Evaluation of Pulsed Plasma Thruster System for μ-Lab Sat II*†

Haruki TAKEGAHARA‡, Miwa IGARASHI§, Naoki KUMAGAI§, Kensuke SATO§, and Kouji TAMURA§
Tokyo Metropolitan Institute of Technology, Dept. of Aerospace Eng.
Asahigaoka 6-6, Hino, Tokyo 191-0065, JAPAN
+81-42-585-8659,
hal@astak3.tmit.ac.jp

Mitsuteru SUGIKI¶
Astro Research Corporation
Kugenuma Tachibana 1-1-4, Fujisawa, Kanagawa, 251-0024, JAPAN

Hidekazu HASHIMOTO¶¶
National Space Development Agency of Japan
Advanced Mission Research Center, Micro Space Systems Laboratory
Sengen, 2-1-1, Tsukuba, Ibaraki 305-0047, JAPAN

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Pulsed Plasma Thrusters (PPT) using Teflon are restudied and developed for the auxiliary propulsion system for small satellites because of its simplicity in recent years. The most promising features of Teflon PPT, compared with the other electric / chemical propulsion system, are as follows. 1) Propellant storage and management system such as reservoir tank, pressure transducer, valves and piping system, is not necessary. 2) For the thrust generation, only two power supplies are required. 3) Precise total impulse control is possible because of its small / discrete impulse bit. 4) Only one moving mechanism (Teflon feed system) is required. 5) Teflon is an inactive material and has no hazardous properties. Considering these advantageous characteristics of Teflon PPT system, simple, light-weight and high durability propulsion system for the small satellite will be realized. TMIT has started its R&D with the collaboration of NASDA. Following the first generation Teflon PPT such as ETS-IV PPE, its R&D for the application to NASDA's μ-Lab Sat II (50kg) as the experimental equipment for the feasibility evaluation of attitude control and de-orbit maneuver has been conducting. This paper describes its present status of the R&D (BBM) and its PPT system test review including PPU (Power Processing Unit) and Capacitor Bank with the results of the successive firing test over 500,000 shots.

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‡ Professor, Senior Member AIAA.
§ Graduate Student.
¶ President, Senior Member AIAA.
¶¶ Senior Engineer,

Introduction

In recent years, Pulsed plasma thrusters (PPT), have become the recipient of much interest in the satellite community. Especially, an interest in satellites of mass less than 100 kg[1], [2] has resulted in a propulsion requirement for micro-thrusters, particularly PPT. Because the design of a small satellite affects the propulsion system by limiting its power, mass, and fuel system complexity. Options for the on-board propulsion systems of small satellites include both advanced chemical and electric propulsion devices. However, the PPT is unique in that it offers operation at low power in simple, solid-state propellant that are highly reliable, compact, and light-weight with a high specific impulse.

These benefits make the PPT an attractive and reliable on-board propulsion alternative for orbit insertion, orbit maintenance, orbit raising and de-orbiting of small satellites. And also, it offers a small, discrete impulse bit which gives satellites mission advantages such as accurate positioning, attitude control, drag makeup, and constellation stationkeeping.

In Japan, PPT is a space-qualified devices and we have an experience that PPT had installed and operated successfully on ETS-IV[3], [4] launched in 1982. Considering the aforementioned requirements for small satellites, Tokyo Metropolitan Institute of Technology has started its R&D with the collaboration of NASDA. In the United States, PPT is being considered, or has been chosen, as the on-board propulsion system for several missions such as Earth-Observing I, Mighty-Sat and Deep-space-III[5], [6].

PPT is commonly described as electromagnetic plasma thrusters[7] in which a Teflon bar is fed into the discharge

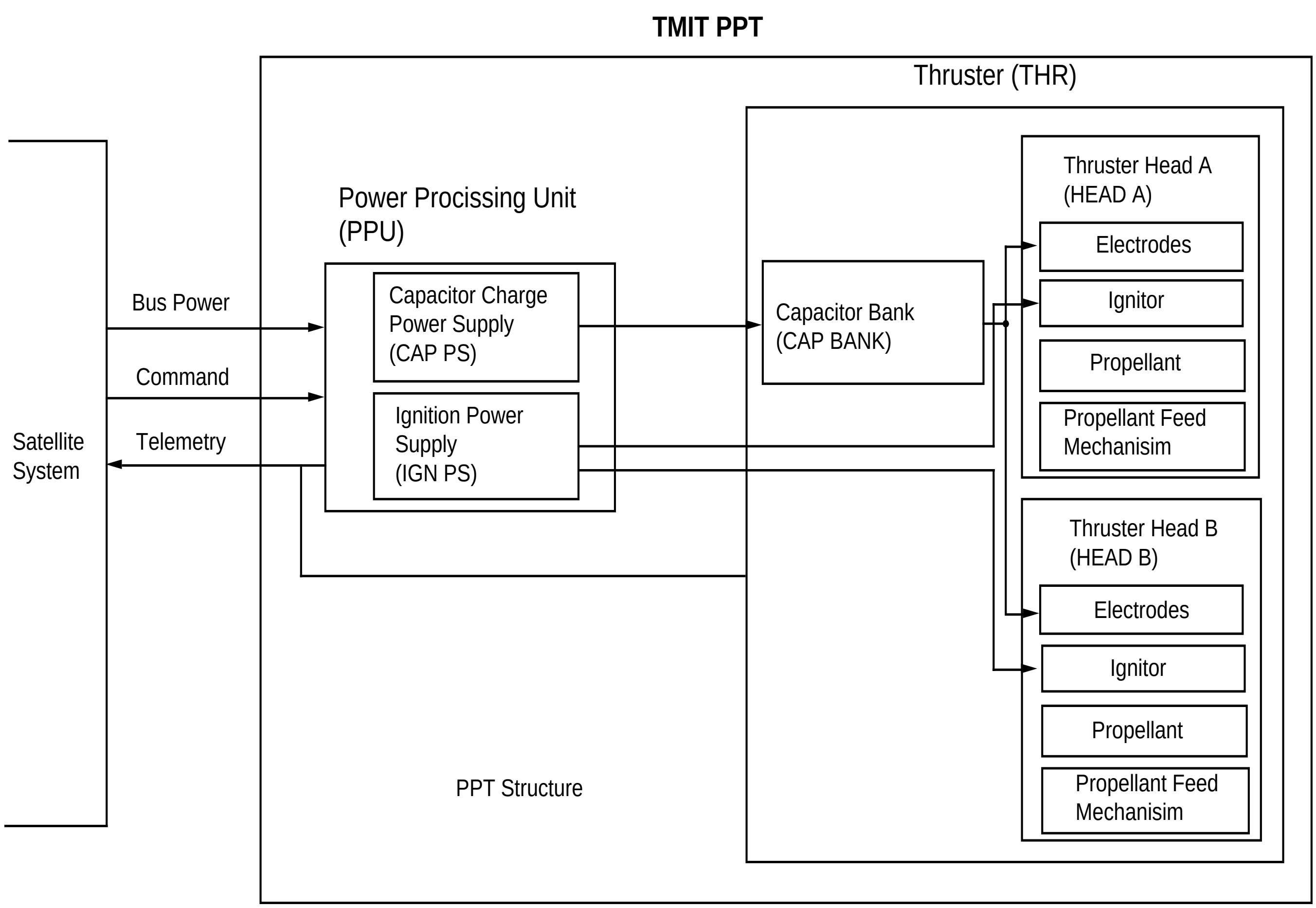


Fig. 1 TMIT PPT Subsystem Block Diagram

chamber between the parallel-plate 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. 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.

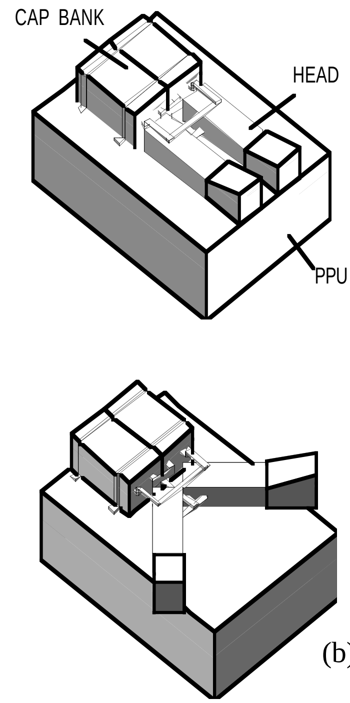
Following the first generation Teflon PPT such as ETS-IV PPE, the thruster performance measurement systems (impulse bit and current waveform) were established and the BBM level system design and each components evaluation have started from 2000. In this paper, the design concept of our smallest PPT and the BBM phase R&D status are presented and the details of the PPT thruster head R&D are presented in another paper[9].

Bread-Board Model for m-LabSat II

PPT Subsystem Design for μ-Lab Sat II

Composition of PPT Subsystem

TMIT PPT subsystem block diagram including PPU (power processing unit), CAP BANK (capacitor bank) and thruster head is shown in Fig. 1. As shown in this figure, one TMIT PPT unit is composed of one PPU (including one capacitor charge power supply and one ignition power supply), one capacitor bank, and two Thruster Head A/B (including electrodes, ignitor, propellant and propellant feed mechanism, respectively). As both electrodes in Thruster Head A and B are connected to the same capacitor bank, they have the same electrical potential at the same time as the capacitor bank is charged. Operating thruster head is to be selected by the ignition command which delivers the high voltage ignition discharge to the cathode. Figure 2 shows the examples of the PPT tentative integration layout using



(a) pararell

(b) perpendicular

Fig. 2 Example of PPT Layout with Checkout Model PPU.

Table 1 Scheduled and Achieved Performance

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

Table 2 Mass Breakdown of PPT System

Component	Number of Parts	Total Mass (g)
HEAD (TMIT-5)	2	126
CAP BANK (BBM CAP)	2	281
PPU (BBM / Check Out Model)	1	350 / 748
Total		757 / 1155

* Excluding PPU Potting, Wire Harness, Nozzle, MLI, Radiation Shield

Table 3 Specifications of TMIT-CAP

	Max. Voltage kV DC	Insulation Resistance MΩ	Capacitance μ F	Dielectric Dissipation tanδ, %	Mass g	Inductance nH
CAP No.1	4.0	5×10^3	1.057	0.24	141	15.4
CAP No.2	4.0	5×10^3	1.059	0.24	140	15.4

the checkout PPU. In the case of (a), one of thruster head is the redundancy, and in the case of (b), this layout is suitable for the attitude control.

Scheduled Performance

The scheduled performance target and achieved values in BBM phase including the H-MST (Half Million Shot Test) results are listed in Table 1. Mass breakdown of PPT system is also shown in Table 2.

TMIT PPT Components

Thruster Head

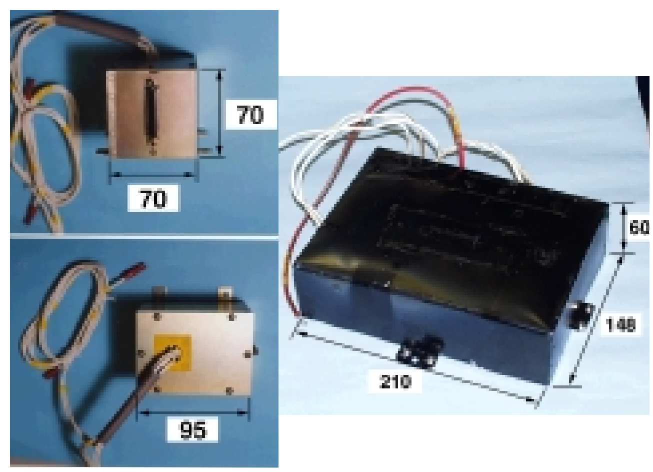
In the BBM phase, three types of thruster head configuration, (1. ETS-IV equivalent model identical to ETS-IV PPE head : Sublimation Area of 5 cm^2, 2. TMIT-6a : Sublimation Area of 3 cm^2, 3. TMIT-5 : Sublimation Area of 0.5 cm^2), were evaluated. Because of the difference of the sublimation area, TMIT-5 showed the highest performance.

Capacitor Bank

Table 3 summarizes the specifications of mica-paper capacitors used in our experiments of BBM phase. The reliability for the charge-discharge cycles during the life time and light-weight are required. In the series of the BBM test, more than one million charge-discharge cycles were confirmed.

Power Processing Unit

One PPU includes two power supplies (capacitor charge power supply and ignition power supply), and ignition power supply has the two output for Thruster Head A and B. Moreover, PPU has the telemetry / command interface for the PPT control. Up to now, telemetry / command interface between μ-Lab Sat II satellite system



(a) BBM PPU (b) Checkout PPU

Fig. 4 Photos of PPU (Unit : mm)

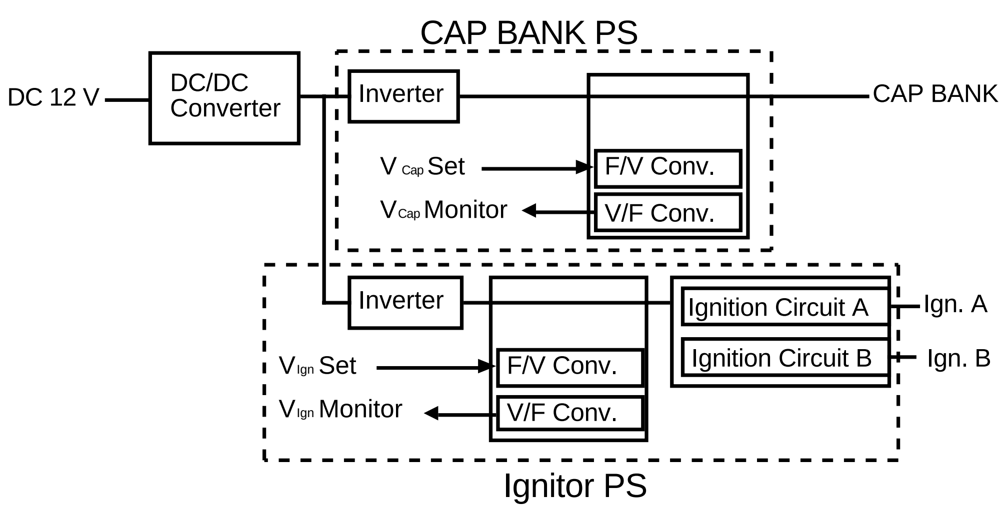


Fig. 3 Schematic Block Diagram of PPU

and the bus voltage (DC12 V) are not determined, the installed interface is tentative. In the BBM phase, two types of PPU (BBM PPU for the estimation of weight and volume and checkout model PPU for the verification of electrical circuit) were fabricated and tested. Figures 3 and 4 show the schematic block diagram of PPU and the photos of each PPU.

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, using the commercial power supplies. As shown in Fig. 5, the performance of PPT (Impulse Bit[10], Mass Shot and Specific Impulse) was fairly constant through the 270,000

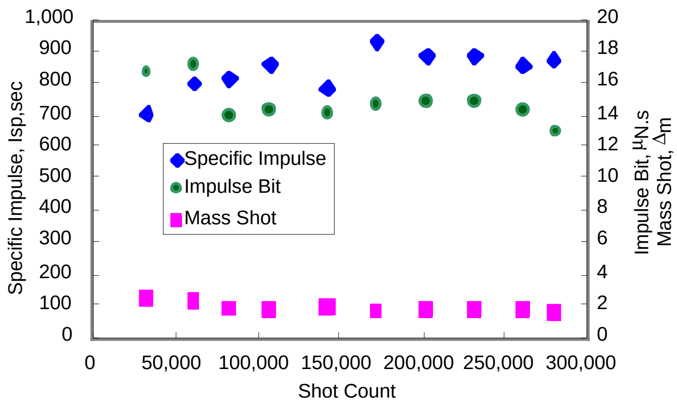


Fig. 5 PPT Performance Trend in 270,000 Shots Successive Test

successive operation with the measurement of impulse bit and mass shot every 30,000shots. As shown in this figure, the slight decrease of impulse bit at the end of the test, some counter measure for the uniform sublimation of propellant is necessary in this small energy level. However, no miss shot was observed in this test, and the reliability of ignition system was eatablished.

PPT Durability Estimation in 500,000 Shots Successive Operation Test (H-MST : Half-Million Shot Test)

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

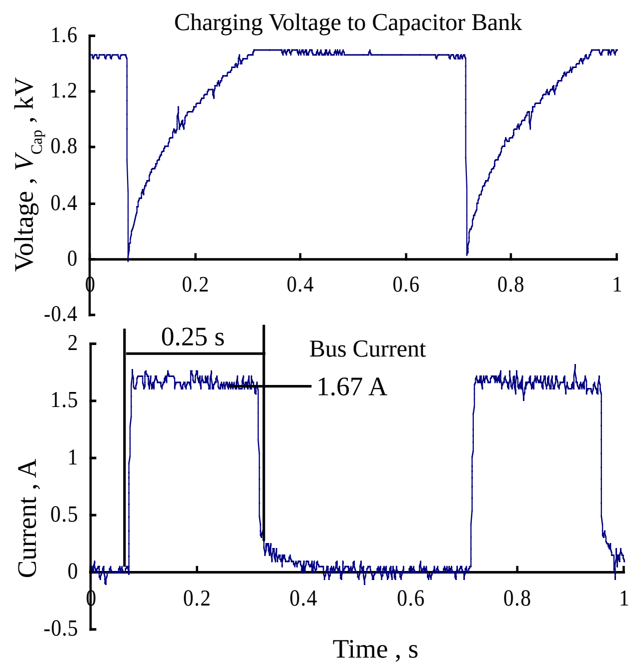


Fig. 7 Profiles of Charging Voltage to Capacitor Bank and Bus Current (Bus Voltage is fixes at12 V)

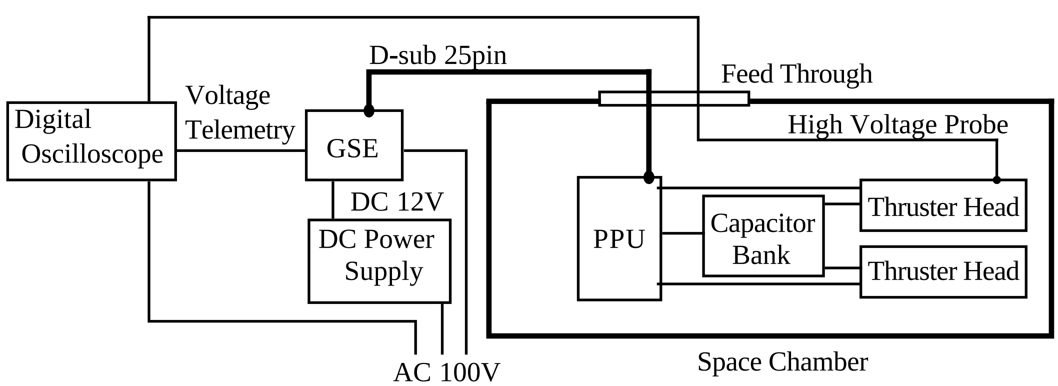


Fig. 6 Setup of 500,000 Shots Successive Operation Test

preliminary measurement of the plume contamination effects from PPT and the baseline data aquisition of temperature profile of each component were conducted. Moreover, in this test, using the thruster head BBM, capacitor BBM, and PPU BBM(checkout model), the interface matching between the each component of PPT system was verified in the vacuum environment. Figure 6 shows the setup of the 500,000 shots successive operation test. However, no critical mismatch of the interface among each component was observed, the electrode erosion, especially cathode, was not be passed over. Figure 7 shows the profile of the charging voltage to the capacitor bank and the bus power current (in this test, bus voltage is fixed to 12 V.)[11]. As shown in this figure and Table 1, power comsumption of PPT amounts to 5 W. The improvement of PPU efficiency is required at EM phase. Only a few errors peculiar to the PPU and thruster head will be modified soon for the EM design.

Summary

1. TMIT has started the R&D of PPT with the collaboration of NASDA. Following the first generation Teflon PPT such as ETS-IV PPE, its R&D for the application to NASDA's μ-Lab Sat II (50kg) as the experimental equipment for the feasibility evaluation of attitude control and de-orbit maneuver, has been conducting.

2. In BBM phase of development, each component of PPT system (thruster head including propellant feed mechanisim, capacitor bank, power processing unit) was fabricated and evaluated its interface and fundamental performance. As a result, no critical interface mismatch between each component was observed, and small and light-weight PPT system is possible with its performance of 927 s of specific impulse at 5 W.

3. 500,000 shots successive operation test (H-MST : Half-Million Shot Test) for the estimation of PPT durability was conducted and its results show no critical trouble for long term operation, excluding the electrode erosion.

In the next phase EM, environmental tests (such as thermal vacuum test, vibration test, shock test) are to be conducted with the full PPT system including the thruster nozzle and PPT fixture, and the precise thrust measurement using thrust stand and the process of propellant sublimation and acceleration will be investigated.

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