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By

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ABSTRACT: A laboratory experiment on the interaction between the high voltage solar array and the ambient plasma has been conducted. In the experiment, an array of electrodes distributed on the honeycomb structure CFRP panel was used to simulate the inter-connectors of the solar array. One of major concerns in the usage of the high voltage solar array in space is the arc discharge on the array. Based on the plasma sheath theories, there is a possibility to control or to prevent the discharge by selecting a potential distribution of the electrode array. As the first step to find the potential distribution which tolerates the discharge, we measured the distribution of space potential surrounding an array of electrodes and measured the current to the electrodes. This paper presents the preliminary results of the experiment suggesting that we can control the discharge by selecting a proper potential distribution of the high voltage solar array.

1. INTRODUCTION

As power consumption of spacecraft increases, power generation at higher voltages and lower currents is required to reduce power loss in the cables and power systems. For kilowatt-class spacecraft, the array voltage near 50 V is currently used. For the International Space Station requiring 100-kilowatt level electric power, power generation more than 100 V is used. Much higher voltages are considered for large commercial satellites and solar power satellites in the future.

Since the inter-connectors of the solar cells are usually exposed to the space environment, the solar array panel interacts strongly with the ambient plasma for the high voltage solar array [1][2]. The interaction sometimes causes electric discharge and current leak from the cells, resulting in the damage of the solar cells and the associated circuits in the worst case. Especially solar array voltage more than 200 V in the low earth orbit has a potential risk for the electric discharge [3].

One approach to prevent the discharge is to shield the inter-connectors from the ambient plasma, but it is very difficult to maintain the insulation for a long time in space environment, considering the thermal cycle and impact of the meteoroids and debris in orbit.

Another approach is to select the distribution of the array voltage to suppress the discharge. The voltage of the inter-connectors ranges from 0 to the solar array voltage with respect to the body of the satellite. According to the theory of the plasma probe [4]–[6], the plasma current to the inter-connector strongly depends on the sheath structure surrounding the solar array panel. On the other hand, the sheath

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structure depends on the distribution of the solar array voltage. It can be possible to design the distribution of the solar array voltage so as to minimize the risk of the electric discharge. We started the experimental study on the interaction between the high voltage solar array and the ambient plasma [7].

In this paper, we describe the experimental results of the distribution of the space potential surrounding the array electrodes, and electrode current. We discuss a model of the sheath on the electrode array and the physical process of the current-voltage characteristics for the multi-electrodes.

2. OUTLINE OF EXPERIMENT

The experimental setup employed in this experiment is shown in Fig. 1. A back-diffusion type discharge plasma source is installed at the end of the large space chamber 2.5 m in diameter and 5 m long. Argon gas is used as the working gas for the plasma source. The base pressure is 10^{-5} Pa, but the pressure is 2×10^{-2} Pa during the experiment when the Argon gas is fed. The plasma density in the chamber is $10^3/cm^3 \sim 10^6/cm^3$. A multi-electrode plate and a Langmuir probe are configured at the opposite side of the plasma source. An emissive probe is installed on a three-dimensional movable platform. A set of high voltage power supplies can generate arbitrary distribution of the bias voltage on the array panel. The current flowing into the electrodes are measured sequentially by a multiplexer and recorded in a data acquisition system. The external view of the space chamber is shown in Fig. 2.

A filament of a small lamp (6 V, 60 mA) is used as the electron emitter for the emissive probe [8].

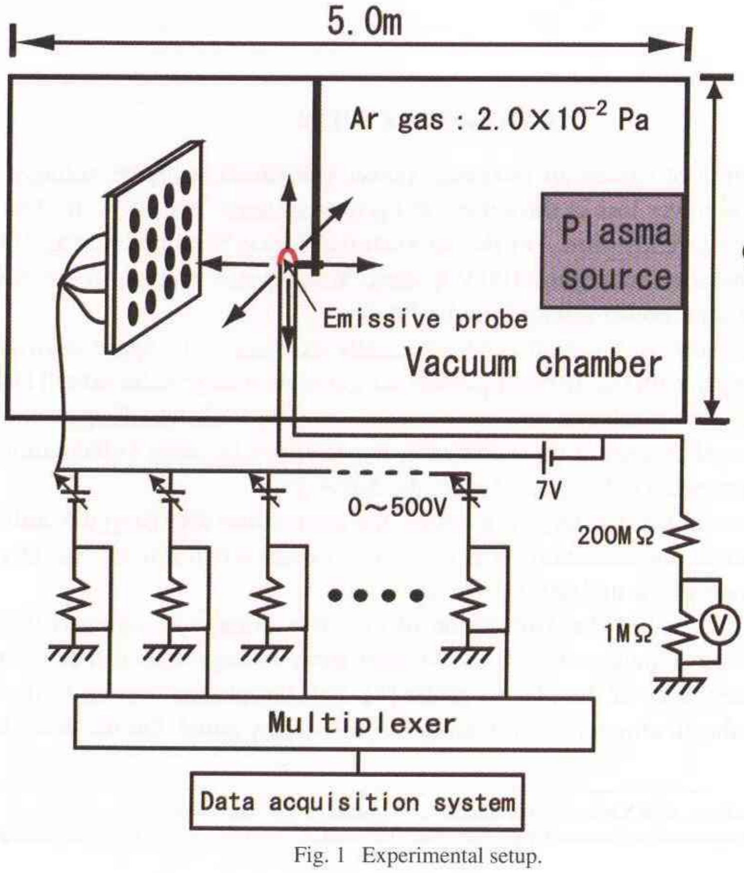


Fig. 1 Experimental setup.

Fig. 2 Large space chamber at ISAS.

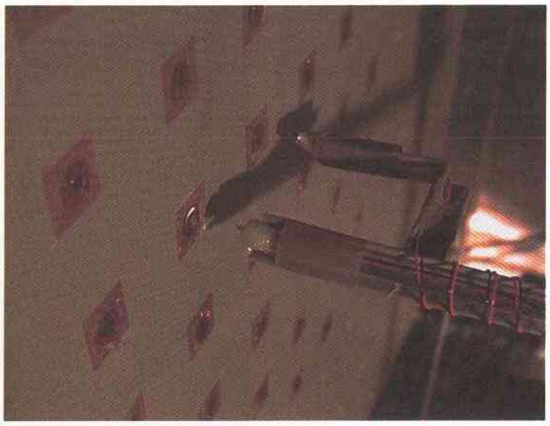


Fig. 3 Emissive probe.

The emissive probe gives an accurate information on the space potential inside the electron sheath if the following two conditions are satisfied;

(1) the capability of electron emission is larger than the electron current flowing into the emissive probe in the sheath,

(2) the current through the voltage detection circuit is much less than the electron current flowing into the emissive probe in the sheath.

The emissive probe we used in the experiment is shown in Fig. 3. The resistance of the voltage detection circuit was 200 M ohms. It was confirmed that the two necessary conditions were satisfied in our experiment.

3. EXPERIMENTAL RESULTS

3.1 Preliminary Result on the 10 × 10 Multi-Electrodes

The panel with 10 × 10 multi-electrodes used in this experiment is shown in Fig. 4. The diameter of the electrode is 5 mm and the center-center distance between two adjacent electrodes is 5 cm. Figure 5 shows numbering of the electrodes of the panel in Fig. 4. Totally 4 kinds of voltage distribution profile on the electrode array have been studied. These voltage profiles are shown in Fig. 6. Each profile is called 10P-type, M-type, V-type and F-type, respectively in this paper. The current to the electrodes was measured for the plasma density of $10^5/cm^3$ and $10^6/cm^3$. The electron temperature was measured as 4~6 eV. The Debye length is 1.8 cm for $10^6/cm^3$ and 4.7 cm for $10^5/cm^3$. Both arc and glow discharges were observed on the array depending on the plasma density and applied voltage, but the data were analyzed only in the parameter range without discharge. Figure 7 shows the distribution of the electrodes current for the voltage profile of Fig. 6 in the plasma of $10^6/cm^3$. There are differences in the current distribution corresponding to the voltage profiles. The average of the electrode current in these voltage profiles is shown in Fig. 8. The average current depends on the voltage profile. The current for the10P-type is quite larger than that for the other types. Figure 9 (a) shows a typical example of the electrode current for the 10P-type in the plasma of $10^5/cm^3$. As shown in Fig. 9 (b), the electrode current increased stepwise from A to C. This is quite different from the voltage-current characteristics for single electrode. The characteristic feature of the current for the multi-electrode array suggests that the sheath structure changed as the applied voltage increased.

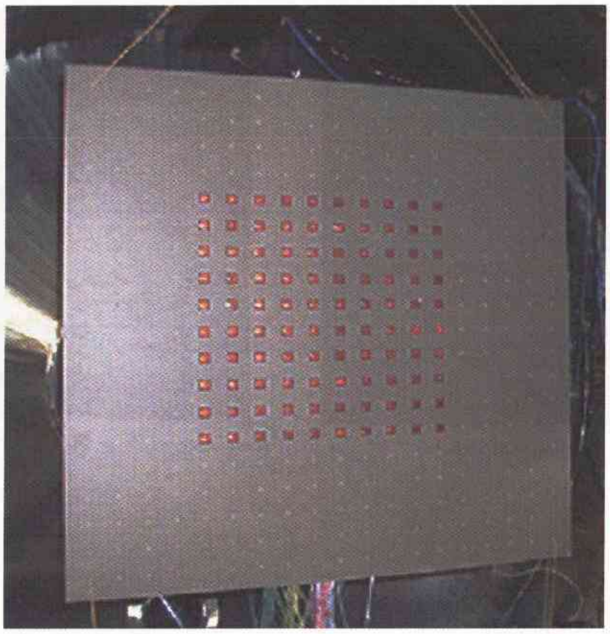


Fig. 4 10 × 10 electrodes on the CFRP panel to simulate the high voltage solar array.

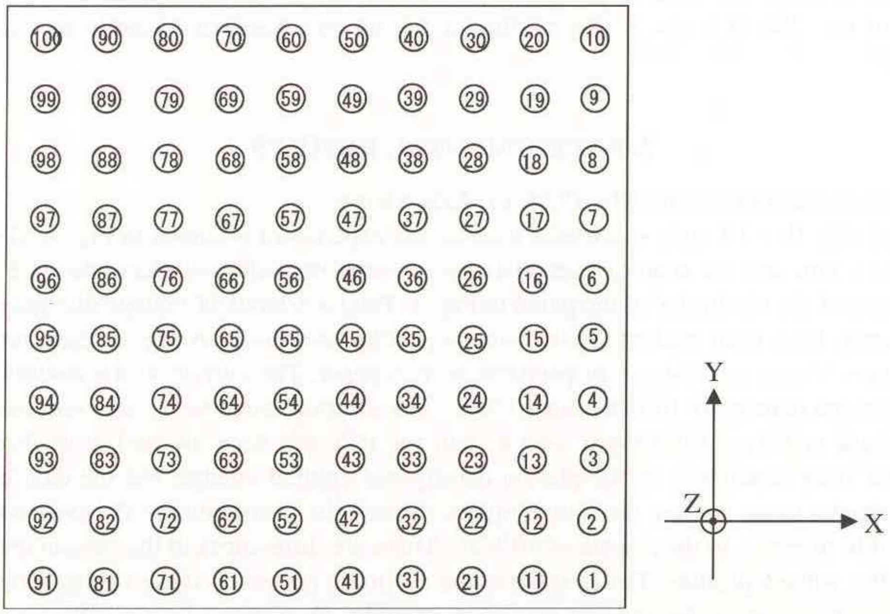


Fig. 5 Numbering of the electrodes.

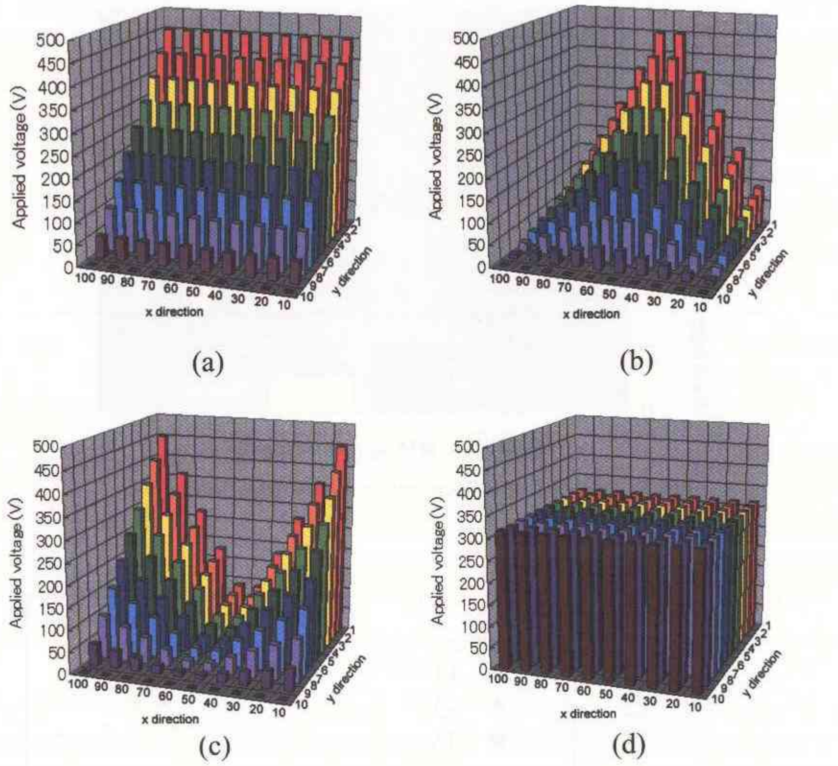


Fig. 6 4 kinds of voltage distribution profile. (a) 10 parallel type. 0–500 V is applied to each line of electrodes. (b) Mountain type. 0-500 V is applied. (c) Valley type. 0–500 V is applied. (d) Flat type. 300 V is applied. Each profile is called in this paper as 10P-type, M-type, V-type and F-type, respectively.

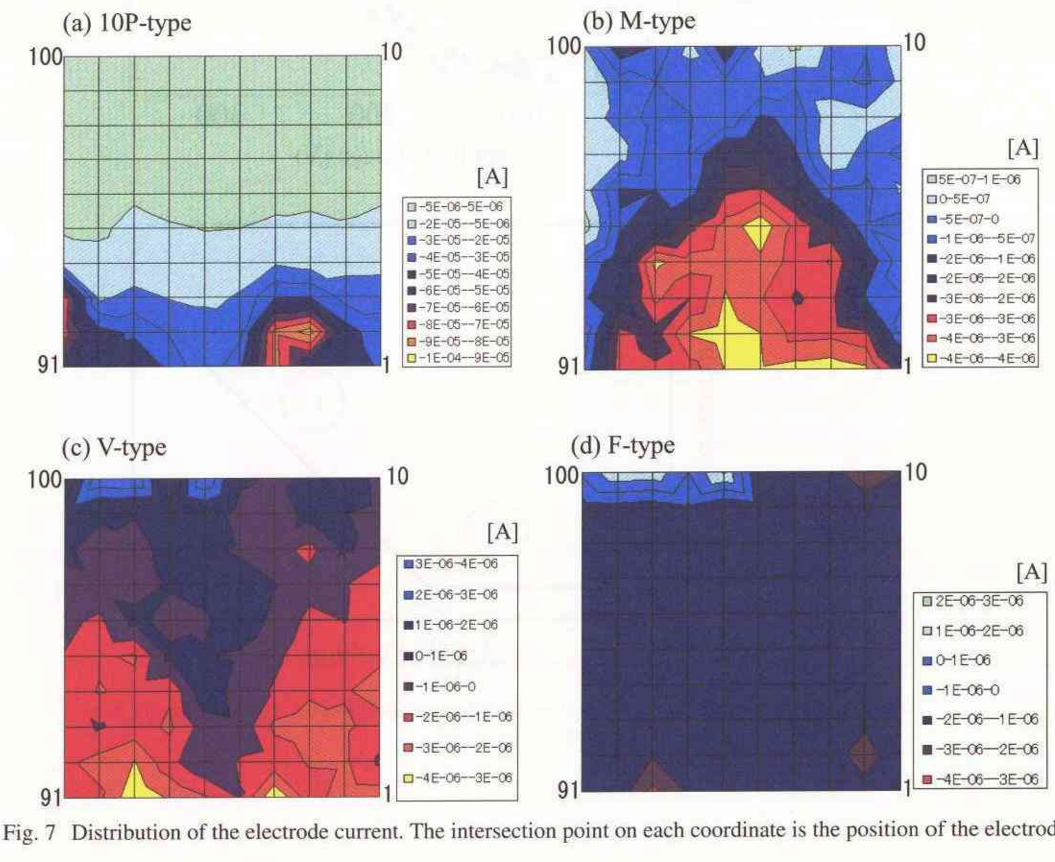


Fig. 7 Distribution of the electrode current. The intersection point on each coordinate is the position of the electrode.

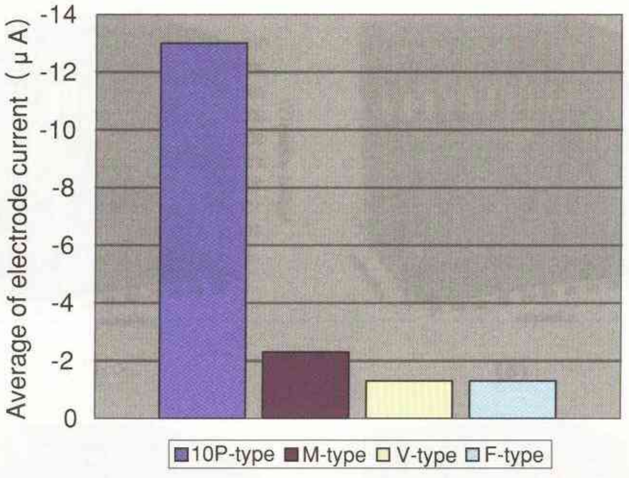
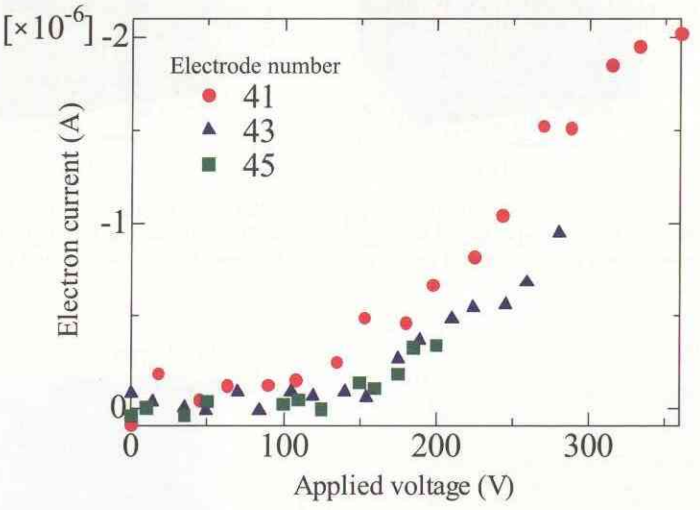


Fig. 8 Average electrode current for each voltage distribution.

(a)



(b)

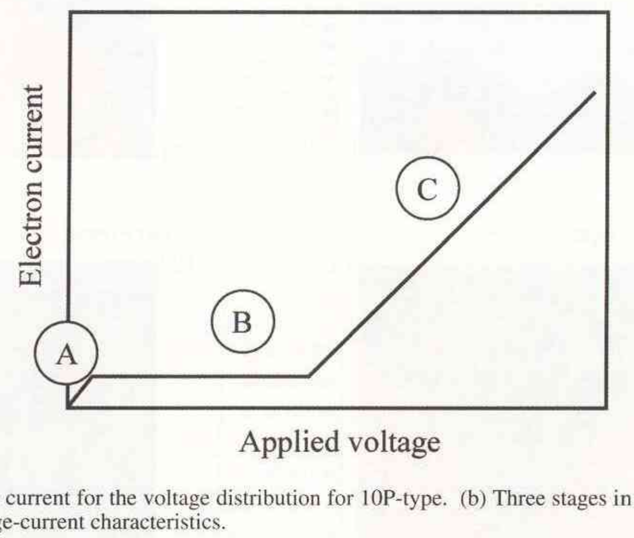


Fig. 9 (a) Electrode current for the voltage distribution for 10P-type. (b) Three stages in the voltage-current characteristics.

3.2 Measurement of Space Potential and Electrode Current of the 3 × 3 Multi-Electrodes

In order to clarify the physical process of the current-voltage characteristics for the multi-electrodes, we measured the distribution of the space potential surrounding the array electrodes using the emissive probe in addition to the electrode current. A 3 × 3 electrodes array in a part of the 10 × 10 electrodes array was used for this experiment. Other electrodes were floating to the ground in this experiment. Figure 10 shows the electron current to each electrode when the bias voltage from 0 to 400 V was separately applied to the electrodes in the plasma of $10^5/cm^3$. The electron current flowing into each electrode is almost same below 200 V. Figure 11 shows voltage-current characteristics when the bias voltage from 0 to 400 V was applied to the electrodes at the same time. This is remarkably different from the characteristics in Fig. 10. The increase of the electrode current is suppressed below 300 V but the electrode current is exponentially increased above 300 V. Each electrode current at 400 V is almost ten times larger than that at 300 V.

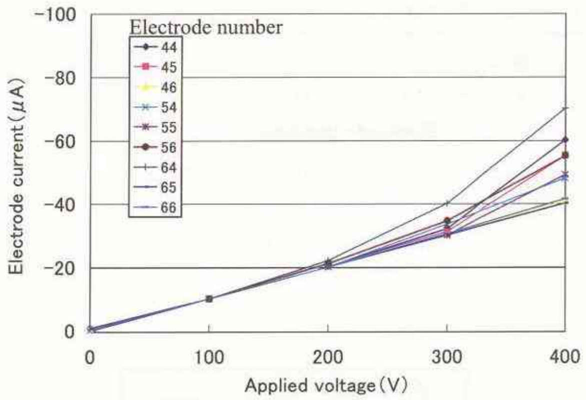


Fig. 10 Voltage-current characteristics when the bias voltage from 0 to 400 V is separately applied to the each electrode.

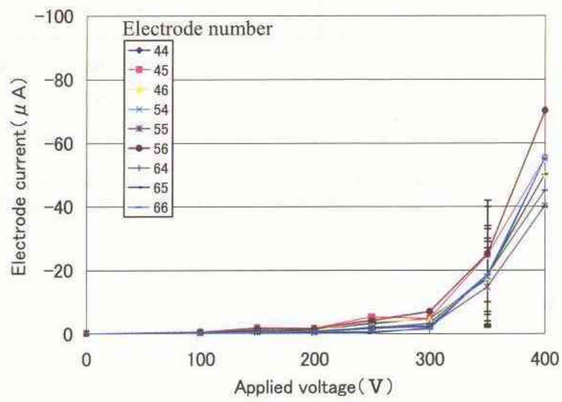


Fig. 11 Voltage-current characteristics when the bias voltage from 0 to 400 V is applied to the electrodes at the same time.

The spatial distribution of the space potential from 2 cm to 10 cm in front of the electrode array biased at 300 V is shown in Fig. 12. In this figure, z is the distance from the plate and x is the position parallel to the plate. The potential distribution at 2 cm from the array has a peak at each electrode, but is rather flat at 5 cm from the array. The profile of the space potential at 10 cm is almost the background level. Figure 13 shows the distribution of the space potential in case of 400 V. The potential distribution for this case does not have clear peaks in the x direction at 2, 5, and 10 cm from the array. Figure 14 shows the distribution of the space potential at 2 cm in front of the array for the bias voltage at 300 V and 400 V. The sheath structure at 2 cm for 400 V is flat as compared with that for 300 V. The space potential in the z direction is shown in Fig. 15. The space potential in the case of 300 V reaches the background level at 10 cm from the array, but in case of 400 V, it reaches the background level at 40 cm. In the hemispherical sheath model, the surface area to collect the electrons is proportional to the square of the radius of the hemisphere. The area of the electron collection in case of 400 V is 16 times larger than that of 300 V. The average current of 9 electrodes is summarized in Table 1. The observed electrode current is proportional to the surface area of the sheath model.

The experimental results suggest that the sheath surrounding each electrode was overlapped, forming a planar sheath when the sheath expanded as the voltage increased. As the voltage increased further, the sheath expanded as if the array was a single electrode. This assumption is schematically illustrated in Fig. 16. Based on the measurement of the space potential for the multi-electrodes, the voltage-current characteristics in Fig. 9 can be reasonably explained by the growth of the sheath. This model suggests that

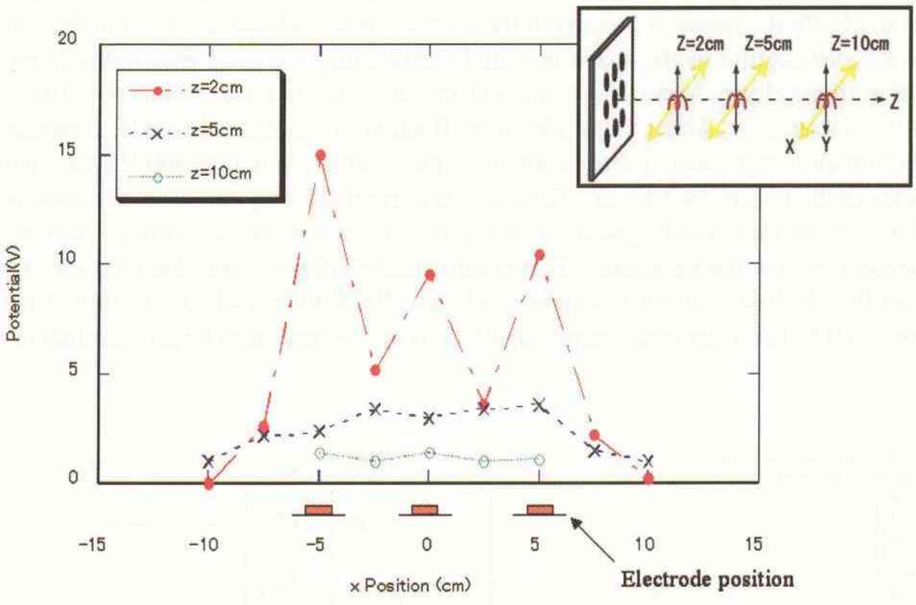


Fig. 12 Distribution of the space potential when the array voltage is 300 V. z is the distance from the plate and x is the position parallel to the plate.

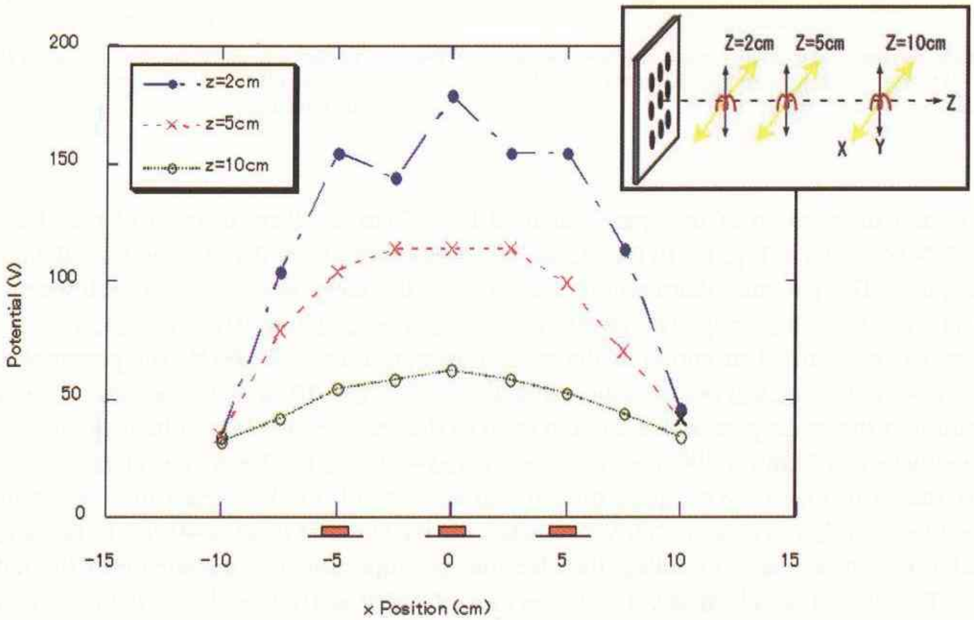


Fig. 13 Distribution of the space potential when the array voltage is 400 V.

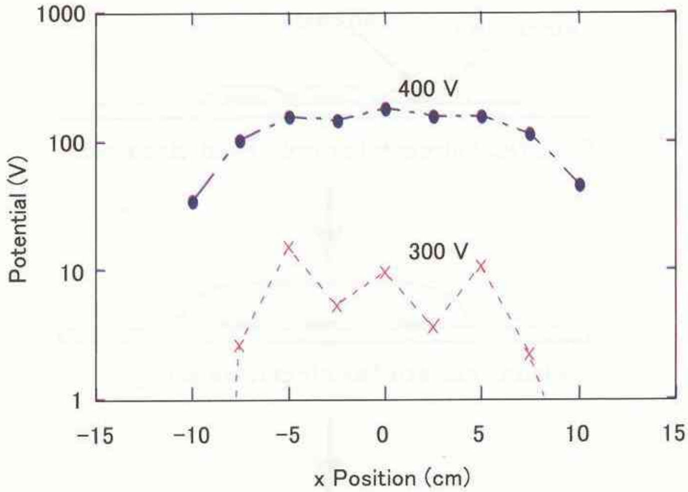


Fig. 14 Distribution of the space potential at 2 cm in front of the array.

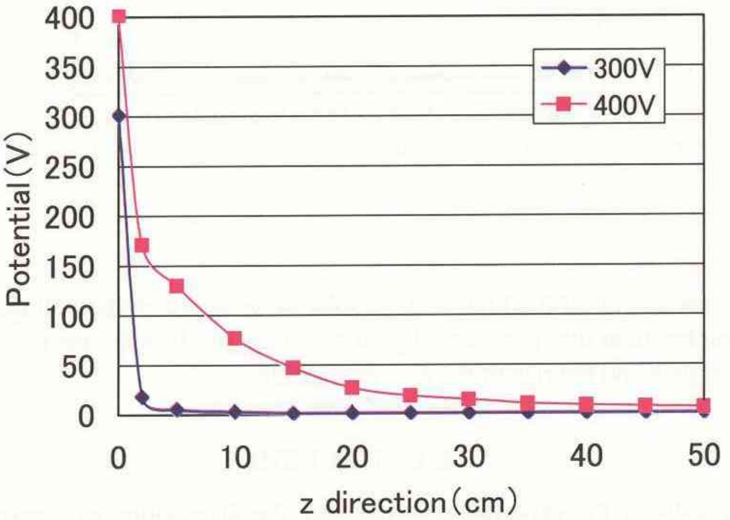


Fig. 15 Space potential in the z direction.

Table 1 Comparison of the electrode current and the sheath surface area in cases of 300 V and 400 V. The electrode current is the average current of 9 electrodes.

Applied voltage	300 V	400 V	Ratio
Sheath radius	10 cm	40 cm	4 times
Sheath surface area	200 cm^2	3200 cm^2	16 times
Electrode current	3.39 μA	50 μA	14.8 times

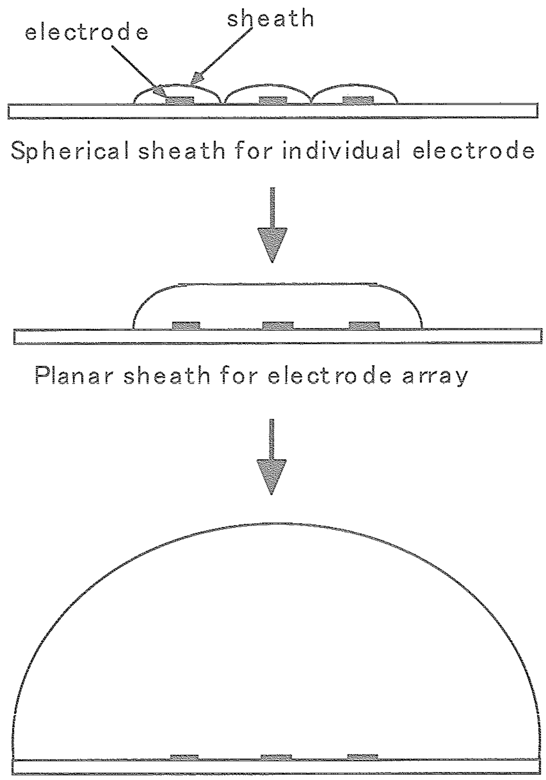


Fig. 16 A model of the growth of the sheath as the bias voltage increases.

the voltage distribution profile of the high voltage solar array in which the voltage near the center of the array is relatively higher than that near the edge of the array can be superior to other voltage profiles in respect of the current leak and the risk of the electric discharge.

4. CONCLUSION

Preliminary results of the experiment to measure the distribution of electrode current and space potential surrounding an array of electrodes are presented, in association with the study on the interaction between the high voltage solar array and the ionospheric plasma. The experimental results suggest that the configuration of the electron sheath on the array changed from individual small spherical structures to a planar structure, and finally to a larger spherical structure as the applied voltage to the electrodes increased. The electron current flowing into each electrode changed with the growth of the sheath structure. This indicates that the electron current to the electrode can be controlled by changing the potential distribution of the array electrodes. Based on the experimental results, we plan to make a next-step experiment to find the potential distribution of the electrode array which minimizes the risk of the arc discharge.

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