Developments of Robust Anode-layer Intelligent Thruster for Japan IN-space propulsion system

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Abstract: **A collaborative research and development project in Japan has started toward practical use of anode layer thruster. High-power electric propulsion systems was proposed for manned exploration missions and for the construction of heavy space structures like the space solar power system. Anode layer thrusters are strong candidates for both missions, because they offer an attractive combination of high thrust efficiency, low propellant consumption, long lifetime, and large thrust-to-mass ratio. The developmental project currently underway is named Robust Anode-layer Intelligent thruster for Japan IN-space propulsion system (RAIJIN). RAIJIN is a 25-kW-class cluster system consisting of five 5-kW-class heads is under development. Besides developing the aforementioned thruster head and high-current cathode, this project is engaged in evaluations of an intelligent power supply, high specific impulse operation, cluster system unification, and feasibility studies of in-space transportation using a high-power thruster based on cost evaluation are in progress**

I. Introduction

High power electric propulsion system would be in the phase for practical application in the near future. It will be used propulsion system as a main propulsion of the Cargo for manned mission to Mars[1,2], as well as that for the construction of heavy space structures like the space solar power system[3,4].

There are many candidates for High power electric propulsions and anode layer type Hall thrusters[5,6] are one of the candidates for them since they offer an attractive combination of high thrust efficiency, exceeding 50%, with a specific impulse range of 1,000-3,000 s, a higher ion beam density than ion thrusters and expected long lifetime.

Collaborative research and development project in Japan has started toward practical use of the anode layer thruster.[1]

The integrated system is termed as “RAIJIN” that stands for Robust Anode-layer Intelligent Thruster for Japan IN-space propulsion system. As a first step, 5 kW class anode layer Hall thruster system is developing and the development of a mono 25-kW-class anode layer thruster for SSPS is also planned through the high-power thruster system in the RAIJIN project. This project consists of four parts: the development of the aforementioned thruster head and high-current cathode, cluster system unification, and mission analyses (see Fig.1 and 2).

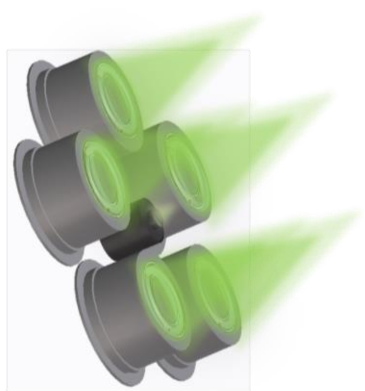


Figure 1. Concept illustration of a cluster system consisting of five thruster heads and a cathode.

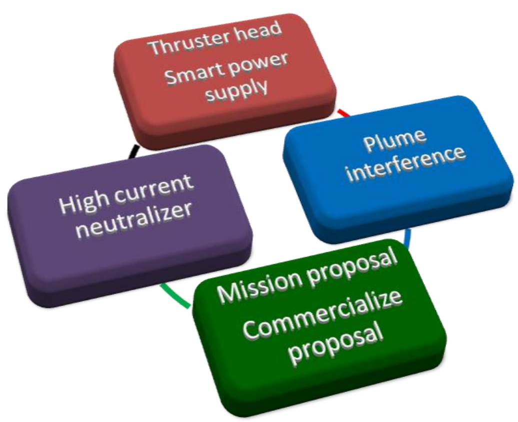


Figure 2. Project configuration of "RAIJIN".

II. Developments of each parts

A. Anode layer thruster (UT-58)

The aim is to develop an anode layer thruster system which shows considerably high efficiency, high thrust-to-weight-ratio, and long lifetime. A 5 kW device for thrust bus system of large satellite and a 25 kW thruster system for mass transportation are planned to fulfill this task. To obtain an optimum design, low-power thrusters are necessary to investigate possible difficulties, and to establish a experimental database for future design choices.

At the University of Tokyo, a 2 kW-class anode layer thruster (UT-58) was designed for evaluating optimum operating conditions and locating potential issues. Cross section of the thruster is shown in Fig. 3, and the operation specifications are listed in Table 1 respectively.

The width of magnetic pole piece can be adjusted to enable a magnetically shielded configuration which is expected to reduce wear of the channel walls significantly, and, thus, extend the lifetime of the thruster.

Thermal analysis showed that the increased dimensions of the thruster in combination with the metal channel walls are advantageous as radiative cooling is improved.

Using both xenon and argon as propellant, the performance of UT-58 was evaluated in which the discharge oscillation amplitude Δ was determined by using Eq. (1). Generally, if this value is below 0.2, the constraints on the power-processing unit are small enough and no significant increase in system mass is yielded. Therefore, a stable discharge regime is defined by using this threshold.

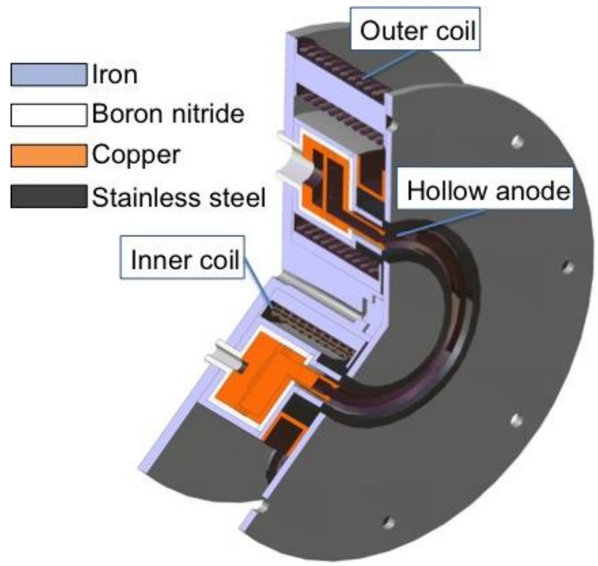


Figure 3. Cross section drawing of UT-58.

$$\Delta = \frac{1}{\bar{I}_d}\sqrt{\frac{\int_0^\tau (I_d - \bar{I}_d)^2\,\mathrm{d}t}{\tau}},\ \left(\bar{I}_d = \frac{\int_0^\tau I_d\,\mathrm{d}t}{\tau}\right) \quad (1)$$

Table 1. Specification and operational condition of UT-58.

Parameter	Value
Mean diameter of acceleration channel	58 mm
Flow channel width of hollow anode	1-3 mm
Anode-tip-to-thruster-exit distance	2-6 mm
Maximum power supply	2 kW
Discharge voltage	100-350 V
Xenon propellant flow rate	2.0-2.5 Aeq
Argon propellant flow rate	2.5-7 Aeq

Anode efficiency results for xenon propellant are plotted in Fig. 4. Anode efficiency was more than 60%, which is comparable to or greater than that of Hall thruster at same power level. When using argon as propellant, thrust performance was reduced as expected, and high efficiency was achieved only by increasing the mass flow rate significantly as is shown in Fig. 5. Stable operation regimes for the same experiments are shown in Fig. 6 with the same diffusion boundaries as indicated in Fig. 4. A maximum anode efficiency of about 24% was achieved which is thought to be further improved by increasing mass flow rate and power input. T hat is, operation at higher power levels than with xenon propellant is reasonable in the selected channel cross-sectional area, and it is possible, thus, to design a smaller thruster for argon propellant.

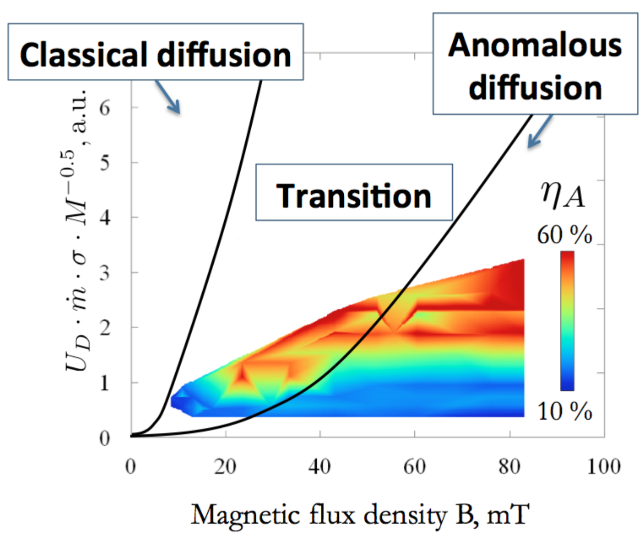
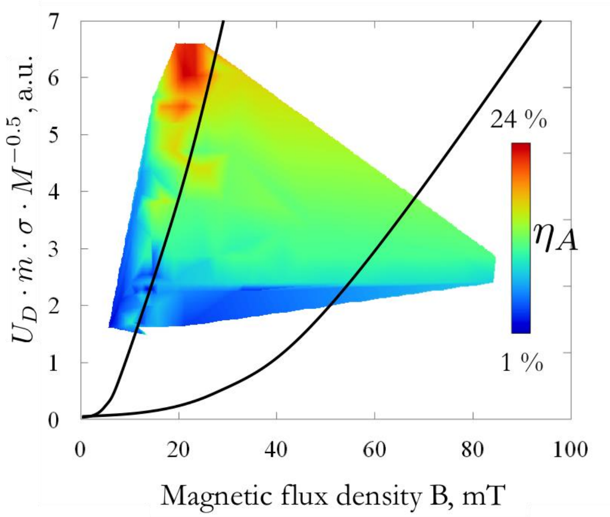


Figure 4. Anode efficiency map for xenon propellant
(Stable operation in either classical or anomalous diffusion regime).



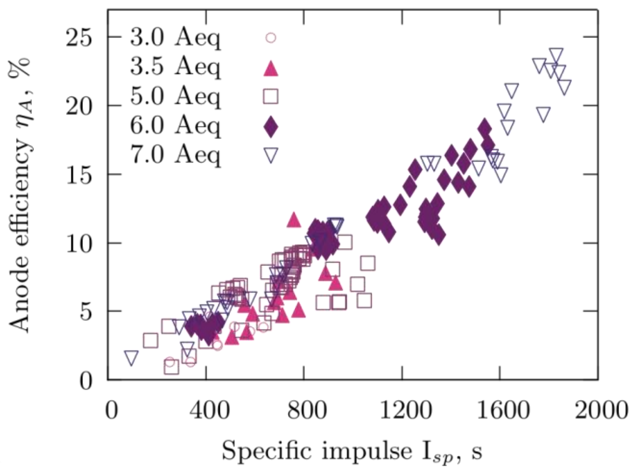


Figure 5. Anode efficiency map with argon propellant. Figure 6. Anode efficiency for various mass flow rate.

A 2 kW anode layer thruster, UT-58, was designed and set up, and the performance with xenon and argon propellant was measured.
-Thermal constraints are likely to be a small issue for large anode-layer thrusters
-More than 60% of anode efficiency was achieved with xenon propellant.
-Stable operation regime was limited with regard to power and magnetic field configuration.
-Operation of the thruster with argon propellant yielded a maximum of 24% of anode efficiency but required much larger flow rates.
-Downsizing the thruster to use with argon propellant at same power is feasible.

B. Inductively coupled plasma cathode

Radio frequency (RF) plasma, especially inductively coupled plasma, cathode (ICP/C) has been studied as one of the candidate for neutralizer of the anode layer thruster system. Compared with traditional hollow cathode (H/C), oxide insert is removed in ICP/C, which affects cathode lifetime sensitively and restricts oxygen exposure. Therefore, the development of the ICP/C will contribute not only the simple cathode system as a flight model, but also economical environment for operating the anode layer thruster at ground facilities. The first subject of ICP/C for the anode layer thruster system is to find the prospect for high current electron emission with high efficiency.

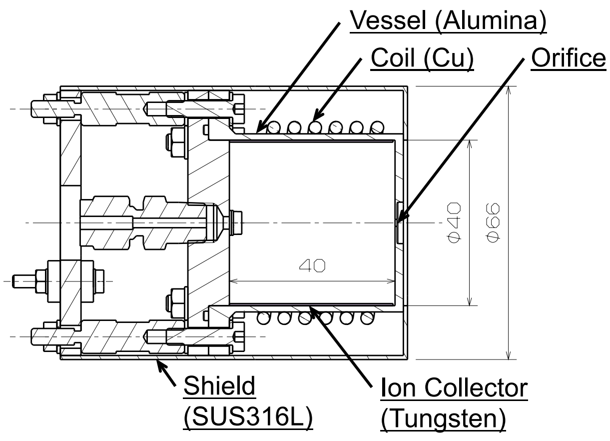


Figure 7. Schematic cross section of inductively coupled plasma cathode.

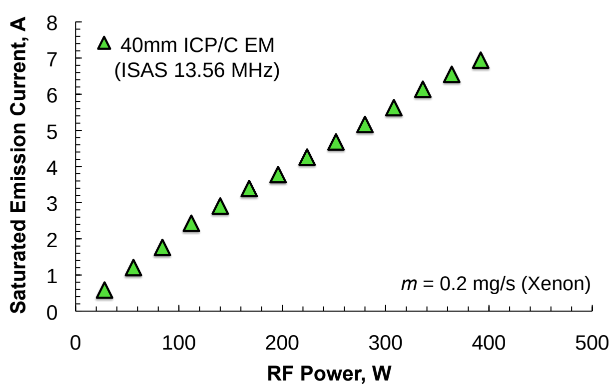


Figure 8. Saturated emission current as a function of RF input power.

The following experiment was carried out for evaluating the performance of ICP/C. Engineering model of ICP/C was designed and constructed at Tokyo Metropolitan University and JAXA, as shown in Fig. 7. The discharge chamber was made by alumina, whose inner diameter and length were both 40 mm. Ion collector, which was made by tungsten and stainless steel, was inserted as an electrode along the inner surface of the chamber. This electrode collected equivalent ion in charge to electron which would emit from the orifice. Anode electrode was set at the front of the orifice, whose distance was 50 mm. RF input power was controlled from 0 to 400 W without reflection power. The frequency of RF was 13.56 MHz. A vacuum chamber simulated 10^{-3} Pa of pressure by a turbo molecular pomp and a cryogenic pomp.

Through the experiment, equivalent electric current between the ion collector and the anode was observed, which means that the current loop was closed in the experimental circuit. Figure 8 indicates saturated electron emission current from the ICP/C on each RF input power. Linear proportional relationship between saturated current and RF input power was confirmed. As the result, 7 A of saturated emission current was achieved at 400 W of RF input power. Improvement of the ICP/C has already been conducted in order to reach 20 A class of emission current.

C. Smart power processing unit

A role of power processing unit (PPU) for driving Hall thrusters will have being more and more important as the demand of high power Hall thruster have been grown. So, PPU is requested lighter, more effective and more easy install. Mitsubishi Electric Corporation (MELCO), Kyushu University, Nagasaki University, Nagano Japan Radio Corporation and Tokyo Metropolitan University have collaborated to develop high power hall thruster systems for next-generation satellites and exploration vehicles. All of the experiments were conducted at Kyushu University. The PPU consists of an anode power regulator (APR) (See Fig. 9) and two coil power regulators. Power regulators are developed with a novel non-isolated converter topology and control unit using digital signal processor. The APR shows good performance: the efficiency of anode power regulator is more than 98%. This PPU have unsupervised learning function and it can keep an optimum operational condition as shown in Fig. 9. That is, PPU scans operational conditions in a certain range, and in the case of Fig.10 that is coil current. The PPU scans the coil current from 1.25 A to 2.75 A(from 0 sec to 105sec). After scan(@105 sec), it calculates the thrust efficiency and it fixes the optimal condition as the thrust efficiency is maximum(the coil current is fixed at 2.7 A from 135 sec to 150 sec).

This self-learning function contributes the reduction of total power consumption, since the optimum operational conditions change as times goes by. Figure 11 shows the thrust efficiency vs. coil current for two acceleration channel configurations: that at beginning of life (BOL) and that simulated acceleration channel at end of life (EOL) condition, as shown in Fig. 12. The EOL channel model has a 12.8-degree angle cut at the channel exit and the channel itself is widened by 2.5mm so that the channel becomes 12.5mm wide.

Figure 9. Photograph of anode power regulator.

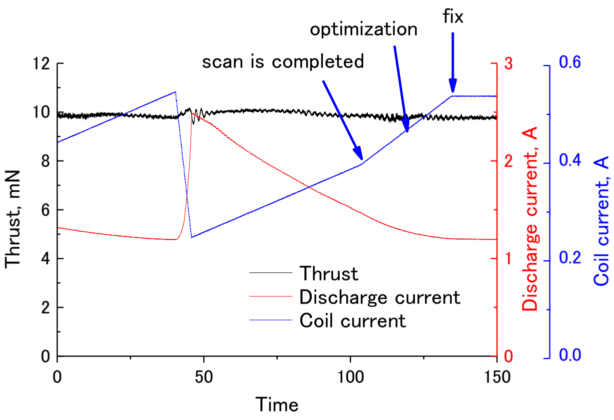
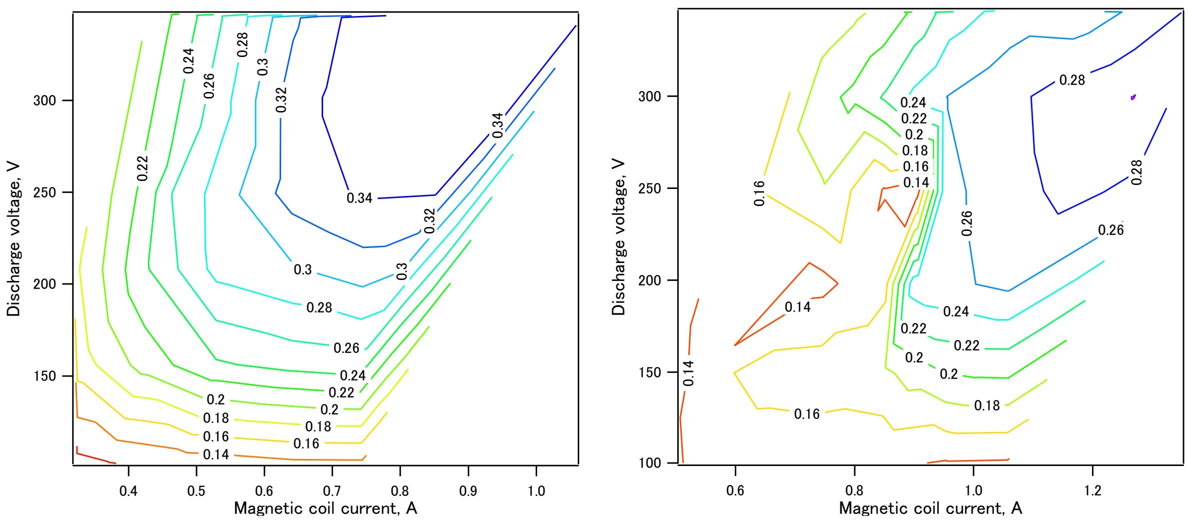


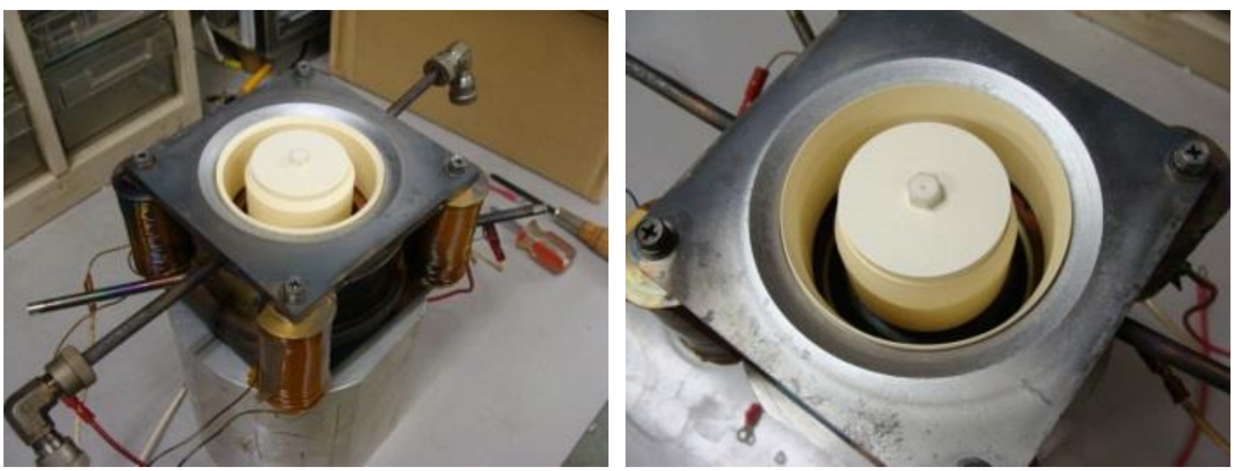
Figure 10. Automatic Power Consumption Controlling.



(a) (b)

Figure 11. Thrust efficiency at mass flow rate of 1.0 mg/s, (a)BOL(b)EOL.

Indeed, the optimal coil current is differs between two configurations; 0.7 A at BOL and 1.2 A at EOL at discharge voltage of 250 V. Therefore, the magnetic flux density control method improves the thrust efficiency from 0.16 to 0.28l; when the coil current is 0.7 A at EOL condition, which is the optimal coil current at BOL condition, the thrust efficiency is 0.16, which is worse than 0.28 at optimal condition at discharge voltage of 250 V and simulated EOL channel configuration. This smart PPU will contribute to enlarge the lifetime of future satellites.



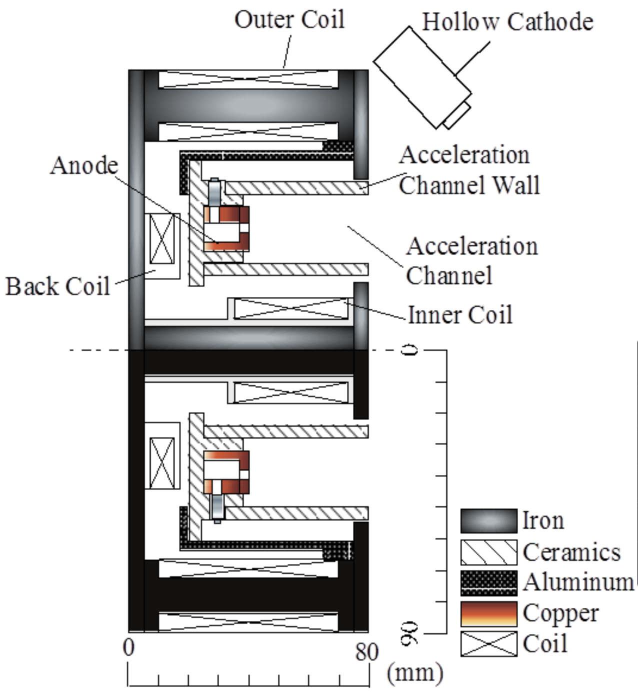
(a) (b)

Figure 12. Photographs of BOL condition (a)and simulated EOL condition(b)

D. High-Power and High-Specific-Impulse Operations of SPT and TAL at Osaka Institute of Technology

At Osaka Institute of Technology (OIT), high-power and high-specific-impulse characteristics were measured with both the laboratory-model SPT-type THT-VI and TAL-type TALT-2, as shown in Figs.13 and 14, in order to obtain basic thruster performances with high discharge voltage and large mass flow rate and to understand practical problems under high power operations.[11,23)]

Figures 15 and 16 show the thrust, specific impulse and thrust efficiency as a function of discharge voltage for THT-VI thruster.[12-16)] The discharge current was almost flat with a constant mass flow rate although not so good with high discharge voltages of 800-1000V. The input power reached above 5 kW. Both the thrust and the specific impulse linearly increase with discharge voltage. The thrust ranges from 50 to 200 mN at specific impulse of 1500-4000 sec. The thrust efficiency reaches above 60 %. Typical thrust performance is a thrust of 110 mN and a thrust efficiency of 61 % at a specific impulse of 3200 sec with an input power of 2.8 kW. As for TALT-2 thruster, the input power and the specific impulse were above 3.5 kW and, 2800 sec, respectively.[21,22] It was found that the both thrusters are promising for the future missions although the operations were thermally severe. At OIT, a new large-scale high-power TAL thruster is under design.



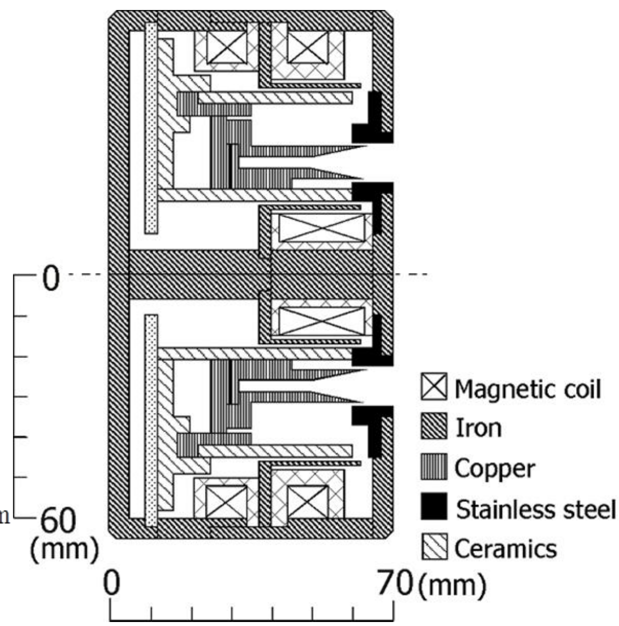
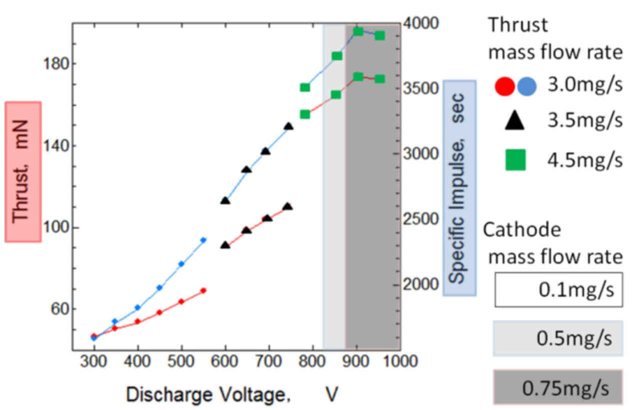


Figure 13. Cross-sectional view of SPT-type THT-VI at Osaka Institute of Technology.

Figure 14. Cross-sectional view of TAL-type TALT-2 at Osaka Institute of Technology.



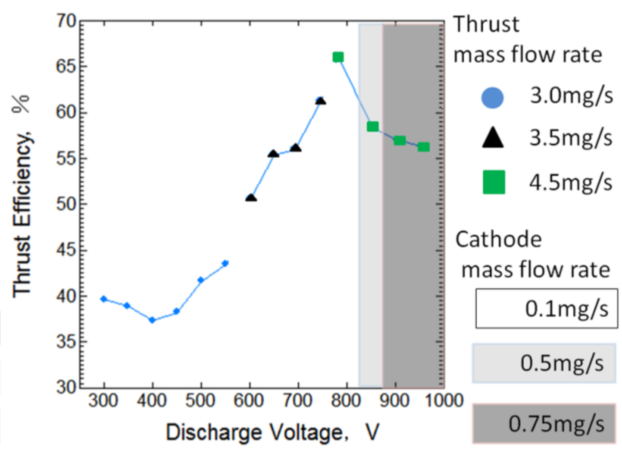


Figure 15. Thrust and specific impulse vs discharge voltage characteristics with THT-VI at OIT.

Figure 16. Thrust efficiency vs discharge voltage characteristics with THT-VI at OIT.

E. Cluster operation characteristics

In high-power operations of a single anode layer thruster, heat measures are not avoided. Because heat measures cause an increase in system mass, a cluster system is applicable for high-power thruster operations. At Gifu University, to investigate the fundamental characteristics of cluster operations, a side-by-side (SBS) cluster system consisting of two thruster heads and a hollow cathode were developed. Figure 17 shows the image of the SBS cluster system. The thruster heads used in the SBS system are of the magnetic layer type having a uniform magnetic field distribution. Because the operation of this type of magnetic layer thruster is well understood owing to various studies[17,18], this type of head was employed for the present, fundamental investigation. In the investigations, xenon gas was used as a propellant.

Figure 18 shows a snapshot of the SBS cluster system during operation. Cluster operation was achieved using a common power supply and independent power supplies for the two thruster heads. Figures 19 and 20 show the discharge current profiles of the two thruster heads and the total current profile for the SBS cluster system using the common power supply for two different distance D_T of two heads. The magnetic fields applied by the two heads were in same directions. As shown in Fig. 19, for the case of a short D_T of 156 mm, the phases of the two current oscillations of the heads were in antiphase. However, in Fig. 20, for the case of a long D_T of 298 mm, some coordinate phases were also observed. These data suggest that an interference in the cluster operation results in the antiphase phenomena in the head discharge current profiles. Similar tendencies were also observed in the case of magnetic field being applied in the opposite direction. However, when cluster operation was achieved using independent power supplies, antiphase characteristics were not observed. The antiphase phenomenon was also observed in the study of cluster operations using the D-55 anode layer cluster by Semenkin et al.[25] As observed in Fig. 19, the antiphase profiles reduced the amplitude of the total current oscillation. This result indicates the possibility of power load reduction and reveals an advantage of the cluster system for high-power thruster system development. On the basis of the knowledge obtained in the above fundamental investigation, a SBS system consisting of anode-layer-type heads has also been designed and constructed for RAIJIN in Gifu University and measurements have begun.

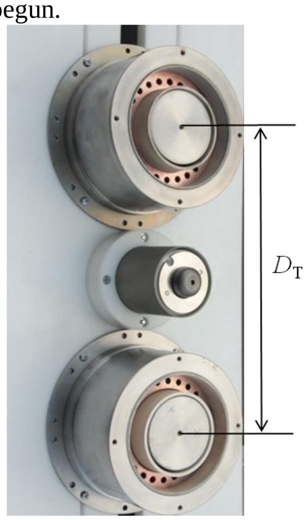


Figure 17. A image of SBS cluster system.

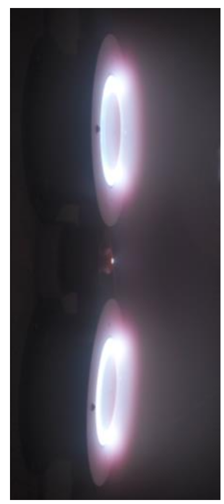


Figure 18. Image of the SBS system in operation.

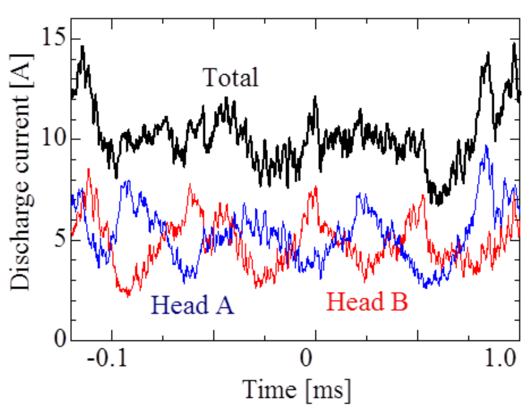


Figure 19. Discharge current profiles of the two thruster heads and the total current for a DT of 156 mm.

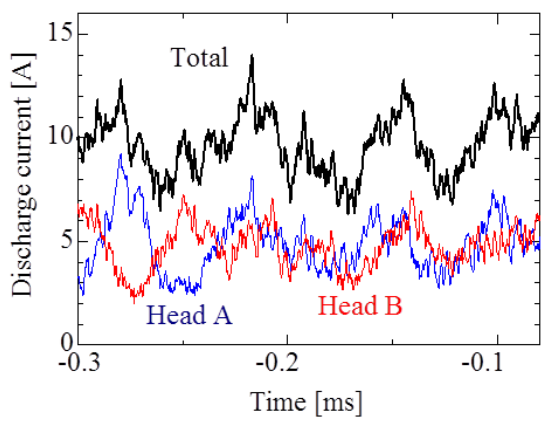


Figure 20. Discharge current profiles of the two thruster heads and the total current for a DT of 298 mm.

F. SPS transportation by anode layer thruster

A feasibility study of in-space transportation of solar power satellite (SPS) using a 25-kW-class anode-layer thruster system was carried out at Tokyo Metropolitan college of industrial technology based on cost evaluation. The SPS is transported from ground to GEO to meet the cost target of 1000 billion yen. Total transportation mass was assumed to be 20000 ton, which would be delivered by a fleet of OTVs with eight 25-kW-class thrusters.

Cost analysis showed that 80% reduction of current transportation cost is necessary to meet cost requirements as shown in Figure 20. From the sensitivity analysis, increasing propulsion efficiency by 20% reduces the transportation cost by 10%.

Selection of propellant was also analyzed considering three cases; xenon, Isp=2000 s, η=0.50; krypton, Isp=3000 s, η=0.40; argon, Isp=4000 s, η=0.30. As shown in Figure 21, the transportation cost using argon is the smallest because of its high specific impulse. Krypton is another candidate due to its moderate cost and thruster performance.

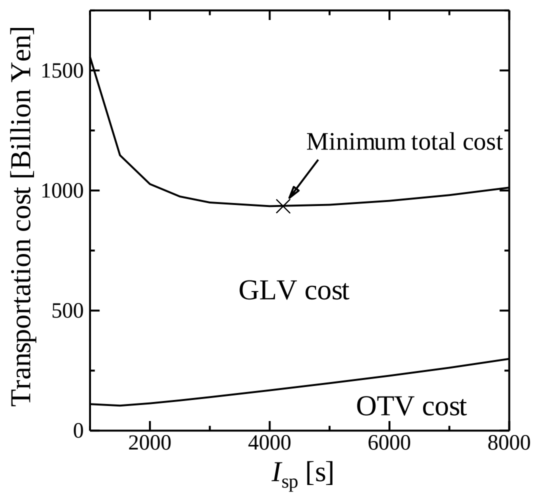


Figure 21. SPS transportation cost with technical innovation of cost reduction of 80%.

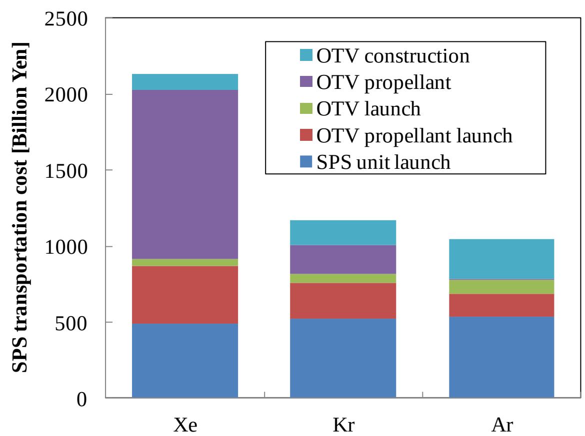


Figure 22. Impact of propellant selection on transportation cost.

III. Summary

The collaborative research and development of a 25-kW-class cluster system consisting of anode-layer thruster heads with anode layer (named RAIJIN) has been started. A high-power thruster head, high-current cathode, 1.4-kW anode-layer thruster (UT-58) have been constructed at the University of Tokyo. A 7-A inductively coupled plasma cathode (ICP/C) have been constructed at the Tokyo Metropolitan University and JAXA. The anode efficiency of UT-58 with xenon propellant exceeded 60%, and the operation characteristics (including stable operation regime) of the device were obtained. A linear proportional relationship between the saturated current and RF input power was confirmed in the ICP/C, and a saturated emission current of 7 A was achieved at 400 W of RF input power.

High-power operation investigations of the intelligent power supply, high specific impulse operation, and cluster system unification were conducted. The application examinations of the smart PPU was carried out. This device, developed at Kyushu University, Mitsubishi Electric Corporation (MELCO), Nagasaki University, Nagano Japan Radio Corporation, and Tokyo Metropolitan University, possesses an unsupervised learning function and maintains optimum operating conditions. The high-power and high-specific impulse characteristics were measured at the Osaka Institute of Technology using both the laboratory-model SPT-type THT-VI and TAL-type TALT-2. Typical specific impulses of THT-VI and TALT-2 are 3200 s and 2800 s with input powers of 2.8 kW and 3.5 kW, respectively. The thrust efficiency of THT-VI exceeds 60%. The operating characteristics of a SBS cluster system (consisting of two magnetic layer thruster heads with uniform magnetic field and a hollow cathode) were examined at Gifu University. Both heads exhibited an antiphase phenomenon of discharge current oscillation, indicating a strong advantage of the cluster system, namely power load reduction.

A feasibility study of in-space transportation of a solar power system using the 25-kW-class anode layer thruster system was also conducted. The study was based on cost evaluation for xenon, krypton, and argon propellants. Krypton and argon proved promising candidates for space transportation.

These results demonstrate the value of continuing the collaborative research and development of the RAIJIN project, aimed at the practical use of the 25-kW-class anode layer thruster system.

References

[1]Website of Hall thruster research group http://art.aees.kyushu-u.ac.jp/research/Hall/inspace/inspace.html

[2]T. Schönherr, M. Hosoda, S. Cho, H. Koizumi, Y. Arakawa, K. Komurasaki, and N. Yamamoto, "Low- cost 20 kW Hall thruster for mass transportation." Asian Joint Conference on Propulsion and Power 2012, Mar. 2012. AJCPP2012-022.

[3]Ito, Y., Nakano, M., Schonherr, T., Cho, S., Komurasaki, K. and Koizumi, H.: In-space transportation of a solar power satellite using a hall thruster propulsion system Renewable Energy Research and Applications (ICRERA), 2012.

[4]Nakano, M., Ito, Y. and Komurasaki, K: In-Space Transportation for Solar Power Satellites Using Electric Propulsion, 56th Conference on Space Science and Technology, 2012 (in Japanese).

[5]Cho, S., Yokota, Y., Hara, Y., Takahashi, Y., Arakawa, Y., Komurasaki, K. and Kobayashi, A.: Development of Lifetime Evaluation Method Using Multilayer Coated Chip, Trans. of Japan Soc. for Aeronautical and Space Sci., Aerospace Technology Japan, 8, ists 27, pp.Pb_51-Pb_54, 2010.

[6]Yamamoto, N., Ezaki, T. and Nakashima, H.: Thrust Performance of a Low Power Hall Thruster, Trans. of Japan Soc. for Aeronautical and Space Sci., Aerospace Technology Japan, 10, No. ists 28, pp.Tb_9-Tb_12, 2012.

[7]Ando, A., Tashiro, M., Hitomi, K. and Inutake, M.: Beam Extraction from a Hall-Type Ion Accelerator, Rev. Sci. Instrum., 79, pp. 1-3, 2008.

[8]Kasagami, S., Okuma, T., Yamamoto, N., Watanabe, H., Nakabayashi, T., Tamida, T., Osuga, H., Aoyagi, J. and Takegahara, H.: Feasibility Study on Hall Thruster with Inductively Coupled Plasma Cathode, Proc. of the Eighth International Symposium on Applied Plasma Science, Advances in Applied Plasma Science, 8, pp.27-30, 2011.

[9]Ozaki, T., Inanaga, T., Nakagawa, T., Kasai, Y., and Matsui, K.: Development Status of High Power Xenon Hall Thruster of MELCO, 25th International Symposium on Space Technology and Science, ISTS paper 2005-b-34, 2006.

[10]Nejoh, Y., Nakamoto, H., Tahara, H.: Investigation on the Cross-Field Ion Transport on the Discharge Current Oscillation and Performance of SPT-100 Type Hall Thrusters, J. Plasma Fusion Res. Ser., 2009, pp.773-779.

[11]Tahara, H.: Research and Development of Hall-Effect Thrusters at Osaka Institute of Technology, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2008-5086, 2008.

[12]Fukushima, K., Omori, S., Agata, H. and Tahara, H.: Performance Change Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 26th International Symposium on Space Technology and Science, ISTS 2008-b-56p, 2008.

[13]Fujita, T., Tonari, T., Shimizu, Y., Shinya, T. and Tahara, H.: Performance Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 27th International Symposium on Space Technology and Science, ISTS 2009-b-10p, 2009.

[14]Sugimoto, N., Nose, M., Togawa, K., Nishida, T., Ikeda, T., Tahara, H. and Watanabe, Y.: Optimization of Acceleration Channel Structure and Material for Magnetic-Layer-Type Hall Thrusters, 28th International Symposium on Space Technology and Science, ISTS 2011-b-18p, 2011.

[15]Tahara, H., Fujita, T. and Shimizu, Y.: Performance Prediction in Long Operation for Magnetic-Layer-Type Hall Thrusters, 31st International Electric Propulsion Conference, IEPC-2009-140, 2009.

[16]Ikeda, T., Fujita, T., Sugimoto, N., Ozaki, J., Tahara, H. and Watanabe, Y.: Optimization of Acceleration Channel Structure and Material for Magnetic-Layer-Type Hall Thrusters, 32nd International Electric Propulsion Conference, IEPC-2011-038, 2011.

[17]Miyasaka, T., Furukawa, T., Soga, T., Nakayama, E., Kitagawa, T. and Zhang, F. Y.: Influence of Propellant-Inlet Condition on Hall Thruster Performance, 28th International Electric Propulsion Conference, IEPC-03-091, 2003.

[18]Furukawa, T., Miyasaka, T. and Fujiwara, T.: Control of Low-Frequency Oscillation in a Hall Thruster, Trans. Japan Soc. Aero. Space Sci., .44, pp.164-170, 2001.

[19]Miyasaka, T., Furukawa, T., Soga, T., Nakayama, E., Kitagawa, T. and Zhang, F. Y.: Influence of Propellant-Inlet Condition on Hall Thruster Performance, 28th International Electric Propulsion Conference, IEPC-03-091, 2003.

[20]Yamamoto N., Nakagawa, T., Komurasaki, K. and Arakawa, Y.: Discharge Plasma Fluctuations Hall Thrusters, Vacuum, 65, pp. 375-381, 2002.

[21]Yuge, S., Kuwamura, Y. and Tahara, H.: Influences of Magnetic Field Topography and Discharge Channel Structure on Performance of Anode-Layer Hall Thrusters, 30th International Electric Propulsion Conference, IEPC-2007-336, 2007.

[22]Shimizu, Y., Shinya, T., Fujita, T., Tonari, T. and Tahara, H.: Influence of Hollow Anode Configuration on Performance of Anode-Layer Hall Thrusters, 27th International Symposium on Space Technology and Science, ISTS 2009-b-12, 2009.

[23]Mito, Y., Ikeda, T., Sugimoto, N., Togawa, K. and Tahara, H.: Research and Development of High-Power High-Efficiency Hall-Type Ion Engines for Space Exploration, International Conference on Renewable Energy Research and Applications (ICRERA) 2012, Nagasaki, 2012.

[24]Kuwano, H., Ohno, H., Kuninaka, H. and Nakashima, H.: Development and Thrust Performance of a Microwave Discharge Hall Thruster, 30th International Electric Propulsion Conference, IEPC-2007-085, 2007.

[25]Semenkin, A. V., Zakharenkov, L. E. and Soldukhin, A. E.: Feasibility of High Power Multi-Mode EPS Development Based on the Thruster wwith Anode Layer, 32nd International Electric Propulsion Conference, IEPC-2011-064, 2011.