Short Pulse Characteristics of a Laser-Assisted Pulsed Plasma Thruster

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Abstract: An objective of this study was to improve the thrust performance of a laser-assisted pulsed plasma thruster. In this study, short-pulse operation of a laser-assisted pulsed plasma thruster was conducted. To estimate the thrust performance of a short-pulse laser assisted pulsed plasma thruster, impulse bit measurement and mass shot measurement were conducted. From the results, impulse bit increased with increase of charge energy. In addition, mass shots also increased with increase of charge energy. From the results, the maximum impulse bit and mass shot for charge energy of 3.0 J were 25 µNs and 0.6 µg/pulse, respectively. The maximum specific impulse and maximum thrust efficiency were 4,000 s and 15 %, respectively.

Nomenclature

Vc	=	*charge voltage in capacitor*
Ec	=	*charge energy in capacitor*
vp	=	*speed of plasma*
td	=	*delay time from laser ablation*
Isp	=	*specific impulse*
η th	=	*thrust efficiencyA* = amplitude of oscillation

I. Introduction

The current trend towards small spacecraft, which is not only mass limited but also power limited, has produced a strong interest in development of micropropulsion devices [1-4]. The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase in launch rate. Although, in the past, many very small spacecraft lacked propulsion systems, future micro-spacecraft will require significant propulsion capability to provide a high degree of maneuverability and capability. The benefit of using electric propulsion for the reduction of spacecraft mass will likely be even more significant for mass limited micro-spacecraft missions [2-4]. Feasibility studies of micro-spacecraft are currently under development for a mass less than 100 kg with an available power level for propulsion of less than 100 watts [1-4]. Various potential propulsion systems for micro-spacecraft applications, such as ion thrusters, field emission thrusters, pulsed plasma thrusters (PPTs), vaporizing liquid thrusters, resistjets, microwave arcjets, pulsed arcjets, etc., have been proposed and are

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under significant development for primary and attitude control applications.In particular, the PPTs are expected to be used for microsatellites and their longterm because of the precise impulse bit controllability [5-9].

On the other hand, small-sized onboard laser plasma thrusters are also under significant development with rapid evolutions of novel compact laser systems. One of the advantages of the laser thrusters is that they can induce high specific impulses. In addition, the system can be very simple and small with significant controllability of the thrust [10-13]. To improve thrust performances and system simplicities of those conventional electric and laser propulsion systems, a preliminary study on a laser-electric hybrid acceleration system have been conducted by the authors [14-20].

A schematic of the rectangular laser-assisted pulsed plasma thruster (LA-PPT) is illustrated in Fig. 1 [14-20]. A basic idea of the system is that a bunch of laser-ablation plasma, induced through laser irradiation on a solid target, is supplied to an acceleration channel and additionally accelerated by electrical means between an anode and a cathode. When the current between the electrodes increases, the plasma can be heated and further ionized through joule heating. Thus, the electrothermal acceleration effect will be significant. With larger current exceeding more than one thousand amperes, the electromagnetic acceleration effect becomes significant. With the interaction of the current and a self-induced magnetic field, a streamwise acceleration of the plasma will be provided [5, 21-22].

Since any solid materials can be used for the propellant in these systems, no tanks, no valves, or piping systems are required for the propulsion system. Also, various materials in any phases can be used for the propellant. Therefore, the system employing this technique can be simple and compact. As the laser-ablation plasma has a directed initial velocity of few tens of km/s, which will be further accelerated by electrical means, significantly high specific impulses can be expected.

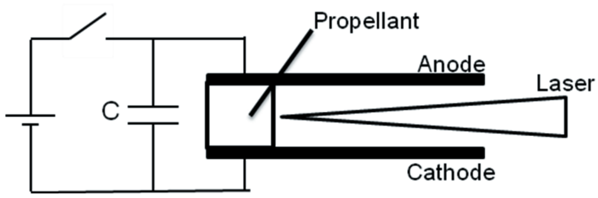

Figure 1. Schematic of a laser assisted pulsed plasma thruster.（LA-PPT）

II. Research Motivation

Figure 2 shows the typical high specific impulse characteristics of the laser-assisted pulsed plasma thruster replotted from our previous report, in which variations of specific impulse with charge energy are plotted for various acceleration channel configurations [20]. From the figure, it can be seen in all the cases that specific impulse increased with the increase of the charge energy. Moreover, thrusters with longer channel length showed higher specific impulses. The highest specific impulse of 7,200 sec was obtained with the 10 mm x 50 mm thruster at the highest charge energy of 8.6 J [20].

Therefore, an objective of this study is to estimate the performance of a LA-PPT in short pulse operation and high voltage operation, impulse bit measurements and mass shot measurements were conducted.

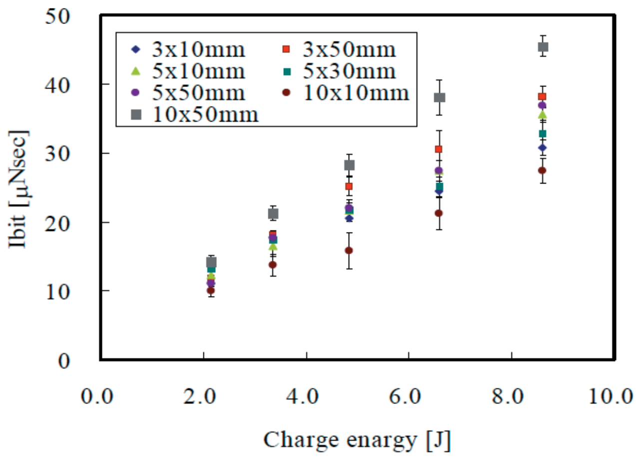

Figure 2. Variation of Impulse bit with charge energy for thrusters with various electrode geometries (electrode length x electrode height) [20].

III. Experimental Setup

To estimate the thrust performance of a short-pulse LA-PPT, an impulse bit measurement and mass shot measurement were conducted.

A photo of the thruster is shown in Fig. 3, in which electrodes made of molybdenum and propellant and insulator made of alumina ceramics. A capacitor bank (TDK, Ultra-high Voltage Ceramic Capacitors UHV-3A: 4 nF, UHV-9A: 2 nF ,total capacitance of capacitor bank: 24,50 nF) was utilized for short pulse (ns-pulse) operation (Fig.4). Furthermore, another capacitor bank (SOSHIN ELECTRIC CO., LTD., CMP91B202155K-02, capacitance: 1.45 μF, total capacitance: 7.25 μF) was also utilized for μs-pulse operation to compare their discharge characteristics. Dimensions of the thruster are listed in Table 1. In this study, relatively larger width and length of the rectangular electrodes of 10 mm x 50 mm were employed, which showed the best thrust performance among various electrode configurations in our previous study.[20]

Table 1. Dimensions of a thruster head.

Channel length: $\boldsymbol{l}$	50 mm
Channel width: $\boldsymbol{w}$	10 mm
Channel gap: $\boldsymbol{h}$	15 mm
Electrode material	Mo
Propellant material	Al_2O_3
Body	Al_2O_3

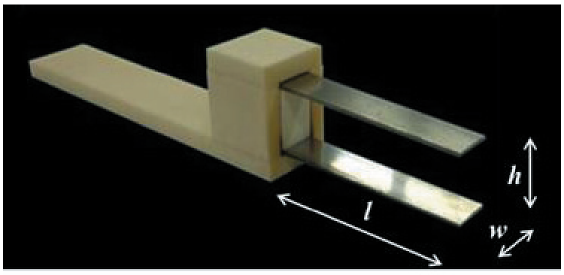

Figure 3. Laser Assisted Pulsed Plasma Thruster (LA-PPT).

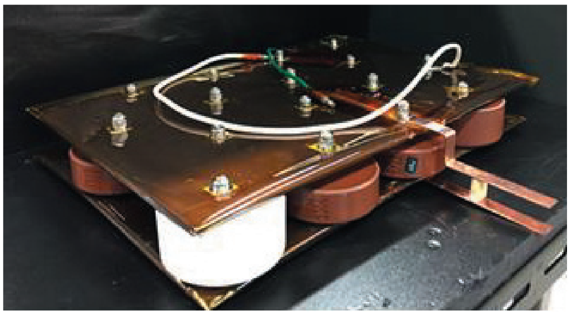

Figure 4. Capacitor bank for a short-pulse LA-PPT.

A. Impulse bit measurement

To measure an impulse bit of a short-pulse LA-PPT, the impulse bit measurement was conducted using a cylindrical target thrust stand shown schematically in Fig.5.[23] A plasma plume, generated from the LA-PPT by an electrical discharge, comes into an entrance hole on the front plate. The bottom plate has a conical shape, and most rebounding gas particles from the bottom plate will leave radially from the target through the slits on the side of the cylinder. Figure 5 shows a schematic of the impulse bit measurement system. The thrust stand consisting of a cylindrical target pendulum measures a reaction force exerted from a plasma plume exhausted from a thruster during operation. The main body of the cylindrical target is made of a polyvinyl chloride (PVC) plate of 0.5 mm in thickness and a pendulum arm of 300 mm in length is made of aluminum. A thruster was installed in front of the target, and impulse bit was calculated from the displacement of the pendulum. Displacement of the pendulum was measured by an inductive displacement sensor (EMIC CORP., NPA-010, resolution: 0.5 μm, range: 0 - 1.0 mm, output voltage: 0 - 1.0 V), and output signals from the sensor were monitored and recorded by an oscilloscope (Tektronix, TDS3034B, band width: 300MHz, the best sampling rate: 2.5 GS/s).

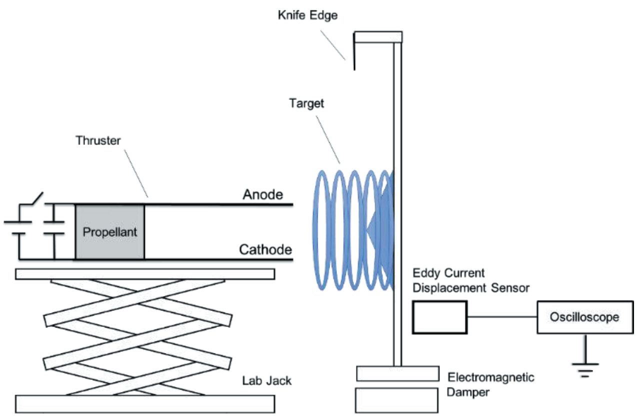

Figure 5. Schematic of an impulse bit measurement system.

B. Mass shot measurement

For the measurement of a mass-shot per pulse-shot of the propellant, or propellant consumption rate per shot, the measurement of the removed volumes of the propellant target surface after the number of shots was conducted with the vision measuring system (Mitsutoyo, QV-APEX302) and then the mass of the removed volume was estimated from the product of the volume by density of alumina. A typical number of pulse-shots to measure the mass-shot was 300 times.

IV. Result And Discussion

A. Discharge current measurement

Figure 6 shows discharge current waveforms for C = 24 nF (V_c = 10 kV, E_c = 1.2 J) and C = 7.25 μF (V_c = 0.6 kV, E_c = 1.3 J), respectively. For C = 24 nF (V_c = 10 kV, E_c = 1.2 J), the current reaches the positive peak value, 14 kA, at 500 ns. Crossing zero at 600 ns, the current reaches the smallest (negative peak) value, -10 kA at 650 ns. After crossing zero at 750 ns, the current reaches the second peak values, 7 kA. The current converges into zero at about 3,000 ns. On the other hand, for C = 7.25 μF (V_c = 0.6 kV, E_c = 1.3 J), the current reaches the positive peak value, 3 kA, at 1000 ns.

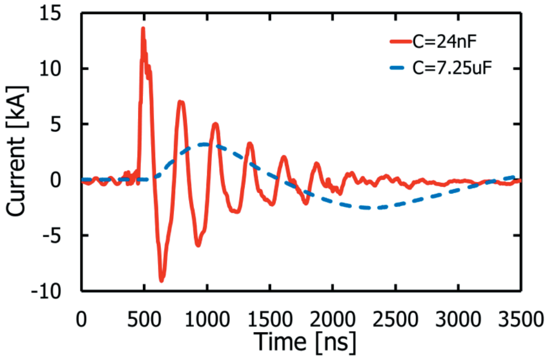

Figure 6. Discharge current waveform for 24 nF of capacitance (V_c=10 kV, E_c = 1.2 J) and 7.25 μF of capacitance (V_c = 0.6 kV, E_c = 1.3 J).

B. ns- and μs-pulse operation

Plots of measured impulse bits with various charge energies for ns- and μs-pulses are shown in Fig.7. In both ns- and μs-pulse cases, it can be seen that impulse bits increase with increasing charge energies. In ns-pulse operation, the impulse bit increases from 3 to 25 μNs with charge energies of 0 to 3 J. On the other hand in μs-pulse operation, impulse bit changes from 3 to 19 μNs with charge energies of 0 to 3 J. It is shown that the ns-pulse case shows higher impulse bits which are about 40% larger than ms-cases.

Variation of measured mass shots, or mass consumption rates per pulse discharge, with charge energies are plotted in Fig.8 for ns-pulses and μs-pulses. In both ns- and μs-cases, mass shots increase with charge energies and the variation of the mass shots are similar, changing from 0.2 to 0.7 μg/shot with charge energies at 0 ~ 3.0 J.

Plots of specific impulses versus charge energies for ns- and μs-pulses are shown in Fig.9. In both ns- and μs-cases, specific impulses increase with charge energies. Higher specific impulses can be obtained in ns-pulse cases, in which I_{sp} = 1,500 ~ 4,300 s for charge energies at 0 ~ 3.0 J, than μs-cases, in which I_{sp} = 1,200 ~ 3,200 s at Ec = 0 ~ 3.0 J.

Variation of thrust efficiencies with charge energies are plotted in Fig.10 for ns- and μs-pulses.Higher thrust efficiencies are obtained in ns-pulse cases, which are 10 ~ 15 % for charge energies at 0 ~ 3.0 J, than μs-cases, 5 ~ 10 % at Ec = 0 ~ 3.0 J.

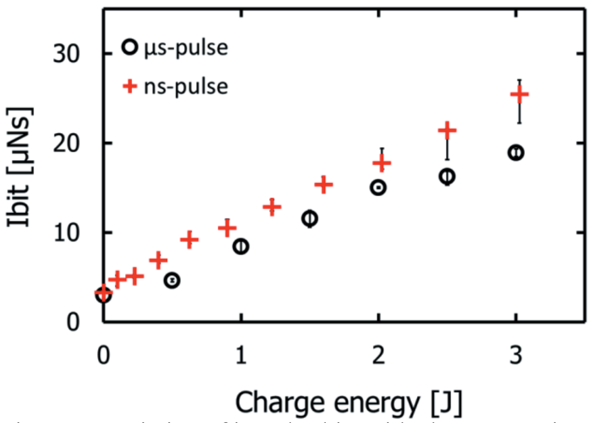

Figure 7. Variation of impulse bits with charge energies for ns- and μs-pulse operation.

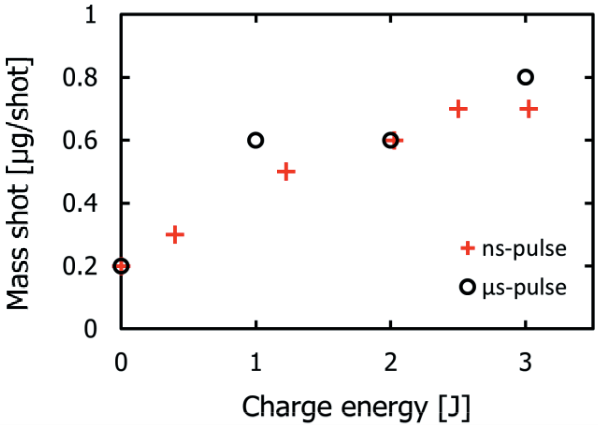

Figure 8. Variation of mass shots with charge energies for ns- and μs-pulse operation.

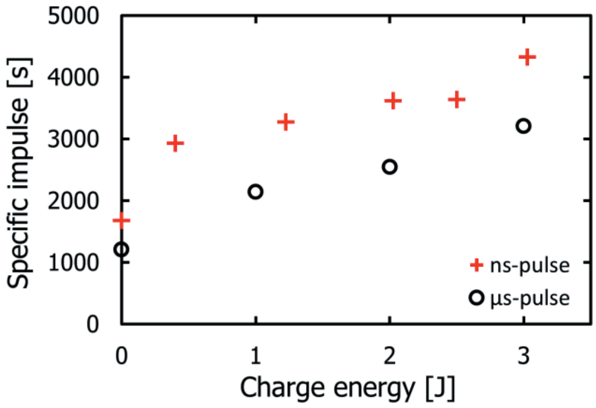

Figure 9. Variation of specific impulses with charge energies for ns- and μs-pulse operation.

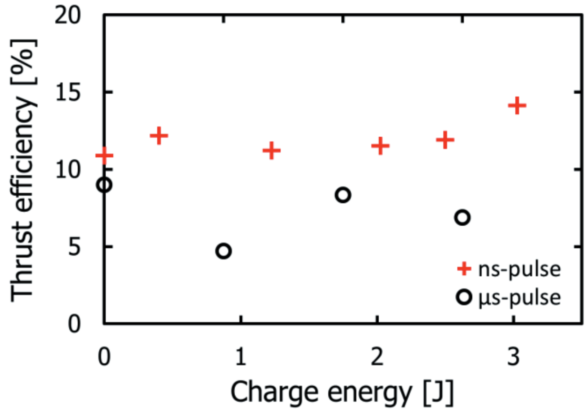

Figure 10. Variation of thrust efficiencies with charge energies for ns- and μs-pulse operation.

V. Conclusion

In this study, to estimate the thrust performance of a short-pulse (ns- pulse) laser-assisted pulsed plasma thruster, an impulse bit measurement and mass shot measurement were conducted.

a) In both ns-and μs-pulse cases, it can be seen that impulse bits increase with charge energies. It is shown that the ns-pulse case shows higher impulse bits which are about 40% larger than μs-cases.
b) In both ns-and μs-cases, specific impulses increase with charge energies. Higher specific impulses(4300s) can be obtained in ns-pulse cases,
c) Higher thrust efficiencies (15 %) are obtained in ns-pulse cases.

VI. References

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