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Numerical Evaluation of Ring Current Inflation for the Application of Magneto Plasma Sail

磁気プラズマセイルへの応用に向けたコイル磁場中のリングカレント生成による磁気圏拡大評価

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Magneto Plasma sail is a space propulsion system which can obtain the electromagnetic force from the interaction between the solar wind plasma and the magnetic field inflated by plasma injection from MPS spacecraft. In the present paper, the increase of the magnetic moment generated by the grad-B drift current of injected thermal plasma has been estimated by 1D, steady state, diffusion equation. Under the assumption of plasma fluid approximation, MPS (coil radius is 2 m, coil current is 10^6 A turn) is expected to obtain the thrust of 10 mN by the ring current inflation when the injected thermal plasma density is 1.5×10^{23} m^{-3}, the temperature is 10 eV.

1. Introduction

A space propulsion system with large thrust, high thrust to power ratio and high specific impulse has been required for deeper space exploration missions. As one of candidates of the space propulsion system for these requirements, Magneto Plasma Sail (MPS) has been proposed [1]. The MPS can obtain the electromagnetic propulsive force by the interaction between the solar wind and an artificially generated dipolar magnetic field inflated by the plasma injection from the spacecraft. By using MagnetoHydroDynamics (MHD) model, Nishida has simulated the thrust production mechanism of the MPS, wherein magnetic inflation is achieved by the plasma injection from the spacecraft [2]. If the MPS spacecraft is surrounded by a radial super-Alfvenic flow of the injected plasma (i.e. Mach Number M_a^2 = plasma beta > 1), it seems that no information is transferred upstream (i.e., to the spacecraft); this implies that the electromagnetic (Lorentz) force (thrust) cannot be transferred to the MPS spacecraft. In addition, Kajimura has conducted the Hybrid PIC simulations for evaluating the MPS thrust and then the simulation results indicating the same tendency of MHD results have been obtained [3]. In addition, it is found that the MPS thrust was comparable to the sum of MPS thrust without injection and the thrust in case for direct plasma injection from the spacecraft. Hence, it is necessary for achieving the magnetic inflation by the plasma with lower energy to inject the plasma with static pressure not dynamic pressure.

If the thermal plasma only with static pressure is injected from the spacecraft, the gradient-***B*** drift current (this is the ring current) is induced. This current can be seen the magnetosphere of the earth. The conceptual sketch of the ring current generation is shown in Fig. 1. In the present study, the increase of the magnetic moment generated by the ring current is estimated by the simple 1D, steady state, diffusion equation. Then the expected thrust value of MPS is calculated from the thrust formula depending on the magnetic moment.

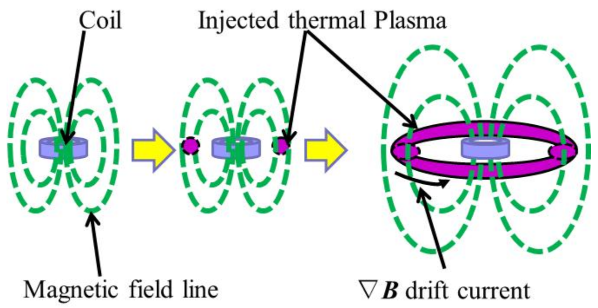

Fig.1. Conceptual sketch of ring current inflation

2. Evaluation of the ring current using 1D steady state diffusion equation.

The simple structure of the ring current in the magnetic field produced by the coil is assumed as shown in Fig. 2. The thermal plasma is injected from the location of the surface of the coil and then the plasma distributes following the 1D, steady state and diffusion equation of Eq. (1). In this equation, D_B indicates the Bohn diffusion coefficient proportional to r^3 ($D_B \propto 1/\boldsymbol{B} \propto r^3$), r is the distance from coil center.

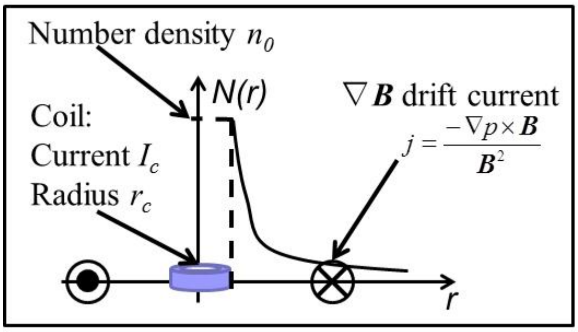

Fig.2. Simple model of structure of ring current.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(D_B r^2 \frac{\partial n}{\partial r}\right) = 0 \quad (1)$$

The diffusion equation (1) for the density is solved on the boundary condition ($r = R$, $n = n_0$ and $r = \infty$, $n = 0$). R is the injection location and n_0 is the number density of injection plasma. The number density and pressure distribution are Eq. (2) and (3).

$$n(r) = n_0 R^4 r^{-4} \quad (2)$$

$$P(r) = n_0 T R^4 r^{-4} \quad (3)$$

The ring current i.e. gradient $\boldsymbol{B}$ drift current is calculated by Eq. (4) substituting Eq. (2) and (3). T is the temperature of the injected plasma. M_0 is the original magnetic moment.

$$|j| = \left|\frac{\nabla p}{\mathrm{B}}\right| = \frac{16\pi n_0 T R^4}{\mu_0 M_0}\frac{1}{r^2} \quad \left(\mathrm{B} = \frac{\mu_0 M_0}{4\pi r^3}\right) \quad (4)$$

The magnetic moment M_p produced by this ring current j is calculated from Eq. (5) and the ratio of this magnetic moment to the original magnetic moment is defined as Eq. (6).

$$M_p = \int_R^{R_{out}} \pi r^2 j r d\theta dr = \int_R^{R_{out}} dr d\theta \frac{16\pi n_0 T R^4}{\mu_0 M} r$$
$$= \frac{8\pi n_0 T R^4}{\mu_0 M_0}\left[R_{out}^2 - R^2\right] d\theta \quad (5)$$

$$M_p \big/ M_0 = \frac{16 n_0 k T R^4}{\mu_0 r_c^4 I_c^2}\left[R_{out}^2 - R^2\right] \quad (6)$$

3. Thrust estimation of MPS

The thrust obtained in MPS can be calculated by Eq. (7). Fujita [4] proposed an approximate formula Eq. (8) for the drag coefficient C_d as a function of r_{Li}/L. r_{Li} is the ion Larmor radius at the magnetospheric boundary which location is defined as the distance L from the boundary to the coil center. In the present case, the distance L increases to L_{inf} by the ring current inflation.

$$F = C_d \cdot 0.5 \cdot n_{sw} m v_{sw}^2 \left(\pi L_{\boldsymbol{inf}}^2\right) \quad (7)$$

$$C_d = \frac{3.4}{\left(r_{Li}/L_{\boldsymbol{inf}}\right)} \cdot \boldsymbol{exp}\left(\frac{-0.22}{\left(r_{Li}/L_{\boldsymbol{inf}}\right)^2}\right) \quad \left(r_{Li}/L_{\boldsymbol{inf}} > 1\right) \quad (8)$$

$$L_{\boldsymbol{inf}} = \left(\frac{\mu_0\left(M_p + M_0\right)^2}{8 n_{sw} m v_{sw}^2}\right)^{1/6} \quad (9)$$

Figure 3 shows the MPS thrust depending on I_c and T and n_0.Under the plasma fluid approximation, MPS (coil radius is 2 m, coil current is 10^6 A turn) is expected to obtain the thrust of 10 mN by the ring current inflation when the injected thermal plasma density is 1.5×10^{23} m^{-3}, the temperature is 10 eV. The number density n_{sw}, velocity v_{sw}, and the temperature T_{sw} of the solar wind is 5×10^6 m^{-3}, 400 km/s and 10 eV, respectively.

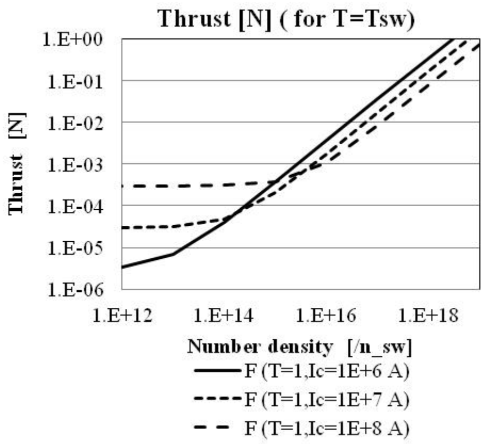

Fig.3. Thrust depending on Ic and T and N_sw.

Acknowledgments

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