Operational Status of 20mN class Ion Engine Subsystem for ETS-VIII

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Abstract

The Engineering Test Satellite VIII (ETS-VIII) of Japan Aerospace Exploration Agency (JAXA) uses a 20mN class xenon ion engine subsystem (IES) for North-South Station Keeping (NSSK). The IES was modified for a larger satellite with longer lifetime based on the former IES. ETS-VIII, a three-ton class geosynchronous satellite with 10 years bus lifetime, was launched 18 Dec. 2006 JST; it reached the planned orbit and all bus systems were checked out. The IES showed good results and is now under normal operation. The total accumulated operation time of the IES in orbit was about 2300 hours till 19th Dec. 2007.

Introduction

MELCO has been developing electric propulsions for about 30 years under some national projects in Japan. MELCO has manufactured several kinds of spacecraft and satellite systems for many years and supplied some kinds of components. In electric propulsion field, MELCO has developed 20mN class ion engine subsystem and is developing 200mN class hall thruster.

The first-generation xenon ion engine subsystem (IES) was applied for NSSK to two JAXA satellites, ETS-VI and Communications and Broadcasting Engineering Test Satellite (COMETS), a two-ton class geosynchronous satellite with 6 years' bus lifetime. ETS-VI and COMETS were launched respectively in 1994 and in 1998. Although both satellites unfortunately failed to be inserted into their planned orbits, the thrusters were successfully operated in orbit and the thruster characteristics agreed with the ground test results[1-11]. Based on the first-generation IES results, the IES was modified to extend the lifetime[12] in order to apply for NSSK propulsion of a larger geosynchronous satellite with longer bus lifetime. Development of the ETS-VIII was initiated on 1998. The satellite was a three-ton class geosynchronous satellite with 10 years' bus lifetime; its main mission objective was to verify the mobile satellite communication and multimedia system technology by using a large-scale deployable reflector (LDR). The ETS-VIII image in orbit is shown in Fig. 1. The satellite is 2.45 m wide, 2.35 m deep and 7.3 m high. The width of the deployed solar paddles is 40 m. The LDR size is 37 m. The regulated bus voltage is 100 V. The satellite used the IES for NSSK maneuver because the modest low thrust level of electric propulsion was suitable for a flexible structure such as LDR as well as propellant mass reduction attributable to high specific impulse. The IES successfully completed all ground tests including the thruster life test[20].

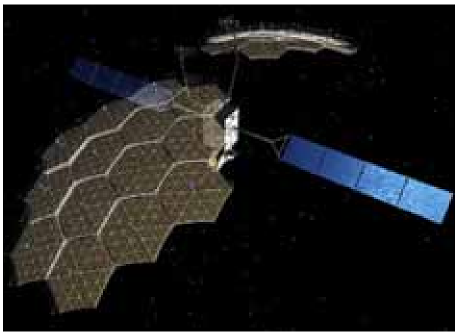


Fig.1 ETS-VIII image in orbit

20mN class ion engine subsystem

Main specific parameters and construction

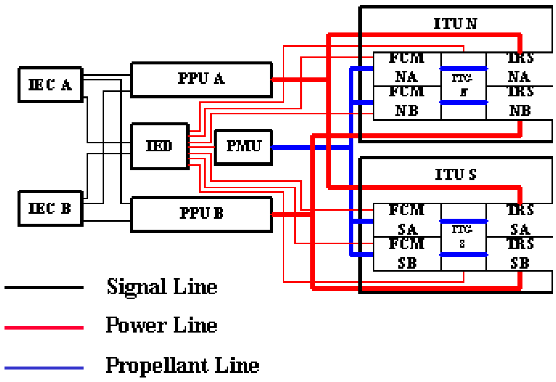
The main specific parameters of the IES are presented in Table 1. In orbit, the north and south ion thrusters will fire for about 5-8 hours, 11 times each two weeks for NSSK alternately.

Table 1 The Main Specific Parameters

Ion thruster type	Kaufman-type
Propellant	Xenon
Thrust at BOL	20.9-23.2mN
Thruster Input Power at BOL	541-611W
Nominal Isp at BOL	2402-2665sec
Total Efficiency at BOL	45.6-49.7%
Total mass of IES	96 kg
Total Impulse	1.15×10^{6} N-sec
Total Operation Time	16,000 hours
Total Number of Firing	3,000 cycles
Power consumption during beam firing	<= 880 W
Thrust vector changing range	+/-5 deg

The ETS-VIII IES comprises five components; two Ion Engine Controllers (IEC), two Power Processing Units (PPU), one Propellant Managing Unit (PMU), one Ion Engine Driver (IED) and two Ion Thruster Units (ITU). A block diagram of the IES is portrayed in Fig. 2. Power consumption and heat dissipation of

IES in nominal firing operation are 880W and 375W respectively. Power consumption of ITU, PMU, IEC, IED and PPU are 753W, 2W, 10W, 9W and 106W, respectively. Heat dissipations of ITU, PMU, IEC, IED and PPU are 248W, 2W, 10W, 9W and 106W, respectively. The dry mass of IES is under 96kg. Mass of ITU, PMU, IEC, IED and PPU are 40.5kg, 18.4kg, 11.4kg, 4.3kg and 21.4kg, respectively.
The IEC controls the operation of PPUs and IED in accordance with sequence logic. The IEC has a command and telemetry interface with ETS-VIII interface unit. The PPU has seven power supplies for operating thrusters. The output of one PPU is switched to north or south thrusters by internal relays. The PMU stores pressurized the xenon propellant and supplies regulated xenon gas to the ITUs. The PMU consists of two xenon storage tanks (TKX), two pyro valves, one Pressure Regulation Module (PRM), some pressure transducers, and some latching valves. The IED supplies electrical power to actuate the latching valves in both PMU and ITUs and to actuate the gimbal stepping motors. One ITU consists of two thrusters (TRSs) flow control modules (FCMs) and ion thruster gimbal (ITG). The TRS generates thrust for NSSK under the supply of electrical power from PPU and xenon propellant from PMU via FCM. The FCM is constructed with four orifices, including an additional orifice, which increases the flow rate for the neutralizer ignition, and two latching valves. It controls the mass flow rate of three routes to TRS independently. The ITG controls thrust vector by mechanical gimbaling under the supply of electrical power from IED. Each ITU is mounted on north and south edges of the anti-earth panel of ETS-VIII. The ITU on the north edge and ITU on the south edge are respectively called the ITU-N and the ITU-S. The PMU is mounted on the lower deck panel of the satellite. The IEC, PPU and IED are installed in the satellite bus module.



Note : IED/PMU have an internal redundancy

Fig.2 ETS-VIII IES Block Diagram

Operational mode of the IES

The IES has several operational modes for hollow cathode conditioning, only the neutralizer hollow cathode (NHC) operation, main discharge operation for health check, beam firing, grid cleaning and thrust vector adjustment.
In IDLG mode, low power is supplied to hollow cathode heaters (both the Main Hollow Cathode (MHC) and NHC for degassing. In NEUT mode, NHC is supplied xenon propellant, the cathode is heated by the heater and the keeper is supplied electric power. The NHC keeper discharge is ignited and maintained. In DISC mode, the MHC and main discharge chamber are supplied xenon propellant, the cathode is heated by the MHC heater and the MHC keeper and the anode are supplied electric power. After the MHC is ignited, the main discharge between the MHC and anode is ignited and maintained. Then plasma is generated. In BEAM mode, after NHC, MHC and the main discharge are ignited, the grid system of the thruster is supplied electric power and the ion beams are extracted. The NHC supplies electrons during ion extraction in order to maintain electrical neutrality. The IES generates thrust for NSSK maneuvering. In order to keep the thrust level, the discharge current can be changed four levels, 3.25A, 3.5A, 3.75A and 4A. During long periods of TRS operation, a short circuit might be created between grid plates by metal flakes. In CM mode, PPU supplies electric power to grid plates to release a short circuit between grid plates. The center of mass of the satellite will move as the propellant is consumed. In ITG mode, ITG moves the cant angle of TRS to aim the thrust vector at the mass center.

Operational Status in orbit

ETS-VIII (Fig. 3) was launched from Tanegashima Space Center on 18 Dec. 2006 JST using H-IIA booster rocket, as shown in Fig. 4. The satellite successfully reached the planned geosynchronous orbit. Before normal operation, satellite bus systems were checked out for function and performance. The IES was checked out for all function modes and performance from 22 Jan. 2007 JST to 29 Jan. 2007 JST. All thrusters showed good operational results. Subsequently, normal operation of the NSSK started from 3 March. To date, both ITU-N and ITU-S are running smoothly.

Fig.3 Photograph of ETS-VIII on ground

Fig.4 Photograph of the launch

Check out[21,22)]

Four thrusters of the IES were checked out for function modes such as IDLG, NEUT, DISC, CM and BEAM mode. Total beam firing time and high voltage break down number are shown in Table 2. High voltage break down occurs between grid plates with degassing at the beginning of life. Even if a break down occurred, the IES automatically started to fire. The number of high voltage break downs was much smaller than we expected. The ignition times of NHC and MHC are about 1.5 minutes.

Table 2 Total firing time of each thruster at check out

Thruster	Total firing time	High voltage break down number
NA	11 hours 36 minutes	12
NB	7 hours 51minutes	17
SA	11 hours 53minutes	6
SB	8 hours	11

As an example, the BEAM mode telemetry data for Vb, Ib, Ia, Vd, Id, Vck, and Vnk of the thruster SA are shown in Fig. 5. When the discharge current changed from 3.25A to 4.0A, the beam current and keeper voltage of the MHC changed because the plasma density in the discharge chamber increases. On the other hand, acceleration grid current, discharge voltage, and keeper voltage of NHC were almost fixed. In Fig. 5, Vb and Ib were zero when the high voltage break down occurred.

In-Orbit Performance Evaluation of Thrusters[21,22)]

A comparison of the performance values in orbit and those of the ground test are shown in Table 3. The values in orbit are the telemetry and design parameter. T, Isp and Ptrs were calculated using the following equations. The design values of Va, Ick, Ink, m_{MHC}, m_{MPF}, and m_{NHC} are, -500 V, 0.5 A, 0.5 A, 2 sccm, 6.5 sccm, and 0.6 sccm, respectively. The value of η_T is assumed as 0.93[8]. Results of the check out indicate that all thrusters of the IES showed good operation and performance.

$$T = \eta_T \cdot Ib \sqrt{\frac{2M \cdot Vb}{q}}$$

$$Isp = \frac{\eta_T \cdot \eta_u \sqrt{\frac{2q \cdot Vb}{M}}}{g}$$

$$\eta_u = \frac{M \cdot Ib}{q \cdot (m_{MPF} + m_{MHC} + m_{NHC})}$$

$$P_{trs} = Vb \cdot Ib + |Va| \cdot Ia + Vd \cdot Id + Vck \cdot Ick + Vnk \cdot Ink$$

Normal operation status

To date the IES has functioned smoothly and continuously from 3 March as shown in Fig. 6. Thruster NA was changed to thruster NB in 26th July because there was a little discharge instability. T and Vd, Vck, and Vnk of each thruster are stable as shown in Fig. 7 and Fig. 8, respectively. The accumulated beam firing time and number are shown in Table 4.

Table 4 Beam firing time and number in normal operation (22 Jan.-19 Dec.)

	Thruster NA	Thruster NB	Thruster SA	Thruster SB
Accumulated beam firing time, hours	480	668	1145.5	8
Accumulated beam firing number, times	88	100	183	2

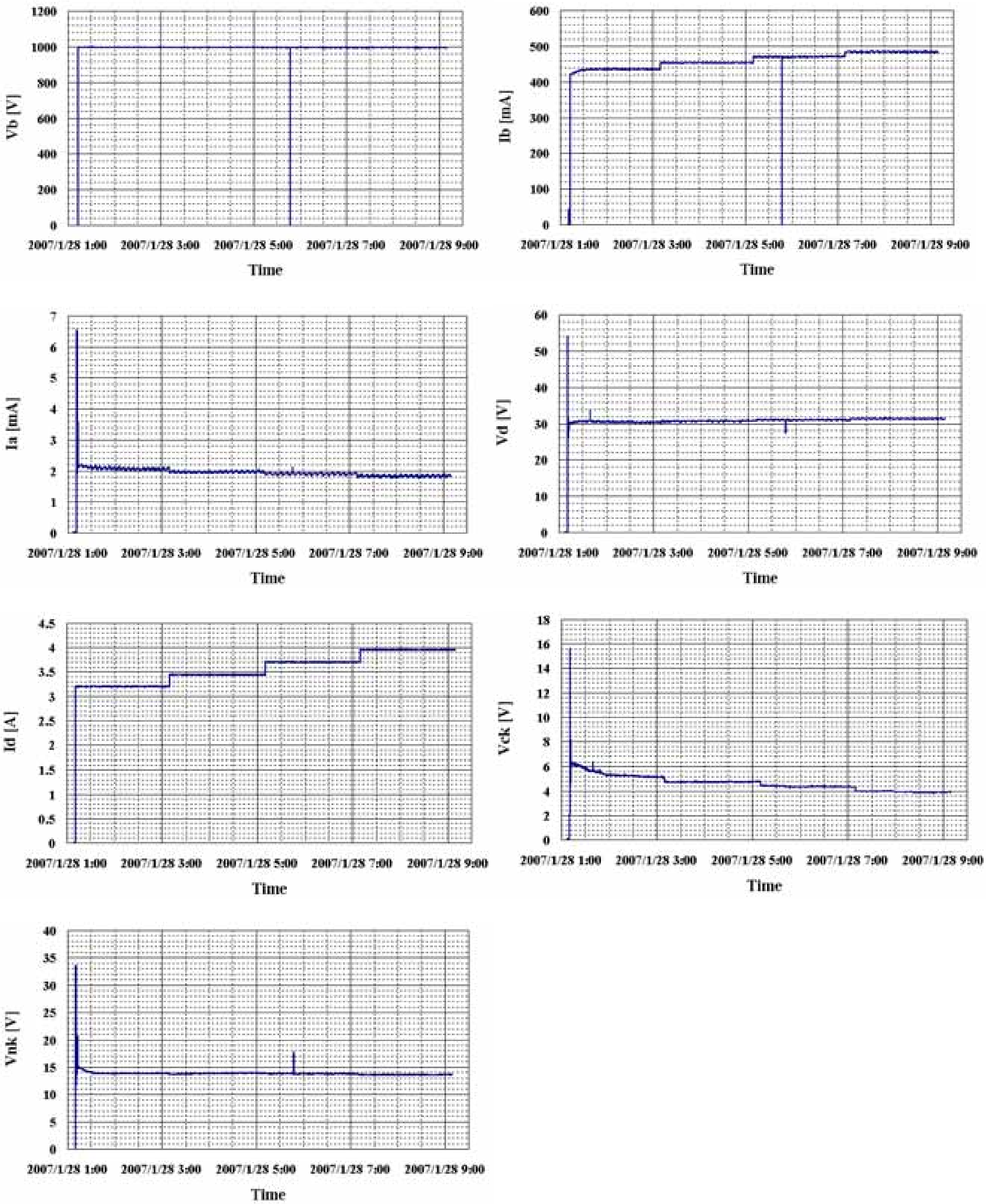


Fig.5 Operational parameter telemetry example of thruster SA

Table 3 Operating parameter comparison of in-orbit and ground tests

Parameter	Thruster NA								Thruster NB							
	BEAM1		BEAM2		BEAM3		BEAM4		BEAM1		BEAM2		BEAM3		BEAM4	
	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground
Vb, V	997	1003.4	997	1002.8	997	1002.3	997	1001.9	995	1003	995	1002.3	995	1002.2	995	1002
Ib, mA	428	442	446	462	461	480	474	494	433	450	451	465	467	482	479	497
Va, V	(-500)	-502.6	(-500)	-506	(-500)	-508.9	(-500)	-511.4	(-500)	-503.5	(-500)	-506.5	(-500)	-509.3	(-500)	-511.8
Ia, mA	1.9	2.2	1.9	2.1	1.9	2	1.9	2	1.9	2.1	1.9	2	1.9	1.9	1.9	1.9
Vd, V	31.1	30.73	31.1	31	31.1	31.22	31.1	31.52	31.4	28.64	31.4	31.54	31.4	31.65	31.4	31.8
Id, A	3.2	3.247	3.45	3.497	3.7	3.747	3.95	4.002	3.22	3.253	3.47	3.498	3.72	3.749	3.98	4.004
Vck, V	5	6.4	4.6	6.1	4.2	5.7	3.8	5.3	5.92	6.8	5.08	6.3	4.55	5.7	4.06	5.2
Ick, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
Vnk, V	13.1	14.5	13.1	14.3	13.1	14.2	13.1	14	13.5	15.9	13.5	15.5	13.5	15.3	13.5	15.2
Ink, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.5	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
mMHC, sccm	(2)	9.38	(2)	9.42	(2)	9.38	(2)	9.4	(2)	9.36	(2)	9.36	(2)	9.36	(2)	9.36
mMPF, sccm	(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)	
mNHC, sccm	(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)	
T, mN	20.7	21.5	21.6	22.5	22.3	23.3	22.9	24	20.9	21.9	21.8	22.6	22.6	23.4	23.2	24.1
Isp, sec	2380	2392	2478	2489	2561	2596	2633	2666	2404	2440	2507	2520	2592	2612	2659	2693
Ptrs	536	553	561	581	584	607	604	630	542	555	568	586	591	611	611	635

Parameter	Thruster SA								Thruster SB							
	BEAM1		BEAM2		BEAM3		BEAM4		BEAM1		BEAM2		BEAM3		BEAM4	
	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground	On orbit	Ground
Vb, V	996	1002.8	996	1002.3	996	1001.9	996	1001.4	994	1003.3	994	1002.7	994	1002.2	994	1001.6
Ib, mA	434	455	453	475	470	483	485	497	434	447	455	469	470	486	482	501
Va, V	(-500)	-504.3	(-500)	-507.6	(-500)	-508.8	(-500)	-511.1	(-500)	-503.6	(-500)	-507.2	(-500)	-509.7	(-500)	-512.3
Ia, mA	2	2.2	2	2.1	2	2	2	2	2	2.3	2	2.2	2	2.1	2	2.1
Vd, V	30.9	31.2	30.9	31.2	30.9	30.89	30.9	30.9	31.2	31	31.2	31.2	31.2	31.2	31.2	31.5
Id, A	3.2	3.245	3.45	3.496	3.7	3.746	3.95	4.001	3.22	3.246	3.47	3.497	3.72	3.747	3.98	4.003
Vck, V	5.4	6.9	4.8	6.4	4.4	5.6	3.9	5.3	6.65	7.9	5.84	7.4	5.29	6.8	4.79	6.4
Ick, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.498	(0.5)	0.498	(0.5)	0.498	(0.5)	0.498
Vnk, V	13.8	19	13.8	18.7	13.8	18.6	13.8	18.5	14.4	20.1	14.4	19.6	14.4	19.1	14.4	18.7
Ink, A	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499	(0.5)	0.499
mMHC, sccm	(2)	9.48	(2)	9.46	(2)	9.44	(2)	9.46	(2)	9.3	(2)	9.28	(2)	9.28	(2)	9.28
mMPF, sccm	(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)		(6.5)	
mNHC, sccm	(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)		(0.6)	
T, mN	21	22.1	22	23.1	22.8	23.5	23.5	24.1	21	21.7	22	22.8	22.7	23.6	23.3	24.3
Isp, sec	2414	2436	2521	2547	2613	2595	2694	2664	2411	2440	2526	2565	2607	2657	2675	2738
Ptrs	542	569	569	597	593	611	615	632	544	562	571	592	594	616	614	639

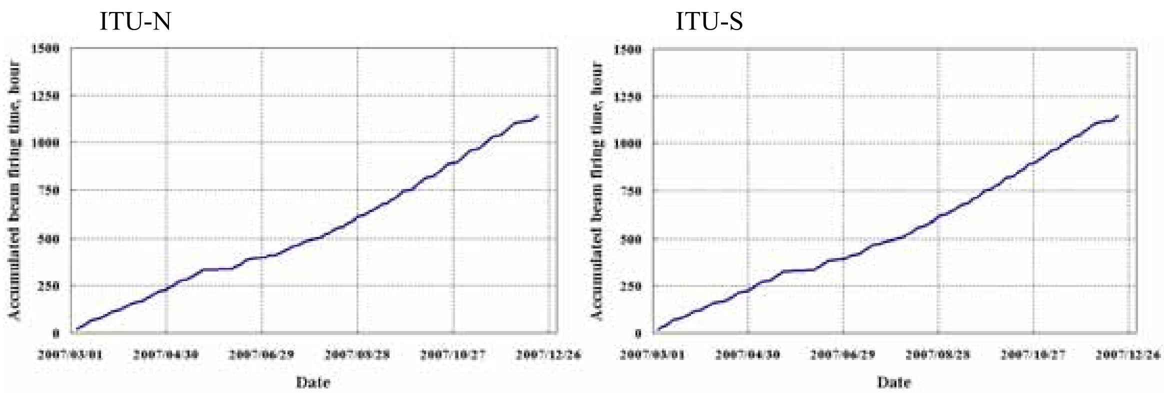
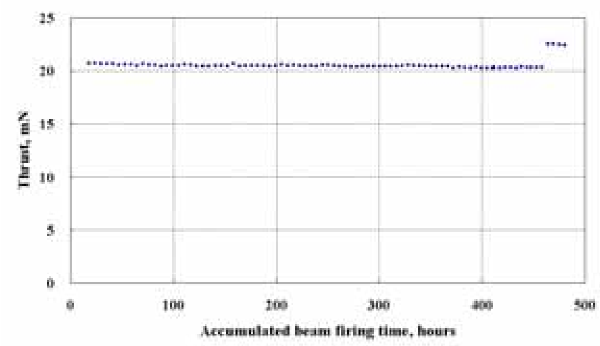
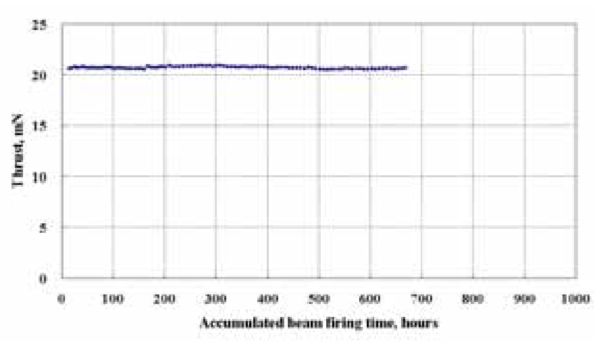


Fig.6 Accumulated beam firing time

Thruster NA



Thruster NB



Thruster SA

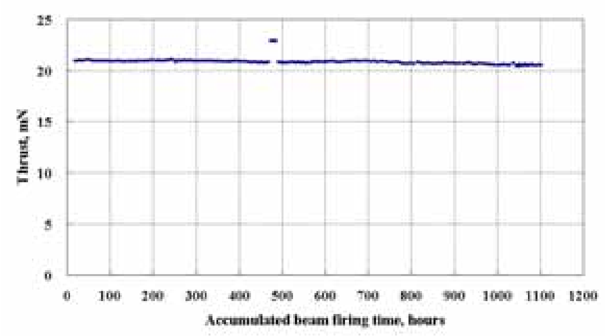
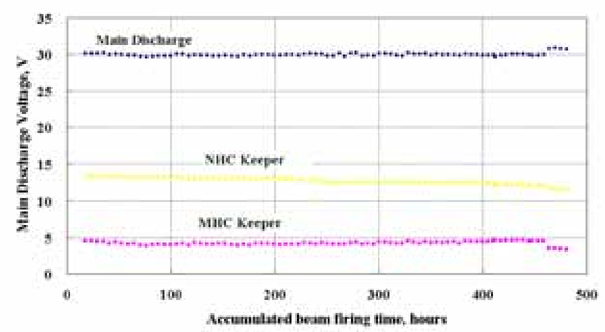
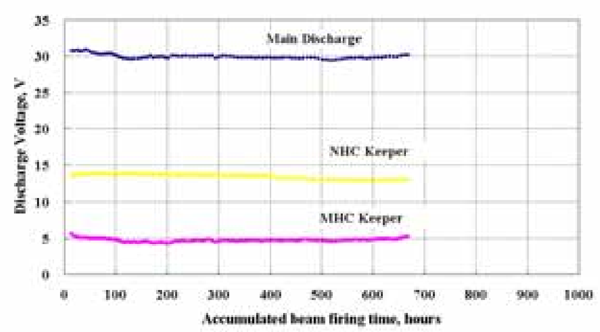


Fig.7 Accumulated beam firing time vs T

Thruster NA



Thruster NB



Thruster SA

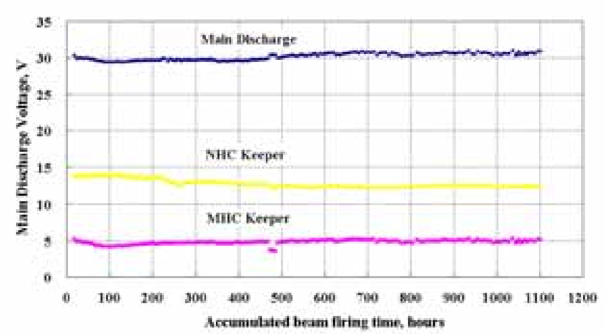


Fig.8 Accumulated beam firing time vs discharge voltage

Conclusion

The IES on ETS-VIII is now under normal operation on geosynchronous orbit. All thrusters showed good operational results at the check. The beam firing time of each ITU in orbit accumulated about 1150 hours from 22nd Jan. to 19th Dec in 2007. We expect to use the 20mN class ion engine with a grid to the wide application such as aerodynamically drag free and deep space exploration.

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Appendix

Nomenclature

g	= gravity acceleration
Ia	= acceleration grid current, mA
Ib	= beam current, mA
Ick	= main hollow cathode keeper current, A
Id	= discharge current, A
Ink	= neutralizer keeper current, A
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
Ptrs	= thruster power consumption, W
q	= electric charge
T	= thrust, mN
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 utilization efficiency
η_T	= thruster efficiency