S6-3

プラズマの可視化技術
Fundamental – Experimental: Visualization Technique of Atmospheric Pressure Plasmas

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1 Introduction

Atmospheric-pressure plasma generated without careful control is non-reproducible. The irreproducible atmospheric-pressure plasma includes high-current arc discharges formed in gas circuit breakers, randomly branching streamer discharges utilized in vast application fields and ultra-dense, micrometer-scale laser ablation plasma determining the quality of the material processing. The systematic understanding of the physics and chemistry existing in the non-reproducible atmospheric-pressure plasma requires detailed diagnosis of the fundamental physical quantities. Among these, the electron density is one of the most essential physical parameters in the atmospheric-pressure plasma, because the electron density determines basic plasma properties, e.g. the Debye length, plasma frequency, particle collision processes and the radiation and absorption mechanisms. However, the spatial dimensionality provided by conventional plasma diagnostic techniques is usually 0 or 1. Therefore, the acquisition of the electron density in the irreproducible atmospheric-pressure plasma is extremely difficult by using the conventional sensors. In order to realize the electron density measurement, there has been an increasing demand for a novel diagnostics capable of visualizing an electron density distribution over the atmospheric-pressure plasma from only a single-shot recording. Here, the single-shot electron density visualization was achieved by Shack-Hartmann type laser wavefront sensors [1]. This new type of plasma diagnostics has been successfully applied for the high-current arc discharges [1], streamer discharges in air [2] and laser ablation plasma. Further, hydrodynamic behavior of the gas surrounding the atmospheric-pressure plasma has recently been reported to have a remarkable influence on the plasma properties. Therefore, a single-shot imaging sensor has been developed for the hydrodynamic behavior [3], in addition to the electron density. In the present report, the measurement principles and application examples of the imaging sensors are demonstrated.

2 Visualization Technique

A detailed description of an electron density measurement using Shack–Hartmann-type laser wavefront sensors was previously reported [1]. Our electron-density-measuring sensors visualize two-dimensional wavefront gradient profiles over the cross-sectional area of expanded laser light transmitted through discharge plasma. Since the wavefront gradients of the laser light are expressed as a function of electron densities in discharge plasma, a two-dimensional electron density image is obtained from only a single recording. **Figure 1** shows the basic concept of the Shack–Hartmann sensor. The Shack-Harmann sensor is composed of an image camera and microlens arrays. The localized wavefront gradients of a laser are converted into shifts of the focal spot positions [1]. These spot shifts are observed using the image camera at any given time after plasma generation. The moving distances of the focal spots for laser wavelength λ are determined by number densities of neutral particles, positive ions and electrons in the plasma. In particular, only the electron contribution to the spot shifts depends on λ, whereas the contribution from neutral particles and positive ions are independent of λ. Therefore, our electron-density-sensing system requires a simultaneous measurement of the spot shifts for two lasers with different wavelengths λ_1 and λ_2. The electron density N_e is obtained from the subtraction between the spot shifts for the two wavelengths with elimination of the influence of other particle densities.

The imaging sensor developed for the hydrodynamic behavior is based on a Schlieren method. Unlike the conventional Schlieren techniques, our sensor is capable of visualizing fine turbulent structures with a specified dimension. **Figure 2** shows an optical configuration of the spatial filter implemented in this study. The spatial filter consisted of a pair of lenslets and a circular aperture. The circular aperture was placed in the confocal plane of the pair of lenslets. When a laser beam is incident on a lenslet, the laser wavefront transmitting through the lenslet is spatially Fourier transformed in the confocal plane [3]. Therefore, the circular aperture operates as a bandpass filter for the laser wavefront. In other words, the specified spatial frequency components can selectively penetrate the circular aperture. Since the spatial frequency of the turbulent gas density is one-order higher than that of the electron density (~ 1 mm), the use of circular aperture for a spatial frequency of ~ 100 μm enables us to extract and visualize the turbulent flow structure.

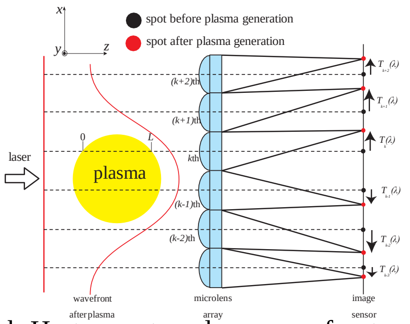

Fig. 1 Shack-Hartmann type laser wavefront sensor [1].

3 Results and Discussion

Figure 3(a) shows a two-dimensional N_e distribution over the primary streamer discharge at t = 8 ns [2]. The origin of t corresponds to the time at the primary streamer initiation at the anode tip. The primary streamer had a branching structure around the gap center. **Figures 3(b) and (c)** show axial N_e distributions over the primary streamer for experiment and simulation, respectively. The experimentally obtained profiles were reproduced in the numerical simulation under the consideration of the dissociative recombination reaction of electrons with cluster ions: $O_4^+ + e \rightarrow 2O_2$ [4], which had not been included in conventional simulation models.

Figure 4 shows a comparison of the hydrodynamic behavior observed around the arc discharges in 100%CO_2 and 90%CO_2/10%C_2F_6. The black cylinders show the light emission from the arc discharges, and the scattered red patterns show the turbulence. The Schlieren images clearly demonstrated that spatiotemporally irreproducible turbulence with fine structures existed only for 90%CO_2/10%C_2F_6. It is widely known that the small turbulence causes cold gas mixing into the arc, which results in more rapid arc cooling, faster electron density reduction and superior interruptioninterruption performance. Therefore, it can be suggested that the random fine turbulence is the determinant factor for the superior interruption performance of a gas circuit breaker.

4 Conclusion

The single-shot imaging sensors of the electron density N_e and turbulence were developed for the air streamer discharge and arc discharge, respectively. These novel techniques are quite useful for the systematic understanding of the physics and chemistry in the non-reproducible atmospheric-pressure plasma.

Acknowledgments

This work was supported in part by JST, PRESTO Grant Number JPMJPR2003, Japan, and the Japanese Ministry of Education, Culture, Sports, Science and Technology, (Grant-in-Aid 18H01418, 19H02122 and 20K20995.)

References

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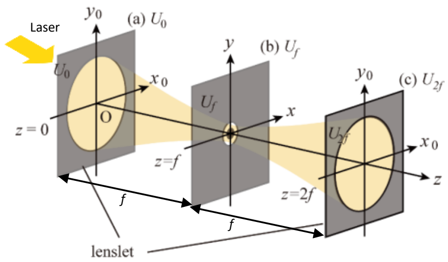
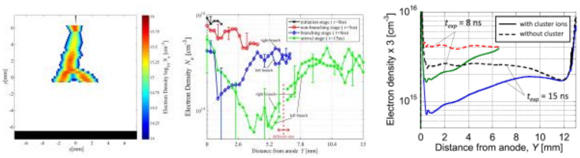
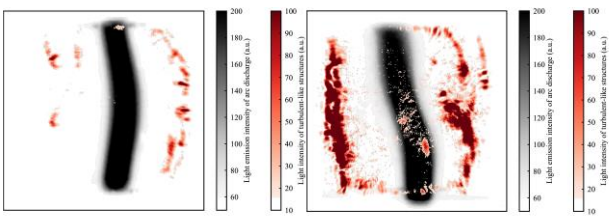


Fig. 2 Bandpass spatial filter [3].



(a) 2D N_e (b) axial N_e (exp) (c) axial N_e (sim)

Fig. 3 Air streamer discharge [2, 4].



(a) 100%CO_2 (b) 90%CO_2/10%C_2F_6

Fig. 4 Turbulent flow structures with spatial frequency of 120-210 μm for (a) 100%CO_2 and (b) 90%CO_2/10%C_2F_6 [3].