Development of Magnetoplasmadynamic Solar Wind Simulator for MagSail Experiment

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Abstract: The Institute of Space and Astronautical Science (ISAS) of Japan Aerospace Exploration Agency (JAXA) is studying a new magnetic sail propulsion system, called MagSail, since 2002. A MagSail travels interplanetary space by capturing the energy of the solar wind. In order to demonstrate the momentum transfer process of the MagSail, we have started to design and manufacture a new solar wind simulator. As for the solar wind simulator, a magnetoplasmadynamic (MPD) arcjet device and a new twelve L-C ladder pulse forming network (PFN) are introduced. In this paper, a design and manufacturing status and very quick results of the simulator are described.

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I. Introduction

THE Institute of Space and Astronautical Science of JAXA succeeded to deploy a very thin membrane structure of 10 m in diameter in space by a Japanese S-310 sounding rocket on August 10, 2004. Figure 1shows a deployed solar sail membrane in space. The petal shape or clover leave shape membrane structure is successfully deployed in Fig. 1. The ISAS is also starting an investigation of solar sail with electric propulsion for future interplanetary mission[1].

Otherwise, a conceptual study of MagSail propulsion was presented by Zubrin in 1991[2]. The MagSail requires an unrealistic spacecraft design with a large hoop coil of 100 km in radius to achieve 1 N-class thrust, hence the idea did not draw much attention so far. In year of 2000, the idea of the MagSail received a renewed interest when Winglee of Washington University proposed Mini-Magnetospheric Plasma Propulsion (M2P2) concept[3], which inflates a weak original magnetic field made by a small coil of about 0.1 m in diameter with an assistance of a high-density plasma jet. Although the feasibility of this compact M2P2 is denied by several researchers, we revised and improved the M2P2 design by enlarging the coil to moderate sizes of about 10 m in diameter, in combination with a properly tuned high-density plasma source to optimize thrust performance[4-7].

In order to demonstrate the improved MagSail concept, several plasma generator devices, such as MPD arcjet, DC arcjet, high specific impulse ion engine, ion beam device and so on, were investigated as for the solar wind simulator. Required performances to the solar wind simulator are, to generate high density plasma of over $10^{18}/m^3$, to generate highly-ionized plasma, to generate high speed plasma up to 10 km/s ~ 100 km/s, to generate over 0.5 msec of plasma life, many propellant gas species are available, several 10 cm of plasma beam diameter at a MagSail simulator and so on. Finally the MPD arcjet was selected as the simulator. Then a solar wind simulator is designed and manufactured. The solar wind simulator is consisted with a magnetoplasmadynamic arcjet, fast acting gas valve, gas supply system, pulse forming network, switching devices, electric power supply, controller, measurement devices, and so on.

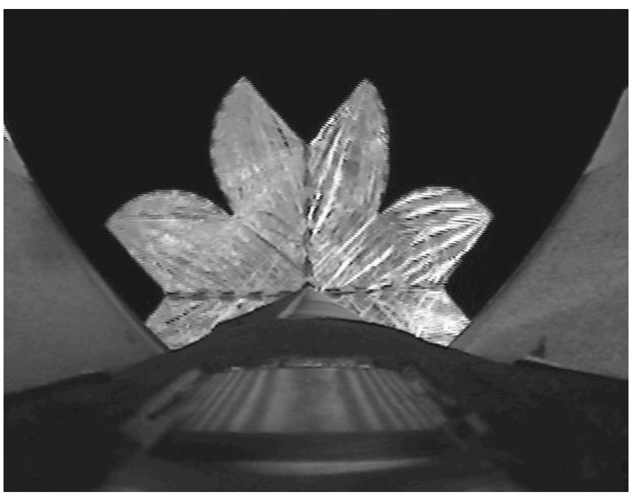

Figure 1. Deployed solar sail membrane in space.

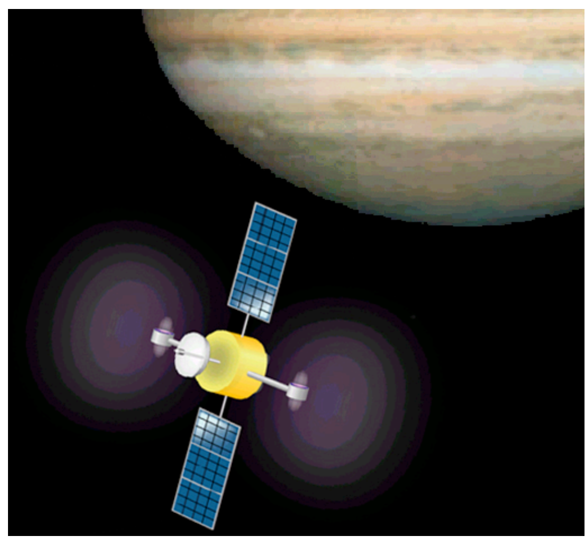

Figure 2. Artist's concept of MagSail.

II. Solar Wind Simulator

A. Magnetoplasmadynamic Arcjet

In ISAS, many investigations for improving the thrust performances of self-field MPD thrusters have been studied[8-10]. A typical MPD discharge chamber of ISAS has a coaxial electrode, nozzle shape discharge chamber, multi-anode electrodes in azimuthally and a short cathode rod in center. Those designing points are adopted in the solar wind simulator.

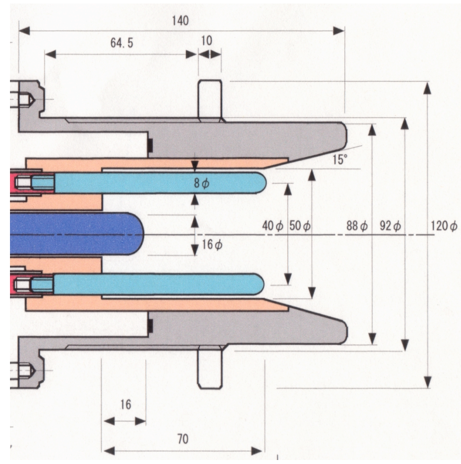

Figure 3. Schematic drawing of discharge chamber.

The new MPD discharge chamber for solar wind simulator is consisted with eight anode electrode rods located in azimuthally, a short cathode rod, an annular floating outer electrode of SUS and insulators. Eight anode electrode rods are, made of Thorium impregnated Tungsten, 8 mm in diameter and 70 mm in length. A short rod shape cathode is made of Molybdenum, 20 mm in diameter and 16 mm in length. These electrodes are able to correspond with unstable low current discharge range and with erosive high current discharge range. The discharge chamber is 88 mm in outer diameter, 50 mm in inner diameter and 100 mm in length. Boron Nitride (BN) and plastic material are used for insulator. Figure 3 shows a schematic drawing of the new MPD discharge chamber. The discharge chamber is attached on the space chamber inner wall as shown in Fig. 4.

A ring shaped Fast Acting gas Valve (FAV) is also attached on the space chamber outer wall as shown in Fig. 5. Electric power supplying terminals are also shown in Fig. 5.

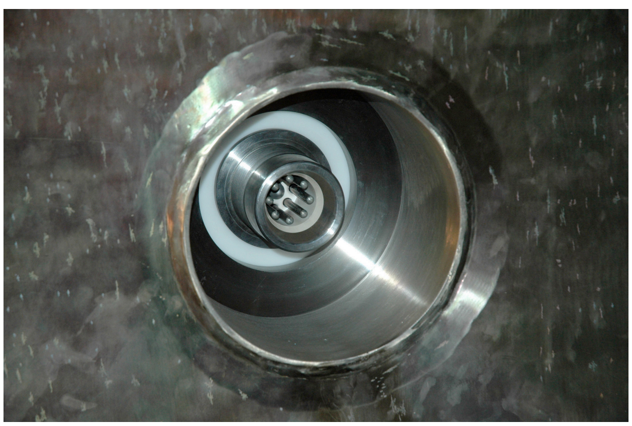
Figure 4. Discharge chamber on space chamber wall.

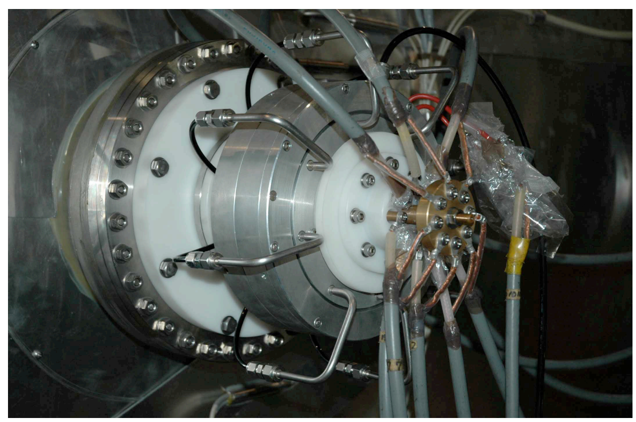
Figure 5. A ring shape Fast Acting gas Valve (FAV) attached on the space chamber wall.

B. Pulse Forming Network (PFN)

To supply a large electric power into the MPD discharge chamber, a new Pulse Forming Network (PFN) is designed and manufactured. Required performance to the new PFN is, to supply over 20 kA in discharge current and about 1 msec pulse width. Reducing total weight of PFN is also required for easy moving in the experiment site. The new PFN is consisted with capacitors, inductance coils, resistances, a switching device and matching resistances. Twenty-four oil filled type capacitors are used. Capacitors were manufactured by Nippon Condenser Co. Ltd. Dimensions of the capacitor are, 490 mm in width, 160 mm in depth, 385 mm in height and 45 kg in weight. The electric characteristics of the capacitors are, 5 kV charging voltage in maximum and 200 μF of capacity. Each capacitor is floated from the ground potential electrically by insulators. Hand made inductance coil of 12 mm diameter wire are provided. Each inductance coil has 8 turns coil wrapped around a polyvinyl chloride pipe of 120 mm in diameter. Each coil has a value of 5 μH inductance. The PFN is consisted with twelve L-C ladder circuits. One L-C ladder is composed of a 200 μF capacitor and a 5 μH inductance coil. A schematic drawing of the PFN is shown in Fig. 6. Resister R1 is a charging and dumping resistance. Resistance R4 is a plasma impedance matching resistance. The value of plasma impedance matching resistance is adjustable from 0 mΩ to 100 mΩ by 10mΩ step. An Ignitron of US National Electronics Co. Ltd. made is used as a switching device for very large current handling. Figure 7 is a photograph of the PFN. A half of L-C ladder network is located on the lower shelf and other half network is located on the upper shelf in Fig. 7. This layout may make a mischief to discharge waveforms, i.e. long cables generate some inductance and resistance.

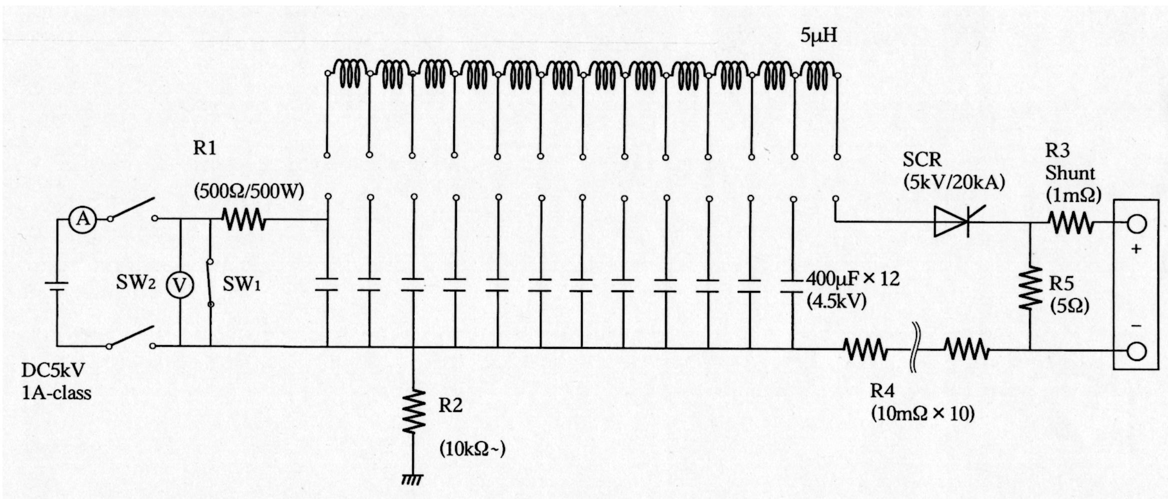

Figure 6. A schematic drawing of the PFN.

Figure 7. Photograph of the Pulse Forming Network (PFN).

C. Test Facility

The solar wind simulator initial test is conducted in the ISAS space science chamber, which is shown in Fig.8. Dimensions of the space chamber are, 2.5 m in inner diameter and 4.5 m in length. The space chamber is pumped down by one turbo-molecular pump and two cryogenic pumps. The achieved vacuum pressure is 10^{-4} Pa or less. Side nozzle and flange of the space chamber is used for the MPD arcjet set-up. The MPD arcjet discharge chamber is set on the inner side of the space chamber and the FAV and electric feed through terminal are set on the outer side as described in section A. The other devices, such as gas supply system, electric switching devices, electric delay circuit devices, electric power supply systems, controllers, sequencers, measurement devices, and so on, are set around the space chamber.

Figure 8. Space Science Chamber of ISAS.

III. Test Results

Using the solar wind simulator, some very quick test results are obtained. In Fig. 9, the argon plasma plume is observed. Very dense and very high speed Argon plasma is generated by the MPD arcjet device, i.e. by the solar wind simulator, in successfully. The simulator is achieved over 20 kA discharge current without any problem. In present time, we have few useful measurement results because of the test has just started. Discharge waveforms of 3 kV charged in the PFN are shown in figures 10 and 11. A case of no matching resistance within the PFN circuit, an over-shoot discharge current waveform is observed as shown in Fig. 10. Otherwise in a case of Fig. 11, a 100 mΩ plasma matching resistance is inserted into the PFN circuit. Some improvement is observed in discharge current waveform. In both figures, horizontal axes shows time in seconds, and vertical axes shows discharge current in kA.

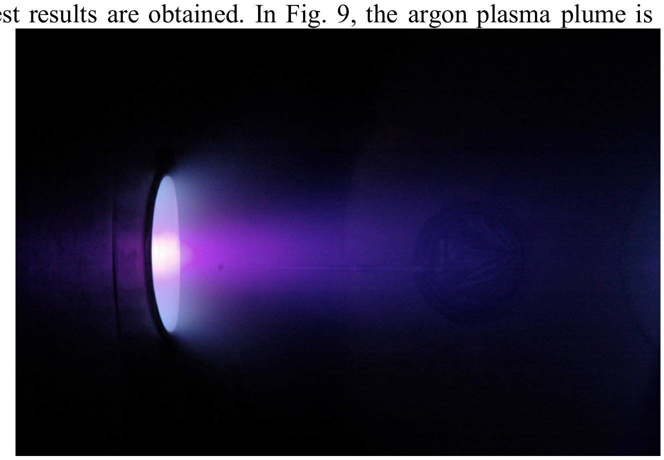

Figure 9. Argon plasma plume from MPD discharge chamber.

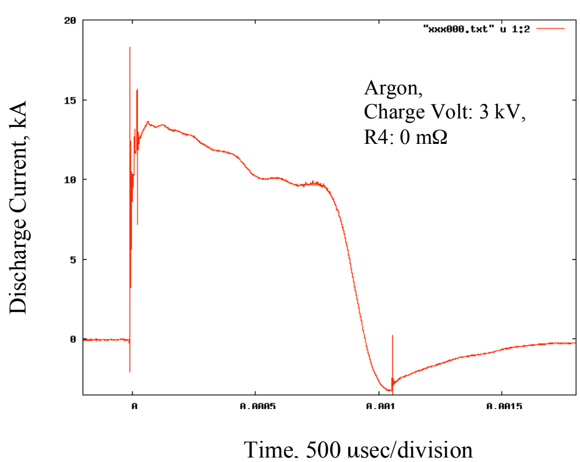

Figure 10. Discharge current waveform, R4 = 0

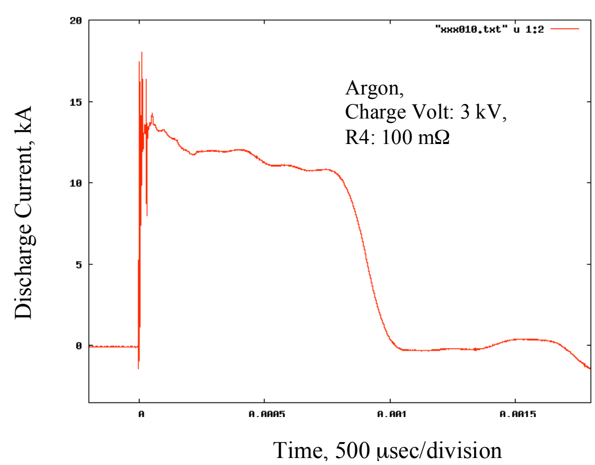

Figure 11. Discharge current waveform, R4 = 100

IV. Summary

As the solar wind simulator, a new MPD arcjet and a new pulse forming network are designed and fabricated. For the initial results, very large dense and fast speed plasma is produced by over 20 kA discharge current. Experimental initial study of MagSail with the solar wind simulator is described in the reference 11. The plasma characteristics from MPD arcjet will be measured in future studies. Before start the future studies of plasma characteristics, the capacitors of the solar wind simulator will be replaced to very new oil filled capacitors made by US General Atomics Electronic Systems Inc. The new capacitor has performances of 5 kV rated charge voltage, 67 μF of capacitance. Dimensions of the capacitor are, 116 mm in width, 95 mm in depth, 267mm in height and 5.2 kg in weight. The matching resistance and coil inductance of PFN will be adjusted to improve discharge waveform to be steadier. After replacement of capacitors, adjustment discharge waveform and obtaining characteristics as for the solar wind simulator, the simulator will be introduce to the MagSail experimental studies.

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