Development Status of High Voltage Power Supply for a 20mN Class Ion Thruster

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Abstract: Japan Aerospace Exploration Agency(JAXA) and Mitsubishi Electric Corporation(MELCO) are developing a new concept Ion Engine System(IES) including a Power Processing and Control Unit (PPCU) for the Super Low Altitude Test Satellite(SLATS). The IES uses an improved model of the 20 mN class Ion Thruster. The high voltage power supply is the most important part in the PPCU. This paper presents the design and test results of the high voltage power supply for the 20mN class Ion Thruster. The high voltage power supply is verified by electrical performance tests and all function tests. In last year, the high voltage power supply has been redesigned to work under an input voltage of between 22 V and 30 V to meet the SLATS system and various small satellites. Key issues of this power equipment are the generation of high voltage in the range of +800V to +1,100V for ion thrusters and the precise regulation of output power to allow fine adjustment of thrust levels. We propose to use the phase shift converter technique for the high voltage power supply. The output power of the high voltage power supply is stabilized over the wide range of load. The efficiency of the high voltage power supply is higher than 90 % when the load impedance conditions are 0.2 A to 0.6A at the input voltage of 22V.

I. Introduction

JAPAN Aerospace Exploration Agency (JAXA) is considering using an electrical propulsion system for the Super Low Altitude Test Satellite (SLATS), which orbits the earth at an altitude of nearly 200 kilometers.[1] The Kiku-8 ion thruster was chosen since it meets the SLATS system requirements due to its good thrust to power ratio and long lifetime for aerodynamic drag compensation. Therefore, based on the Kiku-8 IES development results, the research and development of a new Ion Engine System (IES) started to apply for the SLATS program.[2-5]

One of the most important design changes is to develop a Power Processing and Control Unit (PPCU) that combines power supplies and the control function. The issues for the PPCU are; lighter weight and smaller size, a

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new electrical interface with the power system, and a new autonomous control system for quick plasma ignition. The electrical interface with the satellite system has been changed from the interface with the kiku-8 system. The primary input voltage to the IES Power Processing Unit was 100V+-3V for Kiku-8. And in the first step, it was 32 V to 50 V for the PPCU. The voltage was lower and wider for the SLATS IES. After then, a lower input voltage was required for the PPCU in last year. The PPCU for the SLATS was redesigned to work under an input voltage of between 22 V and 30 V to meet various super low altitude satellite systems. A core equipment of PPCU is the high voltage power supply, whose function is to boost up the voltage of electrical power on the spacecraft main bus. Key issues of this power equipment are the generation of high voltage in the range of +800V to +1,100V for ion thrusters and a precise regulation of output power to allow fine adjustment of thrust levels.

Hence, it was planed to develop the high voltage power supply using the phase-shift control method. Based on the results of the test using the resistance load and shorted load, control methods of the power supply units were selected.

In this study, the efficiency characteristics of the high-voltage power supply and measurement results of the open-loop control are shown.

II. Outline of the IES for SLATS

SLATS is required to be small enough to be launched together with another large satellite on a H-2A rocket. Due to its system limitations, the SLATS IES needs to be as small sized and light-weight as possible. It also needs to have a quick-response performance of the plasma ignition for drag compensation. In addition, the electrical interface with the SLATS system has been changed from the GEO satellite system as the satellite bus voltage is lower than 50V. Therefore, the considerations for SLATS IES are: lighter weight and smaller size, the electrical interface with the power system, and a new autonomous control logic for quick and stable thrust generation.

The IES configuration for SLATS is shown in Figure 1. 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 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.

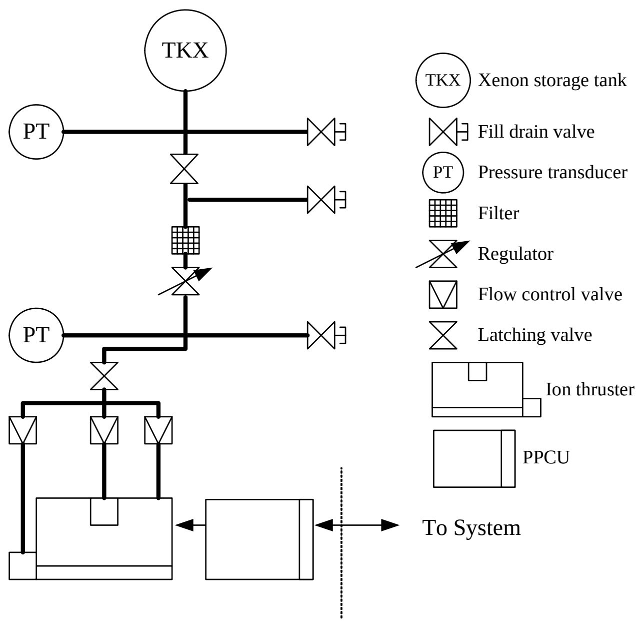

Figure 1. IES Configuration for SLATS

The PPCU is being developed at present. Though a power processing unit (PPU) and a controller are different components for Kiku-8 IES, it was decided to make them as a component called PPCU to reduce manufacturing cost and the size of the IES. The control function is realized with an FPGA instead of a 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 was 100±3V, but the PPCU is redesigned to work under an input voltage between 22V and 30 V to meet the SLATS system and various satellite systems.

The propellant management system is the same as Kiku-8 propellant management system. Xenon is used as the propellant and is stored in 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. The mass flow rate is adjusted at 10.5sccm(including 2sccm for the neutralizer). 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. The SLATS is launched with another large satellite and inserted into the orbit of 500-600km of altitude. The SLATS orbit altitude is reduced to 250km using chemical thrusters. 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. We have over 90 days of the experiment period to get the attitude disturbance data due to air drag and the atomic oxygen data at the surface and inside of the satellite body to use them in the design of practical super low altitude satellites.

III. Requirements of the PPCU and high voltage power supply

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.

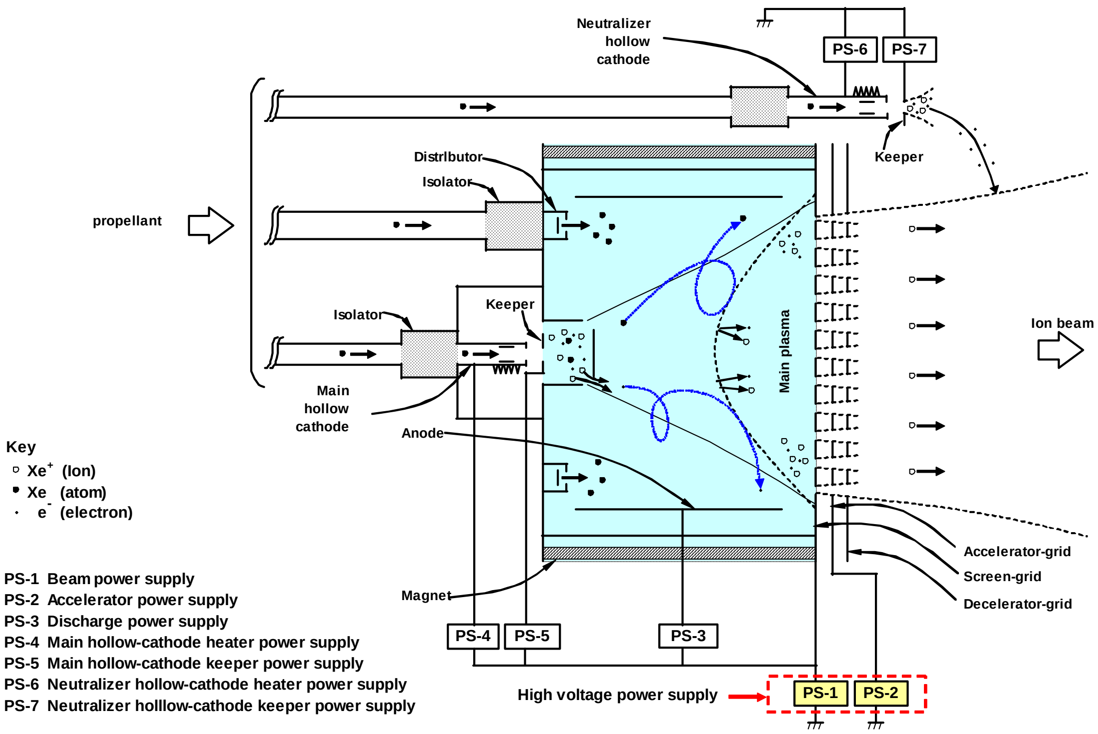

Figure 2 Electrical interface between the thruster and the PPCU

A. 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 (22V-30V). 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.

B. Main specifications

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

(1) Operating bus voltage: 22V to 30V

(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 x 10^4Gy (Si).

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

(6) Random vibration: 10Hz to 2000Hz, 196.1 m/s^2 rms (20Grms)

(7) Shock: 100Hz to 3000Hz, 9806.7 m/s^2 (1000G)

(8) High voltage power supply: Output power requirements are as shown in Table 1.

(These requirements are applied for the 20 mN class Ion Thruster)

Table 1. High-voltage power supply requirements

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
Beam PS	800～1100	0.2～0.6	5	C.V ±3	660	90
Accelerator PS	- 400～ - 550	0.001～0.1	5	C.V ±5	5.5	

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

IV. Design of High Voltage Power Supply

A. Design Points of PPCU

The PPCU should have a compact volume and correspond to the wide load range of the plasma loading resistance. Figure 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 high voltage power supply consists of the beam power supply and accelerator power supply. The signal interface circuit is connected to the satellite communication bus and controls the IES's 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.

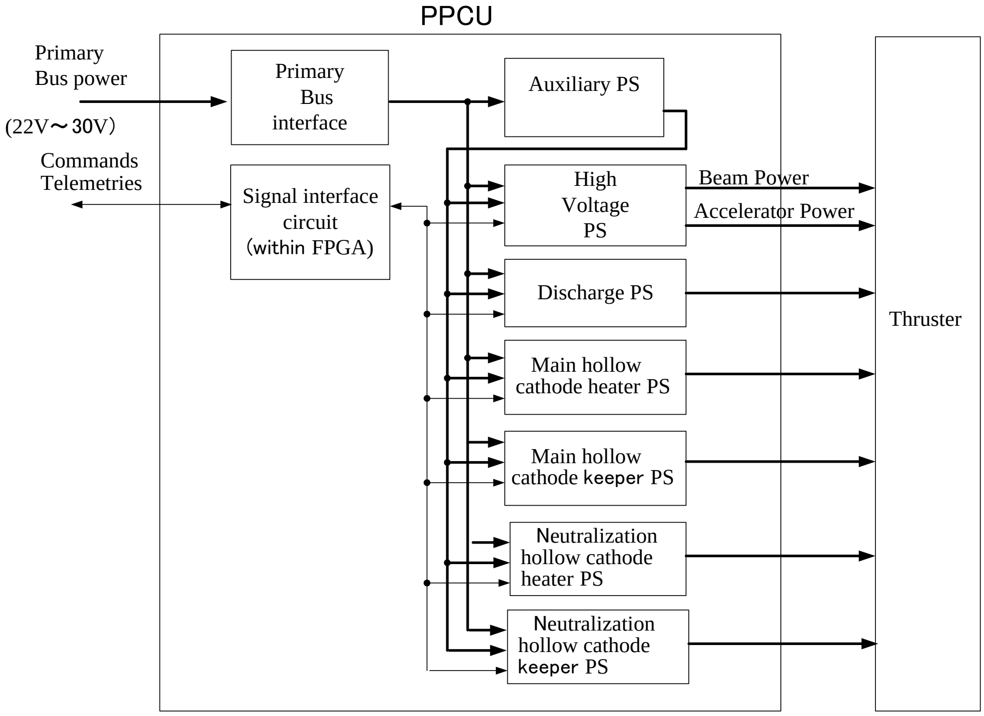

Figure 3. Block diagram of the PPCU

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 of SLATS.

The PPCU was redesigned to work under an input voltage of between 22 V and 30 V to meet various super low altitude satellite systems.

B. Outline of the high voltage power supply

The high voltage power supply is a core equipment of the PPCU, whose function is to boost up the voltage of electrical power on the spacecraft main bus. Key issues of this power equipment are the generation of high voltage for a ion thruster and a precise regulation of output power in order to allow fine adjustment of thrust levels. As mentioned, the high voltage power supply consists of the beam power supply(PS1) and the accelerator power supply(PS2). 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 the minus half of PS1 output voltage. The PS1 and PS2 have slow start characteristics of voltage so that they have the same rise/fall time. They use the same high-voltage transformer to synchronize their output voltage.

The high-voltage power supply accounts for 70% of the electric power handled, and 40% of the volume in the PPCU. Hence, 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 % to achieve total efficiency of the PPCU over 85%.

The PS1 and PS2 also need to protect thrusters against discharge between the high voltage electrode and the return electrode. They have constant current control mode for the grids cleaning operation. If they have short circuit condition with a conductive contaminant (like a metal flake), the high voltage converter is controlled at constant current mode by the grid-cleaning-mode commands. When the PS3, PS5, and PS7 have open circuit condition at the disappearance of discharge (like a extinction of plasma), the high voltage converter is controlled in shut-off mode by autonomous control program in the FPGA.

C. Comparison of Power control method for high voltage power supply

It is necessary for the high voltage converter's switching frequency to be high to reduce size and weight. However, as higher switching frequency increases the switching loss, it is necessary to select the optimal power conversion and regulation methods in light of the reduction of power consumption, component characteristics, mass and weight. Candidates for the power conversion topologies are the partial resonance power conversion and the resonant power conversion. Candidates for the regulation technique are phase-shift modulation method, the pre-

Table 2(a). Comparison for high voltage power converter circuit topologies part1.

Converter Circuit Topology \ Item			Control Method	Efficiency (Constant Voltage control)	EMI Noise	Semiconductor stress (Constant voltage control)	Semiconductor stress (Constant currentl control)	Surge of energy (Constant current control)
Pratial-Resonance		Full-brige	Phase-Shift	good	good	good	good	good
Resonace	Voltage Resonance	Push-pull	Primary Pre-Regulator	fair	good	bad	bad	fair
Resonace	Voltage Resonance	Push-pull	Secondary Mag-Amp	bad	good	good	bad	fair
Resonace	Voltage Resonance	Push-pull	Vector-Combined	excellent	excellent	excellent	bad	bad
Resonace	Current Resonace	Push-pull	Pulse frequency modulation	excellent	good	good	bad	bad
Conventional Squarewave		Full-brige	Pulse width modulation	bad	bad	bad	bad	good

Table 2(b). Comparison for high voltage power converter circuit topologies part2.

Converter Circuit Topology \ Item			Control Method	Regulation range	Size Weight	Reliability	Total
Pratial-Resonance		Full-brige	Phase-Shift	fair	good	good	Best
Resonace	Voltage Resonance	Push-pull	Primary Pre-Regulator	fair	bad	bad	fair
Resonace	Voltage Resonance	Push-pull	Secondary Mag-Amp	good	fair	fair	fair
Resonace	Voltage Resonance	Push-pull	Vector-Combined	good	good	good	good
Resonace	Current Resonace	Push-pull	Pulse frequency modulation	good	fair	fair	fair
Conventional Squarewave		Full-brige	Pulse width modulation	fair	bad	bad	fair

regulator method, the magnetic amplifier method, the vector-combined phase control method, and the pulse frequency method. Table 2 show comparison for the high voltage converter circuit topologies and control methods.

The beam converter should stabilize the output voltage for a wide range of input voltage (22V to 30V), maintaining high power conversion efficiency. As for the conventional converter using the square wave processing, higher switching frequency causes larger power loss of semiconductors. Besides, the square wave converters produce on/off switching surge energy. The reliability of semiconductors is reduced by these stresses.

The power efficiency of the resonance converter is better than the conventional converter for high frequency switching applications because the resonant converter has prominent features of high power conversion efficiency and low switching surge energy at the steady state operation. In order to regulate the resonant converter, the pre-regulator method, the pulse frequency modulation method, and the magnetic amplifier method have conventionally been used. However, these conventional methods have the following drawbacks;

The pre-regulator method leads to low power conversion efficiency because two power stages are cascade-connected. The pulse frequency modulation method on the current resonant converter yields the increase in size and weight of the smoothing output-filter because the operating frequency reaches minimum at the maximum input voltage. The magnetic amplifier method on the voltage resonant converter exhibits control instability when operated at a wide input voltage range because the control loop gain contains the fourth-order phase lag and the value of input voltage.

The vector combined phase control method has prominent features of high efficiency and low switching surge voltage comparing with the conventional control methods in a resonance converter. As the power transfer from primary to secondary is independent of resonance operation, the loss of the resonance circuit is low and size is small. The inverter is essentially a current-fed type as the coil in the primary circuit and the transformer primary winding work as a pseudo-current source.[4]

However, a resonance converter has some benefits only in constant voltage control mode. Besides, the resonance wave converters produce a bigger switching surge energy in constant current control mode. The resonance converter is difficult to operate in constant current control mode with the short circuit. It requires that the secondary road impedance is not a short circuit.

On the other hand, as for the partial resonance power conversion using the phase-shift wave processing, higher switching frequency results in the increase of the off-switching power loss of power semiconductors. However, the power efficiency of the partial resonant converter is better than the conventional converter for high frequency switching applications because the partial resonant converter has prominent features of high power conversion efficiency and low switching surge energy at the steady state operation and in short circuit state. Besides, the partial resonance converters has a compact characteristics. Furthermore, the total performance of a partial-resonance converter with phase shift control method is better than resonance converters shown in Table 2. It is advantageous for load protection, input current limiter design and constant current control design. The switching frequency is set to 40 kHz because of the constraint of the recovery time of high voltage diode.

As the results of trade-off study, we selected the phase shift converter (partial-resonance) for the high voltage power supply.

D. Design of the high voltage power supply

The high voltage power supply is a full-bridge type phase-shift converter. Its schematic is shown in Fig. 4. The high voltage power supply has two output control modes. One is to maintain constant voltage for the beam extraction and the other gives constant current for a grid cleaning sequence. Therefore, the high-voltage power supply has a series impedance for the constant current mode control that is over 20 ohm.

The partial-resonance converter techniques match the high voltage power supply for the 20mN class ion thruster. It has the following advantages;

-Power conversion efficiency is high, because power conversion is carried out by one power stage. Also, the power conversion efficiency is almost independent of the input voltage.

-Operating frequency is independent of the input voltage. As a result, the smoothing output filter is made compact by virtue of the constant high operating frequency.

-Control loop gain is stable at a wide range of input voltage. As a result, the open-loop control frequency is more than 1kHz as the beam converter.

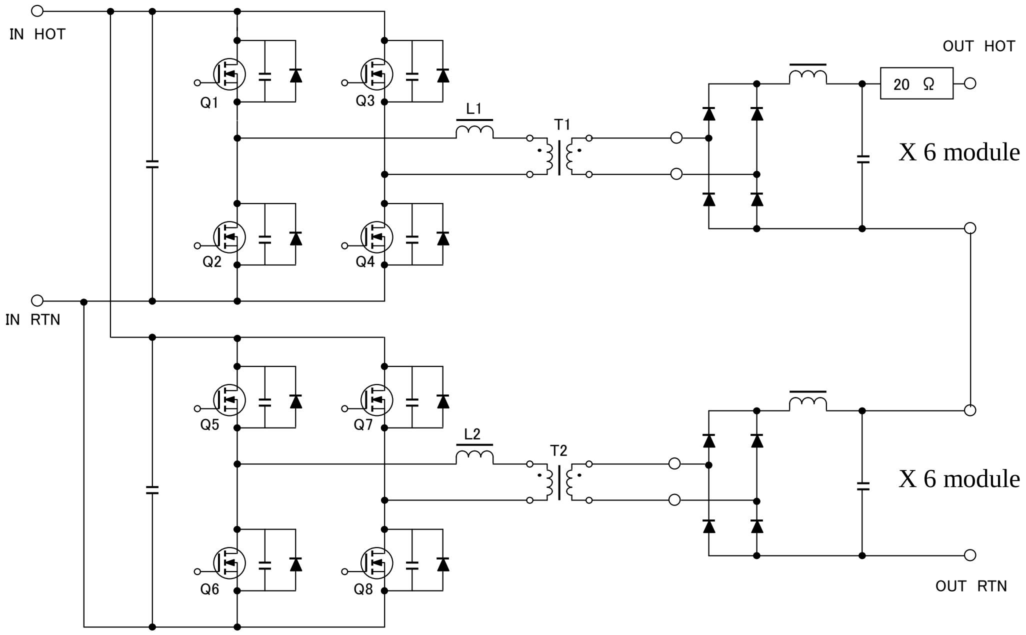

Figure 4. High-voltage power supply main power concept

V. Test Results of high voltage power supply

The high-voltage power supply was manufactured and tested to verify its electric characteristics and its compatibility with the electrical load. Its output power is stabilized in the wide range of the load. The power efficiency of the high voltage power supply versus output current is shown in Fig. 5. The power efficiency over 89.8 % is achieved in the input voltage range of 22 to 24 V and in the output current of 0.3 to 0.6 A for the beam power supply. The test condition is at ambient and PS2 output current is 0.01 A. The efficiency of the high-voltage power supply is higher than 90 % when the load impedance conditions are 0.2 A to 0.6A at input voltage 22V. The measurement result is better than other types of high-voltage power supply. It reduces the switching loss of power MOS FETs.

The open-loop control characteristic is shown in Fig. 6. The test condition of input voltage is 32V. For the performance of the cross over frequency, the open loop gain is over than 1kHz. The cross over frequency is 3.9kHz. That is good performance for plasma ignition. For the performance

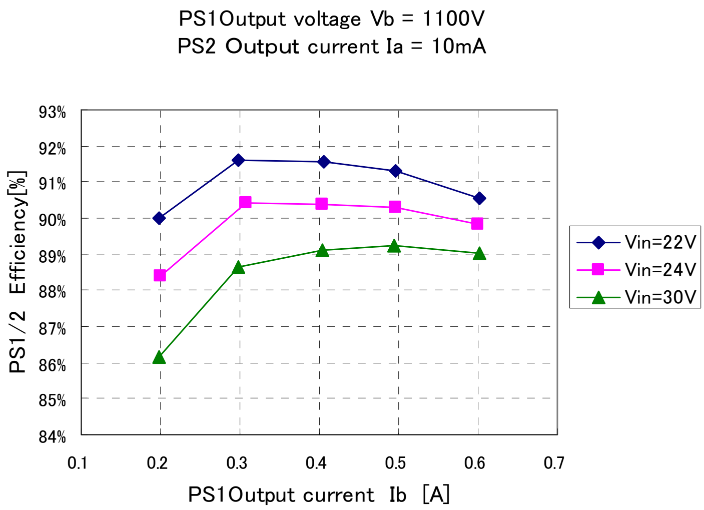

Figure 5. Output current vs Efficiency characteristics.

of the cross over frequency, the phase margin of over than 30 degrees is necessary. The phase margin is 56 degrees. It is a very good performance. All test results show a good performance for the high voltage power supply.

V. Conclusion and Future plan

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.

For application in SLATS, the high voltage power supply BBM (beam power supply and accelerator power supply) has been redesigned as input voltage range was changed. After trade-off study, the phase-shift converter technique was selected for the high voltage power supply.

The high voltage power supply BBM was manufactured and tested it to verify its electrical characteristics and compatibility using an electrical load. The efficiency of the high voltage power supply is higher than 90 % when the load impedance conditions are 0.2 to 0.6 A at input voltage of 22 V. The open-loop test was conducted on the high voltage power supply to verify the transient response and the sequence control. The high voltage power supply achieves the target (for low input voltage) of the main electrical performances.

For application in SLATS, the PPCU has been developed, which has high power efficiency and sequence control function. In 2012, the Engineering Flight Model (EFM) of the PPCU will be developed. After the design and the manufacturing, the qualification tests and acceptance tests of the PPCU EFM, and a coupling test of the PPCU EFM with the ion thrusters FM will be conducted.

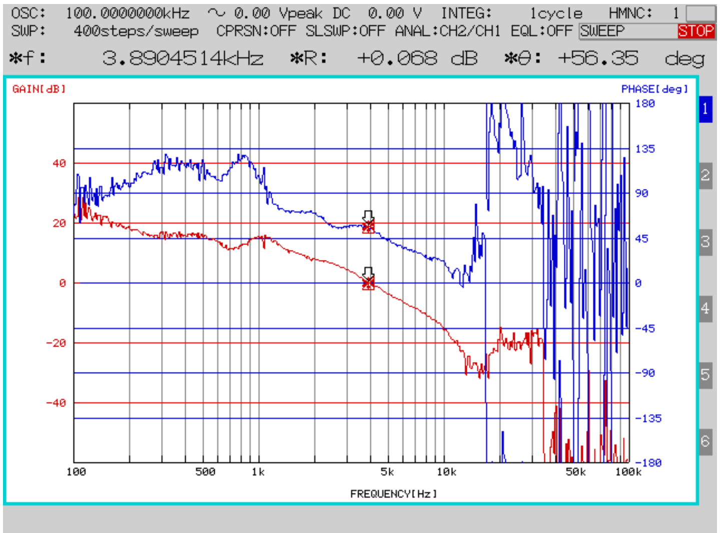

Figure 6. PS 1/2 open-loop control characteristics.

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