Deep Space Maneuver by Microwave Discharge Ion Engines onboard "HAYABUSA" Asteroid Explorer

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Abstract

The microwave discharge ion engine generates plasmas of both the main ion source and the neutralizer using 4GHz microwave without discharge electrodes and hollow cathodes, so that long life and durability against oxygen and air are expected. The MUSES-C "HAYABUSA" asteroid explorer installing four microwave discharge ion engines "µ10s" was launched into deep space by M-V rocket No.5 on May 9, 2003. After vacuum exposure and several runs of baking for reduction of residual gas the ion engine system established the continuous acceleration of the spacecraft toward the asteroid "ITOKAWA". The Doppler shift measurement of the communication microwave revealed the performance of ion engines, which is 8mN thrust force for a single unit with 3,200sec specific impulse at 23mN/kW thrust power ratio. At the end of 2003 the accumulated operational time exceeded 8,000 hour and unit. HAYABUSA will execute the Earth swing-by on June 2004 and arrive at the asteroid in 2005 and return to Earth in 2007.

Introduction

At May 9th 01:29PM, 2003 the MUSES-C asteroid explorers[1] was launched into deep space by the M-V rocket No.5 from Kagoshima Space Center and named "HAYABUSA", which means falcon in Japanese. It was just a moment that the microwave discharge ion engine "µ10s" was space-borne after the 15-year research and development. The vacuum exposure during two weeks and various kinds of test runs in a month enabled "µ10s" to accelerate "HAYABUSA" asteroid explorer continuously at a several meters per second in a day from July. Though the scientific spacecraft were thought impossible to install the electric propulsions due to penalties on weight and electric power, not only the improvement of the electric propulsion but also the technological advancement of the rocket system and the needs for the deep space exploration realize the "HAYABUSA" space mission, which will execute the round trip between Earth and the asteroid "ITOKAWA". In general a round trip space mission requires too large fuel consumption of the conventional chemical thrusters to maneuver the spacecraft. The only electric propulsion makes a spacecraft approach some of the asteroids and keeps a return way to Earth. The electric propulsion with high specific impulse and even low thrust has a big advantage in the orbit maneuver at the low gravity interplanetary space. "HAYABUSA" will arrive at the asteroid in 2005 and return to Earth again in 2007 on the sequence of events illustrated in Fig.1. Table 1 summarizes the "HAYBASA" spacecraft. The "µ10s" cathode-less ECR microwave discharge ion engine system has been researched and developed by the Electric Propulsion Division of Institute of Space and Astronautical Science (ISAS)/ Japan Aerospace Exploration Agency (JAXA) based on the new idea different from others. This paper will report the R&D chorology and the flight status of "µ10s" on "HAYABUSA".

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Table 1 Summary on HAYABUSA spacecraft

Launch weight:	510kg
Chemical Fuel:	67kg
Xe propellant:	66kg
Attitude Control:	three-axis stabilize
Communication:	X band, 8kbps max.
Solar Cell Paddle:	triple-junction cells, 2.6kW at 1AU
Chemical Prop.: 12	bi-propellantthrustersx 290sec Isp
Electric Prop.:	µw ion engines µ10 x 4 3,200sec Isp
Payloads:	Telescope Cameras
	Near Infra-red Spectrometer
	X-ray Induced Fluorescence Spectrometer
	Laser Altitude-meter
	Sampling Mechanism
	Reentry Capsule
	Small Landing Robot
	3D Cameras
	Surface Thermometers

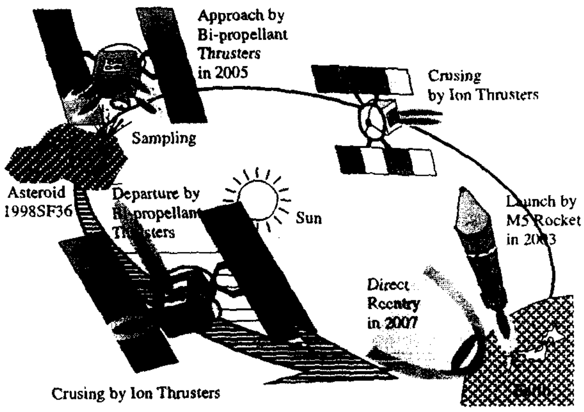

Fig.1 Sequence of events

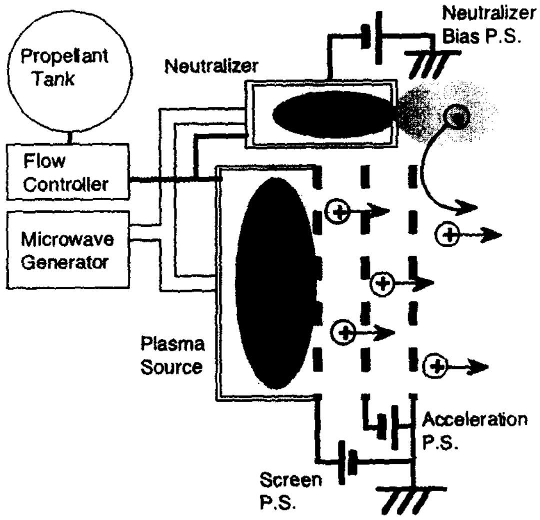

Fig.2 System concept of μ10

System Description

Figure 2 represents the system concept of μ10. The technological features are summarized as follows. The details are described in Refs. 2 and 3.

1) Plasmas are generated by ECR microwave discharge without solid electrodes, which are ones of life critical components in the conventional ion engines. Elimination of the solid electrode makes the ion source durable and high reliable.
2) Neutralizers are also driven by ECR microwave discharge. Deletion of the hollow cathodes releases the ion engine system from performance degradation by oxygen contaminating propellant and time limitation for air exposure during the satellite assembling.
3) A single microwave generator feeds simultaneously both an ion source and a neutralizer. This feature reduces the system mass and simplifies the control logic.
4) Carbon-carbon composite material is applied to the electro-static grid system. The clearance between the grids is kept stable regardless of temperature due to zero thermal expansion. And it prolongs the life of the acceleration grid because of the low sputtering rate against xenon ion.

The Ion Engine System (IES) was designed and assembled using four μ10 ion engines. The character "μ" is pronounced "mju:" and means "microwave" and the upper stage of "μ" rocket. The following number "10" indicates the effective diameter 10cm of the electro-static grid system. The IES system is summarized in Table 2 and Fig.3 and the mass characteristic is broken down in Table 3.

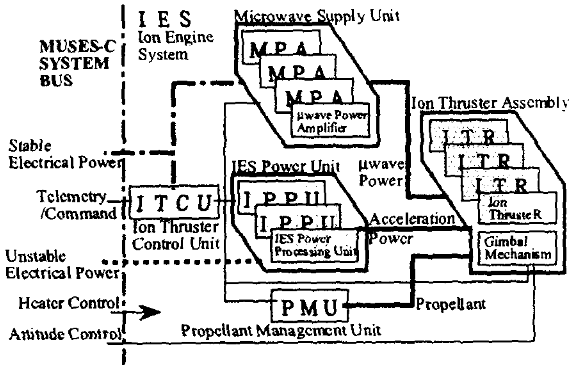

Fig.3 System diagram of IES

Table 2 Specifications of IES on HAYABUSA

Components	Description
Thrusters (ITR)	μ10s, four units Cathode-less ECR plasma generation Carbon-Carbon composite three grid 10cm effective diameter 8mN nominal thrust
Microwave Power Amplifiers (MPA)	Traveling Wave Tubes, 4.25GHz, four units A single Microwave Power Amplifier driving both an ion source and a neutralizer simultaneously 32W for an ion source 8W for a neutralizer 110W total power consumption
IES Power Processing Units (IPPU)	Three units distributed to four thrusters via relay switches 1.5kV to screen grid -330V to acceleration grid 240W total power consumption
Propellant Management System (PMU)	Titanium alloy pressure tank 51 liters in volume 73kg maximum Xe loading Two propellant flow controllers for redundancy Brow-dawn via flow restrictors
IES Pointing Mechanism (IPM)	2 axis gimbal, +/-5deg

Table 3 Mass breakdown of IES on HAYABUSA

Components	Mass, kg	Description
Ion Thruster Assembly	9.2	Four ITRs, 2.3kg/ITR
Mic.wave Supply Unit	9.2	Four MPAs, 2.3kg/MPA
IES Power Unit	6.3	Three IPPUs, 2.1kg/IPPU
Propellant Tank	10.8	Maximum Xe loading 73kg
Prop. Flow Controller	6.5	
IES Pointing Mech.	3.0	
Mechanical Interface	5.0	
Ion Thruster Cont.Unit	3.5	
Electrical Interface	5.7	
Total Mass, kg	59.2	

Each Ion ThrusteR (ITR) is connected to its own Microwave Power Amplifier (MPA), which emits 4.25GHz microwave to generate high density plasma by means of electron cyclotron resonance (ECR). High voltage power generated by three IES Power Processing Units (IPPU) is distributed to four ITRs through relay switches so that simultaneous operation is limited three ITRs. The IES Pointing Mechanism (IPM) mounting four ITRs aligns a combined thrust vector into the center of gravity of the spacecraft. The propellant is supplied to ITRs through flow restrictors by means of brow-down from a sub tank, which is charged gas from the spherical titanium alloy main tank. The Ion Thruster Control Unit (ITCU) manages the IES. Figure 4 shows the configuration of HAYABUSA deploying a pair of the solar cell paddle (SCP). The high gain antenna (HGA) is mounted on upper surface of the body. SCP and HGA have no rotational and tilt mechanisms. IES is mounted perpendicular to the z-axis, with which HGA aperture is aligned. At the high bit rate communication the spacecraft orientates HGA to Earth without IES firing. In case of the cruising the spacecraft makes SCP face the sun in order to generate electrical power and rotate its attitude around the Sun direction to steer the thrust direction of IES. The completed spacecraft before the launch is snapshot in Fig.5.

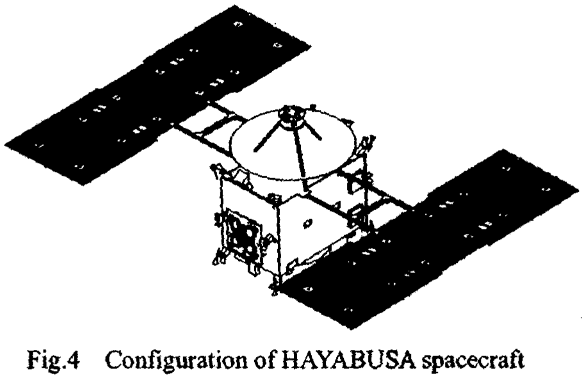

Fig.4 Configuration of HAYABUSA spacecraft

Fig.5 HAYABUSA spacecraft in the clean room

Development

The real time endurance test is a unique way to verify durability of the electric propulsion up to now. In the development scheme on μ10 two runs of the endurance tests were performed. The first test was initiated on August 1997 and ended on July 1999 achieving 18,000 hours accumulated operational time. The second starting from April 2000 was terminated on January 2003 marking 20,000 hours operational time. The vacuum chamber of 2m diameter and 5m long is evacuated by four cryogenic pumps in 800mm diameter below 2E-4 Pa gas pressure during the thruster operation. The internal surface is covered with a titanium shroud panel and a beam damper refrigerated below -40degC. The operation and data acquisition of the thruster and the vacuum facility are fully automated by an UNIX workstation. The chronology of the second endurance test is shown in Fig.6. Figure 7 shows the thruster firings in the endurance test chamber.

The spacecraft was assembled in the clean room of ISAS and was devoted to the thermal vacuum test and the beam extraction test at the end of January 2003. The thermal design of the spacecraft system was verified in the thermal vacuum test, where three of the ion engines were ignited simultaneously without the beam extraction to dissipate heat load over 45 hours. After that the test configuration was changed to the beam extraction test, which purpose is to confirm the workman ship to assemble IES. The spacecraft itself and the internal surface of the thermal vacuum chamber were taken care to protect sputtering and contamination originated from the plasma beam. The beam extraction was demonstrated one thruster by one. Four thrusters successfully exhausted the plasma beam at their full voltage 1.5kV in 2 hours total. In the both tests the ITRs were supplied propellant from PMU in the same manner as the flight configuration. In March the spacecraft was transported to the launch site Kagoshima Space Center. The xenon propellant 66kg was charged into the onboard main tank by means of the liquefaction method newly developed[4]. References 5, 6 and 7 explain the R&D effort on μ10.

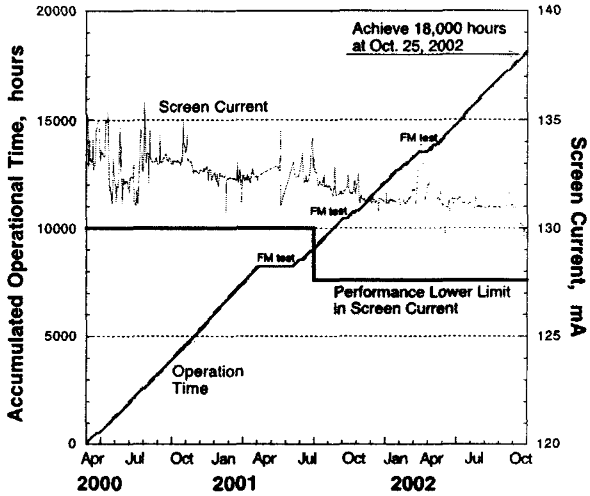

Fig.6 PM endurance test

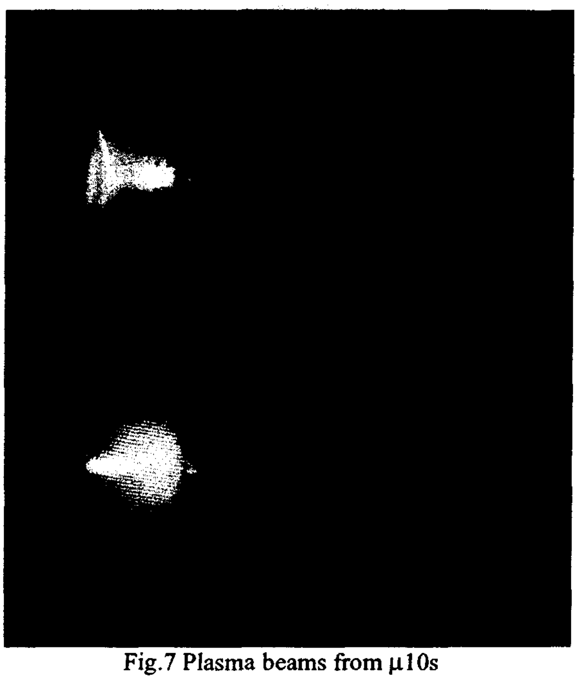

Fig.7 Plasma beams from μ10s

Space Operation

The M-V rocket No.5 input MUSES-C spacecraft into the planned orbit in the deep space on May 9th. The telemetry data from Goldstone tracking center showed to deploy SCP. In the evening of the same day Kagoshima space center caught the signal from HAYABUSA, which is the new name of MUSES-C. The precise orbit determination revealed to need a trim maneuver about 30m/s, which is not little for the chemical propulsion. But the maneuver was cancelled because IES has an enough capability to recover it in the cruising. In the first visible opportunity the launch lock mechanism of IPM was released successfully. IES was exposed to vacuum under keeping around 0degC. At the end of May IES was turned on one by one, in which each ITR ignited plasmas and accelerated it around one hour. The first step was cleared up. In the next step two ITR parallel operation was executed, but lots of large discharges around ITRs were caused by outgas due to temperature rise. Then IES was devoted to baking around 50degC during two days by replacement heaters and solar radiation. It enabled to operate several ITRs simultaneously. The onboard software and operational parameters were tuned for standalone firing of IES without supervision from Earth. The 24 hour operations of single ITR and then of double ITRs were achieved step by step. But triple ITR operations were interrupted by large discharges several times so that the baking including IES and the +X panel was tried again. And then the continuous acceleration by three ITRs was achieved and planned ΔV maneuver by IES was executed from July. Figure 8 shows the time profile of the leak current to the acceleration grid of a specific ITR, which tends to increase under low vacuum condition. The time in the horizontal axis means the accumulated operational

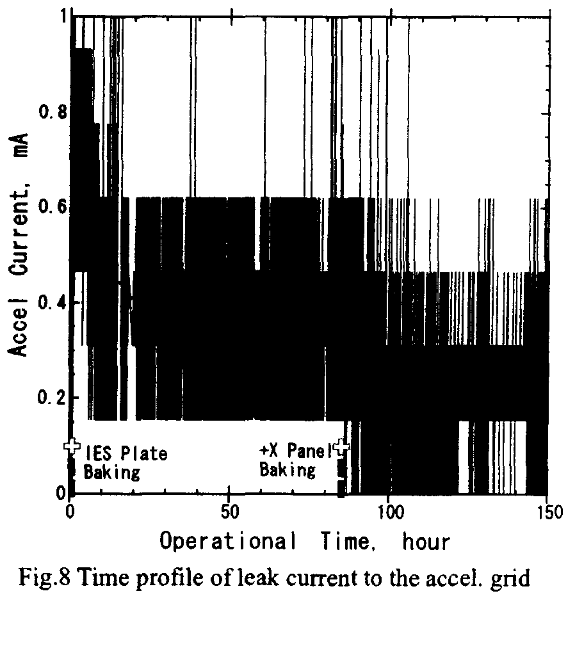

Fig.8 Time profile of leak current to the accel. grid

time of the ITR. The profile is scattered because of current resolution 0.15mA, so that numerically smoothed curve is also indicated in Fig.8. The baking was executed at the elapsed time 0.8 hour and 85 hour. Just after two occasions of the baking the accel current decreased dramatically. In the ground test at 1.5E-4 Pa surrounding the accel current was 0.46mA, which is almost the same to the flight. The quantitative comparison between the ground and the flight is out of accuracy because the telemetry data on the accel current is tuned for large value on extraordinary.

Figure 9 represents the chronology of the total accumulated operational time, which is defined time duration under nominal operation multiplied by number of ITRs. At the end of December 2003 the operational time exceeded 8,000 hour&unit. The spacecraft was accelerated about 500m/s consuming about 8kg propellant. The μ10s and IES on HAYABUSA achieved the space flight heritage of the top in Japan and of the world standard. The north and south station keeping of the geo-stationary equatorial satellites, which is the most popular application of electric propulsions, needs about 50m/s ΔV per year. Table 4 summarizes the experiences of worldwide ion engines reported by 2003. Thought it is difficult to compare with each other because purpose, usage, operational duty, system configuration, thrust level and etc are different, the 1,000 hour operation per a single thruster based on the accumulated operational time and numbers of launched thrusters including standby redundancy is the world standard as the space heritage.

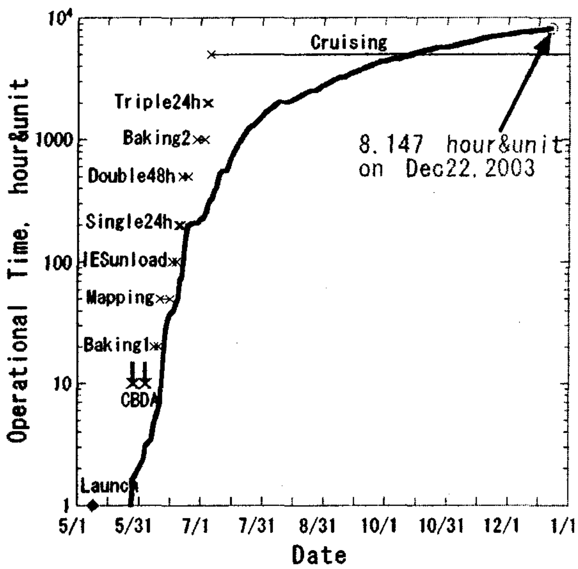

Fig.9 Chronology of the total accumulated operational time of IES

Table 4 Space flight heritage of the ion engines in the world reported by 2003.

Organization	Name	Method	Flight	Ope.	Ref.
NASA(US)	NSTAR	R.Cusp	1	16,265 h	8
Boeing(US)	XIPS13	R.Cusp	52	55,000 h	8
	XIPS25	R.Cusp	24	13,500 h	8
Astrium	UK10	Kauf.	2	703 h	10
(Euro)	RIT10	RF	3	7,812 h	9,10
Melco(Jp)	IES	Kauf.	8	162 h	11
ISAS(Jp)	μ10	μw	4	8,147 h	

The ΔV maneuver by IES in 8,000 hour&unit has concreted to encounter with Earth on June 2004. The orbit of HAYABUSA in the rotational coordinate system is seen in Fig.10, where Earth is fixed at the original point and Sun on the negative horizontal axis. Figure 10 shows the relative location of HAYABUSA against Earth. Though just after the launch the extrapolated orbit never reaches Earth, it changes gradually in accompany with the IES maneuver. HAYABUSA will arrive at Earth on June 2004 and bend the relative velocity vector toward the asteroid ITOKAWA by means of the Earth swing-by.

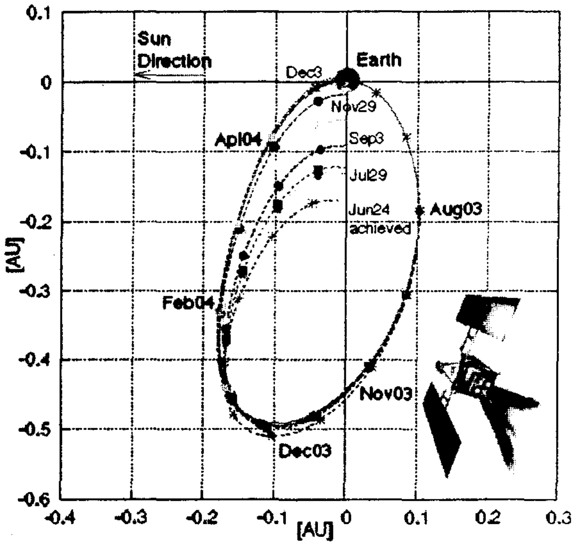

Fig.10 Orbit of HAYABUSA in rotational coordinate system

Performance Evaluation

Typical telemetry data profiles at the turn-on sequence are shown in Fig.11. Three ITRs are turned on one by one in accordance with the timeline commands so as to prevent simultaneous peek powers. At the first of all the neutralizers are biased around –100V. When an ITR is fed propellant and microwave, plasmas in both the ion source and the neutralizer are ignited soon. Once the plasmas exist the bias voltage of the neutralizer drops around zero due to low impedance. And then high voltage 1.5kV is applied to the ITR and the ion beam is exhausted. Three ITRs show almost the same screen currents and individual values on the neutralizer bias voltages.

individual values on the neutralizer bias voltages. The ripple of the propellant supply rate caused by the pressure ripple of the sub-tank affects on the other telemetry data.

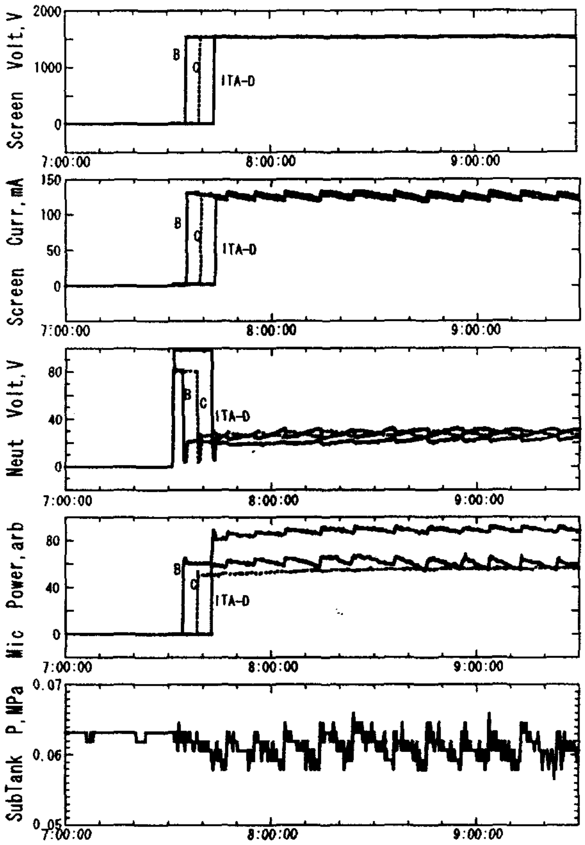

Fig.11 Turn-on sequence

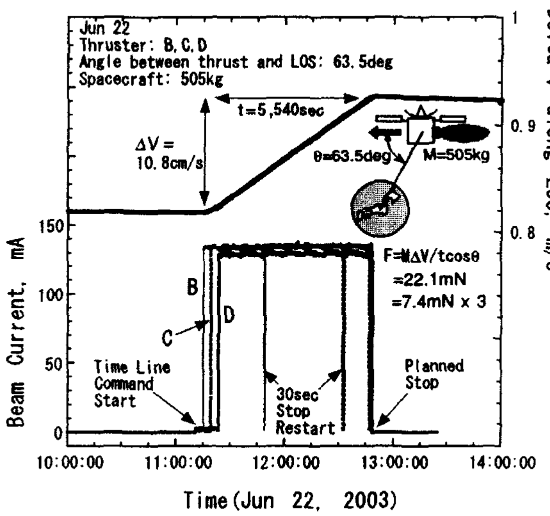

Fig.12 Velocity change of spacecraft by IES firing

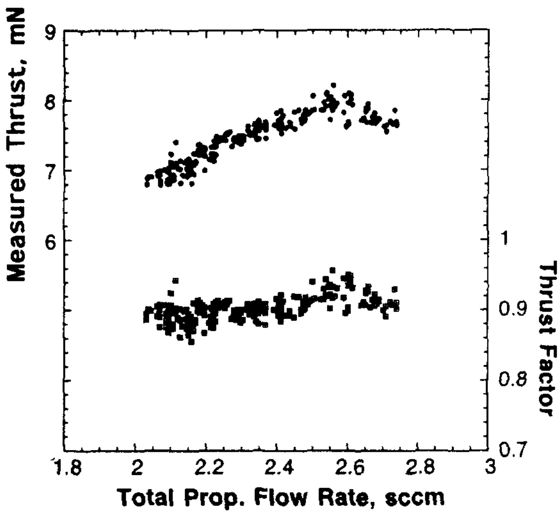

Fig.13 Thrust and thrust factor

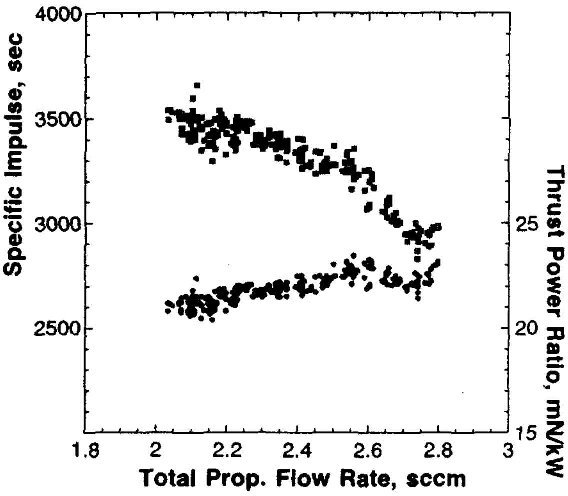

Fig.14 Specific impulse and thrust power ratio

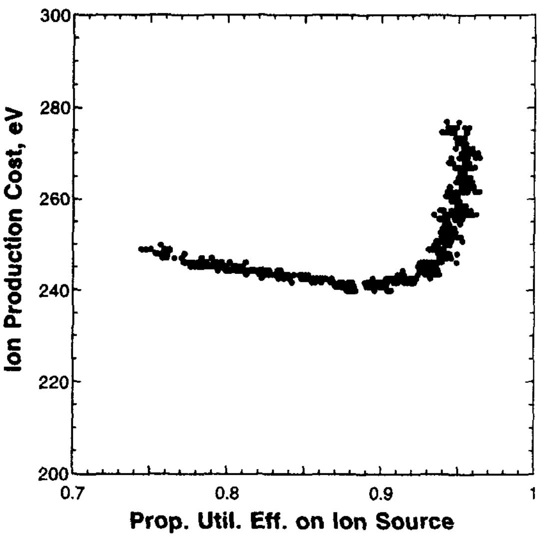

Fig.15 Ion production cost and propellant utilization efficiency

The velocity change of the spacecraft by the IES firing was detected in the method of the range rate measurement, which is the Doppler shift of the communication frequency. The measured velocity change is shown in Fig.12 with the screen currents of three ITRs, which were turned on and off in accordance with the timeline commands. The interruptions were happened twice but automatically restarted. The generated thrust force is calculated using the measured ΔV, the angle between thrust vector and line of sight, the time duration and the spacecraft mass. Based on the measured thrust force in space the performance of μ10s can be evaluated. The precise thrust measurement needs extremely large efforts on the ground because of low thrust. The thrust, thrust factor, specific impulse and thrust power ratio via the propellant supply rate are shown in Figs.13 and 14, the ion production cost depending on the propellant utilization efficiency in Fig.15. The propellant supply rate means summation of gas feed to both an ion source and a neutralizer. The propellant utilization efficiency is calculated based on the propellant flow to only an ion source. The single ITR generates 8mN maximum thrust, where the thrust factor is 93%, the specific impulse 3,200sec, the thrust power ratio 23mN/kW, the ion production cost 240eV and propellant utilization efficiency 87%. They are very consistent with the ground data. The thrust factor is defined a ratio of the exact thrust against the ideal one calculated from the screen current and the screen voltage. The specific impulse is a value of the thrust divided by the total propellant flow to both an ion source and a neutralizer. The thrust power ratio is evaluated by the thrust divided by the total input power to an IPPU and an MPA. The ion production cost means a ratio of the microwave power to an ion source against the extracted ion current. The propellant utilization efficiency is defined the screen current against the propellant supply rate to an ion source.

Summary

The asteroid explorer HAYABUSA was launched into deep space by M-V rocket No.5 on May 9, 2003 from Kagoshima Space Center. It will execute a round trip space mission between Earth and the asteroid ITOKAWA propelled by four microwave discharge ion engines μ10s, of which the space flight was realized based on the R&D during 15 years. The initial operation brought us a lot of space experience and flight data, which are never got on the ground. The μ10 in space is evaluated the thrust 8mN, the thrust factor 93%, the specific impulse 3,200sec, the thrust power ratio 23mN/kW, the ion production cost 240eV and the propellant utilization efficiency 87%. At the end of 2003 the accumulated operational time reached 8,147 hour&unit, which is enough for the space flight heritage. It is very interesting that the ion engines particular at US, Europe and Asia have achievements in space. Variety of the ion engines system in the world proves the healthy engineering challenge. Independent R&D effort not to imitate well-developed systems realizes the μ10s. They are commented that a lot of works were devoted to the MUSES-C space mission in order to adapt the new system μ10s to the existing space technology and the flight bus system as well as the ground support system performs appropriately to continue the acceleration of IES on HAYABUSA. The technology of μ10s is the "foothold in deep space" and will support concretely the future space missions.

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