Full PIC Simulation of Ion Beam Neutralization

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1 Introduction

Ion beam emission and its neutralization by thermal electrons in electric propulsion is one of the most fundamental problems in spacecraft plasma interactions. By emitting the same amount of electrons as the beam ions, the charge neutralization can be basically achieved in the spacecraft environment. However, because of large difference between electron and ion dynamics, the understanding of the neutralization process remains at a rather primitive level. Although the previous works handled uniform ion beam which has an infinite cross section[1,2], we consider a situation in which an ion beam is emitted with a finite radius from a spacecraft[3-6] and simultaneously thermal electrons are released from a different position from the ion emitter [3] for the charge neutralization. Our focus is on the transient process of electron mixing and trapping in the ion beam region in the very vicinity of the ion engine. To examine the transient process in detail, we performed Particle-In-Cell[7] simulations in which both electrons and ions are treated as macro-particles. In Section 2, we introduce our simulation model and parameters used in the simulations. In Section 3, we show some results obtained in the simulation in terms of electron dynamics in the ion beam region. Section 4 contains a summary.

2 Simulation Model

To examine the detail of electron dynamics in the ion beam region in the vicinity of spacecraft, we performed full Particle-In-Cell simulations by using our original simulator software called “EMSES”[8] which we developed for the analysis of spacecraft plasma environment. Like other conventional PIC simulation codes, EMSES basically solves Maxwell’s equation for electromagnetic fields and the equation of motion for a large number of macro-particle with the FDTD scheme. One of the unique features of EMSES is that it can define some internal conduction boundaries which correspond to spacecraft surface and solve interaction with the surrounding plasma. Figure 1 shows the simulation model for the current study. The locations of ion beam emitter and electrons neutralizer are separate. To keep the charge neutrality inside the spacecraft, total fluxes of ion beam and thermal electrons are the same to each other. The ratio of the electron thermal velocity to the ion beam velocity is 1.25. The ion thermal velocity is much lower than the ion drift velocity. In such a situation, we are interested in the transient response of emitted electrons to the ion beam in the vicinity of ion engine.

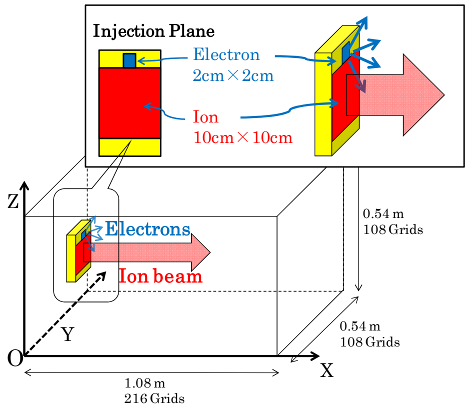

Fig. 1 Simulation model

3 Transient Response of Electrons

We show some snapshots of charge densities measured on a x-z plane including the ion beam. The ion beam basically propagates away from the emitter as time elapsed. Although some diffusion of ions is seen at the beam front as in the bottom panel, the ion beam propagation is generally simple and straight because of ion's large inertia. On the contrary, emitted electrons show very complex signature of density as shown in the right panels. Thermal electrons are emitted from the upper side of the yellow body representing an ion engine. The emitted electrons are overall attracted to the ion beam and propagate along with the ion beam propagation in the x direction. Most of the electrons are trapped by positive potential created by the ion beam. Nevertheless the density profile is not uniform or asymmetric with respect to the ion beam axis. Non-uniform density profiles of electrons are caused by the dynamic electron response to the ion beam. As soon as electrons are emitted from the neutralizer they are quickly attracted to the core of the ion beam and are initially accelerated to the negative z direction. Then most of them penetrate the core part of the ion beam. However, when they pass through the beam, the electrons are decelerated, stagnate, and are accelerated again toward the ion beam. In such a manner, the emitted electrons, which basically propagate with the beam in the x direction, oscillate in the z direction. One of the interesting points seen in the panels is that the electron density values are relatively high at the surface surrounding the ion beam. Since the potential has a peak at the core of the ion beam, electrons are accelerated to the beam core and pass the center of the beam at the maximum velocity. Once they pass the beam core, they start to be decelerated and finally stagnate at the other side of beam surface. This stagnation can cause relatively high density near the surface of the ion beam. The electrons again start to be accelerated back to the beam core by the electric field and this process seems repeated multiple times before the electrons reach at the beam front. In figure 3, we plot a contour map of normalized electrostatic potential and the corresponding electron dynamics in a x-Vx phase space. Because of large electron thermal velocity the ion beam region is not perfectly neutralized and has slightly positive potential as shown in the upper panel. By the presence of the positive potential region, most of the electrons are electrostatically trapped. As shown in the lower phase diagram of Fig. 3, electrons emitted from the neutralizer are quickly accelerated along the beam direction and some electrons escape from the beam front. However, the most electrons are quickly decelerated at the beam front and move back to the opposite direction to the beam propagation. Although not displayed in a figure, a profile of distribution function of the electron velocity along the beam direction measured near the beam front is not a single Maxwellian but consists of two components. One has positive velocity and its peak has three times larger than the ion beam velocity. The other has negative velocity reflected back at the

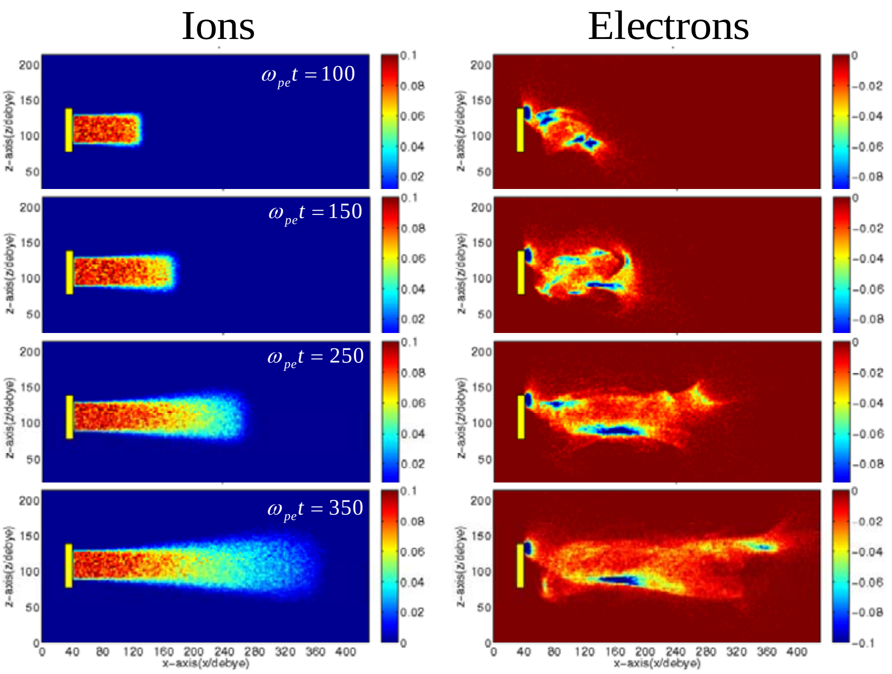

Fig.2 Normalized densities of ion beam and thermal electrons measured on a x-z plane including the ion beam propagation at different times.

ion beam front. The velocity difference between the peaks of the two components seems larger than the width of each distribution function. In such a situation, electron two-stream type instability may occur near the beam front and causes the local enhancement of the electric field and eventually electron heating. Moreover, there may be some interactions between a cold ion beam and the accelerated electrons stated above. However, since the trapped electrons basically move back and force in the potential well of ion beam multiple times, the electron distribution tends to be smeared out and the clear velocity function which has two peaks can be seen only near the beam front. In such a situation, no two-stream instability may be expected because, according to the linear theory, the most unstable electrostatic mode has a wavelength which is much longer than the region where the above velocity distribution is formed.

4 Conclusion

We have been studying the transient behavior of electrons emitted for ion beam neutralization in electric propulsion by performing full PIC simulations with EMSES. We found some interesting signature of electrons in the neutralization process to ion beam. Unlike simple dynamics of ion beam, the behavior of thermal electrons emitted from the neutralizer is very complex. They basically propagate along with the ion beam to neutralize the positive charge. However, in the beam region, electrons are electrostatically trapped and move back and forth in the both directions parallel and perpendicular to the beam propagation. This complex trapping motion of electrons directly causes the electrostatic heating of electrons or the increase of the electron temperature just outside the ion acceleration grid of ion engine. Although counter-streaming electron components are found in the present case, no plasma instability may be expected because such unstable velocity distribution is formed only near the ion beam front. We need further analysis on this point.

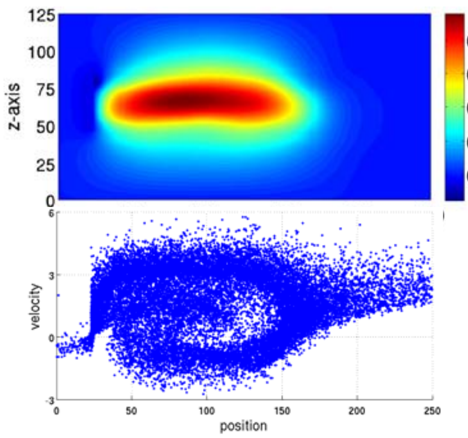

Fig 3. A contour map of normalized electrostatic potential on a x-z plane including the ion beam propagation (Upper panel) and the corresponding electron dynamics in a x-V_x phase space (lower panel).

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