PIC Simulations of Spacecraft Charging and Its Neutralization Process by Plasma Emission*

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We examined the spacecraft charging and its neutralization using dense plasma emission by performing PIC (Particle-In-Cell) simulations. In a two-dimensional simulation space, a conducting body representing a spacecraft is immersed in magnetized plasma. In isothermal plasma such as in the ionosphere, the body becomes negatively charged with respect to the space potential due to large thermal velocity of electrons. In order to neutralize the negative charging of the body, we continuously emit dense plasma from the body which is assumed to be created by a plasma contactor. We particularly examined the electron/ion flux to the charged body and the corresponding potential variation. It is shown that the negatively charged body is neutralized mainly by the enhancement of ion flux of the emitted plasma. As the potential approaches the space potential, the ion current to the body decreases and the net current to the body becomes zero. In the transient process of the charge neutralization, we could see very turbulent current variation at the emitted plasma cloud region, which may cause electromagnetic perturbation in the vicinity of the body.

Introduction

As demonstrated in the construction of International Space Station (ISS), human activities in space have been increasing and it becomes very important to understand interactions between spacecraft and the space plasma environment quantitatively (e.g. [1], [2]). When a non-plasma body such as a spacecraft is immersed in plasmas, it is generally charged due to incoming electron and ion fluxes to the body. When the incoming electron and ion fluxes become equal and the total current to the body becomes zero, the body obtains a floating potential which is a key factor of spacecraft. The floating potential is normally negative with respect to the space potential in the isothermal plasma because electron thermal velocity is much larger than that of ions. In such a situation, electrons in the vicinity of the body are evacuated and an ion sheath is created at the spacecraft surface. When photoelectron or secondary electron emissions are considered, the floating potential is raised and sometimes becomes positive with respect to the space potential. In addition, we will utilize high voltage power in future spacecraft, which requires high power generation and transmission that can be typically larger than 100 volts. The potential gap between spacecraft and the ambient plasma can cause serious environmental interaction such as spacecraft anomalies due to arcing, sputtering, and electromagnetic interference. In this aspect, spacecraft charging and its control is one of the most significant issues to be investigated from a view point of the spacecraft-environment interaction. One of the practical methods to control the spacecraft potential is the use of plasma contactor (e.g. [3] [4] [5] [6]). Plasma contactor is a plasma producing device which provides low-impedance electrical connections between spacecraft surfaces and space plasma. In ISS it is also utilized to control the voltage between the spacecraft and local plasma. The characteristics of

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plasma contactor have been intensively investigated from a technical point of view. However, the transient processes of the charge neutralization and the effect on the environment have not been fully understood from a scientific point of view.

The purpose of the current study is to examine the basic process of the spacecraft charging and potential control by performing PIC simulations. To control the spacecraft potential, we emit dense plasma from a spacecraft into the ambient plasma. We particularly focused on the transient processes of the charge neutralization and the effect on the plasma environment.

Simulation Model

In the current simulations, we use a two-and-half-dimensional full electromagnetic particle code called KEMPO [7]. In KEMPO, we solve Maxwell's equations and equations of motion of electrons and ions. To advance the electromagnetic field with Maxwell's equations in the simulation space, we adopted the FDTD (Finite-Difference Time-Domain) method. Plasma dynamics and associated plasma current are solved by adopting the PIC (Particle-In-Cell) method [8].

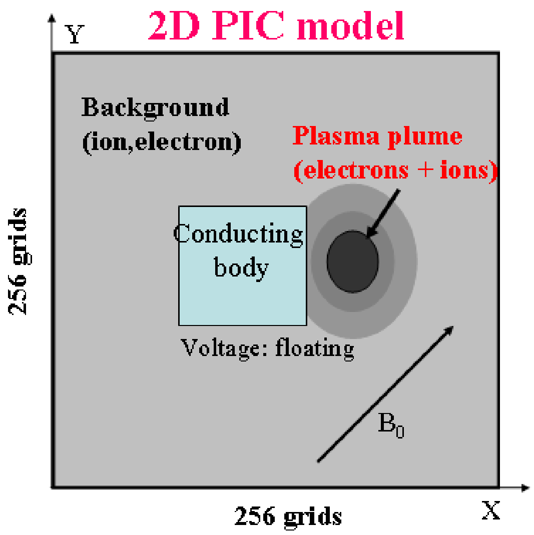

Figure 1 – 2D PIC simulation model

Figure 1 shows a two-dimensional simulation model used in the current studies. We have a conducting body with dimension of $10\lambda_D x 40\lambda_D$ immersed in a magnetized and isothermal plasma environment where λ_D denotes the Debye lenght. We assumed no photoelectrons or secondary electrons emitted from the body. In the ambient plasma, the ratio between the plasma frequency Π_e and the electron cyclotron frequency Ω_e is 4. The static magnetic field Bo points at 45 degrees with respect to the horizontal axis. We started a simulation with no plasma emission from the body in order for the body to achieve a floating potential which should be negative because the electron thermal velocity is much larger than that of ions in the isothermal plasma condition. Once the floating potential is obtained, we started emitting dense plasma at the area of $1\lambda_D x 6\lambda_D$ just in front of one side of the conducting body with the emission rate corresponding to approximately $240n_0$ per unit time in simulation where n_0 denotes the ambient plasma density.

Body Potential and Flux to the Body

Figure 2 depicts the time evolutions of the body potential, total flux and flux of each plasma component. The potential energy and flux are normalized to the thermal kinetic energy and the ambient thermal flux crossing a unit length, respectively. As shown in the top panel, the body potential starting at zero value decreases in time and reaches a floating potential around $-4e\phi/kT_e$ at the time approximately corresponding to $2T_{pe}$ with oscillation at the UHR frequency where T_{pe} denotes one time period of oscillation at the plasma frequency. As shown in the second and third panels, the initial drop of the potential is due to incoming flux of electrons in the vicinity of the body. Since the electron thermal velocity is larger than that of ion, electron flux becomes dominant at the beginning. Around the time of $2T_{pe}$, the total flux becomes almost zero, which implies the incoming electron and ion flux balances each other. At the time of $6.5T_{pe}$ we start emitting dense plasma from one side of the body and we can see a drastic change of potential. As soon as the plasma emission starts, the potential abruptly drops down to approximately $-6e\phi/kT_e$, which is due to

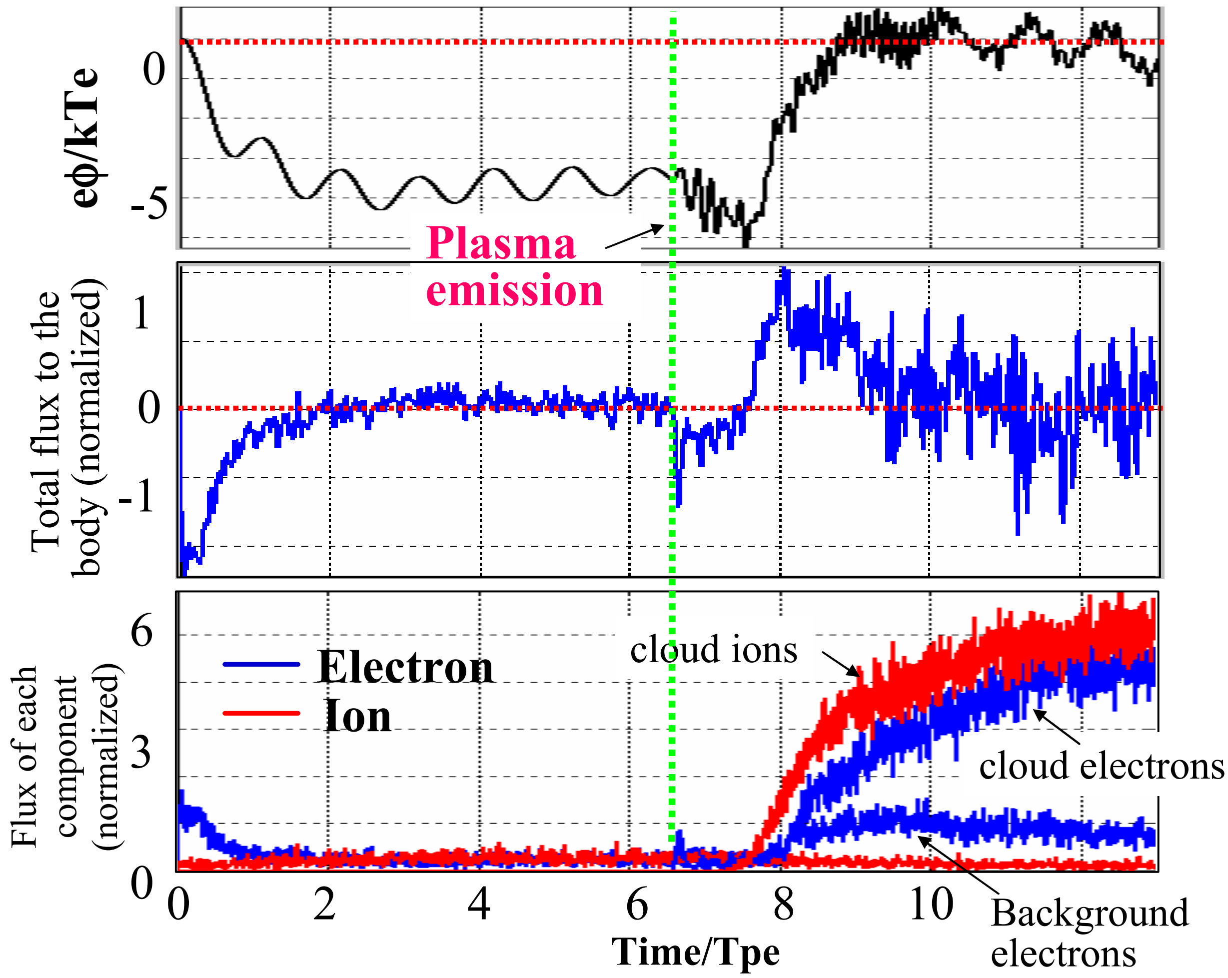

Figure 2 – Temporal evolution of the body potential (top), total flux to the body (middle),and flux of each plasma component to the body (bottom). The physical quantities in the panels are normalized.

excess electron flux returning to the body as shown in the second panel. In the process of continuous emission of dense plasma, however, emitted ions start diffusing and being collected to the negatively charged body after the time corresponding to $7T_{pe}$. As shown in the third panel, the flux of emitted ions to the body increases in time and it eventually overcomes the electron flux as shown in the total flux. Corresponding to this flux variation, the body potential keeps increasing till the total flux again approaches zero around the time of $9T_{pe}$. As in the third panel, although the flux of emitted plasma to the body still increases in time, the total flux reaches a steady state.

Electron Current Model

Plasma contactor can be used as an electron beam emitter to evacuate negative charges from space system efficiently. In this section, we examine the charge neutralization process in the electron beam emission model, which is referred to as electron current model. The basic parameters used in the simulation are the same as the previous stationary plasma cloud model. To realize the electron beam, we provided a certain drift velocity to the emitted electrons while emitted ions are stationary as in the previous model. This situation corresponds to the electron acceleration with a keeper in a hollow cathode.

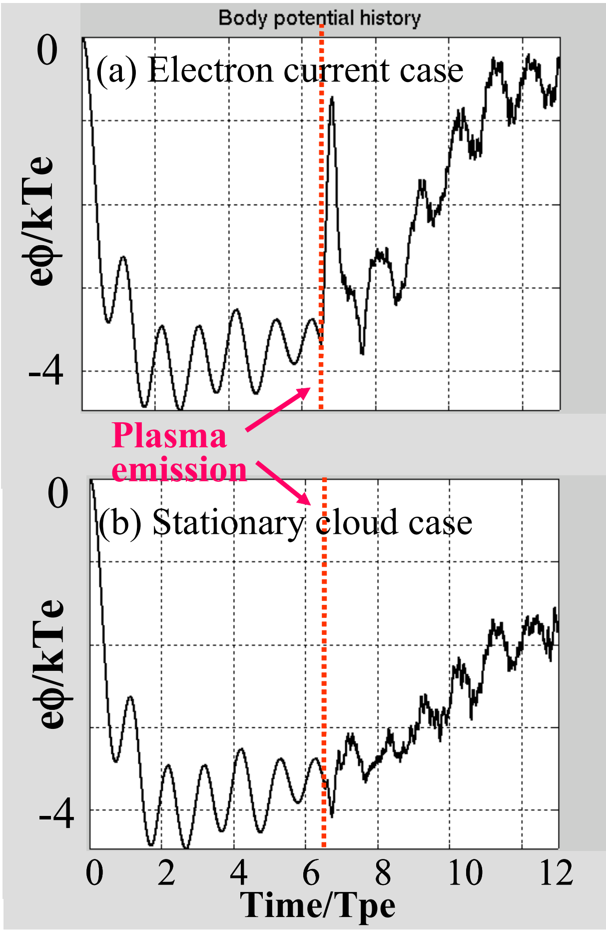

Figure 3 – Temporal variation of the body potential for (a) electron current model and (b) stationary plasma cloud model.

The upper panel in Figure 3 shows temporal evolution of body potential for the electron current model. In comparison, we show the potential evolution for the stationary cloud model in the lower panel. As in the previous simulations, we start with no plasma emission and wait until the body reaches a floating potential which is negative. At the time of $6.5T_{pe}$ we start emitting dense plasma from one side of the body. In the figure, two major differences are found between the two panels after the time of $6.5T_{pe}$. One is the time period which takes the body to recover to the space potential from the negative floating potential. As shown in the upper panel, the charge neutralization is quicker in the electron current model than the stationary plasma model. The other difference found in the two panels is impulsive change of the body potential at the beginning of the plasma emission phase, which is shown in the upper panel just after the time of $6.5T_{pe}$.

Figure 4 shows the temporal variation of flux of each plasma component in the middle panel and two snapshots of electrostatic potential in the bottom panel. Panel (a) in Figure 5 shows the schematic illustration which qualitatively explains the initial situation just after the plasma emission. Since there is a relative velocity between the emitted electrons and ions, charge separation occurs near the body. Namely heavy ions are stationary and remain in the vicinity of the body while electrons escape from the body. In such a situation, as shown in the first snapshot of the potential in Figure 4, a large potential drop is created, causing an intense electric field pointing from the stationary ion cloud. Since the potential at the ion cloud becomes abruptly high due to the charge

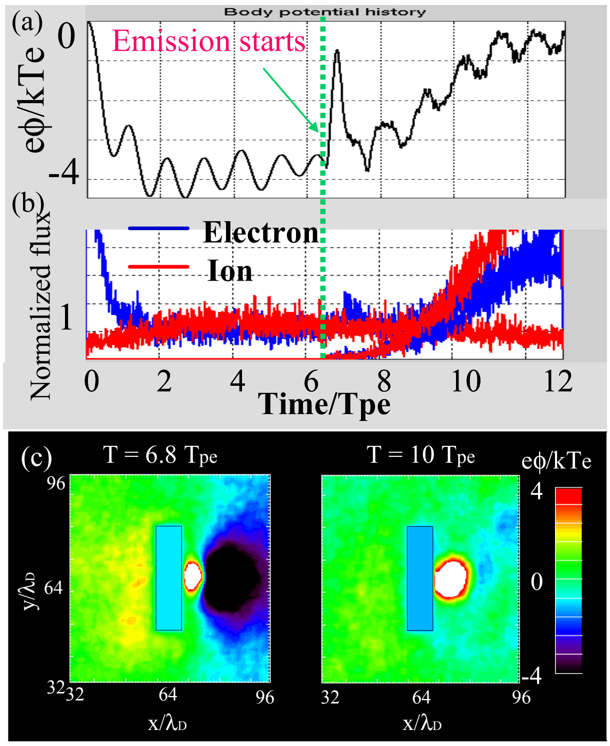

Figure 4 – Temporal evolution of the body potential (top), flux of each component to the body, and (c) snapshots of potential profile in the x-y plane. Rectangular in the potential profile represents the location of the conducting body.

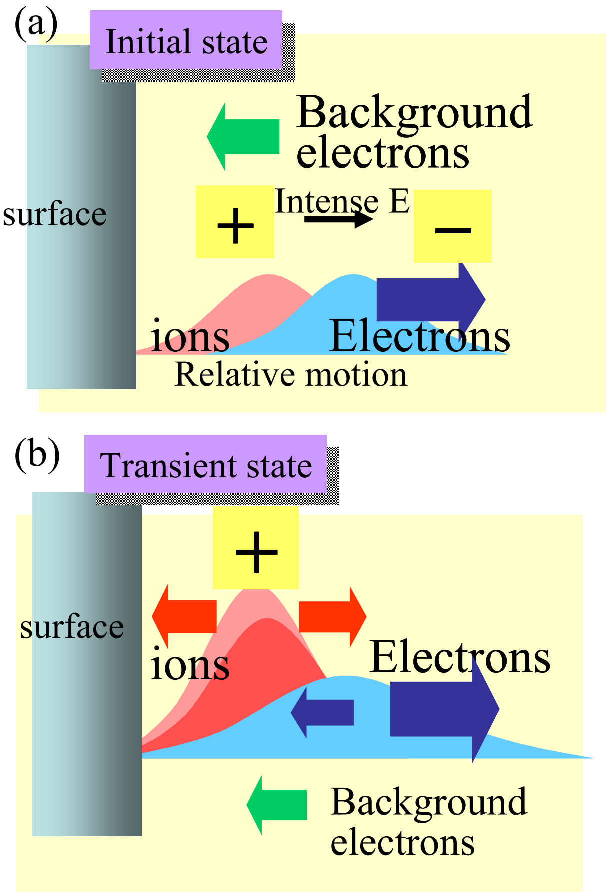

Figure 5 – Schematic illustrations showing (a) initial and (b) transient states of emitted plasma distribution in the electron current model.

separation, the body potential is also boosted up approximately to the space potential as shown in the top panel of Figure 4 showing the potential variation. Then the stationary ions emitted from the body start to attract background electrons near the body and the accumulation of negative charges to the body causes the drop of the potential again to the negative floating potential. The transient flux of background electrons is observed in the time interval approximately from 7 to 8 T_{pe} shown in the middle panel. As we continue to emit dense plasma with the electron drift velocity, the density of emitted ions, which is stationary near the body, increases while electrons move away. As shown in panel (b) of Figure 5 this situation causes potential structure much more positive than that observed in the stationary plasma model in the vicinity of the body. Although some of background as well as emitted electrons are attracted to the body, the ions also diffuse and are attracted to the negatively charged body. In terms of flux to the body, it turns out that the ion flux exceeds the total electron flux. Since the ion flux in the electron current model is much larger than in the stationary plasma cloud model, the charge neutralization takes place quickly in the present case.

Current Variation at the Plasma Cloud Region

Figure 6 shows spatial profiles of current density near the body after the charge neutralization. It is clearly shown that the current profile becomes complex and asymmetry because of the presence of the static magnetic field Bo pointing at 45 degrees up to the horizontal axis. It should be noted that a sort of current loop is formed elongated along Bo. This asymmetric current profile should be closely related to the dynamics of the plasma plume formed in the vicinity of the body. This current loop can be a source of electromagnetic perturbation. We have been analyzing the current loop and associated field perturbation in the charge neutralization process. In addition to the electromagnetic perturbation due to the current variation, because of the relative motion between electrons and ions, current-driven type plasma instability can be possible which causes

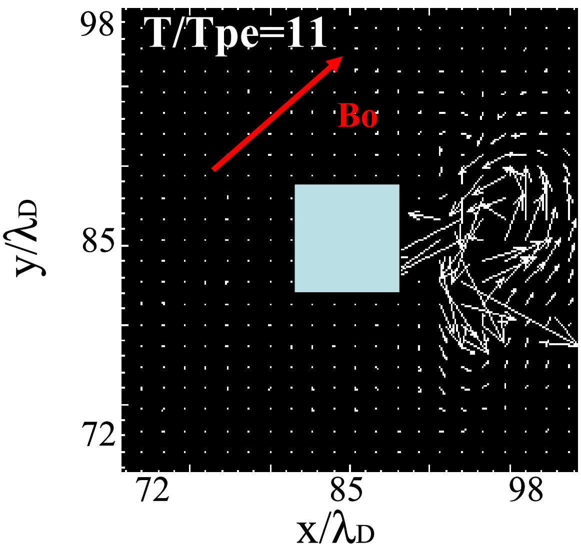

Figure 6 – Snapshot of current density profiles. Each arrow represents current density at each grid point in the vicinity of the body.

electrostatic wave excitation. The instability depends on the beam density as well as the electron drift velocity. The analysis of the electrostatic wave excitation associated with the plasma emission is left as a future work.

Conclusions

We performed PIC simulations to examine the basic process of the spacecraft charging and its neutralization process by a dense plasma emission from spacecraft which has a negative floating potential. We particularly examined the electron /ion flux to the wall and corresponding potential variation. It is shown that the negatively charged wall is neutralized mainly by the enhancement of ion flux of the emitted plasma. As the potential approaches the space potential, the ion current to the wall decreases and a current-balance state is achieved with zero net current to the wall. By performing simulations with electron current model in which we provide a drift velocity to the electrons only, we could confirm that the potential recovery from the negative floating value to the space potential is much quicker than in the stationary plasma cloud model. Spatial distribution of current density is complex due to the presence of the static magnetic field. This current distribution can cause electromagnetic perturbation in the charge neutralization process, which we have been analyzing in detail.

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