Geospace Environment Simulator

–Evaluation of the Plasma Environment around a Spacecraft using Electric Propulsion–

Project Representative
Yoshiharu Omura Kyoto University

Authors
Yoshiharu Omura Kyoto University
Hideyuki Usui Kyoto University
Masaki Okada National Institute of Polar Research
Tastuki Ogino Nagoya University
Tohru Sugiyama Japan Agency for Marin-Earth Science and Technology, The Earth Simulation Center
Naoki Terada National Institute of Information and Communications Technology
Takeshi Murata Ehime University
Daisuke Matsuoka Ehime University
Masao Nakamura National Institute of Information and Communications Technology
Hiroko Ueda Japan Aerospace Exploration Agency
Iku Shinohara Japan Aerospace Exploration Agency
Taketoshi Miyake Toyama Prefectural University
Masaki Fujimoto Tokyo Institute of Technology
DongSheng Cai Tsukuba University

Geospace Environment Simulator Project Team

In exploration and utilization of the geospace environment, it is very important to understand interactions between spacecraft and space plasma environment because they can be hazardous to onboard electronics. To evaluate the spacecraft-plasma interactions quantitatively, we have been developing a proto model of "Geospace Environment Simulator" which has a main numerical engine of full Particle-In-Cell (PIC) simulation. By treating both electrons and ions as particles, we particularly focused on the transient process of the ion beam neutralization by thermal electron emission during the operation of ion propulsion engine. In the current study, we examined the dependence of the charge neutralization of the beam on the ratio between the electron thermal velocity to the ion beam drift velocity. The preliminary results show the possibility of electrostatic beam instability of current-driven type occurring in the vicinity of the beam emitter due to the velocity difference between the two species of plasma. Because of this instability, some electrons are trapped in potential well formed near the ion emitter while others which have high energy can escape the potential well and propagate along the ion beam to neutralize the positive charges. Temporal variation of the excited electrostatic field in the vicinity of the ion emitter and its effect on the spacecraft environment are to be examined as a future work.

Keywords: geospace, plasma simulation, Particle-In-Cell, spacecraft, ion propulsion engine, charge neutralization

1. Introduction

Geospace is the space surrounding the Earth, where the electromagnetic dynamics of space plasmas plays dominant roles. In the geospace environment many spacecraft such as commercial satellites and space station are now in operation in the geostationary orbit as well as in the low-earth orbit. Since spacecraft surface is basically made of conductor and dielectric materials, it is easily influenced by space plasma. As one of the significant spacecraft-plasma interactions to be considered is spacecraft electrostatic charging. Studies on spacecraft charging have been intensively conducted by many researchers since 1970s. Excellent reviews of the progress in the spacecraft charging field have been provided[1), 2)]. Spacecraft charging is determined by the net flux of charged particle at the surface including photoelectrons and secondary electrons. In addition, we also need to consider fluxes of active plasma emission from spacecraft such as ion thruster used in the electric propulsion[3] and plasma contactor for the spacecraft potential control. Since these active plasma emissions have much larger flux than that of ambient plasma, its effect on the spacecraft environment cannot be ignored. In order to mitigate the influence of the space plasma as well as the plasma beam emission on the spacecraft, we need to understand the interaction process occurring between the spacecraft and the plasma environment prior to the actual space activities[4), 5), 6)].

Owing to the recent remarkable progress of computer technology, numerical simulation has become one of the powerful and important research methods in various fields[7)]. NASA developed NASCAP (NASA Charging Analyzer Program[8)]) as an engineering tool to determine the environmental effect on spacecraft surfaces and systems. ESA started the SPIS (Spacecraft Plasma Interaction System[9)]) project in 2002, which aims at developing a software toolkit for spacecraft-plasma interactions and spacecraft charging modeling. NASCAP and SPIS are mainly utilized for obtaining the steady state solution of spacecraft surface potential for the engineering use. For this purpose they introduced some approximations to speed up the estimation of surface charging. In the aspect of plasma process occurring in spacecraft-plasma interactions, however, the numerical approximations hired in these tools are not always appropriate because the plasma dynamics and associated field variation are not self-consistently solved. Considering that transient variation caused by plasma kinetics can affect the steady state solution on the spacecraft-plasma interactions, we believe that full PIC simulations are essential. In such a situation, we started to develop a numerical plasma chamber called Geospace Environment Simulator (GES) by making the most use of the conventional full Particle-In-Cell (PIC) plasma simulations (Fig. 1).

In the present report, we show some preliminary simulation results for the case of ion beam injection in space and its interaction with thermal electrons emitted for the charge neutralization.

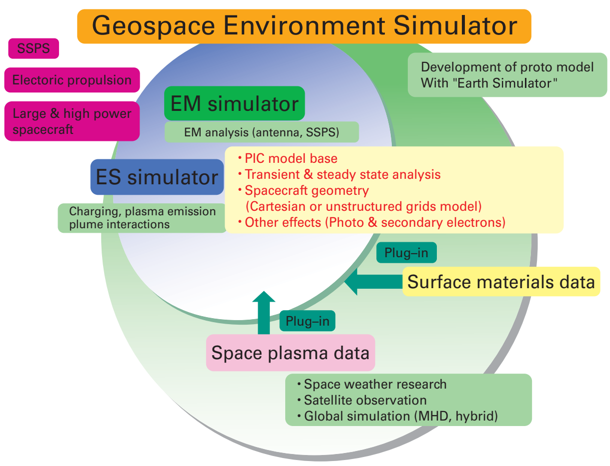

Fig. 1 Concept of GES.

2. 3D PIC simulation on ion beam and thermal electron emission from ion engine

We show a three dimensional simulation model in Fig. 2. For simplicity, we introduced no spacecraft geometry in the model. Instead, we assumed a virtual ion beam emitter in the simulation box with the radius of 0.33 m. Ion current is 0.0023A and the variable parameter is the ion acceleration voltage which varies from 0.5 kV to 5 kV. Thermal electrons of 0.1 eV for the neutralization are simultaneously emitted from the same virtual ion emitter by keeping the current neutrality. The variable parameter is the ratio between the electron thermal velocity and the ion beam velocity v_{the}/v_{ion_beam}.

Here we show some snap shots of simulation results for the case of v_{the}/v_{ion_beam} = 0.07 in Fig. 3. The left panels are three-dimensional spatial distributions for ions and electrons shown in red and blue, respectively. For convenience, we display electron distribution independently in the lower panel. In the right panels, electrostatic potential and particle velocity versus the x axis are shown. As easily found in the left panels, ion beam propagates along the x direction with a slightly diffused in the radial direction. As to the electrons, it seems most of them are diffused around the beam source region. However, if we take a look at the lower left panel, electrons are also moving with the beam ions and contribute to neutralize the beam positive charge. The electrons propagating with the beam can be approximately categorized into two groups. One is found between the beam head and the beam emitter and the other is around at the ion beam head. These two types of electrons are also recognized in the particle phase diagram shown in the lower right panel. The electrons of the first group are quickly accelerated to the velocity of ion beam and are trapped in a potential well created in the vicinity of the beam emitter. As shown in the same panel, some of them are reflected back to the beam emitter. On the contrary, other electrons in the second group are escaping from the potential well and try to propagate with the ion beam for the charge neutralization.

When we increase the velocity ratio by reducing the ion beam velocity, we see another different feature from the previous case. The results are shown in Fig. 4. Most of the elec-

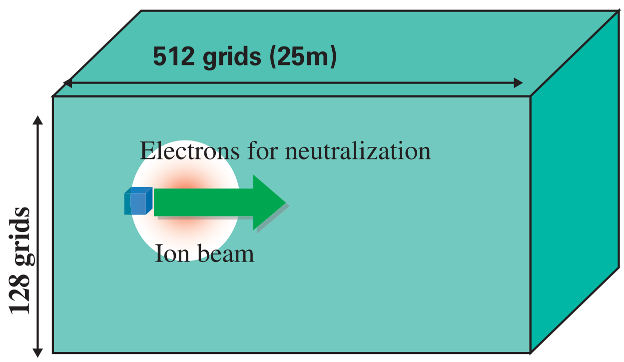

Fig. 2 Three-dimensional simulation model for ion beam injection.

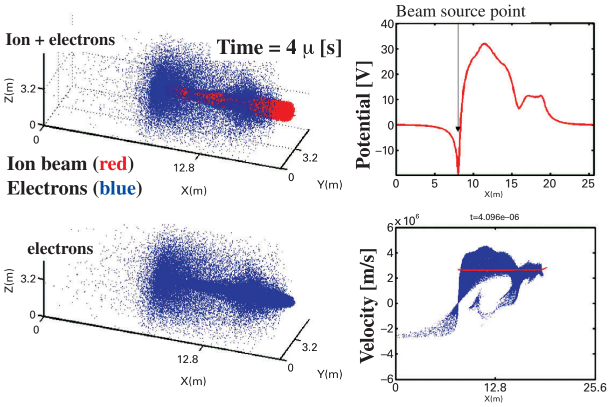

Fig. 3 Spatial distribution of beam ions and electrons for charge neutralization in left panels. Potential and plasma velocity versus the x axis in right panels for the case of $v_{the}/v_{ion\_beam} = 0.07$.

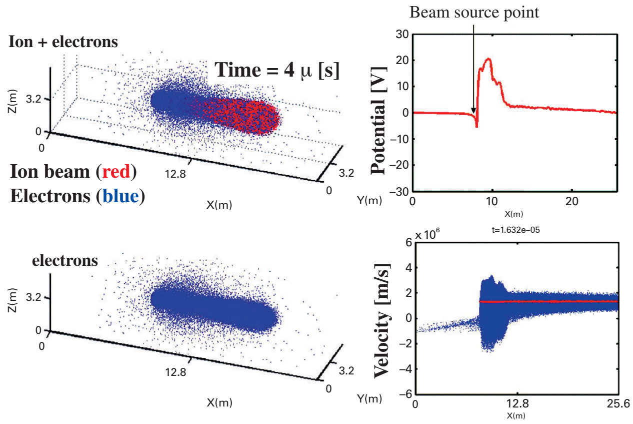

Fig. 4 Simulation results shown in the same manner as Fig. 3 for the case of $v_{the}/v_{ion\_beam} = 0.14$.

trons propagate with the beam ions and the trapping region of electrons becomes very small in comparison with the previous case. In this case, it seems that the ion beam is almost neutralized by the thermal electrons.

3. Discussion

We discuss the simulation results from a view point of ion and electron dynamics shown in the previous two cases. The dynamics are obviously different from ion beam and thermal electrons. In other words, the ion beam neutralization is not so simple as long as the spatial scale of electron dynamics is concerned. In the very vicinity of the emitter, there is a velocity gap between beam ions and thermal electrons. In this situation, we can expect Buneman-type beam instability to occur in the process of the electron acceleration by the ion beam. Meanwhile, beam ions are almost neutralized with the electrons escaping from the potential well beyond a certain distance from the emitter. Then some questions arise such as what determines the location of this interface between the beam instability region and beam neutralization. If we assume that the Buneman-instability taking place near the emitter, the unstable mode has smaller wave length and tends to be damped for slower ion beam. This situation may correspond to the last case of simulation which shows the narrow trapping region of electrons. Since we do not have enough temporal data for the further analysis, we have not quantitatively confirmed the beam instability or its effect on the beam neutralization yet. In order to realize the most efficient neutralization of ion beam, we will reveal the beam neutralization process from the viewpoint of ion-electron plasma interaction in the realistic situation of ion propulsion engine.

4. Summary

We started to develop Geospace Environment simulator (GES) as a numerical plasma chamber for the analysis of spacecraft-plasma interactions. We apply the conventional EM full-PIC plasma simulations to be able to treat the spacecraft surface, plasma emission and collision with neutral particles for the purpose of space engineering use. As one of the examples, we showed some simulation results on the local ion beam injection in three-dimensional space. The simulation results show the Buneman-type instability possibly occurs in the vicinity of beam emitter due to the difference between the beam velocity and the thermal velocity of electrons. Due to this instability, electrostatic potential well is created and some electrons are trapped. On the other hand, other electrons escape the well and follow the ion beam to neutralize the positive charge. It is very interesting that the instability occurs near the source region where the spatial scale of the beam is in the same order of the unstable wavelength. Unlike in the conventional model of uniform plasma, plasma instability in three-dimensional local beam model has been little investigated theoretically or numerically. From this point of view, the present study which focuses on the plasma instability caused by local beam source can be very interesting and significant. In the aspect of space engineering, we will also contribute to the estimation of the optimum condition for beam neutralization by performing simulations in more realistic situations, which is left as future work.

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宇宙環境シミュレータ
– 宇宙機電気推進時のプラズマ環境評価 –

プロジェクト責任者
大村　善治　　京都大学 生存圏研究所

著者
大村　善治　　京都大学 生存圏研究所
臼井　英之　　京都大学 生存圏研究所
岡田　雅樹　　国立極地研究所
荻野　竜樹　　名古屋大学太陽地球環境研究所
杉山　　徹　　海洋研究開発機構・地球シミュレータセンター
寺田　直樹　　情報通信研究機構
村田　健史　　愛媛大学総合情報メディアセンター
松岡　大祐　　愛媛大学理工学研究科
中村　雅夫　　情報通信研究機構
上田　裕子　　宇宙航空研究開発機構　総合技術研究本部
篠原　　育　　宇宙航空研究開発機構　宇宙科学研究本部
三宅　壮聡　　富山県立大学　工学部
藤本　正樹　　東京工業大学　理工学部
蔡　　東生　　筑波大学　電子情報工学系

宇宙環境シミュレータプロジェクトチーム

宇宙開発・利用に不可欠な飛翔体環境の定量理解とその宇宙技術開発へのフィードバックを目指し、実際的な宇宙仮想実験を行う数値チェンバーとして「宇宙環境シミュレータ」を構築することが本プロジェクトの目的である。本年度は、新規に開発を行った領域分割型3次元電磁粒子シミュレーションコードを用いて、イオン推進エンジンから排出されるイオンビームとその電荷中和のために放出される電子の相互作用に着目したシミュレーションを開始し、特にイオンエンジン近傍におけるプラズマ不安定性の有無についての定量解析を行った。準備的なシミュレーション結果からは、イオンビーム速度が電子熱速度より十分大きい場合、イオンビーム放出口近傍において正の電位領域が生じ、放出された電子群の一部はその領域に捕捉され、その一部は放出口に逆流する現象が見られた。この電位領域形成の原因としては、放出イオンビームと電子熱速度の速度差が原因となり生じる電流駆動型のビームプラズマ不安定性が考えられる。またこの電位領域に捕捉されない高速な電子はイオンビームとともに伝搬し、ビームの電荷中和を担う。イオンビーム速度を下げて電子熱速度に近づけた場合、この不安定性は大きな波数、すなわち、小さな波長の電界擾乱が生じる領域で発生しランダウ減衰を受けるため大きく成長しない。擾乱領域はイオンビーム放出口近傍に限定され、放出された電子のほとんどはその領域を越えてイオンビームの電荷中和に貢献できることがわかった。一様プラズマ中におけるビームプラズマ不安定性の理論およびシミュレーションによる定量解析はこれまで盛んに行われてきたが、本課題のように3次元的局所ビームによるプラズマ不安定の理論(ビームのスケールと不安定波の波長が同程度)は皆無であり、この点で本研究の3次元シミュレーション解析は、学術的にも重要でありかつ非常に興味深い。一方、実際的観点から見ても、イオン推進エンジンのイオンビーム電荷中和過程の定量理解は、衛星環境擾乱を最小に抑えるために必要な放出中和電子量を算出する際に基礎的な知見を与えるものである。これらの点で、本研究は宇宙機環境の理解および次期大型イオンエンジン開発において重要である。今後、イオンビーム放出口近傍での擾乱電界の時間領域解析を進め、ビームプラズマ不安定性によるイオンエンジン近傍環境の擾乱、プラズマ加熱加速の可能性、スパッタリングやコンタミ生成など関連する宇宙機への影響について解析を進める。

キーワード：ジオスペース, プラズマシミュレーション, 粒子法(PIC), 宇宙飛翔体, イオン推進エンジン, 電荷中和