Characteristics of High-repetition Rate Operation of a Laser-Assisted Pulsed Plasma Thruster

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Abstract: A fundamental study of high-repetition rate operation of a laser-assisted pulsed plasma thruster (LA-PPT) was conducted, which utilizes a laser beam to generate a plasma from a solid propellant surface and then accelerates the plasma by electromagnetic force. To elucidate discharge characteristics and continuous thrust characteristics under given electrical power inputs, repetitive-pulse operation of the thruster was conducted at 10 Hz. As results, it was shown that discharge pulses were occurring simultaneously with laser pulses at each pulse operated at a repetition rate of 10 Hz. In addition, the maximum thrust was 0.5 mN at 3.9 J/pulse at 10 Hz corresponding to an average power of 39 W. From a combination of the measured thrust and mass consumption rate of the propellant, typical values of specific impulse and thrust efficiency were 8,700 s and 0.50, respectively.

Nomenclature

V_c = Charge Voltage
E_c = Charge Energy
C = Capacitance

I. Introduction

The current trend towards smaller spacecraft, which is not only mass-limited but also power-limited, has produced a strong interest in the development of micro propulsion devices.[1-4] The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase launch rate. Although, in the past, many very small spacecraft lacked propulsion systems, future micro spacecraft will require a significant propulsion capability in order to provide a high degree of maneuverability and capability in terms of thrust, specific impulse, or efficiency. The benefit of using electric propulsion for the reduction in 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. Various potential propulsion systems for micro spacecraft applications, such as ion thrusters, field emission thrusters, pulsed plasma thrusters (PPTs), vaporizing liquid thrusters, resistojets, microwave arcjets, pulsed arcjets, etc., have been proposed and are under significant development for primary and attitude control applications.[4]

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In particular, the PPTs are expected to be used for microsatellites and their long term missions because of the precise impulse-bit controllability.

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 impulse. In addition, the system can be very simple and small with significant controllability of the thrust.[5-12] In order to improve thrust performances and system simplicities of those conventional electric and laser propulsion systems, a preliminary study on a laser-electric hybrid propulsion system was conducted.[13-15] A basic idea of these systems is that a bunch of laser-ablation plasma, induced through laser irradiation on a solid target, is additionally accelerated by electrical means. Since any solid material can be used for the propellant in these cases, no tanks, no valves, or piping systems are required for the propulsion system. Also, various materials in any phase 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 tens of km/sec, which will be further accelerated by electrical means, significantly high specific impulses can be expected.

A schematic of the rectangular laser-assisted pulsed plasma thruster is illustrated in Fig.1. It utilizes laser-beam irradiation to induce plasma ionized from a solid propellant between electrodes, and then an electric discharge is induced in this conductive region. As the current running between the anode and cathode is increased, the plasma can be heated and further ionized through Joule heating. Thus, the electrothermal acceleration effect becomes significant. When current exceeds more than one thousand amperes, an electromagnetic acceleration effect becomes significant. With interaction of the current and self-induced magnetic field, a streamwise acceleration is provided.

Because the use of a shorter laser pulse enables a shorter pulsed-plasma generation, a significantly high peak current can be induced. Since the force induced in the accelerator is dependent on the square of the current, significant improvements in acceleration characteristics can be expected. In addition, depending on laser power, laser-induced plasma produced from a solid propellant usually has a directed initial velocity, and this can also contribute to an improvement in the acceleration performance.

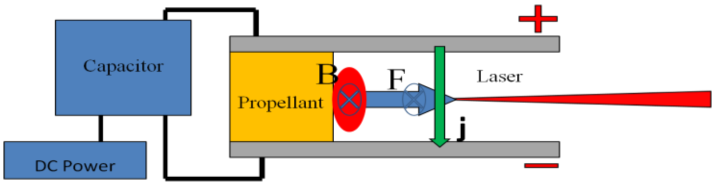

Fig.1 Schematic of laser-assisted pulsed plasma thruster (LA-PPT)

In our previous work, characteristics of thrust performance of the laser-assisted pulsed plasma thruster was conducted for various acceleration channel configurations.[17] Fig.2 shows variations of specific impulse with charge energy for various acceleration channel configurations. From the figure, it can be seen in all 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 10x50 thruster at the highest charge energy of 8.6 J. This high-specific impulse characteristic is one of the major advantages of this propulsion system. In our previous works, all the measurements were conducted with single-pulse operation of the thruster.

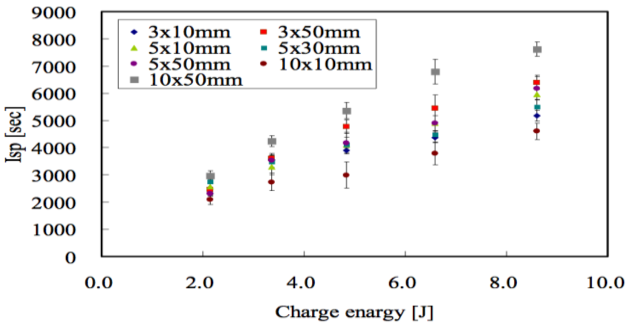

Fig. 2 Variation of specific impulse with charge energies for thrusters with various electrode geometries[17]

On the other hand, in this study, measurements are conducted with repetitive-pulse operation at 10 Hz to elucidate discharge characteristics and continuous thrust characteristics under given electrical power inputs.

II. Experimental

A schematic and photo of a rectangular laser-assisted pulsed plasma thruster are shown in Figs.1 and 3, respectively. The thruster consists of a pair of copper electrodes (5 mm in width, 10 mm in height between electrodes, 50 mm in acceleration channel length) and an alumina propellant (10 mm in height) were used. A schematic of experimental setup is shown in Fig.4. A Q-sw Nd:YAG laser (BMI, 5022DNS10, wavelength: 1064nm, fixed pulse energy: 420mJ/pulse, pulse width: 10 nsec) was used for a laser-ablation plasma source.

The laser pulse was irradiated into a vacuum chamber (10^{-3} Pa) through a quartz window and focused on a target, or a propellant, with a focusing lens (f = 100 mm). Discharge current was monitored with a current monitor (Pearson Electronics, Model-6600, maximum current: 10 kA, minimum rise time: 5 nsec) and an oscilloscope (LeCroy, 9374TM, range: 1 nsec/div ~ 5 msec/div).

In this study, preliminary experiments on switching, or discharge between cathode and anode, and discharge current characteristics of the laser-induced plasma were conducted at repetition rate of 10 Hz. Voltages charged to the electrodes were 500 V ~ 3000 V.

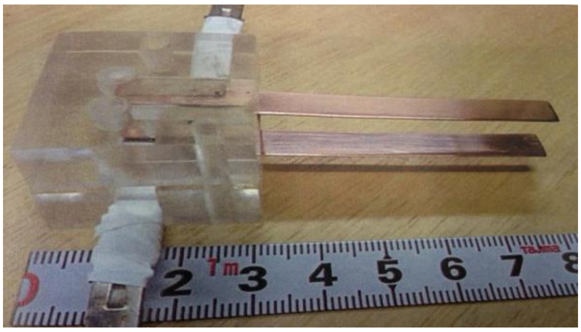

Fig.3 Photo of laser-electric hybrid thruster.

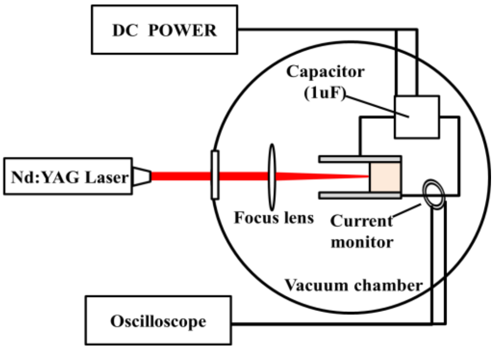

Fig.4 Schematic of experimental setup.

To measure a continuous thrust, rather than an impulse bit, an impulse bit of the thruster, thrust measurement by a pendulum thrust stand was conducted. Fig.5 show a schematic of the impulse bit measurement system. A thrust stand consisting of a ballistic pendulum, a pivot employing a knife edge, and a displacement sensor was installed in the vacuum chamber. A thruster is installed on the thrust stand, an d a thrust is calculated from the response by the reaction force of the thrust. Displacement of the pendulum arm (length: 280 mm, natural frequency: 1 Hz) 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). Output voltages from the sensor were measured by an oscilloscope (Tektronix, TDS3034B, band width: 300MHz, the best sampling rate: 2.5 GS/s).

Experimental setup for mass consumption rate measurement of the propellant is substantially the same as that of the discharge characteristic measurement (Fig.4). To measure the mass consumption rate, a volume, or a three-dimensional profile of a crater, was measured with a laser microscope after the discharging operation at 10 Hz for 50 seconds. From the measured volume and a density of the alumina, the mass consumption rate was estimated.

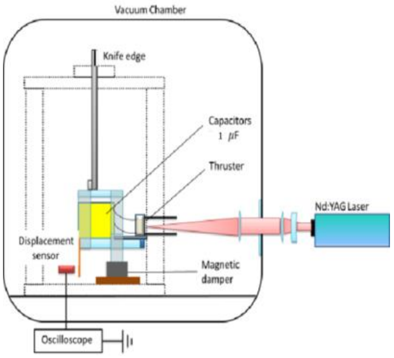

Fig.5 Schematic of continuous thrust measurement system.

III. Results and Discussion

A. Discharge Current Measurement

Fig.6 shows temporal variations of discharge current waveforms of a single pulse discharge for V_c = 500 V to 3000 V. At 1.5μs the currents reach the maximum values for all V_cs. At 4.5 μs the currents reach the smallest (negative peak) values. After crossing zero at 6μs, the currents reach the second peak values. After reaching the second smallest values at 10.5 μs, the currents converge into zero at 30 μs.

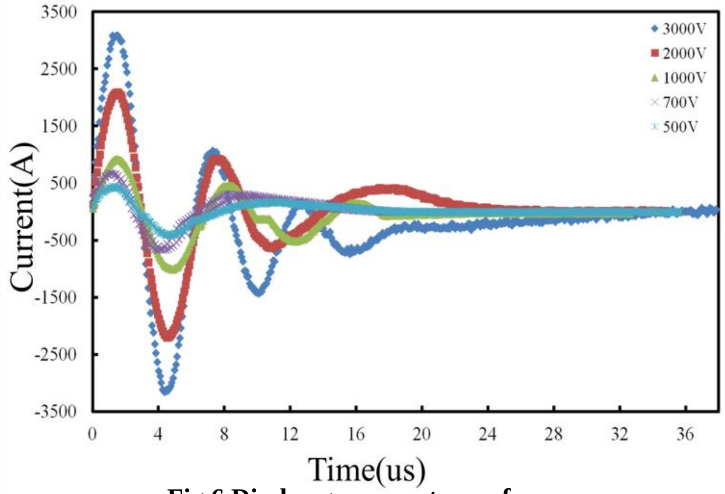

Fig.6 Discharge current waveform

B. Discharge Characteristics Measurement by PD

Repetitive laser emissions (violet line at bottom) and discharge emissions (blue line at top) operated at 10 Hz monitored with photo-diodes were shown in Fig.7 From these outputs, it can be seen that the discharge pulses are occurring simultaneously with the laser pulses at each pulse operated at a repetition rate of 10 Hz.

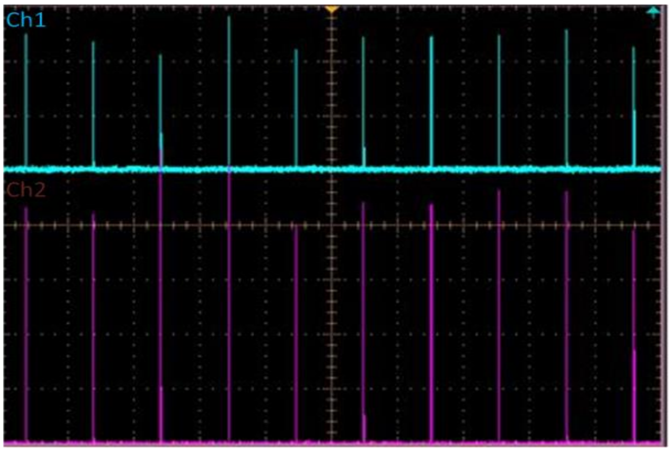

Fig.7 Repetitive laser light and discharge emissions operated at 10 Hz monitored with photo-diodes.

C. Continuous Thrust Measurement

A typical output signal of the displacement of the thrust stand is shown in Fig.8. Although large noise is induced with the discharges at 10 Hz, a dumped oscillation with a frequency of 1 Hz is observed. After about 10 sec, it is shown that the displacement, or a thrust, converges into a constant value.

Plots of measured thrusts and charge energy of the capacitor is shown in Fig.9 From the figure, it can be seen that the thrust increases with charge energy of up to 3.9 J/pulse. The maximum thrust is 0.5 mN at the maximum charge energy of 3.9 J/pulse. Since the repetitive operation is conducted at frequency of 10 Hz, the charge energy of 3.9 J/pulse corresponds to average power of 39 W.

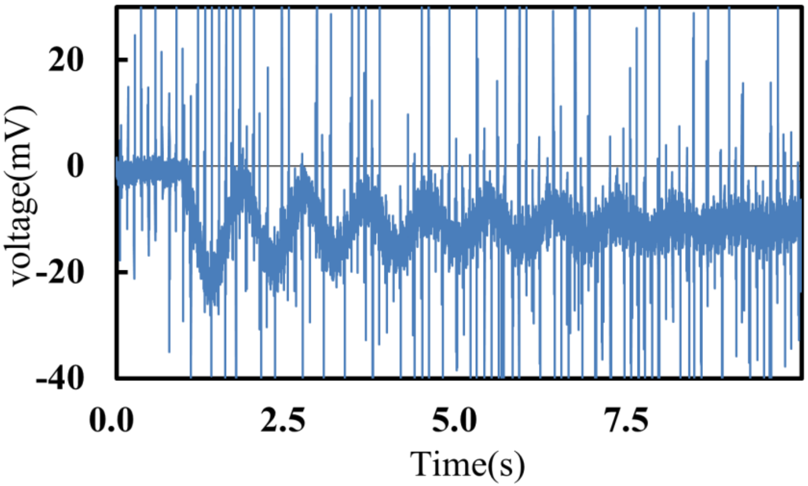

Fig.8 Typical output from displacement sensor (charge energy: 3.92J/pulse)

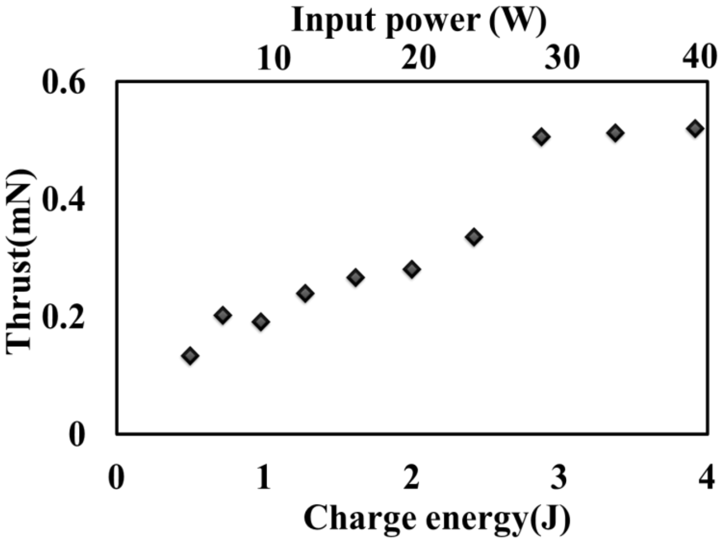

Fig.9 Variation of measured thrust with charge energy.

D. Mass Consumption Rate of Propellant

From a combination of the measured thrust and mass consumption rate of the propellant, typical values of specific impulse and thrust efficiency were estimated and listed in Table 1, which were 8,700 s and 0.50, respectively.

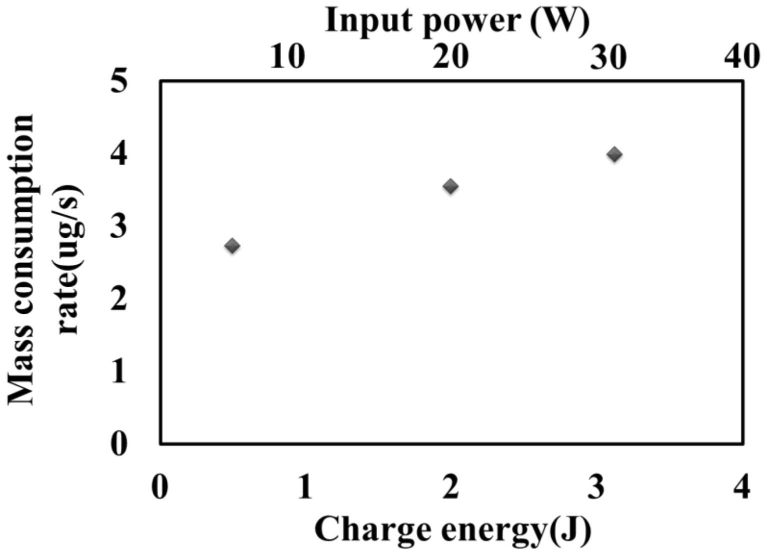

Fig.10 Mass consumption rate of propellant.

Table1. Typical specific impulse and thrust efficiency.

E [J]	Isp [s]	ηt
0.5	5400	0.25
2	8700	0.50

IV. Conclusion

In this study, to elucidate discharge characteristics and continuous thrust characteristics under given electrical power inputs, repetitive-pulse operation of a laser-assisted pulsed plasma thruster was conducted at 10 Hz. As results, it was shown that discharge pulses were occurring simultaneously with laser pulses at each pulse operated at a repetition rate of 10 Hz. In addition, the maximum thrust was 0.5 mN at 3.9 J/pulse at 10 Hz corresponds to average power of 39 W. From a combination of the measured thrust and mass consumption rate of the propellant, typical values of specific impulse and thrust efficiency were 8,700 s and 0.50, respectively.

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