Development and Thrust Performance of a Microwave Discharge Hall Thruster

IEPC-2007-085

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Hirohisa KUWANO *
Kyushu University, 6-1, Kasuga-Kouen, Kasuga 816-8580, JAPAN

Akira OHNO†
The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN

Hitoshi KUNINAKA‡
Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)
3-1-1, Yoshinodai, Sagamihara, Kanagawa 229-8510, JAPAN

and

Hideki NAKASHIMA §
Kyushu University, 6-1, Kasuga-Kouen, Kasuga 816-8580, JAPAN

Abstract: Microwave discharge Hall thrusters have been investigated as a double-stage Hall thruster. Our original microwave discharge Hall thruster, where 2.45-GHz microwaves were employed, needed voluminous waveguides for microwave transmission; therefore direct thrust measurements using a thrust stand were not achieved. Based on the background, by changing wave frequency from 2.45 GHz into 5.8 GHz and developing a new microwave discharge Hall thruster adequate for 5.8-GHz microwaves, the required volume of a waveguide has been decreased: thus a pendulum type thrust stand using a smaller waveguide as a pendulum arm has been built. The 5.8-GHz microwave discharge Hall thruster can be operated in two operating modes; the first one is "non-microwave injection mode" referred to as "single-stage" and the second one is "microwave injection mode" referred to as "double-stage". The thruster channel length can be adjusted to 8 or 13 mm. To examine the influence on thrust performance of microwave, the thrust measurements have been conducted in both single- and double-stage operations for each channel length condition, at xenon flow rates of 1.36, 2.05 and 2.73 mg/s, and discharge voltages of 200, 250 and 300 V. As a result, thrust and specific impulse in double-stage operation have been higher than that in single-stage operation for the same channel length, flow rate, and discharge voltage. Moreover, higher thrust efficiencies in double-stage operation, as compared to single-stage operation, have been attained when the thruster operates at low flow rate such as 1.36 and 2.05 mg/s, and low discharge voltage such as 200 V. The paper also reports on the reduction in discharge current oscillations due to microwave injection.

* Graduate Student, Department of Advanced Energy Engineering Science, E-mail: h-kuwano@hotmail.co.jp
† Graduate Student, Department of Aeronautics and Astronautics, E-mail: ohno@ep.isas.jaxa.jp
‡ Professor, Department of Space Transportation Engineering, E-mail: kuninaka@isas.jaxa.jp
§ Professor, Department of Advanced Energy Engineering Science, E-mail: nakasima@aees.kyushu-u.ac.jp

Nomenclature

F	=	thrust
g_0	=	standard acceleration of gravity
I_d	=	discharge current, or current flowing from an anode to a cathode
I_i	=	ion beam current
I_{sp}	=	specific impulse
L	=	channel length of a Hall thruster
m_{dot}	=	propellant mass flow rate
V_d	=	discharge voltage, or voltage applied between an anode and a cathode
P_{mw}	=	net input microwave power
η_t	=	thrust efficiency

I. Introduction

RECENT studies have shown benefits of dual-mode thrusters, or variable-specific-impulse thrusters that can be operated at constant power for two operating conditions[1,2]. The first operating point is a high thrust but low specific impulse regime (as Hall thrusters) suitable for efficient orbit raising, insertion and repositioning in which the main constraint is minimization of transfer duration. The second operating point is a high specific impulse but low thrust regime (as ion thrusters) suitable for orbit correction such as north-south station keeping in which low-propellant consumption is required. Such a dual-mode thruster is expected to substantially enlarge mission domains: thus a double-stage Hall thruster[3-7], in which the plasma generation region is independent of the acceleration region, has drawn attention as one of promising candidates for a dual-mode thruster.

In our laboratory, as one of such double-stage Hall thrusters, microwave discharge Hall thrusters have been investigated, in which microwave signals are injected into a cylindrical cavity resonator located upstream of the thruster channel, and penetrated into the channel from the upstream region, resulting in generation of microwave-excited surface-wave plasmas. At the beginning of the research, a 2.45-GHz microwave discharge Hall thruster was developed, and tested in order to examine the plasma characteristics and increase the thrust performance[8-10]. In the original thruster, 2.45-GHz microwaves were utilized because magnetrons for frequency of 2.45 GHz were widely applied by industry and empirically guaranteed to generate dense plasmas. However, the waveguides and cavity resonator for microwave transmission and absorption were voluminous: thus the thruster was practically unsuitable for real spacecraft, and direct thrust measurements using a thrust stand were not fulfilled. Note that volume of both waveguides and cavity resonators increases along with the decreasing frequency of microwave.

In our recent study, in order to allow for practical use in real spacecraft and realize thrust measurements with a thrust stand, the microwave frequency for the thruster has been changed from 2.45 GHz into 5.8 GHz, and consequently the volume of waveguides and a cavity resonator has been shrunk. The new microwave discharge Hall thruster developed for 5.8-GHz wave can be operated in two operating modes, or “non-microwave injection mode” and “microwave injection mode”, which are referred to as “single-stage” and “double-stage” respectively.

In addition to the 5.8-GHz thruster described above, also a pendulum-type thrust stand suitable for the thruster with a waveguide has been successfully developed. One of main features of the thrust stand is using a stainless-steel waveguide connected to the cavity resonator as its pendulum arm. The objective of this study is to conduct a thrust performance testing, to compare the results between “single-stage” and “double-stage”, and to examine the influence on thrust performance of microwave injection.

II. Experimental Apparatus

A. 5.8-GHz Microwave Discharge Hall Thruster

Figure 1 shows a cross-sectional view of the 5.8-GHz microwave discharge Hall thruster, and Fig. 2 shows photograph images of the thruster and a hollow cathode. The acceleration channel is 52 mm in inner diameter, 74 mm in outer diameter, and the channel length can be adjusted to either 8 or 13 mm. The channel geometry is resembles that of Magnetic-layer-type Hall thrusters. The wall both of the channel and of the exit plane is made out of boron nitride (BN), and the ring-shaped anode is made of copper. As a cathode, a commercially available hollow cathode (Ion Tech, 07HC-252-011), electron current emitted from which is characterized to be about 5 A on the basis of our preliminary experiment, is installed. The hollow cathode needs both keeper and heater power supplies. In order to form magnet circuits and achieve a strong peak of radial magnetic field (magnetic flux density of 25 mT) near the channel exit, soft irons are installed, and samarium-cobalt (SmCo) permanent magnets are located both inside the

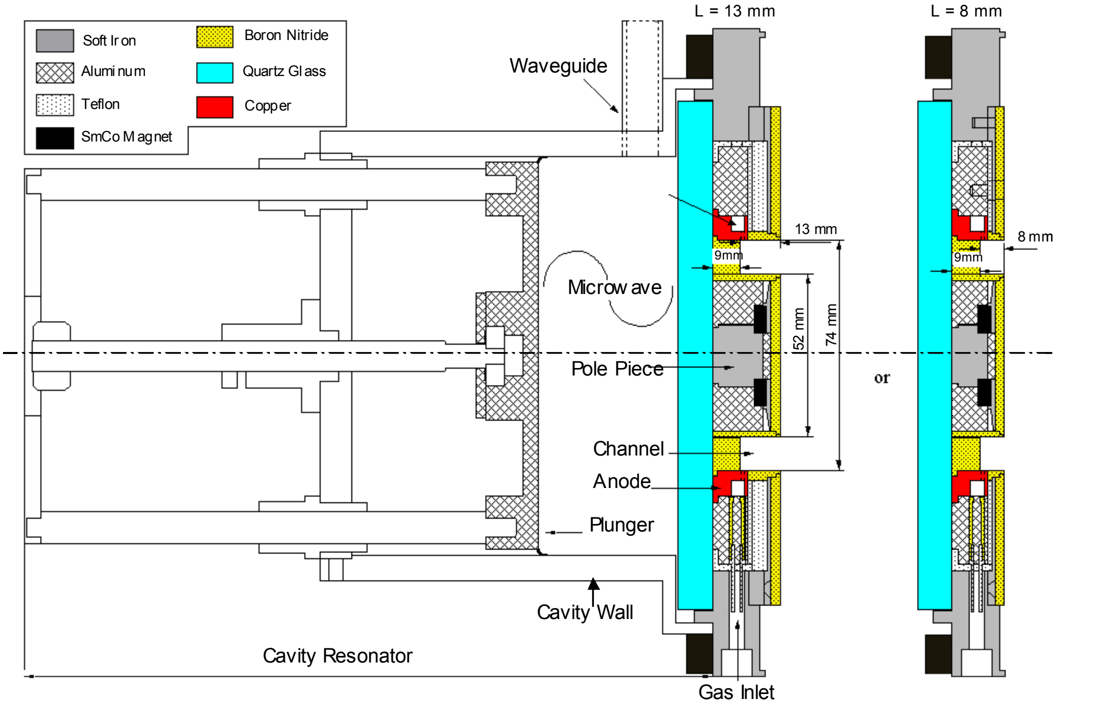


Figure 1. A cross-sectional view of the 5.8-GHz microwave discharge Hall thruster. In the left side of the figure, a cylindrical-cavity resonator is located, and the cavity height can be adjusted flexibly.

center pole piece and circumferentially arranged on the rear edge of the thruster as shown in Fig.1 and Fig.2. Xenon gases are fed into the channel through the gas distributors as propellants.

For microwave transmission and absorption, rectangular waveguides with cross section 10 mm in length and 40 mm in width, and a cylindrical-cavity resonator 128 mm in inner diameter and 30.23 mm in inner length are located upstream of a disk-shaped quartz glass 12 mm thick. Inside of the cavity resonator, TM_{011}-mode standing waves[11], leading to plasmas uniform in the channel circumferential direction, is established. Note that, as compared to the 2.45-GHz microwave discharge Hall thruster, volume of the cavity has been decreased by about 35 %.

Microwaves are generated by a commercially available microwave oscillator 5.8 GHz, 0-750 W (Micro Denshi, MMG-607V) outside the vacuum tank, transmitted through rectangular waveguides, injected into the cylindrical cavity resonator located upstream of the thruster channel, and penetrated through quartz glass into the channel, resulting in generation of microwave-excited surface-wave plasmas. A major feature of such plasmas is that microwaves penetrate into the thruster channel along the plasma-dielectric (i.e. quartz glass) interfaces even in the overdense

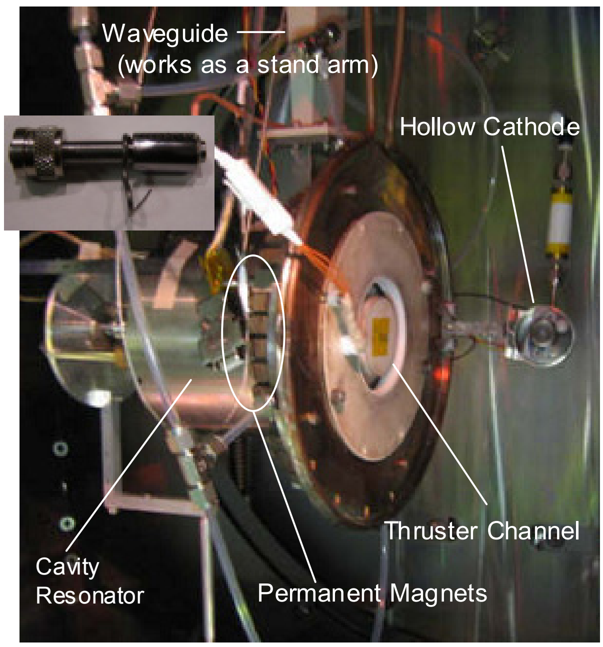


Figure 2. Photograph image of 5.8-GHz microwave discharge Hall thruster mounted on the thrust stand, showing the cathode position. Inset shows a hollow cathode, electron emission from which is characterized to be about 5 A.

plasma mode and the electron heating occurs in a thin skin-depth layer.

Notice that the thruster can be operated in two operating modes, which include "non-microwave injection mode" and "microwave injection mode" referred to as "single-stage" and "double-stage" respectively. The objective of this paper is to compare experimental results between single- and double-stage operations, and to search for operating points in which double-stage operation has the advantage against single-stage operation.

B. Thrust Stand

One might imagine that it is much easier to measure the thrust by pendulum method in plasma-discharging operation. However, microwaves are injected into the thruster through rigid voluminous waveguides: thus in our research, the waveguide is utilized not only as a wave transmitter but also a stand pendulum arm.

Radial bearings are installed at the fulcrum, and vacuum bellows 0.15 mm thick are used for the purpose of maintaining a vacuum around the pendulum moving part. A disk-shaped quartz glass is put between the flexible waveguide and the stand arm, and is also located in a division between a vacuum region and a non-vacuum region as shown in Fig. 3. Therefore microwave signals of 5.8 GHz generated by an oscillator are fed through a rectangular flexible waveguide, the disk-shaped quartz glass, and the inside the stand arm. For the efficient transmission of microwave power from the generator to the thruster, impedance matching[11] is considered over the quartz glass; hence the glass thickness is designed to be 13.4mm.

The displacement of the pendulum arm is detected by an LED sensor (KEYENCE, PA-1810 and PA-1800), the resolution of which is 1 μm. The relation between the displacement and force is calibrated by hanging some weights in order to apply known horizontal force to the thruster thorough a pulley as described in Fig.3.

Figure 4 shows an example of the calibration results, in which response linearity of the sensor output against the weight is observed. The approximated straight line, however, shifts in parallel after experiment because the stand arm strains with thermal drift due to thruster operation. Degree of the parallel shift increases with either the duration of the thruster operation or the value of the discharge voltage, but the gradient of the approximated straight line is considered to be constant.

Based on the above facts, in order to eliminate thermal-effect contribution, thrust is evaluated by dividing difference of the sensor output between "just before" and "after" stopping thruster operation by the known constant gradient attained from the calibration as described in Fig. 4. Notice that the thrust stand can be operated with an accuracy of less-than-2 mN.

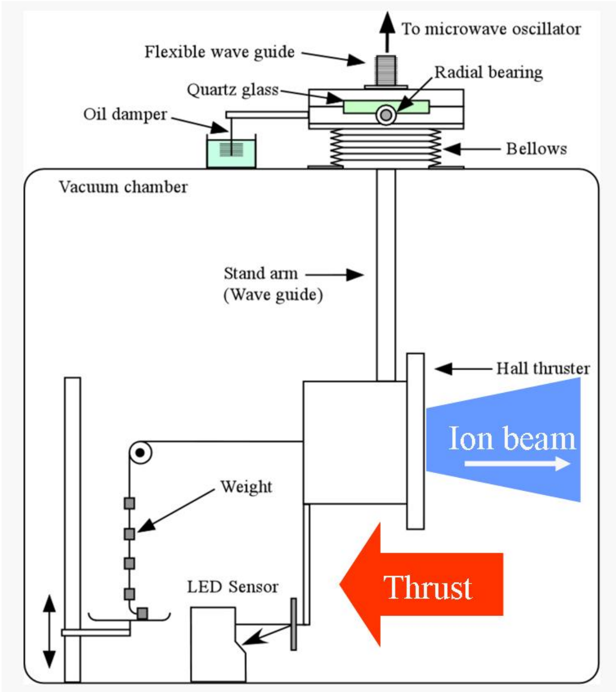


Figure 3. Schematic of the pendulum-type thrust stand, in which the waveguide is used as both a stand arm and a wave transmitter.

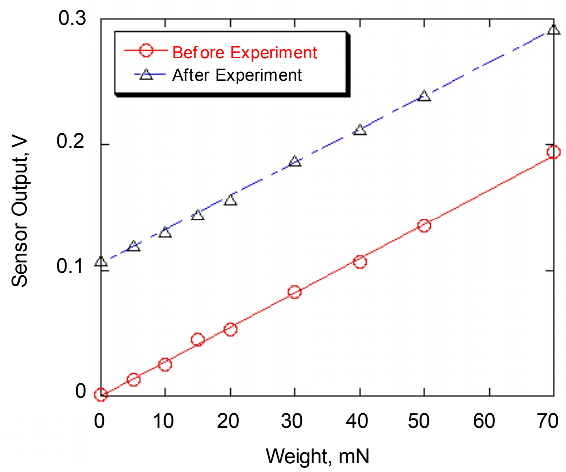


Figure 4. Example of the calibration result, in which the approximated straight line shifts in parallel after experiment because of thermal drift.

C. Discharge Current and Ion Beam Current Measurements

Figure 5 shows a schematic diagram of the experimental setup for measurements of discharge current I_d and ion beam current I_i. Discharge current is the current flowing from the anode to the cathode, or ground, and ion beam current is the net ion beam exhausted from the thruster. Discharge voltage V_d is the voltage applied by the discharge voltage supply. The thruster is mounted on the flange of the vacuum chamber.

In this paper, the discharge current is measured in order to evaluate discharge power consumption, which is the product of I_d by V_d. To monitor the discharge current, a 1-Ω shunt resistance is installed, and potential drop along the resistance is measured.

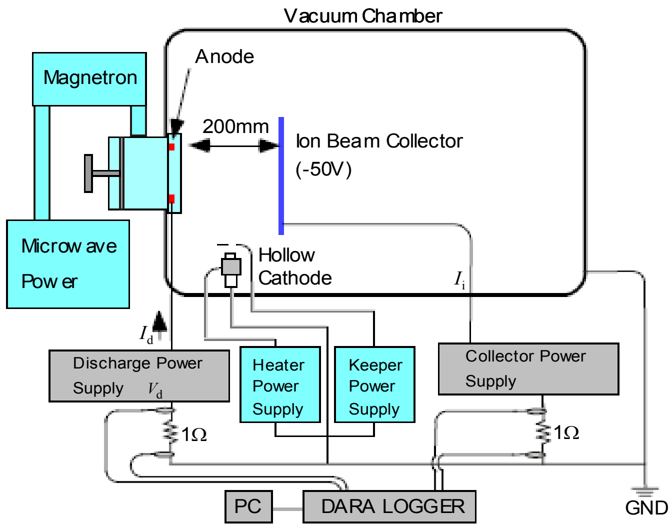


Figure 5. Schematic of the experimental setup for measurement of discharge current I_d and ion beam current I_i.

Moreover, also discharge current oscillations are monitored in this study. For acquiring current oscillations, the shunt resistance is removed, a commercially available DC-50-MHz current probe (YOKOGAWA, 700937) is utilized instead, and an oscilloscope (YOKOGAWA, DL7200, up to 2 GHz in sampling rate) is used. Among the oscillations in Hall thrusters, so-called ionization oscillations[12] at a frequency range of 10^4–10^5 Hz especially are focused on: thus the sampling rate of the oscilloscope is adjusted to such a frequency range.

Also the ion beam current is measured using an ion collecting plate described in Fig. 5. The plate, or the ion beam collector, is placed at a distance of 200 mm from the thruster exit plane, and voltage-biased to –50 V in order to repel incoming electrons[9]. The ion beam current is monitored to compare the characteristic curves of the ion beam current against the discharge voltage for the thrusters both in single- and double-stage operation. Therefore the influence on the current response of the microwave injection can be analyzed.

D. Vacuum Facility

For performance testing, the thruster is set inside a vacuum chamber consisting of a main cylindrical tank 2 m in diameter and 5 m in length, and a sub cylindrical tank 0.8 m in diameter and 1.0 m in length. In order to evacuate, 4 cryopumps (pumping speed for nitrogen: 28000 l/s per single pump) are installed in addition to a rotary pump, a mechanical booster pump, and turbo-molecular pump. Pressure inside the vacuum chamber is kept at 8.2×10^{-3} Pa with 2.73 mg/s (28 sccm) xenon mass flow rate.

III. Results and Discussion

A. Experimental Results and Discussion of Discharge Current Oscillations

Figure 6 and 7 show the oscillograms of the discharge current in both single- and double-stage operations, with the channel length of 8 mm, at the mass flow rate of 2.73 mg/s (28 sccm) and the discharge voltage of 300 V, in both of which oscillations at the frequency of about 25 kHz are recognized. The oscillation frequency is at a range of 10^4–10^5 Hz; thus the oscillations described in both Fig.6 and 7 are classified into ionization oscillations[12]. A comparison between Fig. 6 and Fig. 7 shows that microwave injection can suppress current oscillations.

Several opinions on physical process of the discharge current oscillations at a range of 10^4–10^5 Hz are stated ever[12-15]. In this paper, the physical process inside the channel is considered as below; the velocity of ions exhausted from a Hall thruster is much larger than the diffusion velocity of propellants, and the velocity differential causes a periodic disturbance in the number density of ions and propellants, or neutral gases; thus the disturbance is considered to result in current oscillations.

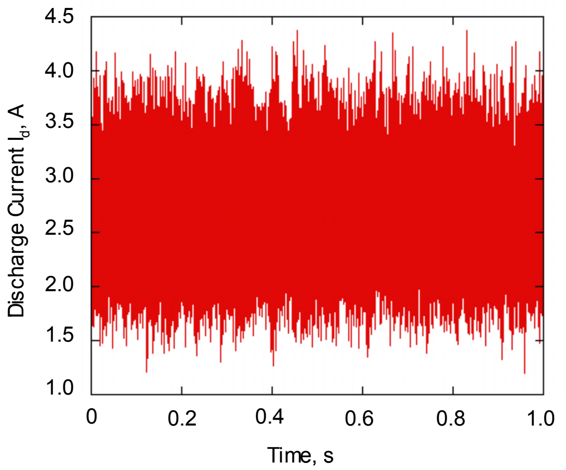


Figure 6. Oscillogram of the discharge current in “single-stage” operation, with the channel length of 8 mm at the mass flow rate of 2.73mg/s (28 sccm) and the discharge voltage of 300 V.

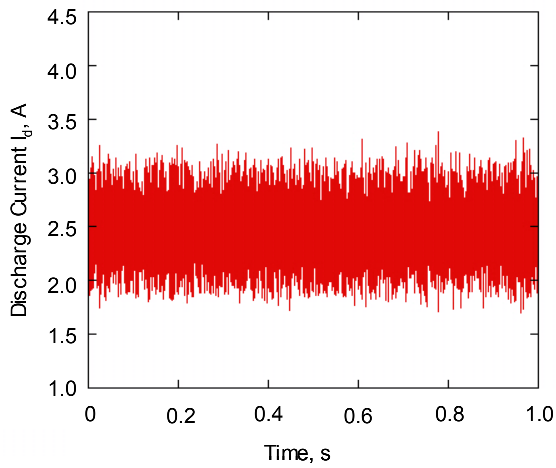


Figure 7. Oscillogram of the discharge current in “double-stage” operation, with the channel length of 8 mm at the mass flow rate of 2.73mg/s (28 sccm) and the discharge voltage of 300 V.

For single-stage operation, whereas the ionization occurs near the channel exit where the peak of the radial magnetic field exists, propellant gases are injected from the anode located upstream of the channel; thus the neutral gases require time to flow to the ionization region. Meanwhile, for double-stage operation, or the microwave injection mode, propellants are ionized near the anode because of the microwave-excited surface-wave plasmas, and the ions are accelerated by the axial electric field. The ion acceleration is considered to relieve the time lag between the propellant gas feed and the ion feed, and leads to reduction in oscillations.

B. Measurements of Current-Voltage Characteristics

Figure 8 shows the characteristic curves of the ion beam current I_d against the discharge voltage V_d. The measurements have been carried out for the channel length of 8 mm at the mass flow rate of 2.73 mg/s in both single- and double-stage operations. The legends, “Double” and “Single”, are referred to as double- and single-stage operations, respectively.

As shown in Fig.8, for entire discharge voltage domain, the ion beam current in double-stage operation is higher than that in single-stage operation. Moreover, the ion beam current in the operation with microwave has a positive value even at the discharge voltage less than 80 V, whereas the thruster without microwave cannot be operated in such a voltage domain.

Therefore the microwave injection is considered to have effect on extending the performance envelope of Hall thrusters because the result in Fig.8 shows elimination of the threshold of the discharge voltage in double-stage operation.

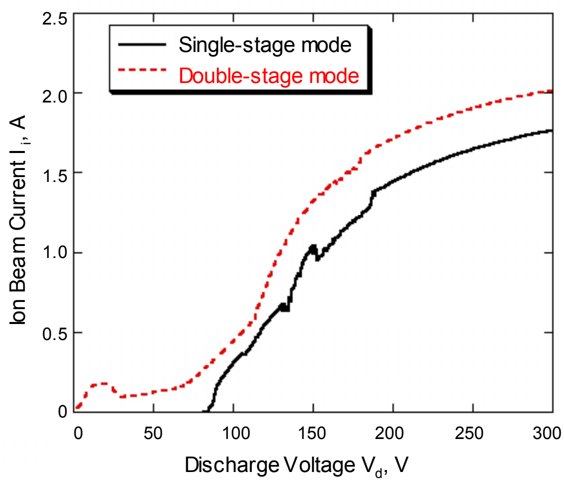


Figure 8. Ion beam current vs. discharge voltage characteristics. The measurements have been conducted for the channel length of 8 mm at the mass flow rate of 2.73 mg/s (28 sccm).

C. Results of Thrust Performance Testing

To measure the thrust performance, the newly developed thrust stand described in Fig. 3 is utilized. Tests are conducted in both single- and double-stage operations for channel length of either 8 or 13 mm, at xenon mass flow rates of 1.36 (14 sccm), 2.05 (21 sccm) and 2.73 mg/s (28 sccm), and discharge voltages of 200, 250 and 300 V, with a net input microwave power of 200 W. The thrust measurements were conducted once for each experimental condition.

The specific impulse is determined by dividing the thrust F by the mass flow rate m_{dot} multiplied by the standard acceleration of gravity g_0, i.e., $I_{sp}= F/m_{\mathrm{dot}}\, g_0$. In addition, the thrust efficiency η_t is estimated from the following equation:

$$\eta_t = \frac{F^2}{2m_{\mathrm{dot}}P_{\mathrm{total}}} = \frac{F^2}{2m_{\mathrm{dot}}(I_{\mathrm{d}}V_{\mathrm{d}} + P_{\mathrm{mw}})} \tag{1}$$

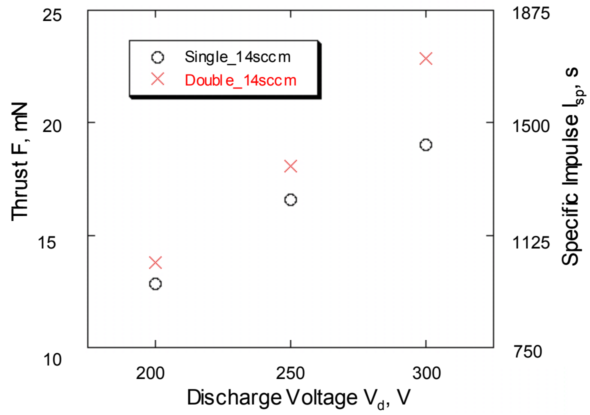
where P_{total} is the total power consumption, I_{d} is the discharge current, and V_{d} is the discharge voltage. P_{mw} is the net microwave power input toward the thruster through the waveguide located after the microwave directional coupler[11]. The "net" input power is evaluated by subtracting the reflected microwave power from the incident microwave power. The power consumption of the hollow cathode is not included in P_{total} because it is about 6 W and almost negligible as compared with P_{total}. Notice that P_{mw} = 0 W for the thruster operating in stage mode, and P_{mw} = 200 W in double-stage mode.

Figure 9 shows the comparison of thrust and specific impulse characterized by the pendulum method between single- and double-stage modes. As a result, the thrust and specific impulse in double-stage operation are higher than that in single-stage operation for the entire thruster conditions. The fact can be explained by considering improvements in acceleration efficiency and propellant utilization efficiency due to microwave injection[9]. Firstly, as shown in Fig. 8, the ion beam current in double-stage mode is higher than that in single-stage mode; thus the microwave operation yields higher values of propellant utilization efficiency, as compared to the operation without microwave. Secondly, by averaging the discharge current of each Fig. 6 and Fig. 7, the discharge current of double-stage operation is lower than that of single-stage operation. Moreover as stated above, the double-stage operation yields higher values of the ion beam current. Therefore, acceleration efficiency is considered to be higher with microwave injection, as compared to operation without microwave. On the basis of the facts stated above, the thrust and specific impulse of double-stage mode exceed that in single-stage mode.

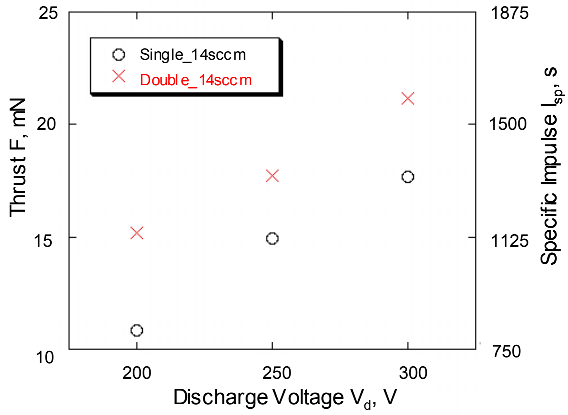
Moreover, the ratio of thrust in double-stage operation to that in single-stage operation tends to be higher with decreasing channel length, discharge voltage, and mass flow rate; thus the highest ratio is attained when the thruster operates with the channel length of 8 mm, at the lowest discharge voltage and mass flow rate condition such as V_{d}= 200 V and m_{dot}= 1.36mg/s (14 sccm).

Figure 10 shows the comparison of thrust efficiency evaluated from Eq. (1). When the thruster operates with low channel length such as 8 mm, at low mass flow rate such as 1.36 (14 sccm) and 2.05 mg/s (21 sccm), and low discharge voltage such as 200 V, higher thrust efficiencies in double-stage operation, as compared to single-stage operation, have been attained, because overdense plasmas can be generated regardless of discharge voltages.

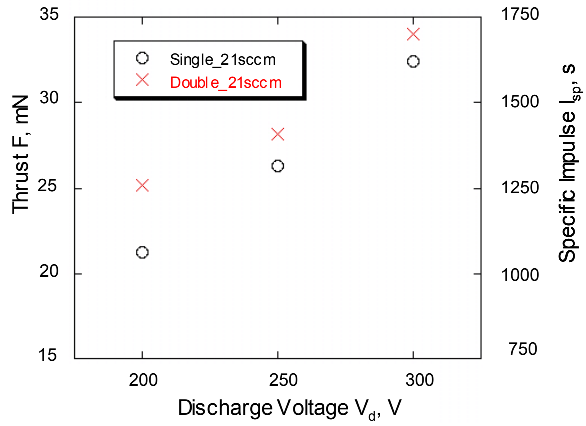
In addition, notice that, at the V_{d} of 300 V the thrust efficiency of double-stage mode is lower than that of single-stage mode, however, the thrust efficiency of double-stage mode increases linearly with increasing discharge voltages whereas the thrust efficiency of single-stage mode gets saturated. Therefore the linear increasing of thrust efficiency for double-stage mode is considered to provide higher efficiency at the discharge voltages more than 300V.



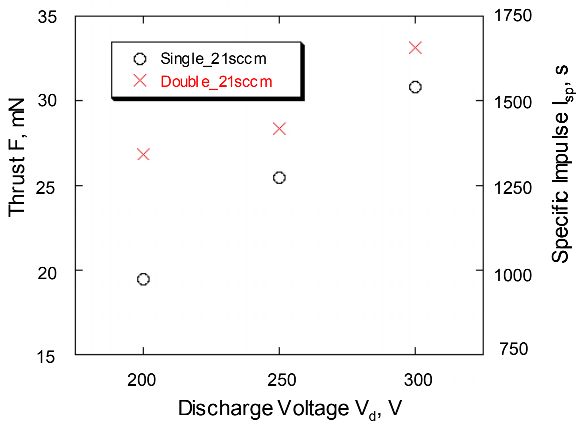
a) L= 13 mm, m_{dot}= 1.36 mg/s



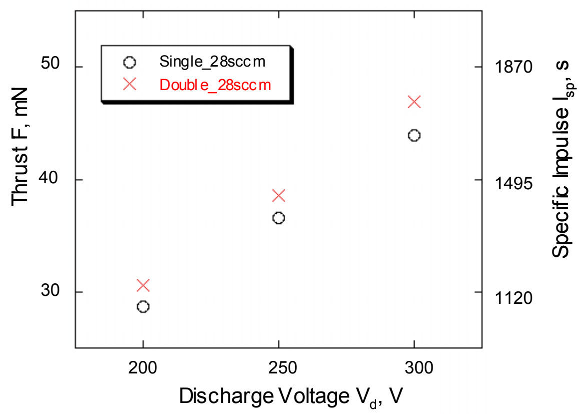
b) L=8 mm, m_{dot}= 1.36 mg/s



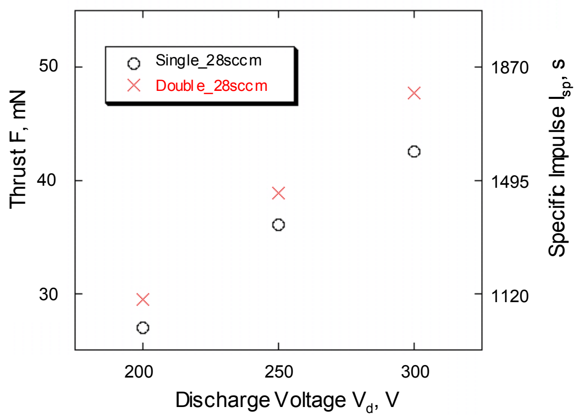
c) L=13 mm, m_{dot}= 2.05 mg/s



d) L=8 mm, m_{dot}= 2.05 mg/s

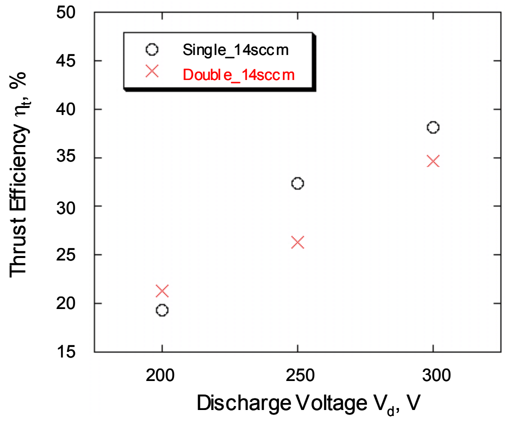


e) L=13 mm, m_{dot}= 2.73 mg/s

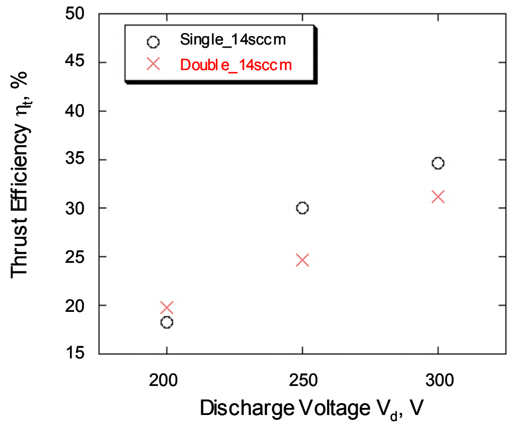


f) L=8 mm, m_{dot}= 2.73 mg/s

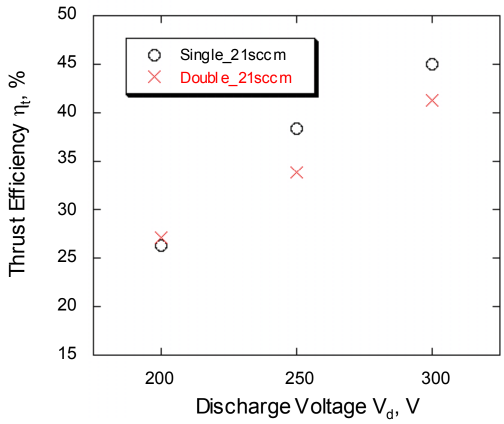
Figure 9. Comparison of the thrust and specific impulse evaluated by the pendulum method between single- and double-stage operations, for channel lengths L of 8 or 13 mm, at flow rates m_{dot} of 1.36, 2.05, and 2.73 mg/s, and discharge voltages V_d of 200, 250, and 300 V.



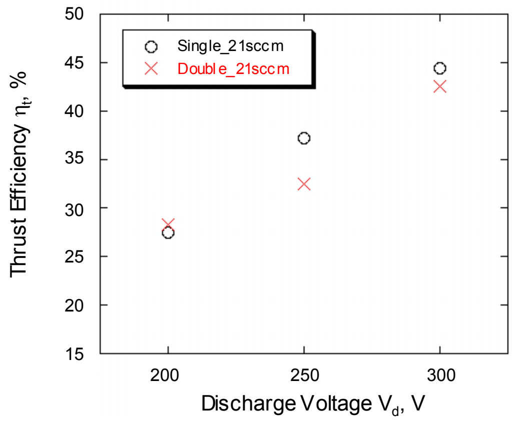
a) L=13 mm, m_{dot}= 1.36 mg/s



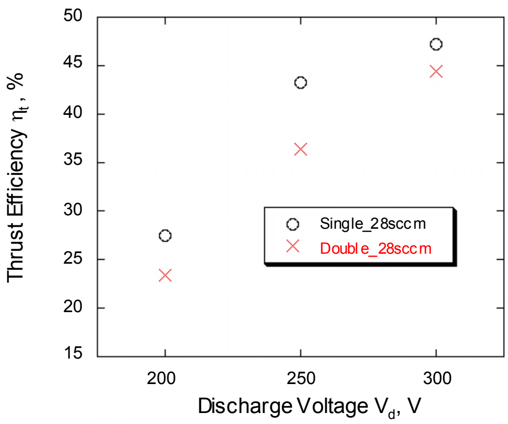
b) L=8 mm, m_{dot}= 1.36 mg/s



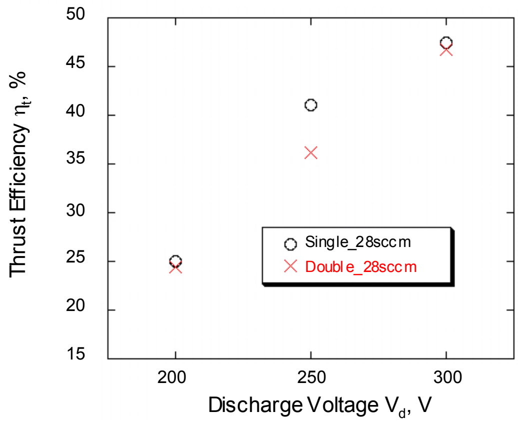
c) L=13 mm, m_{dot}= 2.05 mg/s



d) L=8 mm, m_{dot}= 2.05 mg/s



e) L=13 mm, m_{dot}= 2.73 mg/s



f) L=8 mm, m_{dot}= 2.73 mg/s

Figure 10. Comparison of thrust efficiency between single- and double-stage modes, for channel lengths of 8 and 13 mm, at m_{dot} of 1.36, 2.05 and 2.73 mg/s, and V_d of 200, 250 and 300 V.

IV. Conclusion

A 5.8-GHz microwave discharge Hall thruster using microwave-excited surface-wave plasmas has been developed and thrust measurements have been conducted using a pendulum-type thrust stand, a stand arm of which is made of a waveguide. The thrust measurements show that thrust and specific impulse of operation with microwave injection is higher than that of operation without microwave for entire discharge voltages, and higher thrust efficiency is attained injecting microwave at low discharge voltage such as 200 V. The results of measurements of ion beam current show that the thruster with microwave can be operated at discharge voltage less than 80 V, or "very low voltage domain". Moreover, in the case of discharge voltages of more than 300V, the thrust efficiency in operation with microwave is considered to exceed that in operation without microwave because thrust efficiency of double-stage mode increases linearly with increasing discharge voltages, whereas the thrust efficiency of single-stage mode gets saturated. In addition, double-stage operation is considered to have effect on reduction in discharge current oscillations.

References

[1] Escobar, D., Antón, A., and Ahedo, E., "Simulation of high-specific-impulse and double-stage Hall thrusters," *Proc. 29th Int. Electric Propulsion Conf.*, Princeton, NJ, Oct. 2005, Paper IEPC-2005-040.

[2] Hofer, R. R., Peterson, P. Y., Gallimore, A. D., and Jankovsky, R. S., "A High Specific Impulse Two-Stage Hall Thruster with Plasma Lens Focusing," *Proc. 27th Int. Electric Propulsion Conf.*, Pasadena, CA, Oct. 2001, Paper IEPC-2001-036.

[3] Butler, G. W., Yuen J. L., Tverdokhlebov S. O., Semenkin, A. V., Kochergin, A. V., Solodukhin, A. E., and Jankovsky, R. S., "Multimode, high specific impulse Hall thruster technology," *Proc. 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Huntsville, AL, Jul. 2000, Paper AIAA-2000-3254.

[4] King, D. Q., de Grys, K. H., and Jankovsky, R., "Multi-mode Hall thruster development," *Proc. 37th AIAA/ASME/ SAE/ASEE Joint Propulsion Conf.*, Salt Lake City, UT, Jul. 2001, Paper AIAA-2001-3778.

[5] Sengupta, A., Marrese-Reading, C., Cappelli, M, Scharfe, D., Tverdokhlebo, S., Semenki, S., Tverdokhlebov, O., Boyd, I., Keidar, M., Yalin, A., Surla, V., Markusic, T., and Polzin, K., "An Overview of the VHITAL Program A Two-Stage Bismuth Fed Very High Specific Impulse Thruster With Anode Layer," *Proc. 29th Int. Electric Propulsion Conf.*, Princeton, NJ, Oct. 2005, Paper IEPC-2005-238.

[6] Rossetti, P., Capacci, M., and Noci, G., "Preliminary Experimental Results on a Double Stage Hall-Effect Thruster," *Proc. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Sacramento, CA, Jul. 2006, Paper AIAA-2006-4998.

[7] Rossetti, P., Cesari, U., Saverdi, M., Capacci, M., Siciliano, P., Noci, G., and Gengembrem, E., "Experimental Characterization of a Double-Stage Hall Effect Thruster," *Proc. 41st AIAA/ASME/ SAE/ASEE Joint Propulsion Conf.*, Tucson, AZ, Jul. 2005, Paper AIAA-2005-3879.

[8] Kuwano, H., Kuninaka, H., and Nakashima, H., "Measurment of Plasma Beam Energy Ejected from Microwave Discharge Hall Thruster," *Proc. 29th Int. Electric Propulsion Conf.*, Princeton, NJ, Oct. 2005, Paper IEPC-2005-125.

[9] Kuwano, H., Kuninaka, H., and Nakashima, H., "Investigation of Plasma Condition and Ion Beam Energy of a Microwave Discharge Hall Thruster," *Proc. 24th Int. Symp. Space Technology and Science*, Miyazaki, Japan, May 2004, Paper ISTS 2004-b-34.

[10] Kuwano, H., Kuninaka, H., and Nakashima, H., "Plasma Characteristics in the Acceleration Channel of a Microwave Discharge Hall Thruster and Relationships between Thruster Performance and Acceleration Channel Length," J. Japan Soc. Aero. Space Sci., Vol. 55, No. 639, 2007, pp30-36 [in Japanese].

[11] Ishii, T. K., *Microwave Engineering*, The Ronald Press Company, New York, 1966, p41, 87, 138, 183.

[12] Baranov, V. I., Nazarenko, Y. S., Petrosov, V. A., Vasin, A. I., and Yashnov, Y. M., "Theory of oscillations and conductivity for Hall thruster," *Proc. 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Lake Buena Vista, FL, Jul. 1996, Paper AIAA-1996-3192.

[13] Yamamoto, N., Yokota, S., Watanabe, K., Sasoh, A., Komurasaki, K., and Arakawa, Y., "Suppression of Discharge Current Oscillations in a Hall Thruster," Trans. Japan Soc. Aero. Space Sci., Vol. 48, No. 161, 2005, pp169-174.

[14] Belikov, M., Blinov, N., Gorshkov, O., and Rizakhanov, R., "Experimental Research of Ionization Oscillations in Hall Thruster," *Proc. 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Huntsville, AL, Jul. 2003, Paper AIAA-2003-4706.

[15] Choueiri, E. Y., "Plasma oscillations in Hall thrusters," Phys. Plasmas, Vol. 8, Issue 4, 2001, pp.1411-1426.