Development Status of a New Power Processing Unit of Ion Engine System for the Super Low Altitude Test Satellite

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Abstract: JAXA is researching the super low altitude satellites for next generation earth observation satellites. The Super Low Altitude Test Satellite (SLATS) is the first Test Satellite of them. They orbit the earth at the altitude of nearly 200 kilometers, where the air drag can't be neglected. JAXA plans to use an ion engine system (IES) for the air drag compensation of those satellites. Kiku-8 ion thrusters meet the satellite system requirements due to their low power/thrust ratio and sufficient lifetime. Therefore, based on the Kiku-8 IES, we started the research and development of a new IES in order to use it in the super low altitude satellites. In this paper, we describe the characteristics required for the IES, the preliminary design results of the IES configuration plan for SLATS, the performance requirements for the power processing control unit (PPCU) and the development results of the bread board model (BBM) of the PPCU including the results of the PPCU BBM and the EM Ion Thruster coupling test.

I. Introduction

MANY electric propulsion systems have been used on geostationary (GEO) satellites to reduce the propellant mass for station-keeping or extend the satellite lifetime.[1-5] Japan Aerospace Exploration Agency (JAXA) carries out research and development of electric propulsion systems for a long time.[6] JAXA and Mitsubishi Electric Corporation (MELCO) developed a 20mN class xenon ion engine system (IES) for Kiku-8(ETS-VIII). This thruster can operate at over 20 mN of average thrust from the beginning of life (BOL) to the end of life (EOL) with over 2,200sec of average specific impulse (Isp) and the lifetime longer than 16,000 h.[7,8] Kiku-8 was launched in December 2006. The function and performance of the IES were validated in orbit.[2] The characteristics of the ion thrusters agreed with the ground test results.

Presently, JAXA is researching the super low altitude satellites for next generation earth observing satellites.[9] They orbits the earth at an altitude of nearly 200 kilometers, where the air drag can't be neglected. JAXA considers using an ion engine system for the air drag compensation of those satellites. Air drag compensation suits very well to the performance of ion engine systems by the low thrust, the small amount of propellant and the long lifetime

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required. The Kiku-8 ion thruster was evaluated to meet the satellite system requirements because of its low thrust/power ratio and long lifetime. Therefore, based on the Kiku-8 IES development results, we started research and development of a new IES in order to apply for super low altitude satellites.[7,10,11]

In this paper, we describe the characteristics required for the IES, the preliminary design results of the IES configuration for the SLATS that is the first test satellite of super low altitude satellites, the performance requirements of the power processing control unit (PPCU) and the development results of the bread board model (BBM) of the PPCU.

II. IES Characteristics required by super low altitude satellites

The application for air drag compensation of super low altitude satellites requires that ion engine systems have a slightly different performance from other applications such as North-South station keeping of geostationary satellites or acceleration of space probes. Although high Isp is preferred for geostationary satellites or space probes to reduce propellant mass, the lower power/ thrust ratio is desired for super low altitude satellites rather than higher Isp. The reason is that a solar array paddle can't be always oriented to the sun to minimize air drag and as result, it is difficult to have large electrical power. In addition, the smaller front projection area of satellites is preferable in order to minimize air drag. It means that higher thrust density is desirable for ion thrusters as they are located on the satellite's backward panel. The value of Isp is required to be at least 1,500sec, though it may depend on the satellite's system design. In consequence, the requirement for ion thrusters is that the power/thrust ratio is as small as possible and the thrust density are as high as possible with the Isp higher than 1,500sec and the required lifetime.

Another feature of super low altitude satellites is that those satellites require autonomous altitude control in orbit as the visible time from a ground station is very short. It is necessary that the thrust is automatically generated or stopped using orbit data gained by an on-board GPS receiver to maintain the satellite's altitude without falling down to the earth. When the thrust level is also adjusted in addition to the thrust being set to on/off, an autonomous selection of thrust level is required. The ion engine system needs a rapid response to keep satellite altitude in worse visibility from a ground station comparing with geostationary satellites. Therefore, ion thruster's uncertain characteristics such as high voltage break down (HVBD), discharge ignition time and discharge disappearance must be controlled well by using a smart operation sequence.

III. IES for SLATS

The IES configuration for SLATS is shown in Figure 1. The IES is a single system in order to minimize its weight and size as SLATS is a small satellite. This configuration also reduces the manufacturing cost as well. The SLATS IES consists of a xenon storage tank, a pressure regulator, an ion thruster, a PPCU (including an ion thruster controller), three flow control devices and two latching valves.

The ion thruster is almost the same as Kiku-8 ion thruster as it satisfies the SLATS power and thrust requirements. The thrust of Kiku-8 ion thruster is fixed at 20mN. However, for SLATS the thrust can be selected by command in the range 10mN - 24mN by adjusting the beam voltage and the main discharge current properly. Kiku-8 ion thruster has the lifetime of 16,000 hours at 20mN, so the lifetime satisfies the SLATS requirement.

The PPCU is the one being developed for super low altitude satellites at the moment. It has power supplies and the IES sequence control function.

The propellant management system is the same as Kiku-8 propellant management system. Xenon is used as the propellant and is stored in

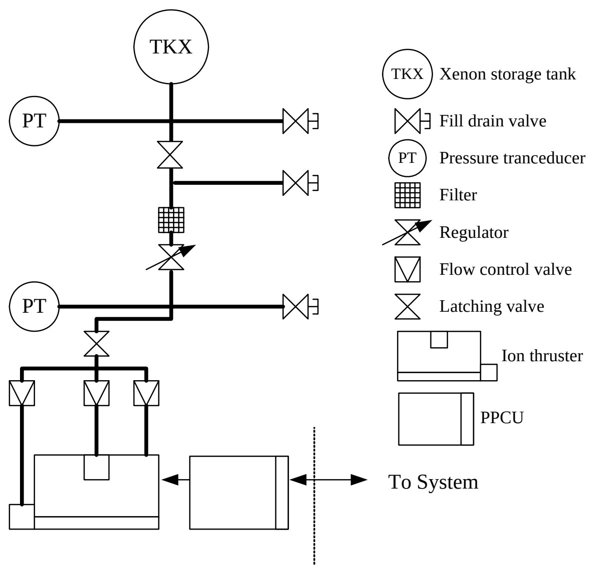


Figure 1. IES Configuration for SLATS

a tank 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. We adjust the mass flow rate at 10.5sccm(including 2sccm for the neutralizer).

The main performance parameters of the SLATS IES are shown in Table 1. After the launch of SLATS, 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 in each operation mode of Idling, Activation, Neutralizer Discharge, Main Discharge and Orbit mode. After check-out, the low-pressure latching valve is closed to save propellant. 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.

Table 1 Main performance parameters of the SLATS IES

item	performance	note
type	direct discharge and electric bombardment	
propellant	xenon	
propellant storage capacity	12kg	including invalid propellant
MEOP	15MPa	LBB designed tank
proof pressure	>1.5 xMEOP	LBB designed tank
destructive pressure	2.0(tank), 2.5(valve), 4.0(tube etc.) xMEOP	LBB designed tank
life time	over 3 years	
power consumption	<370W@10mN <550W@15mN <710W@20mN	
leakage	internal: <0.5Pa・m^3/h(Ghe) external: <1x10^{-7}Pa・m^3/s(Ghe)	
thruster performance	thrust: 10mN～24mN Isp: 1,000～2,390sec(calculated value) (xenon mass flow rate 10.5sccm)	
thruster lifetime	over 8,000 hours	nominal operation

IV. Requirements for the PPCU

Though a power processing unit (PPU) and a controller are different components for Kiku-8 IES, we decided to make them one component called PPCU to reduce manufacturing cost and the size of the IES. We realize the control function with an FPGA instead of the MPU that was used in the Kiku-8 ion engine controller. 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+-3V. On the other hand, the PPCU is designed to work under an input voltage between 32.5V and 50 V so as to meet various low earth orbit satellite systems.

A. Electrical power interface with the thruster

The electrical power interface between the thruster and the PPCU is shown in Figure 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 supply electrical power to each electrode and heater.

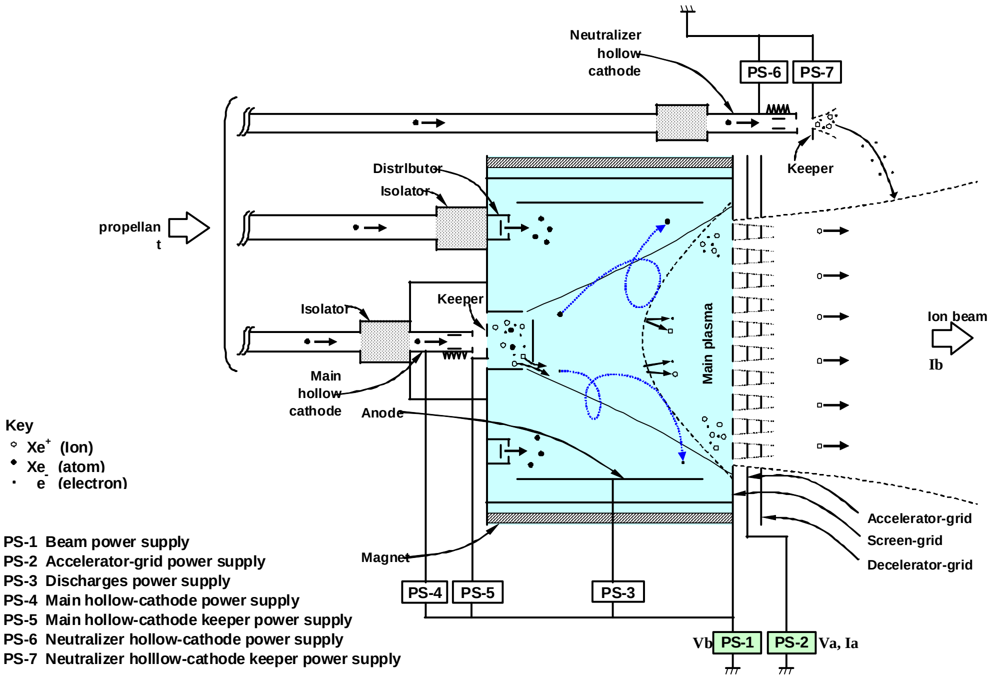


Figure 2 Electrical interface between the thruster ane the PPCU

B. Main functions

The requirements for the main functions of the PPCU are as follows:

(1) Primary Bus interface:

The PPCU is designed to operate with a floating power bus (32.5V-50V). 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 specifications

The requirements for the main specifications of the PPCU are as follows:

(1) Operating bus voltage: 32.5V to 50V

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

(3) Operating temperature: -20 degree C to + 60 degree C

(4) Radiation: The internal radiation environment for unshielded parts is 1.0 X E4Gy (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 (1000G)

(8) Output power: Output power requirements are as shown in Table 2.
(These requirements are for the 20mN-class Ion Thruster.)

(9) PPCU weight: less than 17.8kg

Table 2 Output characteristics requirements of the PPCU

Symbol	Name	Voltage range (V)	Current range (A)	Ripple(%) P.P	Regulation(%) C.V *1 or C.C*2	maximum Power （w）	Efficiency （%） at maximum power
PS1	Beam PS	900～1100	0.2～0.6	5	C.V ±3	660	90
PS2	Acceration PS	- 450～ - 550	0.001～0.1	5	C.V ±5	5.5	
PS3	Dischage PS	45	2～5.5	5	C.C ±5	247.5	88
		90	0.1	10	C.V ±5	12.5	N/A
PS4	Main hollow cathode heater PS	15	1.4～4.0	5	C.C ±3	60	80
PS5	Main hollow cathode Keeper PS	15	0.5	5	C.C ±5	7.5	70
		150	0.01	20	C.V ±5	12.5	N/A
PS6	Neutralization hollow cathode heater PS	15	1.4～4.0	5	C.C ±3	60	80
PS7	Neutralization hollow cathode Keeper PS	30	0.5	5	C.C ±5	15	75
		150	0.01	20	C.V ±5	1.5	N/A

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

V. Design of the PPCU

The PPCU should have a compact volume and correspond to the wide load range of the plasma loading resistance. Fig.3 shows the block diagram of the PPCU. The PPCU 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. The output power characteristics are required by the ion thruster capability. PS1 supplies regulated high voltage from 800V to 1,100V to the screen grid. PS2 supplies regulated voltage from –400V to –550V 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. The high-voltage converter that consists of PS1 and PS2 accounts for 70% of the electric power handled, and 40% of the volume in the PPCU. Therefore, the high efficiency of the high-voltage converter is essential to achieve the high efficiency of the PPCU. As the high-voltage converter handles a power of 600W, the target of the power conversion efficiency is more than 90 %. PS1 and PS2 also need to protect the thruster against the discharge between the high voltage electrode and the return electrode. PS1 and PS2 have slow start characteristics of voltage so that PS1 and PS2 have the same rise/fall time. We conducted a trade-off study of power conversion topologies. Two kinds of converters were selected and designed. One is a full-bridge type phase-shift converter and another is a vector-combined type voltage resonant converter. PS3 is a regulated current power supply for the anode electrode. It supplies 90V to the anode electrode at the discharge ignition and the regulated current specified by command when the main discharge is maintained. We selected a double forward converter as PS3 because it has high power efficiency among 100W-class converters. As for other power supplies, we selected forward converters for PS4 and PS6 and flyback converters for PS5 and PS7.

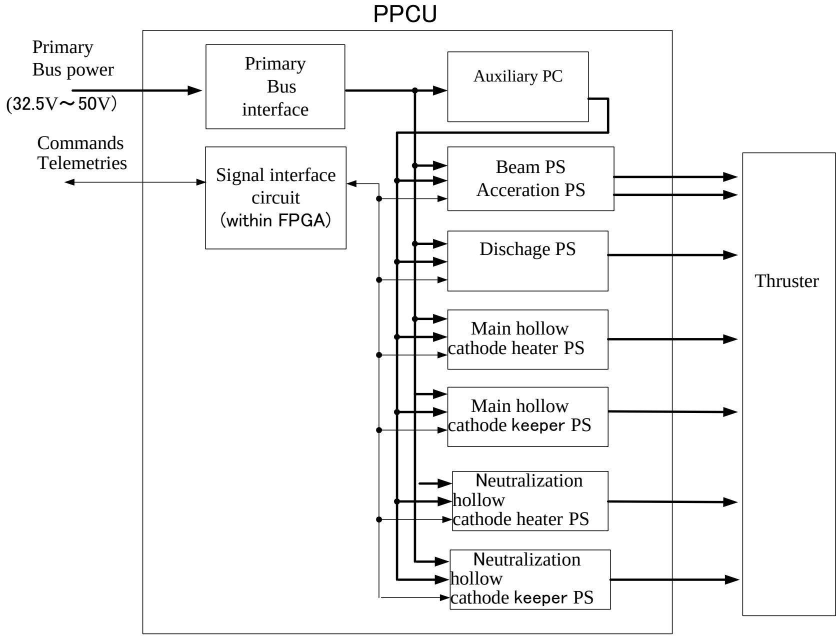


Figure 3. Block diagram of the PPCU

The signal interface circuit is connected to the satellite communication bus and controls the IES power-on/off switching and the operational modes such as the Main discharge mode or the Orbit mode. The control logic of these operational modes is installed in a field-programmable gate array. Table 3 shows the operational modes of the IES. The Orbit mode is used in the altitude keeping operation of super low altitude satellites. The command of thrust on/off is given by the orbit control system.

Table 3 Operational modes of the IES

mode	operation
Idling	low level heater on for PS4 and PS6
Activation	high level heater on for PS4 and PS6
Neutralizer discharge	neutralizer discharge on (PS7 on)
Main discharge	main hollow cathode discharge and main discharge on(PS5 and PS3 on)
Orbit	all discharge on and beam on/off by command from orbit control system(PS3, PS5 and PS7 on and PS1 on/off by command)

VI. Test Results of the PPCU BBM

We have manufactured and tested the PPCU BBM to verify its electric characteristics and its compatibility with the electrical load. The External view of the PPCU BBM is shown in Figure 4.

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 the beam power supply versus input voltage is shown in Figure 5. The power efficiency of more than 90% was achieved in the input voltage range from 32 V to 52 V (at an output current from 0.35 A to 0.7 A) for the beam power supply. The power efficiency of the discharge power supply versus input voltage is shown in Figure 6. The power efficiency of more than 88% was achieved in the input voltage range from 32 V to 52 V (at an output current 3.5 A and a load range from 20 ohm to 24 ohm) for the discharge power supply.

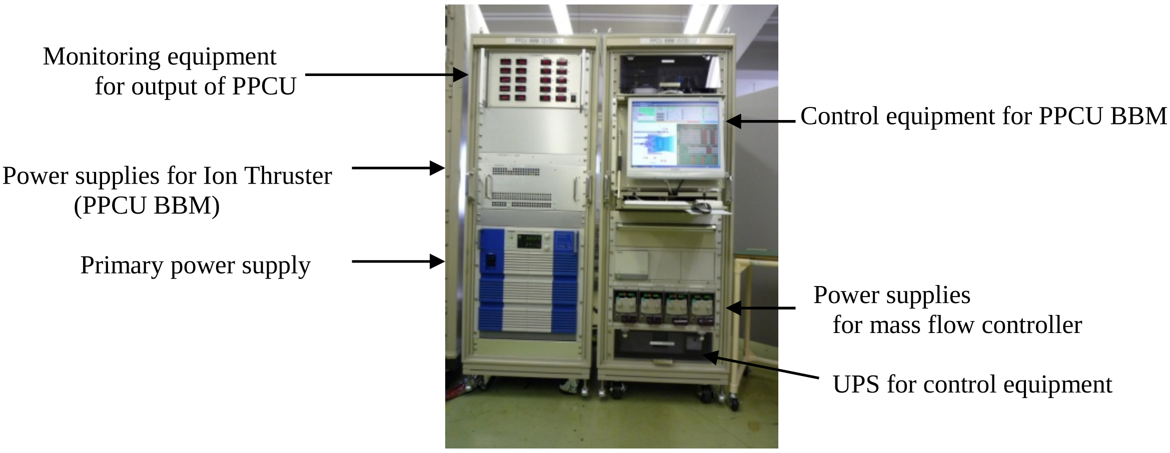


Figure 4. External view of the PPCU BBM

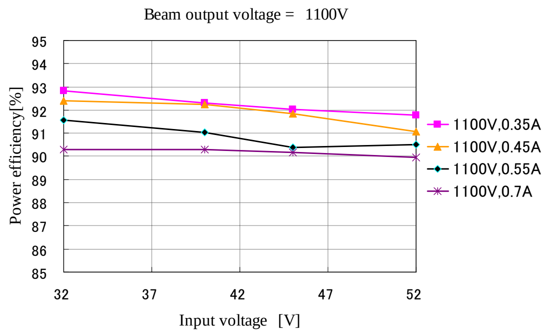


Figure 5. Efficiency of the beam power supply

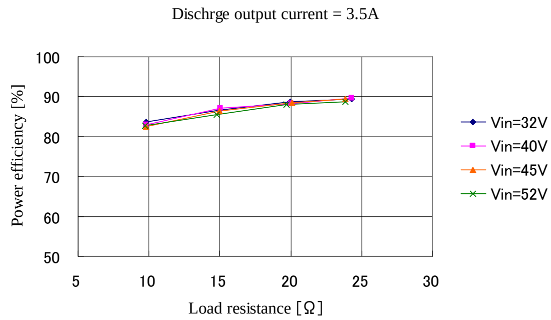


Figure 6. Efficiency of the discharge power supply

B. Coupling test results

1. Test conditions

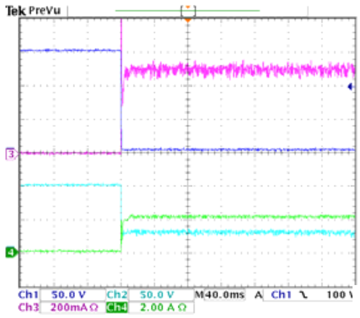
We measured the discharge current responses of the Ion Thruster for various operating points. The performance of the PPU BBM coupled with the Kiku-8 EM ion thruster has been verified. The thruster was installed in a 3 m diameter, 5m long vacuum chamber.

The test conditions are as follows:

a. Pressure: 9.3×10^{-4} Pa (xenon: 8.78×10^{-6} kg/s)
b. PPCU input voltage: 32 V to 50 V
c. Beam voltage range: 800 V to 1100 V
d. Discharge current: 2 A to 4 A
e. Main Cathode Keeper operating current: 0.5 A
f. Main Cathode Heater current: 1.4 A to 4 A
g. Neutralizer Keeper operating current: 0.5 A to 0.7 A
h. Neutralizer Heater current: 1.4 A to 4 A
i. Thruster mass flow rate (Main Chamber and Main cathode):
Main Chamber: 4.39×10^{-6} kg/s to 6.34×10^{-6} kg/s and Main Cathode: 1.95×10^{-6} kg/s to 2.44×10^{-6} kg/s
j. Neutralizer Cathode mass flow rate:
1.95×10^{-6} kg/s

2. Main Cathode Keeper Discharge and Main Discharge ignition transients

The ignition waveform of the main discharge and the main cathode keeper discharge are shown in Figure 7. The PPCU BBM can start up the ion thruster quickly and smoothly under discharge current conditions from 2A to 4A.

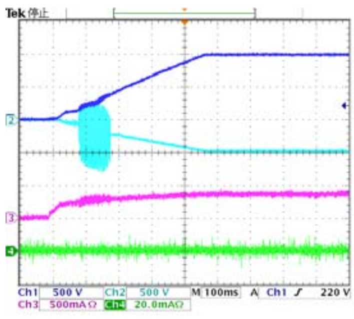


Ch1: Main Cathode Keeper Voltage 50V/div
Ch2: Main Discharge Voltage 50V/div
Ch3: Main Cathode Keeper Current 0.5A/div
Ch4: Main Discharge Current 2A/div
Time: 40ms/div

Figure 7. Ignition Transient waveform of the Main Discharge and the Main Cathode Keeper Discharge

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

The turn-on waveform of the beam power supply is shown in Figure 8. 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.



Ch1: Beam Voltage 500V/div
Ch2: Accelerator Grid Voltage 500V/div
Ch3: Beam Current 0.5A/div
Ch4: Accelerator Grid Current 20mA/div
Time: 100ms/div

Figure 8. Turn-on Transient waveform of the beam power supply and accelerator grid power supply

4. Automatic control test

The PPCU BBM has the operational mode sequence for the simulation of 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 telemetry data result of the Orbit mode sequence is shown in Figure 9. The beam ignition time of the thruster is three or four minutes. This is a very quick response. In this simulation case the beam voltage was changed from 800V to 1000V 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.

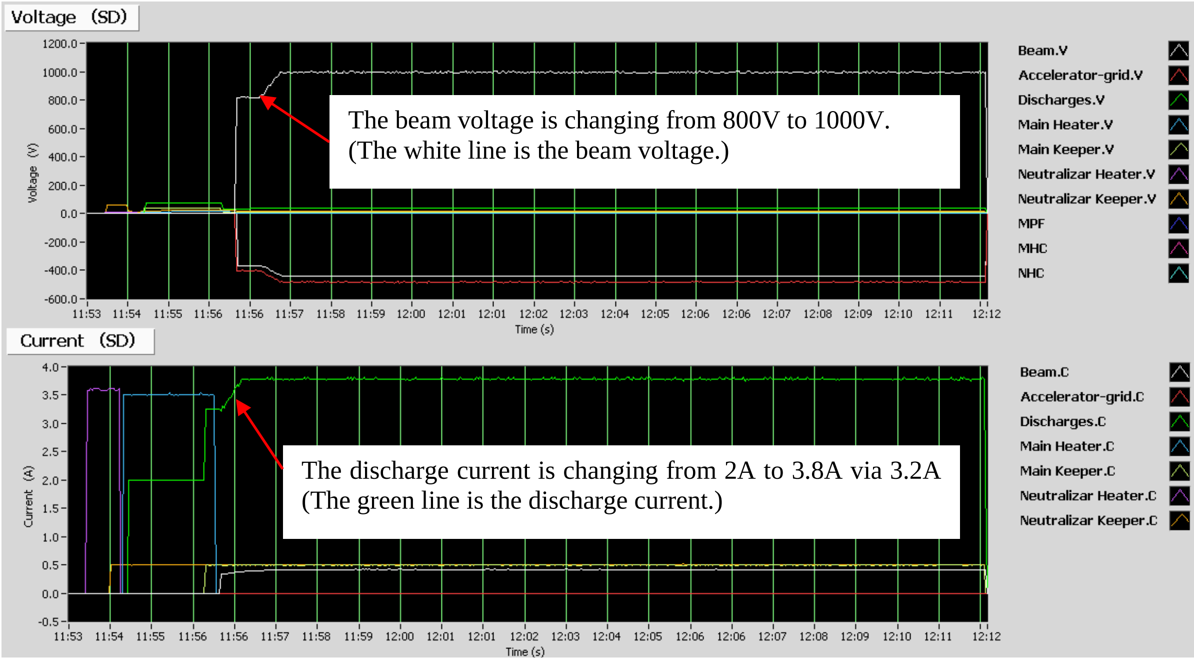


Figure 9. Telemetry data result of the Orbit mode

VII. Future plan

In 2009, we started the design of Engineering Flight Model (EFM) of the PPCU. After the design and the manufacturing, we plan to conduct qualification tests on the PPCU EFM and a coupling test on the PPCU EFM with the FM Ion Thruster.

VIII. Conclusion

The benefit of using an ion propulsion system for super low altitude satellites continues to increase for longer life missions, although the operation of the ion thruster requires a large amount of power consumption. The PPCU BBM has been developed to have high power efficiency and an operating sequence. We have tested it to verify its electrical characteristics and compatibility using an electrical load. The electric power efficiency of the beam power supply developed here is higher than 90% within the wide range of input voltage. Then a coupling test was conducted on the PPCU BBM and the ion thruster to verify the transient response and the sequence control. The test results showed a good performance for the PPCU BBM.

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