Performance Improvement of Pulsed Plasma Thruster for Micro Satellite*†

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Pulsed Plasma Thruster (PPT) is one of the promising propulsion devices because of its simple composition, lightweight, and high durability. TMIT and NASDA have started their collaboration R&D for the PPT equipment to the micro- and nano-satellite propulsion system. This paper describes the performance evaluation of TMIT- PPT BBM. In this test, the effects of the PPT energy level, its density to the sublimation area, the discharge channel dimensions and other thruster parameters on the performance were evaluated. These results show the improvement of the performance and indicate the method to adjusting the thruster design to a given mission.

Introduction

With the trend in satellite design being towards small and low cost, the need for miniaturizing the thruster systems have become apparent. Pulsed plasma thruster (PPT) is one of the promising system for the small, micro- and nano-satellite attitude control, station keeping, de-orbit and drag compensation because of following reasons.

1) Simplicity
   No tankage, seals nor mechanical valves.
2) Light weight and high reliability.
   Only two power supplies.
      : Capacitor charge power supply and ignition power supply.
   Only one moving device.
      : Propellant feed mechanism to discharge chamber.
3) Small impulse bit (impulse per shot) level.
   Precisely impulse control.

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Considering these advantageous characteristics and requirements of small satellites, TMIT and NASDA have started their collaboration R&D for application of PPT to small satellite, μ-Lab Sat II.

μ-Lab Sat II (mass of 50 kg) requires light weight and low power consumption propulsion system and Fig. 1 shows the target of TMIT-PPT impulse bit versus energy compared with the flowing PPTs[1]-[5]. TMIT-PPT is one of the lowest energy level device and it is important to determine the scaling law at that energy level. Scheduled TMIT PPT subsystem block diagram for the practical application including power supplies, capacitor bank and two thruster heads (THR), is shown in Fig. 2. Operation of THR-A or B is chosen by occurrence of ignition discharge of Ignitor-A or B. This paper mainly describes the evaluation of thrusters and details of subsystem design concept and BBM system R&D are shown in another paper [6].

PPT is commonly described as electromagnetic plasma thrusters[7]. In which, as a propellant, Teflon bar is fed into the discharge chamber between the electrodes and ablated into the discharge region by the μ-seconds, k-Amperes level of oscillating discharge pulse. The main scientific deficiency is the lack of full understanding of the process of mass ablation from solid propellant[8]. It is obvious that the ablated mass (mass shot) affects directly to the thruster performance and its quantity depends on the discharge parameters such as dissipated energy, current amplitude and discharge chamber design parameters such as dimensions, aspect ratio, sublimation area and so on. Therefore, this does not allow independent computation of either the mass ablation phenomena or plasma acceleration process, which in turn precludes specific insights that would allow performance improvements.

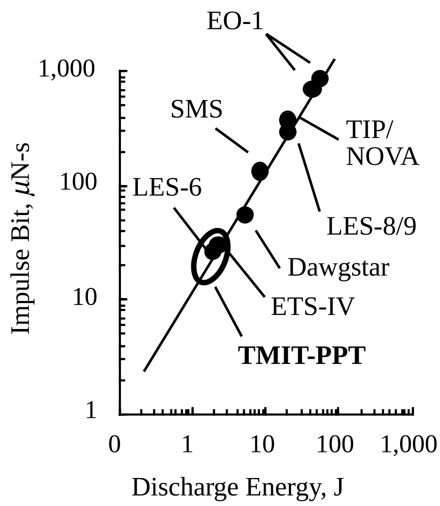


Fig. 1 Target of TMIT-PPT and flowing PPTs. [1]-[5]

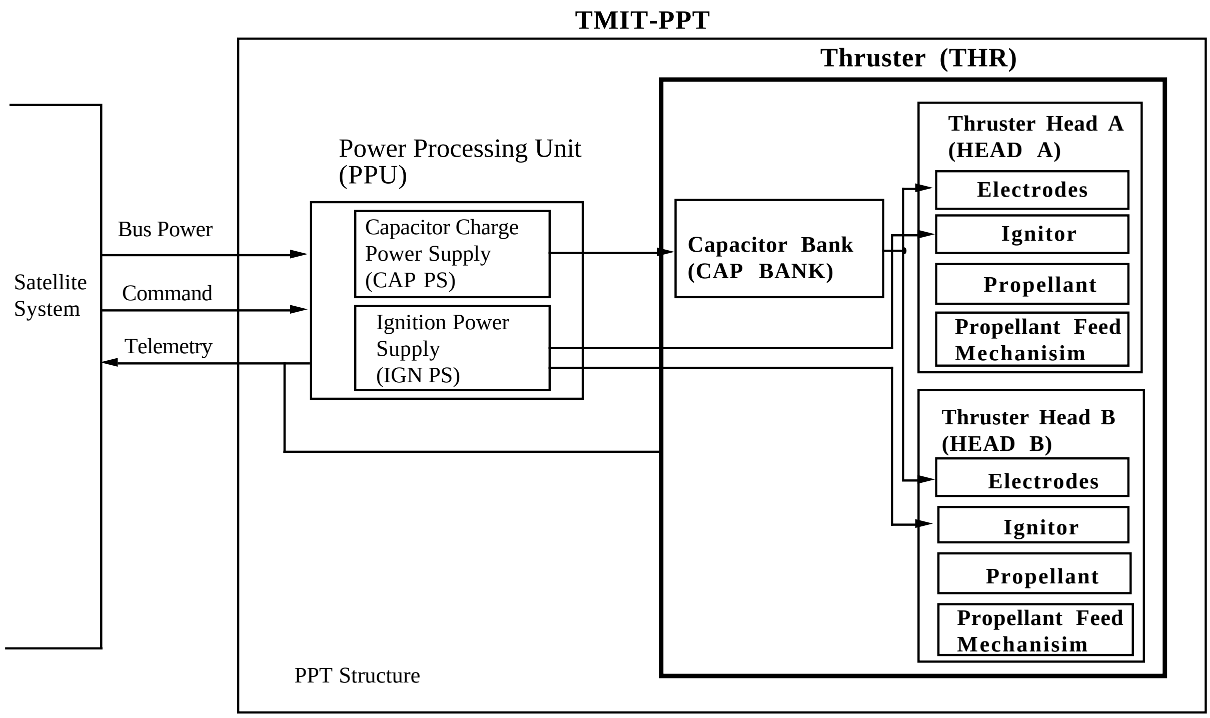


Fig. 2 Subsystem Design.

In this R&D for μ-Lab Sat II, the research for the understanding of the PPT ablation / acceleration process in order to improve the performance is to be conducted in parallel with the development for the PPT application to the satellite. Adjusting the thruster design to a given mission, the effects of the PPT energy level, its density to the sublimation area, the discharge channel dimensions were evaluated. Moreover, the summary of durability test of TMIT-PPT BBM are presented.

Experimental Apparatus and Procedures

Vacuum chamber

Experiments were performed in the vacuum chamber (1 m diam. 2 m length) with two turbo-molecular pumping system (2,000 L/s × 2 EA). Its degree of vacuum was maintained in the range of 10^{-4} Pa before each pulsed thruster operation.

Current Measurement

As the PPT electrical circuit including arc current path is equivalent to L-C-R circuit, the ideal thrust obtained by the electromagnetic acceleration, T_{MHD}, expressed as eq. (1), is proportional to the square of the main discharge current, i : where h is height and d is width of sublimation area.

$$T_{MHD} = f\,\frac{\mu}{2}\frac{h}{d}\int_0^t i^2 dt \qquad (1)$$

Therefore, the main discharge current measurement is one of the key parameters which determines the performance and has much important information on the process of the discharge current propagation and the propellant plasma acceleration. In order to obtain the main discharge current waveform, the Rogowski-Coil technique was adopted[9]. The Rogowski-Coil output was integrated with a RC integrator. The main discharge circuit of PPT is regarded as LCR circuit. Thus, from the obtained current waveform, inductance and resistance were calculated.

Impulse Bit Measurement

Target pendulum thrust measurement method developed by Yanagi and Kimura [10] was adopted to measure impulse bit. As the generated single impulse bit is slight (approximately some tens μN·s), the ignition was initiated and synchronized to the cycle of the target pendulum inherent vibration and the displacement of the target was amplified by this multi-firing. In Figs. 3,4, target and its displacement measuring system using long range laser displacement meter from the atmosphere through the viewing port were shown.

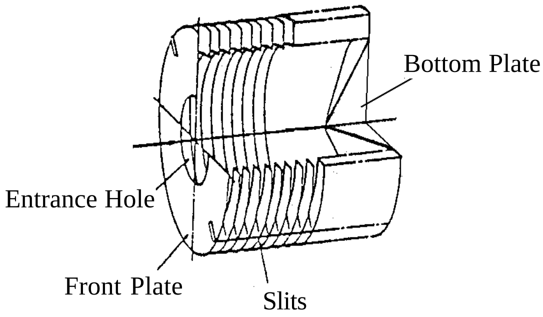


Fig. 3 Thrust Measurement Target.

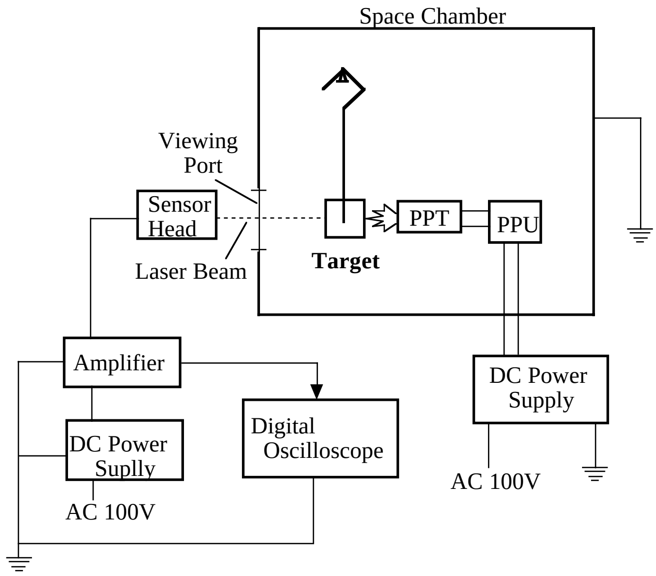


Fig. 4 Setup of Thrust Measurement System.

Mass Shot Measurement

Mass shot (ablated mass per one discharge) is in the order of several μg, and the actual mass shot was evaluated by measuring the decrease of the mass of propellant after ten thousands or more successive discharges and averaged.

Thruster Heads

In the BBM phase, three types of thruster head configuration, (1. ETS-IV equivalent model identical to ETS-IV PPE head[11], [12]. : Sublimation area of 5 cm^2, 2. TMIT-6a : Sublimation area of 3 cm^2, 3. TMIT-5 : Sublimation area of 0.5 cm^2) were evaluated. Figure 5 shows the photo of TMIT-5, which indicated the highest specific impulse at energy of 2 J

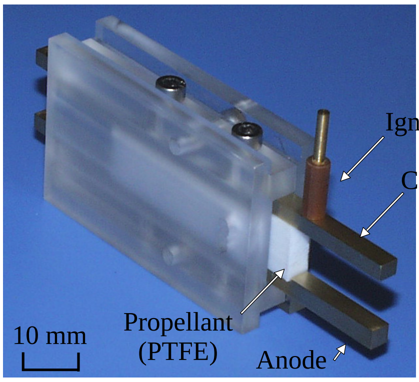


Fig. 5 Thruster Head of TMIT-5.

Capacitors

Table 1 summarizes the specifications of mica-paper capacitors used our experiments of BBM phase. The reliability for the charge-discharge cycle in a life time and lightweight are required. In the series of the BBM test, more than one million charge-discharge cycles were confirmed.

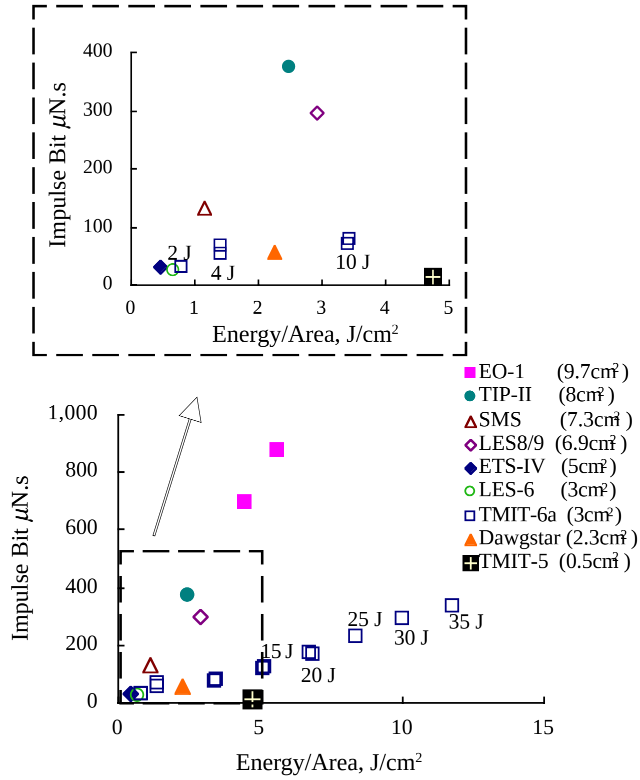
Table 1 Specifications of TMIT-CAP.

	Max Voltage	Insulation Resistance MΩ	Capacitance μF	Dielectric Dissipation tanδ, %	Mass g	Inductance nH
CAP No.1	4.0 k V DC	5X10³	1.057	0.24	141	15.4
CAP No.2	4.0 kV DC	5X10³	1.059	0.24	140	15.4

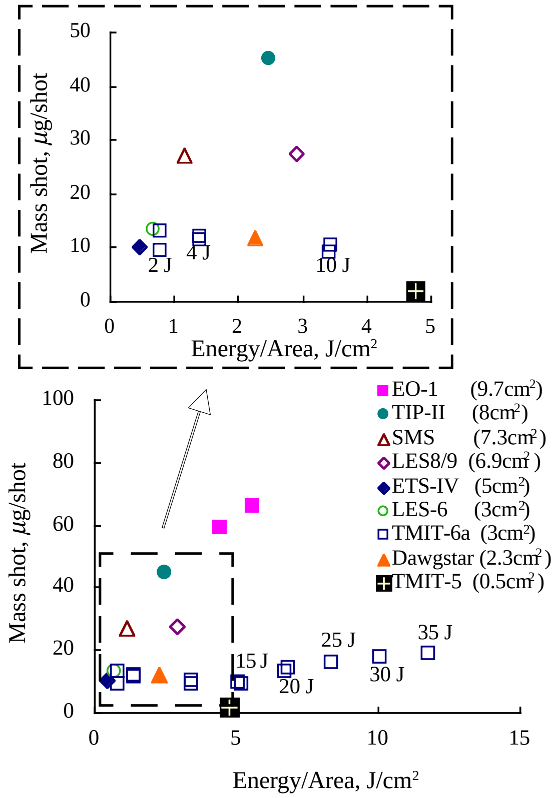
Experimental Results and Discussions

Effect of Energy Density

Figures 6-(a), (b) and (c) show the comparisons of TMIT-PPTs' performance (impulse bit, mass shot and specific impulse) with those of the other thrusters against the energy density (ratio of energy to sublimation area). In the series of the TMIT-6a experiment, its sublimation area was fixed at 3 cm^2, and the effects of the energy density on the performance was evaluated by changing energy to the capacitor bank from 2 J to 35 J. As shown in Fig. 6-(c), the results of the TMIT-6a show the improvement of specific impulse as the increase of energy density. Because, the impulse bit of TMIT-6a shows the monotonic increase with the energy density (Fig. 6-(a)), the mass shot is almost constant.



(a) Impulse Bit versus. Energy/area.



(b) Mass Shot versus Energy/Area.

Fig. 6 Effects of Energy Density on Performance.

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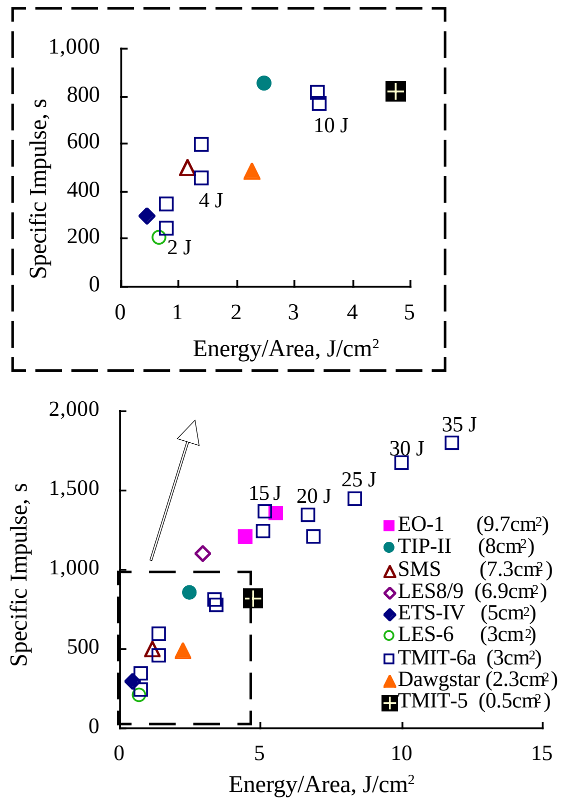


(c) Specific Impulse versus Energy/Area.

Fig. 6 Effects of Energy Density on Performance.

Compared the results of TMIT-5 and ETS-IV with those of TMIT-6a, these three PPT have the same energy data of 2 J and have the different sublimation area (TMIT-5 : 0.5 cm², TMIT-6a : 3.0 cm², ETS-IV : 5.0 cm²), it is obvious that TMIT-5 has the highest specific impulse. Because, impulse bit of TMIT-5 is almost same as TMIT-6a and ETS-IV, on the other hand, its mass shot is smaller than that of TMIT-6a and ETS-IV.

These experimental results on the effects of the energy are summarized as follow.

(1) The increase of the energy into the same area causes an increase of impulse bit with the same mass shot, and then, improves the specific impulse.

(2) The reduction of the sublimation area causes a decrease of mass shot at the same energy, and then, improves the specific impulse.

Figure 7 shows the integral value of the squared current over the discharge time in the case of TMIT-6a. As shown in this figure, the integral value , $\int_0^t i^2 dt$, is proportional to the energy. As the thrust of PPT is expressed as eq. (2), the ratio of electromagnetic acceleration to aerodynamic acceleration becomes larger, and its impulse bit increased.

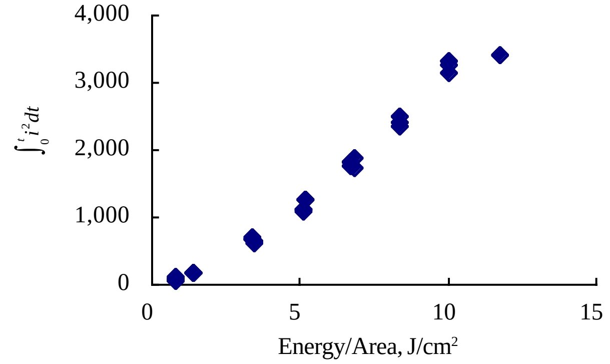


Fig. 7 Integration of Current Squared versus Energy/Area.

$$T = T_{MHD} + T_{GAS} = f\frac{\mu}{2}\frac{h}{d}\int_0^t i^2 dt + f\left[\frac{8(\gamma-1)}{\gamma^2(\gamma+1)}\cdot\Delta mE\right]^{\frac{1}{2}} \qquad (2)$$

According to Guman *et al*., the ratio of energy to ablated mass is directly proportional to the ratio of energy to area, and furthermore, specific impulse is almost directly proportional to the square root of the energy to area ratio. [2] By replotting the Fig. 6-(b), Fig. 8 which shows the relationship among the mass shot per energy and energy per area, is obtained. As shown in this figure, the ratio of mass shot to energy is inversely proportional to the ratio of energy to area. The decrease of mass, when we reduce the sublimation area from 3 cm² (TMIT-6a) to 0.5 cm² (TMIT-5) at the same energy of 2 J, is also shown in this figure. These experimental results by TMIT-6a and TMIT-5 at 2 J case coincide with the other data at larger energy level.

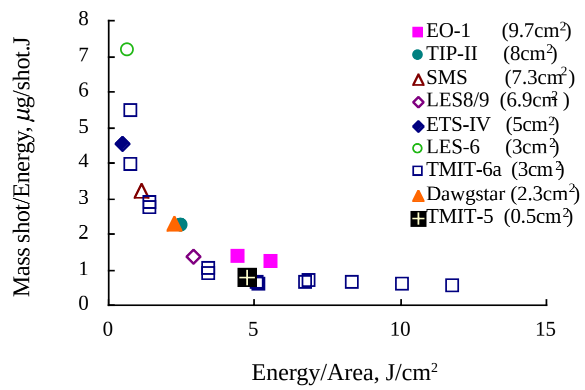


Fig. 8 Mass shot/Energy versus Energy/Area.

PPT Performance Trend in 270,000 Shots Successive Test

In order to estimate the performance trends (impulse bit, mass shot and specific impulse), 270,000 shots successive operation test was conducted. As shown in Fig. 9, the performance of PPT, impulse bit, mass shot and specific impulse was fairly constant through the 270,000 shots of operation with the measurement of impulse bit and mass shot every 30,000 shots. As shown in this figure, the slight decrease of impulse bit at the end of the test, some counter measures for the uniform sublimation are necessary in this small energy level. However, no miss shot was observed in this test, and the reliability of ignition was established. Typical performances are as follows :

Specific Impulse	822 sec
Impulse Bit	14.8 μNs
Mass Shot	1.84 μg
Total Impulse	4.2 Ns
Miss Shot	0.00001 %
Total shots	2.7×10^5 shot

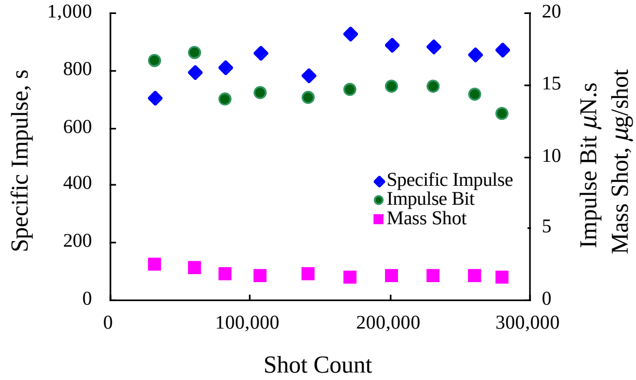


Fig. 9 270,000 Shots of Operation Results.

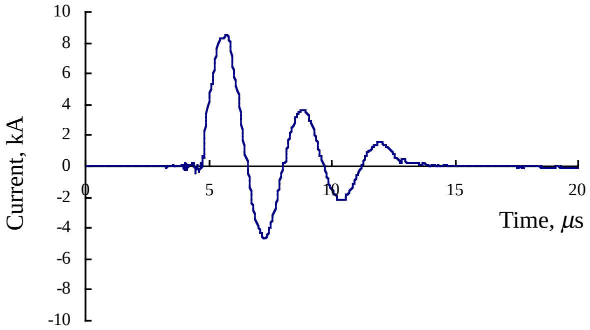
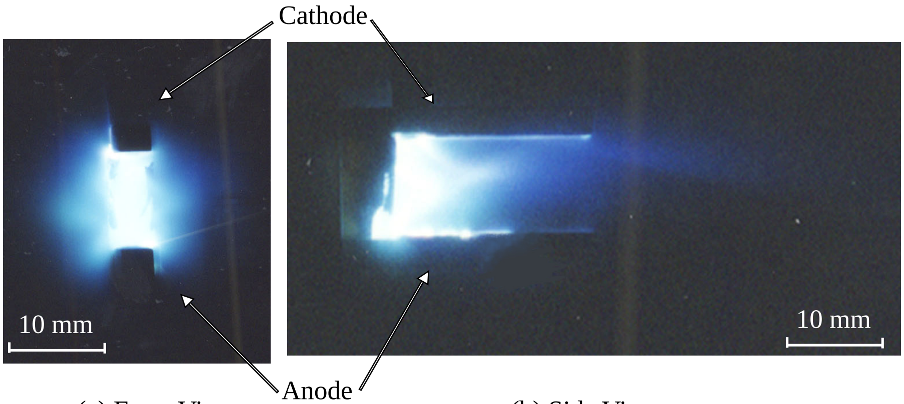


Fig. 10 Current Waveform of TMIT-5.

500,000 Shots Successive Operation Test by TMIT-5

In order to estimate the PPT durability and make the critical items for its long term operation clear, 500,000 shots successive operation test (Half Million Shot Test) was conducted. In this test, performance data was not obtained because of its nonstop firing. However, the preliminary measurement of the plume contamination effects from PPT thruster head and the baseline data acquisition of temperature profile of each component were conducted. Moreover, in this test, using the thruster head BBM (TMIT-5), capacitor BBM, and PPU BBM (checkout model), the interface matching between TMIT-5 and other components was verified in the vacuum environment. Figures 10, 11 show the typical discharge current waveform and photos of the exhausted plume. Its performance through the H-MST is also shown in Table 2 with the performance target and that performance is comparable to that of 270,000 shots test. In this H-MST, propellant feed mechanism was installed in TMIT-5, and the design validity of this mechanism was confirmed. However, The erosion of the cathode made of brass was not negligible and we are going to devise a countermore to suppress the erosion for the EM.



(a) Front View (b) Side View

Fig. 11 Plume of TMIT-5.

Table 2 Scheduled and Achieved Performances. [6]

Items	(Target)	(Achieved)
Satellite Mass	< 50 kg	
Capacitor	2 μ F	2.11 μ F
Capacitor Weight	0.45 kg	0.28 kg
Charge Voltage	1,500 V (Nominal)	1,500 V (Nominal)
	1,000 ~ 2,000 V	1,000 ~ 2,000 V
Charge Energy	2.25 J	2.37 J
	1.0 ~ 4.0 J	1.0 ~ 4.0 J
Pulse Rate	1 Hz (Nominal)	1 Hz (Nominal)
	0.2 ~ 2.0 Hz	0.7 ~ 1.4 Hz
Electrical Power	4 W (Nominal)	5 W (Nominal)**
Impulse Bit		16.5 μ Ns**
Mass Shot		1.78 μ g**
Specific Impulse	> 800s	927 s**
Total Impulse	60 N-s	8.25 N-s**
Dry Weight *	Total < 2.0kg	0.76 kg#
		1.16 kg##
Size	< 210×148 mm	210×148 mm##

* Excluding PPU Potting, Wire Harness, Nozzle, MLI, Radiation Shield and Fixture.

** Obtained in H-MST (Half Million Shot Test)

with BBM PPU

with Checkout Model PPU

Summary

For adjusting the TMIT-PPT to the mission of μ-Lab Sat II, the effects of energy level, its density to the sublimation area and discharge channel dimensions were evaluated. The results show the improvement of specific impulse by the increase of the energy density which is caused by the miniaturization of the thruster. Moreover, some μJ class PPT has the same tendencies with larger energy class PPTs.

270,000 shots of successive operation and H-MST indicate the reliability of TMIT-PPT and BBM phase performance was evaluated and it shows the no critical obstacle to proceed the EM phase.

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