It should be noted that in this study, the electron density distributions in $Y \gtrsim 6.5$ and $\lesssim 6.5$ mm were obtained for different streamers at the same timing. The electron densities N_e in the arrival stage depended on Y. The N_e around Y = 3.9 mm presented a dip of 6 × 10^{14} cm^{-3}, while high N_e just beneath the anode tip indicated the secondary streamer initiation. Such an axially inhomogeneous N_e distribution was induced by a short decaying time constant of N_e in the primary streamer, which could be caused by the dissociative recombination reaction of electrons with cluster ions, $O_4^+ + e \rightarrow 2O_2$ [4].

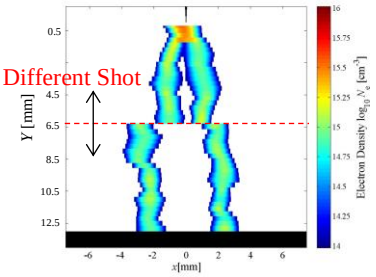


(a) 2-D

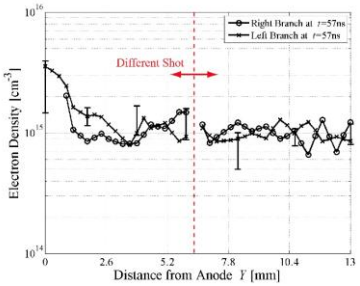


(b) axial distribution

Fig. 1. N_e at primary streamer arrival [2].



(a) 2-D



(b) axial distribution

Fig. 2. N_e at secondary streamer arrival.

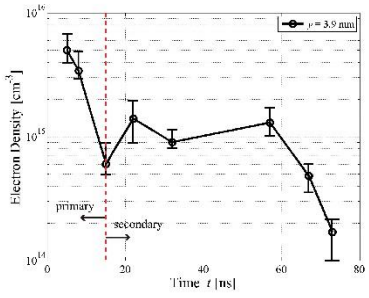


Fig. 3. Time evolution of N_e at Y = 3.9 mm.

Figure 2 represents typical data at the secondary streamer arrival at the cathode, which occurred at t = 57 ns. They were observed by Talbot sensors. During the secondary streamer propagation, almost homogeneous N_e of 0.7-1×10^{15} cm^{-3} were maintained along the Y direction. This temporally stable N_e in the propagating secondary streamer is clearly demonstrated in $22 \leq t \leq 57$ ns of Fig. 3. This means that the decaying time constant of N_e in the propagating secondary streamer was sufficiently longer than the characteristic time scale of secondary streamer propagation of ～40 ns. Numerical analysis using Bolsig+ [5] with published cross-sectional data [6] suggested that considering the reactions in Table 1, such a long decaying time constant was realised at the reduced electric field E/N inside the propagating secondary streamer of ～120 Td. Notably, Fig. 3 also shows that around Y = 3.9 mm, N_e in the propagating secondary streamer was higher than that at the primary streamer arrival. Such a time evolution of the N_e had not been reproduced in a previous simulation study, which predicted that the N_e at every Y-position monotonously decreased with increasing time after the primary streamer arrival [7].

4. Conclusion

The reaction of $O_4^+ + e \rightarrow 2O_2$ could cause the inhomogeneous electron density distribution along Y in the primary streamer. The axially homogeneous and temporally stable electron density in the secondary streamer suggested that E/N inside the propagating secondary streamer was ～120 Td.

Table 1. Main reaction for electron impact ionisation and electron attachment in air/H_2O (1%).

(R1)	$e + N_2 \rightarrow N_2^+ + 2e$
(R2)	$e + O_2 \rightarrow O_2^+ + 2e$
(R3)	$e + H_2O \rightarrow H_2O^+ + 2e$
(R4)	$e + O_2 \rightarrow O^- + O$
(R5)	$e + O_2 + O_2 \rightarrow O_2^- + O_2$
(R6)	$e + O_2 + H_2O \rightarrow O_2^- + H_2O$
(R7)	$e + H_2O \rightarrow H_2 + O^-$
(R8)	$e + H_2O \rightarrow OH + H^-$

5. References

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