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Feasibility Study of an Active Plasma Experimental Platform in Japanese Experimental Module onboard the ISS

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Abstract

A Japanese experimental module (JEM) onboard the international space station (ISS) is directly exposed to space, hence if a plasma device is equiped to the exposed facility of JEM, many kinds of new plasma experiment become possible. However, there is a concern that by emiting plasmas, spacecraft charging and corresponding discharge will severely damage JEM and even ISS. We are proposing an experimental module for JEM in order to clarify such spacecraft-plasma interaction by operating a sub-scaled plasma-emitting floating body that can be deployed from JEM with some diagnostic equipments.

1. Introduction

Since 1960s, there were many space plasma experiments that actively emit charged particles in such forms as electron- or ion-beam from the satellites. Among them, spacecraft charging experiment by such projects as SCATHA, ATS-6, in which the first spacecraft charging, and even successful control by those plasma beams were completed.[1] However, it is regrettable these experiments require a whole spacecraft system that is developed for the specific experiments and available for only a short-term mission period. If a platform for plasma experiment is continuously executable in ISS, international space station, these opportunities will place a great impact on both scientific as well as engineering point of view. Based on such an idea, we are proposing a plasma experimental module for Japanese Experimental Module (JEM) ,that utilizes JEM's unique feature, whose experimental module is directly exposed to space,[2] accordingly, idealistic plasma experiment in semi-infinite space becomes possible. However, before realizing such a plasma experimental facility, strict assessment on the plasma environment around the plasma emitting device should be finished. Plasma experimental module onboard JEM, which we propose, is focused on such assessment, starting from a very small experiment on spacecraft to artificial plasma interaction. In this paper, the need and concept of the plasma experimental module for JEM are described with some initial test results, numerical schemes, and future plans. For the details of theoretical treatment of the problems, please refer to our previous paper.[3]

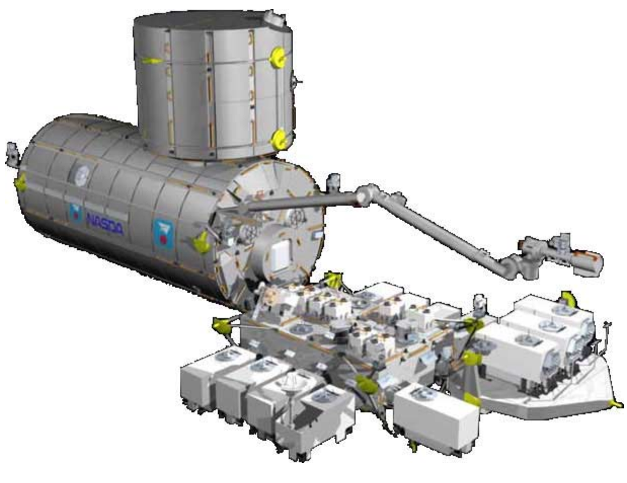


Fig. 1 Japanese Experimental Module (JEM) on ISS. Outside unit is also depicted on the right.(Ref.[2])

2. Problems Caused by Artificial Plasma Emission from Spacecraft

Before describing our proposal, let me consider how a spacecraft emitting artificial plasma changes its spacecraft potential and plasma environment around the spacecraft (Fig.2). Among several charge exchange mechanisms such as inflow- and outflow-charged-particles, and photoemission, current accompanied by active plasma emission is assumed very large and dominant in this paper. In ionosphere, a spacecraft is usually charged to a negative potential because of high energy electrons incident on the spacecraft. To prohibit charging and corresponding discharging, a plasma contactor is employed for the ISS. Because a floating body emitting electron tends to fix its potential to that of surrounding plasma, the plasma contactor can be used to adjust the spacecraft potential to the space potential. For this case depicted in the left figure in Fig.2-a, electrons will flow into a positively biased solar paddle, leading to electrical power loss. In contrast, if a spacecraft emits only ions, the spacecraft potential becomes a negative value around the beam potential. From the negatively biased spacecraft, the ions cannot leave the spacecraft, hence ions will reflect back to the spacecraft. This case corresponds a spacecraft with an ion engine system that has a disordered neutralizer.[4]

These cases of steady state charging are easy to consider. Some difficulties arise when a transient profile has to be considered. Transient change of spacecraft potential is expressed as,

$$CdV/dt=I_b+I_{etc} \qquad (1)$$

where V is spacecraft potential, I_b is artificially emitted current, I_{etc} is other current other than I_b. Here, C, capacitance of a spacecraft, is proportional to the size of the spacecraft, hence, if a small spacecraft ejects large current, V changes very quickly. For example, a $1m^3$ size satellite emitting 100mA/1.5kV ion beam, V changes 1.5 kV in less than 1 ms. For such a rapid potential change, ambient plasma cannot respond, hence the spacecraft potential will continue changing, leading to severe discharging between the spacecraft with a negative potential and ambient plasma, which could damage the spacecraft electrical system. For the case of ISS's plasma contactor is in disorder, the above mentioned discharge and corresponding damage of the ISS can occur. However, such interaction is difficult to predict. As shown in Fig.2-b, the phenomena will depend on: how far the emitted artificial plasma is extended when the discharge starts; or whether the discharge is restricted to only near the spacecraft surface, or large scale discharge involving ambient plasma is expected. These parameters will be determined by the spacecraft size, the scale of artificial plasma emission, and ambient plasma condition. Since artificially emitted plasmas are moving fast and the potential change and expansion is very rapid, a ground testing simulating the real plasma field, or even numerically prediction, is difficult. A mixture of dense near-field plasma and weak far-field plasma further complicates the problem. Our purpose of plasma experimental module for JEM is to scale down such interaction by changing C/I_b values.

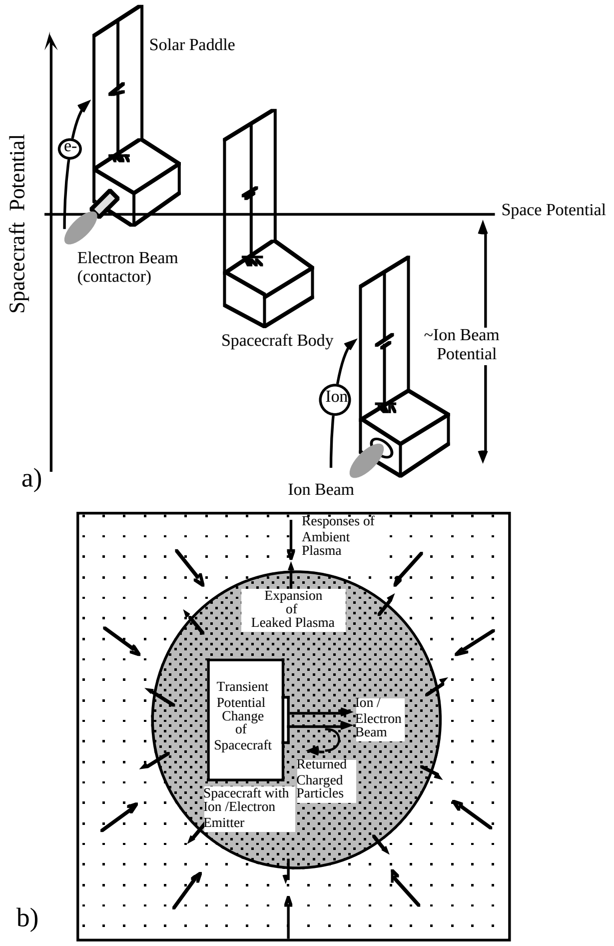


Fig. 2 Spacecraft charging by artificial plasma emission; a) predicted potentials for the case of ion beam emission, and for the case of electron emission, b) schematics of plasma evolution around spacecraft.

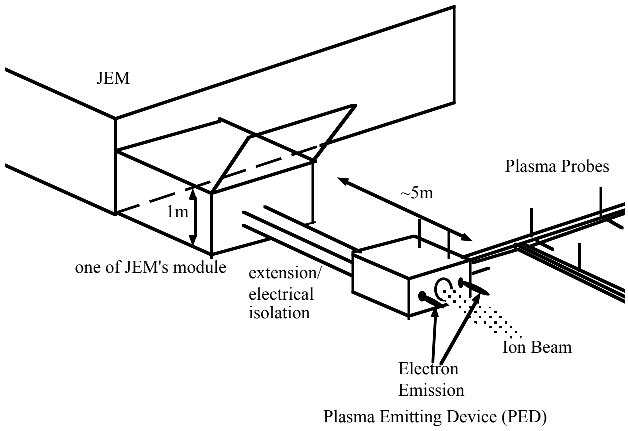


Fig. 3 Plasma experimental module for JEM.

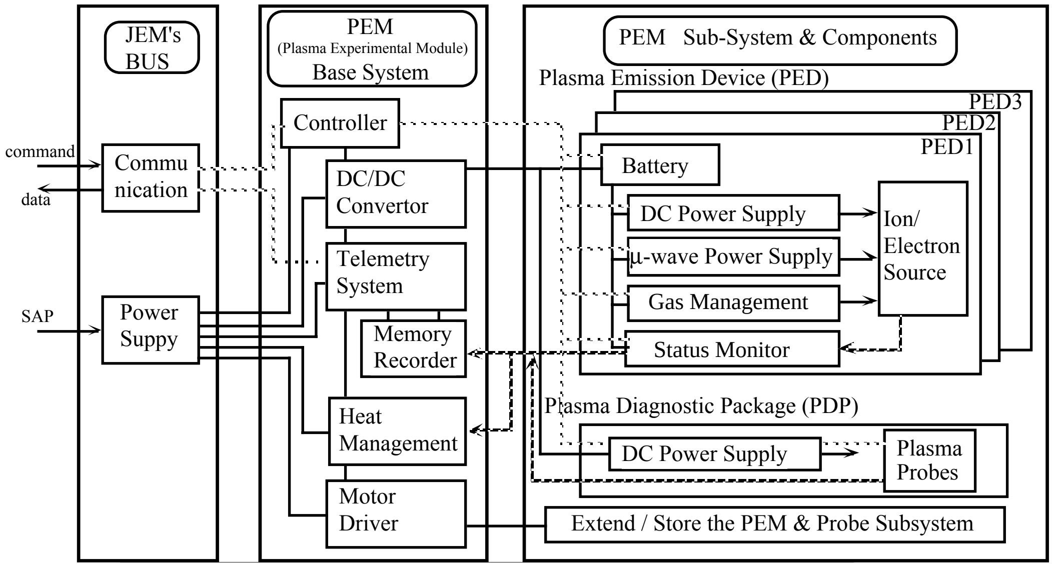


Fig.4 System diagram of plasma experimental module.

3. Concept of Plasma Experimental Module on JEM

Preliminary design of the plasma experiment module is as follows. It consists of an ion source and electron sources both are powered by C-band microwave as shown in Fig.3. Both sources can be operated separately, hence, by starting up or shutting down each of the sources, transient potential profile of both bodies as well as ambient plasma response can be evaluated, the latter of which will be conducted by a diagnostic package of the module using Langmuir probes. Also, by throttling the ion source and changing the bias voltage between the two electron sources, the setup easily operates in a plasma contactor mode, in which ambient plasma parameters are independently changed into a desired parameters by setting leaking plasma from the ion source; this is possible because the ion or the electron source can be easily controlled by changing microwave power. The first plasma experiment we are expecting is, as mentioned, a scaled down simulation of the charging process of ISS itself. In the experiment, the transient profile of the coupling among a scaled-down plasma contactor, ambient plasma, and the module's body, will be measured. To obtain such transient plasma, plasma emission device (PED), which consists of an ion source and two electron sources, is powered by a battery. As in Fig.5, when opening SW3, PED's battery is charged up. Then, SW1 and SW2 is opened, and power of the battery is supplied to power supplies of PED such as microwave amplifier, and DC power supplies, after a controller start the PED's operation. For a period the battery continues, we have a transient plasma evolution both from the ion source and the neutralizers (NEUT1 and NEUT2). The PED is one of subsystems of our plasma experimental module (PEM) as its block-diagram is shown in Fig.4. We have three ion/ electron sources (PED1 to PED3), whose batteries are powered by the base system of PEM. This base system not only supply the power to the PEM, but also controls a plasma diagnostic package (PDP) to qualify the transient plasma evolution around the spacecraft. Hence, the PEM will acquire data concerning the operation of PED, and plasma data near the PED. The PEM itself follows the standard guideline of the design of JEM; it is powered from JEM, it will receive and forward any command and acquired data via JEM's telemetry system directly connected to a ground station. The experimental module will be firstly placed in one of the JEM module in a size 1 m x 1.8 m x 1 m, then being deployed to the PED and the PDP as was depicted in Fig.3. The PEM and its subsystem hence contains a motor driver that extends/ stores the PEM for that purpose.

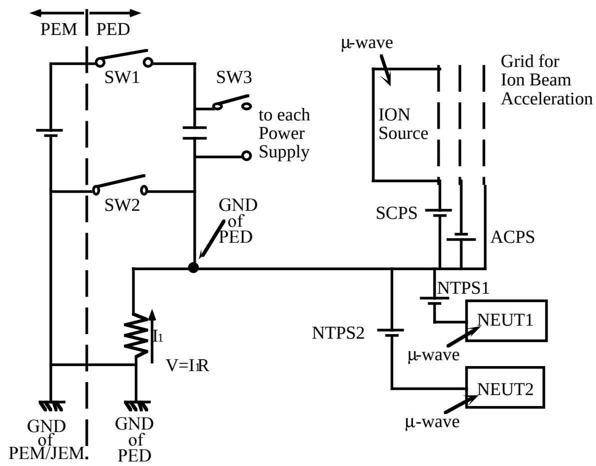


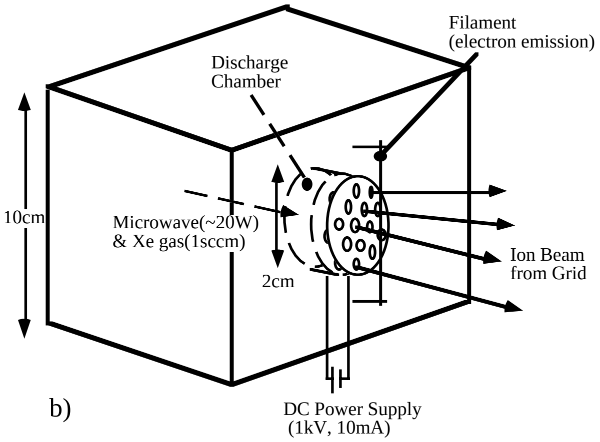
Fig. 5 Electrical connections of plasma experimental module

Note that as in Fig.5, PEDs are electrically isolated from PEM, hence a change of spacecraft potential is directly measured by obtaining I_1 in Fig.5. Such a floating system requires careful assessment whether the plasma emission affects the entire system or not. The below experimental device is being prepared to conduct such assessment prior to the specific design of the PEM.

4. Experimental Setups for Preliminary Ground Tests

Until now, we have completed preliminary evaluation of the low-power plasma emitter in a space chamber in the institute of space and astronautical science (ISAS). The plasma emitter shown in Fig.6-b is located in a conductor body (Fig.6-a), and operated in a total power of 30 W, including an ion optics that accelerates ions up to 1 kV beam, and a filament type neutralizer.

a)



b)

Fig. 6 Plasma emitting device; the first laboratory model.

The main body of the ion source features a very small discharge chamber of 18 mm inner diameter, which almost coincides with microwave neutralizer.[5] The Xe propellant pressure inside the chamber is controlled by a 4-mm-wide orifice diameter; with the conductance of the orifice below 1, the inner pressure is kept at 0.67 to 1.3 Pa for the Xe mass flow rate of 0.5 - 2.0 sccm. Microwave of 4.2 GHz is fed through a coaxial line followed by an L-shaped antenna, whose tip is inserted into a magnetic field formed by front- and back- yokes and block magnets. The strong magnetic field above the ECR condition enables easy startup of the neutralizer, so plasma density, hence the available ion current, can be increased just by increasing the microwave power for this type of discharge chamber. With its quick ignition feature, the microwave powered source is considered appropriate for transient study because there is no time delay after the switch on. However, at this time, only the ion source was powered by microwave. We are going to fabricated full-microwave powered PED in the near future.

To simulate floating spacecraft in space, the plasma emitter and the power supplying unit outside the space chamber are electrically isolated from the ground (Fig.7).

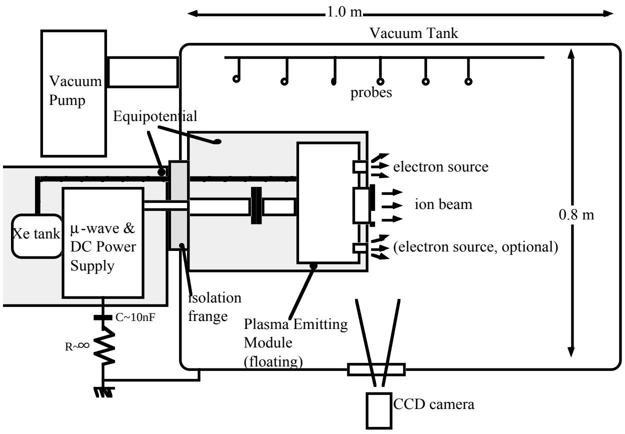


Fig. 7 Experimental setup for charging tests of floating body.

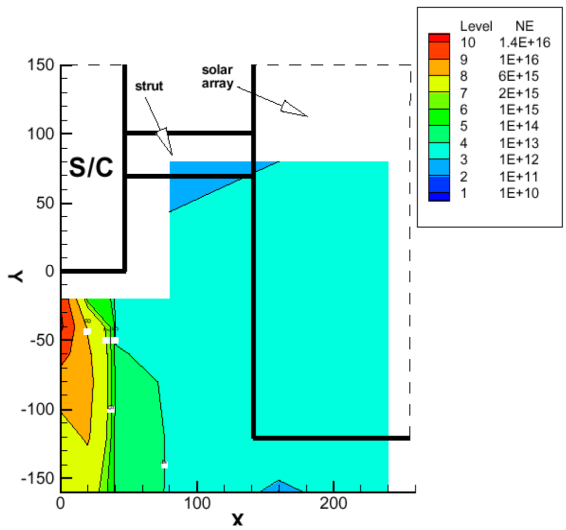


Fig. 8 Plasma density distribution around laboratory model; reproduced from ref.[4] ;unit=m^{-3}.

5. First Charging Experiment of Plasma-Emitting Floating Body in Vacuum Chamber

For the experimental configuration in Fig.7, steady plasmas with ion and electron emission was achieved. An example of plasma density distribution is depicted in Fig.8, and plasma parameters are summarized in Table.1. By scaling down the plasma source and the body size, the ratio between the size of the body and the Debye length was almost the same both for the real scale, $1m^3$ satellite, and for the simulated scaled-down model. This proves that such a scaling-down is effective to study the interaction between the spacecraft and the plasma emitter as far as steady plasma is concerned. In addition to these representative plasma emission, the data for some unusual operation was obtained; for example, when the neutralizer is switched off, the potential of the body dropped to a negative value around the beam potential, accompanied by a virtual cathode in front of the ion source. From the virtual anode, ions are reflected back to the body, which will suppress further charging by ion emission. This is why the ion emitting spacecraft stays at its beam potential. For steady operation including this unusual case, interactions are confined to the field only near the body. Thus if the module is located far from the JEM, no interaction is expected. However, there is a need to get an evidence of this fact for a module that we are going to design, in particular, for a transient plasma, that is not examined in the above experiment. Most of such cases can be checked in ground tests, but difficulties are associated when considering the effect of the vacuum chamber wall. The assessment hence requires a numerical technique that will bridge the ground test condition and the model for the JEM.[3]

As for transient plasma evolution, we have obtained only limited test cases. The result in Fig.9 shows potential profiles of the floating body; in Fig.9-a, while only ion beam is emitted and GND of the body is set to chamber's GND, the GND of the body was suddenly changed to floating. For the ion beam voltage 200 V, the potential of the body was reduced to -160 V, whose absolute value is close to the beam voltage. Also, characteristic time to reach its steady state is discussed. Follows the approximation of eq.(1), that is, $dt \sim CdV/I$=2e-9[F]*200[V]/4e-3[A]=100ms, which corresponds to characteristic time for charging. In Fig.9-b, after following the procedure in Fig.9-a, the neutralizer was switched on. The charging was stopped and the potential of the floating body was recovered to around 0 V. Transient changes of the above cases are, however, rather quiet cases because of a large time scale. This large time scale is a result of large capacitance between the PED and GND, as shown in Fig.7, which was inevitably inserted due to electrical connections between the PED and the power supply. For a rapid charging experiment to execute, we have to reduce this capacitance, and to increase the current emitted from the body. Such fast time scale experiment is the next step of our research.

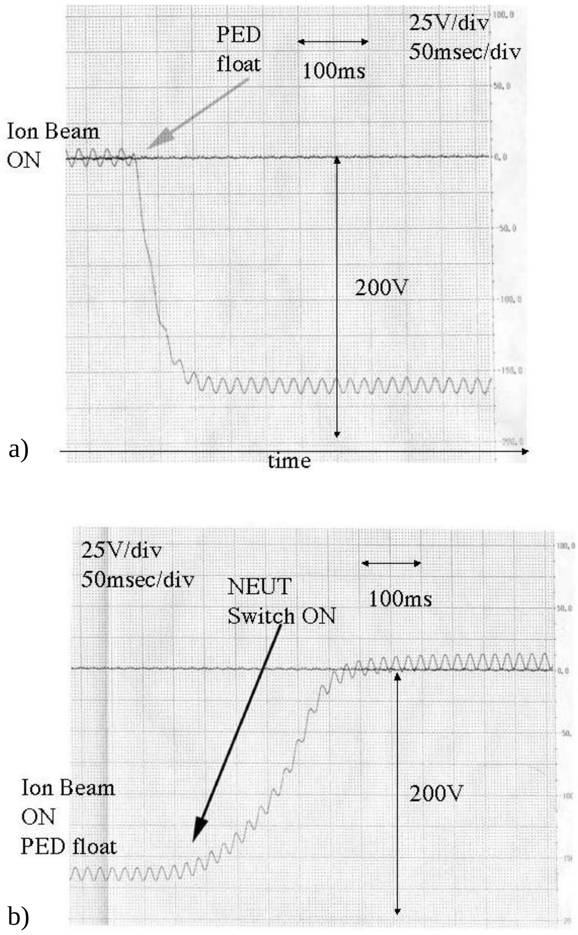


Fig. 9 Transient potential profiles of floating body; a) while only ion beam is emitted, the body was abruptly changed to floating; then in b), neutralizer is switched on.

Table 1. Plasma environment for laboratory model

	small plasma source	$1m^3$ satellite with ion thruster
Ion beam diam.	20mmϕ	100mmϕ
Ion beam current	8mA	140mA
Ion beam current density	$18Am^{-2}s^{-1}$	$25Am^{-2}s^{-1}$
Ambient Plasma Density	$3e14m^{-3}$	$1e12m^{-3}$
Beam Plasma Density	$1e16m^{-3}$	$2e15m^{-3}$
Ambient Debye length (ℓ_{Denv})	1mm	16mm
Beam Debye length (ℓ_{Dbeam})	0.16mm	0.37mm
Representative length (L)	10cm	1m
L/ℓ_{Denv}	100	62.5
L/ℓ_{Dbeam}	625	2700
Capacitance	2nF	10pF

In the next step, transient charging phenomena of the body were experimentally studied for various ion beam currents and ion beam voltages. The currents and the voltages of the ion beam can be easily controlled by changing the acceleration voltage of the small ion source. Also, by inserting an additional capacitance to the circuit, total capacitance of the body, hence the time scale of charging, will be selected for each condition (i.e., a combination of an ion beam current and a voltage) following the equation below.

$$I=I_b=CdV/dt \qquad (2)$$

In Fig.10, voltage changes at the time that the ion beam emitting body being connected to a ground was suddenly isolated, and the beam emitting body becomes “floating body”. I/C=dV/dt line in Fig.10 corresponds to the case the charging time scale is strictly determined by (2), however, for larger I/C values, the values of dV/dt deviate from (2), which means transient responses of the floating body potential is complicated than expected. In contrast to these transient responses, charging voltages at their steady states are not affected by the parameters, I and C, as was shown in Fig.11. The charging voltages are slightly different from the ion beam voltages due to the secondary electron emission by ion impacts.

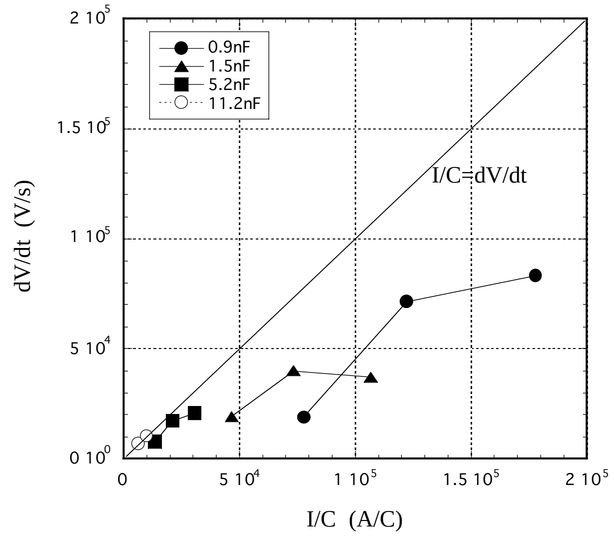


Fig.10 Transient responses of the floating body potential when ion beam is exhausted from the body; experimental results of the ground test; total capacitance is 0.9 nF, 1.5 nF, 5.2 nF, and 11.2 nF; ion beam voltage is 300 to 580 V.

It is important to discuss how the above transient charging tests in the ground chamber will apply to a realistic spacecraft. To simulate spacecraft charging in space, in addition to the parameters in Table 1 (body size, the ion beam current, the ion beam voltage, the ambient plasma), the I/C parameter should be carefully chosen. Since the capacitance of the spacecraft is roughly approximated by a conductor body with known radius, the relation between the spacecraft size and the capacitance is easily obtained. Then, the I/C is determined if the beam current I is available. The beam current I will depend on the condition what kind of plasma device is operated in what power level. For example, the ISS employs 10A-class plasma contactors, while many commercial satellites are equipped with 0.1 to 0.5 A-class ion thrusters for north-south station keeping. In Fig.12, the I/C parameters are plotted against spacecraft size for different beam current levels, with the data of some typical spacecrafts. The time scales currently achieved are very slow, hence we are planning to make a device that can simulate charging phenomena which occurs in a very short time scale, two orders of magnitude smaller than our current experiment. Such a fast charging will be discussed in the future with a compact but large beam current source.

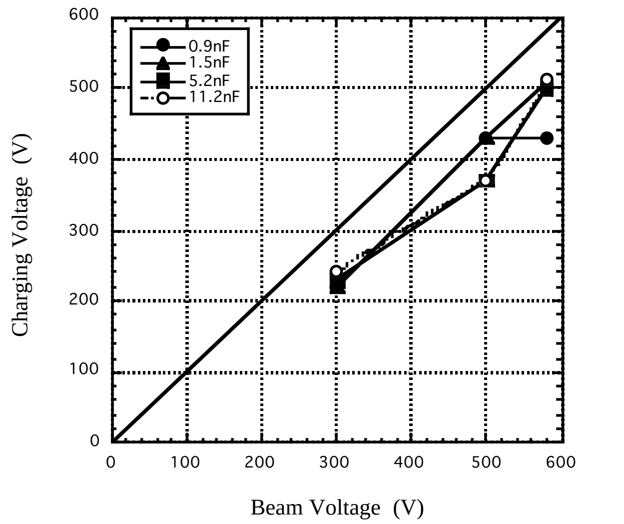


Fig.11 Charging voltage at steady states; experimental results of the ground test.

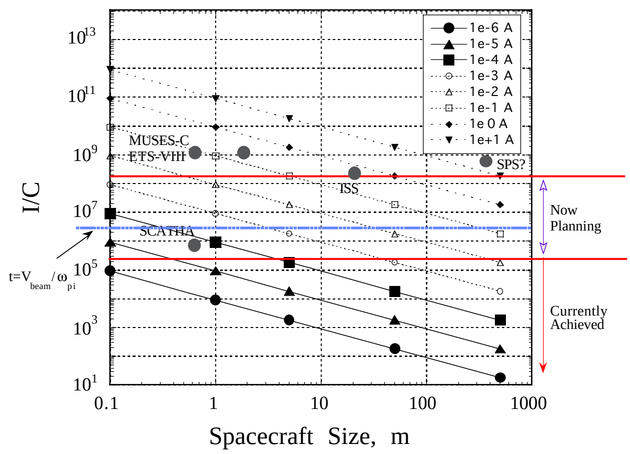


Fig.12 I/C parameters of both ground tests and realistic spacecrafts; I/C of realistic spacecrafts are approximately evaluated from $C=4\pi\varepsilon_0 a$, which is the capacitance of a floating conductor with radius a in infinate space.

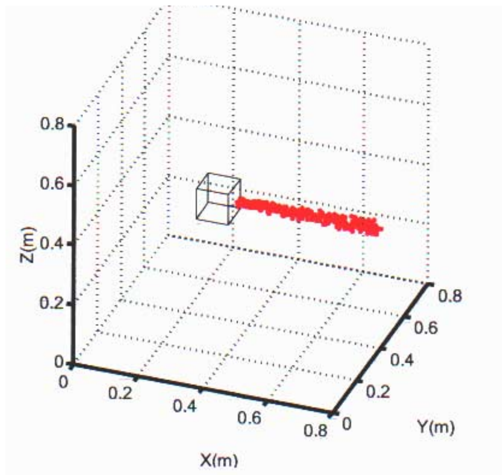
6.Numerial Simulation

Aside from the experimental works, numerical evaluation of the spacecraft charging is very important. One reason is that the spacecraft charging always occurs in an infinite space, that is very difficult to realize in a limited space inside the space chamber on the ground. In this sense, a numerical code is a versatile tool for the evaluation of the spacecraft charging. Another reason is that for the ground testing, due to the effect of electrical connections accompanied by additional capacitances to the circuit, the charging tests cannot obtain a very fast time scale as in space even if the current of the beam is increased. As a result, only some similarity rules on spacecraft charging can be achieved from the ground tests, but a realistic situation should be predicted by the numerical method. Both the experiments and the simulations hence have different roles, therefore we need both tools to assess the transient phenomena of the spacecraft charging.

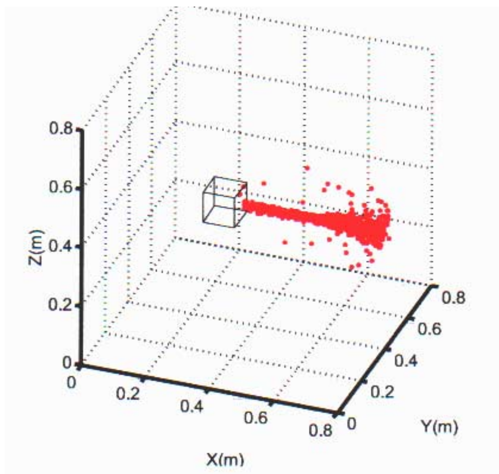
A numerical code we adopted here is an electrostatic code that neglects the effect of the magnetic field.[6] Using this code, time-dependent motions of ions and electrons, both of which experience Coulomb collisions, are accurately calculated. Also, charge exchange collisions between neutrals and the charge particles can be incorporated because the evolution of a slow plasma produced by the charge exchange collisions near the plasma source should be also considered to evaluate the interaction between the spacecraft and the ambient artificial plasma field. Figure 12 shows preliminary simulation results of one of the charging experiment in the space chamber that was already described in this paper. In Fig.12, near the center of the space chamber, a floating body starts emitting an ion beam, which is just leaving the floating body at an early stage of the charging experiment. Then the potential of the body decreases as in Fig.13, because the floating body ejects positively charged particles. The ions leaving the floating body then slowdowns due to the potential slope, and a potential hill as in Fig.14 is formed near the beam emitter where slow ions reside and accordingly the space potential in front of the beam emitter increases. The potential of the body continues decreasing, until most of the emitted ions will be reflected back to the floating body, forming a current loop. Lastly, the potential of the body will reach its steady state. The simulation code successfully reveals the movements of charged particles, and the process of the transient charging of the body. Using this code, variety of transient charging phenomena can be investigated. Also, we are now incorporating the effect of insulators to evaluate realistic spacecraft to plasma interaction.

7. Summary

We proposed a plasma experimental module that is targeting at and designed for JEM's outside modules. Utilizing JEM's unique feature, that is, a compact space experiment is directly exposed to space, many plasma experiments in infinite space become possible. Future evolution includes high powered electric propulsion, the interaction of SPS and plasma, or to demonstrate difficult physical and engineering problem like mini-magnetosphere plasma propulsion. However, before going into a full-scaled experiment, an assessment is required for the interaction between manned spacecraft, JEM, and active plasma experimental module (PEM). Because we don't know the detailed scaling of such interactions, our first mission of the PEM is decided as a scaled-down demonstration of the interaction between emitted plasma and the PEM. This module for demonstration includes both plasma generator and a plasma diagnostic module, which can be deployed as one of JEM's module. The main purpose of the scaled-down module is to reveal transient plasma evolution and transient potential change of the PEM, that will lead to severe discharging, hence hazardous for JEM. An operational limit below which the plasma system is safely used should be surveyed and decided in the future studies.

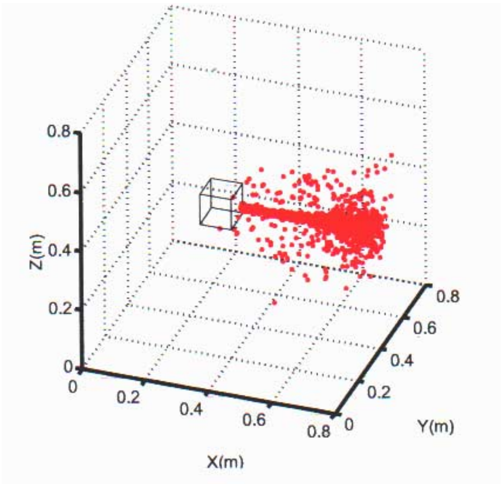


a) t=0.04ms



b) t=0.056ms

Fig.12 Time evolution of ion distribution obtained by electrostatic code; at t=0, ion beam is emitted from the floating body located near the center of the space chamber made of conductor; I_b=0.07mA, V=300V.



c) t=5.8ms
Fig.12 (cont.)

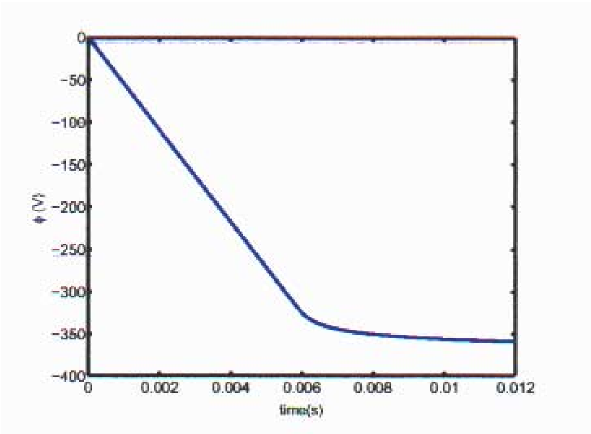


Fig.13 Time history of the floating body potential; this result corresponds to the numerical simulation in Fig.12.

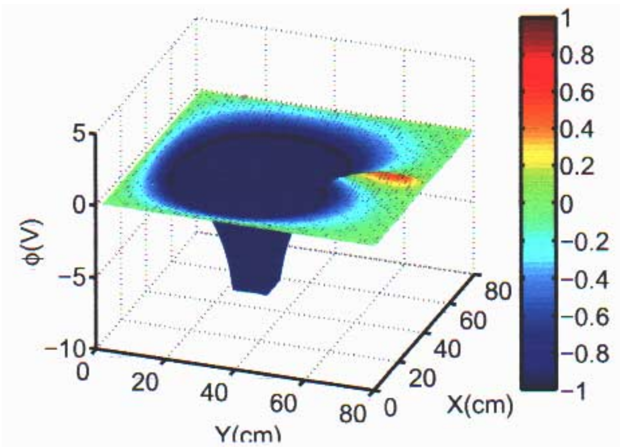


Fig.14 Space potential distribution at t=80µs ; this result corresponds to the numerical simulation in Fig.12.

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