Two-Dimensional Particle-In-Cell Simulation of Magnetic Sails

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Abstract: The magnetic sail is a spacecraft propulsion system using the interaction between the magnetic field and the solar wind. Using the solar wind, which is a super sonic plasma flow mainly consisting of protons and electrons, the magnetic sail provides the efficient thrust in the deep space exploration. In addition, MPS (Magnetic Plasma Sail) is proposed. MPS inflates the original magnetic field by a plasma injection from the spacecraft and MPS is expected to be able to provide a large thrust with a small coil size. In the present study, we conduct a 2D Full-PIC (Particle-In-Cell) simulation for a very small magnetosphere (several 100 m to several 1000 m) generated by MPS since the thrust characteristics of such a small MPS are still unknown. The Full-PIC simulation treats both ions and electrons as particles and charge separation is considered. Hence, we particularly analyze the MPS in terms of how the thrust is affected by charge separation and what injection plasma parameters enhance the thrust efficiently. As a result, it is revealed by 2D Full-PIC simulation that the charge separation and electron Larmor motion affect the thrust of the magnetic sail depending on the magnetospheric size. MPS simulations also revealed that the MPS could generate efficient thrust. By the low-beta plasma injection, the thrust of MPS (15 µN/m) becomes up to 5 times larger than the original thrust of magnetic sail (3 µN/m). The efficiency defined as (MPS thrust) / (Magnetic sail thrust + Plasma injection) is 270%.

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Nomenclature

$\boldsymbol{B}$	=	Magnetic field vector, T
c	=	Light speed (3x10^8 m/s)
C_d	=	Drag coefficient
δ	=	Ion mean free path, m
$\boldsymbol{E}$	=	Electric field vector, V/m
e	=	Elementary charge (1.6x10^{-19} C)
I_{coil}	=	Coil current, A
I_{plasma}	=	Plasma current, A
J	=	Current density, A/m^2
L	=	magnetospheric size, m
m_i	=	Ion mass, kg
m_e	=	Electron mass, kg
M	=	Magnetic moment, Tm^3
μ_0	=	Magnetic permeability (1.26x10^{-6} H/m)
n	=	Plasma density, m^{-3}
N	=	Solar wind density, m^{-3}
r_{iL}	=	Ion larmor radius at magnetopause, m
r_{eL}	=	Electron larmor radius at magnetopause, m
R_{coil}	=	Coil radius, m
R_{plasma}	=	Plasma current radius, m
T	=	Plasma temperature, K
v	=	Particle velocity, m/s
V	=	Solar wind velocity, m/s

I. Introduction

MAGNETIC Sail [1] is a spacecraft propulsion system using the interaction between the magnetic field and the solar wind. Zuburin et al. [1] conceptually designed a spacecraft with a large hoop superconductive coil, which could produce an artificial magnetic cavity (magnetosphere) to reflect the solar wind particles approaching the coil. Due to this interaction, the solar wind flow will lose its momentum, and a corresponding repulsive force would exert on the coil to accelerate the magnetic sail spacecraft in the anti-sun direction without consuming fuels. In addition, Winglee et al. [2] proposed MPS (Magnetic Plasma Sail), or M2P2 (Mini Magneto Plasma Propulsion). As shown in Fig. 1, MPS inflates the original magnetic field by a plasma injection from the spacecraft and MPS is expected to be able to provide a large thrust with a small coil size.

Zubrin et al. [1] theoretically estimated that a 20 N-class magnetic sail is possible by making a 100-km diameter magnetosphere. Following the estimation, several numerical simulations and laboratory experiments have been performed to confirm the thrust of Magnetic Sail and MPS. For a very large magnetosphere, where the ion finite Larmor radius effect can be neglected (MHD scale), MHD simulations are appropriate to evaluate the thrust with the single fluid approximation. The thrust generation mechanism of magnetic sail is revealed by MHD simulations by Nishida et al. [3]. If the ion finite Larmor radius effect should be considered (Ion inertial scale), Hybrid-PIC (Particle-In-Cell) simulations, which treat ions as particles and electrons as a fluid, are used [4]. The thrust characteristics and the experimental formula of the magnetic sail are obtained at Ion inertial scale [5]. In addition, the laboratory experiment using the scale model was performed [6] and Kajimura et al. [7] confirmed the experimental results by the numerical simulation using Hybrid-PIC. As for MPS, MHD simulations [8] and Hybrid-PIC simulations [9] ware also performed. The magnetosphere was inflated and the thrust enhancement was confirmed by using the high-beta plasma injection. However the efficiency of thrust generation is lower than ideal ion thruster and more efficient plasma inflation technique such as using low-beta plasma is required.

In the present study, we conduct a 2D Full-PIC simulation for a very small magnetosphere (several 100 m to several 1000 m, Electron inertial scale) generated by MPS demonstrator spacecraft (Fig. 2) since the thrust characteristics at this scale are still unknown. The Full-PIC simulation treats both ions and electrons as particles and charge separation is considered [10]. Hence, we particularly analyze the MPS in terms of how the thrust is affected by charge separation and what injection plasma parameters enhance the thrust efficiently. In addition, MPS is simulated under both high-beta and low-beta plasma injection cases.

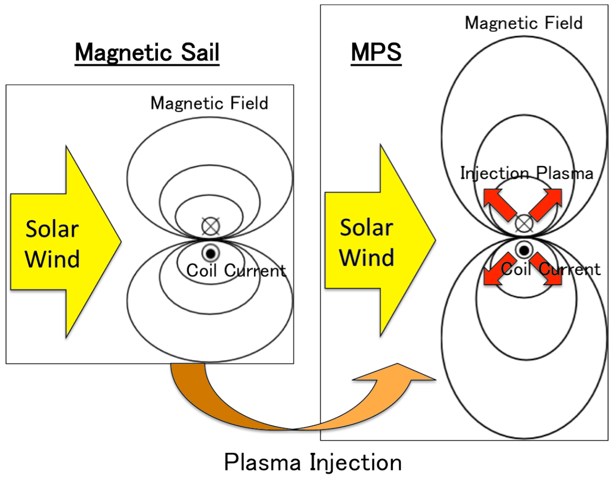

Figure 1. Schematic illustration of Magnetic Sail and MPS. *MPS inflates the magnetosphere around spacecraft by a little plasma injection.*

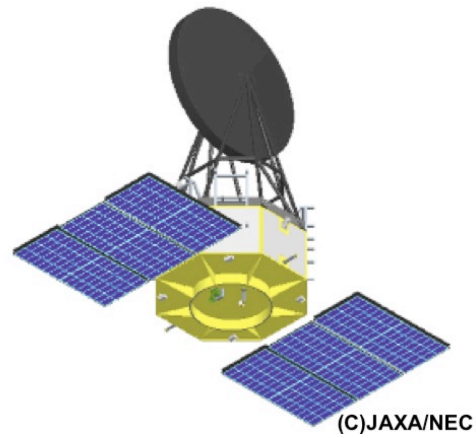

Figure 2. Demonstrator spacecraft of MPS proposed by JAXA MPS working group. *The superconductive coil (r_{coil}=2 m, I_{coil}=200 A* x *1000 Turn) is shaded from solar radiation.*

II. Numerical Model

A. Solar wind properties

The solar wind mainly consists of ions (protons) and electrons. The typical parameters of the solar wind at Earth orbit are listed in Table 1. The ion mean free path δ is approximately 1.5×10^8 km and it is much longer than the typical length of a magnetosphere L (100 m at Electron inertial scale to 1000 km at MHD scale). Hence, direct collisions between particles can be neglected in magnetic sail simulations. However, solar wind plasma particles change their momentum through wave-particle interaction, nevertheless $\delta \gg L$. That is, particles change their energy each other through electromagnetic waves. Here magnetospheric size L is analytically calculated as Eq. (1) from the force balance of the magnetic pressure and the solar wind dynamic pressure.

$$L = \sqrt[6]{\frac{\mu_0 M^2}{16\pi^2 N m_i V^2}} \tag{1}$$

In addition, solar wind plasma particles make a Larmor motion by a magnetic field such as a magnetosphere and interplanetary magnetic field (IMF). Interplanetary magnetic field comes form the Sun. The magnitude and the direction of IMF vary in time and it is expected that IMF has some effects about the thrust and attitude of magnetic sail. When the typical parameters of the solar wind is assumed, the magnetic flux density at the boundary of a magnetosphere (magnetopause) is estimated approximately as 40 nT. Then the ion Larmor radius at the magnetopause is calculated as r_{iL}=100 km and the electron Larmor radius is calculated as r_{eL}=50 m. If L and ion Larmor radius r_{iL} satisfy the condition, $L \gg r_{iL}$, the finite Larmor effect can be neglected and the plasma flow can be treated as a single fluid as MHD simulations. If L and r_{iL} are comparable and $L \gg r_{eL}$ at the magnetopause, ion's finite Larmor radius effect should be considered and electron motion can be assumed as a fluid in Hybrid-PIC simulations. When L and r_{eL} are comparable, both ion's and electron's finite Larmor radius effect should be considered as Full-PIC simulations.

In this research, the magnetic sail and magneto plasma sail (MPS) with very small magnetosphere such as several 100 m (Electron inertial scale) are targeted as the MPS demonstrator spacecraft. In these magnetosphere, the both ion's and electron's Larmor motion affect the MPS thrust generation and the magnetosphere formation. Therefore Full-PIC simulation is required to reveal the mechanism of MPS thrust generation.

Table 1. Typical solar wind parameters at Earth orbit.

Solar wind velocity V	500 km/s
Solar wind density N	5 particles/cm^2
Plasma temperature T	10 eV

B. Full-PIC model

Full-PIC simulation [10] treats both ions and electrons as particles in order to consider the finite Larmor radius effects. In addition, charge separation and an effect of the electric field of the magnetopause are considered. Then the Full-PIC simulation solves the time-evolution of each particle, ion and electron, by the momentum equation, Eq. (2), using Buneman-Boris method and the electromagnetic field by the Maxwell equations, Eqs. (3) and (4) using FDTD method. The electric field is corrected electrostatically by Poisson' equation in order to conserve the energy. The 2D coordinate system used for Full-PIC simulations is shown in Fig. 3. The coil currents are defined at grid points and the self-consistent magnetic field is calculated. Solar wind direction is defined along the z-axis. Each boundary condition is also set as shown. Inflow boundary for particles is set in upstream of the solar wind and outflow boundary is set in other boundaries. Electromagnetic waves are absorbed by all boundaries. In addition, the plasma injection point for the MPS simulation is also defined at the grid points.

$$m_s \frac{d\mathbf{v}_s}{dt} = e\left(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}\right) \quad s = \text{ion, electron} \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \tag{3}$$

$$\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{J} \tag{4}$$

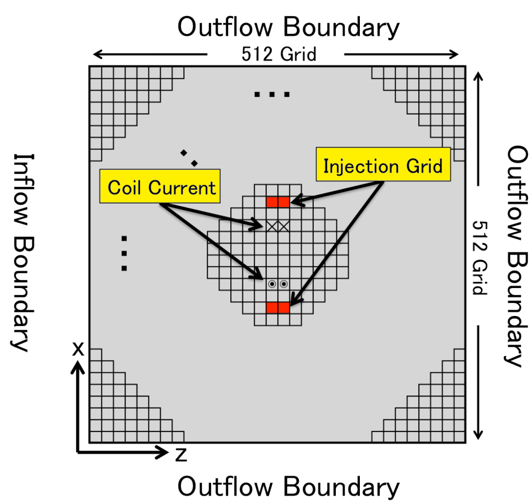

Figure 3. Analysis model for Magnetic Sail and MPS. *Solar wind inflow boundary and outflow boundaries are set. Coil current and plasma injection point for MPS is also defined on a grid.*

III. Numerical Results of Magnetic Sail

A. Magnetic Sail

First, we checked how simulation results are affected by the mass ratio of ion and electron, m_i/m_e. In the real mass ratio, ion (proton) is 1836 times heavier than electron. However, in order to keep a computational effort low, m_i/m_e=10 to 100 is often preferred. Hence, two simulations with m_i/m_e=1836 and m_i/m_e=100 are performed to evaluate the thrust of the magnetic sail. Here, electrons are 18.36 times heavier than the real mass in the case of m_i/m_e=100. Parameters about the solar wind are listed in Table 1 and parameters about the coil of the magnetic sail are listed in Table 2. The magnetic moment of the coil is assumed parallel to the solar wind direction.

Table 2. Parameters about the coil of magnetic sail, *L*=1.4 km.

Current I_{coil}	8×10^3 A Turn
Radius R_{coil}	15 m
Magnetic moment M	2.4×10^6 Wbm/m

The results are shown in Fig. 4. The magnetospheric size (blocking area size) in the case of m_i/m_e=1836, Fig. 4 (a), is approximately 2 times larger than that in the case of m_i/m_e=100, Fig. 4 (b). Furthermore, the thrust of the magnetic sail in case of m_i/m_e=1836 is calculated as 2.0 μN/m and that in case of m_i/m_e=100 is calculated as 0.6 μN/m. As a result, the mass ratio has a significant influence on the formation of magnetosphere and thrust generation. In addition, checking the detail of each ion and electron motion, ions are scattered by the static electric field due to the charge separation at the boundary of the magnetosphere and electrons are scattered by the magnetic field during their Larmor motions. As the mass ratio becomes smaller, the static electric field due to the charge separation at the boundary of the magnetosphere becomes weaker since more electrons penetrate into the deeper magnetosphere and fewer ions are scattered by the electric field. This difference results in the smaller thrust in case of m_i/m_e=100.

For this reason, we performed several simulations about magnetic sail and MPS with the real mass ratio, m_i/m_e=1836 in order to declare the thrust characteristics of magnetic sail in the latter sections.

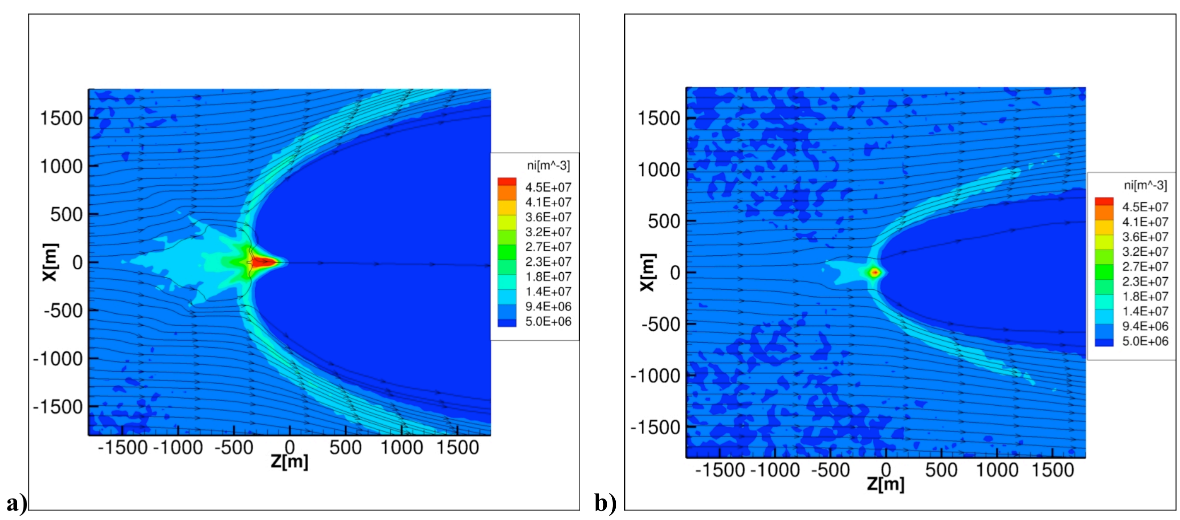

Figure 4. Density distribution of ion and streamline for different mass ratio (m_i/m_e) cases: *a) result for m_i/m_e=1836, b) result for m_i/m_e=100 (L=1.4 km, magnetic moment // solar wind). The wake where particles can't penetrate is formed. The size of wake is affected by the mass ratio of ion and electron.*

B. Thrust characteristics of Magnetic sail

Next, the thrust characteristics about magnetospheric size L are analyzed. The magnetospheric size varies from 200 m to 5500 m according to the coil current. The magnetic moment of the magnetic sail is assumed parallel to the solar wind. Results are shown in Fig. 5. The solid line shows the thrust of the magnetic sail. The thrust becomes lager rapidly as the magnetospheric size becomes larger since more particles are scatted by the magnetosphere and particles lose their momentum. These thrusts are evaluated by calculating drag coefficient C_d defined by Eq. (5) and C_d is shown with the dotted line in Fig. 5. C_d becomes larger rapidly from L=1.4 km to 2.7 km. In these smaller magnetospheres, ions are scattered by the electric field due to charge separation. The change rate of C_d from 2.7 km to 5.5 km becomes smaller than that from 1.4 km to 2.7 km. This is because particles are scattered by not only the electric field at the magnetopause but also the magnetic field. As the magnetospheric size becomes larger, it is expected that more particles should be scattered by the magnetic field rather than the electric field. It is also expected that C_d becomes constant as the magnetospheric size become larger. Thus, it is assumed that the mechanism how the magnetic sail generates the thrust depends on the magnetospheric size.

$$C_d = \frac{F}{0.5 m_i N V^2 (2L)} \tag{5}$$

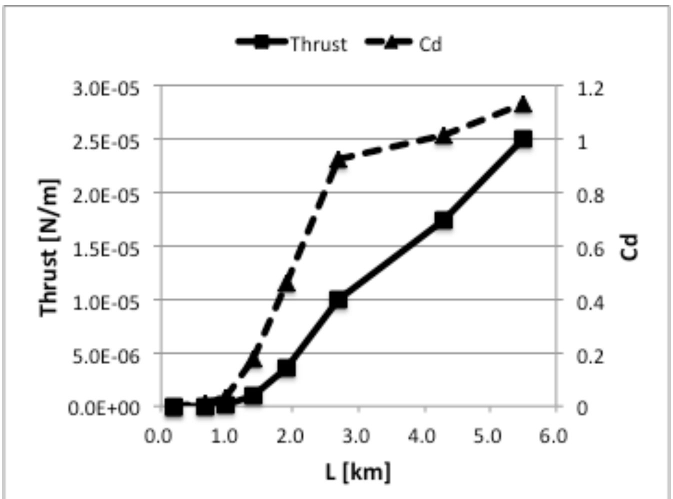

Figure 5. Thrust characteristics of magnetic sails with different magnetospheric size. *The magnetospheric size varied from 0.2 km to 5.5 km by changing coil current.*

IV. Numerical Results of Magneto Plasma Sail

A. Magneto Plasma Sail

Magneto plasma sail inflates magnetic field by the plasma injection from the spacecraft. If the high kinetic beta plasma is injected, the magnetic field extends by the frozen-in of plasma according to the Eq. (6) at MHD scale. Here, kinetic beta is defined as Eq. (7)

$$\frac{\partial B}{\partial t} = -\nabla \times \left(v \times B \right) + \frac{1}{\sigma\mu} \Delta B \tag{6}$$

$$\left(\frac{1}{2} n_i m_i v_i^2 + \frac{1}{2} n_e m_e v_e^2 \right) \Big/ \left(\frac{B^2}{2\mu_0} \right) \tag{7}$$

Simulation results at Electron inertial scale are shown in Fig. 6. The solar wind parameters and coil parameters are same with the parameters listed in Table 1 and Table 2. The coil magnetic moment is set parallel to the solar wind direction. Injection plasma parameters are also listed in Table 3. As shown in Fig. 3, the plasma injection grids are defined around the coil current and particles are added to the grids to fulfill the constant mass flow in Table 3. Plasma is injected toward the magnetic equator in both Case 1 and Case 2. Case 1 indicates the case for high beta and high-energy plasma injection and Case 2 indicates the case for low beta and law-energy plasma injection. As a result, the thrust of 5 μN/m is obtained in Case 2, which is 2.5 times larger than the thrust without plasma injection, 2 μN/m. On the contrary, the thrust obtained in Case 1 is still 2 μN/m and the increase of the thrust by the plasma injection is not observed. The density distribution of ion, the streamline of the plasma flow and the distribution of kinetic beta in Case 1 and Case 2 are shown in Fig. 6. In Fig. 6 (a) for Case 1, the magnetosphere becomes slightly larger than the original magnetosphere shown in Fig. 4 (a). In Fig. 6 (c) for Case 2, the magnetosphere also becomes larger. In addition, the very high-density region is formed around injection point. Fig 6 (b) and (d) represents the distribution of kinetic beta in Case 1 and Case 2. Around plasma injection grids, kinetic beta is high in Case 1, that is, Larmar radius is larger. On the contrary, kinetic beta is low around injection grids in Case 2. The injected plasma is magnetized strongly in the condition of r_L<B/∇B in Case 2. In Case 1, the injected plasma does not meet r_L<B/∇B and the particles can not be accumulated inside magnetosphere. As a result, the plasma current, which is mainly induced by ∇B drift and curvature drift of electron, becomes larger in Case 2. The efficiency of the MPS is considered as "(MPS thrust) / (original magnetic sail thrust + pure plasma injection thrust)". In Case 1, the efficiency is calculated as 40 % by using the pure plasma injection thrust of 3 μN/m. In Case 2, the efficiency is calculated as 200 % by using the pure plasma injection thrust of 0.5 μN/m. Thus, the MPS at Electron inertial scale with low beta and law-energy plasma injection can enhance the thrust efficiently and the different mechanism of magnetosphere inflation from MHD scale is dominant.

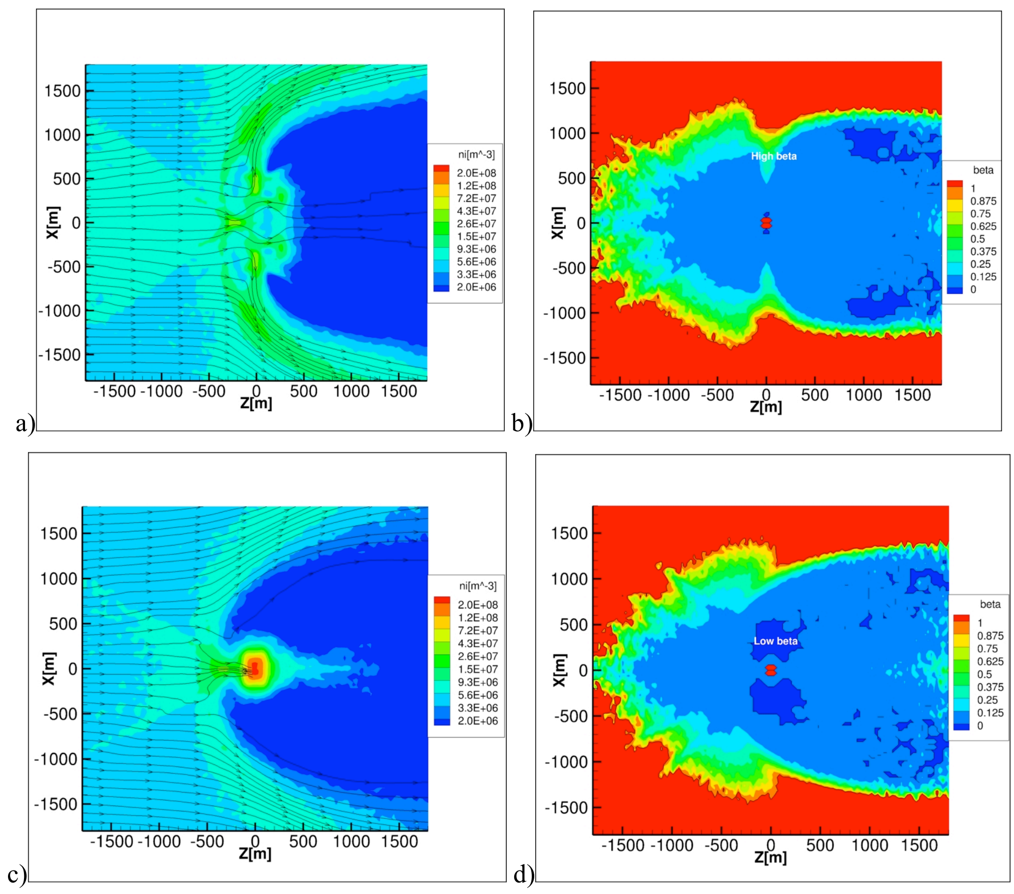

Figure 6. **Distribution of ion density and kinetic beta**: *a, b) result for Case 1 (MPS) with high beta and high-energy plasma injection and c, d) result for Case 2 (MPS) with low beta and low-energy plasma injection (L=1.4 km, magnetic moment // solar wind).*

Table 3. Simulation parameters used for the thrust estimation of the MPS: *Case 1 is the case for high beta and high-energy plasma injection; Case 2 is the case for low beta and low-energy plasma injection; Case 3 is the case for high-energy electron beam injection.*

Parameters	Case 1	Case 2	Case 3
Injection plasma velocity	5000 km/s	500 km/s	Electron 50000 km/s Ion 50 km/s
Injection plasma density	5 particles/cm^2	0.5 particles/cm^2	50 particles/cm^2
Injection plasma temperature	10 eV	1 eV	100 eV
Magnetic moment direction	Parallel	Parallel	Perpendicular

In addition, in Case 3, in which the magnetic moment of the coil is perpendicular to the solar wind direction, more efficient thrust generation is observed. Coil parameters are also adjusted as shown in Table 4. We note that the parameters indicate low beta plasma injection nevertheless the electron has large speed since the electron mass is 1836 times lighter than the ion mass. The electron velocity and the ion velocity are set differently in order to meet both r_{iL}<B/∇B and r_{eL}<B/∇B. Under this condition, both ions and electrons injected from the MPS spacecraft are trapped by the magnetic field. Electrons mainly make ∇B drift and curvature drift motion in the magnetosphere and the strong plasma current is formed around the coil to enhance the original magnetic field. As a result, the magnetosphere becomes larger. Time history of the magnetosphere inflation is shown in Fig. 7. As time passed and the total amount of injected plasma trapped inner magnetosphere increased, the magnetospheric size becomes larger. The solar wind flow is also bended by the enhanced magnetic field and loses its momentum to generate larger thrust. The one-dimensional profiles of magnetic flux density and ion density along z-axis (x=0) are shown in Fig. 8. The magnetospheric size of MPS becomes 3 times larger than original magnetospheric size of magnetic sail and it becomes 2700 m from 900 m as shown in Fig. 8 (a). The higher density around the origin represents the injected plasma trapped by the magnetic field. The thrust is calculated as 15 μN/m that is 5 times larger than the magnetic sail thrust, 3 μN/m. The efficiency is also calculated as 270 %. The equatorial ring current is formed around z=150 m and z=-150 m by the plasma injection. The current enhances the magnetic field outside of the current and reduce the magnetic field inside of the current as shown in Fig. 8 (b). Then the total magnetic moment by the coil current and the plasma current becomes 4.6 times larger than the magnetic moment by the coil current.

Table 4. Parameters about the coil of magnetic sail in Case 3, *L*=2.0 km.

Current I_{coil}	4×10^3 A Turn
Radius R_{coil}	75 m
Magnetic moment M	6.0×10^6 Wbm/m

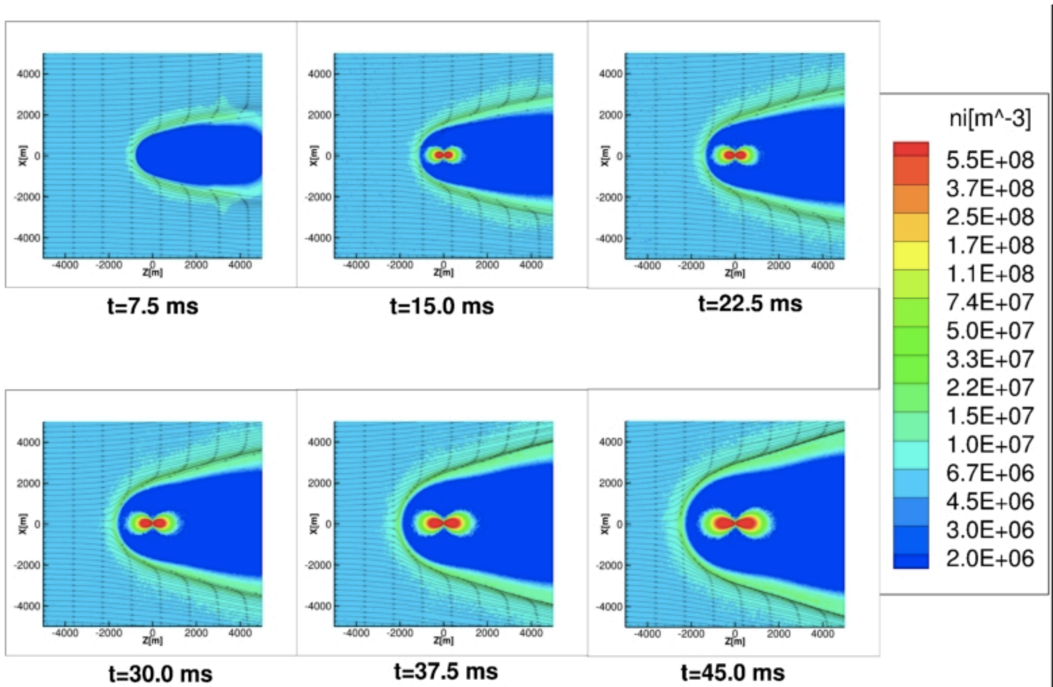

Figure 7. Time history of the MPS magnetosphere in Case 3 (L=2.0 km, magnetic moment ⊥ solar wind). *As time passing, the magnetosphere size (blocking area size) of MPS becomes larger. The plasma injection starts after t=7.5 ms.*

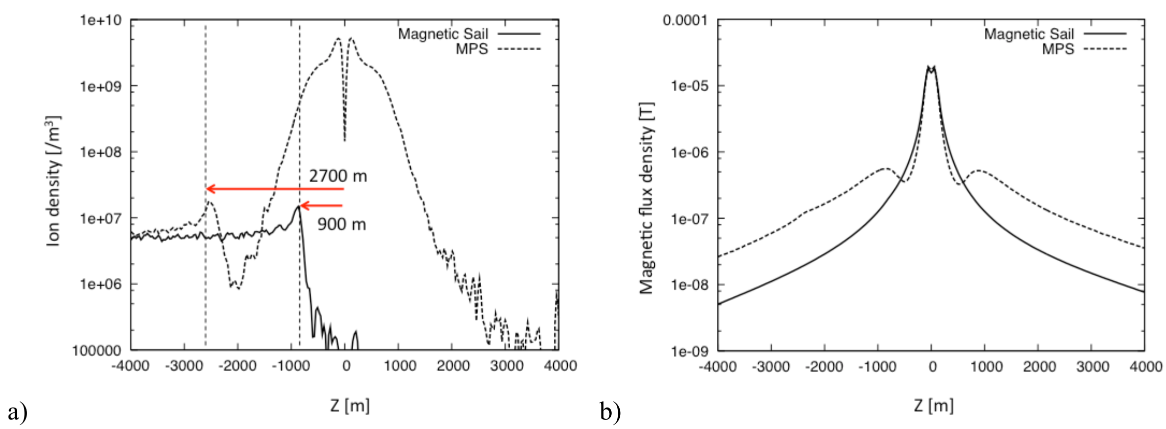

Figure 8. Density distribution of ion and magnetic flux density along z-axis (x=0) for the perpendicular case (magnetic moment ⊥ solar wind). *a) represents ion density of magnetic sail (solid line) and MPS (dotted line). b) represents magnetic flux density of magnetic sail (solid line) and MPS (dotted line).*

B. Discussion

The upper limit of the magnetic moment in 2D is estimated by the simplest assumption as shown in Fig. 9. The plasma current induced by the plasma injection is represented by the opposed line current that flows in the same direction with the coil current. The force applied on the plasma current I_{plasma} is simply calculated as Eq. (8). When the forces are balanced and the plasma current becomes stable, the ratio of the coil current I_{coil} and the plasma current I_{plasma} is calculated as Eq. (9). The total magnetic moment by the coil current and the plasma current is calculated as Eq. (10) by using Eq. (9). The figures in parenthesis mean the scaling factor of the magnetic moment. When parameters used in the simulation (R_{coil}=75 m and R_{plasma}=150 m) are substituted, the factor becomes 6.3. That is, the plasma current is able to enhance the original magnetic moment 6.3 times larger. In fact, the simulation result with high-energy electron achieved 4.6 times larger magnetic moment than the original. In addition, it is found from Eq. (10) that the increase ratio of the magnetic field becomes larger as the plasma injection point becomes nearer the coil.

$$F = \frac{\mu_0}{2\pi}\left(-\frac{I_{coil}I_{plasma}}{R_{plasma}-R_{coil}} + \frac{I_{coil}I_{plasma}}{R_{plasma}+R_{coil}} + \frac{I_{plasma}I_{plasma}}{2R_{plsma}} \right) \tag{8}$$

$$\frac{I_{plasma}}{I_{coil}} = \frac{4R_{plasma}R_{coil}}{R_{plasma}^2 - R_{coil}^2} \tag{9}$$

$$R_{coil}I_{coil} + R_{plasma}I_{plasma} = R_{coil}I_{coil}\left(1 + \frac{4R_{plasma}^2}{R_{plasma}^2 - R_{coil}^2}\right) \tag{10}$$

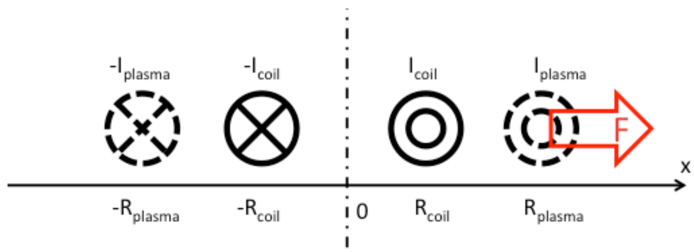

Figure 9. Simplest current model of the MPS. *Along the x-axis, finite opposite currents are defined. The current at x=+R_{coil} and x=-R_{coi}l represents the coil and the current at x=+R_{plasma} and x=-R_{plasma} represents the plasma current induced by plasma injection. The double circle means interior current and the cross-circle means exterior current. The current width and distribution is ignored for simplicity.*

V. Conclusion

We performed 2D Full-PIC simulations for magnetic sail and magneto plasma sail (MPS) with very small artificial magnetosphere in which the electron's finite Larmor radius effect and charge separation between ion and electron become significant. The electron's finite Larmor effect was confirmed by the simulations with the different mass ratio and it is found that electrons give the magnetosphere formation the major influence at Electron inertial scale. The thrust characteristics of very small magnetic sail was obtained by the simulations with 8 magnetosphere sizes. MPS simulations also revealed that the MPS could generate efficient thrust. The MPS thrust was calculated by using three characteristic parameter sets. As a result, the equatorial ring current induced by high-energy electron efficiently enhanced the original magnetic field. The thrust of MPS (15 μN/m) becomes up to 5 times larger than the original thrust of magnetic sail (3 μN/m). The efficiency defined as MPS thrust / (Magnetic sail thrust + Plasma injection) is 270 %. In addition, it is expected by the simplest assumption that the MPS thrust could become larger by adjusting the plasma injection point.

Acknowledgments

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