

# Development History and Current Status of DC-Type Ion Engines at JAXA

IEPC-2007-262

*Presented at the 30<sup>th</sup> International Electric Propulsion Conference, Florence, Italy  
September 17-20, 2007*

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**Abstract:** Development history and current status of DC-type ion engines at JAXA were described. The history contains the work conducted by the former organizations that were unified into JAXA at its foundation in October 2003. The first stage started with 2-mN mercury ion engine development and finished with the flight experiments from 1982 through 1985. The second stage was the development of operational 20-mN-class ion engines for north-south station keeping of geostationary satellites, which started in 1987. However, we had to wait for a long period before achieving north-south station keeping operations in space because of the failures of orbit insertion or launch of the satellites. Finally, the third geostationary satellite that carried ion engines for north-south station keeping was successfully launched and inserted into the geostationary orbit in December, 2006. The first north-south station keeping using ion engines in Japan was conducted in March, 2007. The third stage is on its way, where research and development of ion engines with much higher thrust levels are being conducted. Satisfactorily high thruster performance has been already achieved with 150-mN-thrusters, and current efforts are mainly directed to improving thruster endurance.

## I. Introduction

IN Japan, research and development of various types of electric propulsion systems have been conducted so far by universities, industries, and government institutes and agencies. They have covered the activities from basic research to flight experiments, or even operational use in the case of ion engines.<sup>1</sup>

The situation of electric propulsion development in Japan has been rather complicated. Pulsed plasma thrusters were flight-tested in the rather early phase of electric propulsion development on the Engineering Test Satellite-4 (ETS-4) in 1981, and an extensive flight test of an MPD thruster was conducted on the Space Flyer Unit (SFU) in 1995.<sup>2,3</sup> After these flight tests, however, these types of thrusters still remain in the research phase in Japan. In spite of active research and development of DC arcjet systems in Japan, imported DC arcjet thrusters were adopted in the Data Relay Test Satellite (DRTS), which was launched in 2002.<sup>4</sup>

The history of ion engine systems is rather straightforward, and step by step evolution has been realized though operational use on geostationary satellites was not necessarily smooth because of problems other than ion engines themselves. For DC-type ion engines, research and development were intensively carried out at the former National Aerospace Laboratory (NAL) and the former National Space Development Agency of Japan (NASDA) in cooperation with industries. They were succeeded by the Japan Aerospace Exploration Agency (JAXA), which was founded by consolidating these two organizations and the Institute of Space and Aeronautical Science (ISAS). In this paper,

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the history and current status of DC-Type ion engines are reviewed, and their prospects are discussed. Though microwave ion engines developed at ISAS and succeeded by JAXA have lead the successful flight of HAYABUSA, only DC-Type ion engines are dealt with in this paper.

## II. Ion Engine Flight Experiments

### A. Research and Development of Mercury Ion Engine

In Japan, research and development of ion engines were started at NAL and the Electrotechnical Laboratory (ETL) separately around 1970, when NASA was conducting ion engine space operation tests as the SERT-II project. Both laboratories were being conducted basic research on 5-cm ion thrusters with 2-mN thrust, and with the good results attained, they proposed a space flight test of ion engines on the Engineering Test Satellite-3 (ETS-3), the planning of which had been just started at that time. Their proposal was adopted in the conceptual design of ETS-3, and the project was authorized. The share in the two laboratories was determined. NAL and ETL were charged with ion thruster and power conditioner research, respectively. Ion engine development was completely inexperienced at that time, and was thought to be different in lots of points from conventional devices on satellites. Thus, it was determined to work with a preliminary engineering model (Pre-EM) before developing the engineering model.

The specifications of the Pre-EM thruster were almost the same as those of the engineering model thruster. It was an electron-bombardment mercury thruster of 5-cm anode diameter. Figure 1 shows a cross-sectional view of the Pre-EM thruster. Using the Pre-EM thrusters, a series of tests and measurements were conducted such as performance evaluation, vibration, thermal-vacuum, electromagnetic compatibility tests, and thrust and ion beam divergence measurements.<sup>5</sup>

### B. Development of ETS-3 Ion Engine Subsystem

The development of the ETS-3 ion engine subsystem (IES) was conducted by NASDA. It was started in 1978 with the production and tests of engineering model, and followed by those of prototype model and flight model. With the examinations given after the acceptance test, the development of the ion engine system was completed.<sup>6</sup>

The IES consisted of two ion thrusters, two power processing units, and a power control unit. The two thrusters were of an identical mercury electron-bombardment type of 5-cm anode diameter. In the nominal operating conditions, the thruster was capable of producing a 30-mA beam of mercury ions at a voltage of 1 kV and giving a thrust of 2 mN at a specific impulse of 2,200 s by consuming 68 W of electric power. The propellant tank contained 600-g mercury.

### C. ETS-3 Ion Engine Flight Operations

ETS-3 was launched by an N-1 rocket in September 1982, and inserted into a near-circular orbit of about 1,000-km altitude and 45-degree inclination. The IES was operated in space during the main mission period of one year

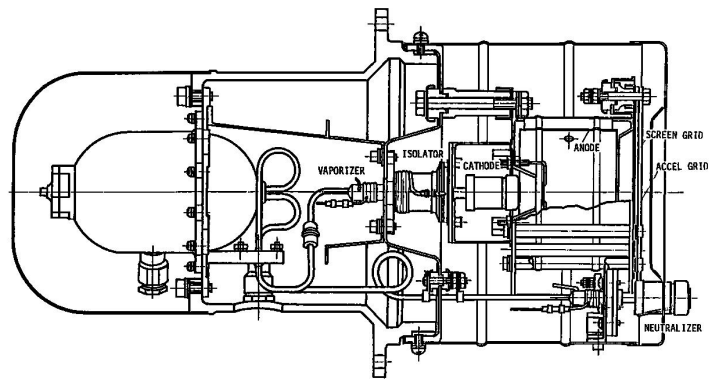


Figure 1. Cross-sectional view of the 2-mN Pre-EM thruster.

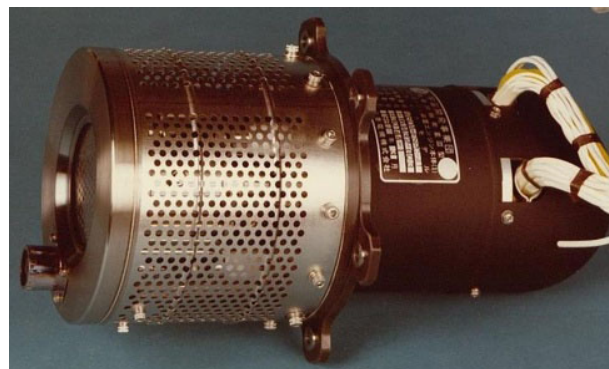


Figure 2. Photograph of the ETS-3 ion thruster.

from the launch and the extended mission period of 18 months after that.

Operation of IES was successful. In the main mission period, a 100 on/off cyclic test and a continuous beam test for over 100 h were performed. The functions of IES were verified as normal. The objectives of the flight test were to demonstrate the ion engine technology in space, to acquire the performance data, to verify the interface compatibilities with other subsystems, and to measure the thrust through the attitude control subsystem data. With these objectives, the flight data were analyzed and evaluated in terms of thruster performance, thermal design, thrust generation, and electromagnetic compatibility. The results revealed the same thruster performance in space as during the acceptance test on the ground, more stable ignition characteristics in space, thermal characteristics as expected, thrust generation equal to the calculated value, and no electromagnetic compatibility problems due to the IES operations. In the extended mission period, more thruster operations were added, and during the whole periods, thrusters 1 and 2 accumulated 53 h and 220 h of beam operation and 45 and 175 cycle restarts, respectively. These flight operations increased the available flight data on ion thrusters, the paucity of which had been considered as one of the barriers to the operational use of ion thrusters.<sup>7,8</sup>

### III. Ion Engines for North-South Station Keeping of Geostationary Satellites

#### A. Progress toward Operational Ion engines for North-South Station-Keeping of Geostationary Satellites

The N-1 rocket that launched ETS-3 was the last one, and new rockets called N-2 were being used as the Japanese launcher in the period while the ETS-3 ion engine operations were being conducted. As the next step, Japan was developing H-1 rockets, and the development was in its final phase at that time. Until H-1 rockets, however, Japan relied upon foreign technology, more or less, in the development of launch vehicles with liquid engines.

In 1984, a new project was started in Japan to develop a new launch vehicle named H-2 which would adopt domestic technologies. By developing H-2 rocket, which has launching capability of 10 tons to LEO and 4 tons to GTO, Japan intended to catch up the world-standard level of the technology. Along with the development plan of H-2 rocket, a development plan of a 2-ton-class geostationary satellite was being studied. The satellite was expected to be used as the satellite bus which would meet the demands for large, long-life geostationary satellites in 1990s, and to realize it, a conceptual study of the Engineering Test Satellite-6 (ETS-6) was started. In this study, it was required that its payload-loading capability should be as high as that of the world-standard levels. However, this requirement was very difficult to meet because of a very large technological gap from the preceding technology of ETS-5, which was the largest geostationary satellite manufactured in Japan before then, and had an initial mass of 550 kg at the geostationary orbit.

In the ETS-6 concept study, payload-loading capability of over 500 kg was targeted, and in its each subsystem design, efforts were made to have it lightened to meet the target. Meanwhile, with the success of the ETS-3 ion engine development and flight operations, we proposed to apply ion engines in place of chemical thrusters to north-south station keeping (NSSK) of ETS-6, with the emphasis of mass savings.<sup>9</sup> In the course of the ETS-6 study, it was recognized that Japan's satellite technology was not so high that it would be difficult to reach this target without ion engines. The adoption of ion engines for ETS-6 NSSK was decided in this way.

#### B. ETS-6 Ion Engine<sup>10,11</sup>

We had a lot of issues which had to be overcome to develop an operational ion engine system on the basis of the ETS-3 ion engine technology and development experiences. Table 1 summarizes the main design parameters of the ETS-6 ion engine system. The beam diameter was increased from 5 to 12 cm to produce the required thrust of 20-mN class. The propellant was changed from mercury to xenon so that the ion engine system would be more compatible with the satellite system, and could be treated much safer in various aspects of the development. The most important task was to increase the thruster life to over 6,000 h, which came from the requirement to conduct NSSK of the 2-ton satellite for ten years. The ETS-6 ion engine system had four thrusters, four power processing units, and two propellant management units. Two thrusters were mounted on each of the east and west sides of the satellite with their thrust directions canted at 30 degrees from the north-south direction. NSSK was to be conducted by operating two thruster simultaneously, one on the east side and the other on the west side. Figure 3 shows a photograph of the ETS-6 ion thruster.

The development of ETS-6 was started in 1987 with the fabrication and testing of the engineering model, and its design was confirmed at the critical design review held in 1990. The fabrication and testing of the proto-flight model, started after that, were completed in 1993. Along with the satellite system development, the IES development was conducted.

ETS-6 was launched in August 1994, but it could not be inserted into the geostationary orbit because of a malfunction in the apogee engine. The satellite was placed in an elliptic orbit but all the systems except for the apogee engine were perfect. Thus, experimental operation tests were planned for the ion engine system. The operation time of the thrusters was much shorter than that in the original plan because of power shortages, but it was confirmed in these operation tests that the ion engine system had the required characteristics in specific impulse, thruster efficiency, and so on.

The original plan for measuring the thrust on orbit was based on the change in orbit parameters due to IES operations as long as 10 h. In fact, however, the thrust evaluation was conducted by measuring the change in rotation speed of the reaction wheel because it was difficult to conduct continuous IES operations for such a long time. The thrust efficiency obtained from the on-orbit measurements was in the range from 95% to 98%, and it agreed well with the value obtained from the ion beam divergence measurements on the ground tests.

In short, the IES flight operations produced the data nearly identical with those in the ground test. Confirmations were made on the endurance against launch environments, thermal design, and operation characteristics in space. The operations were too short to confirm the life of the thruster, or even to obtain the data on that.

### C. COMETS Ion Engine<sup>12</sup>

In 1990, the development of COMETS (the Communications and Broadcasting Engineering Test Satellite) was started in Japan. The satellite was a 2-ton-class geostationary satellite, and aimed at the development and space demonstration of new technologies in communications and broadcasting fields such as inter-orbit communications, advances mobile satellite communications, and upgrading large geostationary satellites.

The ion engine system of the same design as that of ETS-6 was decided to be used also for NSSK of COMETS. This decision indicated that ion propulsion was an indispensable technology for long-life and large-scale geostationary satellites. Due to the differences in the satellite configurations and mission periods, the cant angle of the thruster was changed, and the propellant mass was reduced to 16 kg.



Figure 3. Photograph of the ETS-6 ion thruster.

Table 1. Main design parameters of the ETS-6 ion engine system.

Thruster type	Kaufman-type
NSSK operation	Two thrusters operate simultaneously
Thrust per thruster	23.3 mN
Resultant thrust of two thrusters	40.3 mN
Specific impulse per thruster	Over 2,900 s
IES input power	1,570 W
IES dry mass	Below 98.7 kg
Thruster operation time	Over 6,500 h
Thruster on/off cycle	Over 2,920 times
Total propellant mass	39.7 kg (xenon)

The satellite was launched in February 1998. Unfortunately, it could not be inserted into the geostationary orbit because of a malfunction in the second-stage engine, and was moved to a recurrent orbit. Thus, the operation of the ion engine was conducted as short experimental operations (about 14 h) because the total power was below 1 kW, and because the operation window was very short (about one hour per operation).

#### D. ETS-8 Ion Engine<sup>13,14</sup>

In 1998, the development of ETS-8 (Engineering Test Satellite-8) was started as the third satellite that carried an operational ion engine system in Japan, with the main purpose of dealing with the increasing demands for digital communications, such as mobile phones and other mobile devices. The satellite was designed as a 3-ton-class geostationary satellite with 10-year mission life, and thus the total impulse requirement for its ion engine system was increased from that in ETS-6. The thruster beam diameter was unchanged from ETS-6 and COMETS ion engines, and the thrust level was almost the same. Thus the lifetime requirement had to be increased up to 16,000 h. To meet this lifetime requirement, the thruster design was modified mainly for lowering the discharge voltage because the main life limiting factor in the ETS-6 thruster had been designated to be the screen grid erosion. Table 2 summarizes the main design parameters of the ETS-8 ion engine system.

The configuration of the ETS-8 ion engine system was changed from those of ETS-6 and COMETS in several points. It had four thrusters, two power processing units, and two propellant tanks. The thrusters were arranged into two ion thruster units, and each unit consisted of two thrusters. One of the ion thruster units was installed at the north edge of the anti-earth panel of the satellite and the other at the south edge. Figure 4 shows a photograph of ETS-8, where one of the ion thruster units is seen. For NSSK, one of the north thrusters is operated for a certain period around the ascending node, and one of the south thrusters around the descending node. The output of each of the two power processing units is switched to the north or south thruster by the internal relays.

ETS-8 was launched in December 2006, and it was successfully inserted into the geostationary orbit. Initial checkout of the ion engine system was conducted in January 2007. Operation for NSSK has been conducted since March 2007. In a daily operation, one thruster in one of the thruster units is fired around the descending node, and one thruster in the other thruster unit around ascending node. Each of these thrusters operates for about six hours per day.

#### E. Future Prospects

The success of the 20-mN-class ion engine in ETS-8 has shown the substantial possibilities of applying the ion engines to other fields such as aerodynamic-drag compensation, and interplanetary missions.

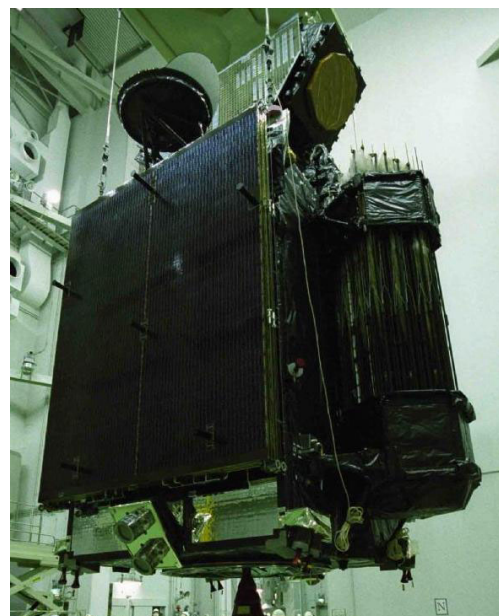
### IV. Next Generation Ion Engine Development

#### A. 25-mN Ring-Cusp Thruster<sup>15,16</sup>

In parallel with the development of the 20-mN-class Kaufman-type thrusters for ETS-6, research on more advanced thrusters was started aiming at higher performance. After a couple of trials in designing and fabrication, we

**Table 2. Main design parameters of the ETS-8 ion engine system.**

Thruster type	Kaufman-type
NSSK operation	Alternate thrusting of north and south thrusters at ascending and descending nodes
Thrust	Over 20 mN (average from BOL to EOL)
Specific impulse	Over 2,200 s (average from BOL to EOL)
IES power	880 W
IES dry mass	96 kg
Thruster operation time	16,000 h
Thruster on/off cycle	3,000 times
Propellant mass	99kg (10-year mission)
Total impulse	$1.15 \times 10^6$ Ns



**Figure 4. Photograph of ETS-8, showing the ion thrusters installed at the lower left corner.**

completed a 25-mN ring-cusp thruster with a 14-cm beam diameter. It gave a satisfactory thruster performance of the ion production cost under 200 W/A at a discharge-chamber propellant utilization efficiency of 90%. With regard to the endurance, a cyclic test of this thruster was conducted with about 600 on/off cycles and total operation time of about 1,900 h. Because it took a very long time before the preceding Kaufman-type thrusters became operational, there was no occasion of replacing the Kaufman-type thruster with the more advanced one.

In the course of this research, various results and experiences were obtained in measurement techniques, test facility development, and so on. These made a great contribution to the flight hardware development of 20-mN IES. Also, this research provided a technological basis for ring-cusp thrusters, with which research and development of the ring-cusp thruster with much higher thrust levels could be started.

### B. 150-mN Ring-Cusp Thruster

Research and development of 150-mN ring-cusp thrusters were started to establish basic technology of future applications which would require high thrust levels. To increase the thrust levels from 20-mN levels up to nearly one-order of magnitude larger ones, we had a lot of difficulties such as the design and fabrication of the ion accelerating grids and hollow cathodes, and thruster thermal design, especially for radiation enhancement. An iterative design and test process was taken to improve thruster performance, where the large-diameter grid design was critical.

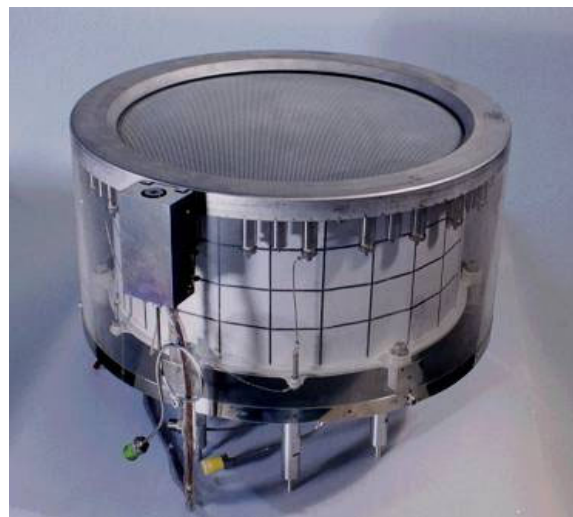
First, research was conducted with laboratory model thrusters with 30-cm diameter grids, and trial fabrications and comparisons were made for several components such as concave and convex dished grids, and plate and axial springs for absorbing thermal expansion of the grids. Then, the first breadboard model (BBM-1) thruster with a 35-cm diameter grid system was designed and fabricated.

With the BBM-1 thruster we obtained an ion production cost less than 140 W/A at a discharge-chamber propellant utilization efficiency of 90%. It produced a thrust of 150 mN at a specific impulse of 3,500 s and with power-to-thrust ratio of 22 W/mN. These performance parameters were as good as, or better than, the target values. The thermal design was also satisfactory.<sup>17</sup>

As the next step, the second breadboard model (BBM-2) thruster was designed to improve thruster durability, particularly, of the grids. Its grids were made thicker than those of the BBM-1 thruster. Figure 5 shows a photograph of the BBM-2 thruster. Using this thruster, an endurance test was conducted mainly to seek the erosion aspect of the grids, and the target operation time of 5,000 h was attained. The test revealed some problems in ensuring the thruster life, and to overcome them, improvements were made both in the thruster and test facility.

In addition, a wide range operation test was conducted to demonstrate the thrusting capability. A thrust range of 80 to 200 mN was obtained without degradation in performance. Also, a couple of vibration tests were conducted for the ion-extraction system, and redesigning was repeated. The latest ion-extraction system was proved to withstand the expected qualification levels of vibrations. A power processor for this thruster was also fabricated. Though it was preliminary, its electrical circuits were designed so that they could be applied to the flight-model power processor.<sup>18</sup>

The latest work on this thruster is fabrication and testing of graphite-orifice hollow cathodes, which can provide much longer life than conventional metal-orifice hollow cathodes.<sup>19</sup> It is known that hollow cathodes are one of the critical components that may determine ion thruster endurance. In our thruster design, however, we consider that the grids are more critical to the thruster endurance than the hollow cathodes. Nevertheless, it is worthwhile to develop graphite-orifice hollow cathodes because they can provide much less variations, or rather degradation, in performance than conventional ones. First, we started with main hollow cathodes whose orifice plate, in addition to the keeper disc, is made of graphite, as shown in Fig. 6. We have already confirmed that they are comparable in performance with the metal-orifice hollow cathodes, and are currently conducting an endurance test of the main hollow cathode. The total operation time reached 11,000 h at the end of August



**Figure 5. Photograph of the 150-mN BBM-2 thruster.**

2007, and no signs of degradation have been seen so far in the data of keeper and discharge voltages, and ignition characteristics.<sup>20</sup>

### C. Future Prospects

In Japan, 20-mN-class ion engines have been developed so far up to the operational phase through ETS-6, COMETS, and ETS-8. However, in advanced countries in this field, they have already flown or almost completed ion engines with much higher thrust levels over 100-mN while we are still in the development level of BBM in Japan. We understand that high-thrust ion engines will be essential technology as long as we aim at playing a major part in space development in the world. Thus, though step by step, we are steadily advancing this technology.

In Japan, we have no authorized flight plans using ion engines of this class at present. We are proposing to apply 100-mN-class ion engines to geostationary satellites in various ways. First, operation time can be shortened when NSSK is conducted with higher-thrust ion engines. Second, a certain part of orbit transfer from GTO to GEO can be conducted using ion engines, resulting in the saving of chemical engine propellant. Third, all of orbit transfer from GTO to GEO can be conducted in place of apogee engines. Finally, we aim at all electric propulsion satellites, where electric propulsion is used also for ease-west stationkeeping, and attitude control. The basic strategy of JAXA indicates that the geostationary satellite bus should be renewed about every ten years to keep up with the world levels. ETS-X, a future engineering test satellite, will be one of the candidate satellites to which 100-mN-class ion engines are applied.

## V. Conclusion

In Japan, an experimental flight test of ion engines was conducted on ETS-3 in a rather early phase of ion engine developments in the world, and soon after that an operational flight plan was made. Unfortunately, however, ETS-6, which was supposed to be the first geostationary satellite that would carry an operational ion engine system, was failed in insertion into GEO, and also COMETS, which carried the ion engine system of the same design, was put in the same situation. After a long blank period, the first NSSK with ion engines was conducted on ETS-8 in 2007. Research and development of the next generation ion engines is currently under way.

## References

- <sup>1</sup>Kuninaka, H., and Komurasaki, K., "Advancing Japanese Electric Propulsion," *30<sup>th</sup> International Electric Propulsion Conference*, IEPC-2007-358, 2007.
- <sup>2</sup>Hirata, M., and Murakami, H., "Impulse Measurement of a Pulsed Plasma Engine on Engineering Test Satellite-IV," *16<sup>th</sup> International Electric Propulsion Conference*, AIAA-82-1875, 1982.
- <sup>3</sup>Toki, K., Shimizu, Y., and Kuriki, K., "On-Orbit Demonstration of a Pulsed Self-Field Magnetoplasma Thruster System," *Journal of Propulsion and Power*, Vol. 16, No. 5, 2000, pp. 880-886.
- <sup>4</sup>Kuninaka, H., "Activities on Electric Propulsion in Japan -Space Flight from Basic Research," *38<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-2002-3563, 2002.
- <sup>5</sup>Nakamura, Y., and Kitamura, S., "Research on 5 cm Diameter Mercury Ion Thruster," *Acta Astronautica*, Vol. 7, 1980, pp. 1075-1089.
- <sup>6</sup>Kitamura, S., and Tabata, J., "Review of Engineering Test Satellite-III Ion Engine Project," *17<sup>th</sup> International Electric Propulsion Conference*, IEPC-84-17, 1984.
- <sup>7</sup>Imai, R., and Kitamura, S., "Space Operation of Engineering Test Satellite-III Ion Engine," *17<sup>th</sup> International Electric Propulsion Conference*, IEPC-84-18, 1984.
- <sup>8</sup>Kitamura, S., Nagano, H., Nakamura, Y., Kudo, I., and Machida, K., "ETS-III Ion Engine Flight Operations in the Extended Mission Period," *Journal of Propulsion and Power*, Vol. 2, No. 6, 1986, pp. 513-520.
- <sup>9</sup>Kitamura, S., Saitoh, N., Nakamura, Y., and Azuma, H., "Ion Engine for North-South Stationkeeping of Large Geostationary Satellites with Long Mission Life," *Journal of the Japan Society for Aeronautical and Space Sciences*, Vol. 33, No. 373, 1985, pp. 100-107 (in Japanese).
- <sup>10</sup>Shimada, S., Satoh, K., Gotoh, Y., Nishida, E., Terukina, I., Nora, T., Takegahara, H., Nakamaru, K., and Nagano, H., "Development of Ion Engine System for ETS-VI," *23<sup>rd</sup> International Electric Propulsion Conference*, IEPC-93-009, 1993.



Graphite Keeper

**Figure 6. Photograph of the graphite-orifice main hollow cathode.**

- <sup>11</sup>Nagan, H., Kajiwara, K., Gotoh, Y., and Nishida, E., "Development and On-Orbit Operation of ETS-VI Ion Engine Subsystem," *20<sup>th</sup> International Symposium on Space Technology and Science*, ISTS 96-a-3-18, 1996.
- <sup>12</sup>Ozaki, T., Nishida, E., Gotoh, Y., and Kajiwara, K., "Performance Evaluation of Ion Engine Subsystem for COMETS on Orbit," *22<sup>nd</sup> International Symposium on Space Technology and Science*, ISTS 2000-b-12, 2000.
- <sup>13</sup>Ozaki, T., Nishida, E., Gotoh, Y., Tsujihata, A., and Kajiwara, K., "Development Status of 20 mN Xenon Ion Thruster," *36<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-2000-3277, 2000.
- <sup>14</sup>Ozaki, T., Kasai, Y., Nakagawa, T., Itoh, T., Kajiwara, K., and Ikeda, M., "20 mN Class Xenon Ion Engine Operation on Orbit," *43<sup>rd</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA 2007-5277, 2007.
- <sup>15</sup>Hayakawa, Y., Miyazaki, K., and Kitamura, S., "Performance Test of a 14 cm Xenon Ion Thruster," *28<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-92-3147, 1992.
- <sup>16</sup>Kitamura, S., Miyazaki, K., and Hayakawa, Y., "Cyclic Test of a 14 cm Xenon Ion Thruster," *28<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-92-3146, 1992.
- <sup>17</sup>Kitamura, S., Miyazaki, K., Hayakawa, Y., Yoshida, H., and Akai, K., "Performance Improvement of 150-mN Xenon Thrusters," *Acta Astronautica*, Vol. 52, 2003, pp. 10-20.
- <sup>18</sup>Hayakawa, Y., Yoshida, H., Kitamura, S., Kajiwara, K., and Okawa, Y., "Status of 150-mN Ion Engine Research at JAXA," *40<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA 2004-3696, 2004.
- <sup>19</sup>Hayakawa, Y., Yoshida, H., Ohkawa, Y., Miyazaki, K., Nagano, H., and Kitamura, S., "Graphite Orificed Hollow Cathodes for Xenon Ion Thruster," *43<sup>rd</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA-2007-5173, 2007.
- <sup>20</sup>Ohkawa, Y., Hayakawa, Y., Yoshida, H., Miyazaki, K., Nagano, H., and Kitamura, S., "Hollow Cathode Life Test for the Next-Generation Ion Engine in JAXA," *30<sup>th</sup> International Electric Propulsion Conference*, IEPC-2007-89, 2007.