

Development of 6-kW-class Hall-Thruster at JAXA

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Abstract: Hall thruster is considered the key propulsion technology for a variety of spacecraft including Earth-orbiting satellites, space transportation systems, and space exploration. To acquire medium-power Hall thruster technology, a 6-kW-class Hall thruster system is under development at Japan Aerospace Exploration Agency (JAXA), which is the first Japanese Hall thruster to be tested onboard the Engineering Test Satellite-9 (ETS-9). Onboard ETS-9, a limited flight experiment of the Japanese Hall thruster subsystem will be conducted along with four main flight-proven foreign Hall thrusters as the bus system. Prototype model thrusters as well as an engineering model power processing unit are devoted to qualification tests. The qualification tests are in progress including an endurance test and system compatibility tests. In 2024, an end-to-end verification of the flight model thruster subsystem with the whole satellite system is planned for preparing the flight that is currently scheduled for FY2025.

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I. Introduction

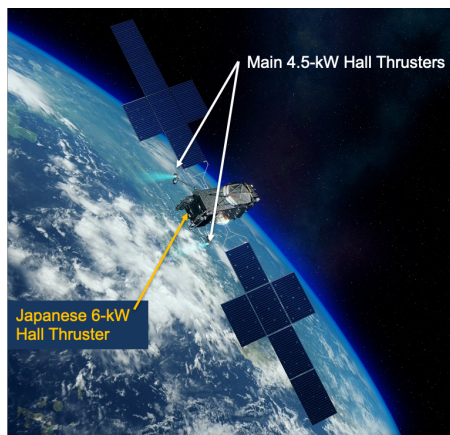
Electric propulsion (EP) activity in Japan so far has been limited to low-power ion thrusters. There is, however, a worldwide trend shifting to use Hall thrusters for Earth-orbiting satellites, space transportation systems, and exploration in medium to high power ranges.^{1,2} For these purposes, there have been several efforts to develop medium-power Hall thrusters,^{3,4,5,6,7} and they were employed for several all-electric propulsion satellites.^{8,9,10,11} To establish Hall thruster technology in Japan, JAXA is working on a 6-kW-class Hall thruster subsystem. The R&D program of Hall thruster covers basic research such as the scaling law for designing acceleration channels and related components for developing a flight system. For the subsystem to be tested onboard Engineering Test Satellite-9 (ETS-9),^{12,13,14} full qualification processes are included and conducted within this program. The thruster is to be used on all-electric propulsion satellites by Japanese industry, and as well, the program is positioned as the steppingstone to the future evolution of Hall thrusters in JAXA's missions. Following the previous papers reporting the status of thruster research and breadboard/engineering models development,^{15,16,17,18,19,20} this paper describes brief overview of the subsystem design and the status of Hall thruster subsystem development for ETS-9.²¹ Details are reported by companion papers in the conference for the thruster subsystem for ETS-9^{22,23,24} and related R&Ds for 6-kW-class thrusters.^{25,26}

II. R&D Program Overview

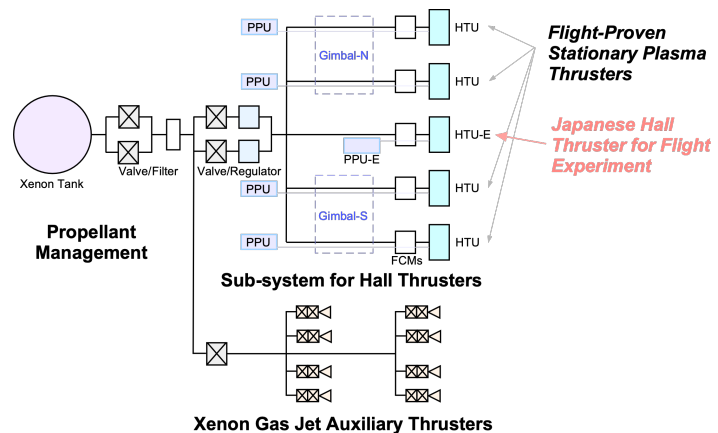
An R&D program for Hall thrusters at JAXA started in 2015 to establish medium to high-power in-space propulsion technology using Hall thrusters. The program adopted a step-by-step approach to establishing Hall thruster technology;²⁷ starting from basic scaling law research and key device development, a 6-kW class thruster was selected as the first development target; then the 6-kW thruster and following line-ups will evolve for a variety of missions. As the first step, a flight system development and in-space demonstration are conducted onboard ETS-9. ETS-9 is going to demonstrate 4 technologies such as high power (25 kW) electric power supply, all-electric propulsion with Hall effect thruster, Geostationary GPS receiver (GPSR), advanced and flexible communication systems for HTS with full digital interfaces.

III. Description of Thruster Subsystem for ETS-9

ETS-9 is an all-electric propulsion satellite. In Fig.1, the image of the satellite as well as its propulsion subsystem are plotted. After the launch into geostationary transfer orbit (GTO), Hall thrusters are operated up to a target orbit, geostationary orbit (GEO), where thrusters change their operations to a lower power to conduct station keeping (SK) operations. The satellite has no hydrazine-based thruster for reaction control system (RCS) but the Hall thrusters and xenon gas jets are used for RCS. As plotted in Fig.1a, main Hall thrusters are mounted on the armed gimbals, which enables thruster vector control for both operational modes. ETS-9 employs four flight-proven systems (SPT-140⁷) as the main thrusters and in addition, one Japanese Hall thruster subsystem is mounted on the bottom surface. The Japanese Hall thruster is not a main thruster, but the experimental operation of the thruster is planned onboard ETS-9. In our current plan, for orbit raising (OR) maneuvers, up to three thrusters are operated simultaneously including the Japanese Hall thruster. For SK operation, only the main thrusters are used but the Japanese thruster is not used due



a) Image of ETS-9 and its thrusters' configuration.



b) Thruster subsystem for ETS-9.

Figure 1. ETS-9 and its thruster subsystem.

to the configuration the Japanese thruster is mounted. Hence limited lower power operation of the Japanese Hall thruster is planned separately from the SK operations by main thrusters.

In the ETS-9 project, a Hall thruster subsystem is newly developed for the Japanese thruster system. A block diagram of the Japanese thruster subsystem is plotted in Fig.2 and its target specification is summarized in Table. 1. As is plotted, the subsystem consists of a Hall thruster unit (HTU-E) and a power processing unit (PPU-E). Hall thruster units consist of a Hall thruster module and a flow control module (FCM), and PPU-E consists of power-supplying units and a controller. Onboard the controller, sequential programs are installed to initiate, monitor, and control the thruster's operation. The controller as well interfaces with the satellite bus system to accept commands and send telemetry data.

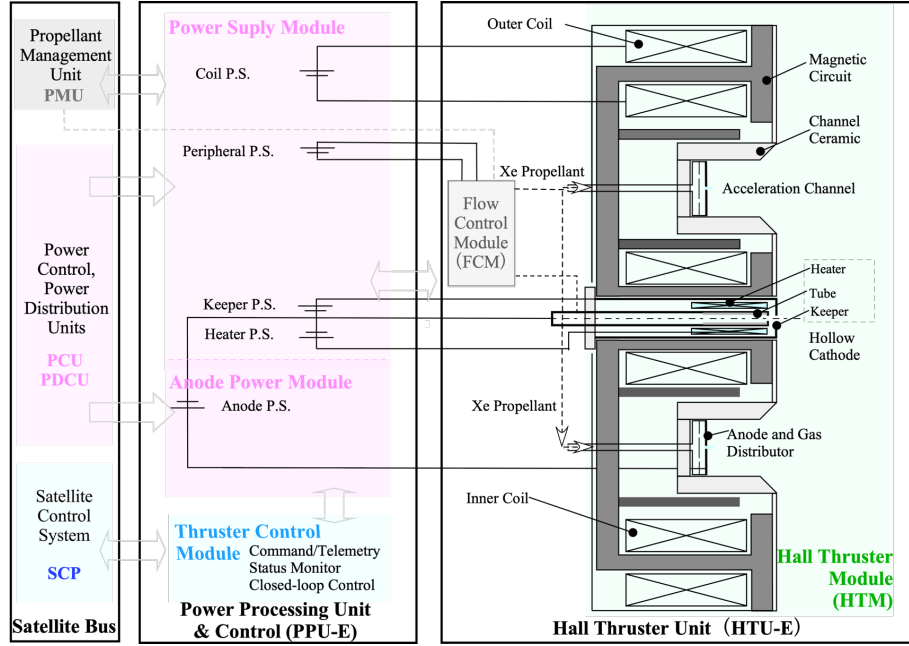


Figure 2. Block diagram of Japanese thruster subsystem for ETS-9.

Table 1. Specification of Japanese Hall thruster for ETS-9.

Maximum Input Power to Thruster	[kW]	6.0
Power Throttling Range	[kW]	4.0-6.0
Discharge Voltage	[V]	300
Performance @BOL*, 6kW	F [mN]	359
	Isp [s]	1,783
Performance @MOL**, 6kW	F [mN]	330
	Isp [s]	1,712
Performance @MOL**, 4kW	F [mN]	219
	Isp [s]	1,589
Operational Time in OR mode	[hours]	>3,000
Total Impulse	[MNs]	~4
Cycles in SK mode	[cycles]	>200
Weight	HTU-E [kg]	26
	PPU-E [kg]	45
Signal Interface	MIL-STD-1553B	
Control Function	Power and Discharge Stability Control	

*BOL=Beginning of Life, **MOL=Middle of Life (when orbit raising is completed)

IV. Thruster Subsystem Design and EM Development

The design and test results of the engineering models (EM) are summarized in this chapter. The pictures of engineering models are provided in Fig.3. These units were designed and manufactured by IHI Aerospace Corporation (IA) and Mitsubishi Electric Corporation (Melco), although FCM is imported from a foreign supplier. The Hall thruster module employed a magnetic-layer-type Hall thruster design with an insulator ring. The effective diameter of the acceleration channel was selected as 150 mm considering the scaling law in terms of thrust characteristics and thermal conditions. Results obtained by intensive studies using breadboard models (BBMs) were reflected in the design of the acceleration channel and the center-mounted hollow cathode.¹⁵⁻¹⁸ The centered hollow cathode employed a LaB₆ insert for electron emission along with a graphite keeper and a tungsten orifice to survive the sputtering by xenon ion bombardment. The thrust performance of the EM thruster is plotted in Fig.4. As shown in the figure, the total thrust performance was about 60%, and the corresponding anode efficiency was above 64%. The figure showed that the data satisfied both the specification for ETS-9 and the requirement for future all-EP satellite applications. Limited 1,000-hour life tests were also conducted for the EM thruster to check the lifetime design and its estimation model obtained in the BBM phase, in which a 4,048-hour preliminary life test was conducted.²⁰ It was confirmed that the 1,000-hour tests of both OR and SK modes reproduced the results in the BBM phase, hence the lifetime design was confirmed to be appropriate.

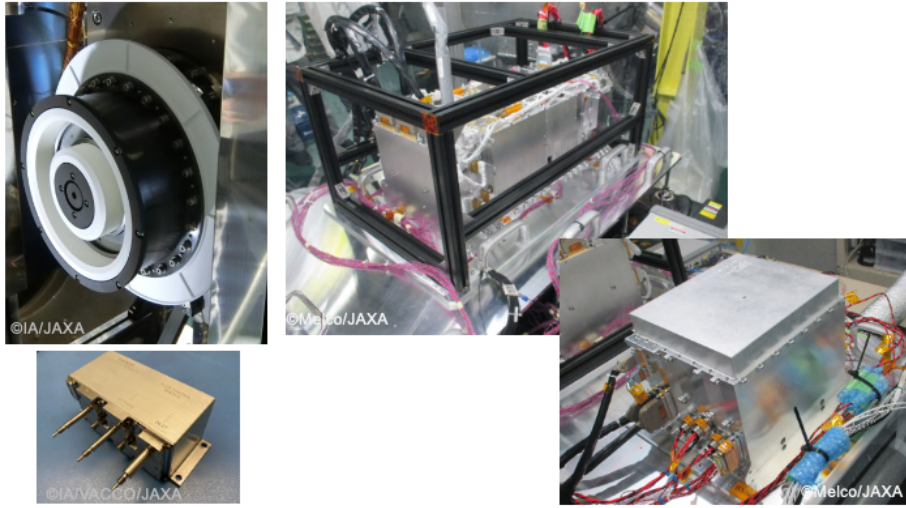


Figure 3. Pictures of engineering models; HTU-E/EM and PPU-E/EM.

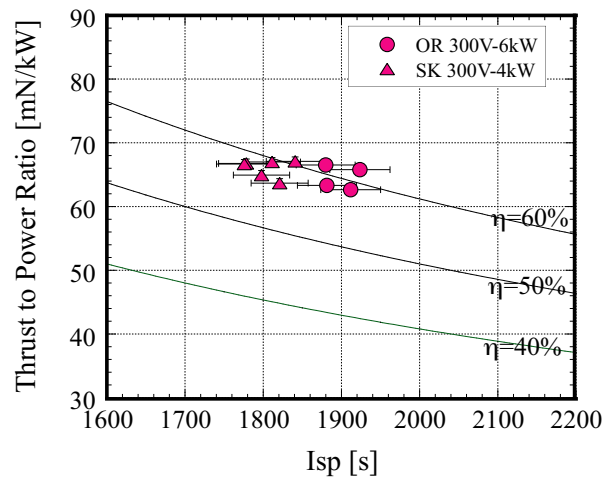


Figure 4. Thrust performance of EM thruster (HTU-E/EM). the data points represent data with different B-fields at constant power.

As for PPU-E, an engineering model (PPU-E/EM) was developed and tested. PPU-E plays some role in supplying electric power to the thruster and components by controlling their operations. Also, command and telemetry interfaces are implemented to communicate with the satellite bus system. These functions as well as design compatibility with the satellite system were evaluated and confirmed. The main unit of PPU-E is the anode power supply unit (APU). By APU, 100 V regulated power from the satellite's power supplying unit is converted to an anode discharge voltage of 300 V. APU consists of two slices of DC/DC converters, each 3 kW, that provide discharge currents up to 20 A through a filter. In addition to APU, peripheral power supplies and control units (PS&C) are equipped to operate a heater, keeper discharge, electromagnetic coils, and other peripheral devices such as FCM.

The most important event in the EM phase development was the integrated operation of the thruster subsystem. The test checked the sequential operation of the subsystem. As was shown in Fig.5, the sequence started with xenon gas purge and cathode heat-up; after 20 minutes of heater operation, the hollow cathode reached the ignition temperature, and then, the B-field and the keeper voltage (up to 100 V) were applied to initiate the keeper discharge. Afterward, the main discharge between the anode and the cathode was started and the keeper discharge was turned off. In this start-up process, the xenon flow rate was set so that 13.3 A main discharge was initiated, and then the flow rate was increased to the full power mode to obtain about 20 A which corresponds to the OR mode. The sequence of the SK mode is not included in Fig.5, but the same condition as in the start-up mode (13.3 A) continues with a keeper discharge power of about 30 W. During these modes, current oscillation control and constant power control were used to keep the current oscillation below 20% (0-peak) and to keep the constant power. The controller in PS&C received detected operational parameters and their status to conduct feedback control via changing operational parameters following a control logic. Both the mass flow rates as well as the B-field were controlled during the controlled sequences.

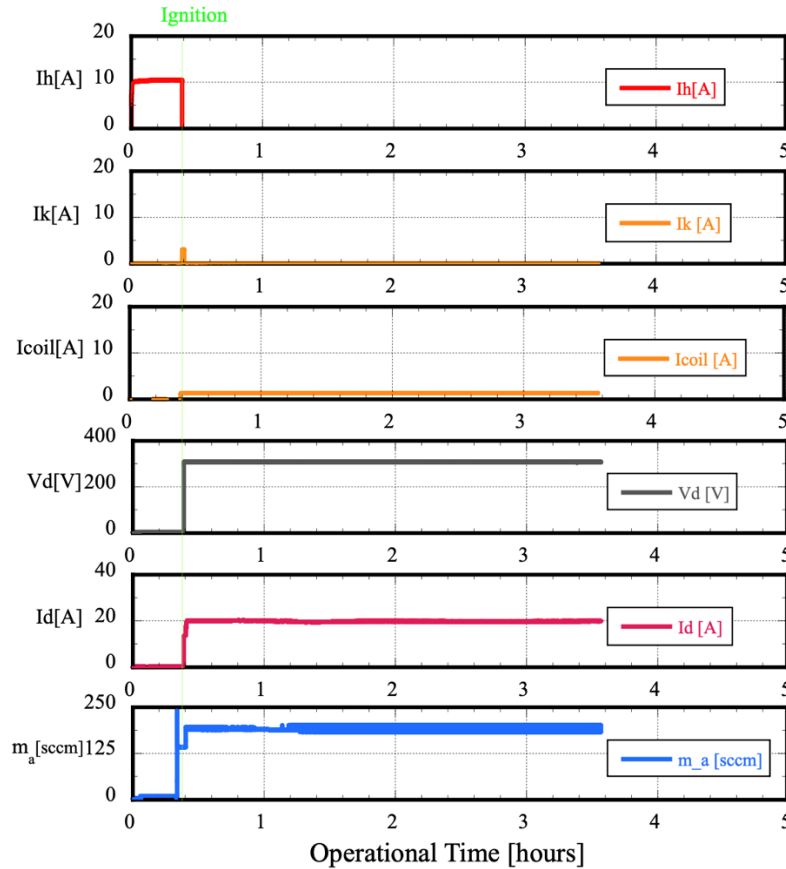


Figure 5. An example of thruster (HTU-E/EM)-to-PPU-E integration tests. 20-min heat-up, ignition, start-up, and OR mode (6 kW) operation; I_h : heater current, I_k : keeper current, I_{coil} : coil current, V_d : Discharge voltage, I_d : Discharge current, and m_a : Xe flow rate to anode.

As far as the Hall thruster subsystem is concerned, the most important design point is to minimize the interaction between the thruster subsystem and the satellite system. For this purpose, the thruster body and its mounting plate are electrically isolated from the spacecraft body; this means that the thruster surface is either connected to the cathode body or covered by insulators. As a result, anode power output is floated from the spacecraft. Although such electrically floated thruster connection can principally block a current between the thruster and the satellite system, careful treatment is still necessary in cases of high-frequency or transient discharges such as surge currents since they can transfer even between isolated bodies. Protection against such surge currents is hence equipped with PPU-E to block in-rush currents toward the spacecraft. All these designs were evaluated at the critical design reviews (CDR). CDR for HTU-E was finished in January 2023, and CDR for PPU-E was also finished in 2023.

V. Qualification Test Status and Flight Model Development

Prototype models of both HTU-E and PPU-E were designed based on the above EM results. HTU-E/PMs were fabricated, and the fabrication of PPU-E/PM is currently in progress. In the case of HTU-E, two models, PM1 and PM2 were fabricated. PM1 is used for a full mission duty cycle (MDC) life test of the thruster. Before the life test, the model was introduced into mechanical tests at acceptance test (AT) levels and then it was devoted to the endurance test at JAXA's Hall thruster development test (DT) vacuum chamber. Figure 6 shows performance data at the nominal operation condition and comparison with the EM thruster; similar values within measurement accuracy were obtained. Also, Fig. 7 shows the history of the thruster's PM life test showing transitional voltage up to around 2,000 hours and the thruster then kept nearly constant characteristics. In parallel to the tests using HTU-E/PM1, HTU-E/PM2 was devoted to mechanical tests at qualification test (QT) levels and a system compatibility test in particular electromagnetic interference (EMI). From the tests, it was found that the electromagnetic signals were mostly below the EMI level for ETS-9 except for the lower frequency region below 200 kHz. As of June 2024, HTU-E/PM1 continues the life test but other tests using PMs were finished. In the case of PPU-E, QT-level tests are currently conducted using EM. Testing using PPU-E/EM is continuing.

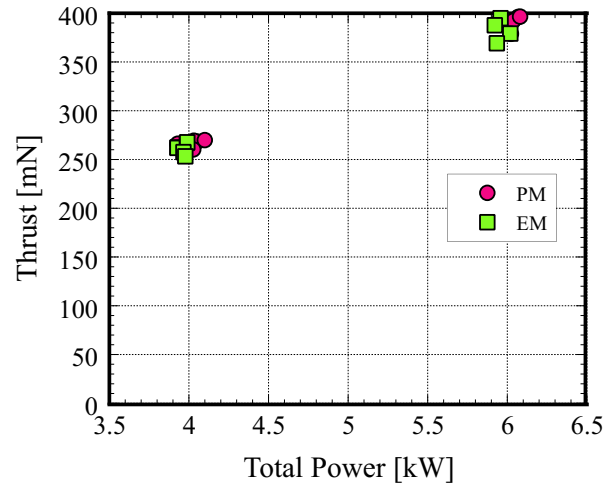


Figure 6. Thrust characteristics of HTU-E/PM2 and EM.

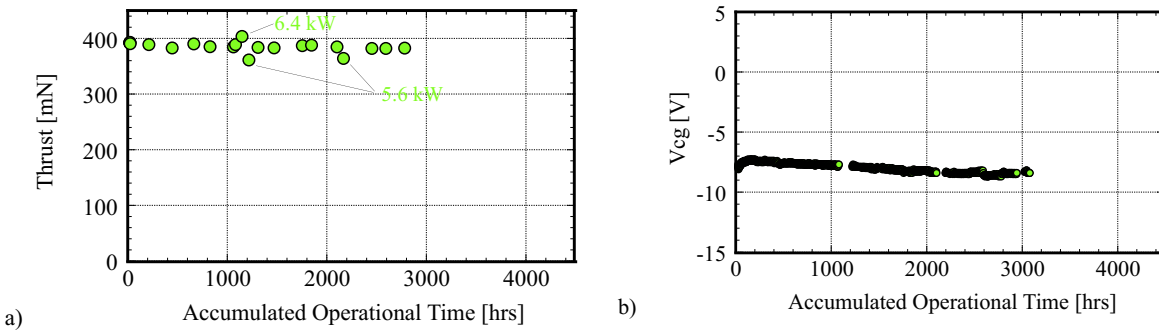


Figure 7. HTU-E/PM1 life test status up to May 2023. thrust and cathode-ground voltage (Vcg) against accumulated operational time.

Flight model development is underway for both HTU-E and PPU-E. Tests at acceptance levels were executed and an integrated test along with the satellite system is underway; the system level integrated test is planned during the thermal vacuum test of the whole satellite system, and end-to-end demonstration (checking ignition and short-term operation of the Japanese Hall thruster system) will be conducted inside JAXA's 13-m-diameter vacuum chamber.

VI. Conclusion

The development status of the Japanese Hall thruster subsystem is presented and its plan for the flight experiment is described. Qualification tests using PM1 and PM2 of the Hall thruster unit (HTU-E) and EM of the power processing unit (PPU-E) are currently going on. As for HTU-E, most of the testing was completed and currently life test continues. Flight model thrusters are under intensive development for the rapidly approaching launch window in FY2025.

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