Japan's Itinerary Towards High-Power Electric Propulsion

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Abstract

With the success of the asteroid explorer mission "Hayabusa", and increasing availability of high electric power in space, Japan is moving to develop a high-power electric propulsion system in the 10 to 100-kW class. With a decades-long expertise in various electric propulsion systems, several concepts are studied to yield the best possible design while enabling new mission types for scientific and commercial application.

Keywords

high-power electric propulsion; Hall thruster; Space Solar Power System (SSPS); Solar Electric Propulsion Systems (SEP)

1. Introduction

In 2003, the HAYABUSA (formerly known as MUSES-C) mission was launched on its long journey to the S-class asteroid 25143 Itokawa to be the first probe to bring back material from the surface of an asteroid, and to be the 6th Japanese satellite to operate with a Japanese-built electric propulsion system. Despite the many issues that HAYABUSA faced on its way, it returned successfully to Earth in 2010, and sparked a wave of space enthusiasm within Japan. Not only could it prove that Japan is able to accomplish such a complicated mission, but it could also successfully bring back invaluable samples from the asteroid that are still under study. On the wave of this success, the Japanese Space Agency (JAXA) initiated two follow-up missions with the aim of using the lessons learnt during HAYABUSA to enable further scientific work. HAYABUSA 2, based on the design of its predecessor, will use further developed technologies, including an improved ion thruster, to visit the C-class asteroid 1999JU3 and bring back samples [1]. Scheduled for launch in 2014, it will take 6 years for the round trip. HAYABUSA MK II is another sample-return mission, for a D-class asteroid, that is currently planned together with ESA in their Marco Polo mission.

However, HAYABUSA did not only have an impact in the scientific world. With 3 movie adaptions, a variety of books, other merchandise, and roadshows, HAYABUSA became well known in the general public, and with the increasing public interest, future space missions are encouraged and expected.

One of the concepts in question rose with the current increase of availability of higher electric power in space. As technologies in Japan are developed to enable more output and to work more efficiently, including power generation, power processing, but also communication, power transmission, etc., the possibility of new space missions is given. With the new mission scenarios, a demand for high-power electric propulsion (EP) came up that culminated in the initiation of the High-Power In-Space Propulsion program by JAXA that is explained in more detail within this paper.

2. High-Power In-Space Propulsion Program Outline

The High-Power In-Space Propulsion program, initiated 2011, has the target to apply a high-power electric propulsion system, made entirely in Japan, on satellite missions. This will not only help to enable new mission scenarios of high scientific interest, but also advance the technology level of EP and their related components in Japan. The program, similar to Europe's HiPER [2], encourages universities and research centers to bring up concepts for EP systems that will be narrowed done to the final candidate in a yet-to-defined selection process. The eventual thruster shall be capable of handling a power input of the order of 100 kW.

For these goals, an itinerary was derived with several milestones and design steps. The first target would be to establish a smaller system in the few kW-class to be employed on an all-electric stationary satellite for in-orbit tests. The experience and the lessons learnt during this mission will help the scaling process towards a high-power system. In a first design requirement, a specific impulse of at least 1900 s, and a thrust of 0.25 N at a power level of 5 kW are targeted.

In the following period, the design will be refined and adjusted to face the higher power level. Concurrently, ground test facilities together with diagnostic means shall be created, and numerical simulations shall support the design process. The eventual design will be applied to scientific satellite missions that are further specified in the next Section. The minimum requirements for this step are an specific impulse of 1900 s, a thrust of 2.5 N at a power level of 50 kW with a specific design mass of β=100 W/kg, defined as:

$$\beta = \frac{2\eta}{\alpha_{Power} + \alpha_{PPU} + \alpha_{Thruster}}, \tag{1}$$

where η is the total thrust efficiency of the thruster, and α is the specific mass for power supply, power processing, and the thruster (wet mass).

From the experience on the satellites, the thruster system shall be further improved to eventually be used as main propulsion system for an asteroid-bound manned mission. The tentative year of launch is around 2028. In the refinement process of the thruster, the thrust should be increased to about 8.2 N to enable a small transfer time at a total power level of about 160 kW, and a specific design mass of β=150 W/kg. With estimated 9,000 hours of necessary operation time, the lifetime of the thruster system is a crucial issue.

3. Mission scenarios

3.1 Space Solar Power System (SSPS)

A commonly considered mission application for high-power EP, the Space Solar Power System is another target in Japan to make use of the technologies developed within the In-Space Propulsion program. SSPS is a possible mission scenario studied, among others, by JAXA to enable a space-bound power plant for various applications [3, 4]. For a 1 GW system in geostationary Earth Orbit (GEO), a total mass of 20,000 tons was estimated, requiring a high number of orbit transfers from low Earth orbit (LEO) to GEO. With high-power EP of a thrust level of 8 N, and by using the current H-IIB launcher specifications, an estimated 15 tons could be transferred to GEO within 100 days. Further technology steps in launcher development and EP technology, could reduce the number of launches and increase the transferable payload. Nevertheless, low-cost technologies are necessary to establish such a project in future, as many missions will be required.

3.2 Solar Electric Propulsion Missions (SEP)

Targeted within the In-Space Propulsion program is the exploration of Near-Earth Objects (NEO). Using a combination of Cryogenic Propulsion Systems (CPS) and Solar Electric Propulsion Systems (SEP), it is envisaged to enable a manned mission to a NEO by 2028. The point of assembly of the spacecraft is chosen to be the Earth-Moon Lagrange Point 1 (EML1) from which the eventual NEO mission will start. To transfer the necessary elements from LEO to EML1, 2 SEP systems are seen necessary where the latter one is also used to move the entire spacecraft from EML1 to NEO and back. The derived specifications for the two missions and the estimated requirements on the EP system are summarized in Table 1.

As one can see, a tremendous amount of propellant is necessary for both missions, and improving the propulsion system to consume less propellant and to be more cost effective will yield benefit for the entire mission. Trajectory optimization and said propulsion improvement will recursively iterate the mission plan in future.

Table 1

Mission Requirements for SEP in the In-Space Propulsion Program

Requirement	SEP-1	SEP-2
Mission		
Transfer task	LEO to EML1	LEO to EML1, NEO approach and return
Transfer time	392 days	266 days + TBD
Total Δv, km/s	~4	~4.7
Solar power, kW	160 (at 34 %)	320 (at 34 %)
Total mass, t	18	44.5
EP system		
Exemplary EP	4 Hall thruster	8 Hall thruster
Specific impulse, s	2000	2000
Propellant mass, t	12 (Xenon)	32 (Xenon)
Power, kW	4×37.5-50	8×37.5-50

4. Electric Propulsion Candidates

Japan has studied on different electric propulsion concepts for the past decades, and, thus, gained a lot of expertise in this field. However, only two of these concepts – the pulsed plasma thruster (PPT) and the ion thruster – were applied on a small number of technology demonstration missions. Table 2 shows a summary of the Japanese satellite missions using EP made in Japan.

Table 2

Japanese Satellite Missions Using Electric Propulsion

Electric propulsion system	Name of mission	Year of launch
PPT	L-4SC-3	1974
	ETS-IV	1981
Ion thruster	ETS-III	1982
	ETS-VI	1994
	COMETS	1998
	Hayabusa	2003
	ETS-VIII	2006

Despite the successful application of the individual thrusters, especially on the long-term mission of HAYABUSA [5], these two concepts are not regarded for the In-Space Propulsion program due to their low thrust level. However, by means of HAYABUSA's follow-up missions, and the scheduled application of PPT on the PROITERES mission, these technologies are still enhanced and continued [1, 6].

4.1 MPD thruster concepts

Four research groups are studying and proposing a concept using magnetoplasmadynamic (MPD) thrusters.

Current research at Nagoya University focuses on a parallel-plate steady-state applied field MPD (AF-MPD) thruster with a power level of about 1 kW (10 A, 100 V), used to study on the effects of electrode geometry and magnetic field as well as to test the hollow cathode in development. Figure 1 shows the concept of the current thruster model. After tests, it will be scaled to a power level of about 100 kW (100 A, 1 kV).

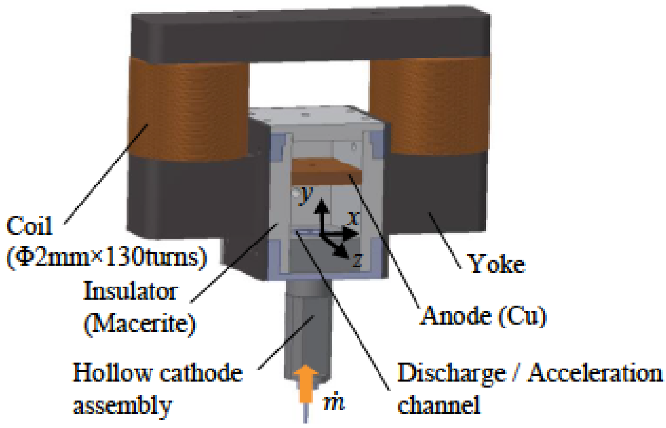

Figure 1 - Parallel-plate steady-state AF-MPD (1 kW – class) of Nagoya University [7]

The High-density Tohoku Plasma (HiToP) facility at Tohoku University is used to study on AF-MPD thruster. With an applied magnetic flux density of up to 0.42 T, and a pulsed operation of about 2 ms duration, performance and operation characteristics are currently under investigation. For an input power of about 800 kW (during the pulsed operation), a thrust of about 6 N at a specific impulse of 2500 s was measured [8]. Different configurations of the magnetic coil, as well as different propellants are studied, and performance and plasma parameters investigated.

Two research groups at JAXA study about MPD thruster. A pulsed applied-field parallel-plate MPD thruster working on Argon is operated at 140 kW pulsed power for an applied-field of 0.33 T. Less than a 1 N of thrust is currently created [9].

Numerical studies on MPD thruster are conducted at JAXA with the aim of elucidating the thrust-creating processes, and designing the eventual high-power thruster based on a numerical approach. Within this work, thrusters in the several 100 kW to 1 MW-class are investigated. Figure 2 shows exemplary results for the electron density in a 4 kA discharge.

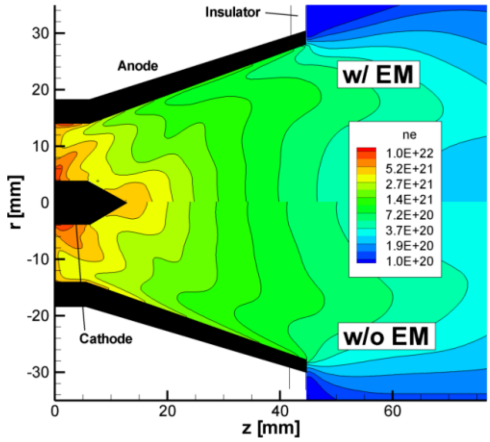

Figure 2 - Numerical computation result for MPD thrusters by JAXA [10]

4.2 Arcjet Thruster Concepts

Two research groups are proposing arcjets as possible candidate for future application.

A 15 kW water-cooled arcjet is currently objecting of study at JAXA, together with Muroran Institute of Technology, working on hydrogen or nitrogen. Thermal analysis and performance extrapolation for high-power arcjets are conducted to enable design proposals [11]. Figure 3 shows the current status of the arcjet.

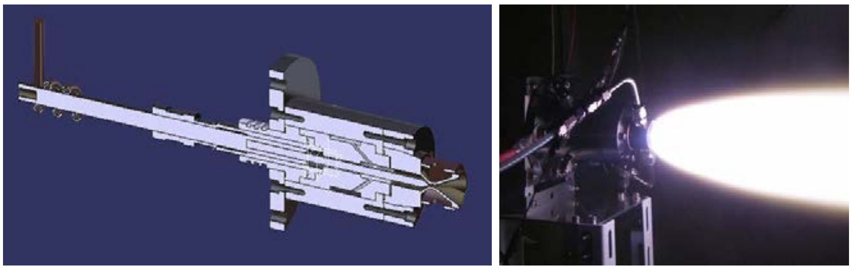

Figure 3 – 15-kW water-cooled arcjet at JAXA [12]

A second arcjet is under development at Osaka Institute of Technology with a current power level of 5-10 kW working on nitrogen, argon, CO_2, HAN (NH_3OHNO_3) or hydrogen. Recent performance tests reported about 220 mN and 300 s at a power of 5.9 kW for N_2/HAN [13].

4.3 Hall Thruster Concept

Hall thrusters are generally seen as the most promising candidate for high-power application, due to their profound flight heritage, their high performance and their good scalability. Thus, many a thruster was studied and developed for high-power application worldwide [14]. Therefore, the University of Tokyo, together with the Kyushu University and Gifu University, decided on a proposal for a high-power Hall thruster. With long research experience in both experimental and numerical studies on both stationary plasma thruster (SPT) and thruster with anode layer (TAL), a profound performance database and physical understanding exists. Figure 4 shows a thruster model and an in-operation image of current TAL research.

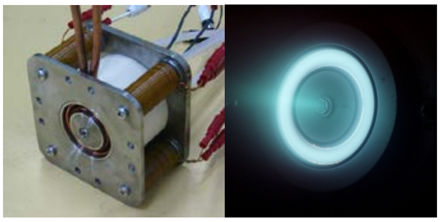

Figure 4 - Thruster model of TAL at University of Tokyo

From the past experience, it was concluded that TAL might be better suited for the application due to their smaller size compared with SPT, and the expected lower cost [15]. Based on the data for the D-80 TAL by TsNIIMash, and scaling of the thruster for higher power, the performance characteristics for the 5 kW, and 100 kW design step respectively, can be estimated, and are summarized in Table 3.

Table 3

Estimated Performance Characteristics

Value	Single	Single	Cluster (x4)
Power, kW	6.3	23	92
Mass flow (Xenon), mg/s	25	75	200
Thrust, N	0.36	1.4	5.6
Specific impulse, s	1500	1900	
Thrust efficiency, %	55		

On-going analyses of the magnetic field configuration and the thermal design will be supported by thorough numerical simulation of performance, and lifetime respectively. Figure 5 shows exemplary numerical results of ongoing analyses of erosion.

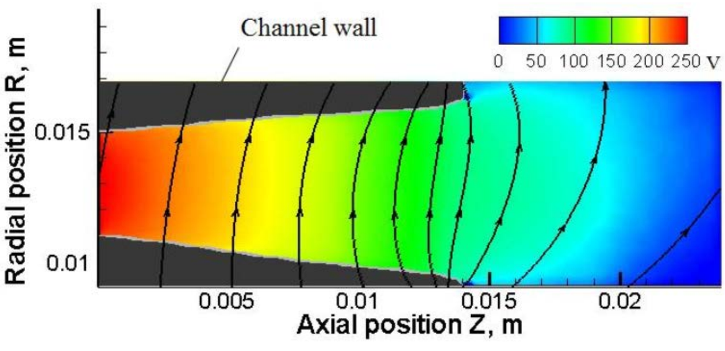

Figure 5 - Numerical results for electric potential distribution, and channel wall shape at EOL (dark grey area) for a 300 W SPT [16]

Due to the scarcity and high cost of Xenon, and the expected high demand for the given mission scenarios (see Table 1), alternative propellants are considered, and currently studied. Using a fair share of other noble gases in the propulsive task could decrease the cost of the overall system, but as the performance changes accordingly a profound analysis is necessary.

As mentioned in Table 3, the 100 kW propulsion system is proposed to be a cluster of several smaller devices in order to allow for easier ground testing, enable fail-safe operation, enable maneuvering thrust control, and wider performance range. However, it will be necessary to show experimentally and numerically that the clustering does not negatively affect the performance. Another crucial part of the system is the neutralizer cathode. For a high-power application, existing hollow cathodes need to be improved to handle higher currents, or different concepts like RF-based cathodes might be looked upon. Lifetime will be a strong requirement.

Last but not least, the mission analysis is a design factor, as optimization of the thruster towards higher specific impulse or higher thrust depends on the requirements imparted from the targeted mission trajectory. Analyses are therefore ongoing.

5. Conclusions

The High-Power In-Space Propulsion program is the next step of scientific application of electric propulsion «Made in Japan». A leap in technology level for EP is expected to be related to the program, but also valuable scientific results are targeted to emerge from the missions, and the development process itself. Many different concepts are studied, but only one will have to chance to follow this itinerary towards high-power EP application.

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