The Ion Engine System for Hayabusa2

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Abstract: Hayabusa2 will be the second asteroid sample return mission by JAXA. The ion engine system (IES) for Hayabusa2 is based on that developed for Hayabusa with modifications necessary to improve durability, to slightly increase thrust, and to reflect on lessons learned from Hayabusa mission. Hayabusa2 will rendezvous with a near-earth asteroid 1999 JU3 and will take samples from its surfaces. More scientific instruments than Hayabusa including an impactor to make a crater and landers will be on board thanks to the thrust enhancement of the IES.

I. Introduction

ASTEROID explorer Hayabusa came back to the earth on June 13, 2010. Hayabusa completed more than 7-year space mission, and finally Hayabusa could return the capsule to the earth, although Hayabusa had a lot of troubles and difficulties. After careful inspections of about 1,500 grains found in the sample container, it turned out that we actually obtained rocky particles from the surface of Asteroid Itokawa. Japan Aerospace Exploration Agency (JAXA) has been studying post-Hayabusa missions for some years with many researchers of universities and laboratories until Hayabusa mission success. There are two post-Hayabusa missions, which are called Hayabusa2 and Hayabusa-Mk2. They are both sample return mission from small solar system bodies. Hayabusa2 is a similar type spacecraft as Hayabusa, but Hayabya-Mk2 is much larger than Hayabusa, because target object locates much father than Itokawa. The first proposal of Hayabusa2 mission was done in 2006. In the year before this, 2005, Hayabusa tried to get the surface material from Asteroid Itokawa, but we could not do this as planned by shooting projectiles. Therefore, we proposed another retry mission to get the surface material surely. The target asteroid is 1999 JU3, which is C-type asteroid. We chose a C-type asteroid, because Asteroid Itokawa is S-type. We thought that we would have much more new results if we explore a different kind of asteroid. In this first proposal of Hayabusa2, the spacecraft was almost same as that of Hayabusa, because we wanted to start it as soon as possible. The launch windows were in 2010 and 2011. However, since the decision was delayed, we missed these launch opportunities. After confirmation of Hayabusa's achievement, we finally and officially started Hayabusa2 project in May of 2011. The next launch window of Hayabusa2 for Asteroid 1999 JU3 will be open in 2014 and 20151. Hayabusa2 spacecraft will be similar to Hayabusa. However, we are planning to have new equipment, which we call “impactor.” It is under discussion now, and the current idea is a small box that contains explosive. After releasing from the spacecraft about a few hundred meters above the surface of the asteroid, the impactor will explode and the lid of it will be accelerated at the speed of 2 km/s or so. We assume the mass of the lid is about 2 kg, so we think a crater about a few meter in diameter will be created on the surface. Then we will try to get the sample inside the crater or to get the ejecta around it. Hayabusa had only one small lander, but Hayabusa2 may have more landers including domestic ones and foreign one. Hayabusa experienced two of three reaction wheels failures. Hayabusa2 will have four wheels for better redundancy. These changes will make the Hayabusa2 spacecraft heavier by about

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10% than Hayabusa. Current development target of the spacecraft wet mass is 570kg. The orbit of Asteroid 1999 JU3 (Figure 1) is similar to that of Itokawa and delta-V requirement of Hayabusa2 will be almost the same level as Hayabusa's 2.2 km/s. This paper briefly summarizes preliminary design of the ion engine system (IES) for Hayabusa2.

![Figure 1. The orbit of 1999 JU3.](image)

II. Ion Engine System Overview

This section summarizes the architecture, functions, mission requirements and development plan of the Hayabusa2's ion engine system.

A. Hayabusa's Heritage and Post-Hayabusa Development Activities

The ion engine system for Hayabusa2 will be developed based on that for Hayabusa. Hayabusa spacecraft had four μ10 ion thrusters on a single plate called “IES plate” which was mounted on top of a two-axis pointing gimbal mechanism as shown in Figure 2. An ion thruster consists of an ion source and a neutralizer both of which utilize microwave discharge with electron cyclotron resonance at a frequency of 4.25 GHz. The maximum thrust generated by a single thruster was 8 mN by consuming a small flow rate (of order 0.3 mg/s) of xenon gas and an electric power of 350 W for plasma generation and ion beam acceleration. A microwave generator was able to drive the ion source and the neutralizer by way of a coupler box (CPBX) which divided microwaves in the ratio of four to one for the ion source and the neutralizer, respectively. Although the number of microwave power amplifiers was the same as the number of thrusters, there were only three IES power processing units (IPPs) which contain three direct current power supplies for high-voltage beam acceleration and neutralizer current control. Three of four thrusters could be operated at the same time by selecting the dedicated IPPUs using three relay switching boxes (RLBX). Propellant xenon was supplied by a propellant management unit (PMU) which had a small accumulator downstream of a main tank by way of regulation valves for bang-bang pressurization. There were four ion thruster valves and eight flow restrictors for ion sources and neutralizers downstream of the accumulator. The xenon flow could only be shut off thruster by thruster and can not be shut off individually for an ion source and a neutralizer. This limitation was similar to that of the microwave supply units because microwave power could not be stopped for either an ion source or a neutralizer, separately. A round-trip asteroid exploration was finally accomplished by these small microwave discharge ion engines. Total accumulated operational time reached 39637 hours for all four ion engines added up consuming 47 kg of xenon propellant. Total duration of powered spaceflight is 25590 hours which provided a delta-V of 2.2 km/s and a total impulse of 1 MN·s, approximately².
The Hayabusa ion engine system is almost identical to the one to be used on Hayabusa2.

During the Hayabusa return trip since 2007, a joint activity of JAXA and NEC to generalize the IES for commercial satellites was started. In this program, many modifications were studied and implemented to a qualification model to make the IES more compatible and attractive to commercial geostationary small satellites of 1 – 1.5 tons class. Input voltage range of IPPU was expanded so that it can also be used on standard regulated bus voltages from 35 to 100 V, as well as on original unregulated 100 V. Ion thruster design was slightly changed and maximum thrust was increased by 20%. The new IPPU is compatible with this higher beam current mode operation. New low-loss DC blocks were developed by ourselves instead of using foreign products. IES thruster control unit (ITCU) was enhanced so that it can control five thrusters at the same time (for possible thrust enhancement option for Hayabusa2), can accommodate two microwave oscillators for redundancy, can monitor subsystem temperatures independently from temperature control subsystem and can control two propellant management units as used in geostationary satellites. This joint development was supported by funding from both JAXA and NEC. NEC started collaboration with Aerojet to expand its low power microwave ion engine business in the U. S. market. These activities helped maintain our capabilities to deliver microwave ion engines again for Hayabusa2, 10 years after Hayabusa mission.

B. IES Mission Requirements and Development Plan

IES specifications and mission requirements are summarized in Table 1. Ion sources will be slightly modified in that their propellant injectors will be added in different places in the discharge chamber and ion optics thicknesses and aperture diameters will be changed so that the maximally available thrust increases by approximately 20% although specific impulse degrades by 10%\(^3\). The total impulse required by this new mission will be 1.2 MN·s which is also 20% larger than Hayabusa's requirement. Estimated total operational hours of all thrusters are 41100 hours which is almost the same as Hayabusa achievement of 39637 hours. The increase of total impulse is due to the increase of spacecraft mass because required delta-V is almost the same as that of Hayabusa. This will be achieved by the thrust enhancement with almost the same thruster operational hours. The xenon load will be nearly the same amount of 60 kg as Hayabusa's 65 kg because both mission needs extra propellant for extended missions after return to the earth. The more instruments on Hayabusa2 requires “diet” of extra xenon. Neutralizers will be improved for longer life according to lessons leaned in the Hayabusa mission and ground experiments\(^4\). Subsystem architecture of Hayabusa2 ion engines is almost identical to Hayabusa's although many components such as valves, pressure sensors, microwave components, and so on will be discontinued in production and be replaced by new alternatives.

<table>
<thead>
<tr>
<th></th>
<th>Hayabusa</th>
<th>Hayabusa2</th>
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<tbody>
<tr>
<td>Thrust per Thruster (mN)</td>
<td>4.4 – 7.6</td>
<td>5.9 – 8.8</td>
</tr>
<tr>
<td>Specific Impulse (s)</td>
<td>2760 – 3000</td>
<td>2400 – 2750</td>
</tr>
<tr>
<td>System Power (W)</td>
<td>280 – 1150</td>
<td>320 – 1200</td>
</tr>
<tr>
<td>Total Operational Hours</td>
<td>39637 (achieved)</td>
<td>41000</td>
</tr>
<tr>
<td>Total Impulse (MN·s)</td>
<td>1.0 (achieved)</td>
<td>1.2</td>
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III. Subsystem Descriptions

This section summarizes the architecture, functions and design change of the Hayabusa2's ion engine system. Hierarchical structure and acronyms of ion engine system for Hayabusa2 and interface block diagram are shown in Figures 3 and 4, which are both identical to those of Hayabusa.

Figure 3. Hierarchical structure and acronyms of ion engine system for Hayabusa2.
A. Ion Thruster Head (ITH)

The original well-tuned μ10 ion thruster can generate 8 mN at a specific impulse (including neutralizer flow) of 3000 s with consuming 32 W of microwaves and 2.35 sccm of xenon flow. Recent work indicated that design change of gas injector layout had the large impact on thrust enhancement\(^3\). The highest thrust of 10 mN is generated when the xenon flow is divided at the ratio of 1:2 between the original injector deep in the waveguide and newly added injectors between magnets, respectively, when the total flow rate is 3.5 sccm. Mass utilization efficiencies are decreased from the original but can be improved by using a small hole accelerator grid whose aperture diameter was decreased from 1.8 to 1.5 mm. Decrease of screen grid thickness from the original value of 0.95 mm to 0.8 mm also helped the mass utilization recovery. The combination of above mentioned modifications (gas distributors, small hole accelerator grid and thinner screen grid) achieved the maximum thrust enhancement shown in Table 1 with acceptable decrease in specific impulse. This thrust enhancement will be required for Hayabusa2 mission because of the increase of spacecraft mass.
B. Neutralizer (NEUT)

Lifetimes of Hayabusa neutralizers were ranges between 9579 and 14830 hours which are both much shorter than the ground test's achievement of 20000 hours by a prototype model (voluntarily stopped). Number of on/off cycles does not seem to be dominant because the longest life was achieved by the one most frequently switched on and off. Most remarkable difference between in-space and on-ground would be the temperature range. Hayabusa ion engines experienced extremely low temperatures several times by accidents and it might have somehow shorten the life time of neutralizers. We have analyzed the stored prototype neutralizer by disassembling it and found many magnetized metal flakes stuck on magnetic yokes where local magnetic surface flux densities are large. These metal flakes may be immersed into the discharge plasma, may become a new source of surface contamination of the dielectric part of microwave launcher by ion sputtering and sputtered metal deposition, and may increase plasma loss. All the flight and ground test data have a common feature that there is a synchronized increase of neutralizer coupling voltage and neutralizer backward power. This may be caused by above mentioned metal coating of dielectric surfaces of a microwave launcher. A start point of the synchronized increases would correspond to an occurrence of delamination and sticking of a piece of flake. Improvement of the neutralizer reliability is the most important current work of our microwave discharge ion engines, and we are considering to cover magnetic yokes with thin molybdenum protectors to reduce the metal flake delamination and sticking*.

Another improvement is planned about neutralizer bracket's electrical insulation. Leakage currents were observed through an electric short circuit at the neutralizer's insulator surfaces contaminated by deposition of sputtered metallic materials generated during crossed operation of the neutralizer A and the ion source B in the final approach to Earth by Hayabusa in which the spacecraft was highly negatively charged relative to the ion engine plume plasma. We will improve shadow shielding of the dielectric insulator between a neutralizer body and its brackets.

C. IES Power Processing Unit (IPPU)

The IPPU converts the 60 – 120 V input power from spacecraft solar arrays (unregulated power bus) into the currents and voltages needed by thruster operation. The IPPU is almost the same as the Hayabusa IPPU with the following exceptions:

1. One of three Hayabusa IPPUs showed unstable oscillatory current limiting behavior at high temperatures in the first year in space. This has already been fixed in the qualification model development for the "generalized" IES.
2. Higher beam current operation up to 180 mA will be possible and verified.
3. Options for constant current operation target of neutralizer current will be changed. Original IPPUs had three options: ×1 of the corresponding screen current (nominal operation), ×1.5 (two neutralizers for three ion sources on one neutralizer failure) and ×2 (one neutralizer for two ion sources on one neutralizer failure). We will have different three options for Hayabusa2: NOMINAL (screen current + 3 mA), HIGH (screen current + 10 mA) and OFF (the neutralizer will be fixed to the spacecraft potential without negative bias voltage).

D. Propellant Management Unit (PMU)

The PMU feeds xenon gas to ion sources and neutralizers. Flow rates for higher thrust operation are a little larger than in the nominal thrust operation of Hayabusa IES. However, no design change is required about this. Only the design change will be replacement of discontinued solenoid valves for regulation valves (RV) and thruster valves (ITHV) to different space-qualified models which were also used in DS1 and Dawn. The low pressure transducer (LPRE) of Hayabusa showed noisy output when the IPPUs were switched on, which degraded flow rate (or thrust level) control accuracy. This electromagnetic interference will be coped with.

E. Microwave Supply Unit (MSU)

The MSU is for ECR plasma generation and includes traveling wave tube amplifiers (TWTA) and passive microwave components such as flexible cables, semi-rigid cables, coupler boxes (CPBX) for microwave distribution between an ion source and a neutralizer, and DC blocks. Only CPBX will have no design change for Hayabusa2. TWTA will be replaced by successors of Hayabusa models of the same manufacturer. Some part of semi-rigid cables will be changed to more heat resistant ceramic cables. The vendor of flexible cables will be switched and unified for entire spacecraft including IES and communication subsystem in accordance with JAXA's space electronic parts selection standard. Figure 5 shows pictures of new low-loss DC blocks jointly developed by JAXA and NEC. The new one has an insertion loss of 0.2 dB which is 0.3 dB smaller than the Hayabusa's made in USA.
This slightly improve electrical efficiency of the thruster and reduce heat dissipation. The oscillator will be replaced by the one to be developed by NEC due to non availability of the original parts.

Figure 5. Newly developed low-loss DC blocks for neutralizers (Left with SMA connector) and ion sources (Right with TNC connector).

F. IES Thruster Control Unit (ITCU)

The ITCU is the controller of the IES. Details of its function were described in a reference\(^5\). In the generalization and commercialization program, a qualification model of enhanced ITCU was developed. However, most of the enhancement will be removed and lightweight for Hayabusa2. Only the new capability will be the generation of user packet telemetry that contains accumulated impulse (time integration of the thrust calculated from voltages and currents). This compact telemetry data will be quickly downloaded and used for radiometric orbit determination without downloading much larger spacecraft housekeeping data which also contains the same telemetry data. This improvement is based on lessons learned from seven-year Hayabusa mission.

G. IES Pointing Mechanism (IPM)

The IPM consists of two-axis gimbals and launch lock mechanisms. Any mechanical design change is planned, but electrical harnesses for non-explosive actuators and hall sensors will be improved for better stress relief and electromagnetic compatibility.

IV. Summary

Hayabusa2 mission started as a JAXA's official project. The ion engine system (IES) for Hayabusa2 is based on that developed for Hayabusa with modifications necessary to improve durability, to slightly increase thrust, and to reflect on lessons learned from Hayabusa mission. Critical design review (CDR) is scheduled in December 2011 and flight model production will start from the beginning of 2012. Launch windows for the Asteroid 1999 JU3 are open in 2014 and 2015.

References