SIMULATION OF ELECTROMAGNETIC INTERFERENCE INDUCED BY ION THRUSTER PLUME

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Abstract

Ion thruster emits high density plasma plume, which may affect the communication wave passing nearby. Also the electromagnetic noise radiated from the current may affect the spacecraft instrument. An electromagnetic particle simulation code has been developed to investigate the effects of the electromagnetic interference induced by the ion thruster plume. The simulation result shows that very little interference occurs between the communication wave and the ion thruster plume, because the plasma frequency is much less than the frequency of communication wave. The strength of electromagnetic noise radiated by ion thruster plume depends on the distribution of charged particles inside the plume. The strength and orientation of static magnetic fields near the spacecraft affects the dominant frequency and the strength of the noise.

1. Introduction

There has been more use of ion thrusters in space, since its first use at the beginning of 90s. Various missions with ion thruster have flown including interplanetary missions. When an ion thruster operates in space, ions are accelerated by high voltage and ejected to space to gain its thrust and electrons are emitted from the neutralizer to neutralize the ion beam. Such effluents are called ion thruster plume and form a high density plasma.

When communication wave from the Earth passes near the ion thruster plume, there is possibility of electromagnetic interference. Also, the ion thruster plume radiates electromagnetic noise by the current induced by the motion of charged particles, which may affect the spacecraft instrument. The purpose of this study is to investigate the interference between the ion thruster plume and the communication wave and the radiation noise induced by the plume via a two-dimensional electromagnetic particle simulation code.

First, we simulate the cut-off phenomenon to verify the simulation code. Secondly, we study the interference between the communication wave and the ion thruster plume, especially the phase-modulation and attenuation of the wave. Thirdly, we study the electromagnetic noise radiated from the ion thruster plume under several conditions.

2. Simulation method

We have developed a two-dimensional electromagnetic PIC (Particle-in-Cell) code to study the electromagnetic effects due to the ion thruster plume. The basic scheme is a standard EM-PIC code described in Ref. [1] except the use of PML(Perfectly matched layer) condition [2] at the boundary. The propagation of electromagnetic wave is calculated by solving the Maxwell’s equation including the source current generated by the motion of charged particles. The motion of charged particles is calculated by integrating the equation of motion taking into account the oscillating fields of the electromagnetic wave. The flow-chart is shown in fig. 1. The collisions between charged particles and neutral particles is not taken into account in this simulation. We assumes Xenon as the ion species and the mass ratio of ion to electrons is taken to be the real one, 238095.

3. Simulation of Cut-off phenomenon

First, we simulate the cut-off of electromagnetic wave by a plasma to verify the simulation code. Figure 2 shows the simulation domain, where the PML region is placed at the boundary to prevent the reflection of the electromagnetic waves. A circle shape of plasma with $10^{18} m^{-3}$ density...
and 200eV temperature is placed in the simulation domain. The source current, $J_z$, oscillates at $100MHz$ in the direction perpendicular to the paper. The plasma density gives the cut-off frequency of $897MHz$.

Figure 3 shows a snapshot of the contour of electric field $E_z$. The interval of contour lines are $1000V/m$ and the electron density is also shown in Fig. 3(b), where the bright area denotes the presence of plasma. The attenuation of electric field and phase shift due to the presence of plasma is clearly seen in Fig. 3(b). The degree of attenuation shows reasonable agreement with one-dimensional theory [3] and discussed in detail in Ref. [4]. We conclude that this code can properly handle the electromagnetic interaction between the plasma and the electromagnetic wave.

4. Electromagnetic interference between ion thruster plume and communication wave

We now simulate the electromagnetic interference between the ion thruster plume and communication wave. The simulation domain is shown in fig. 2. We simulate the ion thruster plume in a coordinate system fixed to the spacecraft. Then, the ion thruster plume is elongated in the beam direction and the variation along the beam is much less than the variation across the beam if we look at the beam at a point sufficiently far from the thruster exit. We consider only a slice of the plume plasma and assume the variation along $z$ (beam direction) is small compared to the variation in that plasma. Then we can consider the electromagnetic interaction between the communication wave and the plume plasma in the plane perpendicular to the beam.

We place a circular shape of plasma at the center of simulation domain. As for the parameters of the plasma, we take the parameters from the measurement of $MUSES-C$ ion thruster made at ISAS, JAPAN [5]. The beam radius is $50mm$ and the electron density and temperature is $2.1 \times 10^{14}m^{-3}$ and $6.5eV$, respectively, which correspond to the values at $800mm$ from the thruster exit. The radiation source is modeled by a sheet current in $z$ direction placed $50mm$ away from the beam. The source current oscillates at $1GHz$ to emit the electromagnetic wave which simulates the communication wave.

Figure 4 shows the time variation of the electric field $E_z$. We also plot the time variation of $E_z$ for the case where no plasma exists. The difference due to the presence of plume is not observed. This is because the plasma frequency is $130MHz$ and much less than the frequency of communication wave. Therefore, we conclude the communicate wave is not affected by the ion thruster plume for a frequency higher than $1GHz$. 
5. Electromagnetic noise radiated from ion thruster plume

The ion thruster plume radiates the electromagnetic noise by the motion of charged particles, which may affect the spacecraft instrument. First, we investigate the effect of charge distribution in the plasma plume. Then, we investigate the effects of static magnetic field on the radiation noise.

5.1 Effect of charge distribution inside the plume

The ion beam emitted from the thruster grid and the electrons emitted from the neutralizer neutralize each other at somewhere in the downstream of the plume. The process of neutralization, however, is not well understood. Therefore we assume four typical cases as the initial distribution of charged particles.

Figure 5 shows the four cases. The circle shape of ion which corresponds to the ion beam is included for all the cases. For the case A, only the electrons are placed separately from the ion beam, which corresponds to the electrons emitted from the neutralizer and the case where the plume is not properly neutralized. For the case B, the plume is completely neutralized and the same number of ions and electrons are placed in the simulation domain. Therefore, this corresponds to the plume in the far downstream.

A plasma is distributed instead of electrons for the cases C and D, because the neutralizer emit the higher density plasma compared than the ion beam. For the case C, the neutralizer emits not only electrons but also slow-ions, which is more realistic assumption than the case A. For the case D, the density of the neutralizer plasma is set to be twice the density of beam ions and the neutralizer plasma surrounds the ion beam which corresponds to well-neutralized situation.

For the four cases shown in Fig. 5. The radius of ion beam is 50mm. The radius of neutralizer electrons and ions for the cases A and C is 20mm. The radius of the neutralizer plasma for the case D is 70mm. The ion beam has a drift velocity of 46900m/s in the z direction and a temperature of 6.5eV and the density $n_i = 2.1 \times 10^{14} \text{m}^{-3}$. The electron density for the case A and B is $n_e = 2.1 \times 10^{14} \text{m}^{-3}$. The plasma density for the case C is $n_e = n_i = 2.1 \times 10^{14} \text{m}^{-3}$. The plasma density for the case D is $n_e = n_i = 4.2 \times 10^{14} \text{m}^{-3}$. The neutralizer electrons and ions have a temperature
of 6.5eV for all the cases and has a Maxwellian distribution as the initial condition.

Figure 6 shows the temporal variation of electron density which shows that electrons oscillate around the ion beam. The oscillation is caused because we produce the initial polarization by placing the electrons separated from the ion beam. For the cases of B and D, the electrons show ambipolar diffusion in the radial directions.

Because the initial polarization field has the strongest component in the z direction, the electric field in the z direction, $E_z$, is dominant as the radiated field. The time variation of the electric field $E_z$ which is measured at the point 300mm away from the center of ion beam is shown in Fig. 7 at the marked point in Fig. 5. The strength of electric field is the strongest for the case C, because of the strongest effect of polarization of plasma. The strength of electromagnetic noise depends on the polarization between the ion beam and the neutralizer electrons. The up-stream of the plume where the neutralization is not complete is the dominant source of the radiation noise.

Figure 7 also shows that the radiation noise have the dominant frequency of 80MHz for the case A and C, 105MHz for the case B which corresponds to the plasma frequency. For the case D, because the plasma density is twice, the oscillation frequency increase to 160MHz.

5.2 Effect of static magnetic field

Although, we have ignored the static magnetic field in the previous section, it usually exists around the ion thruster. Particularly, an ion thruster which generates the plasma by ECR(Electron Cyclotron Resonance) discharge has a magnet circuit, and a strong magnetic field exists. The magnitude of the magnetic field is about 1T near the ion thruster exit for the MESES – C ion thruster, Ref. [5]. Therefore, we study the effects of the static magnetic field. As the initial distribution of the charged particles, we choose the case A in Fig. 5, because it gives the maximum possible radiation noise level.

Figure 8 shows the temporal variation of electron density when $B_z = 3 \times 10^{-3}T$ is applied in z direction. $B_z = 3 \times 10^{-3}T$ gives the gyrofrequency of 84MHz, close to the plasma frequency identified in the previous section. When $B_z$ is applied, the electrons make $E \times B$ drift, where $E$
is produced by the polarization between the electrons and the beam ions. The $E \times B$ drift induces the motion of electrons which circles around the ion beam. This electron motion radiates the elliptically polarized electromagnetic wave in $x-y$ plane. The electric field vector rotates in the same way as the electrons rotate around the ion beam, that is, the clockwise direction.

If we look at the electric field, $E_z$, at the position marked in Fig. 5, we look at the wave propagating in the direction perpendicular to $B$. Then the wave is in extraordinary wave. The extraordinary wave propagates at a frequency higher than $\omega_R = \frac{1}{2} [\omega_c^2 + (\omega_c^2 + 4\omega_p^2)^{1/2}]$, which is $130 MHz$ for the present case [6]. We measured $E_x$ and $E_y$ at the position $300mm$ away from the center of ion beam. The fields $E_x$ and $E_y$ indeed shows the elliptical polarization in the clockwise direction. Because we are looking at the fields at a point very close to the source compared to the wave length, the lower frequency part should dominant. The peak frequency of the spectrum of $E_z$ is at $130 MHz$ which agrees with $\omega_R$, the lowest excited frequency for the X-mode propagation.

Figure 9 shows the effect of magnetic field strength on the spectrum of radiation noise, $E_z$. For $\omega_p \gg \omega_{ce}$, the dominant frequency is determined by the plasma oscillation. For $\omega_p \ll \omega_{ce}$, on the other hand, the dominant frequency is $\omega_{ce}$. When the plasma frequency is resonant with the gyro-motion, the spectrum intensity is $6.11 \times 10^3 V/mHz$ at $f = 130 MHz$ for $B = 3 \times 10^{-3}T$ while $4.15 \times 10^3 V/mHz$ at $f = 2.8 GHz$ for $B = 0.17$ and $6.05 \times 10^3 V/mHz$ at $f = 80 MHz$ for $B = 0$. For the case of ECR thruster, the magnetic field decrease along the beam direction. The result shown in Fig. 9 implies that the radiation noise level increases where the plasma density becomes resonant with the gyro-frequency.

Figure 10 shows the effect of orientation of the magnetic field. When $B_z$ is applied, the magnetic field is parallel to the initial polarization and affects little on the motion of electron. Therefore the noise is mostly made of plasma frequency. Because we are looking at the wave propagation in $y$ direction from the radiation source, where the electric field $E_y$ is parallel to the magnetic field $B_z$, the propagation mode is mostly ordinary wave and has the frequency $\omega \geq \omega_{pe}$. The peak frequency of the $E_z$ is indeed at $80 MHz$ corresponding the plasma frequency.

When the magnetic field is applied in the $y$ direction, the electrons rotate in the counterclockwise on the $x-z$ plane if we look at from $y = -\infty$. Then the wave observed at the marked point in Fig. 5 is the left-hand circularly polarized wave(L-waves). The field $E_x$ and $E_y$ shows a circular polarization at $\omega = \omega_R = 130 MHz$. The peak frequency of $E_y$ is, however, located at $\omega = 110 MHz$, lower than $\omega_R$, but very close to the upper-hybrid frequency $\omega = \sqrt{\omega_p^2 + \omega_c^2} = 116 MHz$ for the present case.

**Conclusion**

We have developed a two-dimensional electromagnetic particle simulation code to investigate the electromagnetic effects of ion thruster plume such as the interference on the communication wave or the noise radiation. Simulation result shows that the influence of ion thruster plume on the communication wave is very little. The strength of radiated noise depends on the polarization of ion thruster plume. The far downstream of plume where the ion beam and electrons are neutralized perfectly radiates weak noise. The upstream of ion thruster plume where the ion beam and electrons are not well-mixed radiate strong noise. The frequencies of radiated noise are determined by the plasma oscillation due to the polarization.

If the static magnetic field around the plume is so low as to satisfy, $\omega_p \gg \omega_{ce}$, the plasma frequency is radiated dominantly from the plume. For, $\omega_p \ll \omega_{ce}$, the gyro frequency is dominant. When the strength of magnetic field is $\omega_{pe} \approx \omega_{ce}$,
Figure 8: Time variation of electron density. The white circle denotes the ion beam.

Figure 9: Spectrum of $E_z$ field for various strength of static magnetic field in z direction.

Figure 10: Temporal profile of $E_z$ field measured at the marked point in Fig.5.

the radiated noise have a dominant frequency which depends on the direction of the magnetic field.

Because the polarization inside the plume is the major source of the radiation noise, we need to investigate the process of neutralization further in future.

References


