Development Status of 6-kW-class Hall Thrusters at JAXA

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Abstract: R&D of Hall thruster for all-electric satellite is in progress at Japan Aerospace Exploration Agency. Design, fabrication and testing of breadboard model (BBM) Hall thrusters were conducted for the flight experiment onboard Engineering Test Satellite 9 (ETS-9). Performance evaluations of BBM4 thruster obtained an Isp of 1,900s at a discharge voltage of 300 V at 6-kW. Preliminary lifetest of BBM4 is also in progress which obtained accumulated continuous operation of 4,048 hours at 6 kW. Also, interfaces with power processing unit (PPU) and mechanical environment were checked through a coupling test between the BBM4 thruster and PPU/BBM and also by using the structural model/BBM thruster. Based on these results, engineering model fabrication and prototype model design are currently in progress.

I. Introduction

Japan Aerospace Exploration Agency (JAXA) is working on the development of a new launch vehicle and a satellite bus. The new H-III launch vehicle, which covers wide launching capability by using different configurations, leads to the necessity of a variety of satellite line-ups among chemical, hybrid, and all electric propulsion (EP). All-EP type propulsion was not in the JAXA's technology list although low-power ion thruster technology was already applied to NSSK of 3- to 5-ton satellites, or mail propulsion for smaller asteroid probes (HAYABUSA/HAYABUSA2) and Earth orbiting mission (SLATS). To overcome the lack in main electric thrusters for medium (3-6ton) satellite and to complete the line-ups, a new 5-ton class all-EP satellite bus is to be tested as Engineering Test Satellite-9 (ETS-9) [1-3]. For the ETS-9 program and future missions, developing plan for a Japanese Hall thruster was started[4]. The test onboard ETS-9 is the first Japanese Hall thruster flight experiment and it's the milestone to strengthen the payload transfer capability of all-EP satellite by Japanese industry in the 2020s, and to widen capabilities of future Earth orbiting satellites, orbital transfer vehicles, and interplanetary spacecraft.

6-kW operation is selected for the developing target to cover wide ranges of future-missions by JAXA. Due to intensive researches in the middle power Hall thrusters worldwide, 6-kW-class is considered as common technology

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in the EP community. It is however still a challenge for JAXA since only low-power EP thrusters were so far dealt with, and expanding the lineup of flight thrusters in terms of thrust level and Isp range will widen EP's application area and lower the cost of various space missions since existing flight thrusters operate at 5-kW or lower power[5-16]. Japanese contribution in this field will be expanded by this development. This paper describes the status of R&Ds of Japanese 6-kW Hall thruster in particular the activities related to Hall thruster breadboard model development and testing for the ETS-9 program. In the following, after describing the Hall thruster subsystem onboard ETS-9 and thruster design, R&D status is briefly overviewed. Also, activities to extend thruster's capability are introduced.

II.Description of Hall Thruster Subsystem for ETS-9

The ETS-9 satellite demonstrates a 5-ton class GEO satellite bus. More than 20 kW power is available for its mission, and this power is also assigned for orbit raising (OR) maneuver from a launched orbit to an operational orbit. Including high power (25 kW) electric power generation and supplying system, five key technologies will be tested; all electric propulsion with Hall effect thrusters, thermal control with deployable radiator, geostationary GPS receiver (GPSR) and advanced communication systems (ACS) for high throughput satellites. JAXA is responsible for the satellite bus development whereas National Institute of Information and Communications Technology (NICT) provides ACS. One of the missions for ETS-9 is to test all-EP propulsion system. After launched into a geostationary transfer orbit (GTO) and three-axis attitude control and solar panel deployment are completed, the satellite starts orbit raising maneuvers toward GEO by using two or up to three Hall thrusters simultaneously. In this case, thrust vector is controlled by swingable arms where two flight proven thrusters (SPT-140) are quipped on each arm; flexible arm-gimbal can provide a variety of thrust direction either for OR maneuvers or station keeping controls.

Figure 2 depicts the block diagram of propulsion subsystem. Four Hall thruster units (HTUs, SPT-140) on gimbal-N and gimbal-S, are operated via Power Processing Units (PPU) which are installed in the satellite main body. Xenon gas is introduced into both HTUs and xenon gas jet auxiliary propulsion system, and the latter xenon gas jet is used only for initial rate damping operation and emergent operation such as safehold. The satellite can complete the mission with four Hall thrusters and the auxiliary gas jet, but a Japanese Hall thruster (HTU-E, experimental) is also equipped for its experimental operation. In the case of HTU-E, full power operation at 6 kW will be tested during OR maneuvers along with HTUs, and both high thrust (>300 mN) and high Isp (>1700s) are targeted as listed on Table.1. Although lower-power operation is limited either during OR maneuver or in GEO, this thruster configuration realizes both reliable all-EP system by flight proven thrusters and flight challenge of the Japanese Hall thruster at the same time.

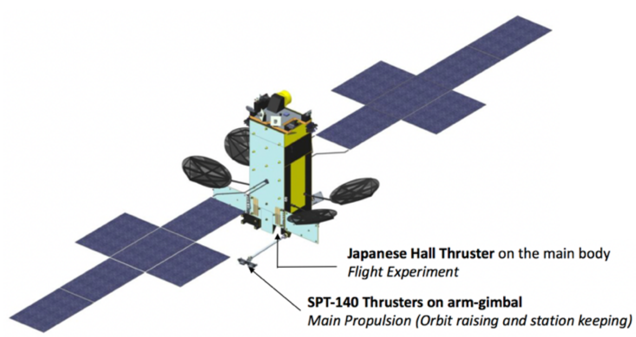

Figure 1. Image of Engineering Test Satellite-9 (ETS-9).

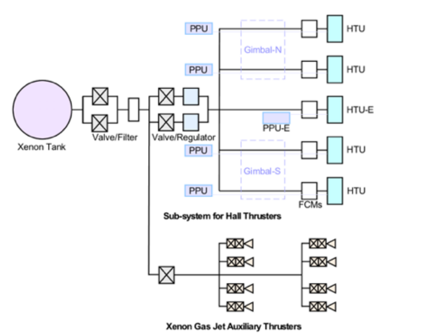

Figure 2. Propulsion Subsystem of ETS-9.

Table. 1. Target Specification of Japanese Hall Thruster for ETS-9.

Maximum Input Power to Thruster [kW]		6.0
Power Throttling Range [kW]		4-6
Discharge Voltage [V]		300
Nominal performance @BOL	F [mN]	359
	Isp [s]	1,710
Weight	HTU-E [kg]	24
	PPU-E [kg]	45
Total Impulse [MNs]		~5
Cycles [cycles]		TBD

Figure 3 shows the schematics of the Japanese Hall thruster subsystem. The subsystem consists of a Hall thruster unit (HTU-E) and a power processing unit and controller (PPU-E). PPU-E has a control module and two power modules for anode and other peripherals, and they interface with the satellite bus (satellite control system, SCP) and power control and power distribution units (PDU/PDCU). The Hall thruster unit (HTU-E) consists of a flow controller module (FCM) and a thruster module (HTM). HTM contains a thruster head and a hollow cathode, and they are compiled and mounted on interface panel.

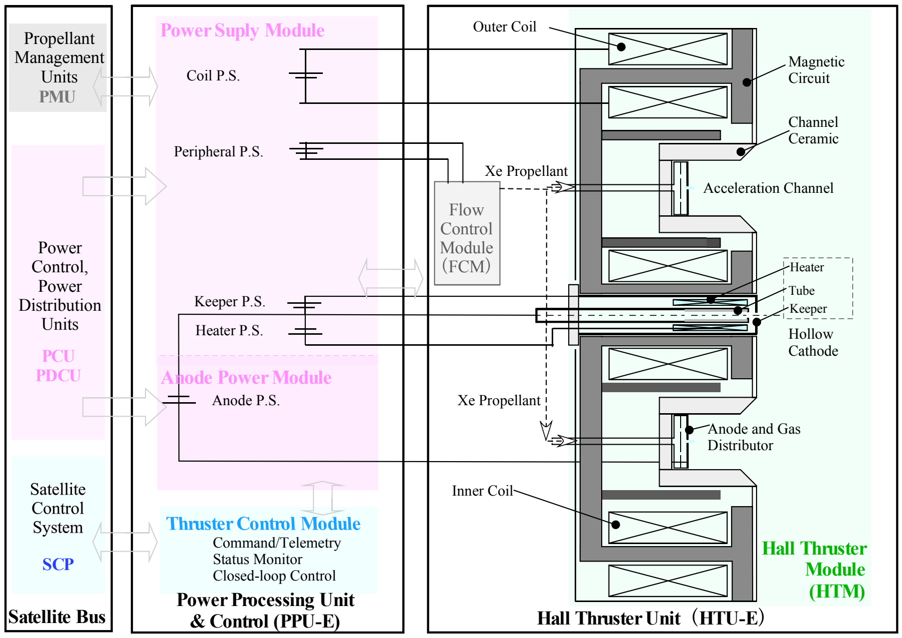

Figure 3. Schematics of Japanese Hall Thruster Subsystem.

Hall thruster is usually designed to produce and accelerate ions in the form of a well-collimated ion beam. To enhance thruster's efficiency and to lower power deposition onto the channel wall, the thruster employed "plasma lens" type magnetic field topology as shown in Fig.4 in the channel[17]. In this topology, a highly skewed upstream magnetic field along with mostly straight B-field at the channel exit was arranged to make a focused ion beam with suppressing ion impingement on the wall. For this purpose, channel and B-field configuration of the 6-kW Hall thruster's needs optimization, and it is conducted by BBM thrusters. As for the cathode, a cathode tube, made of Tantalum, had an insert in the shape of a cylinder that was placed inside the tube and pushed against the orifice, made of Tungsten. The insert was made of a low work function material, Lanthanum hexaboride (LaB6), featuring high electron emission capability and good resistance to contamination. The cathode tube was surrounded by a carbon heater tube and heat shield combination that raised the insert temperature to electron emitting temperatures above 1,400 °C to initiate a discharge. Outside these tube elements, a keeper electrode was placed to start-up and maintain a cathode discharge. To initial a main discharge, a bias voltage was applied between the anode ring in the upstream of the channel and the hollow cathode. Then, the keeper power supply was switched off or set to a constant current mode and a steady state was achieved after the thruster reached a thermal equilibrium.

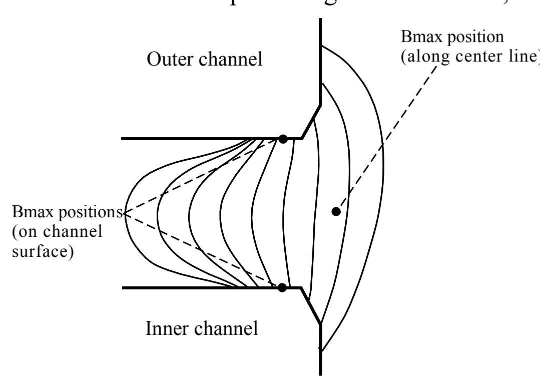

Figure 4. Acceleration Channel Design[17].

As already stated, PPU-E possesses two modules. The anode power module transfers 100-V satellite power to rectifiers through an inverter, and they are controlled by switching devices to provide 300-400 V and 20 A maximum output. Important issues are to cope with transient load impedance variation of the thruster with suppressing electromagnetic noises toward the satellite bus. To suppress the ripple toward the satellite bus, full wave rectification convertor was employed with some input and output filters, and all of them are software controlled. The software automatically seeks for the stable- and high-performance constant power operation onboard via changing the mass flow rate and the B-field strength.

III. R&Ds of Japanese Hall Thruster for ETS-9

A. Development Plan

Four phases from breadboard models to a flight model are planned for the development of the Japanese Hall thruster (HTU-E). Currently, engineering model (EM) fabrication and prototype model (PM) design are in progress. Development plan is provided in Fig.5. In the BBM phase, both a performance test model (BBM4) as well as a structural model (BBM/STM) were fabricated to check thrust performance, characterization of erosion and degradation feature to predict lifetime, and survivability against vibrational/shock for the launch environment. PPU-E development is in parallel progressed, and the first coupling test between BBM4 thruster and PPU-E/BBM in the summer of 2018. Based on these evaluations, engineering model (EM) design was reviewed in 2018 and testing of EM thruster is planned in 2019. All the qualification process excluding life test and EMC (planned to be conducted in the PM phase) are planned in the EM phase; in which coupling test between EM thruster and EM/PPU is the most important step in this phase. Finally, system level compatibility is checked in the FM phase as end-to-end (E2E) thruster operation during vacuum thermal testing of the entire satellite system.

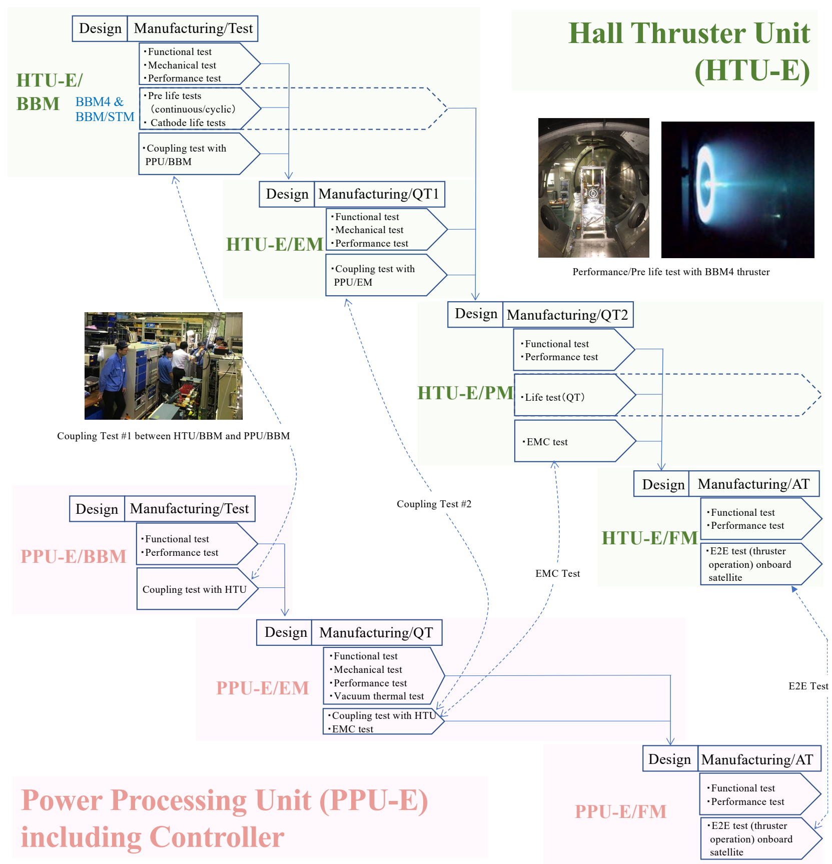

Figure 5. R&D Phases for Japanese Hall Thruster.

B. Breadboard Model Development

For the past three years, four breadboard model thrusters were designed, fabricated and tested. These studies are required because R&Ds of middle power range hall thruster was very limited at JAXA and in the Japanese community, hence it is needed to seek for fundamental design parameters such as scaling dimension, material selection, and interfaces. The effective channel diameter of the thrusters ranged from 100 mm in the case of BBM1a, up to 170 mm diameter for BBM3. Based on the evaluations of these thrusters and the empirical scaling law on *P/D*, where *P* is the power and *D* is the effective diameter, BBM4 thruster (*D*=150 mm) is selected as the base line design[17]. Channel geometry and B-field configuration however needed optimization, so, using BBM4, several parametric surveys were conducted by applying different channels etc. Several design considerations are: 1) symmetry of both magnetic field lines and a magnetic field strength distribution against channel centerline; 2) the channel was designed to complete ionization during the gas flows in the straight part of the channel and then in the chamfered portion of the channel, acceleration should follow. Since the ionization region is considered to end at around Bmax position, the channel is design so that Bmax is positioned on the straight-part of the channel surface as shown in Fig.4.; 3) acceleration region (Bmax) should be located near the channel exit but it is also known that performance is significantly influenced by a slight change of Bmax position[20]. Accordingly, the Bmax position was experimental surveyed; also, 4) radial and azimuthal neutral flow uniformity is obtained by gas injectors. The model, BBM1a, was supplementary used to optimize the configuration although its channel dimension is smaller than BBM4 and it is limited to low-power operation below 2 kW.

C. JAXA Vacuum Chamber for R&D

Up to 2018, most of thruster performance evaluation was conducted in a foreign vacuum chamber[4]. Then, from December 2018, JAXA's vacuum facility (Hall thruster development test (DT) vacuum chamber) became available. The thrusters were tested in two vacuum facilities at JAXA. The dimension of stainless-steel DT vacuum chamber is 3-m-diameter and 8-m-long, which possesses cryogenic pumps to obtain a xenon pumping speed of 230 kL/s. Another vacuum chamber is 2-m-diameter and 5-m-long, which possesses cryogenic pumps to obtain a xenon pumping speed of 110 kL/s. The thruster is mounted on a thrust stand and they are located inside the vacuum chambers as shown in Fig.6. Using the DT vacuum chamber, performance evaluation and some preliminary life tests such as the case at 300 V and 6 kW were performed.

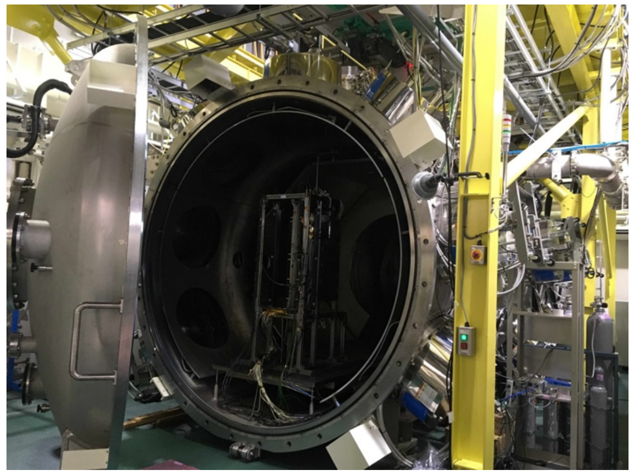

Figure 6. Hall Thruster Development Test (Hall-DT) Vacuum Chamber at JAXA.

D. Preliminary Life Tests using a Breadboard Model

One of the most important BBM test is full-power preliminary life test. History of 4,048 hours of the preliminary life test was plotted in Fig.7. From Fig.7b) and c), it is found that nearly constant performance continued. Hence, as far as the 6-kW operation is judged from the overall trend, it can be said that low-degradation design of BBM4 thruster was demonstrated.

In the following, details of the test are discussed. Operational events during the test were summarized in Fig.7(a). Thrust measurements along with calibration were conducted without breaking vacuum condition at about 100-hours intervals at the timing of gray arrows in Fig.7(a). At these timings, shifts of zero thrust points were evaluated just after stopping thruster operation, and then,

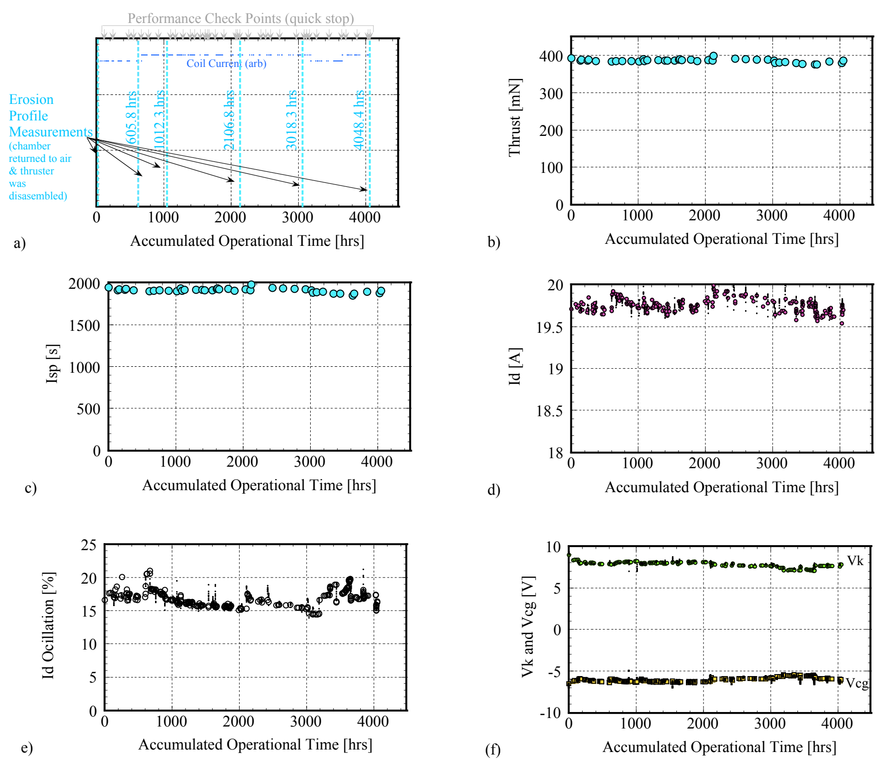

Figure 7. History of 4,048 hours Lifetest of BBM4 Thruster at 6 kW/300 V. a) event, b) thrust, c) Isp, (d) discharge current (*Id*), e) Id oscillation**,** f) keeper voltage (V_k) and cathode-to-ground voltage (V_{cg}).

the thrust stand pendulum was calibrated with known weights. At 605-hours, 1,012-hours, 2,106-hours, 3,018-hours and 4,048-hours, after the thrust measurements, vacuum was broken, and the chamber was returned to atmospheric pressures either to measure geometry or to check the thruster outlook. From Fig.7(b), it is found that thrust slowly decreased from 393 mN to reach a constant value of about 384 mN at around 500 to 600 hours and the same trend was found in Fig.7(c), in which Isp and thrust efficiency were plotted, and they decreased from 1,940 s and 62.9% to reach the constant values of about 1,900s and 60%[19]. However, these are the changes within error bars, and the overall trend up to 4,048 hours are that both the thrust value and the Isp values kept nearly constant values within fluctuations due to measurement or other errors throughout the experiment. Discharge current profile (Id in Fig.7(d)) was not so smooth but data scattered at around 19.7 A, which means discharge impedance was also fluctuating. More apparent fluctuations of the data were found in the case of Id oscillation in Fig.7(e). Id oscillation is defined as the half of peak-to-peak oscillations. Smaller Id oscillation below 20% is the target of this thruster, but temporal violation of this criteria was found at 258 hours and 626 hours. After 670 hours, Id oscillation was found to exceed 20% so the coil current was increased by 4% to suppress oscillations. Coil current adjustment was also conducted at 3,184 hours and 3,656 hours owing to the shifts of operational parameters. In the figures, small dots indicate transient values while starting-up the thruster, and open and closed circles denote equilibrium values. Along the test, V_k and V_{cg} in Fig.7(f) were almost constants, therefore stable cathode operation with high electron emission was confirmed.

Figure 8 shows the performance of the BBM4 thruster after the 4048-hours operation, in which high enough Isp and efficiency was obtained either at full power (6 kW) and lower powers (1.8-4.0 kW). Figure 9 summarizes the profiles of eroded and contaminated surfaces of the Hall thruster. Measured channel surface geometry at 0-, 605-, 1,012-, 2,106-, 3,018-, and 4,048-hours was plotted in Fig.9(a). Channel erosion at the beginning (between 0 and 605 hours) was as large as 2.3 mm near the channel corner, but afterwards, the erosion rate drastically decreased, and only slight change was found between 605 hours and 4,048 hours. It seems that the channel surface geometry was gradually converging into a surface. As indicated in Fig.9c), the eroding chamfer region of the channel at 4,048 hours showed a white-gray surface, but in contrast, the upstream surface in the straight part of the channel was contaminated by black materials. The black surface was observed as a result of deposition of sputtered beam target, and deposition was superior to erosion by ion bombardment there. Vice versa, white channel surface was considered to be continuously eroded by ions, and as a result, erosion was overwhelming against contamination. The white-gray surface would correspond to a transition between the two, and hence the downstream channel surface erosion rate was very low. It is expected thrust efficiency and thrust kept nearly constant values throughout the test because the status of channel surface erosion and contamination didn't change significantly.

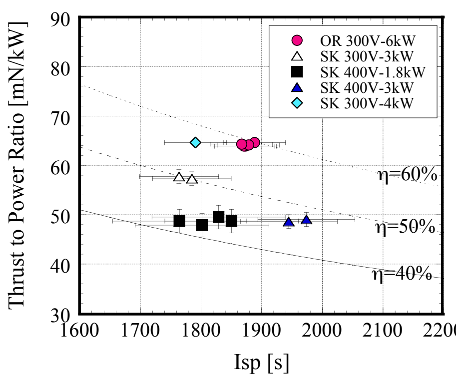

Figure 8. Thruster Performance of BBM4 after 4,048 hours Operation at 6-kW.

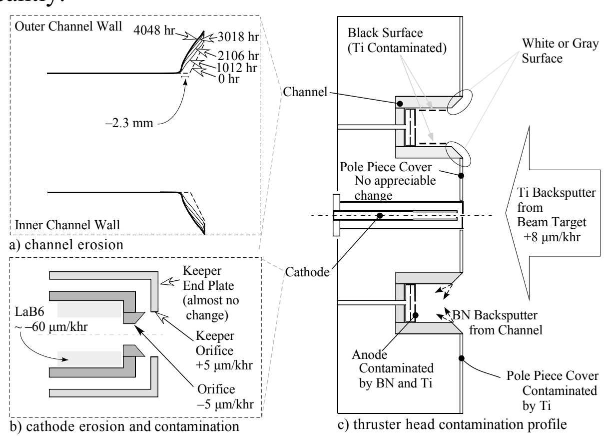

Figure 9. Erosion and Contamination of 4,048hours BBM4 Thruster Operation.

As the next topic, wear of the cathode tube is discussed. The erosion rate of the orifice was found to be very low; only 5 μm change was found from the beginning to 605 hours; in contrast, from 605 to 4,048 hours, very small erosion rates below 1 μm/khrs were found. Since the original orifice diameter was 2 mm, the total 10-μm change will not affect orifice's function to keep the inner pressure inside the cathode tube constant. From these results, it can be said that low erosion operation of the cathode was successfully demonstrated, and stable and unchanged cathode performance throughout the experiment was confirmed. The insert surface was, however, seen to be recessed at a higher rate of 60 μm/khr due to evaporation. Based on the evaporation rate[21], the temperature of the insert is estimated to be 1,560 °C or higher. If a 1-mm thick insert or a thicker insert is used and the evaporation rate doesn't change, 20-

khr operation is possible, and hence, the life is limited but enough for all-electric propulsion satellite that requires accumulated operation of 10 khr in total[19].

There are some items left for the test campaign of BBM4 thruster; they include life test at lower powers for SK maneuvers. To find an operational range available for lower power, an experimental survey was conducted. In this survey, short continuous operations of 200-550 hours were conducted at a couple of conditions changing thruster power and anode voltage. Example histories are plotted in Fig.10, where 4 kW/300 V case and 1.8 kW/400 V case were provided, and both cases used keeper discharge at 3A. From Fig.10, as far as thrust levels and discharge currents are concerned, they showed nearly constant values, but more than 5-V decrease was found for V_k during the test at 1.8 kW/400 V. In this case, contaminated insert surface and corresponding degradation of electron emission was confronted, i.e., that point is considered below the low-power operation limit. In contrast, 4 kW operation seemed fine as far as the data in Fig.10 is concerned. Deep throttling down to 1.8 kW is now considered as the future R&D issue, and 4 kW is set as the lower power operational point for ETS-9.

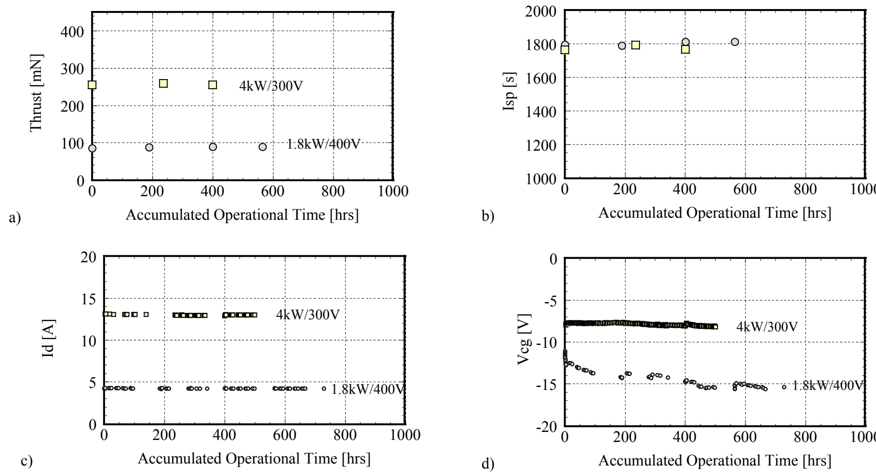

Figure 10. Example Continuous Operation at Low Powers with BBM4 Thruster.

E. Coupling Test with PPU-E Breadboard Model

As a subsystem, a limited coupling test of BBM4 thruster with breadboard model PPU-E was executed. The test performed ignition and transition to full-power operation at 300 V and 6 kW, and also low power operation for the SK mode. The test employed a PPU-E with anode power supply (PS), coil PS, keeper PS, heater PS, and peripheral PS, and also a controller interfacing the satellite bus and the BBM4 thruster head. Based the coupling test results, electrical interfaces are designed and other (thermal and mechanical) interfaces are check along with some analyses in the BBM phase. Full coupling test including controlling capability of PPU-E and EMC is planned in the next EM phase.

IV.R&D to Improve the Thruster for Future Missions

The Japanese Hall thruster for ETS-9 selected typical discharge voltage (300 V) for Hall thrusters but extending operational envelope into either higher voltage or higher thrust will contribute strengthening other types of space mission. For example, the mission trip time of all electric propulsion satellite can be reduced by increasing thrust to power ratio; or higher Isp for station keeping will increase the payload ratio of a satellite. High thrust for OR and higher Isp for SK will be a trend for future Hall thruster development. Another mission that is suited is deep space exploration that requires higher Isp as well as longer lifetime of Hall thrusters either at higher or lower power. As shown in Fig.11, if Hall thruster's line-up of 2-6 kW is added to the JAXA's electric propulsion (ion thrusters), a variety of missions which follow the flight demonstration onboard ETS-9 are expected, and payload benefit hence mission strength is tremendously expanded.

Table. 2 shows expected expansion of the ETS-9's Hall thruster. As previously stated, the thruster for ETS-9 will be improved either by realizing deep throttling capability that assures low power consumption during GEO missions and in this case, power available for the mission payload will be increased. Obtaining a high enough Isp in lower power is the key to realize both high payload ratio and high power allocated to missions. Another target is wide operational range (type WR). Related R&Ds for thruster and PPU (wide range) are going on[22,23].

Current study for future missions is not limited to 6-kW; not only 6-kW BBM4 but also BBM1a (100-mm in diameter) and BBM3 (170-mm in diameter). Some obtained thrust/Isp so far are plotted in Fig. 12. BBM1a's 2-kW class operation is expected to be used for small deep space probe due to its high Isp availability. Also, the plot shows BBM3's operation is available either in wide Isp range or in wide power range, that will be suitable for exploration or transportation of a large vehicle. Along with improved ETS-9 thruster, we'd like to further enrich the future JAXA missions including space transportation by establishing these line-ups step-by-step.

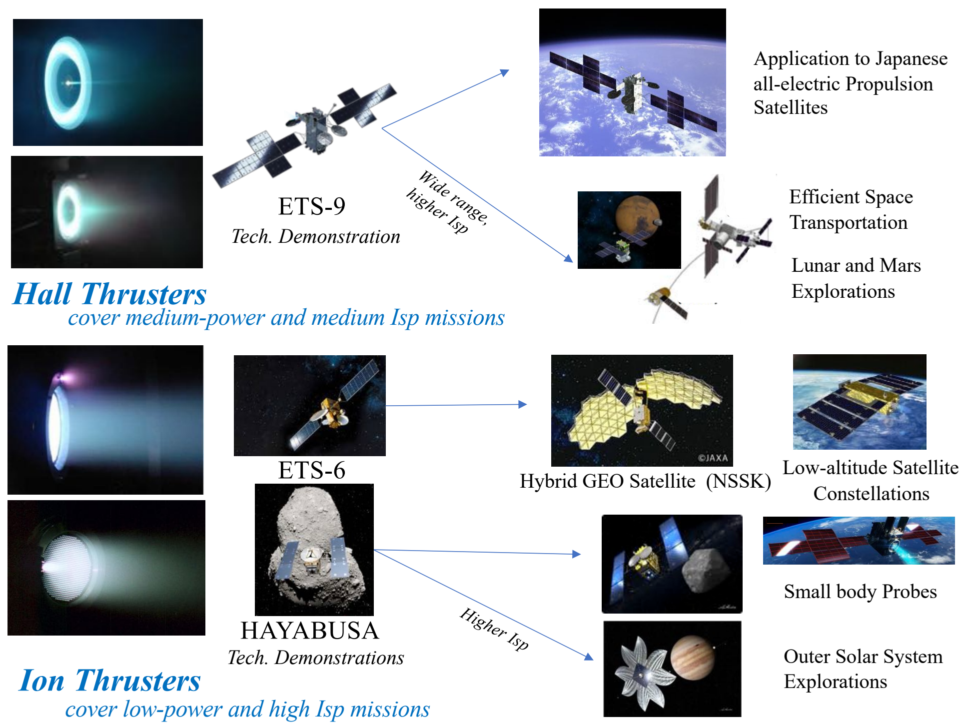

Figure 11. JAXA's EP Missions Benefited from both Hall and Ion Thrusters.

Table. 2. Tentative Target Specification of 6-kW-class Japanese Hall Thruster.

		Thruster for ETS-9	Deep Throttling Type	Wide Range Type
Max Power to Thruster [kW]		6.0	6.0	6.0
Objective		First flight experiment	Improved thruster with deep throttling capability	Improved thruster with wide operational range
Target Mission/Platform		ETS-9	DS2000	TBD
R&D Status		under development	under research	under research
Power Throttling Range [kW]		4-6	2-6*	2-6*
Discharge Voltage [V]		300	300-400*	200-640*
Nominal performance @BOL**	F [mN]	359	390*	390-420*
	Isp [s]	1,710	1,900*	1,900-1,400*
Weight	HTU [kg]	26	TBD	TBD
	PPU-E [kg]	45	TBD	TBD
Total Impulse [MNs]		~5	> 6*	> 6*
Cycles [cycles]		>50	>6,000*	>6,000*

*values under consideration, vulnerable to change, **BOL=Beginning of Life.

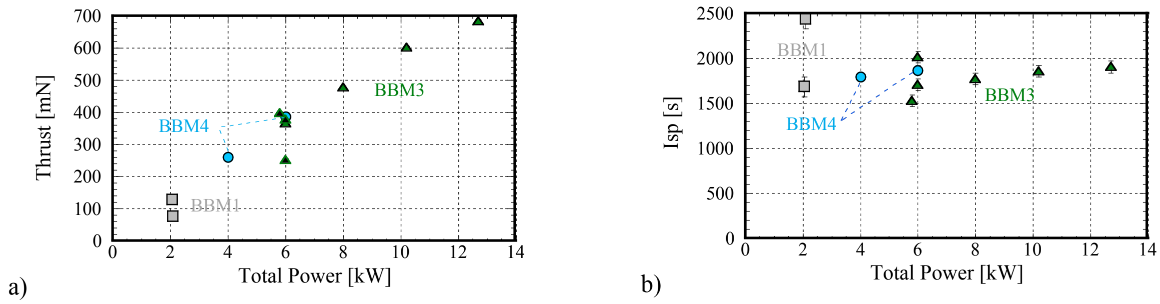

Figure 12. Performance of BBM-series Thrusters (BBM1a(100mmϕ), BBM4(150mmϕ), and BBM3(170mmϕ).

V.Summary

R&Ds of Hall thruster breadboard models were conducted. Among four breadboard models, BBM4 thruster, whose effective channel diameter is 150 mm, was selected as the baseline design for the flight experiment onboard ETS-9. Performance of 63 mN/kW was kept at 6 kW and 300 V even after 4,048 hours of continuous operation. With this and related test campaign results of the breadboard models, preliminary design was completed and reviewed. Fabrication of Engineering Model (EM) and its test is planned in 2019 to demonstrate the performance, the interfaces with its power processing unit (PPU-E) and satellite system by executing performance evaluation, shock/vibrational test, and full coupling test with PPU-E. With these processes, Prototype Model (PM) development will start after the critical design review. In parallel with these activities, preliminary life test using BBM4 will be continued to obtain and check the feasibility of lower-power station keeping mode before full qualification processes starts in the PM phase.

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