Thrust Measurement of Magneto Plasma Sail with Magnetic Nozzle by Using Thermal Plasma Injection

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Abstract: One of the main space propulsion system that generates the thrust for deep space mission is electric propulsion. Magnetic sail is capturing the solar wind plasma with high velocity by using the magnetic field generated by the solenoid coil. According to the past evaluations for the thrust of magnetic sail, the thrust of the magnetic sail equipped with realistic size of coil is not enough. Therefore, magneto plasma sail with magnetic nozzle is proposed. This system combines thermal plasma injection source for expanding magnetic sail and magnetic nozzle for accelerating the injected plasma by deformation of magnetic field. In order to confirm the principle of magneto plasma sail with magnetic nozzle, the laboratory experiment by using vacuum chamber is conducted. The main purpose of this experiment is to measure the thrust of the magneto plasma sail with magnetic nozzle by using a thrust stand hanging from the vacuum chamber ceiling. As experimental results, the thrust of magneto plasma sail is 2 times as large as the sum of the thrust of magnetic sail plus the thrust of magnetic nozzle.

Nomenclature

C_d	=	drag coefficient
L	=	representative length of a magnetosphere, i.e., distance between the center of the coil and the position where plasma β is equal to 1
M	=	magnetic moment
Mi	=	ion Mach number
n_p	=	number density of plasma flow
v_p	=	velocity of plasma flow
β	=	ratio of plasma pressure to magnetic pressure
μ_0	=	permeability of vacuum

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I. Introduction

A development of spacecraft obtaining the large thrust for the moon and planet exploration or deep space mission is necessary to achieve the less mission time and increase the payload ratio. As one of the candidate for realizing the above purpose, magneto plasma sail has been researched in JAXA.[1] The magneto plasma sail is the electric propulsion system developed the magnetic sail[2] proposed by Zubrin in 1990. The schematic illustration of magnetic sail is shown in Fig. 1. Magnetic sail obtains the thrust by capturing the solar wind which consists of high speed plasma flow. The magnetic field in the magnetic sail is generated by the solenoid coil attached onboard the spacecraft. Magneto plasma sail is a propulsion system which generates the thrust by the interaction between solar wind and an inflated magnetic field via a plasma injection. The schematic illustration of magneto plasma sail is shown in Fig. 2. This system is expected not only the same efficiency of fuel consumption of existing electric propulsion systems but also approximately one order higher thrust. So it is proposed by Dr. Winglee that this system has a possibility that it can reach the outside of solar system within 10 years.[3] However, according to the past thrust evaluation of the magneto plasma sail by the ground experiment and by the numerical evaluations[4-7] it is necessary to generate approximately from one to two orders higher thrust than the obtained thrust from the past study for achieving the above expecting performances.

An ion thruster onboard spacecraft for planet exploration, for example Hayabusa2, can generate approximately 10 mN and has a limitation of thrust density at the view of the conservation of space-charge. Only the solution to generate the larger thrust is to increase the size of the thruster. As is the case with an ion thruster, it's difficult for a hole thruster to obtain the high thrust density. So, increase of the weight as increasing the size is also the problem. Recently, the magnetic sail system is proposed as one of the candidate to obtain the higher thrust density. The schematic illustration of the magnetic nozzle system is shown in Fig. 3. Magnetic nozzle is formed by magnetic field generated by the solenoid coil. Magnetic nozzle is the system to accelerate the injected thermal plasma in the diverging magnetic field configuration. Thermal plasma is injected along the central axis of the solenoid coil parallel to the direction of magnetic field line. The injected plasma is inflated by the thermal expansion and compressed by the magnetic field. The inflated plasma is emitted along the diverging magnetic field. The emitted plasma is accelerated by passing through from a converging to diverging nozzle. Applying the Newton's Third Law, an equal and opposite direction force that is the change in momentum of the emitted plasma become the thrust for the spacecraft. The feature of this system is to decrease the loss of energy by mutual action of not a solid wall but a magnetic wall.

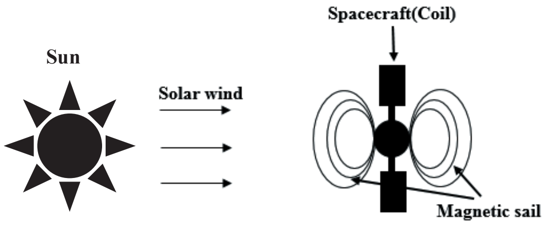

Fig. 1. The schematic illustration of magnetic sail

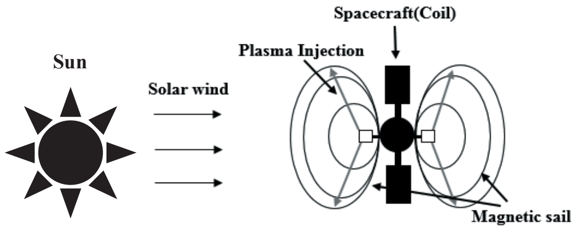

Fig. 2. The schematic illustration of magneto plasma sail

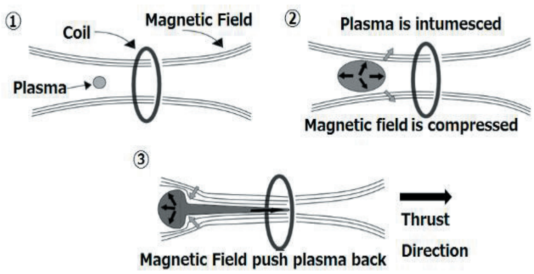

Fig. 3. The schematic illustration of magnetic nozzle system

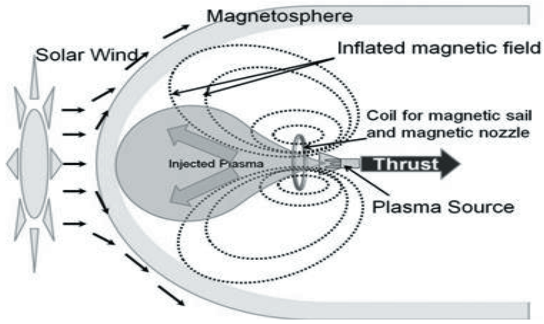

Fig. 4. The schematic illustration of magneto plasma sail with magnetic nozzle[7]

Consequently, compared with another electric propulsion systems, this system may achieve the two points that are a high thrust ratio and a high output ratio. However, this system needs much electric power to obtain the large thrust. Consequently, the temperature of the plasma becomes higher. Moreover, the magnetic nozzle can't accelerate the plasma because of ion with large Gyro radius due to the increase of the temperature results to the loss of the plasma in the magnetic nozzle. It is need strong magnetic field nozzle to obtain large thrust. This power scale is so high to reach the outside of solar system. Thrust of magnetic nozzle haven't evaluated in this way until now under the realistic electric power.

In the present research, it's the purpose to evaluate the thrust characteristics of the new proposed system combined the magneto plasma sail and magnetic nozzle. The schematic illustration of proposed system is shown in Fig. 4.

Magneto plasma sail can utilize the external energy such as solar wind which flows in solar system to obtain the thrust. An advantage of the magneto plasma sail is high fuel efficiency but a disadvantage is the low thrust. Moreover, an advantage of the magnetic nozzle is having electrodeless and long operation life and disadvantage of the magnetic nozzle is needing high electric power to obtain the high thrust. In the present research, the possibility that whether proposed system has the large thrust and high thrust ratio by combining the above system or not is evaluated. This experiment is conducted by using the ground chamber experiment facility.

II. Experimental setup

The schematic illustration of the ground experiment using a vacuum chamber is shown in Fig. 5.

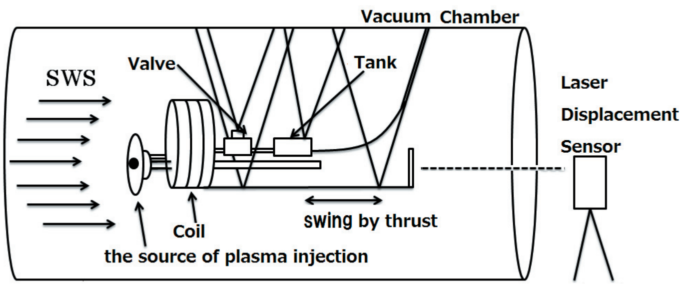

Fig. 5. The schematic illustration of the ground experiment

Table 1. Parameters used in the ground experiment

Solar Wind Simulator Parameters	
Density	1.0e+18[m^{-3}]
Velocity	28[km/s]
Temperature	0.84[eV]
Plasma Injection Source Parameters	
Density	5.0e+20[m^{-3}]
Mass Flow Rate	20[mg/s]
Temperature	0.84[eV]
Solenoid Coil Parameters	
Current	3.6[kA turn]
Turn	20
Radius	0.075[m]
B-field	0.03[T]

The experiment devices consist of Solar Wind Simulator (SWS), the magneto plasma sail thrust stand, operating and measuring system. The thrust stand consists of MPD Arcjet for injecting plasma, the solenoid coil for generating magnetic nozzle and magnetic sail and aluminum bar suspended by four stainless wires. The aluminum bar holds the coaxial cables that bring discharge current to the solenoid coil and the target for the laser as shown in Fig. 5. Solar wind simulator generates hydrogen (H^+) plasma with 38 km/s as the solar wind plasma flow. And plasma injection source injecting near the center of the coil utilizes for the increase of the thrust due to magnetic nozzle and for inflating of the magnetic sail. Magneto Plasma Dynamic Arcjet (MPD) is used as plasma injection source. When the solenoid coil, the plasma injection source and the solar wind simulator operate at the same time, it occurs the interaction between the solar wind plasma which ignites a finite time duration of approximately 1 ms and the plasma injected for the magnetic sail and the magnetic nozzle. This experiment has been conducted under three conditions. First one is the magnetic sail mode which operates the solar wind simulator and the solenoid coil. Second one is the magnetic nozzle mode which operates the solenoid coil and the plasma injection source. Last one is the magneto plasma sail with magnetic nozzle mode which operates the solar wind simulator, the solenoid coil and the plasma injection source. The magneto plasma sail with magnetic nozzle mode combined the magnetic sail mode and the magnetic nozzle mode. The displacement of the magneto plasma sail thrust stand is detected by the laser and the resulting displacement plot is displayed on the oscilloscope. The oscilloscope detects the instantaneous position of the thrust stand in terms of voltage. Parameters used in the ground experiment are shown in Table 1.

III. Experimental result

In the present experiment, the measurement of not only thrust for the magneto plasma sail with magnetic nozzle but also the visibility of the plasma flow are conducted. These data also plan to use for improving accuracy of numerical evaluation. The photographs in case for each operation in the experiment are shown in from Fig. 6 to Fig. 9.

Figure 6 shows the photograph for the magnetic sail mode. When the photographs are taken, a shutter of camera keeps opening in a second. Figure 7 shows the photograph of the plasma injection mode from MPD. Figure 8 shows the photograph of the magnetic nozzle mode. Figure 9 shows the photograph of the magneto plasma sail with magnetic nozzle mode.

As shown in Fig. 6, the solar wind plasma changes the ionization plasma into the unionization one by colliding directly to the solenoid coil. In this process, it emitted the light depending on the plasma density. Moreover, the injected plasma from the solar wind simulator collected the center of the solenoid coil due to the shape of magnetic cusp generated by the solenoid coil. At this moment, the performing of the magnetic sail is confirmed. As shown in Fig. 7, the plasma is injecting from MPD with high injection velocity plus thermal velocity. Furthermore, the luminescence intensity is so strong compared with magnetic sail mode which already shown in Fig. 6. It found that the high density of plasma is emitted due to the luminescence intensity. As shown in Fig.8, compared with plasma injection for MPD mode which already shown in Fig. 7, the injected plasma from MPD is collected in the center of the solenoid coil by the magnetic nozzle generated by the solenoid coil. This is the action due to the magnetic nozzle.

As shown in Fig. 9, when the solar wind simulator run at the same condition of magnetic nozzle mode, the injected plasma from MPD has a little expanse compared with the magnetic nozzle mode which already shown in Fig. 8. The injected plasma from MPD is compressed by solar wind plasma as shown in Fig. 10. Moreover, the shape of magnetic nozzle is spread due to the deformation of magnetic sail by the injected plasma from MPD as shown in Fig. 10.

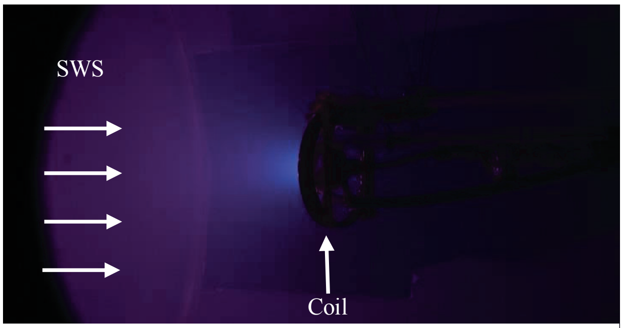

Fig. 6. Magnetic sail mode (solar wind simulator + solenoid coil)

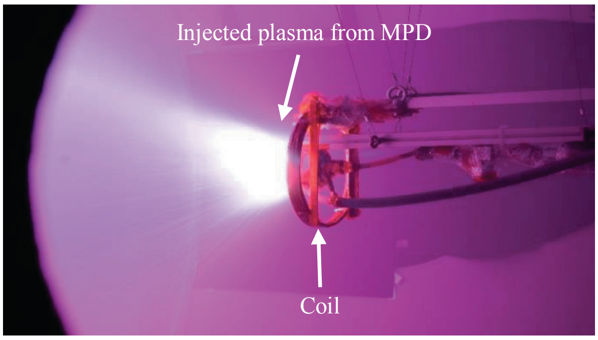

Fig. 7. Plasma injection mode from MPD

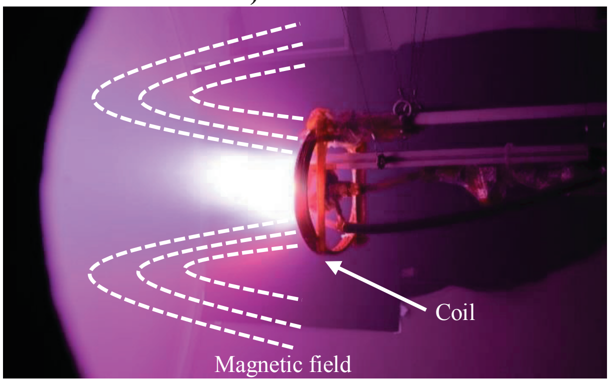

Fig. 8. Magnetic nozzle mode (solenoid coil + plasma injection source)

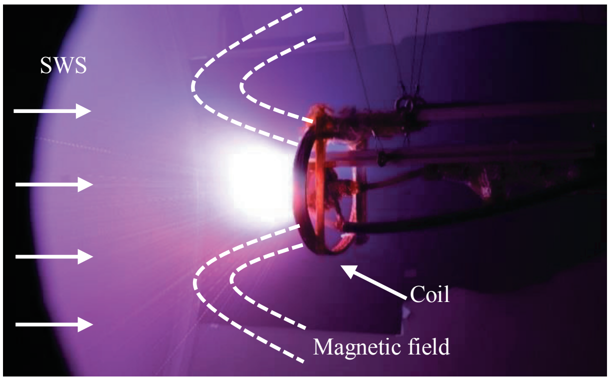

Fig. 9. Magneto plasma sail with magnetic nozzle mode (magnetic sail + magnetic nozzle)

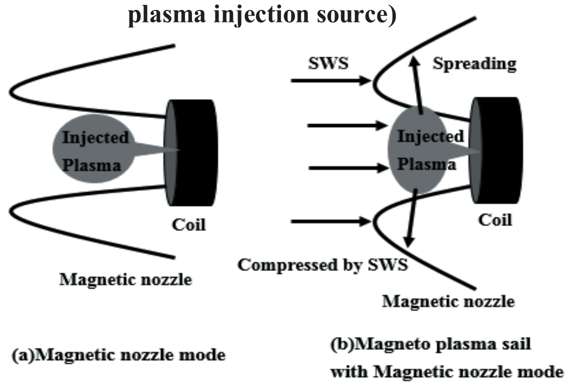

Fig. 10. The action of magneto plasma sail with magnetic nozzle

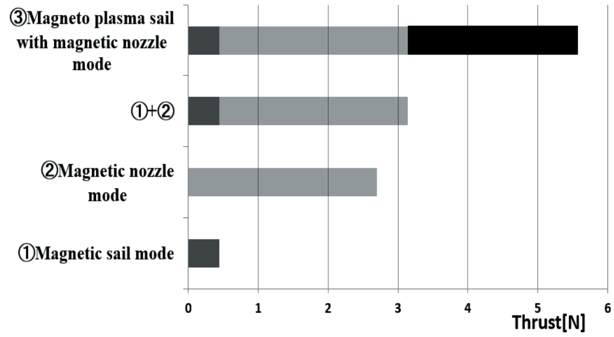

Fig. 11. The results of measured thrust

The thrust in each mode is evaluated from the displacement of the thrust stand in each mode. The results of measured thrust is shown in Fig. 11.

$$\text{(Thrust in case for the magnetic sail)}=\text{(Coil+SWS)}-\text{(Coil)}-\text{(SWS)} \tag{1}$$

$$\text{(Thrust in case for the magnetic nozzle)}=\text{(Coil+MPD)}-\text{(Coil)}-\text{(MPD)} -\text{(The interaction between coil and MPD)} \tag{2}$$

$$\text{(Thrust in case for the magneto plasma sailwith magnetic nozzle)} =\text{(Coil+SWS+MPD)}-\text{(Coil)}-\text{(SWS)}-\text{(MPD)}-\text{(The interaction between coil and MPD)} \tag{3}$$

The method for the measurement of the thrust in each mode is shown below. In case for the magnetic sail mode, the displacement of the coil and the solar wind simulator operating at the same time minus the only displacement of the coil and the only displacement of the solar wind simulator as shown in Eq.(1). The obtained thrust in case for the magnetic sail shows at the bottom of Fig.11 as ①. As shown in Fig. 11, the obtained thrust in case for the magnetic sail is approximately 0.5 N. In case for the magnetic nozzle mode, the displacement of the coil and the plasma injection source operating at the same time minus the only displacement of the coil, the only displacement of the plasma injection source and the interaction between the coil and the plasma source injection as shown in Eq.(2). The obtained thrust in case for the magnetic nozzle shows at ② in Fig.11. The obtained thrust in case for the magnetic nozzle is approximately 2.7 N. In Fig.11, the sum of the thrust of the magnetic sail plus the thrust of the magnetic nozzle is shown as ①+②. The obtained thrust for case the sum of the thrust of the magnetic sail plus the thrust of the magnetic nozzle is approximately 3.1 N. In case for the magneto plasma sail with magnetic nozzle mode, the displacement of the coil, the solar wind simulator and the plasma injection source operating at the same time minus the only displacement of the coil, the only displacement of the solar wind simulator, the only displacement of the plasma injection source and the interaction between the coil and the plasma injection source as shown in Eq.(3). The obtained thrust in the case for the magneto plasma sail with magnetic nozzle shows at the top of Fig.11 as ③. The obtained thrust in case for the magneto plasma sail with magnetic nozzle is approximately 5.6 N. If the obtained thrust in case for the magneto plasma sail with magnetic nozzle is larger than the obtained thrust in case for the sum of the thrust of the magnetic sail plus the thrust of the magnetic nozzle, it indicates that the inflation of magnetic sail occurs in the configuration of the magnetic nozzle. It means that the obtained thrust from the solar wind increases due to the expansion of magnetic sail. These all measurement of the thrust in the present experiment are average value of three times measurements. The thrust for the magneto plasma sail with magnetic nozzle mode is approximately 12 times as large as the thrust for the magnetic sail mode. Furthermore, the thrust of magneto plasma sail with magnetic nozzle mode is approximately 2 times as large as the sum of the thrust of the magnetic sail mode plus the thrust of the magnetic nozzle mode.

The interaction between the plasma flow and a dipolar magnetic field that had a magnetosphere with a representative length L is shown in Fig.12. An approximate formula was then proposed for the drag coefficient C_d as a function of the ratio between the ion Larmor radius at the stagnation point and the representative length L of the magnetosphere. The location of the magnetopause is determined by the pressure balance between the dynamic pressure of the solar wind plasma flow and the magnetic pressure generated by the coil. In turn, the representative length L of the magnetosphere is defined as the distance from the solenoid coil center to the magnetopause. The length L shown in Fig. 12 is obtained from Eq.(4).

The 3-dimensional numerical evaluation shown in Fig. 13 have been conducted[8]. As shown in Fig.13, if size of magnetic field which correspond to L becomes 10 times larger from 1 to 10 km, thrust increases three order. In the research on the magneto plasma sail conducted before, it's difficult to gain the 10 times as large as thrust by the expansion of the magnetic field by injecting the plasma. However, by adding to the magnetic nozzle, the thrust gain of 12 times could be obtained as we showed in this section. MPD is used as the plasma injection source for the magnetic nozzle thruster in the present experiment. This plasma injection source needs high electric power to generate the plasma. Moreover, it is the factor of noise by mutual electromagnetic action between the solenoid coil and the plasma injection source. It's difficult to prepare a high electric power because the energy is limited in the space. So, next experiment will be planning to use the plasma source which is used the helicon waves and conduct the same experiment as the plasma source which utilizes the helicon waves operates with lower electric power to generate the plasma. So, the helicon waves plasma source is expected the improvement of thrust power ratio we have proposed in the present paper.

$$L = \left(\frac{M^2}{8\pi^2 \mu_0 n_p m_i v_p^2}\right)^{\frac{1}{6}} \quad (4)$$

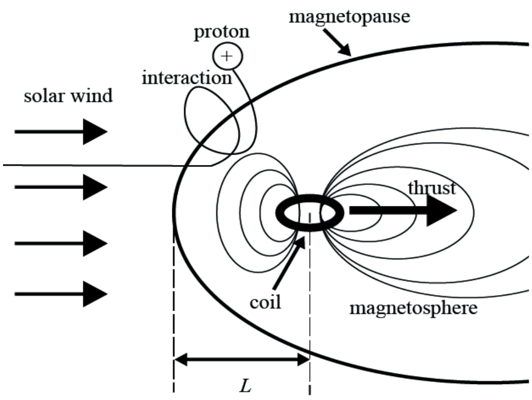

Fig. 12. The schematic illustration of the magnetic sail and streamlines of solar wind

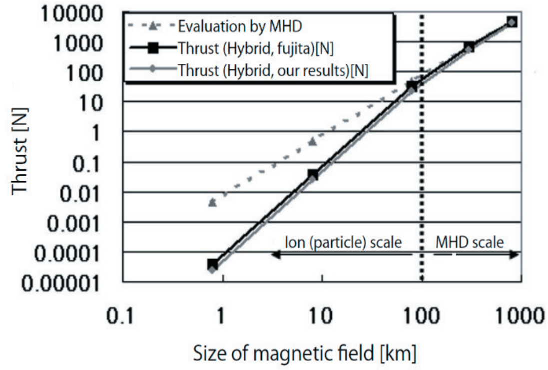

Fig. 13. 3-dimensional numerical evaluation result[8]

IV. Conclusion

In the present study, the new electric propulsion system is proposed. The magneto plasma sail with magnetic nozzle is the system which combined the magneto plasma sail and the magnetic sail. The magneto plasma sail is the system obtained the thrust by capturing solar wind plasma by using the magnetic sail. The magnetic nozzle is the system obtained the thrust by accelerating the injected plasma. The ground experiment of magneto plasma sail with magnetic nozzle is conducted by using MPD as plasma injection source for the expansion of the magnetic sail for the magnetic nozzle acceleration. The thrust of the magneto plasma sail with magnetic nozzle is evaluated quantitatively in the ground experiment. In addition to the thrust of the magnetic sail and the thrust of the magnetic nozzle, the thrust of the proposed system, magneto plasma sail with magnetic nozzle, are measured successfully in the ground experiment. From the experiments, the thrust of magneto plasma sail with magnetic nozzle is approximately 12 times large as thrust of magnetic sail and approximately 2 times as large as thrust of magnetic nozzle. As a result of the obtained thrust, the expansion of the sail by deformation of magnetic nozzle field is confirmed. Moreover, the increase of the thrust by expansion of magnetic field which are the concept of the magneto plasma sail with magnetic nozzle is confirmed. The thrust of the magneto plasma sail with magnetic nozzle is larger than the sum of the thrust of the magnetic sail plus the thrust of the magnetic nozzle. The present ground experiment is conducted under the scale down parameters. As calculated by Eq.(4), a representative length L is equal to 0.2 m. So, ion Larmar radius is equal to 1.67. Moreover, a representative length of the solar wind is 100 km. So, the size of magnetic field in space is calculated by Eq.(5).

$$\frac{100 \times 10^3}{L} = 1.67 \tag{5}$$

Therefore, as using Fig. 13, the size of magnetic field used in space is 60 km. So, the present experiment is equivalent to the spacecraft model with 60 km of the representative length L.

Acknowledgments

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