

Experimental Investigation of Magnetoplasma Sail: Magnetosphere Inflation by Equatorial Ring Current

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Abstract: Magnetoplasma sail (MPS) is a deep space propulsion system, in which an artificial magnetosphere captures the energy of the solar wind to propel a spacecraft. In order to inflate the original magnetosphere, the magnetosphere inflation method by a plasma injection from spacecraft is proposed. This paper describes experimental result of the ring current type magnetosphere inflation. The ring current is equatorial current loop encircling the spacecraft (coil), and the direction of the ring current is same direction as the coil current. The ring current is generated by injecting low kinetic beta plasma magnetizing, and the magnetic field strength is increased by the ring current. We employed a magnetoplasma dynamic arcjet (MPD arcjet) as an inflation plasma source. We generate the low kinetic beta plasma by blocking the plasma flow generated by MPD arcjet (10^{19} m^{-3} , 1 eV, and 0.1 g/s) using the defense wall. The solenoid coil ($\phi 280 \text{ mm}$ and 120 turn) is employed as a MPS spacecraft. The plasma current and the magnetic field are measured by the probe diagnostics. It was proved that the ring current was generated by injecting plasma to a coil magnetic field. The increasing rate of magnetic field is about 1.3 in this study. It was proved that the magnetosphere is inflated by the ring current.

Nomenclature

B	=	Magnetic field, T
F	=	Thrust, N
C_d	=	Thrust coefficient
J	=	Current, A
L	=	Magnetospheric size, m
M	=	Magnetic moment, Tm^3
M_{alf}	=	Alfven Mach number
P	=	Plasma pressure, Pa
r_c	=	Coil radius, m
r_L	=	Larmor radius, m
β	=	Beta
ρ	=	Density, kg/m^3

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I. Introduction

For deep space exploration, a variety of spacecraft propulsion systems were proposed and some of them are under study. One of the next-generation interplanetary propulsion systems is Magnetoplasma Sail (MPS) capturing the solar wind energy as shown Fig.1¹. MPS blocks the solar wind plasma flow by an artificially magnetic cavity and converts the solar wind momentum into the momentum of the spacecraft. The thrust of the MPS is given by,

$$F = C_d \frac{1}{2} \rho_{sw} u_{sw}^2 (\pi L^2) \quad (1)$$

where F is the thrust of the MPS, C_d is thrust coefficient, $1/2 \rho_{sw} u_{sw}^2$ is the dynamic pressure of the solar wind and L is the magnetospheric size. Thrust of the MPS is proportional to the square of the magnetospheric size L (Fig.1) as shown Equation 1.

The magnetospheric size L is proportional to $M^{1/6}$, where $M = \mu_0 n J r_c$ is magnetic moment. Hence, the large current J , a coil with large diameter r_c or many coil turns n are required for a high thrust level (for example, $r_c > 1$ km, $nJ \sim 100000$ ATurn to 1N class). The idea to expand the magnetosphere by the plasma injection was proposed instead of employing a huge coil by Winglee¹. This phenomenon is called the magnetosphere inflation. In previous researches, thrust measurement of MPS without plasma injection was conducted². However, the sufficient magnetosphere inflation was not achieved and the magnetosphere inflation rate (L with plasma injection / L without plasma injection) was only several percent³. The conventional magnetosphere inflation used “Frozen-in magnetic field” to plasma flow, and it was inflated by the high kinetic β plasma⁴. But this method has several problems, one is that magnetopause current is negated by the plasma flow and the thrust of MPS becomes 0 by high Alfvén Mach number plasma ($M_{alf} > 0.1$)⁵. As other problems, the thrust increment by magnetosphere inflation is not so larger than the cases which converted plasma flow into the thrust. This paper presents the experimental results of new type magnetosphere inflation, which we call the ring current type magnetosphere inflation.

Ring current is equatorial current loop encircling the spacecraft (coil) of same direction as the coil current. It is caused by the charged particles trapped in a magnetic field. The component of the ring current is shown follows

$$\mathbf{J}_{ring} = \mathbf{J}_M + \mathbf{J}_B + \mathbf{J}_c = \frac{\mathbf{B}}{B^2} \times \left[\nabla P_{\perp} + (P_{\parallel} - P_{\perp}) \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{B^2} \right] \quad (2)$$

where $\mathbf{J}_M$ is the magnetization current, $\mathbf{J}_B$ is the grad B current, $\mathbf{J}_c$ is the curvature current, $P_{\perp}$ is the perpendicular pressure to the magnetic field and $P_{\parallel}$ is the parallel pressure to the magnetic field⁶. Equation 2 is neglected the polarization current. If the plasma pressure is isotropic ($P_{\parallel} = P_{\perp}$), Equation 2 remains only grad P current. The ring current is corresponded to the diamagnetic current in ideal magnetohydrodynamic. Outside of the ring current, the magnetic field of the ring current cooperates with and strengthens the coil magnetic dipole field. Therefore, the ring current enhances a distant magnetic field and a subsequent inflation of the magnetosphere. In this paper, the demonstration experiment of the magnetosphere inflation by the ring current is conducted. The object of this paper is to prove the magnetosphere inflation by the ring current.

II. Experimental Methods

Experimental setup for this study, shown in Fig.2, consists of a vacuum chamber, a pulse forming network (PFN), a gas supply system, the plasma source for the magnetosphere inflation, a coil simulated the MPS spacecraft and the measuring system. We selected the Mini-MPD arcjet as a plasma source for the magnetosphere inflation. The MPD arcjet can generate the high density plasma. The Mini-MPD arcjet consists of copper anode (24 mm in diameter), a thoriated tungsten cathode rod 11 mm in diameter, they are surrounded by insulators body. A PFN for the Mini-MPD arcjet supplies the discharge current up to 15 kA with a 0.8 ms flat-topped waveform in quasi-steady mode. A high-speed solenoid valve allowed us to feed gaseous propellants featuring a rectangular waveform. The high-speed

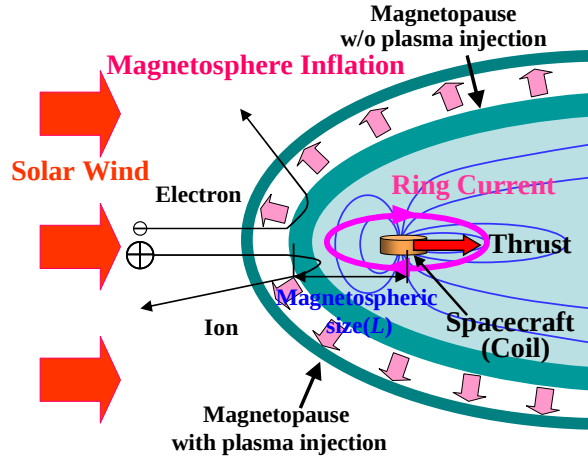


Figure 1. Magnetoplasma sail.

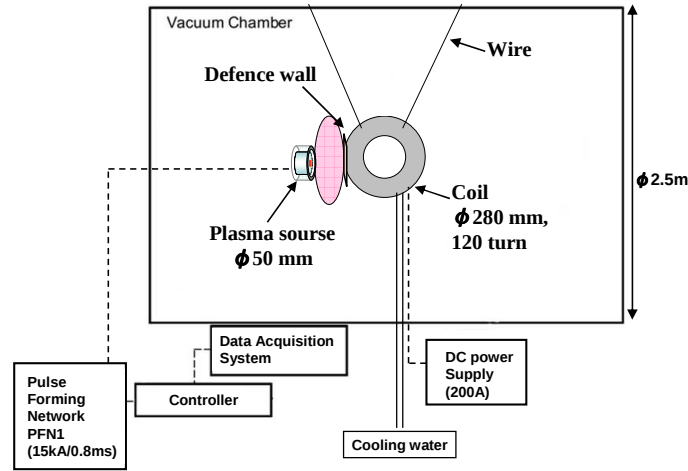


Figure 2. Schematics of magnetic sail experimental facility.

solenoid valve opens and closes valve and the gas in the reservoir flows through choked orifices of 3 mm in diameter. The mass flow rate of hydrogen gas is controlled by adjusting the reservoir pressures, obtaining a gas pulse of about 5 ms, and the flow rate is 0.1 g/s in this experiment. The 280-mm-diameter and 120-turn solenoid coil is selected for the MPS spacecraft simulator. The coil is supplied by the DC power supply, and the maximum current is 200 A. The coil current is 0, 100, 200 A in this study. The coil is directly cooled using the copper tube. This coil is suspended at the center of the vacuum chamber using a wire. In order to generate the ring current, the low kinetic β plasma is required. It is because Larmor radius must be small enough in order to magnetize a charged particle. However, the MPD arcjet is accelerated to the supersonic flow. We generate the low kinetic β plasma by blocking the plasma flow generated by MPD arcjet using the defence wall, as shown Fig.2. The distance between the Mini-MPD arcjet and the defence wall is 50 mm. The number density and the electron temperature at the distance 50 mm from the Mini-MPD arcjet are 10^{19} m^{-3} and 1 eV. The experimental parameter is shown Table.1.

Table.1 Experimental parameter.
(Measurement position is distance 50 mm from the Mini-MPD arcjet.)

Mini-MPD arcjet	
Discharge current	7 kA
Electron number density	$\sim 10^{19} \text{ m}^{-3}$
Electron temperature	$\sim 1 \text{ eV}$
Thermal velocity	$\sim 15 \text{ km/s}$
Coil	
Diameter	$\phi 280 \text{ mm}$
Turn number	120
Current	0, 100, 200 A
Magnetic moment M	$\sim 0.0013 \text{ Tm}^3$
Nondimensional Parameter	
Thermal β	~ 0.014
r_L/L	0.03

The coil is constantly operated. The high-density plasma is generated for about 1 ms and the ring current is generated. The magnetic field and the current in the plasma are measured by the probe measurement. The magnetic probe measuring the magnetic field consists of three-axial magnetic coils with 0.2 mm enamel wire on a small parallelepiped-shaped support (8×8×8 mm), and this is 20-turns-coil as shown Fig3 (a). In this study, we measure on the coil equatorial plane and dominant B_z is measured. The current probe consists in a toroidal solenoid that encircles ferrite core as shown Fig.3 (b). We measure on the coil equatorial plane and J_θ is measured. Two kinds of probes were installed in the opposite side of the plasma source, and measured at $r = 140 - 350 \text{ mm}$ shown Fig.4.

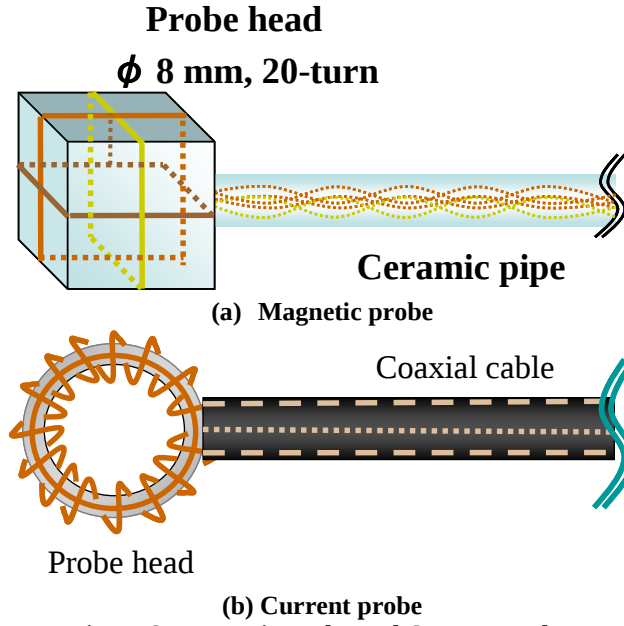


Figure 3. Magnetic probe and Current probe.

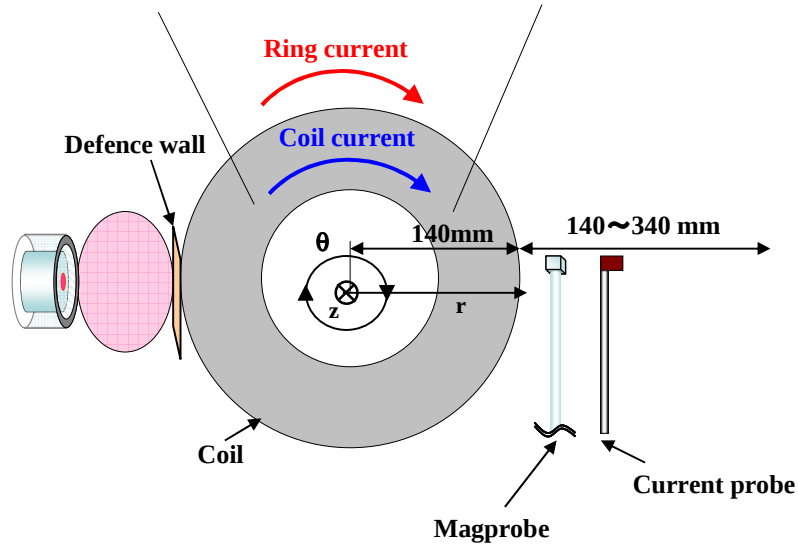


Figure 4. Measurement position.

III. Experimental Results

The experimental results are shown in this section. Figure.5 shows the photograph of the typical experiment. The coil is located at right side of Fig.5 (a), and the MPD arcjet as the inflation plasma source is located at left side. The plasma flow is blocked by the defence wall. The generated plasma is magnetized, and the charge particle is drifted. Figure.5 (a) is the experiment without the magnetic field and Fig.5 (b) is with magnetic field (coil current: 200A). Although the opposite side of coil is not emitting light in the Fig.5 (a), the one in the Fig.5 (b) is faintly emitting light. This means that the plasma come around behind the coil by the drift motion.

The J_θ distribution measured by the current probe is shown Fig.6. The positive value is the same direction current as the coil current. The plasma current is measured on conditions without the magnetic field as shown Fig.6 coil current 100A and 200A. Although the dispersion is large, the same direction current as the coil current is

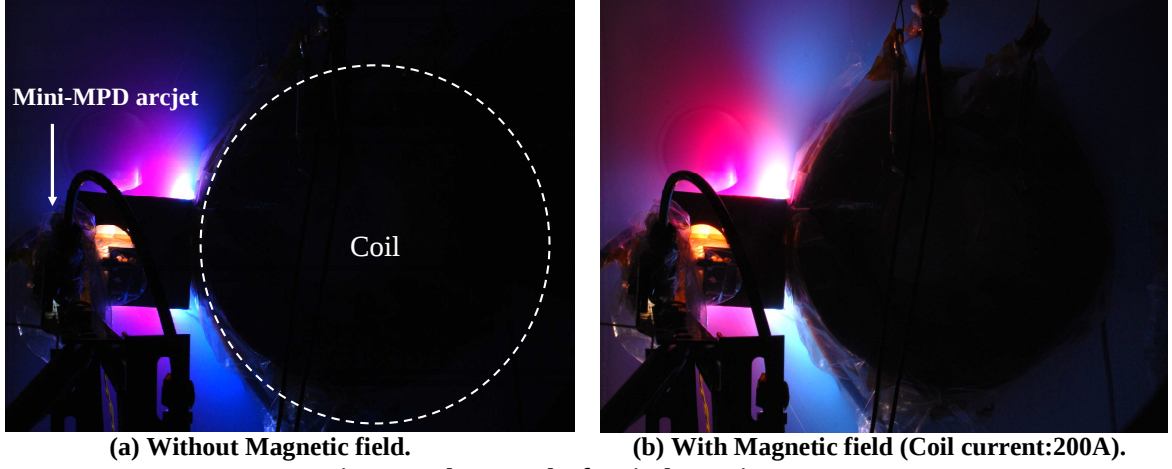


Figure 5. Photograph of typical experiment.

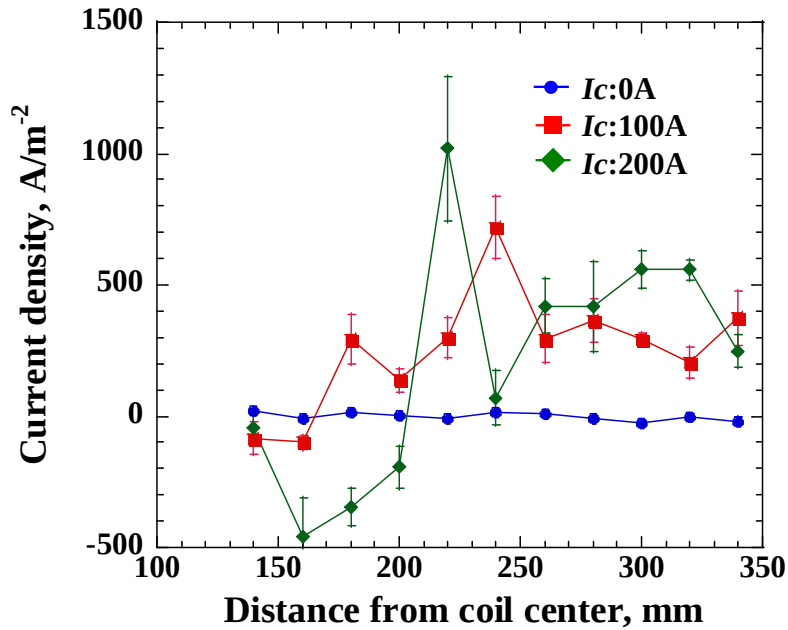


Figure 6. J_θ distribution.

(Discharge current: 7 kA, 10^{19}m^{-3} , 1 eV at the distance 50 mm from the Mini-MPD arcjet.).

measured in far region ($r > 200$ mm). This current is the ring current for the magnetosphere inflation. As this result, it was proved that ring current was generated by injecting in plasma to a coil magnetic field. Near the coil ($J_c = 200$ A: $r < 200$ mm, $J_c = 100$ A: $r < 160$ mm), J_θ is inverse direction as the coil current. If the plasma current is caused by the pressure gradient, the reverse point of J_θ corresponds to the peak of the plasma pressure distribution. In coil neighborhood, the plasma is recombined by the collision of the coil surface. Therefore, it is considered that plasma density becomes low near the coil. The reverse point of the plasma current direction of the 200 A is shifted to the outside than 100 A. Although the charge particle is magnetized only in the strong magnetic field domain near the coil on condition of 100 A, the charge particle can magnetize in a more distant domain on condition of 200 A. The peak point of the pressure distribution is shifted to the outside than the condition of the 100 A.

The magnetic field distribution and the increasing rate distribution of the magnetic field are shown Fig.7. The magnetic field with plasma injection is larger than the magnetic field without the plasma injection. We suppose that the magnetic field has a falloff of the form $1/r^m$. The magnetic field falloff without plasma injection is $m=2.86$. In contrast, the magnetic field falloff with plasma injection is $m=2.56$. The magnetic field is increased by the plasma

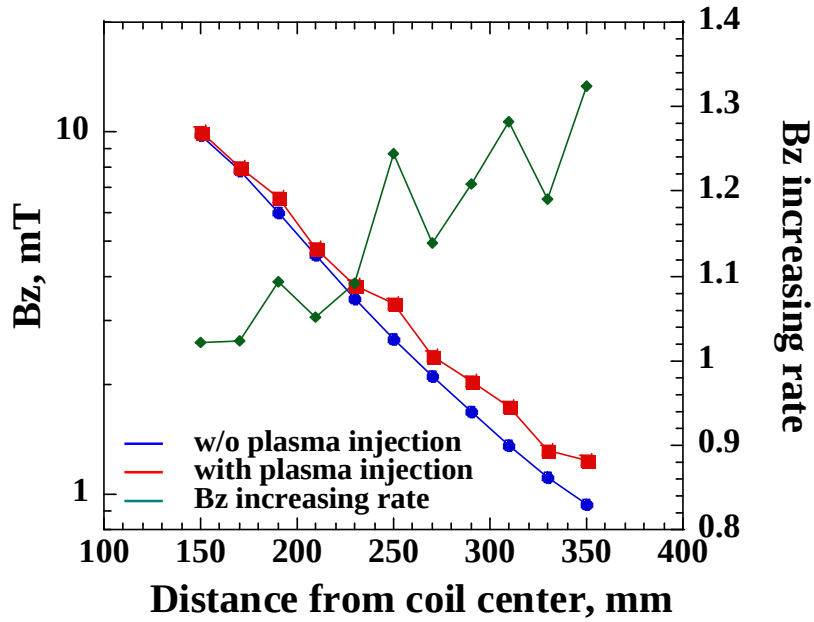


Figure 7. Magnetic field distribution and increasing rate.
(Discharge current: 7 kA, 10^{19} m^{-3} , 1 eV at the distance 50 mm from the Mini-MPD arcjet.).

injection. The red line is shown the increasing rate (B_z with plasma injection / B_z without plasma injection) of the magnetic field. The maximum increasing rate is over 1.3. As this result, it was proved that the magnetic field increased by the ring current. However, in this experiment, the magnetosphere rate is only about 1.1. The optimization of the ring current type magnetosphere inflation is a future subject.

IV. Conclusion

In this study, the experiment of the ring current type magnetosphere inflation was conducted. We generate the low kinetic beta plasma by blocking the plasma flow generated by MPD arcjet (10^{19} m^{-3} , 1 eV, and 0.1 g/s) by the defense wall. The solenoid coil ($\phi 280$ mm and 120 turn) is employed as a MPS spacecraft. The plasma current distribution and the magnetic field distribution were measured by the probe diagnosis, and the main results of this study are follows:

1. It was proved that ring current was generated by injecting in plasma to a coil magnetic field.
2. The increasing rate of magnetic field strength is about 1.3 in this study. It was proved that the magnetosphere is inflated by the ring current.

Acknowledgments

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References

- ¹Winglee, R.M., Slough, J., Ziemba, T., and Goodson, A., "Mini-Magnetospheric Plasma Propulsion: Tapping the Energy of the Solar Wind for Spacecraft Propulsion," *Journal of Geophysical Research*, Vol.105, No.21, 2000, pp.21, 067-21,078.

²Ueno, K., Funaki, I., Kimura, T., Horisawa, H., and Yamakawa, H., “Thrust Measurement of Pure Magnetic Sail using Parallelogram-pendulum Method,” *Journal of Propulsion and Power*, Vol.25, No.2, 2009, pp.536-539

³Funaki, I., Kimura, T., Ueno, K., Horisawa, H., Yamakawa, H., Kajimura, Y, Nakashima, H., and Shimizu, Y., “Laboratory Experiment of Magnetoplasma Sail, Part 2: Magnetic Field Inflation”, *30th International Electric Propulsion Conference*, IEPC-2007-94, Florence, Sept. 2007.

⁴Slough, J., “High Beta Plasma for Inflation of a Dipolar Magnetic Field as a Magnetic Sail“, *22nd International Electric Propulsion Conference*, IEPC-01-202, Viareggio, Oct. 1991.

⁵Nishida, H., Funaki, I., Ogawa, H., and Inatani, Y., “MHD Analysis on Propulsive Characteristics of Magneto Plasma Sail“, *30th International Electric Propulsion Conference*, IEPC-2007-195, Florence, Sept. 2007.

⁶Parker, E.N., “Newtonian Development of the Dynamical Properties of Ionized Gases of Low Density“, *Physical Review*, Vol 107, No 4, 1957, pp.924-933.