Helicon magnetoplasmadynamic plasma thruster for large thrust and high specific impulse electric propulsion

IEPC-2015-383／ISTS-2015-b-383

Presented at Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan July 4 – 10, 2015

Kazunori Takahahsi[1], Atushi Komuro[2], and Akira Ando[3]
Department of Electrical Engineering, Tohoku University, Sendai 980-8579, Japan

Abstract: **A new concept of a magnetic nozzle plasma thruster 'helicon magnetoplasmadynamic thruster' operated at a few hundreds of kW is proposed and tested in a laboratory experiment. Central cathode and peripheral anode biased at a few hundreds of Volts are installed upstream and downstream of a helicon source. When a helicon plasma is produced in the source by supplying a 13.56 MHz pulsed rf power to a helicon antenna, a large electric current of ~ kA is induced between the cathode and anode. The plasma density above 10^{20} m^{-3} is obtained in the magnetic nozzle downstream of the source, which is a thousand times higher than that with only the conventional helicon source. The supersonic and high density plasma flow is maintained for only a few tens of microseconds at this moment.**

Nomenclature

P_{rf}	=	rf power
V_{MPD0}	=	charge voltage of the capacitance between the cathode and anode
V_{MPD}	=	measured voltage between the cathode and anode
I_{MPD}	=	MPD current
I_B	=	solenoid current
V_B	=	charge voltage of the solenoid circuit
m_{dot}	=	argon mass flow rate
I_{is}	=	ion saturation current of the Langmuir probe

I. Introduction

PLASMA flow expansion in an expanding magnetic field called 'magnetic nozzle' and subsequent plasma acceleration include many aspects of physics relating to electric propulsion devices. Representative magnetic nozzle plasma thrusters are an applied-field magnetoplasmadynamic thrust (MPDT) [1], a variable specific impulse magneto plasma rocket (VASIMR) [2], and a helicon plasma thruster (HPT) [3].

The MPDT is often operated at the discharge power above several hundreds of kW [4], where the linear and nonlinear interaction between the discharge current above a few kA and the magnetic field play important roles in improvement of the thruster performance. Such large electric current is sustained by an arc discharge between the central cathode and the peripheral anode; hence much flow rate (typically a few hundreds of mg/s) of the propellant

[1] Associate Professor, Department of Electrical Engineering, kazunori@ecei.tohoku.ac.jp
[2] Assistant Professor, Department of Electrical Engineering, komuro@ecei.tohoku.ac.jp
[3] Professor, Department of Electrical Engineering, akira@ecei.tohoku.ac.jp

gas has to be introduced in to the thruster head to trigger and maintain the arc discharge. Since a very high power above a few hundreds of kW to MW can be input into the discharge, a thrust above several N has been obtained by the MPDT.

The HPT consists of only insulator source tube surrounded by an rf antenna and a solenoid to create the magnetic nozzle. Since the helicon wave discharge can generate a high density plasma in low pressure of order of mTorr, the thrust can be operated at a very low gas flow rate (typically 0.5-10 mg/s) and a rf power less than several kW. The highest thrust to this date seems to be ~60 mN for 6 kW rf power [5]. The plasma is generated inside the insulator source cavity, the plasma has no net current, i.e., current-free; then the pure interaction between the plasma-induced current and the applied magnetic field can be experimentally investigated. Some of the vigorous researches have shown that the Lorentz force arising from the plasma-induced electron diamagnetic current and the applied radial magnetic field can significantly improve the HPT performance [3,6-8]. According to the series of the HPT research, the Lorentz force is proportional to the electron pressure inside the magnetic nozzle, while the plasma density in the magnetic nozzle of the HPT is typically less than 10^{17}m^{-3}. Increasing the electron pressure in the magnetic nozzle will lead further development of the large thrust plasma thruster.

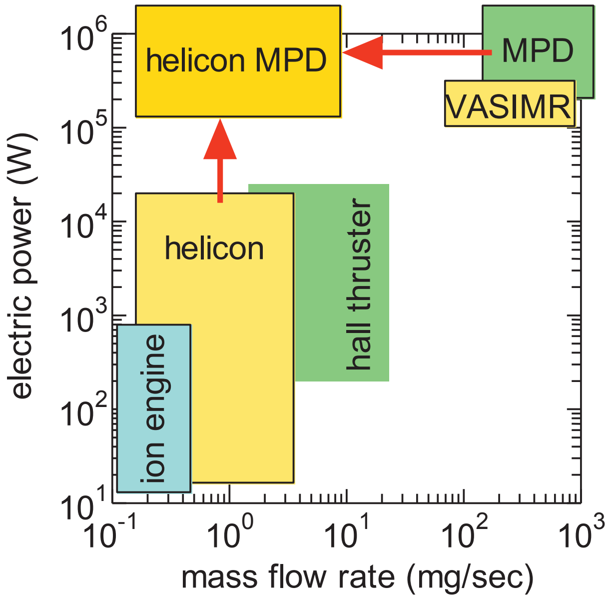

Figure 1. Operational parameter of various types of electric propulsion devices in electric power versus mass flow rate.

VASIMR has an additional ion cyclotron resonance heating, where the ions are heated in the direction perpendicular to the external magnetic field. Their energy is converted into the axial energy via a magnetic expansion process, which can be well understood by single particle dynamics. Above 200 kW rf powe has been applied to the thruster head so far; then thrust of ~6N has been obtained [2].

The operational electric power and mass flow rate of various types of electric propulsion devices are shown in Fig. 1. It is found that the MPDT and VASIMR require much gas flow rate, while the HPT is operational for the low mass flow rate. Operating the thruster for electric power close to that of the VASIMR and MPDT, and for the low mass flow rate close to that of HPT, might expand the application of the electric propulsion for various space missions. Here a new concept of the high power magnetic nozzle plasma thruster operated at low pressure (low mass flow rate) is proposed and preliminarily tested by attaching the thruster head to a small laboratory device. It is demonstrated that the presence of the high density helicon plasma triggers and sustains the MPD discharge between the cathode and anode even for low argon gas flow rate of 1-6 mg/s. The measurement at ~10 cm downstream of the source exit shows the high density plasma above 10^{20} cm^{-3} and the supersonic plasma flow of Mach 1.8 is detected. Such situation is sustained only for a few tens of microseconds at this moment.

II. Experimental setup

II-1. Diffusion chamber and thruster head of the helicon MPD thruster

Experiments are performed by attaching the presently proposed helicon MPD source to the HPT-XS machine (Fig.2) at Tohoku University, which has a 13 cm diameter and 55 cm long diffusion chamber evacuated by a 300 L/s turbomolecular pump to a base pressure of 5 x 10^{-5} Pa. A schematic diagram of the helicon MPD thruster head is also shown in Fig.2. A 2.4 cm diameter and 15 cm long quartz tube (source tube) is contiguously connected to a nozzle-shaped cylindrical copper anode, which is further connected to the diffusion chamber via an insulated flange. A 3.2 mm diameter tungsten rod cathode is mounted on the flange upstream of the source tube and introduced into the quartz tube via a 4 mm inner diameter ceramic bush. Argon gas is continuously introduced from the aperture between the cathode and the ceramic bush via a mass flow controller. The maximum flow rate of the mass flow controller is 6 mg/s for argon. The absolute gas pressure is measured by a capacitance manometer connected to a chamber side port at z = 5 cm, where z = 0 is defined as the downstream exit of the copper anode. The measured

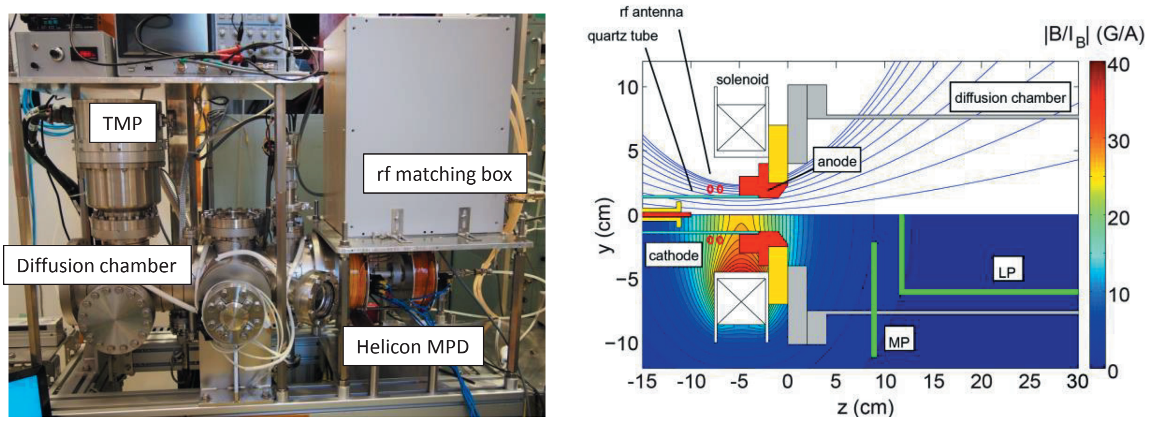

Figure 2. (left)Photograph of the HPT-XS machine at Tohoku University for testing the helicon MPD thruster. (right) Schematic diagram of the helicon MPD thruster head.

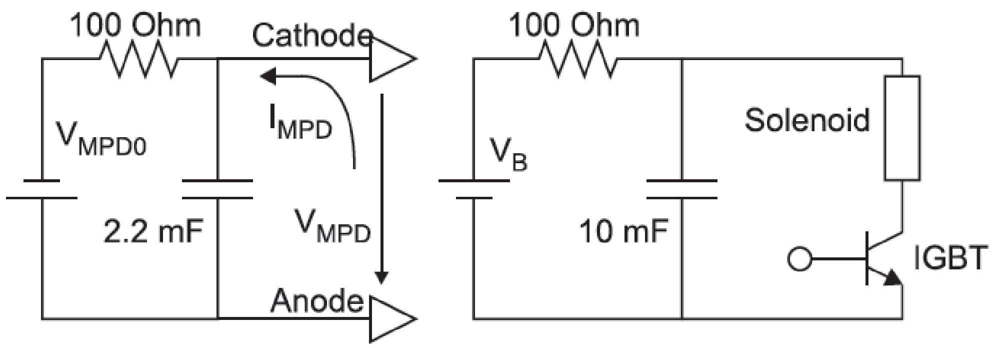

Figure 3. Schematic of the electric circuits connected to the electrodes (cathode and anode), and the solenoid.

pressure for the mass flow rate of m_{dot} = 6 mg/s is 1.6 Pa. A double turn rf loop antenna is wound around the source tube at z ~ -7.5 cm and powered from a 13.56 MHz and 1 kW rf generator through an impedance matching circuit. A solenoid is centered at z = -4.8 cm to provide a magnetic nozzle. The calculated magnetic field lines and strength normalized by the solenoid current I_B are shown by the solid lines and the contour color in Fig. 2. The field has a spatial peak of 26.8 G/A on axis at around z = -5 cm and decreases down to ~10 % at z = 10 cm.

II-2. Plasma diagnoses

An axially movable 0.9mm diameter planar Langmuir probe (LP) facing to the radial wall is installed from the downstream vacuum flange to estimate the plasma density and electron temperature. Furthermore, a Mach probe (MP), which consists of two detection tips facing to upstream and downstream sides of the plasma flow, is inserted from the radial port at z = -9.5 cm. The ion current ratio of the two probe tips gives the plasma flow velocity. The difference in the surface area of the two probe tip is calibrated by rotating the probe in the simple helicon plasma.

II-3. Electrical circuit of the solenoid and the MPD electrodes

In this section, the electrical circuit connected to the solenoid and electrodes are described. The schematic diagram of the external circuits for the electrodes and the solenoid are shown in Fig. 3. The anode and cathode are connected to an electrolytic capacitor (2.2mF) as shown in Fig.3 and charged by the voltage V_{MPD0}, where the circuit is entirely isolated from the ground to ensure that the current loop is formed between the cathode and the anode. The voltage V_{MPD0} can be increased up to 450 V due to the dielectric strength voltage of the capacitor. To operate the helicon MPD thruster for various magnetic field strength, the solenoid in the wide range has to be supplied. The solenoid current I_B is pulsed by using the previously reported pulsed circuit [9] utilizing the power semiconductor

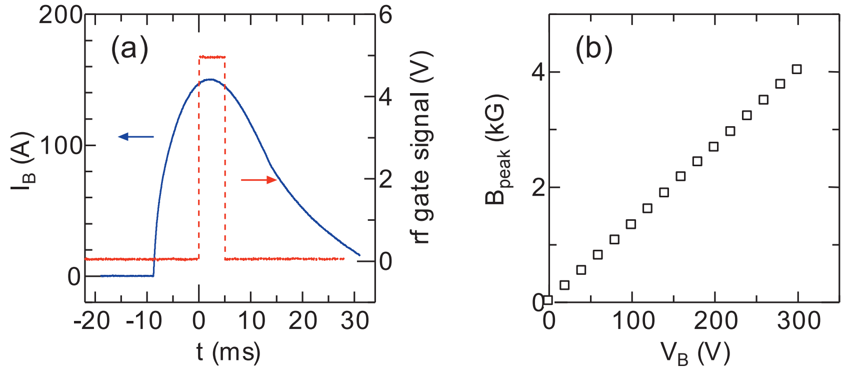

Figure 4. (a) Temporal evolution of the solenoid current I_B and the rf gate signal, where the rf power is turned on for 5 V gate voltage. (b) The spatio-temporal peak magnetic field strength as a function of the charge voltage V_B.

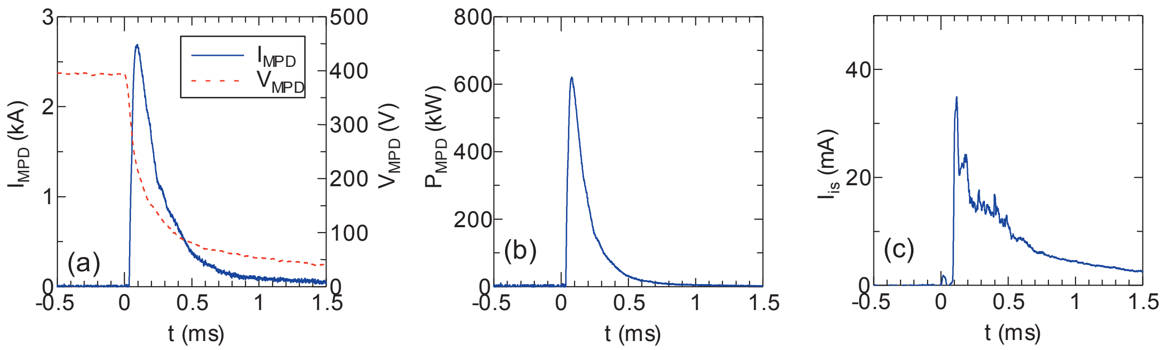

Figure 5. Temporal evolutions of (a) I_{MPD} and V_{MPD}, (b) the electric power, and (c) the ion saturation current I_{is} of the LP located at z = 15 cm.

Insulated Gate Bipolar Transistor (IGBT). After the 10 mF capacitor connected to the solenoid and the IGBT is charged by a dc voltage V_B, the IGBT is turned on; then a pulsed current can be supplied to the solenoid. The solenoid current is measured by a current sensor.

III. Experimental results

The temporal evolution of the solenoid current I_B is plotted by a solid line in Fig.4(a), where the gate signal of the IGBT is turned on at t = -9 ms. The temporal peak value of the magnetic field strength at the solenoid center is plotted in Fig. 4(b) as a function of the charge voltage V_B. It is found that the magnetic field up to about 4 kG is applicable in the present experiments. The rf generator is also pulsed with the pulse width of 5 ms and is turned on at t = 0 as plotted by the dashed line in Fig.4. When the voltage V_{MPD0} between the cathode and anode is chosen as zero, the source is operated as a simple traditional helicon source.

Typical temporal evolution of I_{MPD} and V_{MPD} are plotted by solid and dashed lines in Fig. 5(a), respectively, for m_{dot} = 6 mg/s, V_{MPD0} = 400 V, and V_B = 250 V. When turning on the rf power at t = 0, a pulsed large current of a few kA is triggered between the cathode and anode at the delay time of a few tens of μs. Here, it should be noted that such large current I_{MPD} is never detected with no rf power for the gas flow rate being tested even if the voltage is increased up to maximum. Hence this experiment demonstrates that the MPD discharge is triggered for the low mass flow rate by combining with the helicon discharge, so called helicon MPD thruster. The power calculated from I_{MPD} and V_{MPD} is also plotted in Fig.5(b). Although a quasi-steady plasma cannot be maintained at this moment, the electric power above 500 kW can be applied to the thruster head with the compact power supply.

The ion saturation current is also measured at z = 15 cm and the raw current signal is plotted in Fig. 5(c). The peak current of about 30 mA is detected at the initial time of the discharge. By using an electron temperature of ~3 eV estimated from the time-resolved I-V characteristics, the plasma density at this position is found to be above 10^{20} m^{-3}. On the other hand, the ion saturation current for the simple helicon source operation (V_{MPD0} = 0), the plasma density at the same position was about 10^{17} m^{-3}. Therefore, the presently proposed helicon MPD thruster can yield the plasma density a thousand times higher than the for the simple helicon source. According to the recently suggested electron diamagnetic model imply the thrust induced by the electron diamagnetic drift current is proportional to the density in the magnetic nozzle. Hence the significantly larger thrust is expected to be obtained. To verify this, the authors have developed an accurate target technique to measure an impulse bit. The measurement of the thrust will be performed hereafter. The recent publication from the authors has shown the measurement of the plasma flow velocity by the Mach probe technique. The result shows the Mach number of about 1.8. However, such high density and high speed flow can be maintained only for a few tens μs. Some of the detailed results can be found in Ref. [10]. Therefore, the thruster and source development including the power supply and gas injection system should still be progressed.

IV. Summary

The new concept of the magnetic nozzle helicon MPD thruster is proposed and preliminarily tested by attaching the thruster head to the compact diffusion chamber. The high density plasma in the magnetic nozzle is produced by combining the helicon discharge and the MPD discharge under the low pressure less than 1.6 Pa. Then the plasma density above 10^{20} m^{-3} is obtained. Thrust assessment, optimization of the thruster structure, power supply, and electrical system still remains further issue.

Acknowledgements

This work is partially supported by a grants-in-aid for scientific research (Grants No. B25287150 and A26247096) from the Japan Society for the Promotion of Science and the Yazaki Memorial Foundation for Science and Technology.

References

[1]Zuin, M., Cavazzana, R., Martines, E., Serianni, G., Antoni, V., Bagatin, M., Andrenucci, M., Paganucci, F., and Rossetti, P., "Kink Instability in Applied-Field Magneto-Plasma-Dynamic Thrusters," *Physical Review Letters*, 92, 225003 (2004).

[2]Longmier, B.W., Cassady, L.D., Ballenger, M.G., Carter, M.D., Chang-Diaz, F.R., Glover, T.W., Ilin, A.V., McCaskill, G.E., Olsen, C.S., and Squire, J.P., "VX-200 Magnetoplasma Thruster Performance Results Exceeding Fifty-Percent Thruster Efficiency," *Journal of Propulsion and Power*, 27, 915 (2011).

[3]Takahashi, K., Charles, C., Boswell, R.W., "Approaching the Theoretical Limit of Diamagnetic-Induced Momentum in a Rapidly Diverging Magnetic Nozzle," *Physical Review Letters*, 110, 195003 (2013).

[4]Tobari, H., Ando, A., Inutake, M., and Hattori, K., "Characteristics of electromagnetically accelerated plasma flow in an externally applied magnetic field," *Physics of Plasmas*, 14, 093507 (2007).

[5]Takahashi, K., A. Komuro, and Akira, A., "Recent progress of helicon plasma thruster development," *Proceedings of the 34rd International Electric Propulsion Conference*, IEPC Paper 2015-294, Kobe Japan, 2015.

[6]Fruchtman, A., "Electric Field in a Double Layer and the Imparted Momentum," *Physical Review Letters*, 96, 065002 (2006).

[7]Ahedo, E. and Merino, M., "Two-dimensional supersonic plasma acceleration in a magnetic nozzle," *Physics of Plasmas*, 17, 073501 (2010).

[8]Takahashi, K., Charles, C., Boswell, R., and Ando, A., "Effect of magnetic and physical nozzles on plasma thruster performance," *Plasma Sources Science and Technology*, 23, 044004 (2014).

[9]Takahashi, K., Sato, D., Takaki, K., and Ando, A., "Development of a compact magnetically expanding plasma source with a strong magnetic field," *Plasma Sources Science and Technology*, 22, 055002 (2013).

[10]Takahashi, A. Komuro, and Ando, A., "Low-pressure, high-density, and supersonic plasma flow generated by a helicon magnetoplasmadynamic thruster," *Applied Physics Letters*, 105, 193503 (2014).