Performance of Power Processing Unit for 250mN-class Hall Thruster

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Abstract: The Institute for Unmanned Space Experiment Free Flyer (USEF) and Mitsubishi Electric Corporation (MELCO) are developing the next generation ion engine system under the sponsorship of the Ministry of Economy, Trade and Industry (METI). The system requirement specifications are a thrust level of over 250mN and specific impulse of over 1500 sec with a less than 5kW electric power supply, and a lifetime of over 3,000 hours. These target specifications required the development of both a Hall Thruster and a Power Processing Unit (PPU). The PPU Second Engineering Model (EM2), including all power supplies, is a model for the Hall Thruster system. The EM2 PPU showed the discharge efficiency is over 95.5% at output power between 2.8kW to 4.5kW, when operational temperature was between –25 degC to +55 degC. It is also shown that the EM2 PPU can start up the Hall Thruster quickly and smoothly under these conditions. Weighing only 11.9kg, the EM2 PPU is also the 4.5kW class's smallest and lightest qualification test model. This paper reports on the qualification test results of the EM2 PPU and the EM2 Hall Thruster coupling test results.

Nomenclature

Q	=	mass flow rate, Kg/seconds
Va	=	anode voltage, V
B	=	magnetic flux density, T
Ic	=	inner magnet current plus outer magnet current, A

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G = gravitational acceleration, 9.8m/(seconds x seconds)

I. Introduction

AN electric propulsion system is an essential technology for the orbit control of satellites in space. In recent years, geosynchronous satellites and spacecraft with hall thruster systems have been launched and operated by a number of countries. [1-6] The Institute for Unmanned Space Experiment Free Flyer (USEF) and Mitsubishi Electric Corporation (MELCO) have been developing the next generation ion engine system under the sponsorship of the Ministry of Economy, Trade and Industry (METI) [7-13] since 2003. The system requirement specifications are a thrust level of over 250mN and specific impulse of over 1500 sec with a less than 5kW electric power supply, and a lifetime of over 3,000 hours. These target specifications required the development of both a hall Thruster and a Power Processing Unit (PPU). In the 2003 fiscal year, the breadboard model (BBM) discharge power supply and keeper power supply were developed. In the 2004 fiscal year, the development model (DM) of the PPU was made and tested. This model was used mainly to evaluate the adjustment of the hall thruster system and the power supply, which consists of seven types (discharge power supply, cathode keeper power supply, cathode heater power supply, two magnet power supplies, mass flow controller power supply and house keeping power supply) [7-8]. In the 2005 to 2006 fiscal year period, we carried out a life test of new PPU parts using First Engineering Model (EM1) and in 2006 the EM1 PPU was developed. The EM1 PPU was matched with the First Engineering mode Hall Thruster (EM1 HT) [9-13]. The EM2 PPU and the Second Engineering Model Hall Thruster (EM2 HT) were developed in 2007[14]. Since 2008, we have been coupling tests between the EM2 PPU and the EM2 HT. EM2 PPU achieves target performance in all qualification tests.

II. Requirements of the EM2 PPU

The anode power conditioner voltage was increased up from 300V on the EM1 PPU to 350V on the EM2 PPU. The development targets of the EM2 PPU are: 1) to adapt the PPU to the EM2 Hall Thruster and 2) to increase the operating range of the EM2 PPU in comparison with the EM1 PPU. The target weight of the EM2 PPU is 13kg. This target means more than 2.5kg/kW of mass-power ratio. We used the metal oxide semiconductor field effect transistors (MOSFET) that were available as single event effect (SEE) radiation-hardened parts, in order to estimate the power efficiency of the EM2 PPU by using the same MOSFET parts of flight model PPU. It is important to develop both an anode power conditioner and the keeper power conditioner, which supply electric power to the electric discharge load of the hall thruster. The power efficiency target of the anode power conditioner is more than 93% in order to achieve the PPU total efficiency. The internal radiation environment for unshielded parts is 1 X 10^4Gy (Si). The power conditioner of the EM2 PPU followed the circuit method design of the EM2 PPU.

A. Electrical power interfaces

The EM2 HT electrical power interfaces are shown in Figure 1. The EM2 HT uses electric power to ionize the xenon propellant and produce thrust. The EM2 HT needs five kinds of electrical interfaces (anode, cathode keeper, cathode heater, inner magnet and outer magnet). Each electric element and mass flow controller requires independent electric power conditioners. The electric power to anode, cathode keeper, cathode heater, inner magnet, outer magnet, and mass flow controller are supplied by the power conditioners PC1, PC2, PC3, PC4, PC5, and PC6 respectively. The auxiliary power conditioner (PC7) supplies a printed circuit board of each power conditioner.

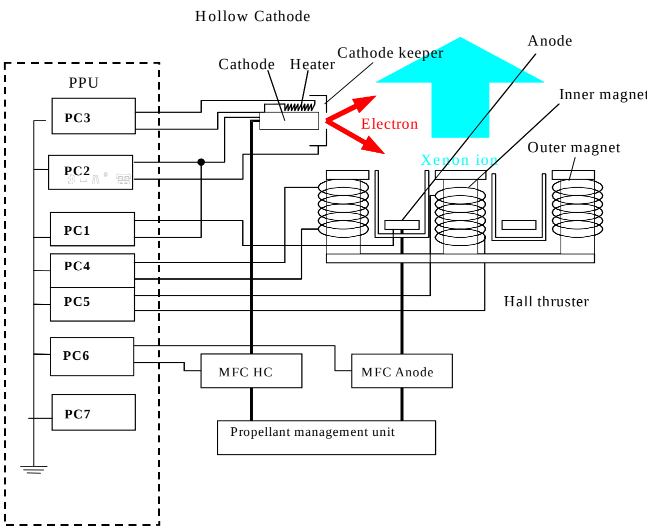


Figure 1. EM2 HT power interfaces

B. Main functions

The main functions of the EM2 PPU requirements are as follows:

(1) Primary Bus interface:

The PPU is designed to operate with regulated +100V power bus. The PPU has main bus protection and electromagnetic compatibility (MIL-STD-461E).

(2) Power conditioners (PC1 to PC7):

The PPU supplies the Hall Thruster according to the seven conditioners power specific power profile. These power conditioners' supplies must be floating from the primary bus.

(3) Signal interface:

The signal interface communicates between the satellite communication bus and the PPU, in accordance with RS422 interface bus.

(4) Automatic sequence

The PPU automatically controls and surveys the thruster operation of start-up, stop, failure recovery and any other necessary operating sequences.

C. Main specifications

The main specifications of the EM2 PPU requirements are as follows:

(1) Operating bus voltage: 100V±3V

(2) PPU total efficiency: more than 93% (at 4500 W of the anode conditioner output power.)

(3) Operating temperature: -20 degrees C to + 45degrees C

(4) The internal radiation environment for unshielded parts is 1.0 X 1.0E4Gy (Si).

(5) Sine vibration: 10Hz to 100Hz, 20 G

(6) Random vibration: 10Hz to 2000Hz, 22.3Grms

(7) Shock: 100Hz to 3000Hz, 1000G

(8) Output power requirements are as shown in Table1. (These requirements are for the 250mN-class hall thruster.)

(9)EM2 PPU weight: less than 13.0kg

Table 1. EM2 PPU output power requirements

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
PC1	Anode PC	250～350	7～18	10	C.V ±5	4500	92
PC2	Keeper PC	25	0.5～1.0	5	C.C ±5	25	75
		100	0.01	25	C.V ±5	10	N/A
PC3	Heater PC	40	2.0～4.0	10	C.C ±3	160	85
PC4	Inner magnet PC	5	0.4～1.5	2	C.C ±3	8	30
PC5	Outer magnet PC	12	0.4～2.5	2	C.C ±3	30	30
PC6	Mass flow PC	10	0.4	2	C.V ±3	4	N/A
		-10	0.4			4	

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

D. Construction

The block diagram of the PPU is shown in Figure 2. The PPU consists of the seven power conditioners (PC1 to PC7), signal interface circuit and primary bus interface. The power of these conditioners is provided through the input filter from the primary bus interface. The signal interface circuit is the interface between the satellite communication bus and the PPU. The EM2 PPU has the same function as the DM PPU

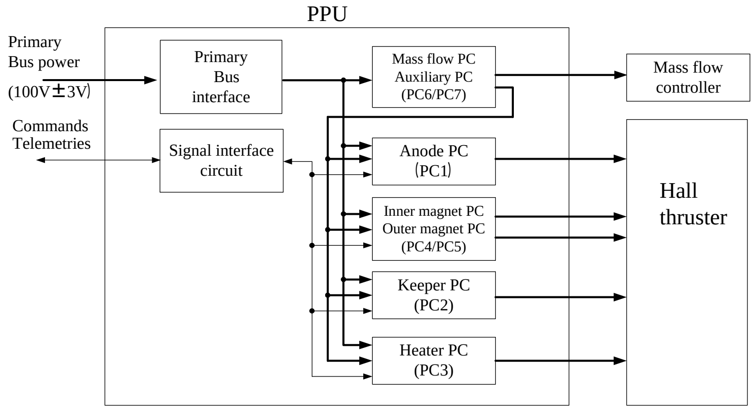


Figure 2. The PPU block diagram and electrical interfaces

Figure 3. External view of EM2 PPU

Figure 4. Internal view of EM2 PPU

III. Qualification test results

The EM2 PPU is designed to achieve light weight and low volume, and to minimize the temperature increases caused by the high power parts. The External view of EM2 PPU is shown in Figure 3. External dimensions are 473mm x 347mm x 97mm (LxWxH), and the mass is 11.9kg. The maximum anode output power limit is designed 6000 W for margin of EM2 Hall Thruster. The total power to mass ratio of the EM2 PPU is 11.9kg/4.7kW (2.5kg/kW). The maximum heat dissipation of the EM2 PPU was as high as 350W and the thermal design was the most critical design aspect. The anode conditioner, which has high power parts, is located at the bottom of the aluminum alloy chassis, and the other low power conditioners are located above and the on side of the chassis. The Internal view of EM2 PPU is shown in Figure 4. The electrical parts of the anode conditioner had very high dissipation. When these parts were mounted on the conventional printed circuit board (PCB) made with polyimide, the junction temperature of these parts went beyond the allowable temperature. To solve this problem, a metal core

PCB was used to realize good thermal conductivity. This PCB had adequate coefficient of thermal expansion (CTE) to mount large ceramic parts. The layout design of several conditioners was optimized to avoid thermal coupling of each conditioner. As a result, the junction temperatures of the electrical parts used in the EM2 PPU stay within the upper temperature limits. We have designed the mechanics of the EM2 PPU to be adaptable for use in as wide range of satellite programs as possible.

A. Test flow

Figure 5 shows the EM2 PPU qualification test flow. The thermal vacuum test is eight cycles. The EMC tests are Conducted Emissions, Conducted Susceptibility, Radiated Emissions, and Radiated Susceptibility.

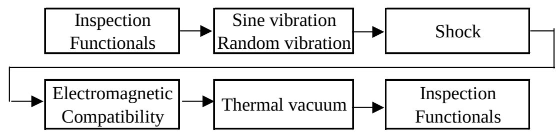


Figure 5. Qualification test flow

B. Inspection and Function tests

The EM2 PPU verified the electrical performance tests and all function tests. The output power of the anode power conditioner and all other power conditioners were stabilized over the wide range load. The power efficiency of the anode power conditioner versus output power is shown in Figure 6. An anode conditioner power efficiency of more than 95% was achieved in the output power range from 1.8kW to 4.5kW (at output voltage from 250 to 350V). The peak power efficiency of the EM2 PPU had been 96.2%. The power efficiency of the EM2 PPU was better than the DM PPU, because the internal cable of the EM2 PPU was shorter than DM PPU, and so the heat dissipation loss from the cable was very small. In addition, the high-voltage rectifier diodes used on the EM2 PPU were changed to Sic-diodes from the Si-fast recovery diode used on the DM PPU. The EM2 PPU total efficiency was more than 94%. The EM2 PPU achieved high power efficiency and reduction in size and weight in comparison with the DM PPU.

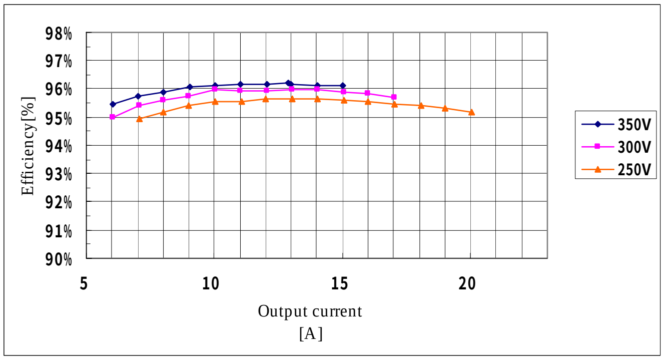


Figure 6. Efficiency of the anode power conditioner

C. Sine vibration and random vibration tests

The EM2 PPU was tested to qualification sine vibration levels as shown in Table 2. The EM2 PPU survived the qualification vibration with no structural damage. Function tests carried out after the vibration tests were also successful. Figure 7 shows the sine vibration levels. The EM2 PPU was tested to qualification random levels shown in Table 3. The EM2 PPU survived the qualification vibration test with no structural damage. Function tests carried out after the vibration tests were also successful. Figure 8 shows the random vibration levels.

D. Shock tests

The EM2 PPU was tested to qualification shock levels shown below in Table 4. The EM2 PPU survived the qualification shock tests with no structural damage. Function tests carried out after the shock tests were also successful. Figure 9 shows the input shock levels.

Table 2. Qualification Sine vibration levels

AXIS	FREQUENCY (HZ)	PSD LEVEL (G/Hz)
X,Y,Z	5 - 27.96 27.96 - 100 Sweep Rate	12.7mmDA 20G 2octaves/min

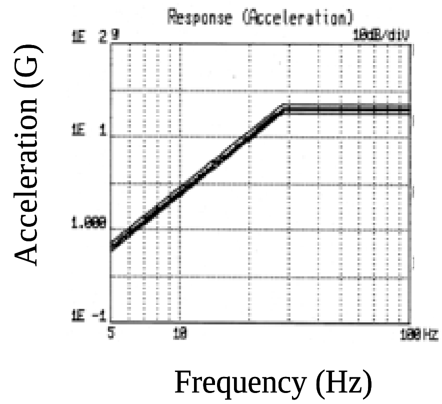


Figure 7. Input sine vibration levels

Table 3. Qualification Random vibration levels

AXIS	FREQUENCY RANGE(HZ)	PSD LEVEL (G/Hz)	OVERALL LEVEL (Grms)	DURATION (seconds)
X,Y,Z	20 - 50 50 - 270 270 - 400 400 - 1000 1000 - 2000	+6dB/oct 0.5 -4dB/oct 0.3 -6dB/oct	223	180

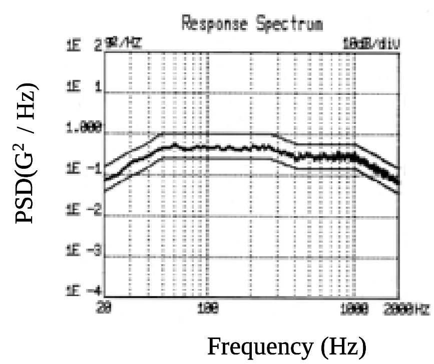


Figure 8. Input random vibration levels

Table 4. Qualification Shock levels

AXIS	FREQUENCY(HZ)	SRS
X,Y,Z	100 - 1000 1000 - 3000	+8 dB/oct 1000G

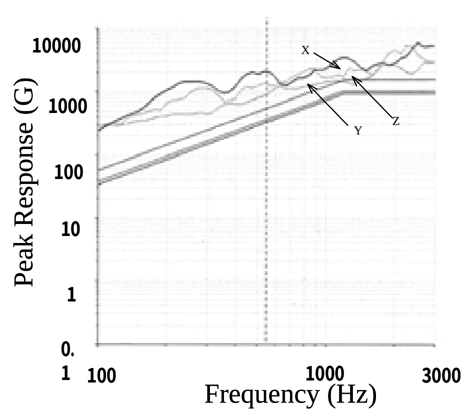


Figure 9. Input shock levels

E. Thermal vacuum tests

The power efficiency of the anode power conditioner versus output power is shown in Figure 10. Anode power conditioner power efficiency of more than 95% was achieved in the output power range from 1.8kW to 4.5kW. (At output voltage of 350V)

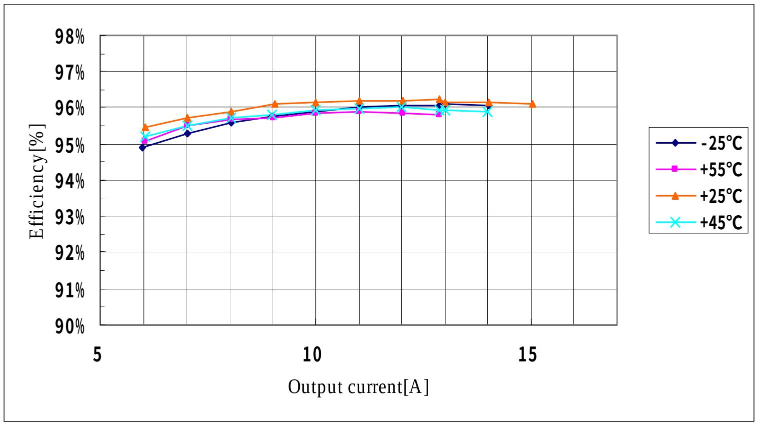
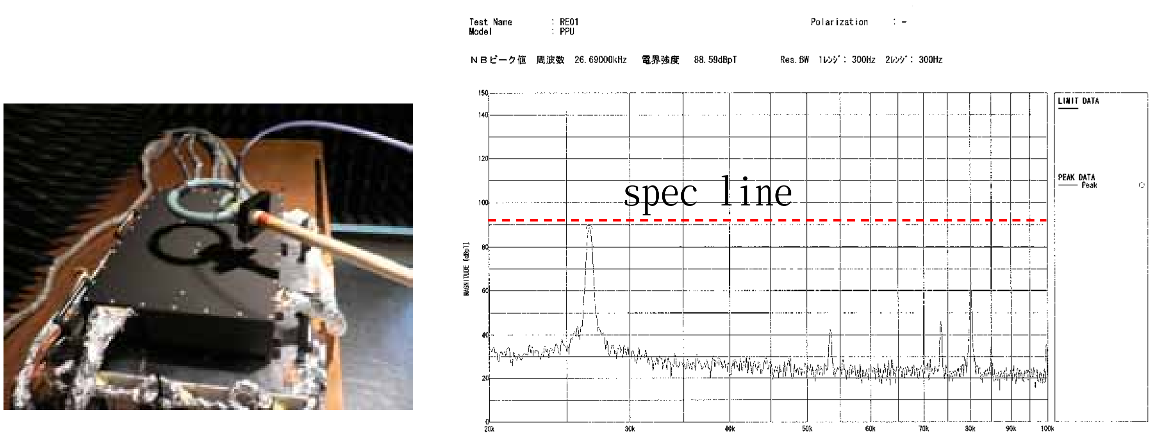


Figure 10. Efficiency of the anode power conditioner
(Thermal vacuum tests)

F. EMC tests

The EM2 PPU verified the electromagnetic compatibility tests. The target specification of the EM2 PPU is MIL-STD 461 and MIL-STD462 conformity standard. The EM2 PPU successfully achieved that level. Figure11 shows the external view of RE02 test.



Peak level is 88.59 dBpT

Figure 11. External view of RE test and a test result (20K to 100KHz)

IV. Coupling test results

A. Test conditions

We measured the discharge current responses of the hall thruster for various operating points. The EM2 PPU has confirmed that the performance of the EM2 HT meets the specified requirements. The EM2 HT was installed in a 3 m diameter, 5m long vacuum chamber.

Test conditions are as follows;

a. Pressure: 1.3×10^{-6} Pa (Background),
1.9×10^{-3} Pa (xenon: 1.46×10^{-5} kg/s)
b. PPU input voltage: 100 V
c. Anode voltage range: 250 V to 350 V
d. Inner magnet current: 0.4 A to 1.5 A
e. Outer magnet current: 0.4 A to 2.5 A
f. Keeper ignition voltage: 100 V
g. Keeper operating current: 1A
h. Heater current: 2 A to 4A
i. Thruster mass flow rate:
7.32×10^{-6} kg/S to 1.46×10^{-5} kg/s
j. Hollow cathode mass flow rate:
9.76×10^{-6} kg/s

The coupling test normal configuration is shown in Figure 12.

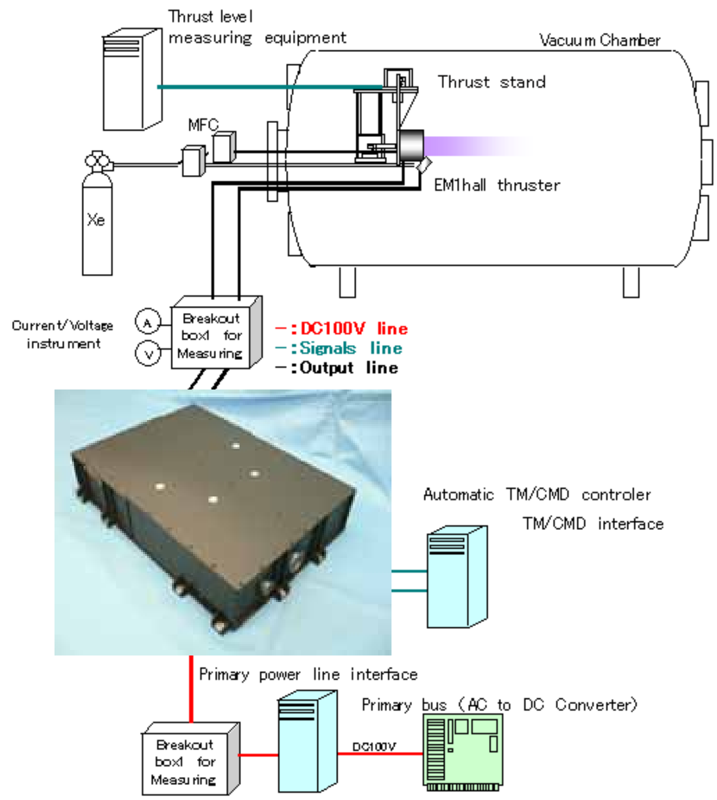


Figure 12. Coupling test normal configuration

B. Behavior at low frequency in discharge current characteristics

We evaluated a low frequency discharge current with the EM1 hall thruster and the EM2 PPU. The EM2 HT 250mN-thrust operation with the EM2 PPU is shown in Figure 13. The amplitude measurement results at low frequency of discharge current (or the discharge current oscillations) are shown in Figure 14.

Figure 13. EM2 HT 250mN-thrust Operation with EM2 PPU (at EMC Test)

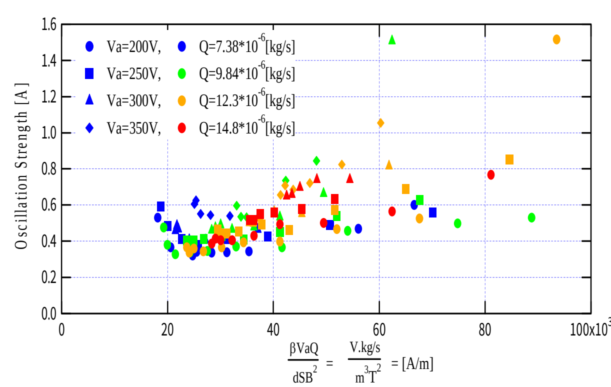


Figure 14. Behavior at low frequency in discharge current characteristics

In Figure 14, the vertical axis shows the normal deviation value of the low frequency of discharge current. The horizontal axis shows the governing parameters consisting of the anode voltage (Va), the xenon gas mass flow rate (Q) and the magnetic flux density (or inner magnet current plus outer magnet current are Ic) [9-10]. The EM2 PPU could suppress the low-frequency discharge current amplitude in less than 1.5A. The EM2 HT was confirmed to be stable for operating.

C. Consumption power versus the thrust characteristics

Figure 15 shows the characteristics of the input power of the PPU versus the specific impulse of the EM2 hall thruster. Figure 16 shows the characteristics of the input power of PPU versus the thrust level of the EM2 hall thruster. The EM2 HT shows the thrust level is 251mN and the specific impulse is 1697 seconds when the PPU input power is 4630W. At that time, the EM2 PPU total efficiency is 94.1%. We achieved target performance. (thrust level, specific impulse, and power)

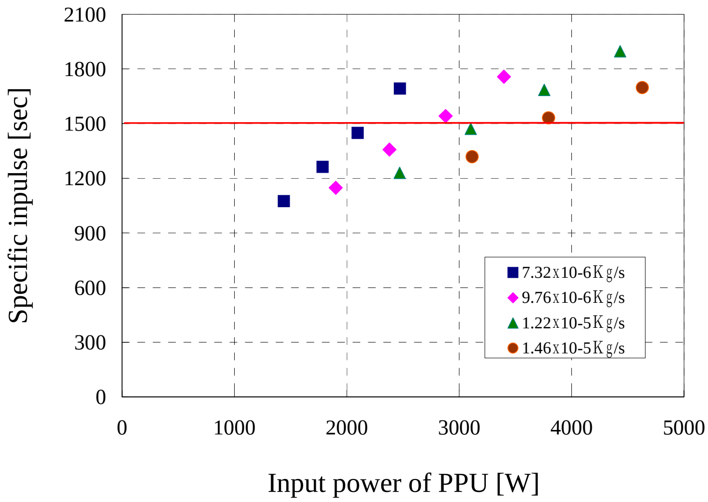


Figure 15. Specific impulse characteristics

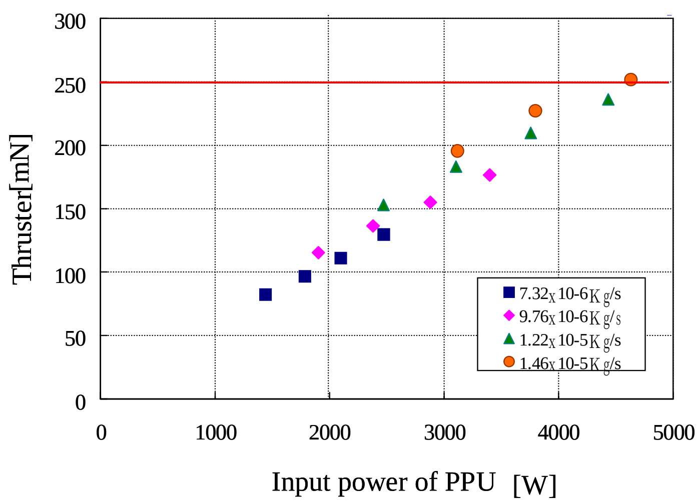
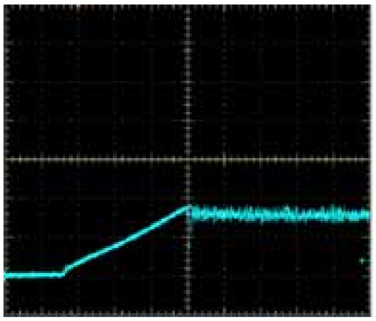


Figure 16. Thrust level characteristics

D. Primary current of operational transients

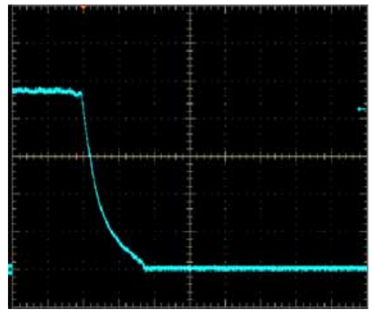
The EM2 PPU verified the primary inrush current of operational transients. Figure 17 shows primary current of the EM2 PPU for a startup discharge of EM2 HT at 100mN thrust. Figure 18 shows primary inrush current of the EM2 PPU for a close discharge of EM2 HT at 250mN thrust. These primary currents remained within operating specifications ($1x10^5$A/seconds) at all times. As a result the EM2 PPU completed the primary current specification of operational transients.



Input Current:10A/div

Time:100ms/div

Figure 17. Primary inrush current (Turn-on of Anode PC at 100mN thrust)



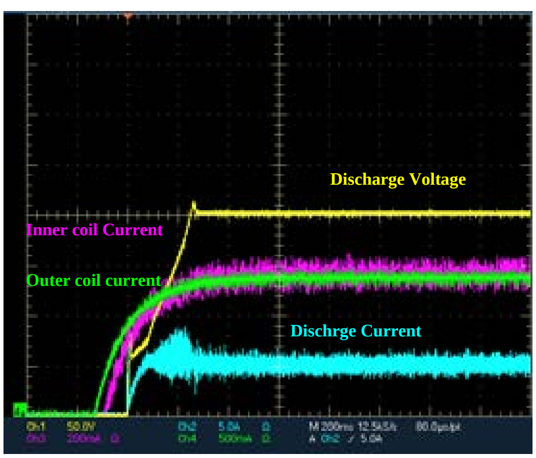
Input Current:10A/div

Time:100ms/div

Figure 18. Primary inrush current (Turn-off of Anode PC at 250mN thrust)

E. Discharge voltage and current of Turn-on transients

EM2 PPU of a start-up discharge ignition waveform is shown in Figure 19. The discharge turn-on peak current is 9A. The EM2 PPU can start up the EM2 Hall Thruster quickly and smoothly under 100mN to 250mN conditions. The discharge voltage, inner magnet current and outer magnet current are synchronous turn-on for reducing the low frequency discharge oscillation.

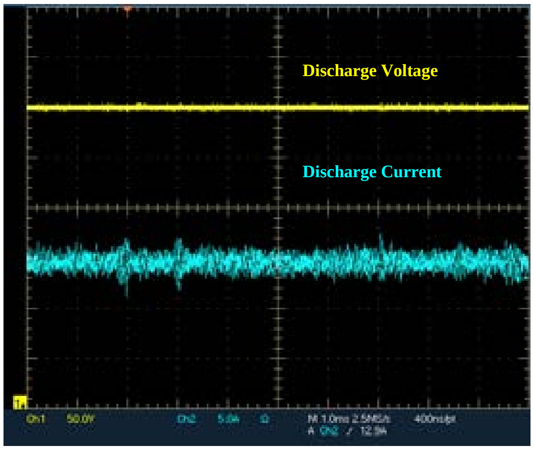


Ch1: Discharge Voltage 50V/div
Ch2: Discharge Current 5A/div
Ch3: Inner Magnet Current 0.5A/div
Ch4: Outer Magnet Current 0.2A/div
Time: 200ms/div

Figure 19. Discharge voltage Turn-on Transients waveform (Turn-on of Anode PC at 100mN thrust)

F. Operating discharge waveform

The operating discharge voltage and discharge current waveform is shown in Figure 20. Figure 20 is 250mN thrust. The discharge oscillation current is a very low current (5Apeak to peak).



Ch1: Discharge Voltage 50V/div
Ch2: Discharge Current 5A/div

Time: 200ms/div
Inner Magnet current: 1.3A
Outer Magnet current: 2.5A
Discharge voltage: 300V

Figure 20. Operating discharge waveform
(250mN thrust)

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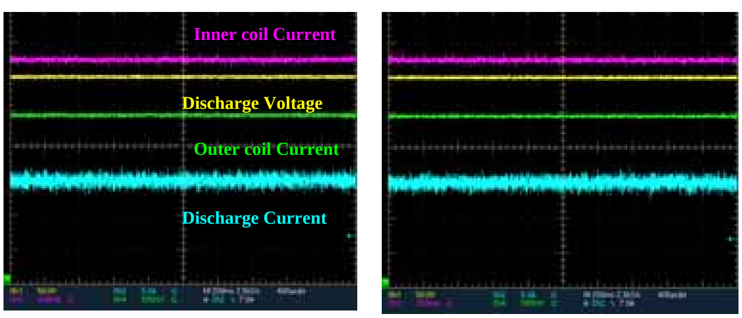
G. Coupling EMC test

Figure 21 shows the discharge voltage waveform at conducted susceptibility test. The EM2 PPU reduce the low frequency noise and supply the clear discharge voltage to the EM2 Hall Thruster.



Ch1: Discharge Voltage 50V/div
Ch2: Discharge Current 5A/div
Ch3: Inner coil current: 0.2A/div
Ch4: Outer coil current: 0.5A

Discharge voltage: 300V
Time: 200ms/div

Left photo is input noise level 3 Vpp   Right photo is no noise.

Figure 21. Discharge waveform at CS Test
(Test of Low frequency: 30Hz to 100kHz)

V. Conclusion

The EM2 PPU has been developed to be of light weight and have low volume. The EM2 PPU weight is 11.9Kg, and external dimensions are 473mm x 347mm x 97mm (LxWxH). The power to mass ratio of the EM2 PPU is 11.9kg/4.7kW (2.5kg/kW). The EM2 PPU maximum anode PC output power is 5250 W. The Hall Thruster propulsion systems have achieved more than 250mN as thrust level and more than 1500sec as specific impulse under 5.0kW on input power. Furthermore, the EM2 PPU has satisfied all test requirements, including the qualification test with electrical load equipment and coupling tests between the EM2 PPU and 250mN-class hall thruster.

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