LABORATORY SIMULATION OF CHARGING RELAXATION BY PLASMA FLOW

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Abstract

In a space plasma simulator , a segmented ion collector in series with negatively char ged condensers were expo sed to argon plasma flow in order to understand phenomena of spacecraft negative charging and its mitigation by plasma flow. The time variations of neutralization current and ion sheath shape were measured. The mitigation process was expected to depend on plasma velocity and plasma number density, i.e., ion velocity and ion flux, and their dependence intensively changed with the attack angle of plasma flow to the negatively charged surface. In cases that a negatively-charged insulating surface disappears from a plasma source with a high plasma velocity, i.e., at wake condition, electrical breakdown fears occurring by a large difference in mitigation time between the absolute charging of the spacecraft conductive main body and the local charging of the insulating surface, as predicted from equivalent electrical circuits between a spacecraft and the space plasma around it.

Introduction

Spacecraft are in a severe environment in space. Their surfaces are exposed to ener getic and reactive particles, such as electrons, ions, protons and oxygen atoms and ultraviolet light, during space missions. Then, electrostatic interactions between the surface materials and the space plasma, such as negative or positive sheath creation, and charging and arcing phenomena, frequently occur.

In satellites, the current generated by a solar array is leaked by impact of ions, and the solar array is still degraded by sputtering and arcing due to the collected ions.[1-3] The electrical breakdown of negative charging on insulating surfaces causes intensive damages in the satellite systems. Furthermore, in plasma contactor operations, negative charging is expected to be mitigated by ions attracted from the plasma, resulting in surface degradation as well as in the case of high voltage solar arrays. The mechanism of the material degradation, the structure of electrical sheaths, and charging and arcing processes must be understood.

In Osaka University , a ground facility was developed for simulation of space plasma and mater ial interaction.[4,5] Using the simulator, the structure of an ion sheath created around a high voltage solar array and the degradation of surface materials near the array due to high energy ion bombardment were investigated.[6-8] The mitigation of negative charging by plasma flow, i.e., the feature of plasma contactor operations, has also been studied.[7,8]

In the present study , equivalent electrical circuits between a spacecraft and the space plasma around it are made in order to simply and clearly understand phenomena of spacecraft charging and its mitigation by plasma flow. A segmented ion collector in series with negatively charged condensers are exposed to argon plasma flow in order to examine the mitigation. An ion sheath is expected to be created in front of the ion collector surface although the sheath comes to be small as exposing; that is, a transient sheath is constructed. The neutralization current is measured for variations in the attack angle of plasma flow to the negatively charged surface. An emissive probe is used to examine time variations of the ion sheath shape around the ion collector. The hazard of electrical breakdown under mitigation of negative charging by plasma flow is discussed.

Modeling of Spacecraft Negative Charging and Its Mitigation by Plasma Flow, and Hazard of Electrical Breakdown

Figure 1 shows the equivalent electrical circuit between a spacecraft and the space plasma around it. The insulator on the surface of the spacecraft is a kind of thermal control films such as Kapton films. The condenser between the spacecraft conductive main body and the space plasma has a capacitance of C_0, that between the insulating surface and the space plasma C_1 and that between the insulating surface and the spacecraft conductive body C_2. In general, the capacitance C_2 is much larger than others, and the condenser C_2 can store lots of charge. The condenser C_0 is charged to a voltage of V_1; that is, the absolute charging potential of the spacecraft conductive body corresponds to V_1 (minus value) on the space plasma potential, and then that of the insulating surface to V_2 (minus value). Therefore, the local charging potential of the insulating surface corresponds to V_2-V_1 on the spacecraft conductive body potential, and the insulating surface has lots of negative charge.

As shown in Fig.2(a), when a plasma is released from a spacecraft, i.e., in plasma contactor operations, the electrons discharged spread into the space plasma; the ions are attracted to the negatively-charged insulating surface. In general, the resistance R_1, as shown in Fig.2(b), is smaller than R_2 because R_1 and R_2 are related to electron and ion motions, respectively; that is, electron mobility is larger than ion one. Accordingly, both switches of S_1 and S_2 are closed in the equivalent electrical circuit, and the charges in three condensers are discharged through the resistances R_1 and R_2. However, the local charging potential of the insulating surface come to be large, and the spacecraft has the hazard of electrical breakdown between the insulating surface and the spacecraft conductive body. This is because the relaxation time of the condenser C_1 is longer than that of C_0 owing to $R_1 < R_2$, resulting in coming to be a large $|V_2-V_1|$ with lots of charge in the condenser C_2.

Hence, we need to predict motion of ions from a plasma source to an insulating surface for safe use of plasma contactors. It is important to examine changes of mitigation process of negative charging with variations in ion number density, ion velocity and attack angle of ion flow on charging surface etc.

Experimental Apparatus and Conditions

The space plasma simulator developed in Osaka University, as shown in Fig.3, consists of a vacuum tank, a vacuum pump system and a plasma accelerator.[4,5,7,8] The electron cyclotron resonance (ECR) plasma accelerator is set on the flange of the large stainless vacuum tank 0.7 m in diameter x 1.5 m long. The main vacuum pump is an oil-free turbo-molecular pump with a high pumping speed of 5 m^3/s. The tank pressure is kept some 10^{-3} Pa during all experiments.

The ECR plasma accelerator is a type of magnetic-field-expansion plasma accelerators. Plasma is generated by ECR heating of the interaction between microwaves and divergent magnetic fields induced by a solenoidal coil around a discharge chamber and is electrostatically accelerated by micro electric fields induced by charge separation in the magnetic fields. Microwaves of maximum 3 kW and 2.45 GHz are introduced into the discharge chamber. An orifice is set to the downstream exit of the discharge chamber to produce a low density plasma flow. Argon is used as the working gas.

A spacecraft model, as shown in Fig.4, is located at 650 mm downstream from the plasma accelerator. The model has a segmented ion collector, and each segment is connected to a condenser with a capacitance of 400 pF corresponding to that of Kapton films 25_m thick. The segments are numbered. All condensers are charged up to -200 V, and then the spacecraft model is exposed to plasma flow. The angle between the plasma flow and the normal line of the ion collector surface can be changed. The neutralization current is defined as the current from the condenser to the ground; i.e., it agrees with the ion current attracted from plasma to the ion collector. The time variations of the boundary between the bulk plasma and an ion presheath around the ion collector are also measured with an emissive probe biased to -15 V just below the plasma potential.

Plasma parameters of electron temperature, plasma density and ion ener gy distribution (average ion velocity) are controlled by varying microwave input power, magnetic field shape and strength, and working gas mass flow rate. They are measured with a Langmuir probe, a Faraday cup and an electrostatic energy analyzer in front of the spacecraft model. Two plasmas named A and B, as shown in Table 1, are generated by changing operational conditions. The number density of plasma A is equal to that of plasma B although the plasma axial velocity of A is higher than that of B. Accordingly, we can mainly examine effects of ion velocity and implicitly ion flux on mitigation process of negative charging.

Experimental Results and Discussion

Figures 5 and 6 show the time variations in neutralization current for the segmented ion collector with plasmas A and B, respectively. In all experiments, the electric charge by integration of the neutralization current agreed with that which had been stored in the condenser before exposure.

The neutralization currents for the segments 1, 2 and 3 near the center of the ion collector at an attack angle of 0 deg, i.e, at ram condition, as shown in Figs.5(a) and 6(a), have high peaks at the start of exposure to plasma flow. Since the peaks for plasma A are higher than those for plasma B, the mitigation times for these segments with A are shorter than those with B. The times are order of 10^{-2} sec. On the other hand, the neutralization currents for the outside segments 4 and 5 gradually increase; have peaks and then decrease. The peaks and the mitigation times for plasma A are higher and shorter, respectively, as well as for the inside segments. As a result, the mitigation of negative charging for plasma A with the higher ion velocity and the larger ion flux is found to be faster than that for plasma B.

The waveforms of neutralization current at 90 deg, as shown Fig.5(b), are complicated. The neutralization currents for the segments 1 and 3 are highest at the start of exposure; that for the segment 5 has the second peak; that for the segment 2 has a slow change of up and down, and that for the segment 4 is very small compared with those for other segments. These characteristics roughly agree with those of a steady-state ion sheath created on a metal plate parallel to plasma flow; that is, the ion sheath shape extends outward downstream by inertia of ions.[6-8] Accordingly, plasma flow influences the motion of ions and the ion sheath structure. The mitigation time for each segment is reasonable considering waveform of neutralization current. The times are order of 10^{-1} sec. The peaks and the mitigation times for all segments with plasma A were slightly higher and shorter, respectively, than those with plasma B.

As shown in Figs.5(c) and 6(b), the neutralization currents for the inside segments 1,2 and 3 at 180 deg, i.e., at wake condition, are very high compared with those for the outside segments 4 and 5 at the start of exposure. Since the peaks are much smaller than those at 0 and 90 deg, long times of order of second are needed for mitigation of negative charging. Furthermore, since the peaks for plasma A are smaller than those for plasma B, the mitigation times with A are longer than those with B. These characteristics disagree with those at 0 and 90 deg. This is expected because of larger inertia of ions for plasma A with the higher ion velocity. Consequently, in cases that a negatively charged surface disappears from a plasma source with a high plasma velocity, i.e., at wake condition, electrical breakdown fears occurring by a large difference in mitigation time between the absolute charging of the spacecraft conductive main body and the local charging of the insulating surface as mentioned above.

Figures 7 and 8 show the time variations of the boundary between the bulk plasma and an ion presheath, named the ion sheath boundary or shape, around the segmented ion collector with plasmas A and B, respectively. The flat-like ion sheath boundaries at 0 deg, as shown in Figs.7(a) and 8(a), move toward the ion collector surface with time; that is, the ion sheath comes to be small. The boundary has a wave-like shape near the ion collector surface. This is expected because the ion flux near the center of the ion collector is high owing to lens effect of electric field in the ion sheath. Therefore, mitigation of negative charging is expected to intensively occur near the center of the ion collector compared with the outside. The ion sheath boundary for plasma A rapidly approaches the ion collector surface compared with that for plasma B. This is because of the higher ion flux for plasma A.

The ion sheath at 90 deg, as shown in Fig.7(b), is large at 2 msec although it may be larger downstream just at the start of exposure as predicted from the steady-state sheath feature.[6-8] The sheath boundary near the downstream region rapidly moves toward the ion collector surface although the boundary at the upstream region slowly approaches the collector surface. Hence, the ion sheath shape is found to drastically change with time. The direction of ion motion can be inferred from the inner normal directions of the ion sheath contours as follows. At first after the start of exposure a large amount of ions is collected at the downstream region on the ion collector; then the mitigation of negative charging at that region is finished, and finally ions are attracted at the upstream region. Also, the moving speed of the ion sheath boundary for plasma A was slightly higher than that for plasma B.

The flat-like ion sheath boundaries at 180 deg, as shown in Figs.7(c) and 8(b), slowly approach the ion collector surface after the start of exposure although near the collector the moving speed of the ion sheath boundary at the center comes to be high resulting in the rapid mitigation of negative charging near the center. This is expected because ions attracted from the outside freestream to the wake are concentrated near the center of the ion collector; i.e., the ion flux is very small near the edge of the collector owing to inertia of ions. It is very remarkable that the moving speed of the ion sheath boundary for plasma A with the higher plasma velocity is much lower than that for plasma B and also that the moving speed is very low compared with those at 0 and 90 deg. Therefore, at wake condition, particularly with a high plasma velocity, electrical breakdown fears occurring by a large difference in mitigation time between the absolute charging of the spacecraft conductive main body and the local charging of the insulating surface as mentioned above.

Consequently, the characteristics of time variations of ion sheath shape agree with t hose of neutralization current. Mitigation process of negative charging by plasma flow is expected to depend on plasma velocity and plasma number density, i.e., ion velocity and ion flux, and their dependence intensively changes with the attack angle of plasma flow to negatively charged surface by effect of inertia of ions.

Conclusions

In order to simply and clearly understand phenomena of spacecraft char ging and its mitigation by plasma flow , the equivalent electrical circuits between a spacecraft and the space plasma around it were made. The spacecraft was found to have the hazard of electrical breakdown between the spacecraft conductive main body and the insulating surface during the mitigation. In the space plasma simulator, the segmented ion collector in series with negatively charged condensers were exposed to argon plasma flows with changing plasma velocity under a constant plasma number density. The time variations of neutralization current and ion sheath shape were measured. The mitigation process was expected to depend on plasma velocity and plasma number density, i.e., ion velocity and ion flux, and their dependence intensively changed with the attack angle of plasma flow to the negatively charged surface by effect of inertia of ions. In cases that a negatively-charged insulating surface disappears from a plasma source; in the shade on view from a plasma source; i.e., at wake condition, particularly with a high plasma velocity, electrical breakdown fears occurring by a large difference in mitigation time between the absolute charging of the spacecraft conductive main body and the local charging of the insulating surface.

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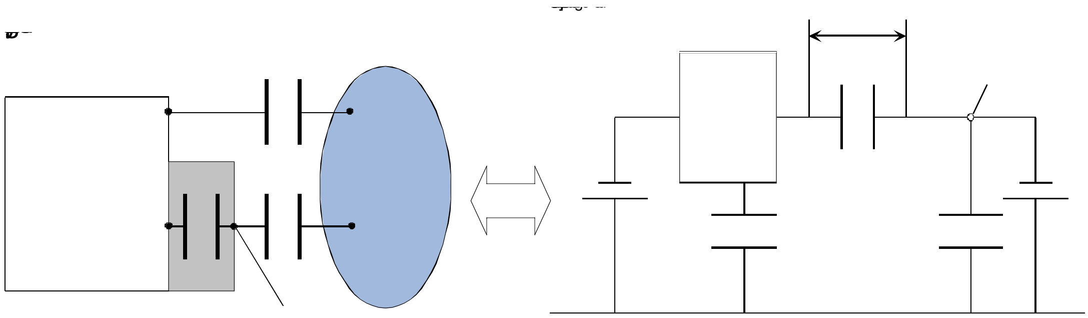
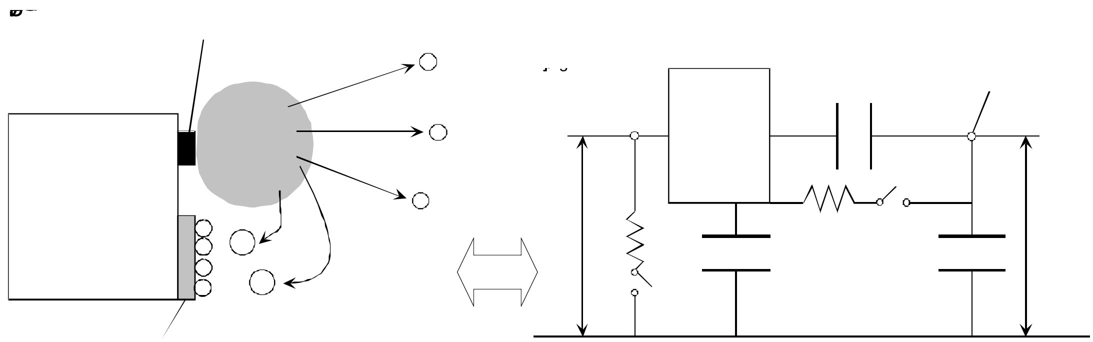


Fig.1 Equivalent electrical circuit between spacecraft and space plasma under negative charging.



(a) (b)

Fig.2 Feature of plasma contactor operation.
(a) Mitigation process of negative charging.
(b) Equivalent electrical circuit between spacecraft and space plasma.

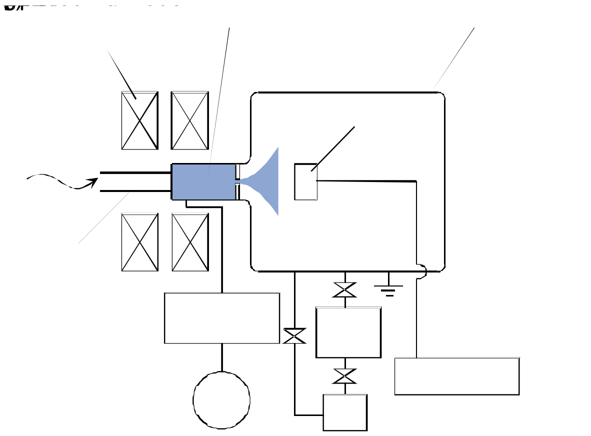


Fig.3 Experimental setup of mitigation of negative charging using space plasma simulator with electron cyclotron resonance plasma accelerator.

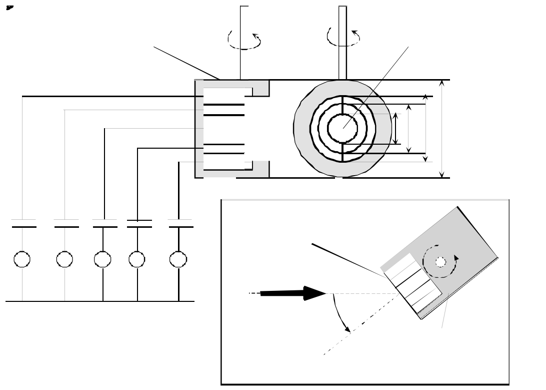
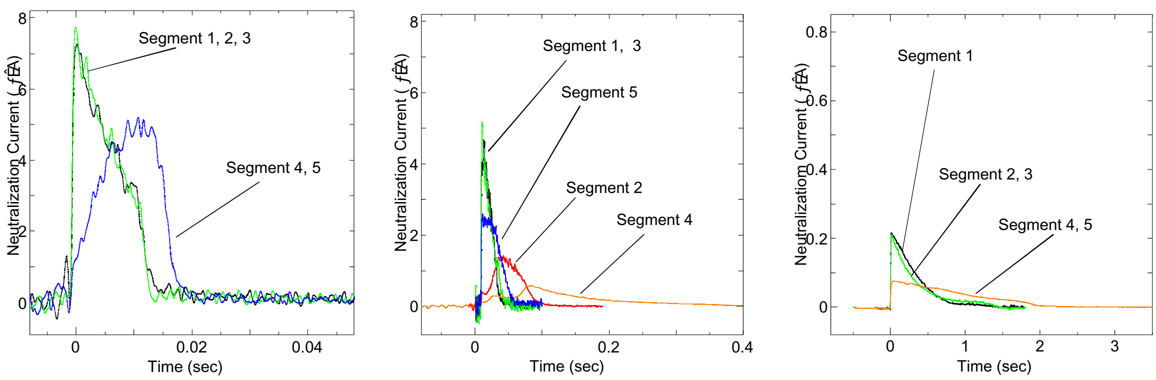


Fig.4 Spacecraft model with segmented ion collector.

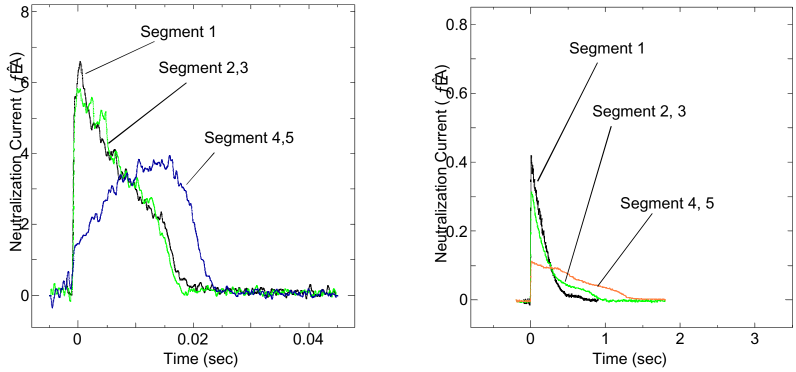
Table 1 Plasma characteristics of plasmas A and B generated by space plasma simulator.

	A	B
Plasma Density (m^{-3})	6.1?~10^{12}	6.1?~10^{12}
Electron Temperature (eV)	1.6	0.9
Ion Axial Current Density (mA/m^2)	16.4	10.7
Plasma Axial Velocity (km/s)	10.6	9.1



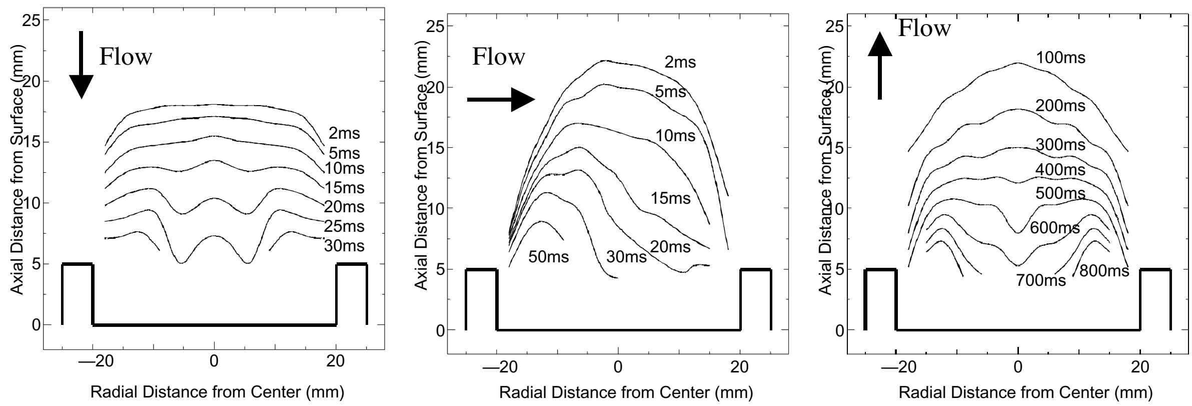
(a) (b) (c)

Fig.5 Time variations in neutralization current for segmented ion collector at attack angles of 0, 90 and 180 deg with plasma A. (a) 0 deg; (b) 90 deg; (c) 180 deg.



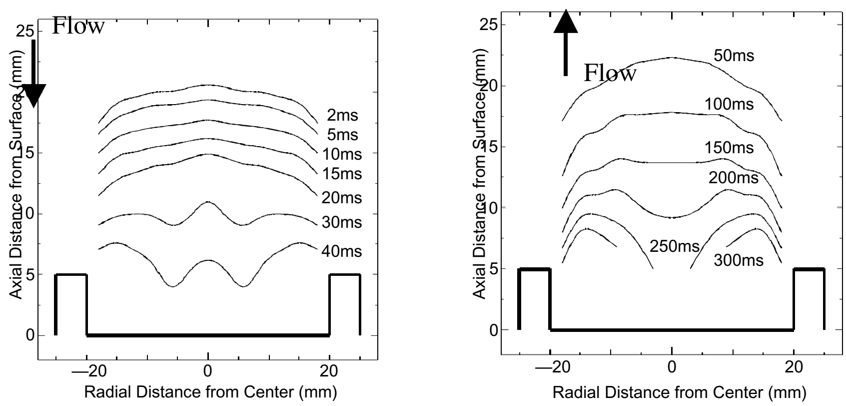
(a) (b)

Fig.6 Time variations in neutralization current for segmented ion collector at attack angles of 0 and 180 deg with plasma B. (a) 0 deg; (b) 180 deg.



(a) (b) (c)

Fig.7 Time variations of ion sheath shape around segmented ion collector at attack angles of 0, 90 and 180 deg with plasmas A. (a) 0 deg; (b) 90 deg; (c) 180 deg.



(a) (b)

Fig.8 Time variations of ion sheath shape around segmented ion collector at attack angles of 0 and 180 deg with plasmas B. (a) 0 deg; (b) 180 deg.