Research and Development of Electrothermal Pulsed Plasma Thruster Systems for Powered Flight onboard the Osaka Institute of Technology 2nd PROITERES Nano-Satellite

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Abstract: Since 2007 the Osaka Institute of Technology (OIT) have been developing small/nano-satellites on The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES). The 2nd PROITERES nano-satellite has been developed since 2010. In July 2018, the 2nd PROITERES nano-satellite was determined to be launched as a piggyback payload of the H-IIA rocket (main satellite: GOSAT-2 and Khalifasat) from the Tanegashima Space Center of the Japan Aerospace Exploration Agency (JAXA). The main mission of the 2nd PROITERES nano-satellite is to achieve long-distance powered flight of change of 50-100 km in altitude on near-earth orbit by electrothermal PPT systems. In this research, a high-power PPT and long-time operation system with Multi-Discharge-Room type PPT (MDR-PPT) was developed. The high-power single PPT head achieved a maximum impulse bit of 2.47 mNs and a total impulse of 92.0 Ns with a repetitive 110,000 shots operation at an input energy of 31.59 J.

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I. Introduction

THE development of small/nano-satellites has become quite common at research universities. Since 2007, researchers at Osaka Institute of Technology (OIT) have developed small/nano-satellites on The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES). The 2nd PROITERES nano-satellite has been developed since 2010. The image of the 2nd PROITERES nano-satellite is shown in Figure 1, and the specification is shown in Table 1. In July 2018, the 2nd PROITERES nano-satellite was launched as a piggyback payload of the H-IIA rocket (main satellite: GOSAT-2 and Khalifasat) from the Tanegashima Space Center of the Japan Aerospace Exploration Agency (JAXA). The main mission of the 2nd PROITERES nano-satellite is an orbital altitude change from 50 km to 100 km from the satellite's orbit input position by Pulsed Plasma Thrusters (PPTs). An image diagram of the main mission is shown in Figure 2.In order to achieve the main mission, the PPT for the 2nd PROITERES nano-satellite aimed to improve thrust by installing 30 W class PPT. In addition, in order to achieve the main mission, it is important not only to improve thrust but also to obtain a high total impulse. In order to enable long-time operation system with Multi-Discharge-Room type PPT (MDR-PPT) were developed at OIT.

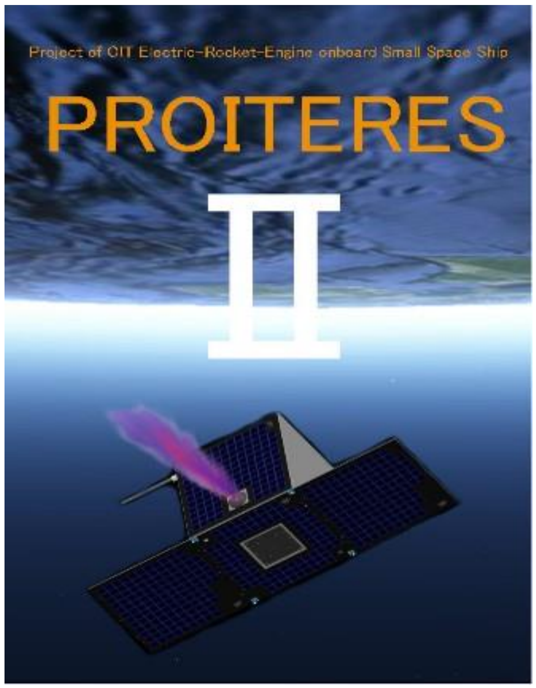
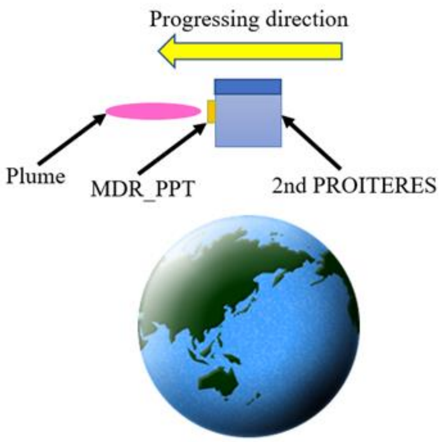


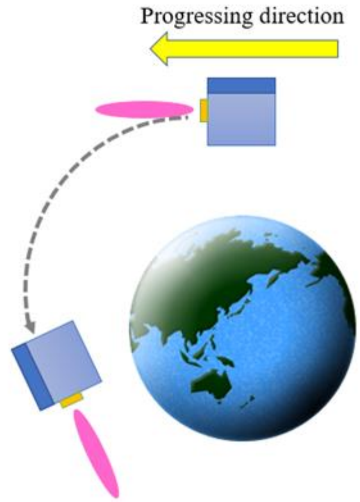
Figure 1. Image of 2nd PROITERES nano-satellite.

Table 1. Specification of 2nd PROITERES nano-satellite.

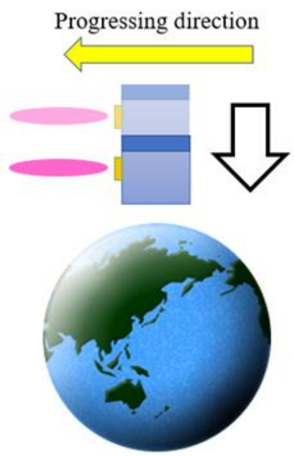
Mass, kg	45
Size, mm	470 x 470 x h 450
Electrical power, W	60
Altitude, km	613
Lifetime, year	1 - 2



(a) Mission Strat



(b) Powered Flight



(c) Orbital Altitude Change
Figure 2. Image of the main mission.

II. Pulsed Plasma Thrusters

The electrothermal PPT and electromagnetic PPT in PPTs from difference in acceleration principle. The electromagnetic PPT has been often developed as a thruster for small satellite. That's because the electromagnetic PPT's small impulse bit is suitable for attitude control and position control of the satellite. Therefore, improvement of impulse bit is needed to do powered flight. So OIT has developed the electrothermal PPT where impulse bit more expensive than the electromagnetic PPT can be expected. The electrothermal PPT and electromagnetic PPT shown in Figures 3 and 4.

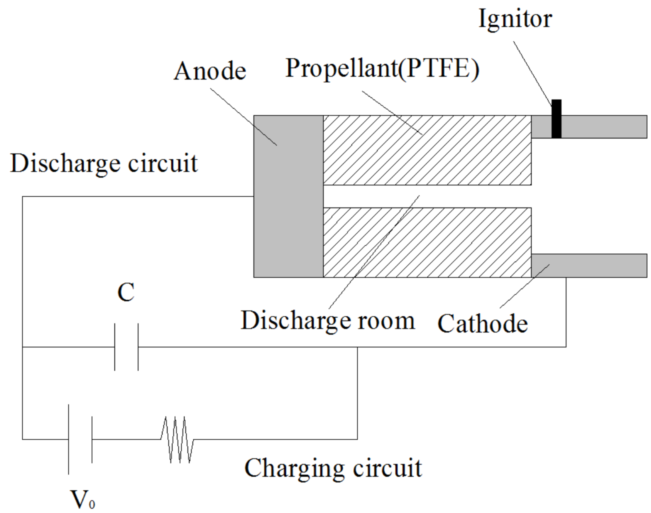


Figure 3. Electrothermal pulsed plasma thruster.

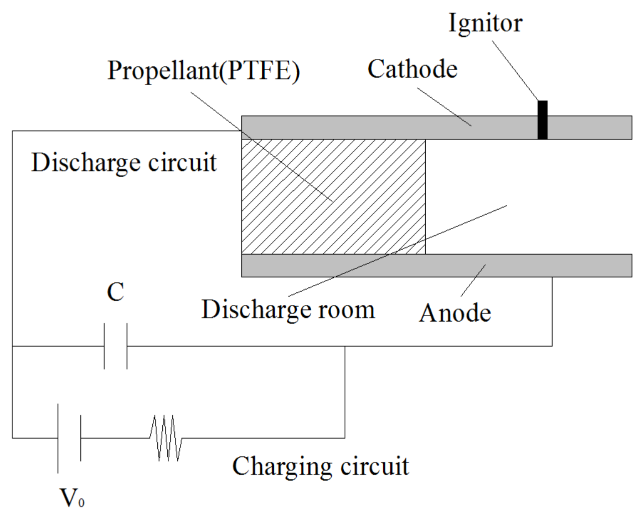


Figure 4. Electromagnetic pulsed plasma thruster.

III. Experimental Apparatus

The vacuum test facility at OIT (Figure 5) Consists of a vacuum chamber with 0.6 m diameter and 1.2 m length, two rotary pumps, a turbo molecular pump, a DC power supply system and a thrust measurement system. The pressure of the vacuum chamber can be kept at approximately 0.026 Pa during the experiment. The impulse bit of the PPT is measured by the pendulum method. (Figure 6) Therefore, the PPT head and capacitors are mounted on the pendulum, which moves around fulcrums of two needles with low friction. The sensitiveness of the pendulum is variable by changing the weight mounted on the top of the pendulum. (Figure 7) The displacement of the pendulum, which indicates the impulse bit of the PPT, is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter). The thrust calibration is conducted by collisions of various steel balls to the pendulum from various distances. The calibration line is shown in Figure 8. The pendulum has a high sensitivity and a good linearity.

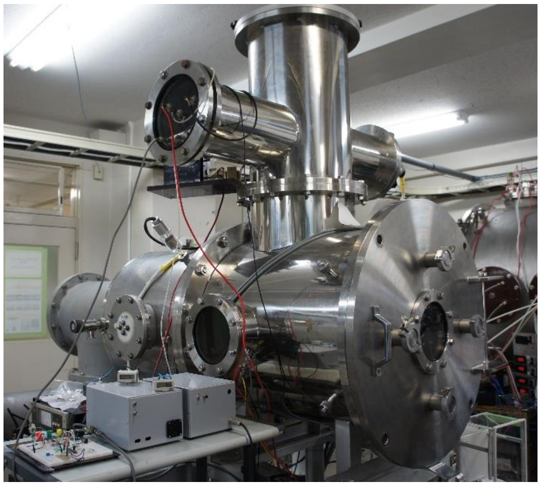


Figure 5. Vacuum test facility at OIT.

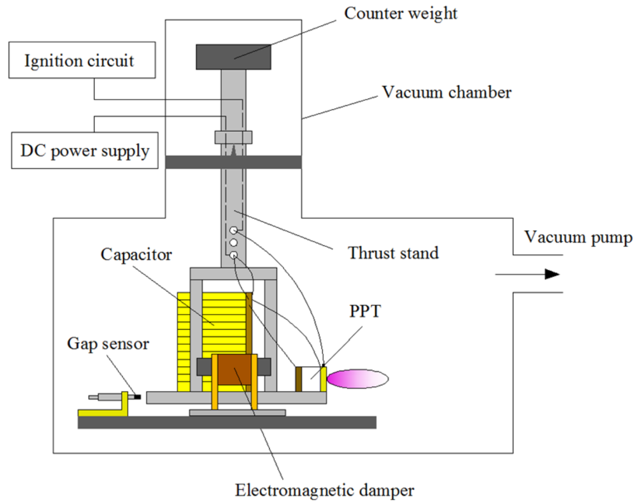


Figure 6. Schematic view of measurement system.

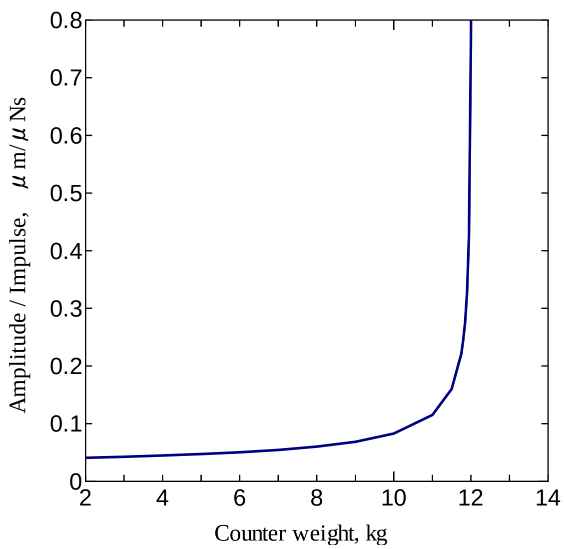


Figure 7. Sensitiveness of the pendulum.

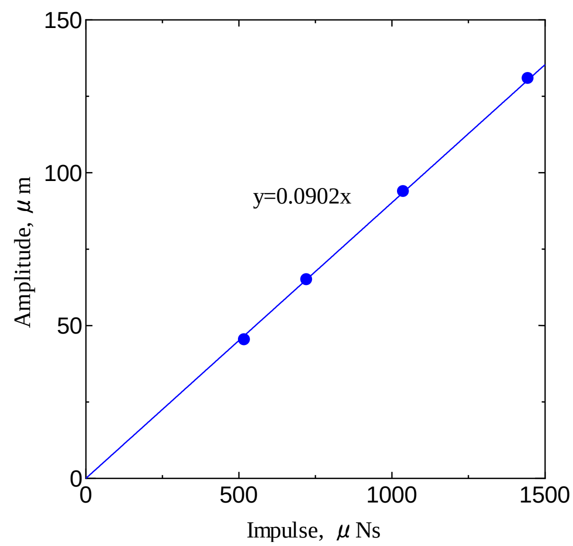


Figure 8. Callibration line.

IV. Thrust Performance with High-power PPT

In order to achieve the main mission, the PPT for the 2nd PROITERES nano-satellite aimed to improve thrust by installing 30 W class PPT. In the 2nd PROITERES nano-satellite, 13 of mica paper capacitor (CMP91B202155K-02, SOSHIN ELECTRIC Co., Ltd.) (Figure 9) having a capacitance of 19.5 μF and a rated voltage of 2 kV is use as the capacitor, and the input energy is 31.59 J.

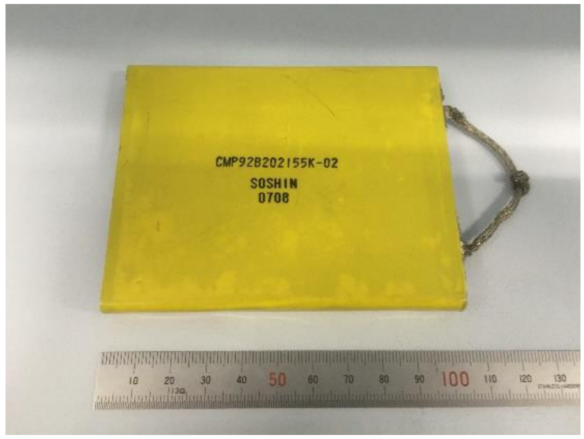


Figure 9. Mica paper condenser (CMP92B202155K-02).

Initial performance of this high-power PPT was measured for an operation of 350 shots. The experimental PPT head is shown in Figure 10 and the experimental conditions are presented in Table 2. The discharge room diameter fixes it to 4 mm than a precedent study. The performance characteristics of the PPT were measured for discharge room lengths between 10 and 50 mm in order to determine the optimum discharge room dimensions.

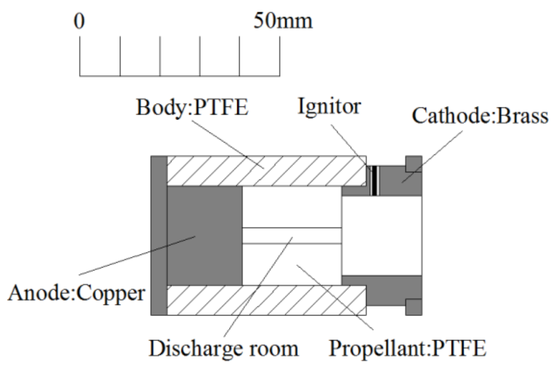


Figure 10. Schematic view of experimental PPT head.

Table 2. Experimental conditions with high-power PPT.

Discharge room diameter, mm	4
Discharge room length, mm	10/15/20/25/30/35/40/45/50
Nozzle (cathode) diameter, mm	20
Nozzle (cathode) length, mm	18
Capacitance, μF	19.5
Charging voltage, kV	1.8
Input energy, J	31.59

Figures 11, 12, 13, and 14 show the experimental results. As a result of experiments, the impulse bit showed the maximum value when the discharge room length was 50 mm. The impulse bit was 2.47 mNs, the mass shot was 738 μg, the specific impulse was 342 s, the thrust efficiency was 13.1%. It was confirmed that the impulse bit becomes larger as the discharge room length becomes longer, and the specific impulse becomes smaller.

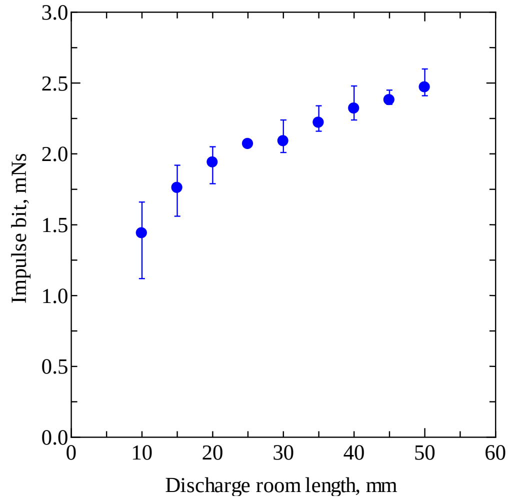


Figure 11. Impulse bit vs. Discharge room length.

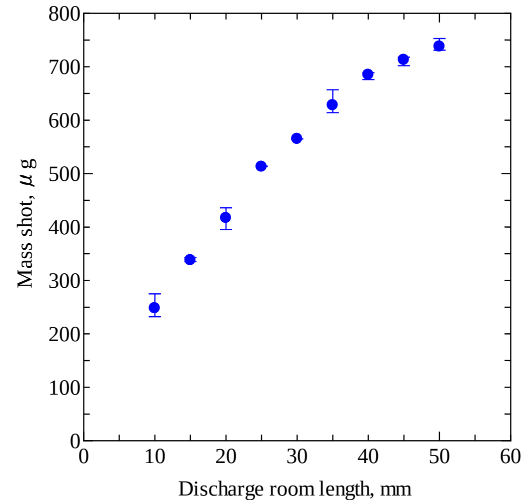


Figure 12. Mass shot vs. Discharge room length.

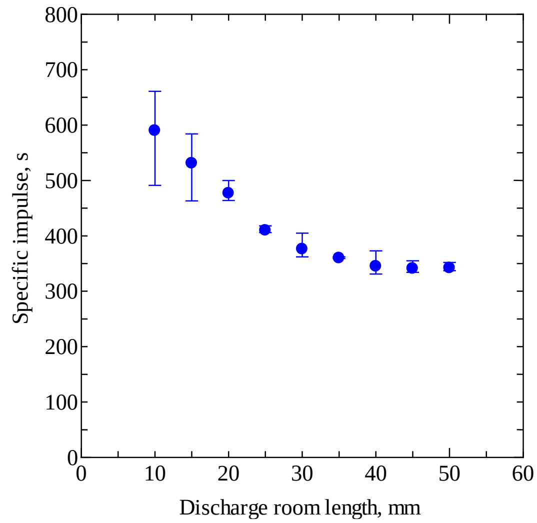


Figure 13. Specific impulse vs. Discharge room length.

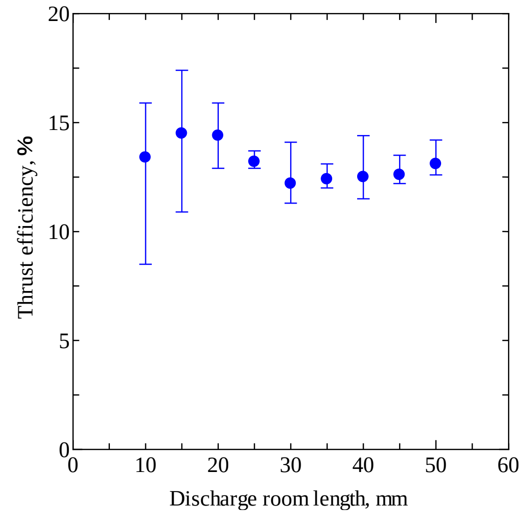


Figure 14. Thrust efficiency vs. Discharge room length.

V. Long-time Operation PPT System

A. Multi-Discharge-Room type PPT (1st MDR-PPT)

For the 2nd PROITERES nano-satellite, a long-time operation PPT system is required to change the altitude/orbit. Therefore, a new PPT system with the Multi-Discharge-Room type electrothermal PPT (MDR-PPT) was developed at OIT. The MDR-PPT has plural discharge rooms in one single thruster. The ignitors are mounted in each discharge room and can be selected separately to change the discharge room.

An operation experiment of 1,000 shots was performed using the 1st MDR-PPT. The1st MDR-PPT head is shown in Figure 15 and the experimental conditions are presented in Table 3 and the 1st MDR-PPT head after the experiment is shown in Figure 16.

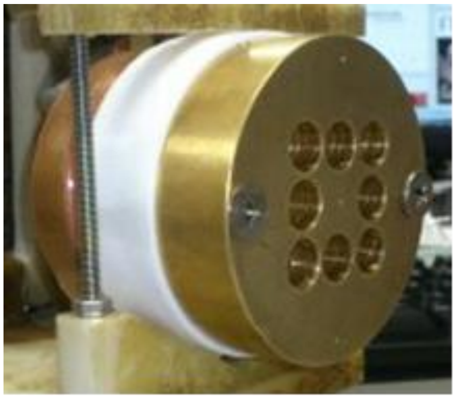


Figure 15. 1st MDR-PPT head.

Table 3. Experimental conditions with 1st MDR-PPT.

Discharge room diameter, mm	5
Discharge room length, mm	10
Nozzle (cathode) diameter, mm	7
Nozzle (cathode) length, mm	19
Capacitance, μF	19.5
Charging voltage, kV	1.8
Input energy, J	31.59
Shot number	1,000

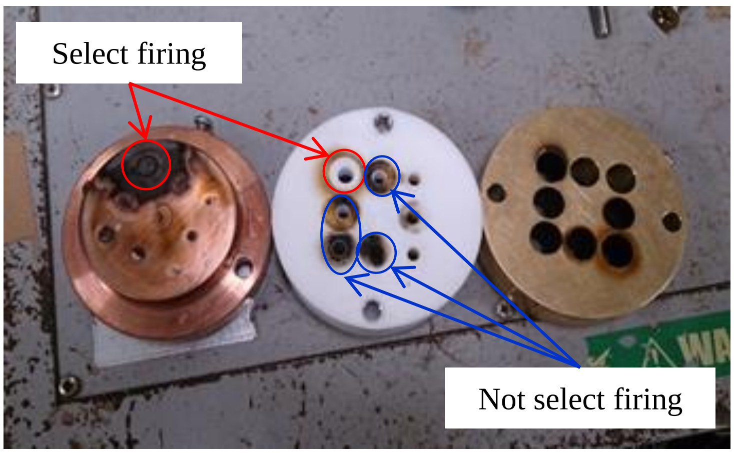


Figure 16. Parts of 1st MDR-PPT head after test.

Figure 16 is shown that unexpected discharged were induced in some discharge rooms in which no firing was selected. The following two causes were inferred:

1) The plasma which was generated in the 1st MDR-PPT leaked out from the gap between the propellant and the nozzle or the anode.
2) Excessive ablation of propellant occurred by repetitive operation under high-temperature conditions lead to a short between the discharge rooms.

B. 2nd MDR-PPT

The 2nd MDR-PPT was produced considering the cause of induction caused by the operation experiment of the 1st MDR-PPT. The overview and structure of the 2nd MDR-PPT head are shown in Figure 17 and 18. The feature of the 2nd MDR-PPT is that the anode, the propellant, and the cathode (Nozzle) are independent and wrapped in the PTFE body. With this structure, improvement in airtightness inside the discharge chamber can be expected. Also, the pressing board for fixing plays the role of heat sink, and improvement of cooling performance can be expected.

An operation experiment of 1,000 shots was performed using the 2nd MDR-PPT. The experimental conditions are presented in Table 4 and the 2nd MDR-PPT head after the experiment is shown in Figure 19.

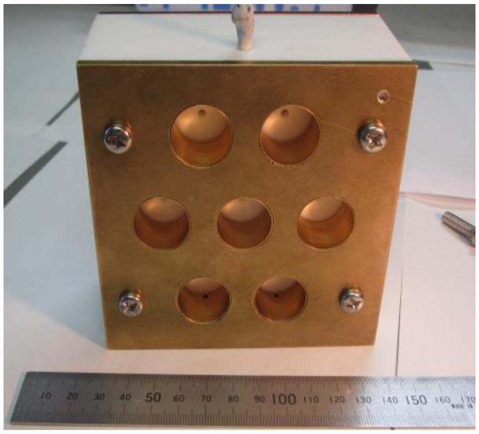


Figure 17. Overview of 2nd MDR-PPT head.

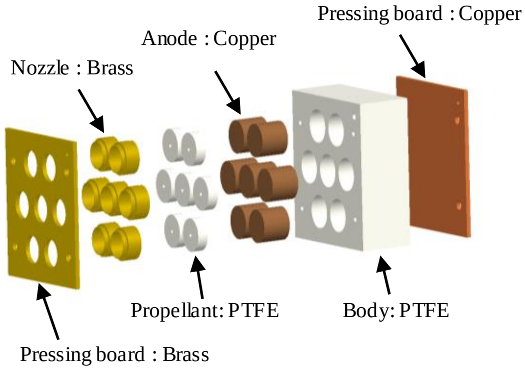


Figure 18. Structure of 2nd MDR-PPT head.

Table 4. Specification of 2nd MDR-PPT.

Discharge room diameter, mm	4
Discharge room length, mm	10
Nozzle (cathode) diameter, mm	20
Nozzle (cathode) length, mm	18
Size, mm	59 x 110 x h 110
Mass, kg	2.75

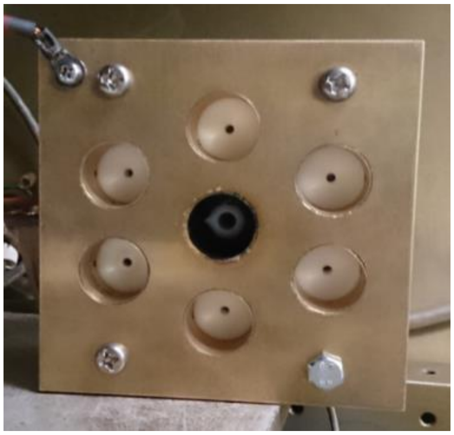


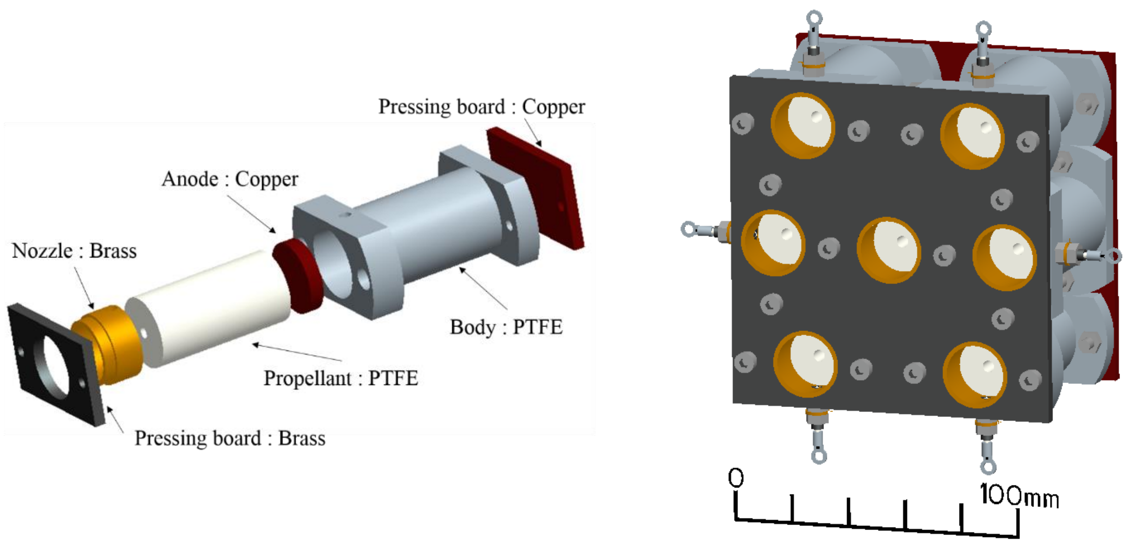
Figure 19. 2nd MDR-PPT head after test.

Figure 19 is shown that discharged were induced only in discharge rooms in which firing was selected. The induction problem could be solved by reviewing the design. However, the 2nd MDR-PPT had the following four drawbacks.

1) The body has parts which be not effective for thrust performances, and the weight is high.
2) Ignitors cannot be unify parts for every discharge room because the ignitor lengths are different.
3) To attach the ignitors in the nozzles with a PTFE tape is not reliable.
4) The airtightness of each discharge room cannot be equalized when it is disassembled once because two pressing board and a body are fixed only at the four corners.

C. 3rd MDR-PPT

Figure 20 shows a 3D model of the 3rd MDR-PPT which was designed in consideration of the drawbacks of the 2nd MDR-PPT. As can be seen from Figure 20, the structure in which the anode, the propellant, and the cathode were wrapped in a PTFE body was maintained. And the PTFE body was shaped to lighten the mass. Thereby, it was possible to reduce the weight by about 33% compared with the 2nd MDR-PPT. Moreover, by separating the body for each discharge room, it was possible to unify the length of the ignitor, and it was possible to uniformly tighten the discharge room by the pressing board. The specification is shown in Table 5.



(a) Structure of single head for 3rd MDR-PPT. (b) Overview of assembly.
Figure 20. 3D model of 3rd MDR-PPT head.

Table 5. Specification of 3rd MDR-PPT.

Discharge room diameter, mm	4
Discharge room length, mm	50
Nozzle (cathode) diameter, mm	20
Nozzle (cathode) length, mm	14
Size, mm	112 x 73 x h 112
Mass, kg	1.85

VI. Power Processing Unit

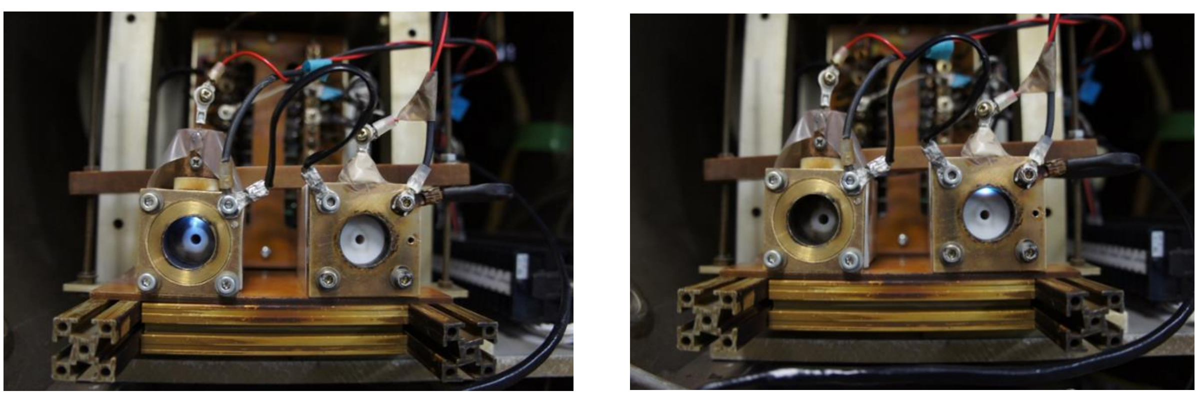
The Power Processing Unit (PPU) or the MDR-PPT system of the 2nd PROITERES nano-satellite was specially developed by OIT and High Serve Inc. The photograph of the PPU is shown in Figure 21, and the specifications are presented in Table 6. The MDR-PPT head can select seven firing discharge rooms by the PPU. The ignition voltage is 3,000 V, and the charging voltage is 1,800 V.

In this experiment, simulated discharge chamber switching was carried out using PPU and two PPTs. As a result of the experiment, it was possible to confirm the ignition discharge in both atmosphere and vacuum environment respectively. Figure 22 shows the state of ignition discharge in the atmosphere.

Figure 21. PPU for MDR-PPT system.

Table 6. Specification of PPU.

Mass,　kg		0.5
Size,　mm		120 x 185 x h 40
Power consumption,　W		30
Input voltage,　V		DC 28
Charge time,　s		< 1.5
Output voltage,　kV	to CAP	1.8
	to Ignitor	3.0



(a) Select left discharge room.　　(b) Select right discharge room.

Figure 22. Ignition discharge test in the atmosphere.

A total impulse measurement experiment was carried out using high-power PPT and PPU. As the propellant, one having a discharge room length of 50 mm which showed the highest impulse bit in the previous chapter was used. Figure 23 shows the experimental result. As shown in Figure 23, it was confirmed that the impulse bit slowly decreased as the shot number increased. The initial impulse bit of 2.56 mNs decreased to 0.55 mNs after 110,000 shots. For the entire operation a total impulse of 92.0 Ns could be generated. This total impulse is the impulse that makes it possible for a powered-flight of about 4.1 km for the 2nd PROITERES nano-satellite with a mass 45 kg. By using MDR-PPT, the 2nd PROITERES nano-satellite can perform powered-flight of about 28.7 km.

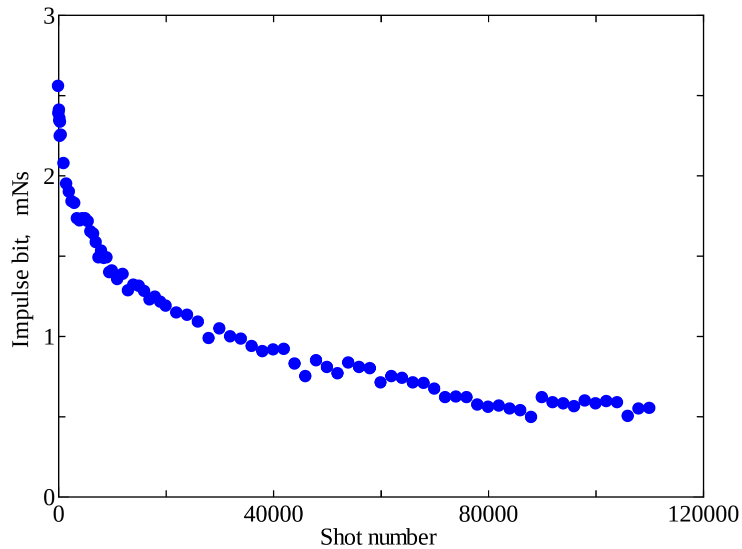
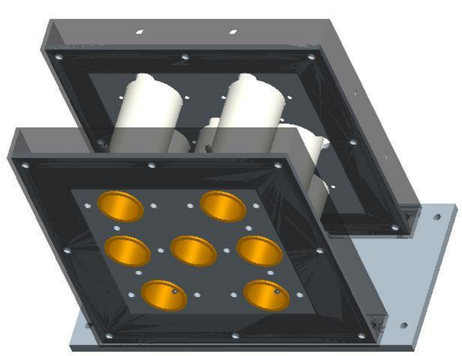


Figure 23. Total impulse vs. Discharge room length.

VII. PPT System for the 2nd PROITERES Nano-satellite

A design change was made to make the 3rd MDR-PPT a PPT system for mounting on a 2nd PROITERES nano-satellite. The 3rd MDR-PPT uses an anode panel and a cathode panel as a structure and an electrode. In the present design, it becomes the two point grounding of the capacitor and the cathode. Therefore, the team changed the anode panel / cathode panel to insulator and wire directly to the anode / cathode. Furthermore, to secure the strength, the team attached the aluminum frame. Furthermore, an aluminum frame was attached to ensure strength. Figure 24 shows the modified MDR-PPT.

The PPT system for mounting a 2nd PROITERES nano-satellite consists of an MDR-PPT head and a capacitor (13 mica paper capacitors connected in parallel) and a PPU. Each device is housed in a housing. The capacitor and the MDR-PPT head were placed as close as possible to reduce the energy loss due to the resistance of the circuit cable. Also, the placement of each device was decided considering the position of the center of gravity at the time of mounting on the satellite. The designed PPT system is shown in Figure 25, and the size of each device is shown in Table 7.


(a) Front side.

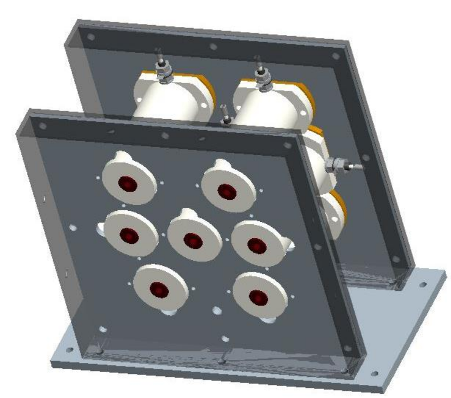

(b) Back side.

Figure 24. 3D model of MDR-PPT head.

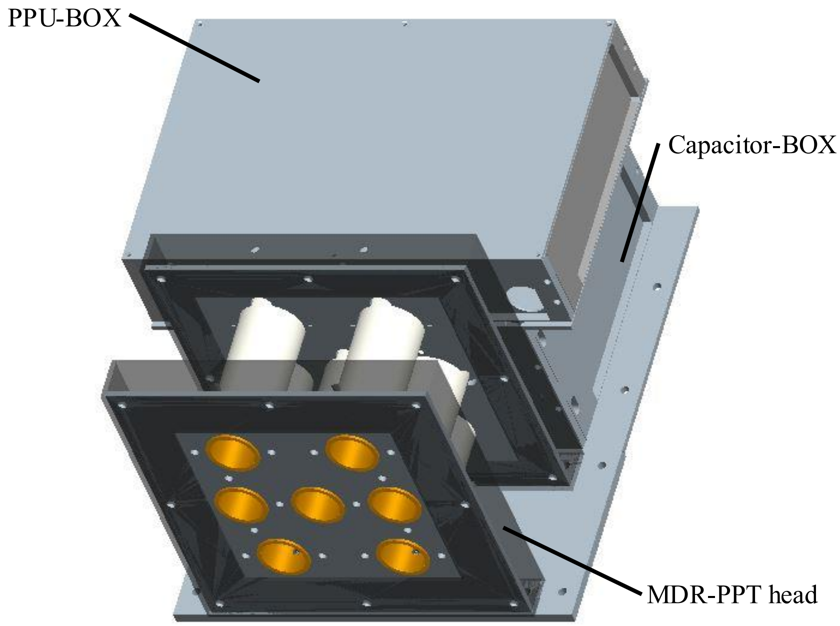


Figure 25. PPT system.

Table 7. Size of PPT system.

PPT system, mm	235 x 244 x h 153
MDR-PPT head, mm	244 x 93 x h 153
PPU-BOX, mm	244 x 142 x h 46
Capacitor-BOX, mm	202 x 142 x h 89

If this powered flight, which is the main mission of the 2nd PROITERES nano-satellite, can be achieved with this PPT system, it can be expected to be diverted to other small/nano satellites. Moreover, by changing the number of discharge chambers of the MDR-PPT head and the number of mica paper capacitors, the range of the mission can be expanded.

VIII. Conclusions

The following results were obtained:

1) A high-power PPT head showed initial performance of impulse bit at 2.47 mNs, the mass shot was 738 μg, the specific impulse was 342 s, the thrust efficiency was 13.1% at 31.59 J per shot with a discharge room length of 50 mm.
2) A new PPT system with the 1st MDR-PPT for long-time operation was developed. However, with the 1st MDR-PPT unexpected discharges occurred in the discharge rooms.
3) The induced problem that occurred in the 1st MDR-PPT was solved by the 2nd MDR-PPT design.
4) The 3rd MDR-PPT which was designed considering the drawbacks of 2nd MDR-PPT.
5) The discharge chamber switching experiment using PPU and two PPTs was conducted and the ignition discharge was confirmed in both the atmosphere and the vacuum environment in each selected discharge chamber.
6) A total impulse of 92.0 Ns was obtained in a repetitive 110,000 shot operation with a discharge room length of 50 mm of a single PPT head.
7) Design change was successfully made to make the 3rd MDR-PPT a PPT system for mounting on a nano-satellite.

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