

# Development Status of Power Processing Unit for 200mN-class Hall Thruster

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**Abstract:** Mitsubishi Electric Corporation (MELCO) has been developing a Hall thruster and its power processing unit (PPU). An anode power supply and a cathode keeper power supply of the PPU for a hall thruster demand high technique. The anode power supply needs large power, high voltage, and high efficiency. On the other hand, the cathode keeper power supply requires good constant voltage- constant current (CV/CC) characteristics. Therefore, at first, MELCO designed and fabricated these power supplies as the prototype productions in 2003, and using 3kW class MELCO breadboard model (BBM) Hall thruster, we confirmed both power supplies achieved very good performances and characteristics. In 2004, the development model (DM) PPU was designed, fabricated, and tested. It consists of seven power supplies for an anode discharge, a cathode keeper, a cathode heater, two magnetic coils, mass flow control devices and auxiliary power supply. An anode power supply efficiency is 92.6% for nominal 3kW at voltages between 200V to 300V. Discharge power can be set up to 4kW. In 2005, we are planning on evaluation PPU-

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**DM using MELCO DM hall thruster and MELCO engineering model (EM) hall thruster. In this paper, the development status of MELCO PPU and our future plan are reported.**

## I. Introduction

Mitsubishi Electric Corporation (MELCO) has developed the power processing unit for 20mN-class xenon ion thruster, kaufman-type applied to the north and south station of GEO satellites for position control in 1989.<sup>1</sup> MELCO develops the 20mN-class xenon ion engine subsystem PFM for Engineering Test satellite VIII (ETS-VIII) under the contract of Japan Aerospace Exploration Agency (JAXA). In many countries, a the hall thruster propulsion systems for use on geosynchronous satellites or spacecrafts have been developed in recent years.<sup>2-7</sup> At present, MELCO participates in the development project of the next generation ion engine technology for Institute for Unmanned Space Experiment Free Flyer (USEF), Ministry of Economic, Trade and Industry (METI), and New Energy and Industrial Technology Development Organization (NEDO). The target of this project is the development of the electric propulsion system, which achieve over 250mN thrust level and over 1500sec specific impulse under supplying 4.5kW power and over 3000hr lifetime. Since 2003, MELCO started developing a hall thruster and its power processing unit (PPU) and completed the design, manufacturing and testing in 2004. Our activity of PPU development for the hall thruster is described in this paper. The DM PPU was matched with the hall thruster DM, and showed stable operation and met all target specification. In 2005, we are developing the EM of the PPU for life test.

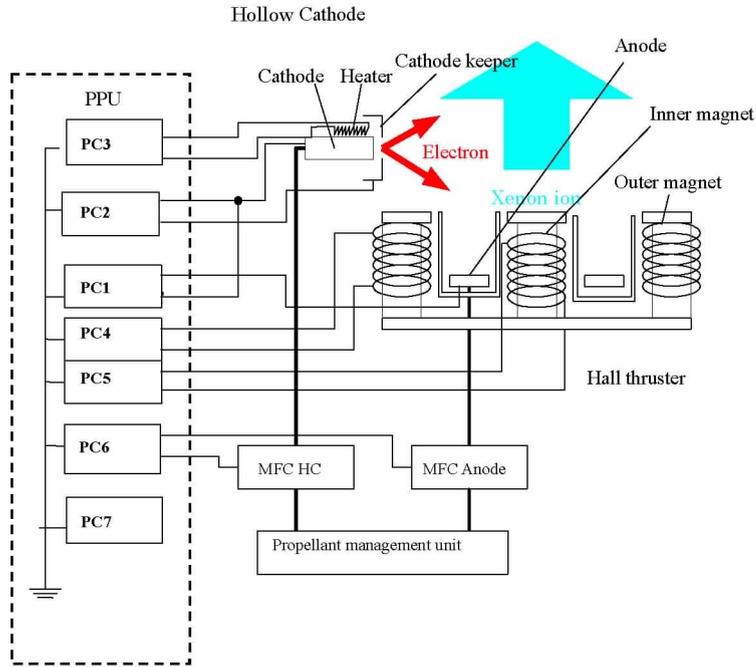
## II. Outline of the PPU

The hall thruster employs electric power to ionize the xenon propellant and accelerate the ion. A block diagram of the power supplies, which is to energize the hall thruster/power system, is shown in Figure 1. The hall thruster has five electrodes (anode, cathode keeper, cathode heater, inner magnet and outer magnet) and the mass flow controller. These electrodes and mass flow controller require independent stabilizer electric power conditioners. The electric power to anode, cathode keeper, cathode heater, inner magnet, outer magnet electrode, and mass flow controller are supplied by the power conditioners PC1, PC2, PC3, PC4, PC5, and PC6 respectively, and the auxiliary power supplies are supplied by the power conditioner PC7. The PPU also outputs twelve telemetry signals, which are anode voltage, anode current and so forth. The PPU has protection circuits to prevent power supplies and the hall thruster from being damaged at high voltage breakdown

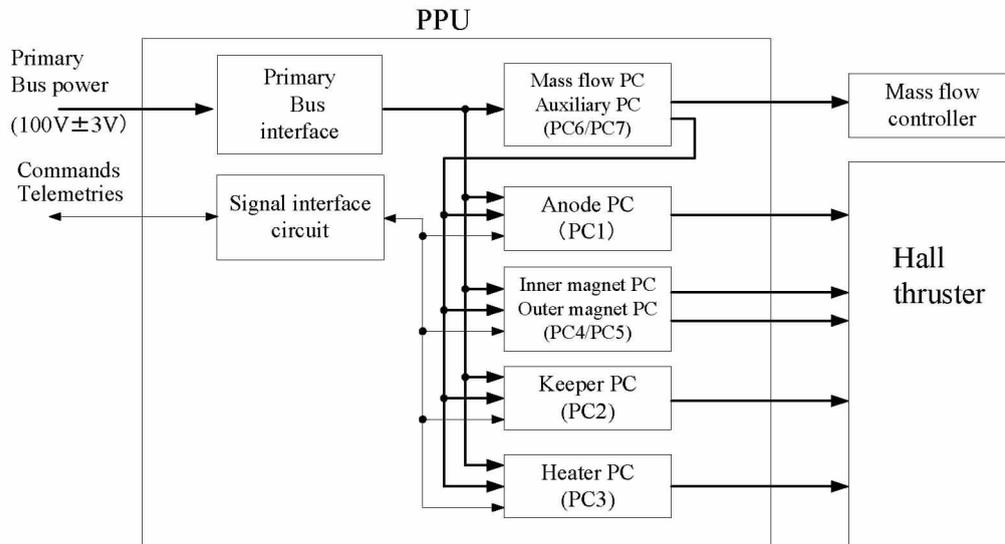
### A. Main functions of the PPU

A block diagram of the PPU is shown in Figure 2. PPU is constituted of the following elements (See Fig.2)

- 1) Primary Bus interface: main bus protection and electro-magnetic compatibility.  
The PPU is designed to operate with regulated +100V power bus.
- 2) Power conditioners (PC1 to PC7): the hall thruster is supplied according to their specific power profile. The power of these supplies is provide through the input filter. These supplies must be floating.
- 3) Signal interface circuit: the interface between the satellite communication bus and the PPU, in accordance with RS422 interface bus. Sequencer, automatically controls and surveys the thruster operation of start-up, stop, failure recovery and so on.



**Figure 1. The hall thruster/power interfaces**



**Figure 2. Block diagram of the PPU**

## B. Requirements of the PPU

The PPU requirements are:

1. Operation with a 100 volt regulated bus. ( $100V \pm 3V$ )
2. Efficiency of PC1 :92 % minimum  
PPU total efficiency :90% minimum  
(This specification is middle step target of the PPU)
3. Operating maximum temperature : + 60°C
4. The internal radiation environment for unshielded parts on the order of  $1 \times 10^4$ Gy (Si).
5. Output power requirements as shown in table1.  
(This specification is middle step target of the PPU)
6. PC1 to PC6 adapted the 200mN-class hall thruster.
7. DM PPU weight: less than 26.4kg (this specification is middle step target of the PPU, 4500W/170W/kg).

**Table 1. DM 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        | 200~300           | 5~15              | 10            | C.V $\pm 5$                   | 3000              | 92                              |
| PC2    | Keeper PC       | 25                | 0.5~1             | 5             | C.C $\pm 5$                   | 25                | 80                              |
|        |                 | 125               | 0.01              | 25            | C.V $\pm 5$                   | 12.5              | N/A                             |
| PC3    | Heater PC       | 40                | 2.0~4.0           | 10            | C.C $\pm 3$                   | 160               | 85                              |
| PC4    | Inner magnet PC | 10                | 0.2~2.0           | 5             | C.C $\pm 3$                   | 5                 | 60                              |
| PC5    | Outer magnet PC | 12                | 0.2~0.6           | 5             | C.C $\pm 3$                   | 5                 | 60                              |
| PC6    | Mass flow PC    | 15                | 0.7               | 3             | C.V $\pm 3$                   | 3                 | 80                              |
|        |                 | -15               | 0.3               |               |                               | 9                 |                                 |
| PC7    | Auxiliary PC    | 5                 | 1                 | 3             | C.V $\pm 5$                   | 5                 | 70                              |
|        |                 | -15               | 0.5               |               |                               | 7.5               |                                 |
|        |                 | 15                | 1.5               |               |                               | 22.5              |                                 |

Note.\*1:C.V, constant voltage

\*2:C.C, constant current

## III. BBM PPU

At first, MELCO designed and fabricated anode and keeper power conditioners as the elementary trial productions. The anode power conditioner is required that the electric discharge characteristic shall be as fast as  $0.3 \mu$  sec for turn-on/off, the voltage control characteristic shall be as stable as  $\pm 5\%$ , and the efficiency shall be as high as 92%. The keeper power conditioner is required that the electric discharge characteristic shall be well stable within  $200 \mu$  sec after turn-on, and the current control characteristic shall be as stable as  $\pm 5\%$ . We confirmed that these electrical discharge characteristics and control characteristics met the requirement with the BBM thruster.<sup>8</sup>

### A. Anode power conditioner

Since the anode power conditioner needs large electric power and high voltage, we adopted a full bridge circuit. Figure 3 shows the anode power conditioner circuit. The power converter topology is full-bridge type and rectifier circuit is current doubler technology. Main transformers (T1 and T2) are relatively large in size, yet the ring-type cores (toroidal cores) improves the electrical and mechanical performance because the toroidal cores enable minimizing the leakage inductance in a transformer. The main transformer tolerated the shock test up to the level of 1000G. (at 0.002 seconds half sine).

The efficiency versus output voltage is shown in Figure 4. Efficiency of anode conditioner is more than 94.6% in the output voltage range from 200 to 300V for the output power of 3000W constant. Maximum efficiency is 96.0%.

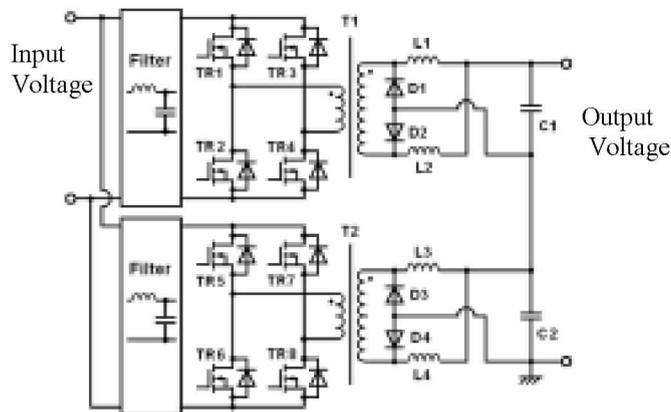


Figure 3. Anode power conditioner circuit

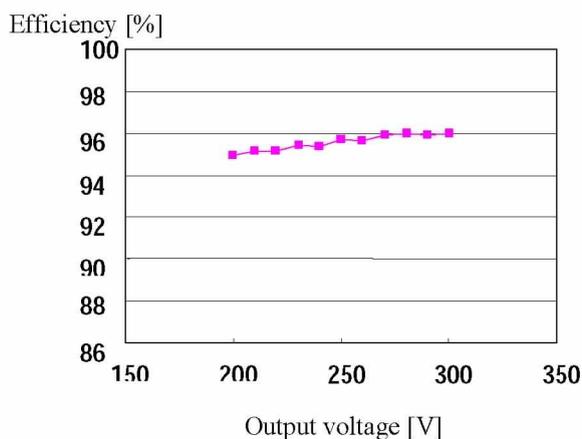


Figure 4. Efficiency versus output voltage

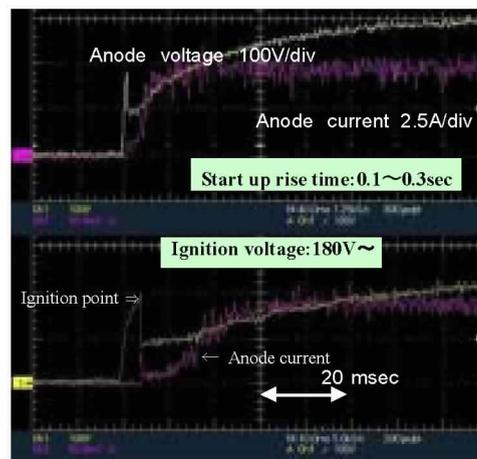


Figure 5. Anode power conditioner start-up waveforms

The anode power conditioner has been adapted to BBM thruster. Fig.5 shows the anode voltage and the anode current waveform at thruster start up. Upper graph is shown with the time scale of 0.04 seconds/div and lower graph is shown with 0.01 seconds/div. and the resulting anode voltage drop due to the anode power conditioner capacity. The drop off voltage followed right after the turn-on peak is determined by the anode power conditioner capacity. Controlling anode voltage, inner magnet current, outer magnet current and xenon flow rate, the thruster can start up quickly and smoothly

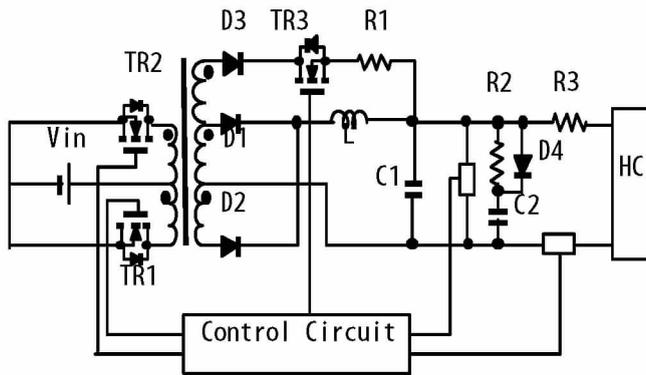
### B. Keeper power conditioner

BBM keeper conditioner is shown in Figure 6. We confirmed that the electric discharge transient characteristic was as quick as 150 microseconds or so with the experimental model. A development circuit of the keeper conditioner is shown in Figure 7.

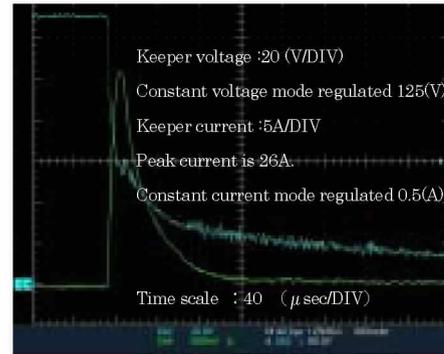


Figure 6. BBM keeper power conditioner

The push-pull type converter for the keeper conditioner has been selected to minimize the rectifier inductor. Faster ignition of the keeper electrode is desired, therefore, this rectifier circuit (C1, C2, R1, R2 and R3) has been designed in such way that its impedance matches well to the impedance of the hollow cathode keeper design. At first, we designed the main transformer with PQ type core because the keeper conditioner requirements of high voltage and high efficiency. However, PQ type core is almost three times larger than planar type core, therefore, the main



**Figure 7. Keeper power conditioner circuit**



Test method:  
Keeper power conditioner : C.V=125V, C.C=0.5A  
Xenon : 5secm, pressure :  $4 \times 10^{-4}$  Pa ( $3 \times 10^{-6}$  Torr)

transformer has been built with the planar type core to make the keeper conditioner small.

The keeper power conditioner has been adapted to BBM thruster. Fig. 8 shows the keeper voltage and the keeper current waveform at the ignition. BBM Keeper conditioner ignition characteristic is so smooth with the constant voltage and current that ensures the ignition. Efficiency of keeper conditioner is more than 80% at output current range from 0.9 to 1.0A at output power 25W constant.

**Figure 8. Keeper power conditioner ignition characteristic**

#### IV. DESIGN of DM PPU

At middle step, we designed, manufactured and tested the DM PPU. It consists of seven power conditioners for an anode discharge, a cathode keeper, a cathode heater, two magnetic coils, mass flow control devices and auxiliary power conditioner.

##### A. Anode power conditioner and Keeper power conditioner DM PPU Design

An anode power conditioner of electrical circuit and a keeper power conditioner of electrical circuit are reflected to BBM design. The anode conditioner peak power capability of the 300V regulator assembly is over the 4000W.

##### B. Heater conditioner

This power conditioner is used before hall thruster start up, to heat the hollow cathode. The maximum current is 4A, and the maximum power is 160W. The higher switching frequency of heater power conditioner is desirable to reduce its size and weight. Candidates for the power conversion method are the conventional square wave power conversion and the resonant power conversion. Candidates for the regulation technique are classified into the pulse frequency modulation method, the pulse width modulation method, the pre-regulator method and the magnetic amplifier. Table 2 presents comparison for the power conversion and regulation methods. Reducing the number of semiconductor parts improves the reliability of the heater power conditioner and reduced its mass. Switching frequency was set to 200 KHz because of the constraint of the recovery time of rectifiers diode, therefore, we selected the square wave power conversion and double forward converter method.

**Table 2. Comparison for conversion and regulation method**

| ITEM \ TYPE                     | Conventional squarewave  | Resonance  |  |  |
|---------------------------------|--|--|--|--|
|                                 | Double forward   | Voltage resonance  |  | current resonance  |
|                                 |  | MAG-AMP  | Pre-regulator  | PFM  |
| Efficiency                      | good   | excellent  | fair   | excellent  |
| Stress                          | Mos FET:2set<br>bad ASO curve<br>good voltage rating<br><br>Diodes:3set<br>reverse recavary<br>stress is large | Mos FET:2set<br>bad ASO curve<br>good voltage rating<br><br>Diodes:2set<br>reverse recavary<br>stress is large | Mos FET:2set<br>bad ASO curve<br>good voltage rating<br><br>Diodes:3set<br>reverse recavary<br>stress is large | Mos FET:2set<br>bad ASO curve<br>good voltage rating<br><br>Diodes:2set<br>reverse recavary<br>stress is large |
| Size,Weight                     | good   | fair<br>by existence<br>fair of reactive<br>power  | bad  | fair<br>by existence<br>fair of reactive<br>power  |
| EMI,Noise                       | bad  | good   | bad  | good   |
| Reliability                     | good   | good   | fair   | good   |
| Regulation<br>(wide load range) | good   | good   | good   | fair   |
| Total                           | excellent  | good   | fair   | fair   |

**C. Inner magnet power conditioner and Outer magnet power conditioner**

The inner magnet power conditioner and outer magnet power conditioner are dynamic current controlled buck, which interfaces with a load consisting of magnet coil. The magnet coil current is controlled and regulated to be equal to a reference given externally or internally by the sequencer. The maximum current is 2A, and the maximum power is 20W. These power conditioner requirements are wide range load regulation and wide range controlled current 0.2A to 2.0A. Therefore, we selected 2steps conversion method. This technique was called post regulator method. The first stage, an isolation converter changes 15V from preliminary bus voltage. Second stage, the post regulator is buck (step-down) converter topology because the post regulator requirements are high efficiency and wide range controlled current. The magnet coil impedance in the hall thruster is important because it has very large inductance and we have carefully designed the current controlled loop.

**D. Mass flow power conditioner and Auxiliary power conditioner**

The mass flow power conditioner and the auxiliary power conditioner are dynamic voltage controlled. Each of the power conditioners provides an output current limitation. The auxiliary power conditioner supplies internal signal circuit and the function of multi output voltages provide start-up sequence. The development target of these power conditioners is their miniaturization and achieving higher efficiency. We used the commercial parts of space class because the design of the power conditioner was not fixed yet at the time of parts procurement. We will improve these power conditioner that are one conditioner type. Bus under-voltage protection functions are implemented in the auxiliary power conditioner to protect the signal interface board. The protection circuit has the hysteresis characteristics of activation at approximately 50V and bus shutdown at 60V.

### E. Signal interface circuit

This signal interface circuit contains filed programmable gate array (FPGA) to realize internal controlled sequence. Also the signal interface circuit regulates many telemetries and commands. The telemetries include all data of output current and voltage of the DC sources. The telemetries available from that system are the status parameters of the logic and other housekeeping parameters. DM PPU is the RS422 interface because the RS422 interface allows to communicate with the spacecraft controller unit of MELCO or any heritage units.

### F. Mechanical/Thermal Design

The stand-by (no-load) power of the unit is 18W. (nominal) The throughput efficiency of the hall thruster power is better than 90% in full power mode. All power dissipating power conditioner are assembled on the module frame near the bottom to achieve a good thermal coupling to the massive base plate of the unit. The DM PPU is designed based on a modular mechanical design. This means that the printed circuit boards with their electronic components are mounted on a mechanical frame. These modules are screwed side by side on the DM PPU base-plate. The DM PPU mechanical housing is made from Al-Alloy. DM PPU is shown in Figure 9.



Size:520mm×420mm×192H mm

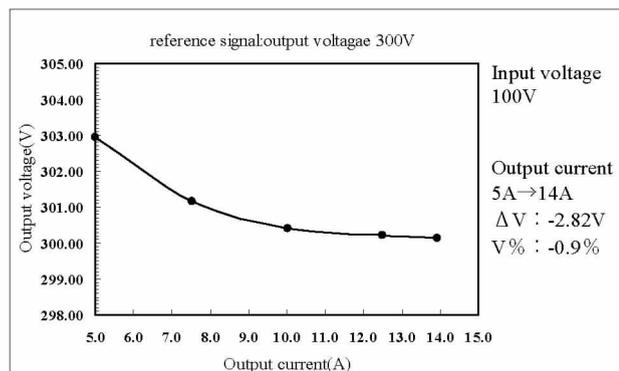
**Figure 9. DM PPU**

## V. Test results of DM PPU

### A. Electrical performance test

The electrical test of an anode power conditioner results satisfied the requirement. The load regulation of anode power conditioner was measured by the electrical lode. The output voltage versus output current is shown in Figure 10. The anode power conditioner stabilized wide rage load. Efficiency for the BBM PPU measures 96% for anode power conditioner at 3000W. DM PPU have been 92.6%, because the FET drivers used on the BBM unit were not guaranteed to meet the required radiation levels and the rectifiers diode used on BBM unit were Sic-diode, DM unit were Si-fast recovery diode.

Efficiency of keeper conditioner is more than 66% in the output current range from 0.5A to 1.0A (at load impedance is 25ohm constant). The peak efficiency for the BBM PPU is 87.2% for keeper power conditioner at 25W. DM PPU have been 80.3% because the FET drivers used on the



**Figure10. Anode conditioner load regulation**

BBM unit were not guaranteed to meet the required radiation levels and the rectifiers diode used on BBM unit were Sic-diode, DM unit were Si-fast recovery diode. The keeper power conditioner result of regulation mode test is shown in Figure11. The keeper regulation mode changes from constant voltage control to constant current control when the keeper discharge dummy is on. We confirm that the electric discharge transient of dummy load characteristic is as quick as in the order of 1000 microseconds with the DM model. Test conditions are as follows

- a. Input voltage : 100V
- b. Load change :  $15K\Omega \rightarrow 20\Omega$
- c. Keeper current reference : 1A

The keeper power conditioner regulation mode tests were successful, and the DM PPU started and operated the hall thruster simulator without any difficulty.

The efficiency of outer magnet power conditioner versus output current is shown in Figure 12. The degradation of the efficiency at the low output current (0.2A to 0.5A) is attributed to the following phenomena. Inside the low output current range, the output power is extremely low and the switching duty for power conversion is also extremely low. The outer magnet power conditioner efficiency of more than 60% is achieved in the output current range from 0.6A to 0.7A(at impedance=20ohm)

The inner magnet power conditioner efficiency of more than 60% is achieved in the output current range from 1.5A to 2.3A(at impedance=5ohm). The outer magnet coil impedance and inductance are larger than inner magnet impedance because the outer magnet coils consist of six of them in series. Therefore, inner and outer power conditioner test results were better than series regulator topology. The electrical test of DM PPU conditioner results satisfied the requirement as well.

The output current versus Heater power conditioner efficiency rent is shown in Figure 13. The heater power conditioner stabilized wide rage current. The heater power conditioner efficiency of more than 84% is achieved in the output current range from 2.0A to 4.0A(at impedance=10ohm)

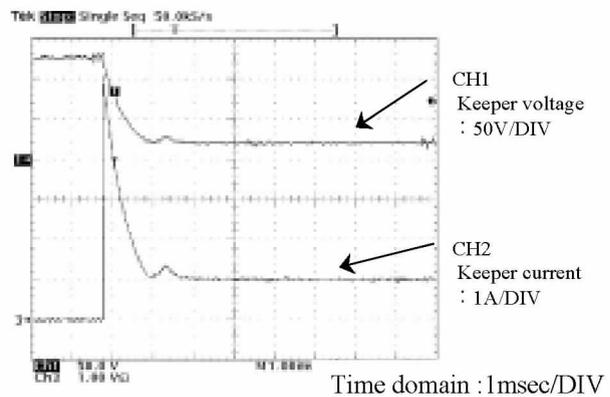


Figure11. Keeper regulation mode test

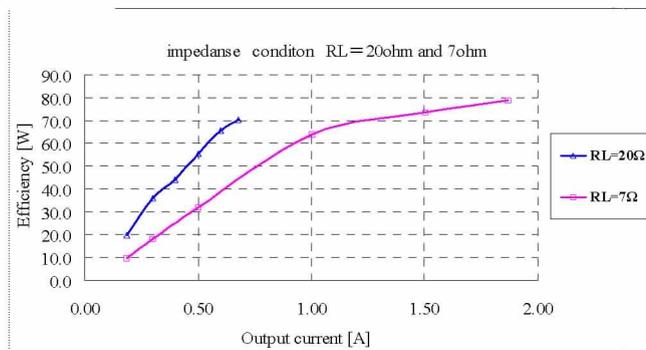


Figure12. Outer magnet efficiency versus output current

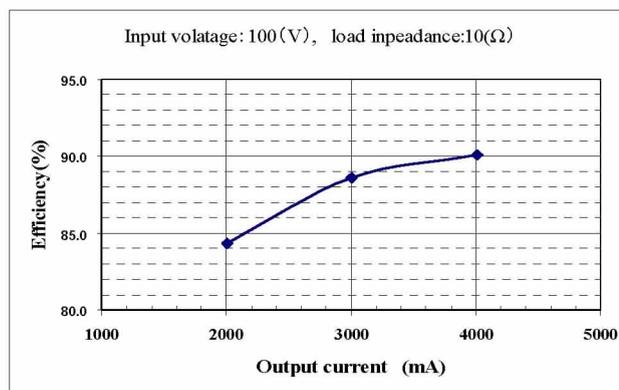


Figure13. Heater power conditioner efficiency

## B. Coupling test with DM 200mN-class hall thruster of MELCO

The electrical testing of the DM PPU has confirmed that the performance of the DM 200mN-class hall thruster of MELCO concept meets the specified requirements. The step responses have been measured for various operating points.

DM PPU coupling test configuration is shown in Figure 14. The DM thruster was installed in a 3 m diameter, 5m long vacuum chamber. Figure 15 shows the hall thruster operating waveforms. (anode voltage, anode current, keeper voltage and keeper current waveforms)

Test conditions are as follows.

- a. Pressure :  $1.3 \times 10^{-6}$  Pa (Background)  
 $1.9 \times 10^{-3}$  Pa (xenon: 150 sccm)
- b. PPU input voltage: 100 V
- c. Anode voltage range  
200 ~ 325 V
- d. Inner/Outer magnet current  
0.40 ~ 0.75 A
- e. Keeper ignition voltage: 125 V
- f. Keeper operating current: 1 A
- g. Heater current: 2.8 A
- h. Thruster mass flow rate:  
50 ~ 150 sccm
- i. Hollow cathode mass flow rate;  
10 sccm

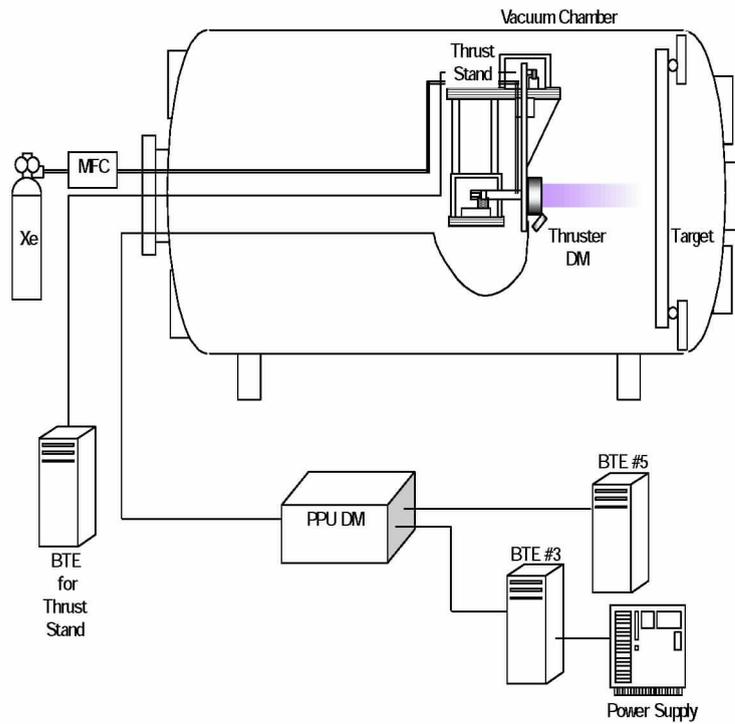
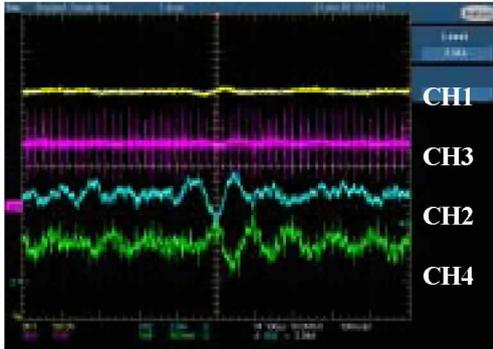


Figure14. DM PPU coupling test configurations

The electrical test was conducted with the hall thruster manufactured by MELCO and the subsequent testing with the DM hall thruster was also conducted. DM hall thruster integration tests were successful, and the DM PPU started and operated the DM hall thruster without any difficulty. Figure15 shows the keeper voltage noise under minimum anode current and its periodic cycle is 200  $\mu$  sec which attributes to the switching frequency of keeper conditioner.



CH1: Anode voltage (300V: 50 V/DIV)

CH2: Anode current (4A: 2A/DIV)

CH3: Keeper voltage (8V: 5V/DIV)

CH4: Keeper current (1A: 500mA/DIV)

**Figure15. DM PPU coupling test waveforms**

Coupling test between the DM PPU and 200mN-class hall thruster have been conducted using space chamber and the following items have been verified at this test

1. Nominal operation characteristic. (at 200mN thrust)
2. Maximum operation characteristic. (at 250mN thrust)
3. Minimum operation characteristic. (at 70mN thrust)
4. Start, restart characteristic.
5. Protection function.

## VI. Future plan on PPU

The PPU development plan continues with the hall thruster and coupling test of the anode, the magnet coil and the keeper. Several months of extensive testing followed to characterize and maximize beam stability and to decide the best configuration for the inner magnet conditioner and the outer magnet conditioner. Most of the electrical performance goals have been met with the DM PPU. The DM PPU weight is 25.2Kg. The mechanical layout and packaging design is currently on going, and the weight of the flight version is not final. The mechanical design has resulted in 12kg of total mass. The steady state output voltage of anode power conditioner is 350Volts. Delivered power to the anode will be in the range of 4500Watts. In 2005, we are developing the EM of the PPU for life test and in 2006, we will develop the elegant Engineering Model (EM #2) for 200mN-class hall thruster. This model will go through the qualification test.

## VII. Conclusion

- (1) Following subjects of PPU for 200mN-class hall thruster has been described herein.
  - Requirement and function
  - Design of BBM PPU
  - Design method of the anode power conditioner and the keeper conditioner
  - Design of DM PPU
  - Future plan on PPU
- (2) Following tests were conducted and they were all successful and maximum output power of 4500W for an Anode was confirmed.

- Electrical performance test with electrical load equipment
- Coupling tests between DM PPU and 200mN-class hall thruster

### **Acknowledgments**

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