

Potential Distribution Measurement of Surface Discharge in SF₆

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Sensing techniques with a Pockels crystal have been applied to directly measure the potential and electric field distribution of surface discharge creeping on a dielectric material. The transient change of potential distribution with a surface discharge, which propagates on a 780 μm thickness BGO crystal in SF₆ at 160 ~ 760 Torr pressure, is measured with high time and spatio resolution by using Pockels sensor, a CCD camera and a streak camera.

Little significant difference is recognized between the potential distribution along a negative discharge and that along a positive one. The distribution of E_x along a streamer has a triangular profile and E_x has its maximum near the head of it. The value of E_x around the streamer head keeps around the critical value for the gas ionization. During subsequent stepwise propagation of the streamer, a leader, whose electrical conductivity is relatively high, is being inside previous discharges.

Keywords: Pockels, surface discharge, potential distribution, SF₆, stepwise

1. Introduction

Surface discharge on a dielectric material has a great influence on the insulating performance of electrical apparatus and electronic devices. Information on the potential and the field profile along the surface discharge is required for quantitatively discussing and clarifying the propagation process.

Sensing techniques with a Pockels crystal have been applied to the space charge measurement of electrical discharge⁽¹⁾⁻⁽²⁾.

We proposed a new system based on sensing techniques with a Pockels crystal for measuring the transient potential distribution of surface discharge without any disturbance to the electric field distribution, and have been measuring mainly the potential distribution of a surface discharge in atmospheric air⁽⁵⁾⁻⁽⁹⁾. In this paper, the transient change of the potential distribution with a surface discharge in SF₆ is measured with high space and time resolution.

2. Measurement System

Fig. 1 shows a schematic diagram of the measurement system used in this study. The system consists of an Ar ion laser, a cylindrical beam expander, a polarised beam splitter (PBS), Bi₄Ge₃O₁₂ Pockels crystal (BGO, 16 in relative permittivity ϵ_r) with a diameter of 50mm, a streak camera and a CCD camera. As shown in Fig. 2, surface discharge occurs and propagates directly on the surface of the BGO.

Since the principle and the structure of this system have been already reported in the previous papers⁽⁶⁾⁻⁽⁸⁾, the details are omitted in this paper.

As the BGO crystal has the Pockels effect, the light

intensity recorded with a streak and a CCD cameras, I_{out} is given by

$$I_{out} = \frac{I_{in}}{2} (1 - \cos kV_{BGO}) \quad (1)$$

where I_{in} is an input light intensity, k is a constant and V_{BGO} is the potential difference applied to the BGO.

To calibrate an exact potential value on the BGO, a plate electrode is attached on the insulating plate and the light intensities are measured for all points on the measuring surface of the plate while changing the voltage applied to the plate electrode. From these data, an experimental equation showing the relationship between the output light intensity and the potential on the BGO

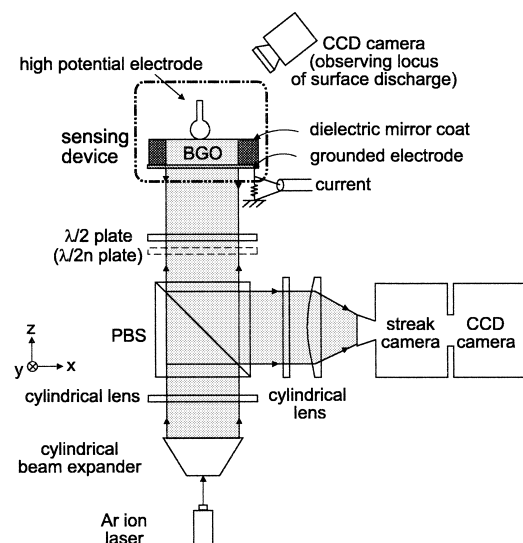


Fig. 1. Experimental setup.

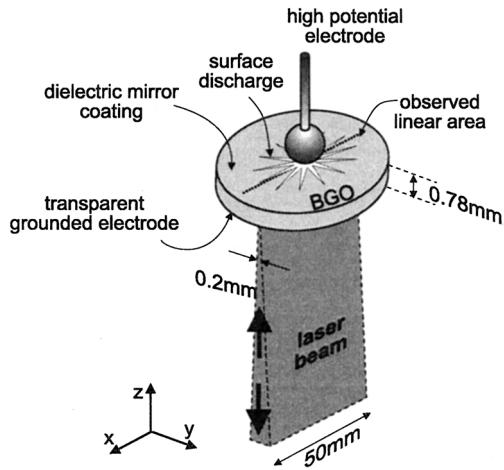


Fig. 2. BGO sensor device.

is derived for all 512 points along the measured linear path of 50 mm.

With this system, the potential profile on the surface of the BGO along a linear path of 50mm in maximum length can be measured quantitatively and continuously without causing any field disturbance. Considering the specification of the streak camera system, the minimum resolution of this system reaches 2-3 ns in the domain and 0.05mm in space domain⁽⁷⁾.

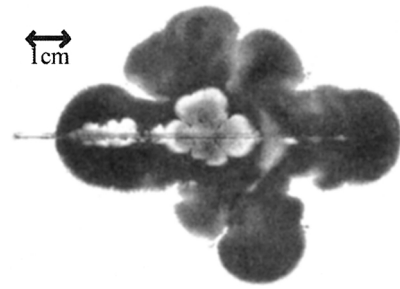
Equation (1) shows that I_{out} changes as a cosine function of a potential difference applied to the BGO. This fact also suggests that there is a limited range in the measured potential difference for holding a single-value relationship between the detected light intensity and the potential difference. This limit is defined as a half wavelength voltage V_{π} . The value V_{π} for this system is 14.5kV. The minimum detectable potential depends on the stability of the laser output. Experimentally it is confirmed to reach 0.1kV⁽⁷⁾.

3. Experimental Results

3.1 Lichtenberg Figure Pattern of Surface Discharge Fig. 3 shows the Lichtenberg figure pattern of a negative surface discharge in SF₆ at 380 Torr pressure. A 4mm ϕ sphere electrode is set on a 2 mm thickness PMMA plate and an impulse voltage of -44 kV in peak value is applied.

When a negative impulse voltage is applied to a sphere electrode set on an insulating material, negative surface discharge propagates radially at first from the electrode. This negative surface discharge is considered to consist of innumerable thin negative surface streamers⁽¹⁰⁾. If the applied voltage is increased, a surface leader is formed in the streamers and a stepwise subsequent discharge propagates in front of the previous discharge. When a thread or a scratch is set/cut on the insulating material, these stepwise subsequent discharges propagate along it. Fig. 3 corresponds to the Lichtenberg figure of such a stepwise discharge.

Fig. 4 shows the Lichtenberg figure pattern of a positive surface discharge under the similar experimental condition that of Fig. 3. An impulse voltage of 36

Fig. 3. Lichtenberg figure of a negative surface discharge in SF₆ at 380 Torr pressure.Fig. 4. Lichtenberg figure of a positive surface discharge in SF₆ at 380 Torr pressure.

kV in peak value is applied to the 4mm ϕ sphere electrode. The positive surface discharge consists of many filament-like streamers. When the applied voltage is increased, a surface leader is also formed and stepwise subsequent discharges propagate in front of the previous discharge as well as the negative polarity.

In air or nitrogen, the positive surface discharge rarely propagates stepwise⁽¹¹⁾, and it is hard to control the propagation direction of positive surface discharge. In SF₆, stepwise subsequent discharge often propagates along a thread or a scratch set/cut on the insulating material.

The shape of the positive surface discharge is influenced considerably by the experimental condition. As the gas pressure is reduced, each filament-like positive streamer becomes thick and develops longer. As the intrinsic capacitance of the insulating plate is larger, the larger number of filament-like streamer occurs with a tight clearance and it becomes easier to control the propagation direction of surface discharge⁽¹¹⁾.

3.2 Potential Distribution along a Negative Streamer A negative impulse voltage shown in Fig. 5 is applied to a 4 mm ϕ sphere electrode that is set on a BGO crystal, and a negative surface discharge shown in Fig. 6 occurs from this electrode and develops on the BGO in SF₆ at 160 Torr pressure. This negative surface discharge consists of innumerable thin negative surface streamers which develop radially from the electrode. The potential distribution along a negative surface streamer, which develops along the observed linear area, is measured. Fig. 7 shows the transient change in the potential $V(x, t)$ on the BGO surface with the prop-

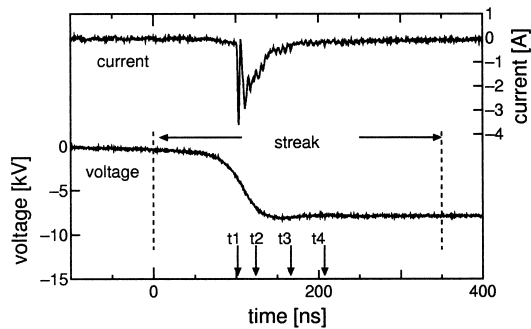


Fig. 5. Voltage and current profiles.

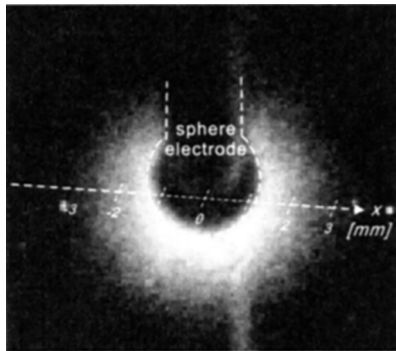


Fig. 6. Still photograph of negative surface discharge in SF₆ at 160 Torr pressure.

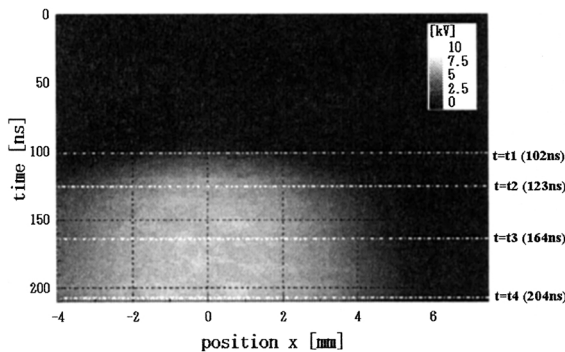


Fig. 7. Potential distribution of negative surface streamer in SF₆ at 160 Torr pressure.

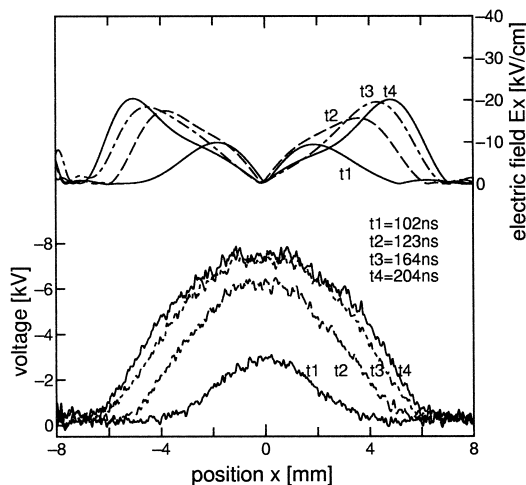


Fig. 8. Transient change in potential and electric field distribution along negative surface streamer in SF₆ at 160 Torr pressure.

Table 1. Maximum intensity of electric field along negative surface streamer.

kind of gas	SF ₆	SF ₆	SF ₆	air
pressure [Torr]	160	460	760	760
development length* [mm]	4.8	3.1	1.6	4.6
max of E _x [kV/cm] (measured)	20	33	58	25
max of E [kV/cm] (estimated from measured profile)	21	37	82	26
E _{cr} [kV/cm]	18.7	42.1	88.9	24.7

*It is defined the position where E_x takes its maximum when a streamer stops, for convenience.

agation of the surface streamer. The transient change in the potential distribution is shown in the bottom part of Fig. 8. These potential profiles are derived from Fig. 7 by extracting measured data on a line parallel to the t-axis.

The propagation direction components of the electric field E_x can be calculated from the slope of measured potential distribution profiles. The potential profile is approximated with a polynomial function and E_x profile is derived as its differential function.

To examine this fitting method, the potential and electric field distribution near a rod electrode (2, 5 or 8 mm in diameter) were obtained and compared with the theoretical profile computed numerically using the charge simulation method. It was confirmed that the experimental result agreed with the theoretical one with 25 % uncertainty in the maximum⁽¹²⁾.

The transient change in the distribution of E_x is shown in the top part of Fig. 8. At each time, the distribution of E_x has its maximum near the head of streamer. During the propagation of the surface streamer, the maximum value of E_x varies around 19 kV/cm, which is the critical value of the electric field ionization in SF₆ at 160 Torr pressure. The profiles of |E| along the surface streamer can be calculated with charge simulation method from this measured potential profile⁽⁶⁾. In the neighbor of head of the streamer, the intensity of |E| is estimated to excess 21kV/cm.

The potential distributions along a negative surface streamer in SF₆ at 460, 760 Torr pressure are also measured with the same method.

The maximum values of E_x and |E| at each pressure are shown in Table 1, in comparison with the critical electric field strength E_{cr} for the gaseous ionization. These data are measured under applying impulse voltage of 7 ~ 10kV in peak value to the electrode. It is possible to say |E| near the head of streamer in SF₆ keeps its value around electric-field ionization intensity.

The value of E_x in the stem of a streamer in SF₆ decreases gradually with the propagation of the streamer. At x = 3mm it decreases from 15.0 kV/cm (t = t₂) to 12.6 kV/cm (t = t₄). While a streamer propagates, the conductivity in the stem of it is being increased.

For the physical explanation of the surface discharge

in non-uniform electric fields, the two-region model is generally used⁽³⁾. One of the two regions corresponds to the head of the streamer where the electric field is high enough to cause ionization phenomena, and the other corresponds to the stem of the streamer where the electric field is low. The stem of a streamer plays a role as the transfer passage of the electrical charges caused in the ionization phenomena at the head of the streamer.

3.3 Potential Distribution along a Negative Stepwise Discharge The potential distribution along a negative stepwise surface discharges in SF₆ at 760 Torr pressure is measured. To control the propagation direction of the surface discharge, a thread (silk thread or hair, 50 μm in diameter) is put on the BGO crystal.

Figs. 9, 10 and 11 show applied voltage waveform, the transient change in the potential $V(x, t)$ on the BGO and potential and E_x distributions along it, respectively. A 6 mmφ circular cone electrode is used. The divergence angle of its tip is 30 degree. The conical electrode is set just on the position of $x = 0$ mm, and the impulse voltage is stressed at $t = -350$ ns. The streak camera observing the potential distribution starts at $t = 0$ ns and ends at 348 ns.

The first surface discharge (stage “I”) occurs around $t = -200$ ns and the surface discharge propagates forming two more steps in the direction of the right (stages “II” and “III”) as shown in Fig. 12. Simultaneously with these step propagations, current pulses appear in Fig. 9 and the high potential region expands in Fig. 10.

Since there is little change between the potential distribution profiles at $t = t_5$ & t_6 , and $t = t_9$ & t_{10} , it is natural to say the discharge at the stage “III” starts around $t = 140$ ns and stops around $t = 180$ ns.

Considering E_x profiles at t_6 shifted the streamer development length (equals to 0.7 mm) along the x-axis, it coincides well with that of t_{10} around the head of the discharge. As well as stepwise negative surface discharge in the atmospheric air⁽⁷⁾, it can be said that the E_x distribution around the head of the surface discharge keeps a particular profile when the surface discharge stops.

During the propagation of the discharge at stage “III”, a leader is being formed inside previous discharges. For example, the value of E_x at $x = 1.3$ mm decreases from 40.2 kV/cm (at $t = t_6$) down to less than 17 kV/cm (at $t = t_7$). At the time $t = t_7$, the value of E_x in the region of $x = 0 \sim 1.5$ mm is below 10 kV/cm.

3.4 Potential Distribution along a Positive Streamer The potential distribution along a positive surface streamer in SF₆ at 160 Torr pressure is measured with the same method as mentioned in the section 3.2. The experimental conditions are set similar to those of the section 3.2 except for the polarity.

Figs. 13, 14 and 15 show the applied voltage waveform, the still photograph of a positive surface discharge and potential and E_x distributions along it, respectively.

Compared with the negative surface streamer described in section 3.1, there are small differences in the

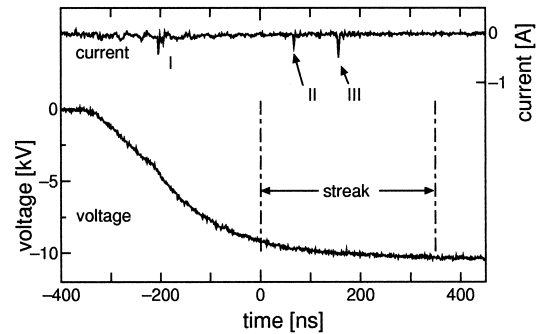


Fig. 9. Voltage and current profiles.

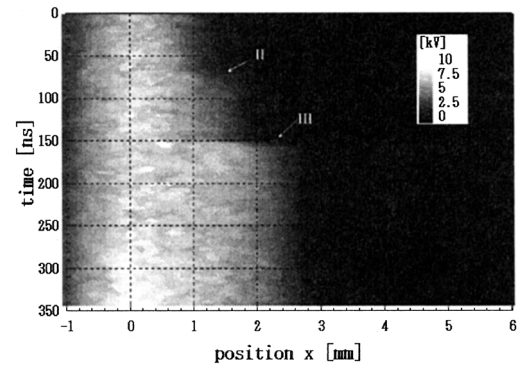


Fig. 10. Potential distribution of negative stepwise surface discharge in SF₆ at 760 Torr pressure.

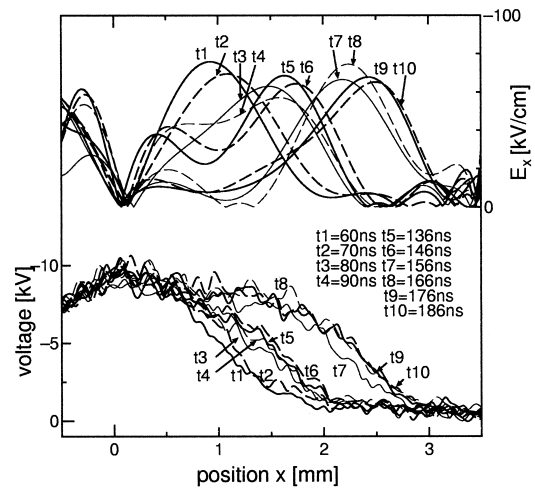


Fig. 11. Transient change in potential and electric field distribution along negative stepwise surface discharge in SF₆ at 760 Torr pressure.

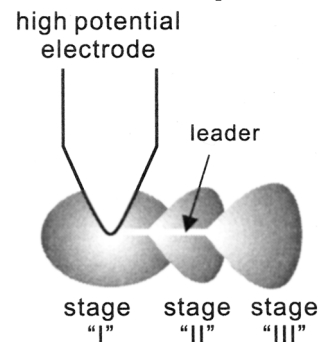


Fig. 12. Schematic illustration of negative stepwise discharge.

shape and the intensity of E_x distribution.

As the gas pressure is reduced to 160 Torr, each filamentous streamer becomes thick. Furthermore, as the intrinsic capacitance of an insulating plate is relatively large compared with that of 2mm thickness PMMA plate, larger number of streamer occur densely. From the still photograph, it is difficult to recognize each filament-like streamer.

At any time, the distribution of E_x has a triangular profile and E_x has its maximum near the head of the positive streamer. The value of E_x around the positive streamer head keeps around the critical value for the gas ionization (18.7 kV/cm).

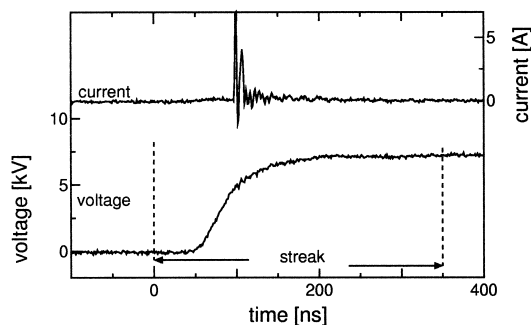


Fig. 13. Voltage and current profiles.

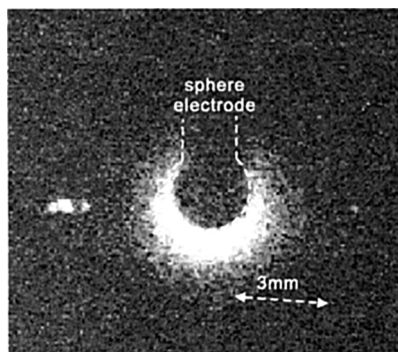


Fig. 14. Still photograph of positive surface discharge in SF₆ at 160 Torr pressure.

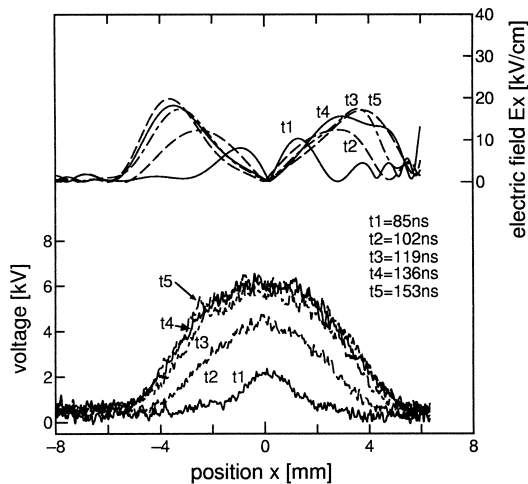


Fig. 15. Transient change in potential and electric field distribution along positive surface streamer in SF₆ at 160 Torr pressure.

This is in contrast to a positive streamer developing in atmospheric air⁽⁸⁾⁽⁹⁾. In case of the positive streamer in air, the potential decreases linearly with increasing the length x except in the neighbor of the electrode and E_x in the streamer is kept a low electric field less than the critical value for the gas ionization.

This difference is due to the shape of discharge. The filament of positive streamers in the atmospheric air has a very sharp tip shape, and propagates keeping a distance each other while that in SF₆ at 160 Torr pressure propagates densely. In the case of the atmospheric air, the electric field component perpendicular to the propagating direction is high and totally the electric field strength $|E|$ can exceed the critical value for the gas ionization.

3.5 Potential Distribution along a Positive Stepwise Discharge The potential distribution along a stepwise positive surface discharges in SF₆ at 360 Torr pressure is measured. Figs. 16, 17, 18 and 19 show the applied voltage waveform, the still photograph of a positive stepwise surface discharge, the transient change in the potential $V(x, t)$ on the BGO and potential and E_x distributions along it, respectively.

The first surface discharge (stage "I") occurs around $t = -250$ ns and the surface discharge propagates having two more steps in the direction of the left as shown in Fig. 18. The second discharge (stage "II") starts to propagate at $t = t_1$ and stops at $t = t_4$. The third discharge (stage "III") starts at $t = t_5$ and stops at $t = t_{10}$. E_x reaches its maximum at $x = -3.7$ mm ($t = t_1$), $x = 5.4$ mm ($t = t_5$) and $x = -8.0$ mm ($t = t_{10}$), respectively. From Fig. 17, it is difficult to distinguish the second discharge from the third discharge. The E_x distribution around the streamer head of third discharge ($t = t_{10}$) is similar in profile to that of the first discharge

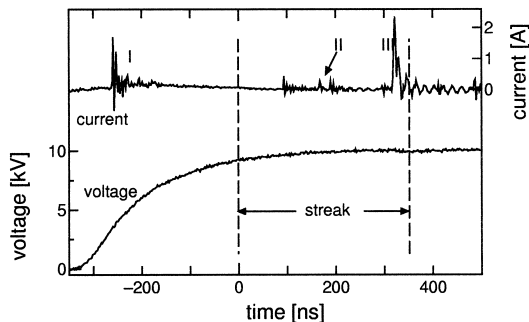


Fig. 16. Voltage and current profiles.

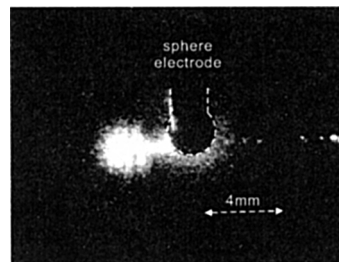


Fig. 17. Still photograph of stepwise positive surface discharge in SF₆ at 360 Torr pressure.

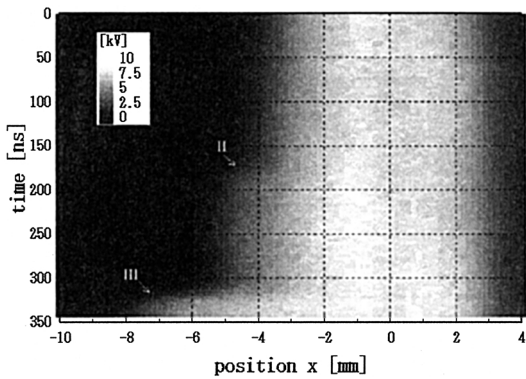


Fig. 18. Potential distribution of stepwise positive surface discharge in SF₆ at 360 Torr pressure.

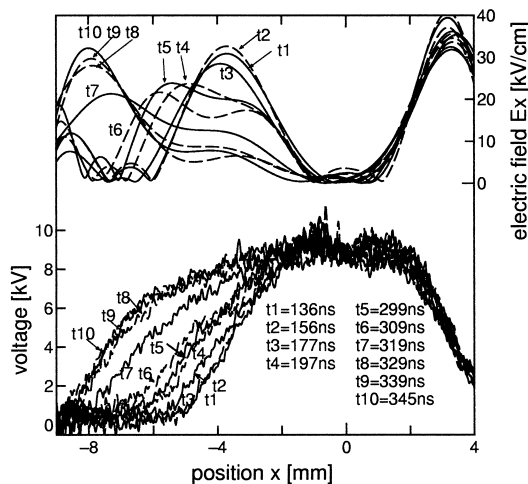


Fig. 19. Transient change in potential and electric field distribution along stepwise positive surface discharge in SF₆ at 360 Torr pressure.

($t=t_2$). As well as the negative polarity, the E_x distribution around the head of the surface discharge keeps a particular profile in principle when the surface discharge stops.

With the propagation of these subsequent discharges, the leader is formed inside previous discharges just like the negative stepwise discharge described in the section 3.2. At the time $t=t_8$, the value of E_x in the region of $x=0 \sim 5.4$ mm is below 7 kV/cm.

4. Conclusion

An optical method for measuring the transient potential distribution of surface discharge using Pockels effect was developed. The potential distributions along a surface discharge in SF₆ at 160 ~ 760 Torr are measured with high time and spatio resolution.

The experimental results obtained from the measurement are summarized as follows:

(1) The distribution of E_x along a negative streamer has a triangular profiles and E_x has its maximum near the streamer head. The value of E_x around the streamer head keeps around the critical value requiring for the gas ionization.

(2) In contrast to the potential distribution along

a streamer in air, little significant difference is recognized between the potential distribution along a positive streamer in SF₆ and that of a negative one. The potential distribution profile along a streamer is sensitive to the shape and arrangement of the filament-like streamers.

(3) During the propagation of the subsequent stepwise discharge, the leader is being formed inside previous discharges. The electric field intensity E_x inside the negative leader at 760 Torr pressure is less than 10 kV/cm. That inside the positive leader at 360 Torr pressure is less than 7 kV/cm.

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