Lineup of Microwave Discharge Ion Engines “μ” series

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Abstract

Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency (ISAS/JAXA) successfully developed and operated the microwave discharge ion engines onboard Hayabusa asteroid explorer. The μ10 ion engines feature the cathode-less plasma generation in both the ion generators and neutralizers with the results of long life and high reliability in space. Based on the space achievements of μ10 ion engines with 8mN thrust, 3,000sec Isp and 350W consumption power, several programs are currently under developments: μ20, μ10HIsp and μ1. The first is a 20-cm diameter microwave discharge ion engine, aiming to achieve 30mN/kW in the thrust-to-power ratio for the asteroid sample return mission larger than Hayabusa. The second is a high Isp version of μ10, and exhausts the plasma beam over 10,000sec Isp using 15kV acceleration voltage for deep space missions to such as Jupiter and Mercury. The third is μ1 to be adapted to small satellites for drag-free.

Microwave Discharge Ion Engines

The cathode-less microwave discharge ion engines have the technological features as follows:

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 from heater failures and hollow cathode emitter performance degradation 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 electrical shorts between the grids.

The mechanism to produce the primary electrons (PE) is illustrated in Fig.1. A mirror magnetic field is generated in the magnetic track and confines the electrons, which are accelerated whenever they pass through the ECR regions and produce plasma by collision ionization. Figure 2 shows the electron energy distribution. PE generates plasma and is dumped in the thermal electrons, whose energy is insufficient for ionization. The DC discharge ion generator, which is the most popular, accelerates electrons emitted from a cathode to generate PE by a DC electric field. On the other hand, the microwave discharge ion generator recycles the thermal electrons to PE for efficient plasma generation. The discharge

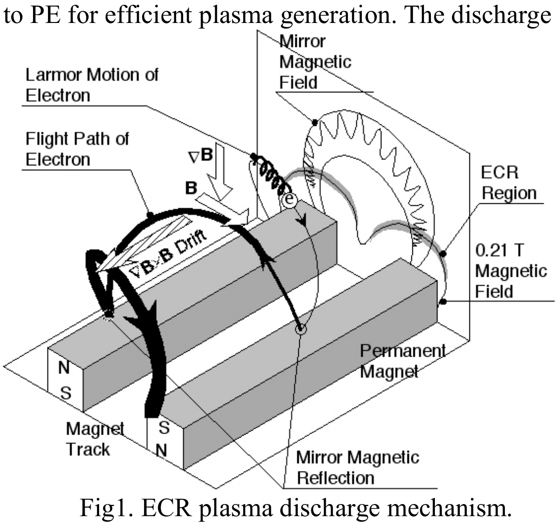

Fig1. ECR plasma discharge mechanism.

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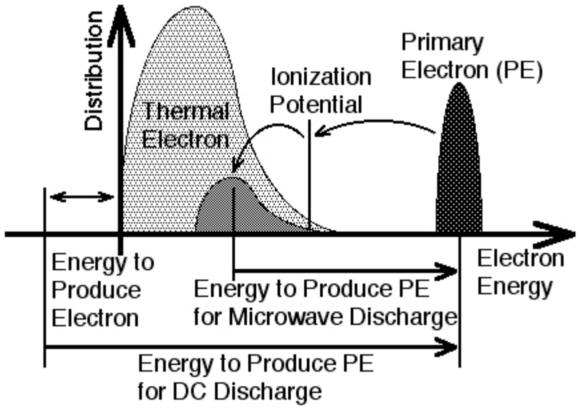

Fig.2 Electron energy distribution.

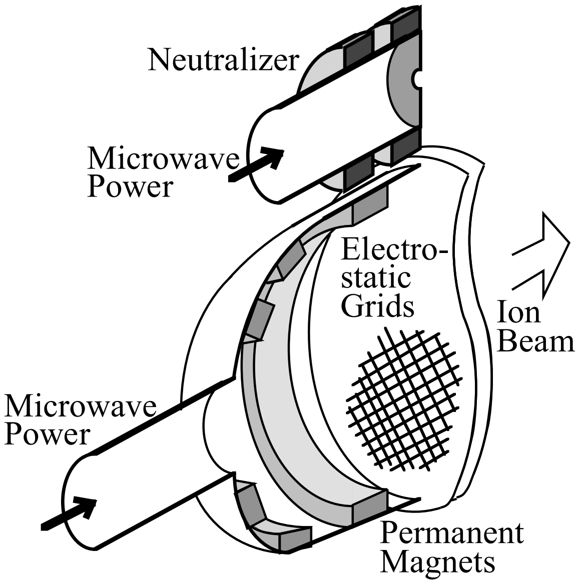

Fig.3 Configuration of microwave discharge ion engine.

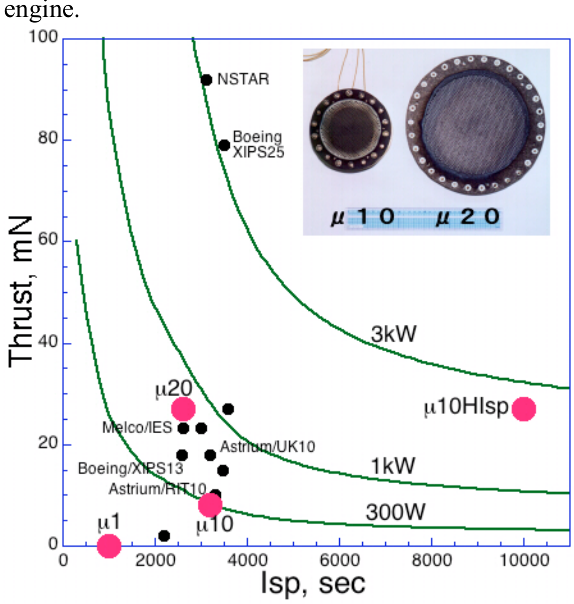

Fig.4 Lineup of microwave discharge ion engines.

chamber and the neutralizer of the ion engine employ samarium-cobalt permanent magnets. Input microwave power is fed through a waveguide or a coaxial cable as shown in Fig.3.

Table 1 Performance of "μ" series ion engines.

Items	μ10	μ20	μ10HIsp
Ion Prod. Cost	230eV	200eV	230eV
Beam Current	140mA	500mA	140mA
μw Power	32W	100W	32W
Screen Voltage	1,500V	1,200V	15,000V
Specific Imp.	3,000sec	2,800sec	10,000sec
Thrust	8mN	27mN	27mN
System Power	350W	900W	2,500W
Thrust/Power	23mN/kW	30mN/kW	11mN/kW

The four types of ion engines: μ10, μ20, μ10HIsp and μ1 are researched and developed in the laboratory and applied in space. Figure 4 and Table 1 show the distribution of them in the performance.

μ10 onboard Hayabusa Asteroid Explorer

The μ10 ion engine with 10cm effective diameter was developed for in order to dedicate to the Hayabusa space mission. The ground qualification schemes are described in detail in Refs. 1, 2, 3, and 4. Four μ10 are installed on the Hayabusa spacecraft 510kg BOL mass, and three of them can generate thrust simultaneously. The dry mass of IES is 59kg including a gimbal and a propellant tank, which was filled with xenon propellant 66kg. A single μ10 is rated at 8mN thrust, 3,000sec Isp, and 350W electrical power consumption so that the Hayabusa spacecraft is accelerated 4m/s per a day by the maximum thrust 24mN.

The Hayabusa asteroid explorer was launched in May 2003. Since July IES have been continuously accelerating the Hayabusa, which reached a distance of 0.86AU from Sun in February 2004 and 1.7AU from Sun in February 2005. These distances are the farthest that an electric propulsion system has yet attained in the solar system. Depending on the solar distance IES was operated between 250W and 1.1kW in electrical power. The Hayabusa succeeded in rendezvousing with the asteroid Itokawa in September 2005 after a 2-year flight, producing a delta-V of

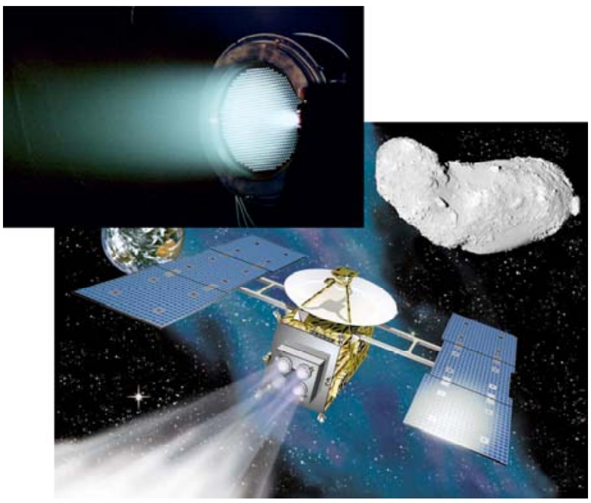

Fig.5 μ10 ion engine and Hayabusa asteroid explorer.

1,400m/s, while consuming 22kg of xenon propellant and operating for 25,800 hours. Reference 5 reports the details of the space operation on IES. The Hayabusa executed the scientific observation[6] staying around the asteroid in September and October 2005. And in November it succeeded twice touchdowns on the asteroid. Though the spacecraft was seriously damaged after the successful proximity operation, the xenon cold gas jets from the ion engines rescued the Hayabusa. The new attitude stabilization method using a single reaction wheel, the ion beam jets, and the solar pressure was established and enabled the homeward journey aiming the Earth return on 2010. At the end of October 2007 the ion engines µ10 have produced the total delta-V 1,700m/s with the total accumulated operational time 31,400 hours.

µ20 with 30mN/kW Thrust Power Ratio

In order to advance the technology of the cathode-less microwave discharge ion engine "µ" family we are developing µ20 ion engine, which is a 20cm diameter microwave discharge ion engine. The sample return mission from multiple asteroids needs µ20 with 30mN/kW in the thrust power ratio. The µ10 system generates a 140mA ion beam with 32W microwave power so that the ion production cost is 230eV, which is average in 10cm-class ion generator. However, the conversion efficiency of the microwave generator is not good so that the total efficiency and the thrust power ratio are inferior to those of the electron bombardment type ion thrusters. The µ20 system aims to generate ions at less than 200eV ion production cost. And optimized design on the microwave network will achieve the target thrust power ratio.

In order to fill the µ20 ion generator with dense plasma the configurations of the magnetic track were investigated. The µ10 ion generator has a pair of magnetic rings. Because the µ20 is larger than the µ10, the single magnetic track can not produce uniform and dense plasma in the µ20 ion generator. The try and error experimental approach succeeded to realize 500mA ion beam with 100W microwave power, that is 200eV ion production cost, using four magnetic rings generating three magnetic tracks with two magnetic bridges, which promote plasma uniformity due to ExB or grad B drift of the high energy electrons.

The 20cm diameter grid assembly was machined using the high stiffness carbon-carbon composite material, which was evaluated on the physical properties. Optimizing the magnetic strength and the nozzle configuration made the microwave discharge neutralizer emit 500mA electron current with consumptions of 1sccm xenon flow and 15W microwave power. The contact voltage is enough low for long life over 10,000 hours.[7]

The integrated test using the ion generator, the grids and the neutralizer has started in 2007.[8]

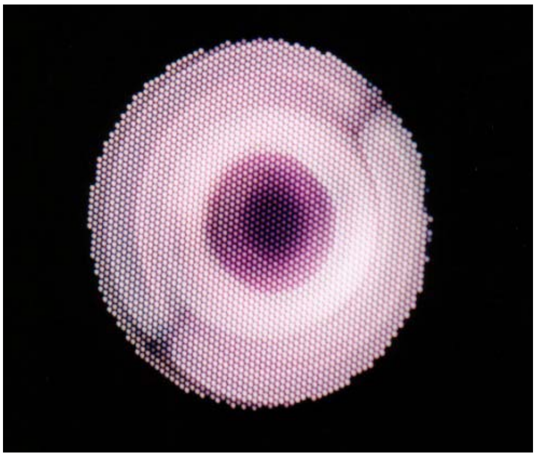

Fig.6 µ20 ion generator

µ10HIsp with 10,000sec Isp

The deep space powered flights to such as Jupiter and Mercury require the ion engines with high specific impulse 10,000sec, which results in the screen voltage over 10kV, so that the power penalty of the ion production becomes very minor. The issue on durability should be focused on rather than low ion production cost in field of EP with high specific impulse. The highly biased ion generator of the electron bombardment ion thruster is fed power, command and telemetry through isolation transformers and/or optical equipments, which are nervous and weighty components. The µ technology eliminates these isolations because the ion generator includes no active electronics devices highly biased in electricity. Whereas, the DC block as a microwave component, which transmits microwave damming up DC voltage, and the gas isolator are very important. We developed the DC block and the gas isolator with 30kV electrical isolation capability in order to dedicate to the µ10HIsp ion engine, which uses the ion generator and neutralizer same to µ10. The electro-static grid system was designed by a computer-aided technology and machined from carbon-carbon composite material. The integrated system successfully demonstrated 10,000sec Isp and 22mN thrust at 2kW system power consumption with 15kV screen voltage as seen in Fig.7. R&D effort is devoted to thrust enhancement to 27mN

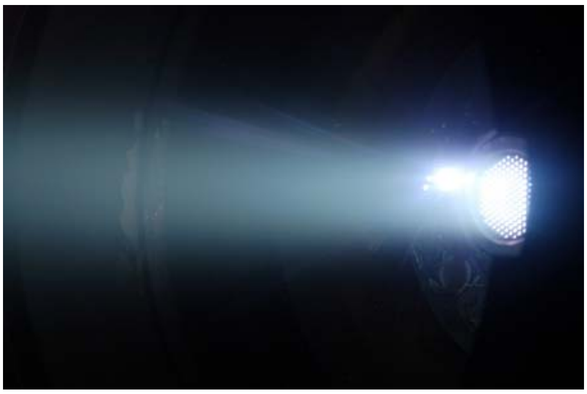

Fig.7 Beam exhaust from µ10HIsp

μ1 Ion Engine

For example drag free satellites need low thrust, precise thrust control, analogous thrust throttling, quick response, continuous acceleration and high Isp. In order to adapt to small satellites and spacecraft μ1 ion engine ranging 0.1mN thrust is under research and development.

Summary

Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency (ISAS/JAXA) successfully developed and operated the microwave discharge ion engines onboard Hayabusa asteroid explorer. The μ10 ion engines feature the cathode-less plasma generation in both the ion generators and neutralizers with the results of long life and high reliability in space. In fact they have logged 31,400 hours of total operational time in space. Based on the space achievements of μ10 ion engines, with 8mN thrust, 3,000sec Isp and 350W consumption power, several programs are currently under developments: μ20, μ10HIsp and μ1. The first is a 20-cm diameter microwave discharge ion engine, aiming to achieve 30mN/kW in the thrust-to-power ratio and 500mA ion beam current with ion production cost of 200eV. It will contribute the asteroid sample return mission larger than Hayabusa. The second is a high Isp version of μ10, and exhausts the plasma beam over 10,000sec Isp using 15kV acceleration voltage. A high voltage power supply system, high voltage gas isolator, high voltage DC block for microwave transmission and etc. are under developments and qualification for space application such as Jupiter and Mercury missions. The third is μ1 to be adapted to drag-free satellites.

References

[1] Kuninaka, H. and Satori, S., "Development and Demonstration of a Cathode-less Electron Cyclotron Resonance Ion Thruster", Journal of Propulsion and Power, Vol.14, No.6, November/December 1998, pp.1022-1026.

[2] Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., and Satori, S., "Development of Microwave Discharge Ion Engine System for Asteroid Sample and Return Mission MUSES-C", Journal of Space Technology and Science, Vol.13, No.1, 1999, pp.26-34.

[3] Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., Nishiyama, K., and Horiuchi, Y., "Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster", Journal of Propulsion and Power, Vol.18, No.1 January/February 2002, pp.169-175.

[4] Kuninaka, H., Nishiyama, K., Funaki, I., Shimizu, Y., Yamada, T., and Kawaguchi, J., "Assessment of Plasma Interactions and Flight Status of HAYABUSA Asteroid Explorer Propelled by Microwave Discharge Ion Engines", IEEE Transaction of Plasma Science, Vol.34, No.5, October 2006, pp.2125-2132.

[5] Kuninaka, H., Nishiyama, K., Funaki, I., Yamada, T., Shimizu, Y., and Kawaguchi, J., "Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer", Journal of Propulsion and Power, Vol.23, No.3, May-June 2007.

[6] Fujiwara, A., Kawaguchi, J., Yeomans, D.K., Abe, M., Mukai, T., Okada, T., Saito, J., Yano, H., Yoshikawa, M., Scheeres, D.J., Barnouin-Jha, O., Cheng, A.F., Demura, H., Gaskell, R.W., Hirata, H., Ikeda, H., Kominato, T., Miyamoto, H., Nakamura, A.M., Nakamura, R., Sasaki, S., and Uesugi, K., "The Rubble-pile Asteroid Itokawa as Observed by Hayabusa," Science, Vol.312, No.5778, June 2006, pp.1330-1334.

[7] Kuninaka, H. and Nishiyama, K., "Development of 20cm Diameter Microwave Discharge Ion Engine "μ20"", AIAA 2003-5011, 2003 JPC at Huntsville.

[8] Nishiyama, K., Kuninaka, H. and Nakai, T., "Two-dimensional Characterization of Microwave E-fields and Beam Profiles of the ECR Ion Thruster μ20", IEPC-2007-25, 30th International Electric Propulsion Conference, Florence, September 2007.