PIC Simulations of the Space Environment Effects of Plasma Contactor

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Abstract

We performed PIC simulations to examine the neutralization process of spacecraft charging in a situation where a dense plasma cloud is emitted from a spacecraft. In particular, we focused on the transient process in terms of flux to the spacecraft and the potential variation. We paid our attention to two specific situations: one is a case of electron collection to a high potential satellite in the electrodynamic tether system and the other is a case of potential control for a negative floating potential body. In the first case, a high-potential biased satellite and a dense plasma cloud in its vicinity are initially set in an ambient plasma in a one-dimensional cylindrical simulation model. The simulation results show that, as analyzed in the previous studies, electron flux to the high potential wall is enhanced due to the acceleration of the ambient electrons by intense electric field induced at the boundary between the plasma cloud and the ambient plasma. The spatial profiles of electron acceleration and corresponding electric field are studied. It is basically shown that a dense plasma cloud can provide a low-impedance electrical connection between spacecraft and ambient plasma. In the second case, in order to examine the charge neutralization process of a floating potential body, we emit a dense plasma from a spacecraft which achieved 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.

Introduction

In the solar-terrestrial physics, " space weather " has become an important key phrase. In the space weather research, in-situ and ground-based observations as well as theoretical analysis have been intensively conducted to understand various phenomena occurring in the solar-terrestrial environment in association with the solar activity.

Meanwhile, human activities in space have been increasing as demonstrated in the construction of International Space Station (ISS). In such a situation, quantitative information regarding the variation of spacecraft environment due to the change of the solar activity and its influence on spacecraft is required in the engineering aspect. In particular, we are anxious to evaluate the spacecraft charging effect which may cause satellite anomalies due to arcing, sputtering, and electromagnetic interference[1].

In order to understand the spacecraft charging, we need to examine the spacecraft-plasma interactions by using data obtained in the space weather research as input parameters. In consequence of the space-environment interaction, the local plasma environment may be also modified. In this sense, the spacecraft-environment interaction and the space weather is closely related to each other.

In the present study, we focus on the transient process of spacecraft charging and its neutralization with a dense plasma emission from a plasma contactor [2-8]by performing PIC simulations. Plasma contactor is a plasma producing device which provides low-impedance electrical connections between spacecraft surfaces and a space plasma. In ISS it is also utilized to control the voltage between the spacecraft and local plasma. The characteristics of 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. Since the associated phenomena are closely related to the kinetic effect of electrons and ions of emitted plasma plume as well as the ambient plasma, we used PIC model in the numerical analysis which also enables us to examine the transient process of the charge neutralization. In the simulations, we adopted two specific situations: one is a case of electron collection to a high potential satellite in the electrodynamic tether system and the other is a case of potential control for a negative floating potential body. In both case, we examine the basic function of dense plasma cloud placed near spacecraft wall in the charge neutralization process of spacecraft. In the present paper, we report some of the preliminary results obtained in the simulations.

Simulation of electron collection to a high potential satellite

In order to understand that a dense plasma can provide a low-impedance electrical connection between a spacecraft and ambient plasma, we performed a one-dimensional PIC simulation. The simulation model we adopted is schematically illustrated in Figure 1. In a cylindrical coordinate, we set a conducting body with a fixed potential of $e\Phi/kT_e=12.5$ in the center and a dense and isothermal plasma cloud with a Gaussian distribution in its vicinity in an ambient plasma. For simplicity, we assumed no static magnetic field or relative motion between the body and the ambient plasma. In Figure 2, we show the time evolution of electron and ion flux to the high potential wall. At the early stage of the simulation, some of the cloud electrons located in the very vicinity of the satellite wall are mainly collected with a large flux value because electrons have much larger thermal velocity than ions. After this transient response, the incoming flux of the cloud electrons decreases and the flux of the ambient electrons start increasing with a large oscillation at a high frequency. The average flux is more than the double of that for the no-cloud case which is shown in green line in the figure. This result ensures that the plasma cloud can become a low-impedance electrical connection between the high potential wall and the ambient plasma. The high frequency of the electron flux approximately corresponds to the plasma frequency of the dense cloud. It should be noted that the flux of the ambient and cloud compensate for each other. Namely, in the temporal flux variation, maximum peaks of the ambient flux correspond to minimum peaks of the cloud flux and vice versa.

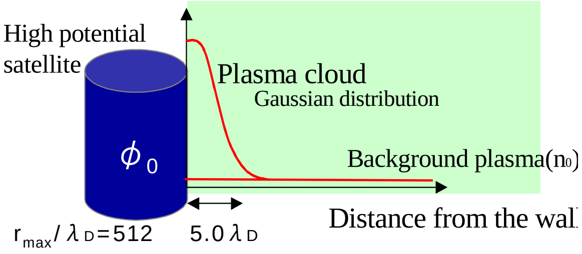

Fig. 1: 1D simulation model

Figure 3 shows snapshots of spatial distribution for the ambient and cloud electrons in v_r velocity space, the electric field, and potential where v_r. denotes the radial velocity from the spacecraft. As in the top panel, some of the ambient electrons have negative velocity, which implies that they are accelerated toward the satellite wall while the cloud electrons seem stationary shown in the second panel. The acceleration of the ambient electrons is, as shown in the third panel, caused by intense electric field pointing outward from the satellite wall. The electric field is particularly intense at the edge of the plasma cloud. The corresponding potential profile is show in the bottom panel and it is suggested that the intense electric field is caused by a potential difference between the cloud center with a positive potential and the ambient plasma with a reference potential. Due to the initial diffusion and collection of cloud electrons to the satellite, ions becomes rich at the cloud center, which can cause the positive potential compared to the space potential at the ambient plasma region. It is interesting that a dense plasma cloud which is supposed to be a large reservoir of electron

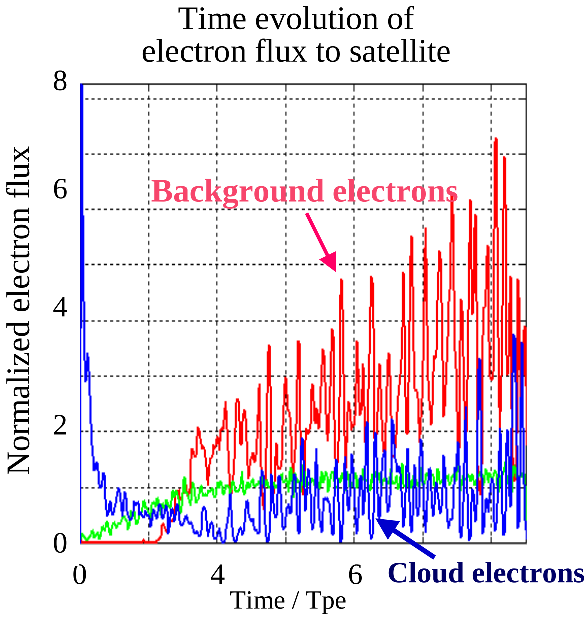

Fig.2: Incoming electron flux to satellite: background electrons and cloud electrons are indicated in red and blue lines, respectively. Green line represents the electron flux in case with no cloud.

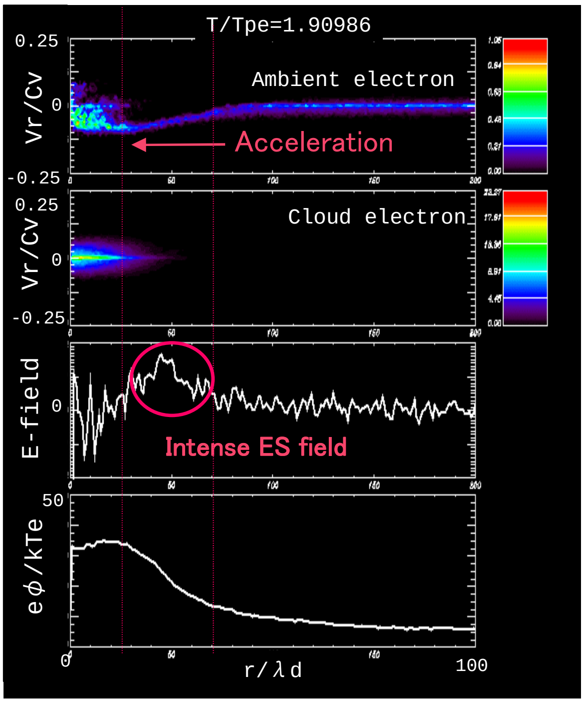

Fig.3: Snapshots of v_x-r phase diagram for ambient and cloud electrons, electric field, and potential

flux actually contributes to the enhancement of the ambient electron flux to the high potential wall by creating an intense electric field at its edge.

Simulation of charge neutralization of a negative floating potential body

As the second case, we examined a transient process of charge neutralization of a floating potential conducting body by plasma emission. Figure 4 shows a two-dimensional simulation model. We have a conducting body with $10\lambda_D$x$10\lambda_D$ in a magnetized and isothermal plasma environment where the ratio between the plasma frequency and the electron cyclotron frequency is 4. The static magnetic field points at 45 degrees with respect to the horizontal axis. We started a simulation with no plasma emission from the body in order to achieve a floating potential which should be negative because the electron thermal velocity is much larger than that of ions. Once the floating potential is obtained, we started emitting a dense plasma at the area of $1\lambda_D$x $6\lambda_D$ just in front of one side of the conducting body with an emission rate corresponding to approximately 240 n_o per unit time in simulation where n_o denotes the ambient plasma density.

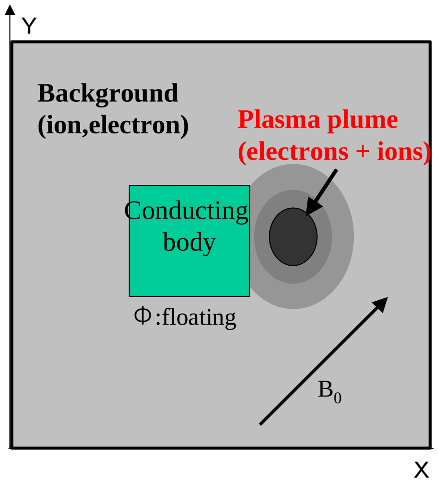

Fig.4: 2D simulation model

Figure 5 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 –3.5 $e\Phi/kT_e$ at the time approximately corresponding to 2 T_{pe} with oscillation at the UHR frequency where T_{pe} denote 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 el 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

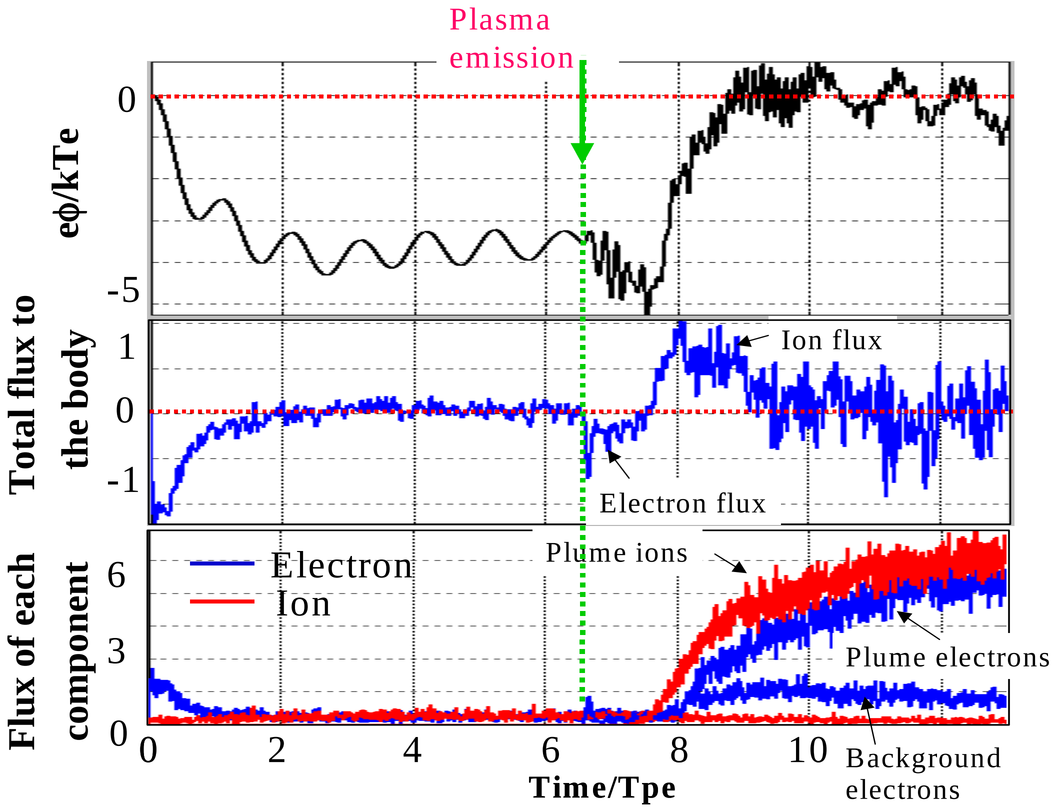

Fig.5: Time evolutions of the body potential, total flux and flux of each plasma component. Flux is normalized to the ambient thermal flux crossing a unit length.

2 $T_{pe,}$ the total flux becomes almost zero, which implies the incoming electron and ion flux balances each other. At the time of 6.5 T_{pe} we start emitting a dense plasma and we can see a drastic change of potential. As soon as the plasma emission starts, the potential abruptly drops down to approximately $-5\ e\Phi/kT_e$,which is due to 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 to be collected to the negatively charged body after the time corresponding to 7 $T_{pe.}$ 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 9 $T_{pe.}$ 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.

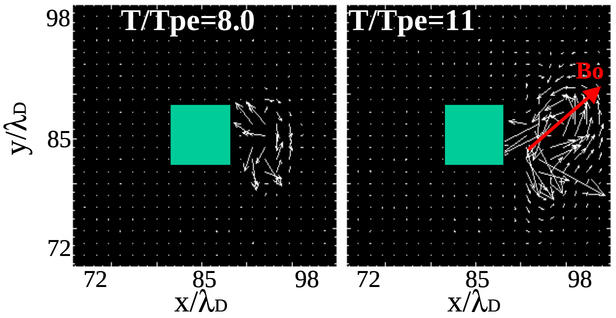

Fig.6: Spatial profiles of current density near the body at T/ T_{pe} = 8.0 and 11.

Figure 6 shows spatial profiles of current density near the body at different times. As shown in the left panel which corresponds to the interval when ion flux is dominant, arrows indicating the current density at each grid point tend to point toward the body. This current is due to ion flux to the body. At the later time, the current profile becomes complex and asymmetry because of the presence of the static magnetic field B_o pointing at 45 degrees up to the horizontal axis. It should be noted that a sort of current loop is formed elongated along $B_{o.}$. 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 will examine the field perturbation due to a plasma plume formed in the charge neutralization process in the future analysis.

Conclusions

We performed PIC simulations to examine the neutralization process of spacecraft charging in a situation where a dense plasma cloud is emitted from spacecraft wall. Two specific situations are considered in the present study. One is a case of electron collection to a high potential satellite, which is a similar situation to the electrodynamic tether. The other is a case of potential control of a negative floating potential body by a plasma cloud emission. In the first case, we could confirm enhancement of ambient electron flux to the body. Ambient electrons are accelerated by intense electric field created at the edge of a dense plasma cloud assumed in the vicinity of a high-potential biased conductor. This implies that the plasma cloud can provide a low-impedance connection between the high potential body and the ambient plasma. In the second case, in order to examine the charge neutralization process, we emit a dense plasma from spacecraft wall which reached 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. 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. The detailed analysis is left as a future work.

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