A New Orbit Control Algorithm for the 20 mN Class Ion Engine System

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Abstract: JAXA is researching presently the super low altitude satellites for next generation earth observing satellites. The Super Low Altitude Test Satellite(SLATS) is the first demonstration satellite of this type. The use of an ion engine system (IES) for air drag compensation is considered effective. The IES in the SLATS consists of an ion thruster, a power processing control unit (PPCU) and a propellant management unit. The PPCU has not only power supplies but also an automatic controller for several operational modes. The ORBIT mode is used in the altitude keeping operation of the SLATS. In this mode, the ion thruster maintains the main discharge and the neutralizer hollow cathode discharge, and generates thrust according to the thrust ON/OFF command from the orbit control system. Since the SLATS cannot seen by ground stations all the time, an autonomous thruster control such as automatic recovery from high voltage break down or discharge disappearance is applied so that the SLATS does not fall out of its orbit to earth. The PPCU BBM was manufactured and tested to verify its electric characteristics and sequence control. The PPCU BBM has satisfied all test requirements.

Nomenclature

Vb	=	beam voltage
Ib	=	beam current
Va	=	accelerator grid voltage
Ia	=	accelerator grid current
Vd	=	discharge voltage
Id	=	discharge current
Vch	=	main hollow cathode heater voltage
Ich	=	main hollow cathode heater current
Vck	=	main hollow cathode keeper voltage
Ick	=	main hollow cathode keeper current
Vnh	=	neutralizer hollow cathode heater voltage

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Inh	=	neutralizer hollow cathode heater current
Vnk	=	neutralizer hollow cathode keeper voltage
Ink	=	neutralizer hollow cathode keeper current
MPF	=	main propellant feed
mMPF	=	mass flow rate of MPF
MHC	=	main hollow cathode
mMHC	=	mass flow rate of MHC
NHC	=	neutralizer hollow cathode
mNHC	=	mass flow rate of NHC
Isp	=	specific impulse

I. Introduction

JAXA and MELCO developed a 20mN class xenon ion engine system (IES) for North-South station keeping (NSSK) of the Kiku-8 which is a geostationary satellite. This thruster can operate at over 20 mN of average thrust from the beginning of life to the end of life with over 2,200sec of average Isp and the lifetime longer than 16,000 h. Kiku-8 was launched in December 2006. The function and performance of the IES were validated in orbit.[1]

Presently, JAXA is developing the Super low altitude test satellite (SLATS) for next generation earth observing satellites.[2,3] The SLATS orbits the earth at an altitude of nearly 250 kilometers, where air drag cannot be neglected. JAXA adopted to use an ion engine system for air drag compensation of the SLATS. Air drag compensation suits very well to the performance of IES by its features of low thrust, small amount of propellant and long lifetime. The Kiku-8 ion thruster was evaluated to meet the SLATS system requirements because of its thrust range, low thrust/power ratio and long lifetime.[4] Therefore, based on the Kiku-8 IES, research and development of a new IES was started to apply for the SLATS program.[5-8]

In this paper, the design results of the SLATS ion engine system, the performance requirements of the power processing control unit (PPCU) and the development results of PPCU are described.

II. Ion Engine System for the SLATS

The IES configuration for the SLATS is shown in Fig. 1. Since the SLATS is a small test satellite, the IES is a single system in order to minimize its weight and size. This configuration also reduces the manufacturing cost as well. The SLATS IES consists of a propellant management unit (PMU), an ion thruster and a PPCU (including an Ion thruster controller). The PMU supplies xenon gas to the ion thruster. The PPCU supplies electrical power to the ion thruster according to on-board control sequence. The ion thruster generates ion beam and thrust.

The PMU is almost the same as Kiku-8 propellant management system. Xenon is used as propellant and is stored in three tanks at a pressure of approximately 7MPa. The xenon mass flow rate into the thruster is controlled properly through a high-pressure latching valve, a regulator, a low-pressure latching valve and mass flow control devices. The mass flow control device is a fixed orifice and the mass flow rate is determined only based on the upstream pressure. The mass flow rate is adjusted at 10.5sccm (including 2sccm for the neutralizer).

The ion thruster is almost the same as Kiku-8 ion thruster since it satisfies the SLATS power and thrust requirements. The thrust of Kiku-8 Ion thruster is fixed at around 20mN. However, for the SLATS the thrust can be selected by command in the range 11-17mN by adjusting the beam voltage and the main discharge current properly. The Kiku-8 ion thruster has the lifetime of 16,000 hours at 20mN, so the lifetime satisfies the SLATS requirement.

The PPCU is being developed at the moment. Though in the Kiku-8 IES a power processing unit and a controller are different components, they are combined in a component called PPCU to reduce manufacturing cost, mass and size. The electrical interface with the satellite system has been changed from the Kiku-8 system. The primary input voltage of the Kiku-8 PPU is 100V. On the other hand, the SLATS PPCU is designed to work under an input voltage between 24V and 32 V. The control algorithm is different from that of the Kiku-8 IES. The SLATS keeps its altitude by thrust on/off control. The on/off command must be given to the PPCU autonomously as the visible time from a ground station is very short. The thrust is automatically generated or stopped using orbit data gained by an on-board GPS receiver.

The main performance parameters of the SLATS IES are shown in Table 1. The SLATS will be launched together with another large satellite on a H-2A rocket and inserted into the orbit of 500km~600km altitude. After the separation of SLATS from the rocket, the high-pressure latching valve is opened and xenon is sent to the downstream of the regulator. Then the low-pressure latching valve is opened and xenon is sent to the ion thruster. The initial check-out of the IES is done to confirm performance of the IES system. After check-out, the low-pressure latching valve is closed to save propellant. The orbit altitude is reduced to 250km using chemical thrusters and atmospheric drag. After reaching the altitude of 250km, the experiment of altitude control begins by using the IES. The Ion thruster generates thrust autonomously when the satellite altitude is lower than the target altitude. The SLATS has GPS receivers to get the altitude data. The experiment period of over 90 days is planned to get the attitude disturbance data due to air drag and the atomic oxygen data at the surface and inside of the satellite body. Those data will be used in the design of practical super low altitude satellites.

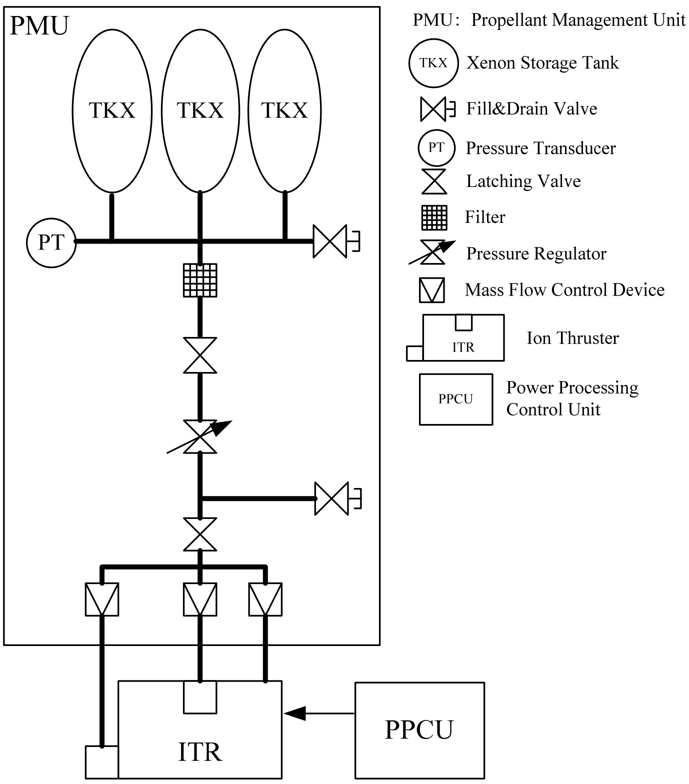

Fig.1. Ion Engine System in the SLATS

Table 1. Main performance parameters of the SLATS IES

item	performance	note
type	Kaufman type	
propellant	xenon	
thrust	11.5～17mN(tentative)	
mass flow rate	10.5sccm	
mass	43kg	
primary voltage	24～32V	
power consumption	<403W@11.5mN <580W@17mN	
signal interface	RS422	
propellant mass	12kg	
MEOP	15MPa	LBB designed tank
proof pressure	>1.5 ×MEOP	LBB designed tank
burst pressure	2.0(tank), 2.5(valve), 4.0(tube etc.) ×MEOP	LBB designed tank
leakage	internal: <0.5Pa･m^3/h(Ghe) external: <1x10^{-7}Pa･m^3/s(Ghe)	

III. Requirements for the PPCU

A. Electric power interface with the thruster

The electrical power interface between the thruster and the PPCU is shown in Fig. 2. The Ion thruster has five electrodes (screen grid, accelerator grid, anode, main cathode keeper, and neutralizer cathode keeper) and two heaters (main cathode and neutralizer cathode). PS1~PS7 supplies electrical power to the electrodes and heaters.

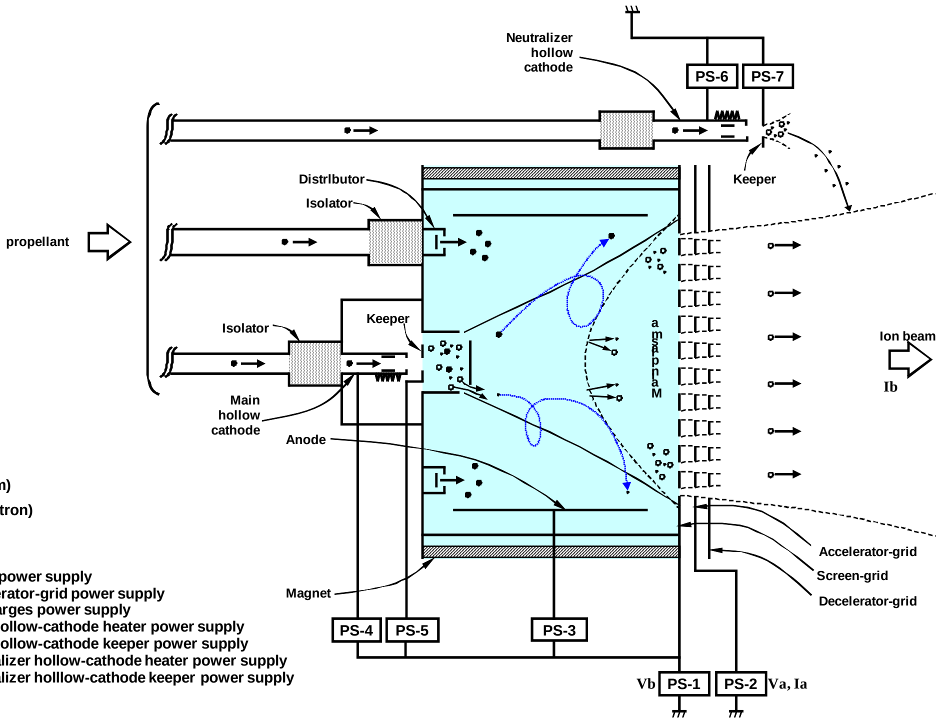

Fig.2. Electrical interface between ITR and PPCU

B. Main Functions

The main functions of the PPCU are as follows:

(1) Primary Bus interface:

The PPCU is designed to operate with a floating power bus (24V-32V). The PPCU has main bus protection and electromagnetic compatibility (MIL-STD-461F).

(2) Power supplies (PS1 to PS7):

The PPCU supplies power to the ion thruster according to their specific power profile. These power supplies must be floating from the primary bus.

(3) Signal interface:

The signal interface between the satellite communication bus and the PPCU is in accordance with RS422 interface bus.

(4) Automatic sequence:

The PPCU has the automatic controller for the operating modes and other necessary operating sequences.

C. Main Specification

The main specifications of the PPCU are as follows:

(1) Operating bus voltage: 24V to 32V

(2) PPCU total efficiency: more than 85% (at 480 W of the beam power supply output power.)

(3) Operating temperature: -20 degree C to + 55 degree C

(4) Radiation: The internal radiation environment for unshielded parts is 1.0×10^4Gy (Si).

(5) Sine vibration: 10Hz to 100Hz, 196.1 m/s^2 (20 G)

(6) Random vibration: 10Hz to 2000Hz, 218.7 m/s^2 rms (22.3Grms)
(7) Shock: 100Hz to 3000Hz, 9806.7 m/s^2 (1,000G)
(8) Output power: Output power requirements are as shown in Table 2.
(9) PPCU mass: less than 26.4kg

Table 2. Output characteristics of PPCU

Symbol	Name	Voltage range (V)	Current range (A)	Ripple (%) P.P	Regulation (%) C.V *1 or C.C*2	maximum Power （w）
PS-1	Beam PS	800～1,100	0.2～0.6	5	C.V ±3	660
PS-2	Accelerator PS	- 400～ - 550	0.001～0.1	5	C.V ±5	5.5
PS-3	Discharge PS	45	1.5～3.5	5	C.C ±5	140
		100	0.1	10	C.V ±5	12.5
PS-4	Main hollow-cathode heater PS	15	1.4～4.0	5	C.C ±3	60
PS-5	Main hollow-cathode Keeper PS	15	0.5	5	C.C ±5	7.5
		150	0.01	20	C.V ±5	12.5
PS-6	Neutralizer hollow-cathode heater PS	15	1.4～4.0	5	C.C ±3	60
PS-7	Neutralizer hollow-cathode Keeper PS	30	0.5	5	C.C ±5	15
		150	0.01	20	C.V ±5	1.5

Note. *1:C.V, constant voltage
*2:C.C, constant cuurent

IV. Design of the PPCU

The PPCU should have a compact volume and correspond to the wide load range of the plasma loading resistance. The block diagram of the PPCU is shown in Fig. 3. It consists of the seven power supplies (PS1 to PS7), an auxiliary power converter, a signal interface circuit and a primary bus interface. The input power of the seven power supplies and the auxiliary converter is provided through the input filter from the primary bus. PS1 supplies regulated high voltage from 800 V to 1,100 V to the screen grid. PS2 supplies regulated voltage from -400 V to -550 V to the accelerator grid. The PS2 output voltage is designed to be minus half of PS1 output voltage. PS1 and PS2 use the same high-voltage transformer to synchronize their output voltage and to have the same rise/fall time. They also have slow start characteristics of voltage. As the high-voltage converter handles a power of 600W, the target of the power conversion efficiency is more than 90 %. They have power capacity to protect the thruster against the discharge between the high voltage electrode and the return electrode. A full-bridge type phase-shift converter is selected for the PS1 and PS2. PS3 is a regulated current power supply for the anode electrode. It supplies 100 V to the anode electrode at the discharge ignition and the regulated current specified by command when the main discharge is maintained. A parallel forward converter is selected as PS3 because it has a high power efficiency among 100W-class converters. Besides, forward converters for PS4 and PS6 and flyback converters for PS5 and PS7 are selected, respectively.

The signal interface circuit is connected to the satellite communication bus and controls the SLATS IES's power-on/off switching and the operational modes. The control logic of these operational modes is installed in a field-programmable gate array. Table 3 shows the operational modes of SLATS IES. In the IDLG mode, PS4 and PS6 heat up the cathode inserts of two in hollow cathode at a low temperature for degassing. In the ACTV_N mode, PS6 heats up the cathode insert of the neutralizer hollow cathode at a high temperature for the activation. In the ACTV_M mode, PS4 heats up the cathode insert of the main hollow cathode at a high temperature for the activation. In the NEUT mode, PS6 and PS7 generate NHC discharge under supplying xenon. In the DISC mode, PS3, PS4 and PS5 generate main discharge in the main discharge chamber under supplying xenon. The IDLG to DISC modes are used in the check-out and aging in orbit. The ORBIT mode is used for altitude keeping operation of the SLATS. In this mode the ion thruster maintains the neutralizer keeper discharge and main discharge, and produces ion beam according to the satellite controller command. The command of thrust on/off is given by the orbit control system. The ORBIT mode algorithm is shown in Fig. 4. In the ion thruster operation, uncertain anomalies such as the short-circuit between the grids called high voltage break down (HVBD), no discharge ignition or discharge disappearance might occurs. Since the SLATS cannot be seen by ground stations all the time, an autonomous recovery operation is necessary so that the SLATS does not fall out of its orbit to earth. In the ORBIT mode, many recovery flows are installed. In the CM mode, PS1 and PS2 supply electrical power to the grids for opening short-circuit between the grids. The CM mode is manually operated from the ground station.

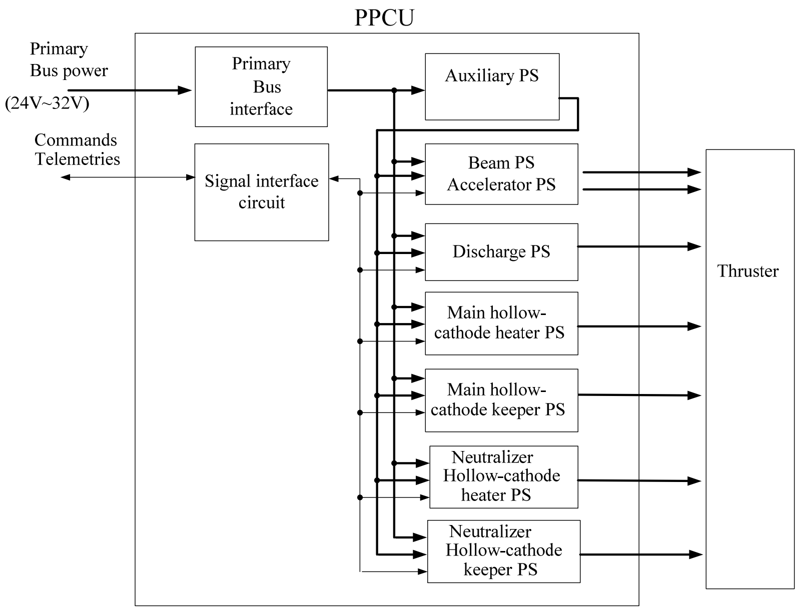

Fig.3. Block diagram of the PPCU

Table 3. Operational modes of SLATS IES

Mode	Operation
IDLG	Neutralizer and main hollow-cathode heating (PS-4 and PS-6 on, low level)
ACTV_N	Neutralizer hollow-cathode activation (PS-6 on, high level)
ACTV_M	Main hollow-cathode activation (PS-4 on, high level)
NEUT	Neutralizer discharge on (PS-7 on)
DISC	Main hollow-cathode discharge and main discharge on (PS-5 and PS-3 on)
ORBIT	All discharge on and beam on/off by command from orbit control system (PS-3, PS-5 and PS-7 on and PS-1 on/off by command)
CM	Grid cleaning, short-circuit opening (function for failure)

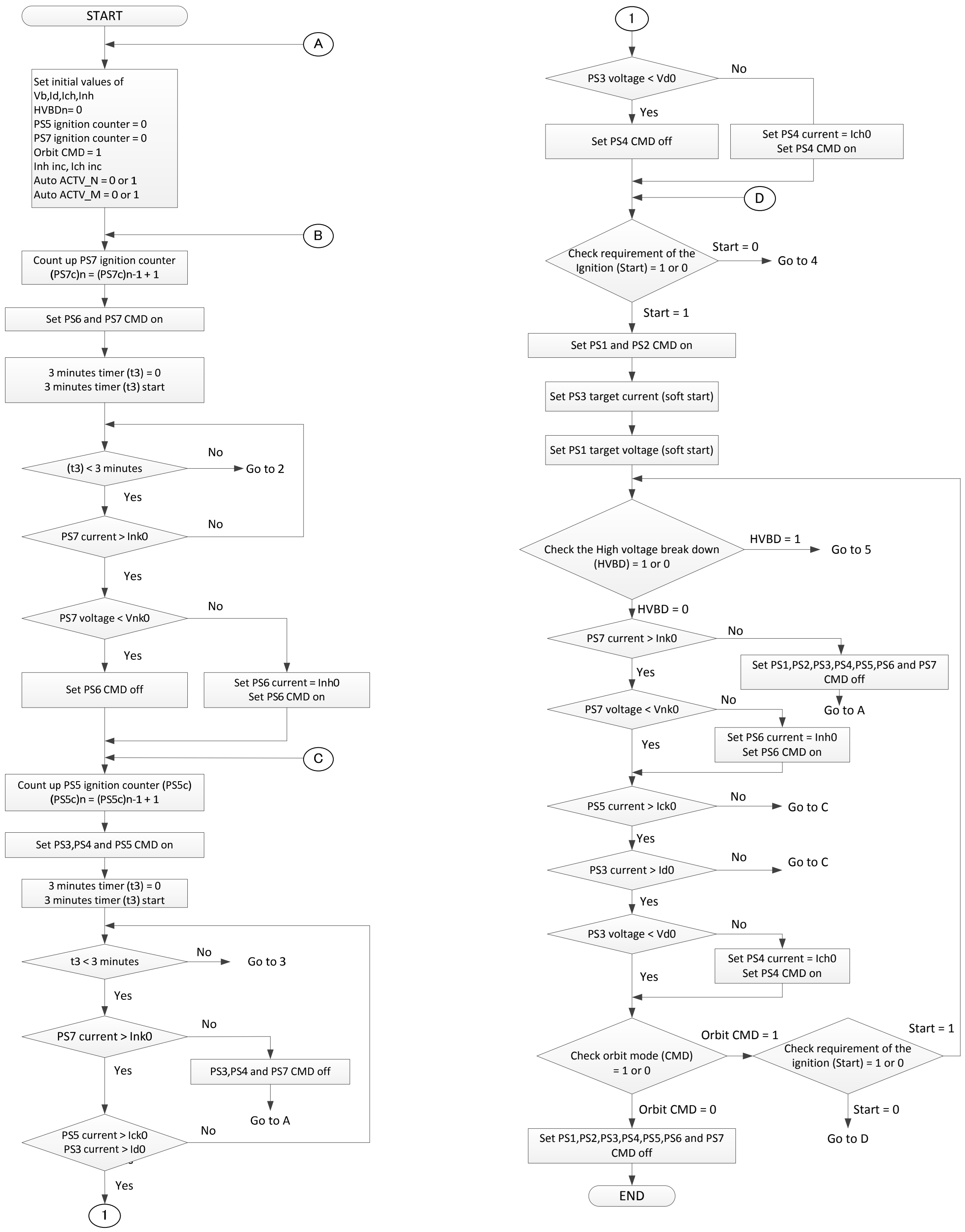

Fig.4. ORBIT mode algorithm (1/2)

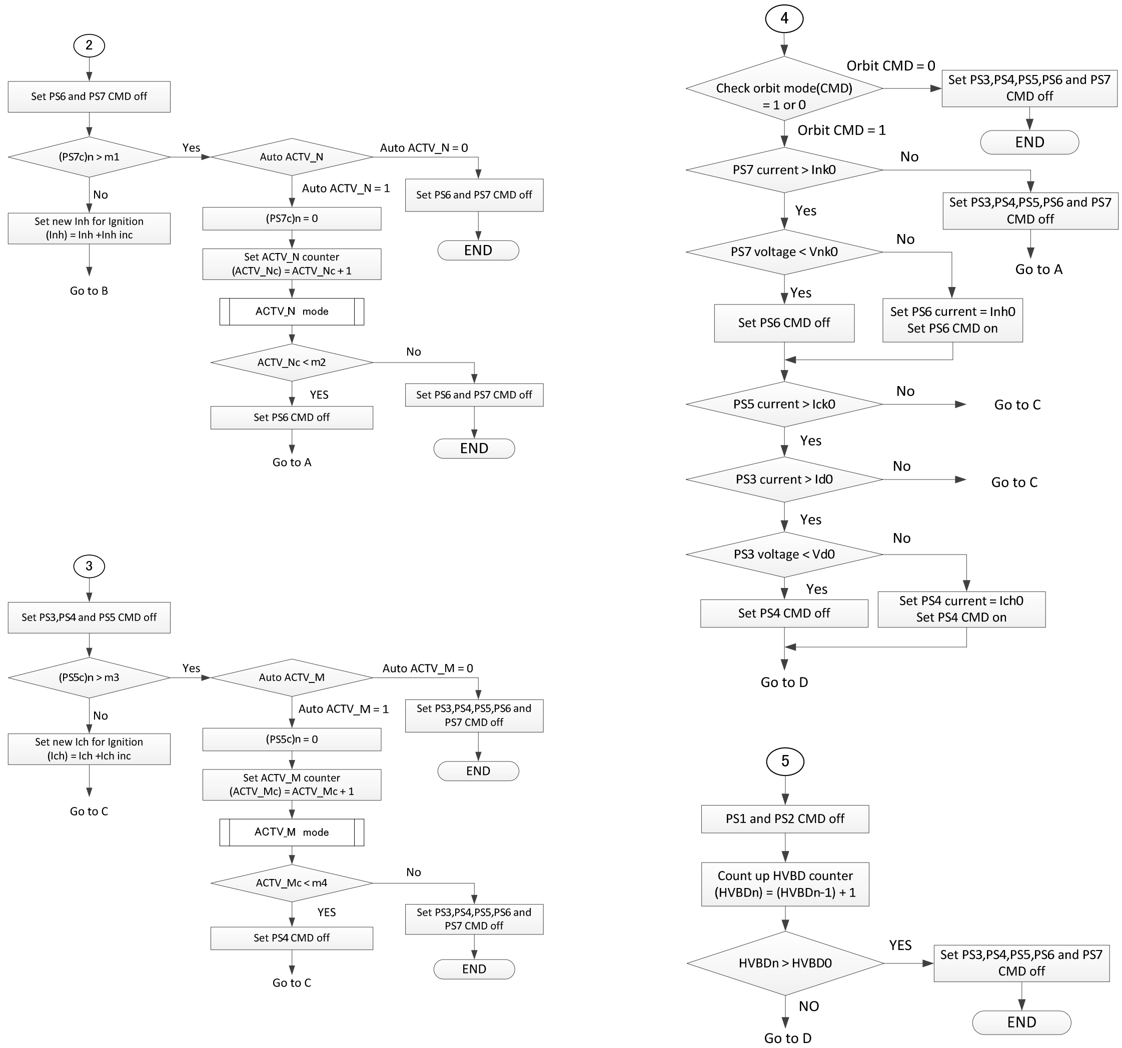

Fig.4. ORBIT mode algorithm (2/2)

V. Test Results the PPCU BBM

The PPCU BBM was manufactured and tested to verify its electric characteristics and its compatibility with the electrical load. The photo of the PPCU BBM is shown in Fig. 5.

A. Inspection and Function test results

The PPCU BBM was verified by the electrical performance tests and all function tests. The output power of the beam power supply and all other power supplies are stabilized over the wide range of the load. The power efficiency of more than 85% was achieved.

B. Beam voltage and Beam current of Turn-on transients

The PPCU BBM can start up the ion thruster quickly and smoothly under beam voltage conditions of 800 V to 1100V. The beam voltage and accelerator grid voltage are turned on synchronously.

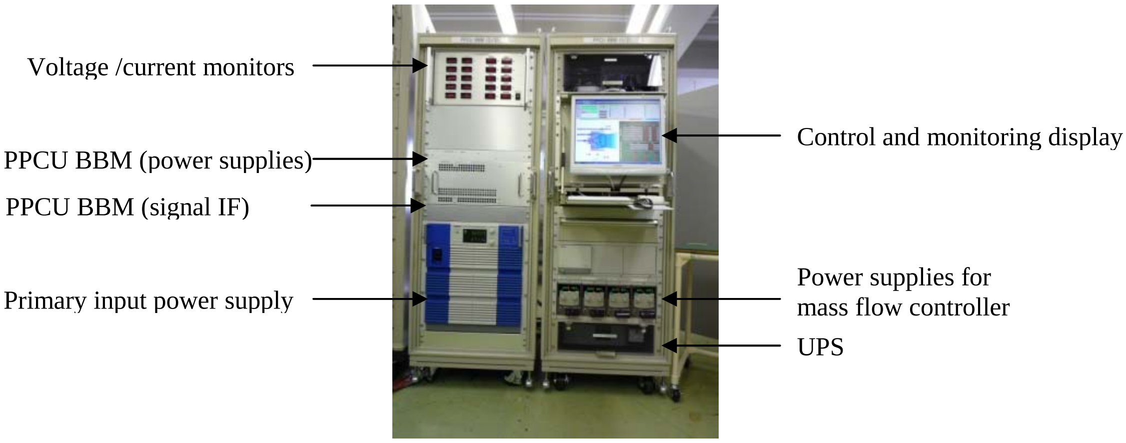

Fig.5. PPCU BBM and Test Equipment

C. Automatic control test

The PPCU BBM has the operational mode sequence to simulate the SLATS operation. In the ORBIT mode the neutralizer discharge, the main cathode keeper discharge and the main discharge are maintained. Then the beam voltage and the accelerator grid voltage are supplied by command. In this beam generation state the main discharge current and the beam voltage can be changed and adjusted by command. The time chart of the beam voltage and the accelerator voltage in the ORBIT mode are shown in Fig. 6. The beam voltage increases from 800V to 1,000V in about 30 seconds. The telemetry data of the beam voltage and the discharge current in the ORBIT mode are shown in Fig. 7. In this simulation case, the beam voltage was changed from 800V to 1,000V after the discharge current was increased from 2.0A to 3.8A at the beam voltage of 800V. The PPCU BBM has satisfied all test requirements.

Fig.6 Results of the operation voltages
Blue line: the beam voltage
Red line: the accelerator voltage

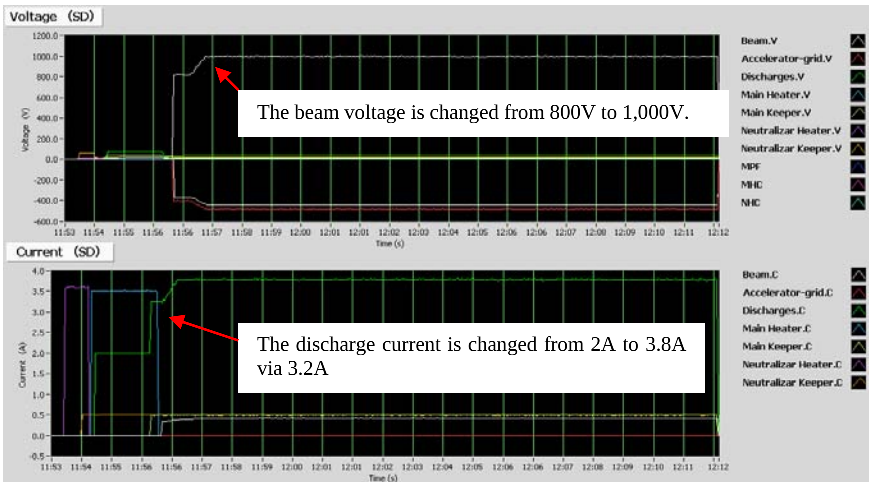

Fig.7. Telemetry data results of the ORBIT mode

VI. Conclusion

The design results of the SLATS ion engine system, the performance requirements of the power processing control unit (PPCU) and the development results of PPCU were shown. Particularly, a new orbit control algorithm was shown in detail. In the ion thruster operation, uncertain anomalies such as the short-circuit between the grids called HVBD, no discharge ignition or discharge disappearance might occurs. Since the SLATS cannot be seen by ground stations all the time, an autonomous recovery operation is necessary so that the SLATS does not fall to earth. In the orbit control mode, many recovery flows are installed.

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