Development Status of 20 mN Class Xenon Ion Thruster for ETS-8*†

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A 20mN xenon ion thruster is under development for ETS-8. This paper describes the result of plume diagnosis and life test in progress of the ion thruster. As a part of plasma interaction study between ion thruster plume and high voltage solar array, plasma parameters of the ion thruster plume were measured by a Langmuir probe. As a result, the value of plasma density outside ion beam was below $1\times10^{14}/m^3$ at a distance of 500mm-1000mm from the thruster exit plane. In life test, the beam firing times of DM thruster and ETS-8 EM thruster have amounted to 9,400hours and 5,800hours in September 2001, respectively. The life test data show no fatal problem for thruster operation and its performances are stable during these test period.

Nomenclature

Ci = beam ion production cost, W/A
D = probe diameter
e = electronic charge
g = gravitational acceleration
Ia = accelerator grid current, mA
Ib = beam current, mA
Ick = main hollow cathode keeper current, A
Id = discharge current, A
Ink = neutralizer keeper current, A
Ji = ion current into Langmuir probe
Jeo = electron saturation current
k = Boltzmann constant
T = thrust, mN
M = mass of xenon
m_{MHC} = main hollow cathode flow rate, SCCM
m_{MPF} = main propellant feeder flow rate, SCCM
m_{NHC} = neutralizer flow rate, SCCM
ne = electron density
ni = ion density
Ptrs = thruster input power, WS = probe area
Te = electron temperature
Va = accelerator voltage, V
Vb = beam voltage, V
Vck = main hollow cathode keeper voltage, V
Vd = discharge voltage, V
Vnk = neutralizer keeper voltage, V
η_u = propellant utillization efficiency, %
η_T = thruster efficiency

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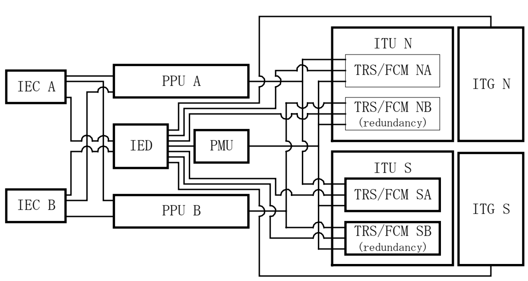
Introduction

The Ion Engine Subsystem (IES) of Engineering Test Satellite 8 (ETS-8) is being developed by Mitsubishi Electric Corporation (MELCO) under the contract with National Space Development Agency of Japan (NASDA).

The IES is used on ETS-8 for north-south station keeping (NSSK). The IES block diagram and main design parameters are shown in Fig.1 and Table 1, respectively. After the performances of the components have been verified in each development test, the interface verification test and EMC test of the subsystem are now carrying on[1-5]. In this development, it is essential to extend the lifetime of thrusters. Before the ETS-8 program started, the development model (DM) thruster was modified in order to extend the lifetime of ETS-6 thruster[6]. ETS-8 EM thruster was designed on the basis of the DM thruster. After two EM thrusters passed the performance test, cyclic life test of ETS-8 EM thrusters and DM thruster started. Now the life test of one EM thruster was suspended and used in the subsystem level test and an additional test.

The ETS-8 EM thruster plume measurement test was carried out. ETS-8 has high voltage solar arrays. On the orbit, the 100V solar arrays will be exposed to comparatively dense plasma under the ion thruster operation. It is essential to make clear the influence of the ion thruster originated plasma on the solar arrays. Thus plasma interaction between the ion thruster plume and the solar arrays has been investigated in both the numerical analysis and the ground experiment[7-10]. As a part of this study, plasma parameters of the ion thruster plume were measured by a Langmuir probe. This technique can be used to investigate the plasma parameters of the ion thruster plume[11-12].

This paper describes the results of the plume measurement and the life test in progress.



IEC : Ion Engine Controller, PPU : Power processing units

ITU : Ion thruster unit, PMU : Propellant management unit

IED : Ion engine driver, ITG : Ion thruster gimbal

TRS : Ion thruster, FCM : Flow control module

Fig.1 ETS-8 IES Block Diagram

Table 1 The Main Design Parameter

1.Thrust Method	Kaufman-type xenon ion thrusters
2.Operation configurations	One north thruster at ascending node and one south thruster at descending node
3.Average Thrust from BOL to EOL	Over 20mN
4.Average Isp from BOL to EOL	Over 2,200sec
5.Weight	95kg
6.Total Impulse	1.15×10^{6}N-sec
7.Total Operation Time	16,000hours (with average thrust of 20mN)
8.Total Number of Firing	3,000cycles

Thruster[2]

The photograph of the ETS-8 EM thruster is shown in Fig.2. The thruster is 12cm diameter Kaufman type ion thruster and the thrust level is about 20mN. The EM thruster is identical with the DM thruster except its screen grid and main hollow cathode. The screen grid of the DM thruster is made of molybdenum plate and that of the EM thruster is coated by ceramic on Mo plate for anti sputtering. The main hollow cathode of the EM thruster is modified the cathode insert in order to extend the lifetime by decreasing cathode temperature during operation. Table 2 shows performance test results of both DM and EM thrusters.

Plume Measurement[7]

Thruster Operation

On the orbit, the thruster is operated in five modes, idling mode (IDLG mode), activation mode (ACTV mode), neutralizer mode (NEUT mode), discharge mode (DISC mode) and beam mode (BEAM mode). In both IDLG mode and ACTV mode, electric power is supplied to two hollow cathode heaters without gas feed. In NEUT mode, only the neutralizer hollow cathode (NHC) keeper discharge is ignited and kept with gas feed. In DISC mode, only the main discharge is ignited and kept. In BEAM mode, the thruster generates thrust. In both BEAM mode and DISC mode, comparatively dense plasma will be generated around the thruster. In DISC mode, there are low energy ions, which flow out through the grid open area by thermal motion. In BEAM mode, there are high energy beam ions, neutralizer electrons and charge exchange ions.

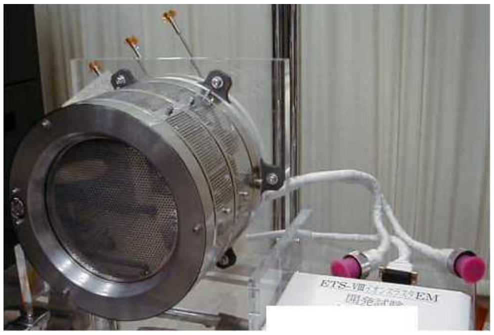


Fig.2. The photograph of ETS-8 EM Thruster

Table 2 Performance Test Results of the thrusters

Note : See Appendix about the calculation of T and Isp

DM

Parameter	Value			
Vb, V	1000	1000	1000	1000
Ib, mA	468	492	511	528
Va, V	-500	-500	-500	-500
Ia, mA	3.6	3.7	4.1	4.8
Vd, V	32.6	32.7	32.8	32.8
Id, A	3.00	3.25	3.50	3.75
Vck, V	8.7	8.2	7.8	7.4
Ick, A	0.5	0.5	0.5	0.5
Vnk, V	24	24	24	24
Ink, A	0.5	0.5	0.5	0.5
m_{MPF}, SCCM	6.5	6.5	6.5	6.5
m_{MHC}, SCCM	2.0	2.0	2.0	2.0
m_{NHC}, SCCM	0.6	0.6	0.6	0.6
T, mN	22.7	23.9	24.8	25.6
Isp, sec	2606	2740	2869	2940
Ci, W/A	209	216	226	235

ETS-8 EM(#1)

Parameter	Value			
Vb, V	1003	1003	1003	1003
Ib, mA	473	491	509	520
Va, V	-474	-476	-478	-479
Ia, mA	2.5	2.6	3.0	3.5
Vd, V	32.5	32.4	32.5	32.6
Id, A	3.26	3.51	3.76	4.01
Vck, V	6.3	5.3	4.8	4.2
Ick, A	0.5	0.5	0.5	0.5
Vnk, V	16.3	15.3	15.6	15.9
Ink, A	0.51	0.51	0.51	0.51
m_{MPF}, SCCM	6.5	6.5	6.5	6.5
m_{MHC}, SCCM	2.0	2.0	2.0	2.0
m_{NHC}, SCCM	0.6	0.6	0.6	0.6
T, mN	23.0	23.9	24.7	25.3
Isp, sec	2640	2740	2840	2900
Ci, W/A	224	232	241	251

Measurement System

The measurement was carried out by a modified commercial plasma diagnostic system. The system is composed of a probe power supply, a personal computer with analytical software, a Langmuir probe and a probe positioning system. The plasma diagnosis system, a probe power supply unit and analytical software (ESPsoft^{TM}), is ESPION^{TM} of Hiden Analytical. The value of scanning voltage is from –200V to +100V. The single probe and the positioning system for angular scan of the probe was modified. The probe is a cylindrical Langmuir probe (a 1 mm diameter × 10 mm long tungsten wire). It was mounted on an arm, rotated in the region of –80°- +80° by a stepping motor. The arm has two port for the probe at distances of 500mm and 1000mm from rotation axis. At the measurement, one probe was mounted on the one port and another port was blinded.

Test Configuration

The measurement of the plume was performed in Ion Engine Space Chamber at Kamakura Works of MELCO. The space chamber is a 3-m in diameter and 5-m in length, and has a cryo-pumping unit. The thruster can be operated under the ambient pressure of 8×10^{-4} Pa with xenon flow. Ion thruster is located in the chamber. Ion beam is directed onto a titanium target plate, which is mounted on the end wall of the chamber and electrically floated from ground potential.

The thruster is operated using the Power-Processing-Unit Bench-Testing-Equipment (PPU-BTE), which is equivalent to the flight PPU. The power supply contains seven power modules (screen, acceleration, discharge, two keepers, and two heaters). The power supply is controlled by a personal computer.

The propellant feed system provides controlled flow of xenon to the thruster through three separate feed lines, for the main hollow cathode (MHC), main propellant feeder (MPF) and NHC. Each propellant flow rate is independently controlled by three commercial mass-flow-controllers.

Measurement test configuration and photograph are shown in Fig.3 and Fig.4, respectively. The rotation axis of the arm was aligned with the thruster beam exit plane. The origin of the angle (0°) was the thruster centerline. The probe was explored within 80° on either side of the centerline at the horizontal plane including the thruster centerline. The NHC was symmetrically located with respect to the scanning area.

Results and Discussion

Operating parameters of the thruster are shown in Table 3 at the measurement. Id was changed from 3.25A to 4.0A by 0.25A. So T changed from 20.8mN to 23.3mN.

Typical current-voltage (J vs.V) data in BEAM mode and in DISC mode are shown in Fig.5. J-V plot in BEAM mode shifts right because the floating voltage of the beam target was about 25V, while J-V plot in DISC mode does not shift because the floating voltage was nearly zero.

The experimental results for plasma density determined at two distances from the exit plane in BEAM mode and DISC mode are shown in Fig.6. Inside ion beam, high energy (+1keV) beam ion can reach the probe against probe applied voltage (+100V max). So plasma density inside ion beam is calculated by using Eq.(1) from ion current within 12.5° from the centerline. The secondary electron from the probe surface was neglected. Plasma density outside ion beam is calculated by using Eq.(2) from electron current in the region beyond 12.5°.

$$J_i = D L e n_i v_i \qquad (1)$$

$$J_{e0} = \frac{1}{4} S e n_e \sqrt{\frac{8kT_e}{\pi m_e}} \qquad (2)$$

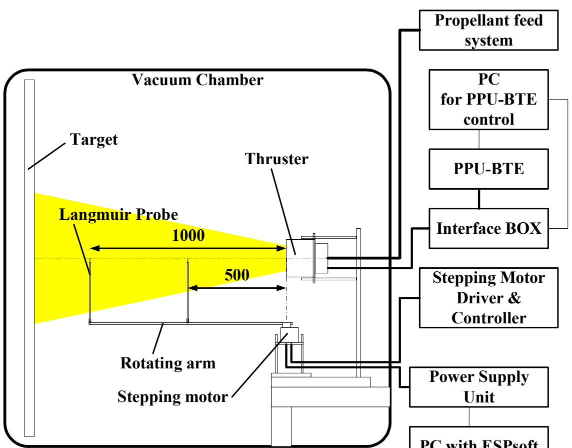


Fig.3 Test configuration

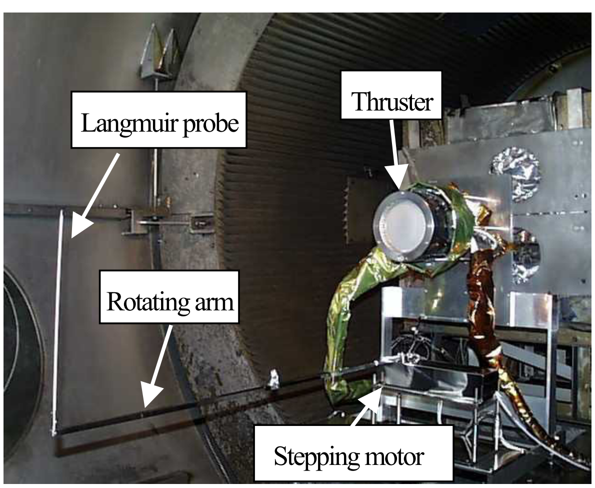


Fig.4 The photograph of the test configuration

Table 3. Operating parameter

Note : See Appendix about the calculation of T and Isp.

Parameter	Value				
	BEAM				DISC
	1	2	3	4	
Vb, V	999	999	999	999	N/A
Ib, mA	430	449	465	480	N/A
Va, V	-469	-473	-472	-474	N/A
Ia, mA	2.1	2.0	1.9	1.8	N/A
Vd, V	31.4	31.9	32.2	32.7	29.1
Id, A	3.26	3.51	3.76	4.00	3.27
Vck, V	6.2	5.7	5.1	4.6	5.8
Ick, A	0.50	0.50	0.50	0.50	0.50
Vnk, V	16.3	16.3	16.2	15.9	N/A
Ink, A	0.50	0.50	0.50	0.50	N/A
m_{MPF}, SCCM	6.5	6.5	6.5	6.5	6.5
m_{MHC}, SCCM	2.0	2.0	2.0	2.0	2.0
m_{NHC}, SCCM	0.6	0.6	0.6	0.6	0.6
T, mN	20.8	21.8	22.6	23.3	N/A
Isp, sec	2390	2500	2590	2670	N/A

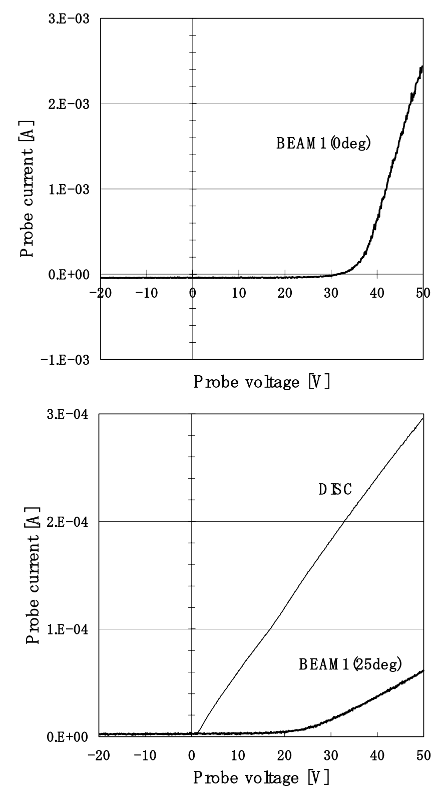


Fig.5 Example of current-voltage characteristics (at distance of 1000mm from the thruster exit plane)

Electron temperature in BEAM mode and DISC mode are shown in Fig.7. The main results of the plume measurement test are summarized as follows :

1. In BEAM mode, the values of plasma density at 500mm and 1000mm in 20° were about $1\times10^{14}/m^3$ and $5\times10^{13}/m^3$, respectively. The values were not different in thrust level change by 10%. In DISC mode, the values of plasma density at 500mm and 1000mm at center were about $7\times10^{13}/m^3$ and $2\times10^{13}/m^3$, respectively.
2. In BEAM mode, the values of electron temperature were about 3eV inside ion beam and 5-15eV outside ion beam. The difference of electron temperature between inside and outside ion beam was due to the difference of plasma potential. The value of plasma potential inside ion beam was about 10V higher than the one outside ion beam. In DISC mode, the values of electron temperature were about 1-2eV in all scanning area.
3. The plume density profile of the ion thruster is sharper than that by the hall effect thruster (SPT-100)[13] as shown in Fig.8. Thus the plasma interaction by the hall thruster plume will be more severe than that by the ion thruster one.

Plasma Interaction Experiment[10]

A ground-based plasma chamber experiment to study the interaction between the solar arrays and the ion thruster plume plasma was carried out at Kyushu Institute of Technology under the plasma density of this measurement result. The experimental results verified that the ETS-8 solar arrays has the design margin against plasma interaction with ion thruster plume.

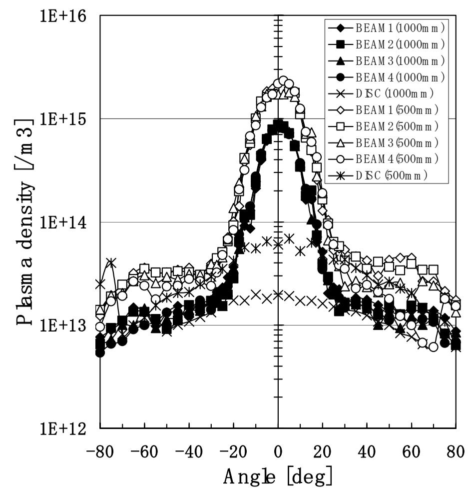


Fig.6 Plasma density profile

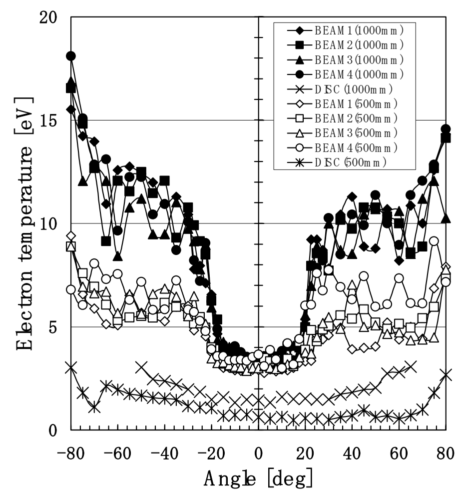


Fig.7 Electron temperature

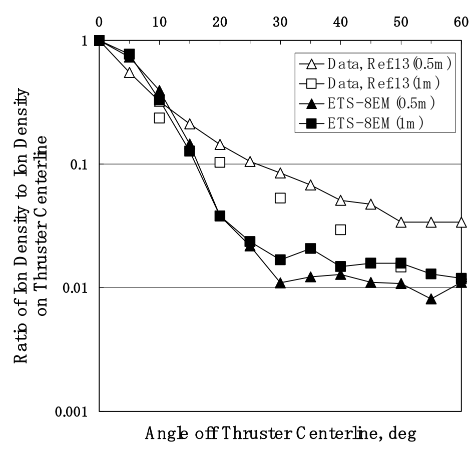


Fig.8 Plume density profile comparison between the Ion thruster and the Hall thruster

Thruster Life Test

The cyclic life test of the ETS-8 EM thrusters (#1, #2) and the DM thruster were started from September 1999, November 1999 and November 1998, respectively. The purpose of the life test is to confirm the lifetime of the thruster and to obtain performance change data for long time operation in the life test. The operational goal is listed below :

1. Total impulse is beyond 1.15×10^6 N-sec (=16,000 hours×20mN)
2. Total number of firing is beyond 3,000cycles

Test Configuration

The life test of the thruster was performed in Ion Engine Space Chamber at NASDA Tsukuba Space Center.

The space chamber is a 4-m in diameter and 4.75 m in length, and has six sub-chambers, which are 0.55m in diameter and 0.5 m in length. The thruster can be operated under the ambient pressure of 4×10^{-4} Pa with xenon flow. Each ion thruster is located in the sub-chamber. Ion beam is irradiated on an aluminum target assembly, which is mounted on the end wall of the chamber and electrically floated.

Each thruster is operated using the PPU-BTE and the propellant feed system, which consists of three commercial mass-flow-controllers.

Present Results

The life test of the ETS-8 EM thruster #1 and the DM thruster is undergoing. The test of the EM thruster #2 was suspended in May 1999 in order to be used in subsystem level test. Operating condition of the thrusters is shown in Table 5. The operating parameters except Id are maintained constant. Id had been set the value of 3.25 A from start to March 2000 and changed the value of 3.75 A from April 2000 for the purpose of accelerating the accumulation of the total impulse. Present results are shown in Table 6.

The performance trends of EM#1 and DM thrusters during the test are shown below. T, Vd and Ci are shown in Fig.10-12 respectively.

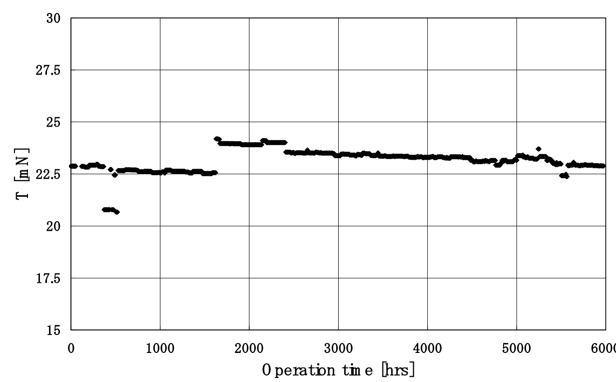
Table 5. Operating point in the life test

Parameter	Value
Vb / Va, V	1000 / -500
Id, A	3.25, 3.5, 3.75, 4.0
Ick / Ink, A	0.5 / 0.5
m_{MPF} / m_{MHC} / m_{NHC}, SCCM	6.5 / 2.0 / 1.0
Operation mode	Cyclic operation
ON time / OFF time, hours	5.4 / 0.5

Table 6 Thruster life test present result

Parameter	Operational goal	Result in September 2001		
		EM#1	EM#2	DM
Status	N/A	in progress	suspended	in progress
Total Impulse, N・sec	1.15×10^6	4.88×10^5	1.41×10^5	7.94×10^5
Beam firing time, hours	16,000	5,856	1,755	9,416
Cycle Number, Cycles	3,000	1,090	327	1,784
Average Thrust, mN	>20	23.2	22.3	23.4
Average Isp, sec	>2,200	2,546	2,455	2,566

EM(#1)



DM

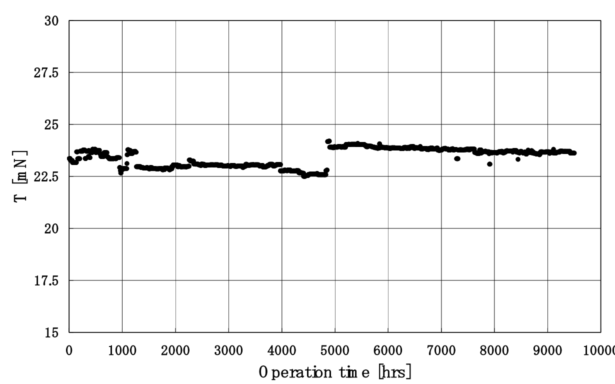


Fig.10 Thrust versus operating time

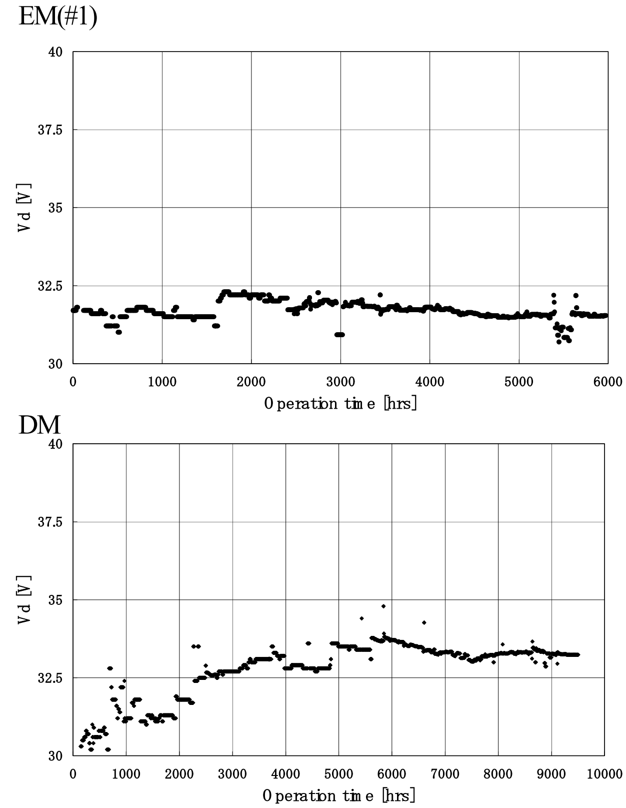


Fig.11 Discharge voltage versus operating time

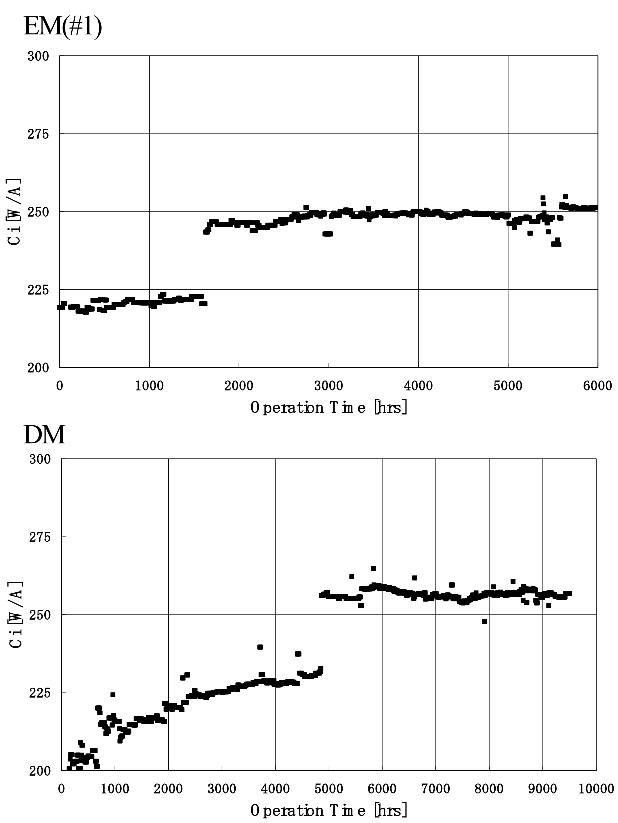


Fig.12 Beam ion production cost versus operating time

To date, the main results of the life test are summarized as follows :

1. The operation times of the EM thruster #1, #2 and the DM thruster are 5,856 hours, 1,755hours and 9,416hours, respectively. The average values of T of EM thruster #1, #2 and DM thruster are 23.2mN, 22.3mN and 23.4mN, respectively. Thus accumulated total impulses of EM thruster #1 and DM thruster have amounted to 42% and 69% of the ETS-8 requirement, respectively.
2. The fluctuations of operational parameters are smaller than we expected. The values of T and Isp of the EM thruster #1 and the DM thruster are 23.2mN, 2,546sec, 23.4mN and 2,566sec, respectively. Both values satisfy ETS-8 requirement, over 20mN and 2,200sec, during this period. Although Vd of the DM thruster gradually raise, the value keeps below 35V. So screen grid erosion, that is, life limitation factor of ETS-6 ion thruster, is small.
3. MHC and NHC in all thrusters are operated under good condition although some fluctuation in Vck and Vnk are observed. The ignition characteristics are good judging from the result that both MHC and NHC are ignited within 5 minutes.

Conclusions

After the component level test, the thrusters are evaluated in subsystem level test and life test. Furthermore the plume measurement test of the thruster was conducted in order to verify ETS-8 high voltage solar arrays design. The results of the plume measurement test and the life test in progress are summarized as follows:

1. In BEAM mode, the values of plasma density at 500mm-1000mm from the thruster in 20° was below $1\times10^{14}/m^3$. Plasma interaction test between the solar arrays and the thruster plume showed the design margin of the solar arrays against the plasma interaction.
2. The accumulated total impulses of the EM thruster #1 and the DM thruster have amounted to 42% and 69% of the ETS-8 requirement, respectively. The average values of T

and Isp satisfy the ETS-8 requirement, over 20mN and 2,200sec. The life test data show no fatal problem for thruster operation and its performances are stable during these test period.

The subsystem level test of ETS-8 IES EM is undergoing. The results of the subsystem level test and the life test of the thrusters will be reported in our other paper.

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Appendix

The following equations were used in the calculation of performance parameters. The value of η_T is assumed as 0.93[14].

$$T = \eta_T I_b \sqrt{\frac{2MV_b}{e}}$$

$$Isp = \frac{\eta_T \eta_u}{g}\sqrt{\frac{2eV_b}{M}}$$

$$\eta_u = \frac{MI_b}{e\left(m_{MHC} + m_{MPF} + m_{NHC}\right)}$$