# EXPERIMENTAL STUDY OF MAGNETIC SAILS

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**A magnetic sail is a unique propulsion system, which travels interplanetary space by capturing the energy of the solar wind. In order to simulate the interaction between the artificial magnetic field produced around a spacecraft and the solar wind, a scaled-down laboratory experiment was conducted in a space chamber. Preliminary results showed some strong interactions between the high-density ($10^{19}$ $m^{-3}$) and high-velocity (17 km/s) plasma flow and an artificial magnetic field of about 1 T, hence the possibility of the magnetic sail simulator is provided; however, further improvement is required to realize a collision-less solar wind plasma flow in the laboratory.**

## 1. Introduction

For the case of the Earth, a large-scale interaction between the Geomagnetic field and the solar wind occurs. It is intensively discussed that, as a result of such interactions, what amount of the momentum of the solar wind will transfer to the Earth.[1] A magnetic sail (MagSail) realizes analogous interactions between the solar wind and an artificial magnetic field produced around a spacecraft, to obtains a force in the direction of the solar wind (Fig.1). In order to demonstrate the momentum transfer process of the magnetic sail, we design an experimental simulator of the magnetic sails that operates in a space chamber. In this paper, the experimental simulator of the MagSailisdescribed, and some preliminary experimental results are provided.

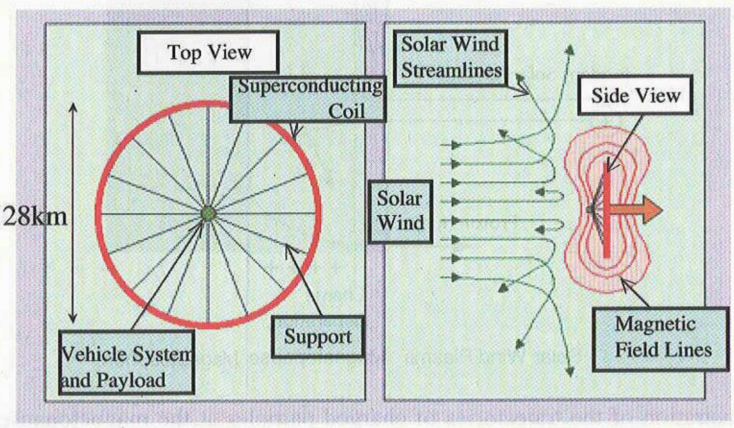


Fig. 1 Interaction between magnetic sail and the solar wind.

## 2. Scaling Parameters of MagSail

Figure 1 shows the schematics of interactions between the magnetic field around a spacecraft and the solar wind.[2] When the current is initiated in a coil attached to a spacrcraft, the MagSail is in operation, and charged particles entering the field are decelerated/deflected according to the B-field they experience, thus imparting the momentum to the current loop. In the case of large scale interaction between the plasma and the magnetic field, ions cannot enter the region near the loop, forming so-called a magnetosphere or a magnetic cavity around the loop. Because the density of the solar wind plasma flow is very small, the plasma behaves as collision-less particles, whose movement separates the region between the plasma and the magnetic field. Simplified picture of this boundary is schematically depicted in Fig.2. At the boundary, there is a balance between the total internal (magnetic) and external (plasma) pressures:

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$$\frac{1}{2} n\, m_i\, u^2 = \frac{B^2}{2\mu_0} \qquad (1)$$

where $n$ is the plasma number density, $m_i$ ion mass, $u$ velocity of the solar wind, $B$ the magnetic flux density at the boundary, $\mu_0$ the permeability in vacuum. On this boundary, the two charged particles, ions and electrons, impinge at right angles. The external space is considered as magnetic field-free. Because of their heavier mass, the ions tend to penetrate more deeply into the magnetic field than electrons. This sets up a charge separation, and outward pointing electric polarization field thus restraining the ions. Before they can be deflected by the magnetic field, they are returned by this polarization field with very little actual charge separation needed. The electrons, however, experience the Lorentz force and gain energy in the polarization field. The transverse velocity component of the electrons accounts essentially for the electric current in the interface, which in case of the magnetopause is usually referred to as Chapman-Ferraro current. In the artificial case of equal external velocity $u$, of the incident ions and electrons, the combined penetration depth, $\delta$, is of the order of geometric mean of the electron and ion gyroradii. If one uses eq.(1) and replaces $u/B$ by gyro-radius, one finds a thickness of the order of the plasma skin depth $\delta$:

$$\delta = c/\omega_p \qquad (2)$$

where where $c$ is the light velocity, $\omega_p$ plasma frequency. Hereafter, $\delta$ is referred to as the thickness of the magnetopause in this paper. In the laboratory experiment, however, diffusive effect, with collision frequency $\nu_{ei}$, enlarges the magnetopause thickness $\delta$ to $\delta_D$:

$$\delta_D = \nu_{ei} c^2 / u\, \omega_p^{\ 2} \qquad (3)$$

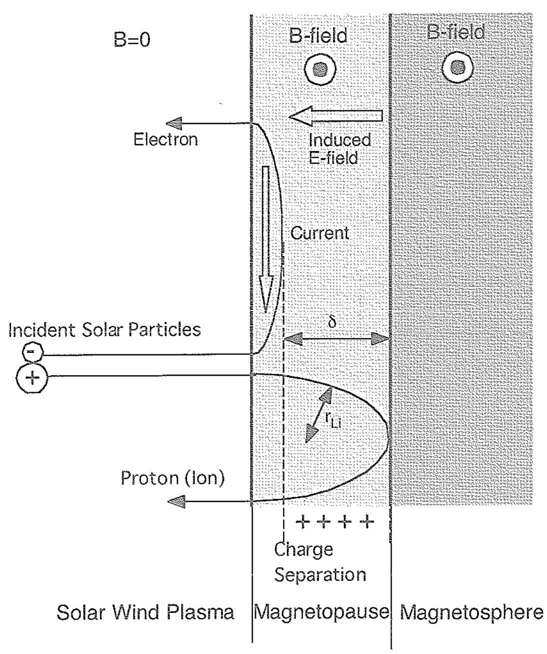


Fig.2 A schematic illustration of the trajectories of charged particles at the magnetopause; ions and electrons incident normally on a plane boundary layer when the polarization electric field due to charge separation is present.

Along with $\delta$, the magnetic cavity, $L$, is an important parameters to describe the scaling law of the MagSail. From the pressure balance at the magnetopause (eq.(1)), $L$ is derived as follows.[3]

$$L = \sqrt[6]{\frac{B_0^2}{2\mu_0 n\, m_i\, u^2}}\; a \qquad (4)$$

From eq.(2), $\delta$ in the solar wind plasma depends only on the plasma density, hence calculated as $\delta \sim 1$ km. Thus, depending on the size of the magnetic cavity, $L$, two operational modes of the MagSail are expected (Fig.3). One is thick magnetopause mode, when the thick magnetosheath develops around the coil of the MagSail, hence the incident ions penetrate deeply into the magnetic cavity. Another is thin magnetopause mode, when all the ions impinging on the cavity is reflected within this thin magnetopause. It is anticipated that the large effective area for the interaction between the solar wind and the magnetic cavity will lead to large thrust, but this should be checked via the experimental simulator described in the next chapter.

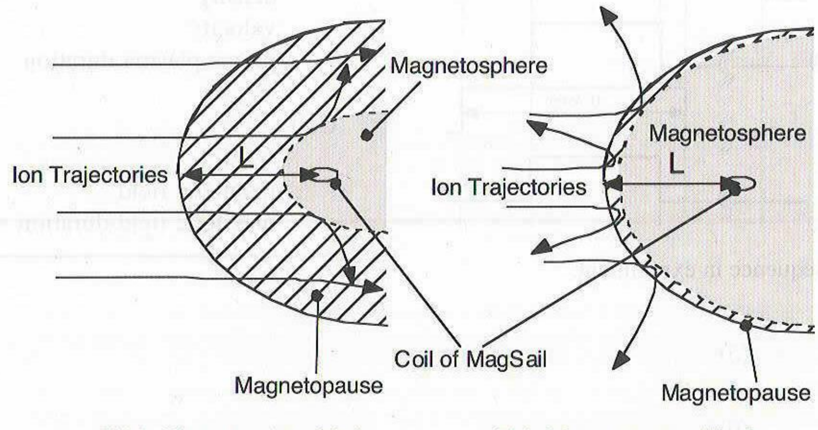


Fig.3 Two operation modes of the MagSail ($\delta$~$L$(left) and $\delta << L$(right))

## 3. Experimental Apparatus

In our preliminary experiment (Fig.4), a coil of 20 mm in diameter was used to produce up to 1 T magnetic field at the center of the coil. Into the magnetic field, a plasma jet from an MPD arcjet was introduced to observe possible interactions using the Langmuir probes.

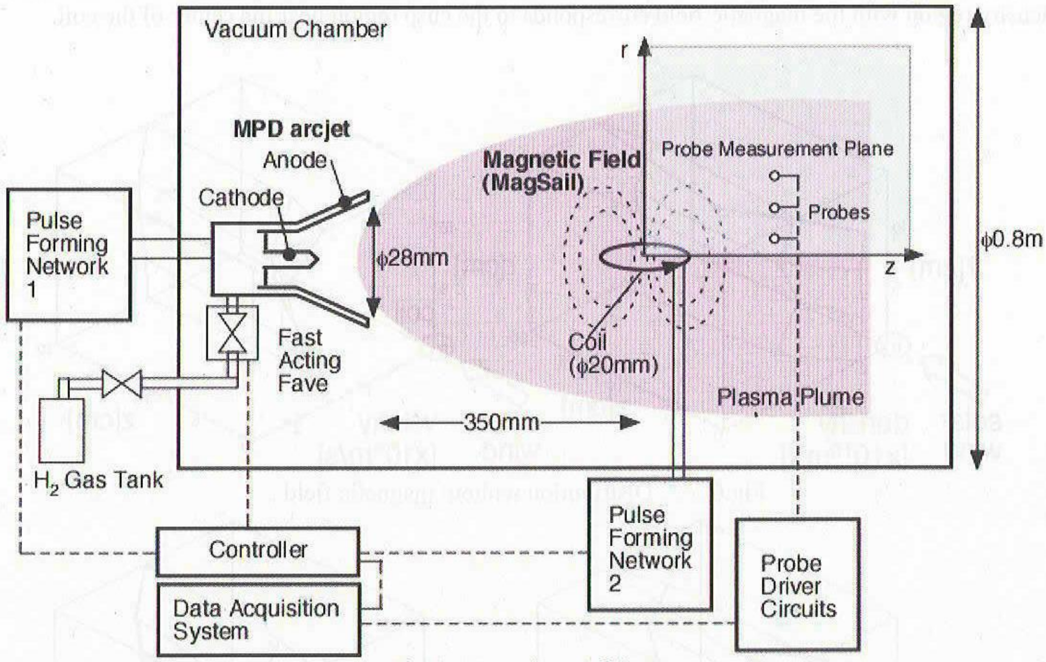


Fig.4 Experimental Setup.

Both the MPD arcjet and the coil simulating the MagSail are operated in a pulse mode; the sequence of operation is summarized in Fig.5. After the gas feed and the magnetic field by the coil reach a steady state, the firing of the MPD is initiated. During the firing of the MPD, Langmuire probe output was established in a quasi-steady mode, from which the density and the velocity of the flow are obtained. Operational parameters are summarized in Table.1.

To determine the $n$ and $u$ from the probe, we used two equations:

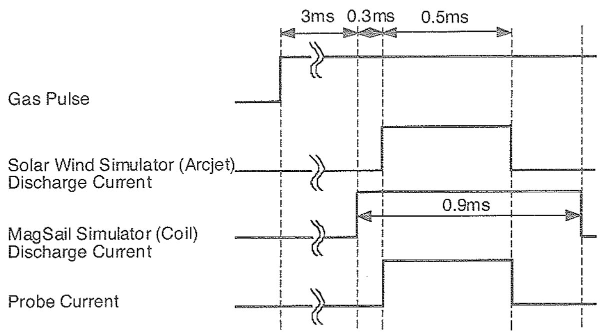


Fig.5 Sequence in experiment.

Table.1 Operational parameter of simulator.

| | | |
|---|---|---|
| MPD arcjet plume plasma | | |
| | density | $2x10^{19}$ $m^{-3}$ |
| | velocity | 17 km/s |
| | plume plasma duration | 0.5 ms |
| Coil | | |
| | size | 2cmφ |
| | magnetic field | up to 1 T |
| | magnetic field duration | 0.9 ms |

$$j_{//} = \kappa en\sqrt{\frac{kT_e}{m_i}} \qquad (5)$$

$$j_{\perp} = enu \qquad (6)$$

where $j_{//}$ is the current into the probe (with probe surface parallel to the plasma flow), and $j_{\perp}$ is the perpendicular current into the probe.

## 4. Preliminary Results and Discussion

Figure 6 and 7 show the plasma density and the velocity profile without/with the added magnetic field around the coil. Only the flows in the downstream region of the coil are measured and plotted. For the case with the magnetic field, a large density plasma exists near the coil indicates strong interaction between the magnetic field and the plasma flow. This high density region with the magnetic field corresponds to the cusp region near the center of the coil.

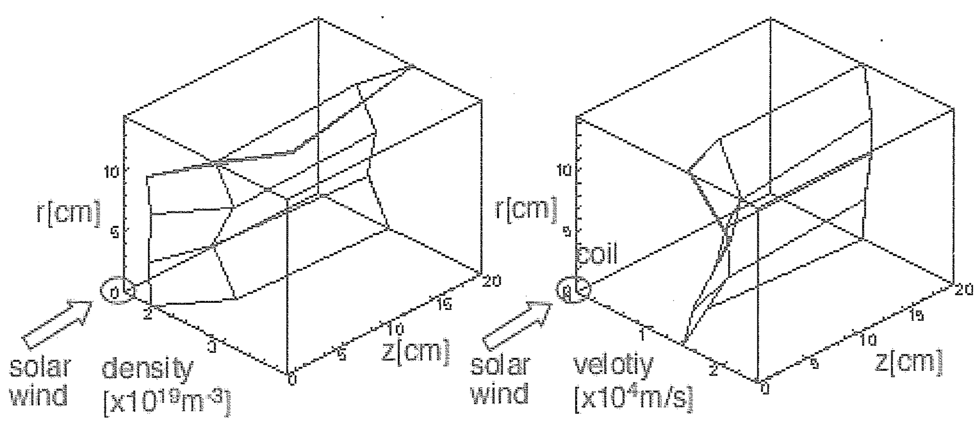


Fig.6 Distribution without magnetic field .

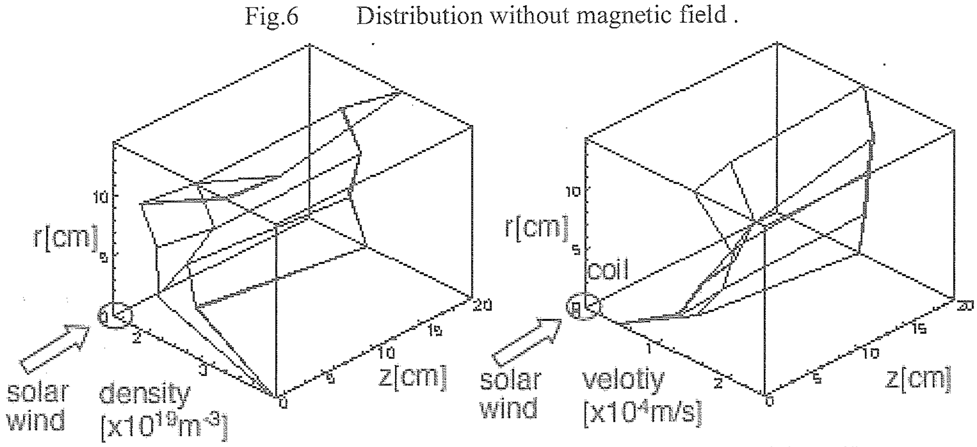


Fig.7 Distribution with magnetic field (1 T at the center of the coil).

Although the interaction at the cusp is apparently large, the downstream density with the magnetic field is only slightly reduced in comparison with the case without the magnetic field. This means that a large amount of plasma penetrates into the cavity, hence the interaction is expected to be in the the thick magnetopause mode defined in Fig.3To estimate a force on the coil, momentum change of the simulated solar wind, $F$, is evaluated. Using $F$, non-dimensional thrust coefficient, $C_d$ is defined as follows and plotted in Fig.8.

$$C_d = \frac{F}{1/2\rho u^2 S} \qquad (7)$$

where $S=\pi L^2$ is the characteristic area with $L$ being the cavity size defined in eq.(4), and $\rho=nu$ is the simulated solar wind density. Discrepancy between the experimental and numerical[5] $C_d$ will be, for example, explained based on Fig.9, in which magnetic cavity is difficult to identify, but the cavity diffuses around the coil.

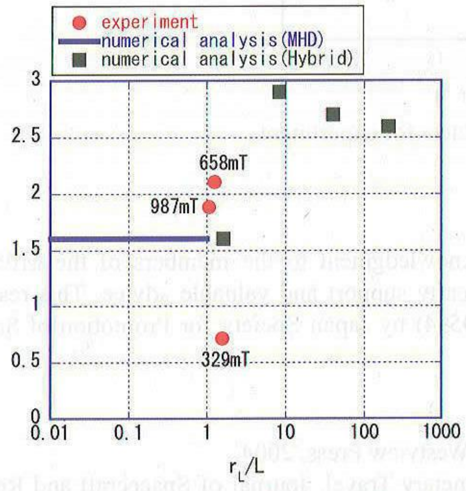


Fig.8 Estimation of thrust coefficient.

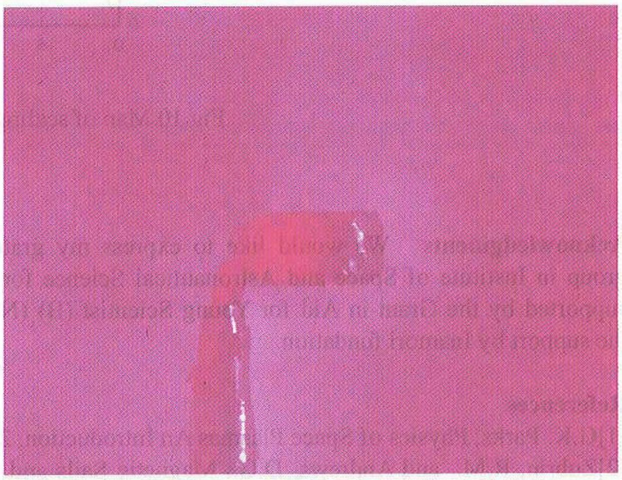

Fig.9 Photo of plasma flow around the coil (1 T).

To establish the conditions $r_{Li}$~$L$ and $\delta_D$ << $L$ in ground experiment, which is expected to be valid for a realistic scalie MagSail operation, both high-density and high-velocity plasma flow is required, however, until now, only moderate $\delta_D/L$~0.5 is realized (Fig.10). Note that $\delta_D$ is larger than $\delta$ in this experiment, hence dominates the thickness of the magnetopause in this experiment.

Due to this diffusive interaction between the plasma jet and the magnetic field, the magnetic field cannot prevent the fast ions into the magnetic cavity. The scaling parameters in this experiment is plotted in Fig.10, in which you can see that diffusive magnetopause ($\delta_D$) dominates the collision less sheath thickness, $\delta$, hence a large collisional sheath develops around the coil. The situation is explained based on Fig.3, in which two operational modes of the MagSail were illustrated. For small $\delta_D$ values in comparison with $L$, large magnetopause develops and $\delta_D$ is comparable to $L$. In this thick magnetopause mode, the effective area that reflects ions is smaller than $L$ as illustrated in Fig.3. To efficiently reflect the incident ions, the magnetopause should be thin, hence $\delta_D/L$ <<1 is required for the MagSail experiment. In this thin magnetopause mode, all the ions will be reflected back at $L$. In contrast, if the magnetopause develops, almost all ions enter into the field near the coil; in this case, the ions exchange momentum dominantely by the Lorentz force, $uxB$. In the thin magnetopause mode, however, the ions are reflected by the induced electric field rather than $uxB$ force because $\delta_D$<<$r_{Li}$. Large effective area in the case of the thin magnetopause mode is apparently useful to obtain large interaction and corresponding large thrust.

## 5. Summary

An experimental simulator of the MagSails was designed and fabricated. A high-density plasma jet above $10^{19}$m$^{-3}$ is supplied by an MPD arcjet, from which a high-speed plasma jet around 20 km/s is ejected. If a 20-mm-radius coil is inserted into the plume, moderate interaction and corresponding decrease of both the density and the velocity was observed in the downstream region of the coil with 1 T magnetic field at the center of the coil. Corresponding momentum change of the simulated solar wind, however, is different from the results obtained from the numerical simulations, which indicates that a large magnetopause in front of the coil prevents efficient momentum transfer from the simulated solar wind to the coil. Possible improvement is to decrease the magnetopause thickness $\delta_D$ by increasing the velocity of the jet form the MPD arcjet.

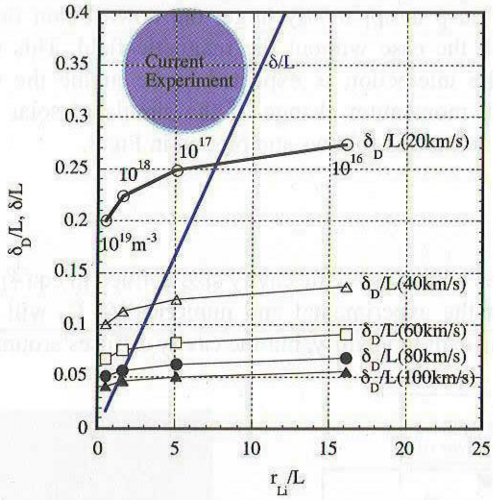


Fig.10 Map of scaling parameters for experiment.

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