Numerical Simulation of Microwave Plasma in Air Breathing Ion Engine

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1. Introduction

Lowering of the orbiting altitude provides many advantages for Earth observation satellites such as high-resolution and small consumption power etc. Super-Low Earth Orbit (SLEO) satellite was pioneered by Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) which orbits at the altitude of 200 km. It equips ion engine to compensate drag of the upper atmosphere. Ion engine carries xenon gas as propellant. Large volume of high-pressure xenon tank weighs on the available volume inside the satellites for mission equipments. Moreover, SLEO satellites have to reduce the cross-section of the satellites because of the drag in the upper atmosphere. Air Breathing Ion Engine (ABIE) concept was proposed by Nishiyama for such applications in 2003 [1]. ABIE does not carry propellant. The Upper atmosphere is compressed inside ABIE and microwave plasma was formed by the compressed atmosphere which is composed of atomic oxygen and molecular nitrogen. Since the pressure of atmosphere at the altitude of 200 km is not high enough to maintain plasma, compression and plasma formation processes of the upper atmosphere is the key technology of ABIE. However, formation of continuous gas flow at 8 km/s in a ground-based facility is not an easy task [2]. Laser detonation method, originally developed as a laser thruster, has been used to simulate 8 km/s atomic oxygen flow in the ground-based facility for material degradation studies. However, it forms pulsed beam and not suitable for ABIE studies. Thus, ABIE has been studied only in theoretical basis [3].

In this study, plasma formation property inside ABIE was studied by a numerical simulation based on Particle-In-Cell (PIC) method. Electromagnetic Spacecraft Environment Simulator (EMSES) was applied in this calculation. The purpose of this simulation is to establish the design guideline of ABIE.

2. Simulation model

EMSES is a computational code based on Maxwell's equations and Newton's law developed for studying spacecraft plasma interactions [4]. In our simulation, plasma particles can collide with neutral particles, of witch spatial distribution is stationary, in the collision process only movement of electron is considered. For electrons moving in one direction (beam), electron density is affected by the impact ionization or scattering with neutral atoms. Decrease in the electron beam density is given by the equation below:

$$dI_1 = -\sigma I_1 n_2 dx \qquad (1)$$

where I_1 is electron density (or intensity), n_2 is neutral particle density, x is the beam direction, and σ is the cross-section of election/neutral collision. The reaction between neutral and electron is characterized by σ which depends on the collision energy [5]. Null-collision method was applied for the classification of reactions [5]. Collision probability of electrons per unit time Δt is given by

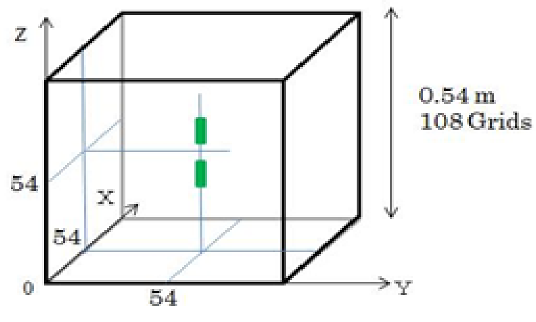
$$P_i = 1 - \exp(-\Delta t v_i \sigma n_t(x_i)) \qquad (2)$$

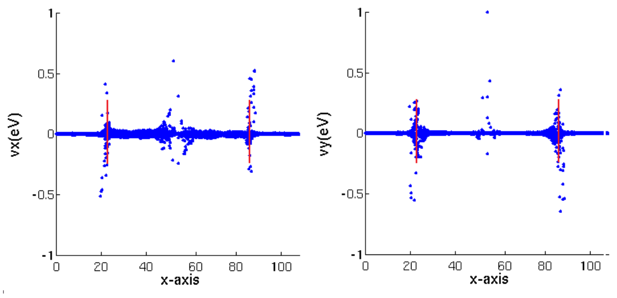
where v_i is speed of the incident electron, n_t (x_i) is neutral particle density at x_i.

The simulation space consists of 108 x 108 x 108 grids. To emit microwave, the dipole antenna consisted in two 5-grid-long electrically conducting rods with a 2-grids spacing was located in the center of the simulation space as shown in Figure1. The diameter of dipole antenna was ignored because the actual diameter of antenna was much smaller than the wavelength of microwave. For electron cyclotron resonance (ECR) with microwave, dipole magnetic field given by Equation (3) was used in this calculation.

$$\boldsymbol{B}_{dipole} = (3 \times \frac{\boldsymbol{m}_d \cdot \boldsymbol{r}}{r^5} \cdot \boldsymbol{r} - \frac{\boldsymbol{m}_d}{r^3}) \qquad (3)$$

where $\boldsymbol{r}$ is position vector from the center of magnetic field, and m_d is dipole moment vector [6]. In order to reflect





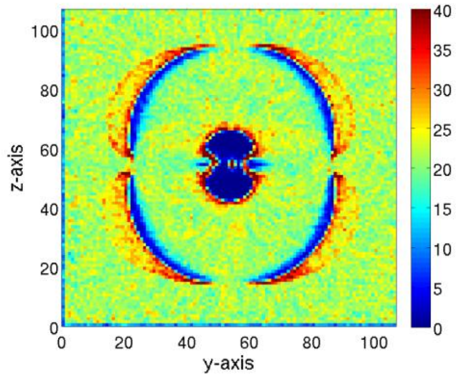
magnetic field to plasma dynamics, the magnetic field distribution over the computational area was calculated. Then, all plasma particle in simulation reflect the magnetic field distribution in the equations of motion shown in Equation (4)

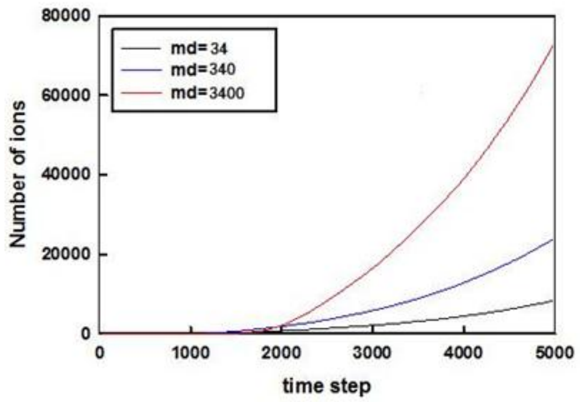
$$\frac{dv}{dt} = \frac{q}{m}\left(E + v \times \left(B + B_{dipole}\right)\right) \qquad (4)$$

3. Computational results and discussion

3.1 ECR simulation

The accuracy of ECR simulation was confirmed by the phase diagram (Figure 2). The simulation parameters are shown in Table1. The red lines in the each panel's abscissa are the resonat points of ECR theroretically obtained. From the figure we can confirm that electrons are accelerated in both x- and y- directions at the ECR points. It was, therefore, confirmed that the EMSES calculation in this study provides spacially accurate results. Figure 3 shows the electron density distribution in the yz plane at x = 54 (middle of antenna gap).





In the figure the electron flow from inside to outside near the ECR points.

3.2 Collision simulation

Collision between neutral particles and electrons was included in the same computational model as shown in the previous section. The collision frequency of 1E-4 Hz and 3 type of magnetic field (m_d = 34, 340 and 3400 T) were introduced. The number of ions generated by the impact ionization was plotted in Figure 4. A strong correlation between the number of ions and magnetic field are shown in Figure 4. Although not shown in figure difference in spatial distribution in the ions is also observed. These results would give important information to optimize the antenna and magnet design inside ABIE.

4. Conclusions

Numerical simulations on microwave plasma inside the ABIE were carried out with The EMSES code. Because the precise ground-based experimental simulation is difficult for ABIE, the design guideline of ABIE would be established through the combination of limited ground-based experiment and computational results obtained in this study.

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