# Hayabusa Asteroid Explorer Powered by Ion Engines on the way to Earth

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Hitoshi Kuninaka[*], Kazutaka Nishiyama[†], Yukio Shimizu[‡], Ikko Funaki[§], Hiroyuki Koizumi[**],
Satoshi Hosoda[††] and Daisuke Nakata[‡‡]
*Lunar Planetary Program Group*
*Japan Aerospace Exploration Agency*
*Yoshinodai, Sagamihara, Kanagawa 229, JAPAN*

**Abstract: The microwave discharge ion engines made Hayabusa explorer, launched in 2003, rendezvous with an asteroid in 2005. After successful touch-downs at the asteroid surface it was lost due to chemical-fuel leakage. Xenon cold gas jets from the neutralizers resumed attitude control of the spacecraft again. The ion engines were reignited in 2007 aiming at Earth return in 2010. Hayabusa passed through aphelion with the ion engine exhausting plasma jet on August 2009, when the total accumulated operational time reached 35,000 hour & unit in space.**

## I. Introduction

The cathode-less electron cyclotron resonance ion engines, μ10, propelled the Hayabusa asteroid explorer, launched in May 2003, which is focused on demonstrating the technology needed for a sample return from an asteroid, using electric propulsion, optical navigation, material sampling in a zero gravity field, and direct re-entry from a heliocentric space. It rendezvoused with the asteroid Itokawa after the deep space flight in two years with a delta-V of 1,400 m/s, 22 kg of xenon propellant consumption and 25,800 hour & unit of the total accumulated operational time of the ion engines. Though it succeeded in landing on the asteroid on November 2005, the spacecraft was seriously damaged. It delayed the Earth return in 2010 from the original plan in 2007. Reconstruction on the operational scheme using remaining functions and newly uploaded control logic made the Hayabusa leave for Earth in April 2007. It is on the way to Earth passing through an aphelion as of August 2009. The total accumulated operational time reached 35,000 hour & unit consuming 40 kg Xenon propellant. This paper reports the recent status of the Hayabusa space mission.

## II. Microwave Discharge Ion Engine

The technological features of the microwave discharge ion engines are described in detail in Ref. 1, and listed briefly as follows:

[*] Professor, JSPEC, kuninaka@isas.jaxa.jp
[†] Associate Professor, JSPEC, nishiyama@ep.isas.jaxa.jp
[‡] Research Associate, JSPEC, shimizu@isas.jaxa.jp
[§] Associate Professor, ISAS, funaki@isas.jaxa.jp
[**] Research Associate, ISAS, koizumi.hiroyuki@jaxa.jp
[††] Visiting Researcher, ISAS, hosoda@ep.isas.jaxa.jp
[‡‡] Visiting Researcher, JSPEC, nakata@ep.isas.jaxa.jp

1) Xenon ions are generated using ECR (electron cyclotron resonance) microwave discharge without solid electrodes, which in conventional ion engines are the critical parts and the cause of flaking leading to electrical grid shorts. Thus, the elimination of the solid electrodes makes the ion engine more durable and highly reliable.
2) Neutralizers are also driven using ECR microwave discharge. The removal of the hollow cathodes releases IES (ion engine system) from heater failures and performance degradation of electron emitter due to oxygen contaminating the propellant, as well as air exposure during satellite assembling.
3) A single microwave generator simultaneously feeds the ion generator and the neutralizer. This feature reduces the system mass and simplifies control logic.
4) DC power supplies for ion acceleration have been reduced to three. This feature also has the advantage of making the system lighter and requiring simpler operational logic.
5) The electrostatic grid system is fabricated from a carbon-carbon composite. The clearance between the grids is kept stable regardless of the temperature since there is no thermal expansion. This prolongs the life of the acceleration grid due to the low sputtering rate against the xenon ions. Low wettability of carbon seldom causes permanent electrical shorts between the grids.

The μ10 ion engine with 10 cm effective diameter was developed for in order to dedicate to the Hayabusa space mission. **Table 1** summarizes the specification of IES. The ground qualification schemes are described in detail in Refs. 2, 3 and 4. Four μ10 are installed on the Hayabusa spacecraft, and three of them can generate thrust simultaneously. The dry mass of IES is 59 kg including a gimbal and a propellant tank, which was filled with xenon propellant 66 kg. A single μ10 is rated at 8 mN thrust, 3,000 sec Isp, and 350 W electrical power consumption so that the Hayabusa spacecraft is accelerated 4 m/s per a day by the maximum thrust 24 mN.

Table 1 Specifications of IES on Hayabusa.

| | |
|---|---|
| Ion ThrusteRs (ITR) | Four μ10s,<br>cathode-less ECR microwave discharge plasma generation<br>carbon-carbon composite 3-grid electro-static acceleration<br>10 cm effective diameter, 8 mN nominal thrust |
| Microwave Power Amplifiers (MPA) | Traveling Wave Tubes, 4.2 GHz, four units<br>A single MPA driving both an ion generator and a neutralizer simultaneously<br>32 W for an ion generator, 8 W for a neutralizer,<br>110 W total power consumption |
| IES Power Processing Units (IPPU) | Three units distributed to four ITRs via relay switches<br>1.5 kV to screen grid, –330 V to acceleration grid<br>240 W total power consumption |
| Propellant Management System (PMU) | Titanium alloy pressure tank, 51 liters in volume,<br>73 kg maximum Xe loading<br>Two propellant flow controllers for redundancy<br>Blow down via flow restrictors |
| IES Pointing Mechanism (IPM) | Two axis gimbal, +/-5 deg |

## III. Hayabusa Asteroid Explorer

The Hayabusa space mission aims to retrieve surface material of the asteroid to Earth. Total launch mass of the spacecraft is 510 kg including chemical fuel and Xenon propellant. The artist image of Hayabusa asteroid explorer under the powered flight in deep space is seen in **Fig.1**. The solar cell paddles (SCP) can generate 2.6 kW electrical power at 1 AU from Sun. The IES is mounted on the side panel perpendicular to the z-axis, toward which an active surface of SCP faces. In cruise mode, the spacecraft orients the SCP face toward Sun in order to generate electrical power and rotates its attitude around the solar direction to steer the thrust direction of the IES. **Table 2** summarizes the main feature of Hayabusa asteroid explorer.

Fig.1 Hayabusa asteroid explorer executing the powered flight in deep space.

Table 2 Main specification of Hayabusa asteroid explorer.

| | |
|---|---|
| Launch mass: | 510 kg including 67 kg of chemical fuel and 66 kg of Xenon propellant |
| Attitude Control: | 3 axis stabilization, 3 reaction wheels |
| Communication: | X band, 8 kbps max. |
| Solar Cell Panel: | Triple-junction cells, 2.6 kW at 1 AU |
| Chemical Thruster: | 12 Bi-propellant RCS thrusters, 20 N thrust, 290 sec Isp |
| Electric Propulsion: | 4 ECR ion engines μ10, each producing thrust of 8 mN, Isp of 3,000 sec, thrust power ratio of 23 mN/kW, dry mass of 59 kg |
| Thermal Control: | CPU-controlled replacement heater, Variable liquid-crystal radiator, High-conductivity super graphite, loop heat pipe |
| Payloads: | Telescope Cameras, Near Infra-red Spectrometer, X-ray-Induced Fluorescence Spectrometer, Laser Altitude-meter, Small Landing Robot, Sampling Mechanism, Re-entry Capsule |

## IV. Outward Journey

On May 9th, 2003, the M-V rocket launched the Hayabusa spacecraft into deep space. At the end of May, four ITRs were turned on one by one. After test operations and parameter tuning, the delta-V maneuver was started in July. In the first year, the spacecraft stayed on a 1-year Earth-synchronous orbit and changed its orbital eccentricity using IES maneuvers. The purpose of this space operation was to accumulate a relative velocity compared to the Earth, which would then be converted into orbital energy at the moment of the Earth swing-by. By the end of March 2004, the IES had reached 10,000 hour & unit of operational time and had generated a delta-V of 600 m/s while consuming 10 kg of propellant. On May 19th, 2004, Hayabusa passed through the Earth at a point 4,000 km above the Pacific Ocean, and was input into the transfer orbit toward the target asteroid. On the transfer orbit to the asteroid, the IES continued to accelerate Hayabusa. Three of four ITRs, supplied enough electric power, accelerated the spacecraft with their full capability until August 2004. From September 2004, the IES was throttled down in order to adapt to a reduction of solar power due to an increase in the solar distance. The IES generated a maximal thrust of 25 mN while consuming 1.1 kW of electrical power and a minimal thrust of 4.5 mN while consuming 250 W of electrical power. On February 18th, 2005, Hayabusa reached the aphelion at a distance of 1.7 AU from Sun. On August 28th, 2005, the IES completed the outward journey and handed over the space maneuvers of the Hayabusa spacecraft to the bi-propellant thrusters at a distance 4,800 km from the target with an approach speed of 9 m/s. The total operational time was 25,800 hour & unit, while consuming 22 kg of xenon propellant and generating a delta-V of 1,400 m/s. The detail is reported in Ref. 5

## V. Rescue Operation

During the proximity operation with the asteroid the Hayabusa lost the functions of two of three reaction wheels. And just after the lift-off from the asteroid surface chemical fuel leak disabled the function of the RCS thrusters and disturbed to control the attitude of spacecraft. Then the Hayabusa was missing on December 8th, 2005. Revolution motion in the heliocentric space gradually made Sun shine on SCP so that the Hayabusa recovered electrical power. A set of commands from Earth initiated the Hayabusa again and established the beacon communication on January 23rd, 2006 fortunately. The Xenon cold gas jets from the canted neutralizers generated enough torque over several tens micro newton meter to control the attitude of spacecraft. The combination of torques from four neutralizers and the timing on the spin cycle enabled to control of the attitude of spacecraft on three axes. Successful reorientation of the spin axis toward Sun and Earth restored the microwave telemetry data with high bit rate on February 25th, 2006. On April the checkout operation revealed the wholesome of IES for the ion acceleration. From January to June in 2006 the rescue operations consumed 9 kg xenon propellant in the Xenon cold gas jets. The detail is reported in Ref. 6.

## VI. Homeward Journey

In order to execute the homeward journey the non-spin attitude control scheme, illustrated in **Fig.2**, using the RW-Z (reaction wheel on Z axis), the IES thrust vector control, the cold Xenon gas jets and the photon pressure torque was established. The only available reaction wheel RW-Z, which is set along the z-axis, takes a biased momentum of the spacecraft so as to stop a body spin. The thrust vector control of IES by the gimbal can actively generate torques around the y- and z-axes. The IES torque around the z axis is also dedicated to desaturate the RW-Z. The cold gas jets from IES under pause have a function of attitude control as well as the thrust vector control. The x-axis torque induced by swirling plasma jet from IES is balanced with the solar pressure torque.

After the test operation the Hayabusa spacecraft executed successfully the first leg of orbit maneuver from April to October 2007, which decreased the aphelion of orbit as seen in **Fig.3**. It experienced the perihelion 0.95AU as the minimum solar distance on June 9th, 2007 with IES turned on. The second leg of orbit maneuver was started from February 2009. It is planned to continue until March 2010 for a perihelion up. As of August 2009, Hayabusa is passing through the aphelion at 1.63 AU from Sun with IES on, and IES achieves the total accumulated operational time 35,000 hour & unit and total delta-V 1,900 m/s as seen in **Fig.4**. In contrast with the outward journey, in which it was adjusted on seven parameters of time, position and velocity in order to rendezvous with the asteroid, the spacecraft is controlled so as to accord with Earth on four parameters of time and position except velocity for fly-by in the homeward journey. At the moment of fly-by with Earth in June 2010 the reentry capsule will be dropped into Earth atmosphere. The Hayabusa will come back Earth in 2010 after half revolutions around Sun as seen in **Fig.5** (a) in the inertial coordinate system.

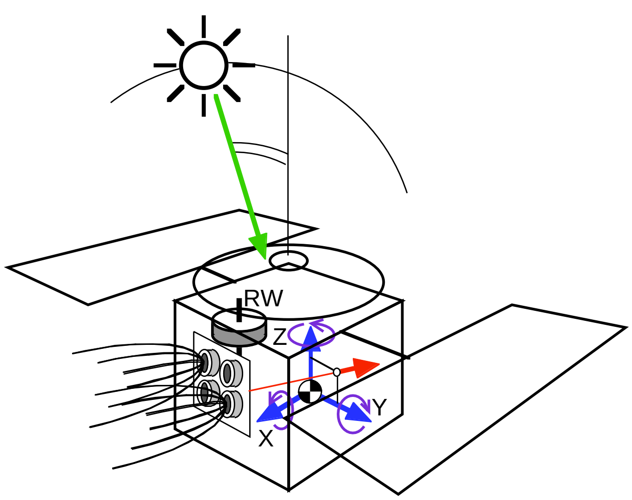



Fig.2 Attitude control by means of RW, IES thrust vector control, cold gas jets and photon pressure torque.

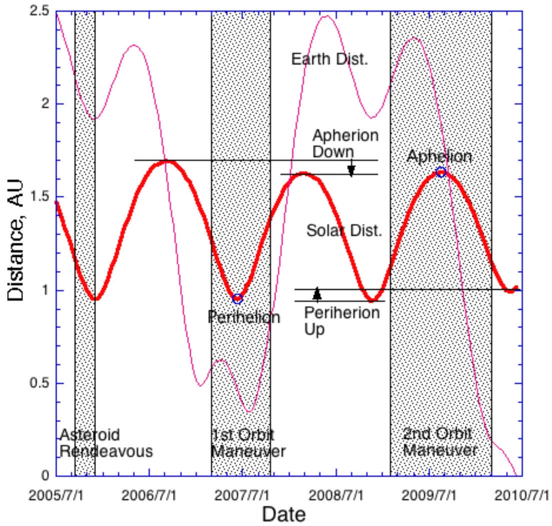



Fig.3 Past record and future plan of Sun/Earth distance from Hayabusa.

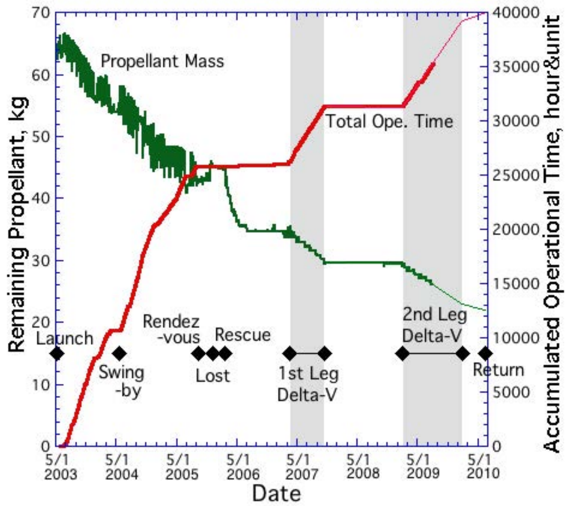
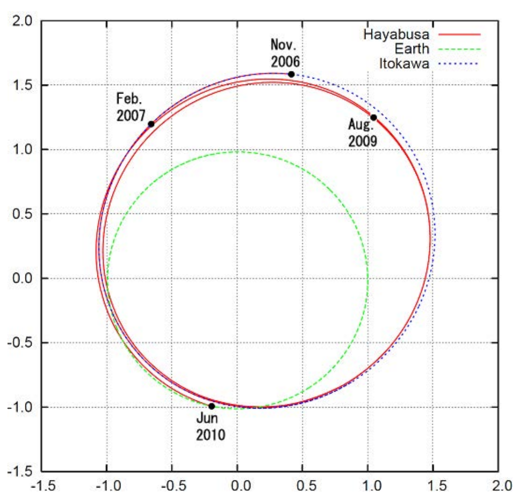
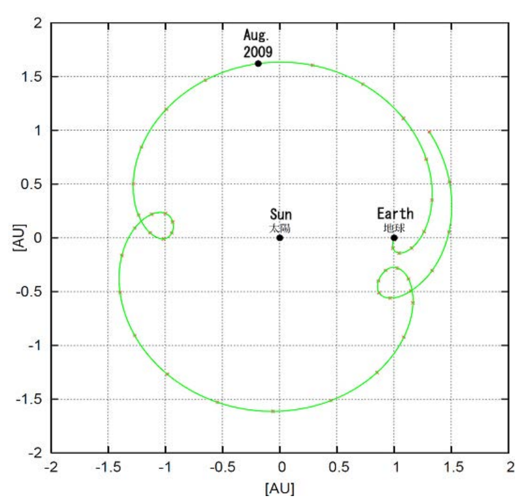



Fig.4 Flight chronology of Haybusa on operational time of IES and remaining Xenon propellant.




(a) Inertial coordinate system




(b) Rotational coordinate system

Fig.5 Orbit of Hayabusa spacecraft

## VII. Summary

Hayabusa asteroid explorer has continued powered flight in deep space using the microwave discharge ion engines since 2003. IES achieved the total accumulated operational time 35,000 hour & unit and total delta-V 1,900 m/s as of August 2009 and brought us a lot of experience and knowledge, which will contribute future space missions. Hayabusa is on the way to Earth. IES has a remaining duty 200 m/s in delta-V and 4,000 hour & unit in operation with enough propellant 25 kg for Earth return in June 2010.

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