Development of Electrothermal Pulsed Plasma Thruster System Flight-Model for the PROITERES Satellite

IEPC-2011-034

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

Masamichi Naka[1], Ryuta Hosotani[2] and Hirokazu Tahara[3]
Osaka Institute of Technology
Asahi-Ku, Osaka, 535-8585, Japan

and

Yosuke Watanabe[4]
Osaka University
Toyonaka, Osaka 560-8531, Japan

Abstract: The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) will be launched in 2012, because the launching was delayed due to change of schedule of Indian PSLV launcher. The main mission is powered flight of small/nano satellite by electric thruster. This study aims at improvement in discharge stability by changing detailed configuration of PPT system. As a result, a new PPT head Flight-Model (FM), i.e., a nearly-optimized PPT head with high discharge stability was designed. From endurance tests with the two PPT head FMs connecting the PPU FM, the total impulse of each PPT head reached 5.0 Ns with no miss-firing. Finally, all interfaces among the PPT system, the onboard computer and the satellite electric power BUS unit were completely accepted. Furthermore, the research and development of the 2nd PROITERES satellite with high-power and large-total-impulse PPT system are also introduced.

I. Introduction

THE Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES), as shown in Fig.1, was started at Osaka Institute of Technology in 2007.[1-7] In PROITERES, a nano satellite with electrothermal pulsed plasma thrusters (PPTs) will be launched in 2012, because the launching was delayed from the end of 2011 due to change of schedule of Indian PSLV launcher. The main mission is to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. The raising in Sun Synchronous Orbit will be carried out by the PPTs.

Our satellite R&D groups are divided into eight sections. We take a student and staff member meeting one time a week and examine the satellite system. Each section developed Bread Board Model (BBM) and Engineering Model (EM) of the satellite in 2007-2009.

Pulsed plasma thrusters, as shown in Fig.2, are expected to be used as a thruster for small/nano satellites.[8-14] The PPT has some features superior to other kinds of electric propulsion. It has no sealing part, simple structure and high

[1] Graduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[2] Undergraduate Student, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[3] Professor, Department of Mechanical Engineering, and tahara@med.oit.ac.jp.
[4] Research Associate, Graduate School of Engineering Science, and watanabe@me.es.osaka-u.ac.jp.

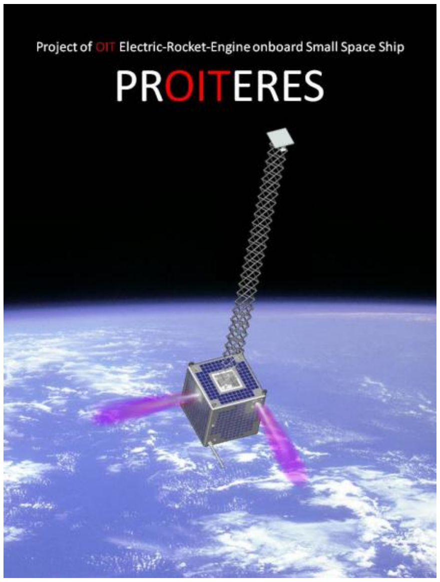


Figure 1. PROITERES satellite on orbit.

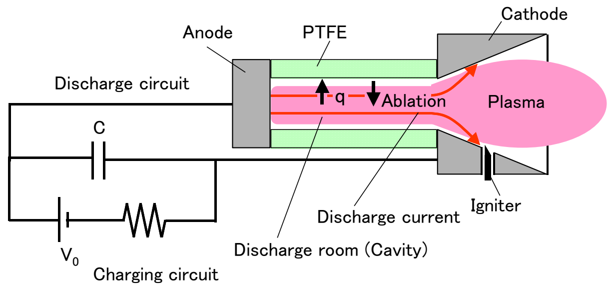


Figure 2. Electrothermal pulsed plasma thrusters.

Table 1. Specification of satellite.

Mass	15kg
Outside dimension	290mm×290mm×290mm (Without extension boom)
Orbit	Orbital inclination: 99.98[deg], Eccentricity：0
Altitude	670km
Commencing time	April, 2007
Life time	1-2 years
Rocket	PSLV（India）
Launch	2012
Attitude control	Magnetic attitude control Gravity-gradient stabilization

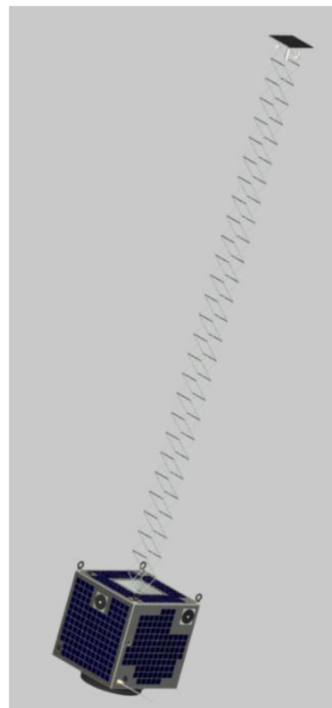


Figure 3. PROITERES satellite.

reliability, which are benefits of using a solid propellant, mainly Teflon® (poly-tetrafluoroethylene: PTFE). However, performances of PPTs are generally low compared with other electric thrusters.

At Osaka Institute of Technology, the PPT has been studied since 2003 in order to understand physical phenomena and improve thrust performances with both experiments and numerical simulations. We mainly studied electrothermal-acceleration-type PPTs, which generally had higher thrust-to-power ratios (impulse bit per unit initial energy stored in capacitors) and higher thrust efficiencies than electromagnetic-acceleration-type PPTs. Although the electrothermal PPT has lower specific impulse than the electromagnetic PPT, the low specific impulse is not a significant problem as long as the PPT uses solid propellant, because there is no tank nor valve for liquid or gas propellant which would be a large weight proportion of a thruster system.

In this study, improvement in discharge stability of the PPT system is presented for satellite onboarding. Length, diameter and angle of the nozzle, diameter and position of the ignitor hole of PPT heads are changed in order to improve the operational stability of the PPT system. Furthermore, all interfaces among the PPT system, the onboard computer and the satellite electric power BUS unit are examined. Furthermore, the research and development of the 2nd PROITERES satellite with high-power and large-total-impulse PPT system are also introduced.

II. “PROITERES” Satellite Overview

The specification of the satellite, as shown in Table 1 and Fig.3, is as follows. The weight is 15 kg; the configuration is a 0.29 m cube; and the minimum electric power is 10 W. The altitude is 670 km in Sun

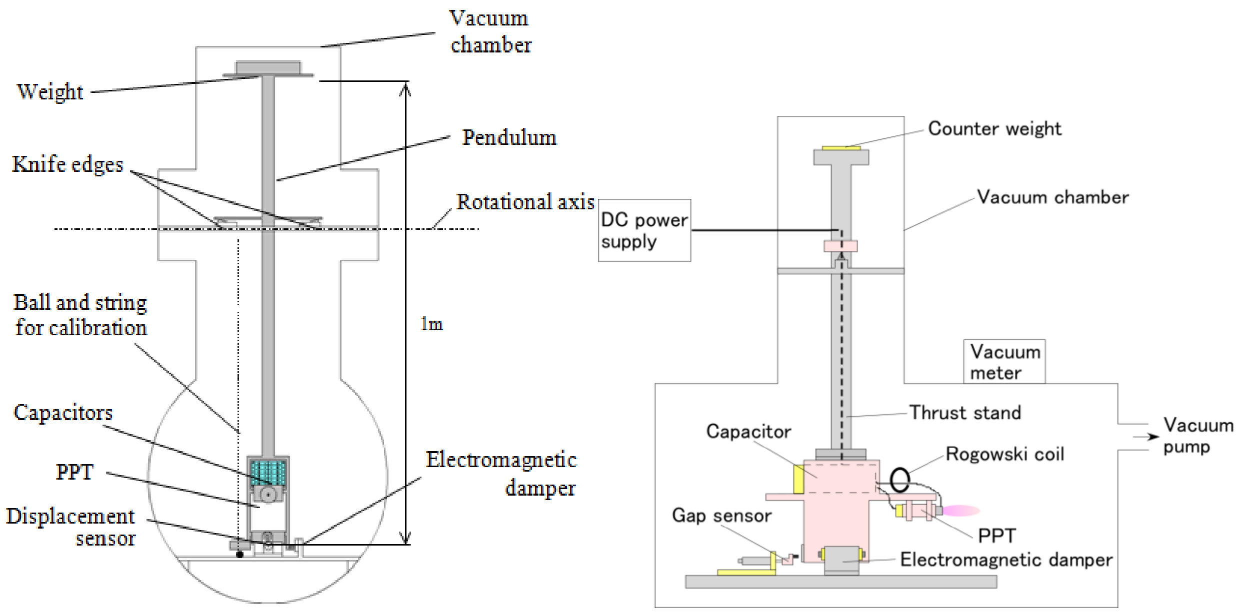


Figure 4. Thrust stand installed in vacuum chamber.

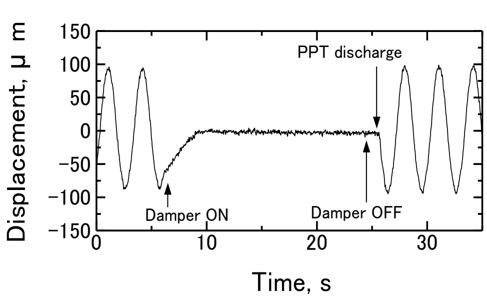


Figure 5. Typical signal of displacement in a measurement of impulse bit.

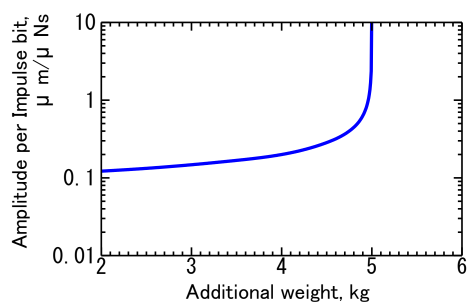


Figure 6. Sensitiveness of thrust stand vs top weight.

Synchronous Orbit. The lifetime is above one year. The launching rocket is PSLV in India, and the window will be Oct.-Dec. of 2012.

III. Thrust Measurement System

Figure 7. Vacuum chamber.

Figure 4 shows a thrust stand in a vacuum chamber for precise measurement of an impulse bit. The PPT and capacitors are mounted on the pendulum, which rotates around fulcrums of two knife edges without friction. The displacement of the pendulum is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter) near the PPT, which resolution is about ±0.5 μm. The electromagnetic damper is used to suppress mechanical noises and to decrease quickly the amplitude for the next measurement after firing the PPT. It is useful for a sensitive thrust stand because it is non-contacting. The damper consists of a permanent magnet fixed to the pendulum and two coils fixed to the supporting stand. The control circuit differentiates the output voltage of the displacement sensor and supplies the current proportional to the differentiated voltage to the coil. Accordingly, the damper works as a viscosity resistor. The damper is turned off just before firing the PPT for measurements without damping, and turned on after the measurement to prepare for

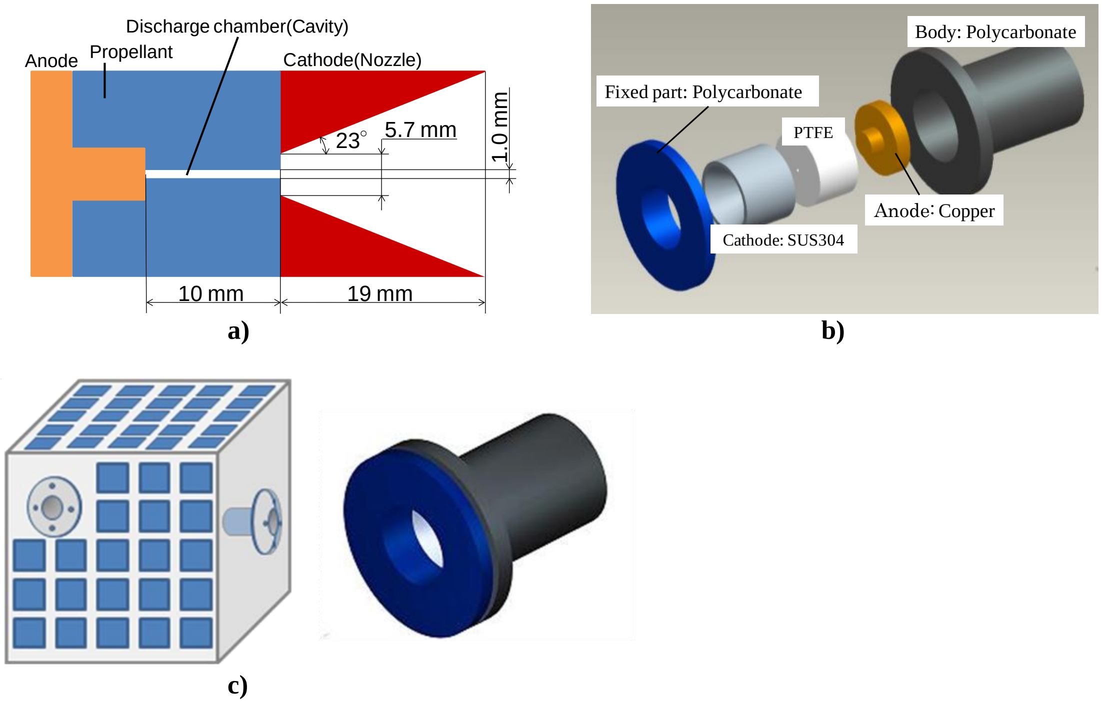


Figure 8. PPT head FM.
a) Cross-sectional view, b) illustration of structure, c) PPT installation on satellite.

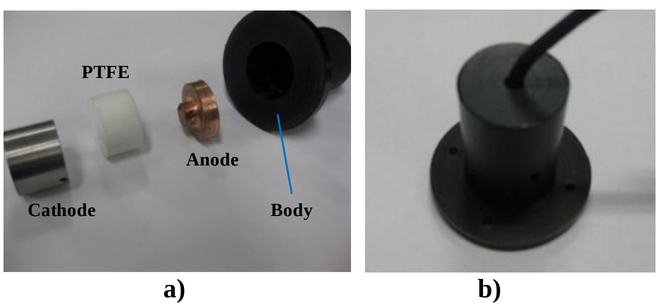


Figure 9. Photos of PPT head FM.
a) Structure, b) back view.

Figure 10. Photo of exhaust plasma plume from PPT head FM.

the next measurement. Figure 5 shows a typical signal of displacement in measurement of impulse bit. Sensitiveness of the thrust stand is variable by changing the weight mounted on the top of the pendulum as shown in Fig.6. A calibration of the thrust stand is carried out by collisions of balls with various masses to the pendulum from various distances corresponding 15-1400 μNs.

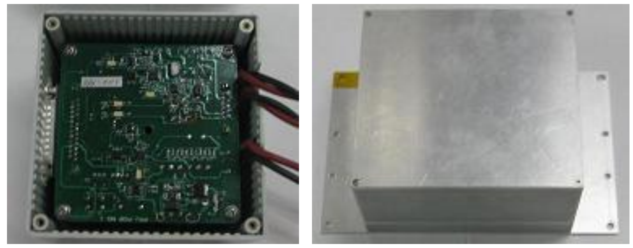
Figure 7 shows a vacuum chamber 1.25 m in length and 0.6 m in inner diameter, which is evacuated using a turbo-molecular pump with a pumping speed of 3,000 l/s. The pressure is kept below 1.0×10^{-2} Pa during PPT operation.

IV. Final Design and Tests of PPT System

We conducted lots of performance measurement and endurance test with PPT heads connecting a power processing unit (PPU) Engineering-Model (EM) specially developed by Osaka Institute of Technology (OIT) and High Serve Ltd. As a result, a PPT head Flight-Model (FM), as shown in Figs.8-10 and Table 2, was developed. The PPT system achieved a total impulse of 5.4 Ns with 43,000 shots at a charging energy of 2.43 J/shot and a repetitive frequency of 1.0 Hz. However, the PPT head FM was needed to be improved. This is because lots of miss-firing and anomalous discharge occurred when the PPT head FM connecting a PPU FM designed by OIT and High Serve Ltd.,

Table 2. Specification of PPT head FM.

Items	PPT
Mass	138 g
Size	30(h) x 50(w) x 40(d) mm
Cavity length	10 mm
Cavity diameter	1.0 mm
Ignitor hole diameter	3.0 mm
Ignitor hole position	3.0 mm
Nozzle length	19 mm
Nozzle diameter	5.7 mm
Nozzle half angle	20 deg
Material propellant	PTFE
Material anode	Cu
Material cathode	SUS304
Material body	Polycarbonate



a) b)

Figure 11. Photos of power processing unit FM. a) Interior view, b) outer case.

Table 3. Specification of power processing unit FM.

Items		PPU
Mass		710 g
Size		100 x 100 x 50 mm
Power Consumption		5 W
Input Voltage		DC 12 V±10 %
Charge Time		1.0 sec
Output Voltage	to CAP	1.8 kV
	to Ignitor	2.25, 2.7 kV
Operating Frequency		Optional

Figure 12. Photo of capacitor for PPT system FM.

Table 4. Specification of capacitor for PPT system FM.

Max Voltage	Capacitance	Mass	Inductance
4.0 kV DC	1.5 μF	188 g	44.0 nH

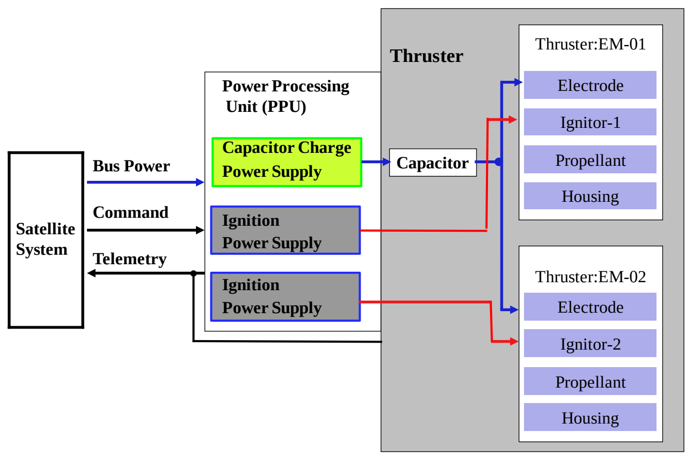


Figure 13. Operational diagram of PPT system FM.

as shown in Figs. 11 and 12, and Tables 3 and 4, was operated with a practical scheme shown in Fig.13 or after vibration tests. We determined to improve the PPT head FM, specially nozzle configuration with ignitor; that is, the PPT head FM must be optimized considering discharge stability.

First, we numbered all PPT head FMs made by student members in OIT Manufacturing Center; i.e., PPT head FM was selected by serial number (S/N).

A. Optimization of PPT Head Structure

Length, diameter and angle of the nozzle, diameter and position of the ignitor hole were changed as shown in Fig.14 and Table 5.

The ignition voltage was measured with the straight and divergent nozzles shown in Fig.15. Judge, as shown in Table 6, was made; that is, ignition easily occurred with the straight nozzle although no ignition with the divergent nozzle. As a result, we selected the straight nozzle. Next, as shown in Fig.16, we changed diameter of the straight nozzle from 6 to 10 mm. The diameters of 6, 7 and 8 mm, as shown in Table 7, are accepted from no miss-firing and lower ignition voltages. Finally, we selected 7 mm of nozzle diameter from the highest total shot of 40066 shots.

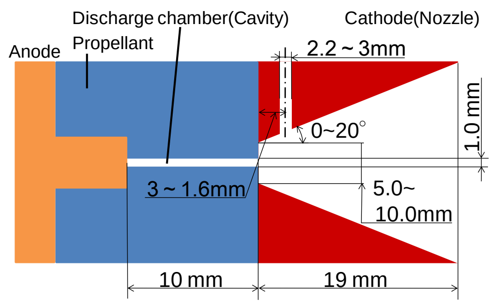


Figure 14. Variations in structure of PPT head.

Table 5. Detailed variations in structure of PPT head and operational conditions.

Discharge chamber (Cavity)	Length [mm]	10
	Diameter [mm]	1.0
Nozzle	Length [mm]	19
	Half angle [deg]	0, 20
	Diameter [mm]	5.7, 6.0～10.0
Ignitor hole	Diameter [mm]	2.2～3.0
Ignitor hole position	Length [mm]	1.6～3.0
Capacitance [μF]		1.5
Charging voltage [V]		1800
Stored energy [J]		2.43

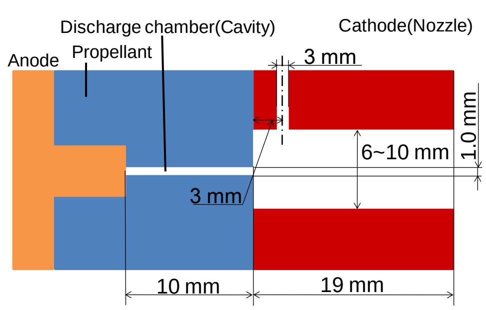
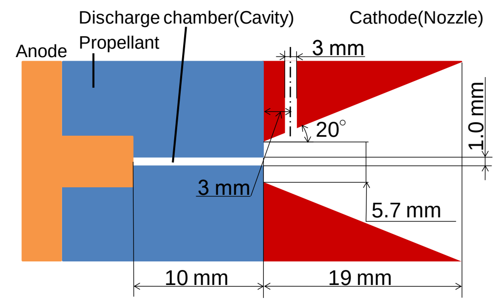


Figure 16. Variations in structure of PPT head.

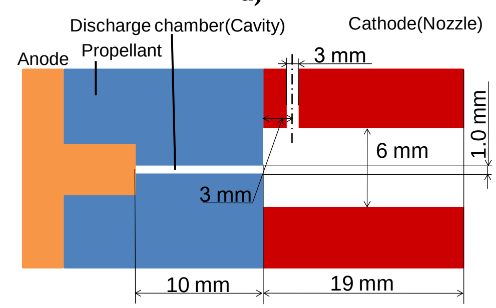
Table 7. Judgment of ignition for change in nozzle diameter.

Nozzle diameter [mm]	6.0	7.0	8.0	9.0	10.0
Ignition voltage [V]	990	1080	1160	1290	1360
Judge	○	○	○	△	△
Total shot	39781	40066	32886	30061	30107

As shown in Fig.17, diameter of the ignitor hole was changed from 2.2 to 3.0 mm. Ignition, as shown in Table 8, easily occurred with all diameters of the ignitor hole. Therefore, we selected 2.2 mm of the hole diameter because of the highest total shot of 40531 shot. The position of the ignitor hole, i.e., the distance between the downstream end of the



a)



b)

Figure 15. Changes in nozzle geometry for PPT head FM. a) Straight nozzle, b) divergent nozzle.

Table 6. Judgment of ignition for change in nozzle geometry.

Nozzle type	Straight	Divergence
Ignition voltage [V]	990	1650
Judge	○	×
Total shot	39781	0

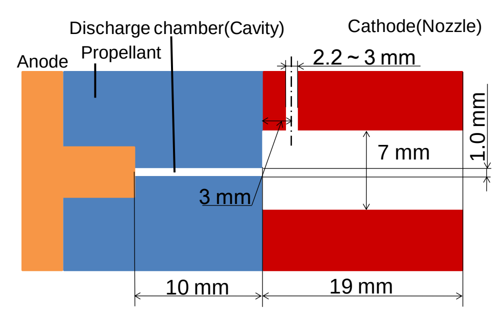


Figure 17. Changes in ignitor hole diameter for PPT head FM.

Table 8. Judgment of ignition for change in ignitor hole diameter.

Ignitor hole diameter [mm]	2.2	2.4	2.6	2.8	3.0
Ignition voltage [V]	880	900	960	1010	1080
Judge	○	○	○	○	○
Total shot	40531	40227	40095	40110	40066

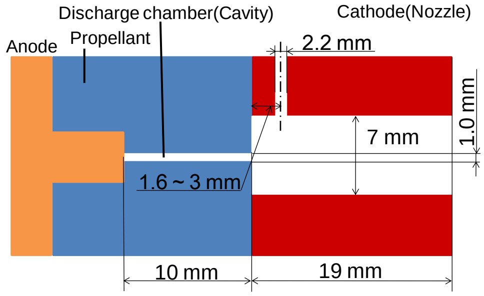


Figure 18. Changes in ignitor hole position for PPT head FM.

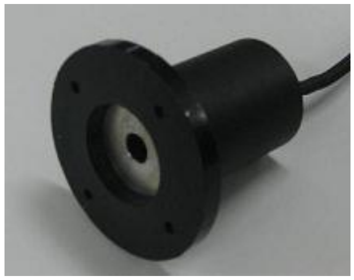


Figure 19. Photo of newly developed PPT head FM.

Table 9. Judgment of ignition for change in ignitor hole position.

Ignitor hole position [mm]	1.6	2.0	2.5	3.0
Ignition voltage [V]	450	610	740	880
Judge	△	○	○	○
Total shot	31968	42567	41427	40531

Table 10. Specification of newly developed PPT head FM.

Items	PPT
Mass	142 g
Size	30(h) x 50(w) x 40(d) mm
Cavity length	10 mm
Cavity diameter	1.0 mm
Ignitor hole diameter	2.2 mm
Ignitor hole position	2.0 mm
Nozzle length	19 mm
Nozzle diameter	7.0 mm
Nozzle half angle	0 deg
Material propellant	PTFE
Material anode	Cu
Material cathode	SUS304
Material body	Polycarbonate

discharge cavity and the ignitor hole, as shown in Fig.18, were also changed from 1.6 to 3.0 mm. In a case of the position of 1.6 mm, as shown in Table 9, miss-firing frequently occurred although easy ignition with another positions. As a result, 2.0 mm of the position of the ignition hole was selected with the highest total shot of 42567 shot.

Consequently, we could design a new PPT head FM shown in Fig.19 and Table 10, i.e., a nearly-optimized PPT head with high discharge stability. From endurance tests with the two PPT head FMs connecting the PPU FM, the total impulse of each PPT head reached 5.0 Ns with no miss-firing.

B. Tests with PPT-Head, PPU and OBC

Figure 20 shows the setup of tests with PPT head FMs, PPU FM and the onboard computer. The two PPT head FMs and the PPU FM were installed in the vacuum chamber, and the computer board used in PROITERES satellite and stably-supplying DC electric power sources of 5 and 12 V were outside it. The voltages of 5 and 12 V are satellite bus voltages of the onboard computer and the PPT system, respectively. As a result of the tests, the system could be completely operated.

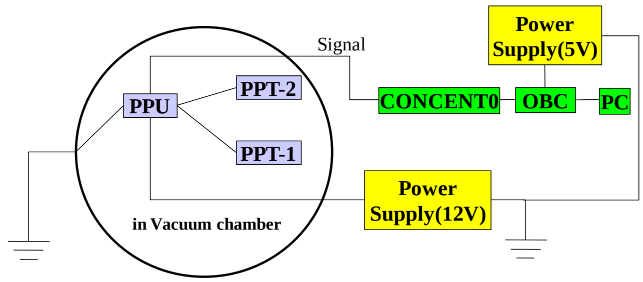
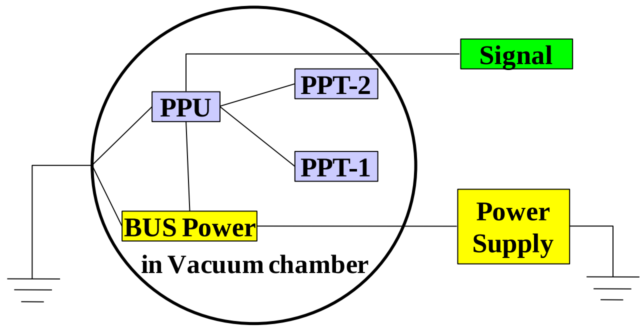
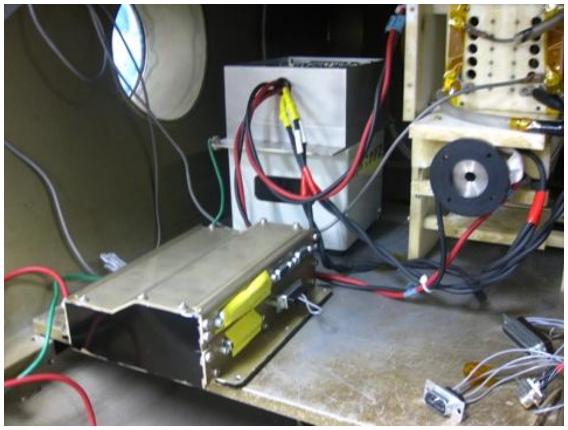


Figure 20. Setup of tests with PPT head FMs, PPU FM and onboard computer.

C. Tests with PPT-Head, PPU, OBC and Satellite BUS Unit

Figure 21 shows the setup of tests with PPT head FMs, PPU FM, the onboard computer and the satellite electric power BUS unit. The two PPT head FMs, PPU FM and satellite BUS unit were installed in the vacuum chamber. The PPT system is connected with the satellite BUS unit with 12 V. As a result, the system could be successfully operated. Consequently, all interfaces among the PPT system, the onboard computer and the satellite electric power BUS unit are completely accepted.





a) b)

Figure 21. Setup of tests with PPT head FMs, PPU FM, onboard computer and satellite electric power BUS unit. a) Connection scheme, b) photo.

V. 2nd PROITERES Satellite R&D

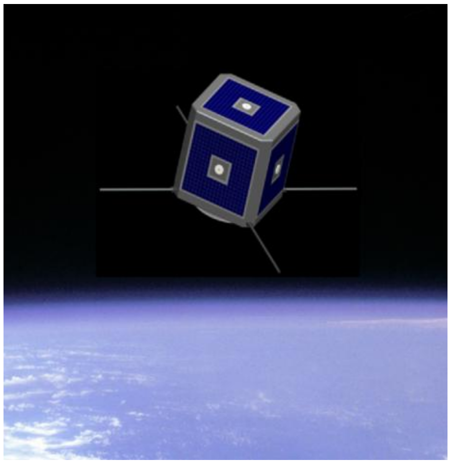


Figure 22. Illustration of 2nd PROITERES satellite.

As next projects, we started the research and development of the 2nd PROITERES satellite in Oct. 2010. The 2nd satellite of PROITERES series, as illustrated in Fig.22, is a 50-kg earth-observation satellite with high-power and large-total-impulse pulsed plasma thruster system for practical use. The PPT system with 10-15 kg is provided with four thruster heads with Teflon feeding mechanisms, and the total impulse per one thruster head is 2500 Ns at an input power of 25 W. As a result, we can change totally the altitude of the satellite up to 400 km, and on the lower orbit of 200 km we can keep the altitude up to one month. The 2nd PROITERES satellite is under development.

VI. Conclusion

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES, a nano satellite with electrothermal pulsed plasma thrusters (PPTs) will be launched in 2012, because the launching was delayed from the end of 2011 due to change of schedule of Indian PSLV launcher. The main mission is powered flight of nano-satellite by electric thruster. Length, diameter and angle of the nozzle, diameter and position of the ignitor hole were changed in order to improve the operational stability of PPT system. As a result, a new PPT head Flight-Model (FM), i.e., a nearly-optimized PPT head with high discharge stability was designed. From endurance tests with the two PPT head FMs connecting the PPU FM, the total impulse of each PPT head reached 5.0 Ns with no miss-firing. Finally, all interfaces among the PPT system, the onboard computer and the satellite electric power BUS unit were completely accepted. The PROITERES satellite FM with the PPT system FM is under final checking tests.

As next projects, we started the research and development of the 2nd PROITERES satellites in Oct. 2010. The 2nd satellite of PROITERES series is a 50-kg earth-observation satellite with high-power and large-total-impulse pulsed plasma thruster system for practical use. The PPT system with 10-15 kg is provided with four thruster heads with Teflon feeding mechanisms, and the total impulse per one thruster head is 2500 Ns at an input power of 25 W. The 2nd PROITERES satellite is under development.

References

[1]Ikeda, T., Yamada, M., Shimizu, M., Fujiwara, T., Tahara, H., and Satellite R&D Team of Students and Faculty Members of OIT," Research and Development of an Attitude Control System for Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship," *27th International Symposium on Space Technology and Science*, Paper No. ISTS 2009-s-02f, Tsukuba, Japan , 2009.

[2]Yamada, M., Ikeda, T., Shimizu, M., Fujiwara, T., Tahara, H., and Satellite R&D Team of Students and Faculty Members of OIT," Progress of Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship," *27th International Symposium on Space Technology and Science*, Paper No. ISTS 2009-s-05f, Tsukuba, Japan, 2009.

[3]Yamada, M., Ikeda, T., Fujiwara, T., and Tahara, H.," Progress of Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship," *31st International Electric Propulsion Conference*, Paper No. IEPC-2009-051, University of Michigan, Ann Arbor, Michigan, USA, 2009.

[4]Takagi, H., Yamamoto, T., Ishii, Y., and Tahara, H.," Performance Enhancement of Electrothermal Pulsed Plasma Thrusters for Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship," *27th International Electric Propulsion Conference*, Paper No. ISTS 2009-b-16, Tsukuba, Japan, 2009.

[5]Takagi, H., Yamamoto, T., Ishii, Y., and Tahara, H.," Performance Enhancement of Electrothermal Pulsed Plasma Thrusters for Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship," *31st International Electric Propulsion Conference*, Paper No. IEPC-2009-254, University of Michigan, Ann Arbor, Michigan, USA, 2009.

[6]Ozaki, J., Ikeda, T., Fujiwara, T., Nishizawa, M., Araki, S., Tahara, H., and Watanabe, Y.," Development of Osaka Institute of Technology Nano-Satellite "PROITERES" with Electrothermal Pulsed Plasma Thrusters," *32nd International Electric Propulsion Conference*, Paper No. IEPC-2011-035, Wiesbaden, Germany, 2011.

[7]Tahara, H., Ishii, Y., Tanaka, M., Naka, M., and Watanabe, Y.," Flowfield Calculation of Electrothermal Pulsed Plasma Thrusters for the PROITERES Satellite," *32nd International Electric Propulsion Conference*, Paper No. IEPC-2011-037, Wiesbaden, Germany, 2011.

[8]Burton, R. L., and Turchi, P. J.," Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol.14, No.5, 1998, pp.716-735.

[9]Edamitsu, T., Tahara, H., and Yoshikawa, T.," Performance Characteristics of a Coaxial Pulsed Plasma Thruster with PTFE Cavity," *Proc. Asian Joint Conferences on Propulsion and Power 2004*, 2004, pp.324-334.

[10]Edamitsu, T., Tahara, H., and Yoshikawa, T.," Effects of Cavity Length and Material on Performance Characteristics of a Coaxial Pulsed Plasma Thruster," *24th International Symposium on Space Technology and Science*, Paper ISTS-2004-b-6, 2004.

[11]Rysanek, F. and Burton, R. L.," Performance and Heat Loss of a Coaxial Teflon Pulsed Thruster," *27th International Electric Propulsion Conference*, Paper IEPC-01-151, 2001.

[12]Burton, R. L., Wilson, M. J., and Bushman, S. S.," Energy Balance and Efficiency of the Pulsed Plasma Thruster," AIAA Paper 98-3808, 1988.

[13]Edamitsu, T., Tahara, H., and Yoshikawa, T.," Performance Measurement and Flowfield Calculation of a Pulsed Plasma Thruster with a PTFE Cavity," *Asian Joint Conference on Propulsion and Power 2005*, Paper AJCPP2005-22083, 2005.

[14]Edamitsu, T., and Tahara, H.," Performance Measurement and Flowfield Calculation of an Electrothermal Pulsed Plasma Thruster with a Propellant Feeding Mechanism," *29th International Electric Propulsion Conference*, Paper IEPC-05-105, 2005.