Characteristics of a Laser-electrostatic Hybrid Propulsion System

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Abstract:To find the optimum electrode geometry of a laser-electrostatic hybrid thruster, speed of ions and number of ions were experimentally estimated with a Faraday cup for various electrode configurations. From the results, it was shown that, in a case of 10-mm-diameter electrode placed in front of a laser ablation target, the speed of ions increased with increasing acceleration voltages. Typical ion speeds, measured at 80 mm away from the target, were 16 km/s and 32 km/s for the acceleration voltages of 0 V and 500 V, respectively, with electrode gap of 20 mm.

Nomenclature

J	=	discharge current
B	=	induced magnetic field
Z	=	target-acceleration electrode gap
V_{tg}	=	voltage of Cu propellant (target)
V_{ac}	=	voltage of outer electrode

I. Introduction

SMALL-sized onboard laser plasma thrusters are under significant development with rapid evolutions of compact but high power laser systems[1-3]. One of the advantages of such laser thrusters is the use of solid-state materials for the propellant. Since any solid material can be used for the propellant, tanks, valves, or piping systems, which are necessary for thrusters with liquid or gaseous propellant, are not required for the laser propulsion system. Therefore, the laser thruster system can be very simple and compact. Also, significant controllability of thrust is possible by changing the input laser power. In order to further improve the thrust performances and system simplicities of conventional laser propulsion systems, a preliminary study on a laser-electric hybrid propulsion system was conducted by authors[4-7].

Our laser-electric hybrid acceleration system is depicted in Fig. 1The basic idea of these systems is that a laser-ablation plasma, induced by the laser irradiation on a solid target, is additionally accelerated by an accelerator grid. Since the laser-ablated plasma with an initial velocity of about 15 km/s [6,7], is further accelerated by an electrostatic or electromagnetic method, thrust and specific impulses can be significantly increased.

A. Laser-Electric Hybrid Acceleration Thrusters

In the laser-electric hybrid acceleration thrusters, depending on electrode configuration, plasma density, electrical input-power (voltage and current), etc., acceleration regimesof the laser-ablation plasma can be classified into three types, i.e., i) electrostatic acceleration, ii) electromagnetic acceleration, and iii) electrothermal acceleration. Especially for the laser-ablation plasma, depending on laser conditions such as pulse energy, fluence, etc., plasma

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density distribution can be widely controlled. Moreover, this can also be increased through additional electric discharges.

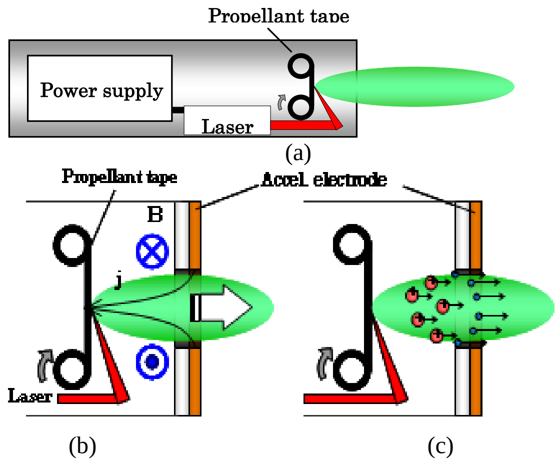

Figure 1. Schematics of laser ablation thrusters
(a) pure laser thruster, (b) laser-electromagnetic hybrid thruster, and (c) laser-electric hybrid thruster.

Therefore, optimizing the electrode configuration for additional electric acceleration, and controlling a power source, or voltage and current, adapting each acceleration mechanism, the propulsion system satisfying all the above acceleration regimes through i) to iii) can be achieved with one thruster configuration. Namely, this system enables a robust conversion between high specific impulse operationand high thrust density operation in regard to mission requirements. Each of two typical types of the acceleration schemes are currently being investigated as described in following subsections.

B. Laser-Electromagnetic Hybrid Acceleration Mode

One of the laser-electric hybrid acceleration modes considered in our recent studies is the laser-electromagnetic acceleration. In order to improve thrust performances of electromagnetic acceleration thrusters such as pulsed-plasma thrusters, or PPTs, effects of utilization of a laser beam are being investigated.

The PPTs, utilizing a solid propellant usually PTFE (Teflon®), have attracted a growing interest for their system simplicity and advantages on miniaturization and mass reduction for the use of attitude or orbit control thrusters for small-sized spacecrafts, despite their low efficiency[8-10]. In the PPTs, it is difficult to complete the process including phase changes and electromagnetic acceleration simultaneously during a discharge pulse, because there is a delay in phase changes of the solid-propellant after the pulse discharge initiation. Various masses including low-speed macroparticles can have quite different velocities. Since residual vapor or plasma from the late-time evaporation of the propellant surface remains in the discharge chamber due to the delay, which cannot contribute to the impulse bit, it has been difficult to improve this mass loss of the propellant and namely thrust efficiency[7,8,9]. In order to reduce this late-time ablation and to improve thrust efficiency, effects of utilization of laser-pulse irradiation, or assistance, were investigated, which can induce a conductive plasma from a solid-propellant surface in a short duration, i.e., using a short-duration conductive region of the plasma between electrodes, short-pulse switching or discharge can be achieved[4-6]. Since the use of a shorter pulse of the laser enables a shorter duration of a pulsed-plasma in this case, a higher peak current and significant improvement of thrust performances can be expected. In addition, depending on the laser power the laser-induced plasma occurring from a solid-propellant usually has directed initial velocity, which can also improve the thrust performance compared to conventional PPTs. A schematic of a coaxial laser-electromagnetic acceleration thruster is illustrated in Fig. 1(b) [6].

C. Laser-Electrostatic Acceleration Mode

As for another mode of laser-electric hybrid thrusters, a preliminary investigation on a laser-electrostatic hybrid acceleration thruster is conducted, in which alaser-ablation plasma is accelerated by an electrostatic field[7]. The mechanism of this mode is as follows. Firstly, a focused laser pulse is irradiated on to a solid target, or propellant. Then, a laser-induced plasma, or laser-ablation, occurs at an irradiating spot of the propellant surface. In the laser-ablation process, first of all, electrons are emitted from the surface, and, then, ions are accelerated through ambipolar diffusion[6,7]. These ions are further accelerated with an additional acceleration electrode. Since the laser-induced plasma having the directed initial velocity is further accelerated by an electrostatic field, high specific-impulse can be expected.

The objective of this study is to investigate the optimum electrode configurations and to observe the acceleration characteristics of the laser-electrostatic hybrid acceleration mode.

II. Experimental Apparatus

Ion speed and ion number exhausted from the thruster were measured using a Faraday cup. Experimental apparatus is shown in Fig. 2The Faraday cup was placed at 50 mm and 80 mm away from the surface of the ablation target. The ion current was amplified by an amplifier (DC to 10MHz) and was monitored by an oscilloscope (Tektronix, TDS3034B, sampling rate: 2.5GS/s, frequency bandwidth: 300 MHz). The ion velocity distributionswere calculated from the division of the distance between the target and Faraday cup by the time-of flight of the ions. Mean velocities of the ions were calculated from the integration of the ion velocity distributions. In addition, from delays of the peak ion currents of the Faraday cups located at different positions, average ion speeds were also estimated. In these measurements, it was shown that the mean velocities of ions estimated at two positions and the average ion speeds were consistent.

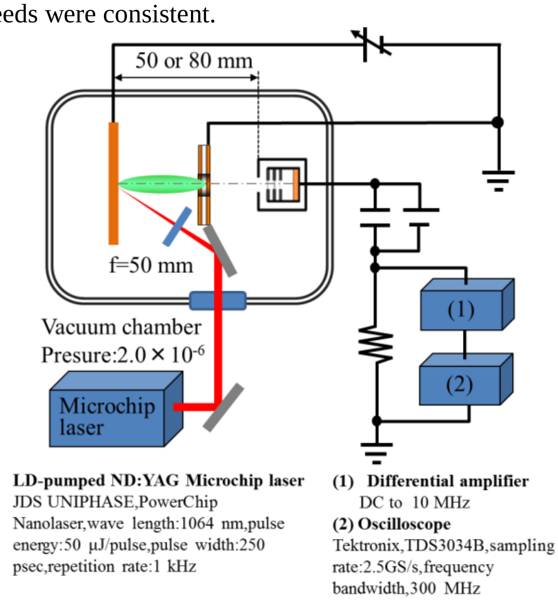

Figure 2. Experimental setup

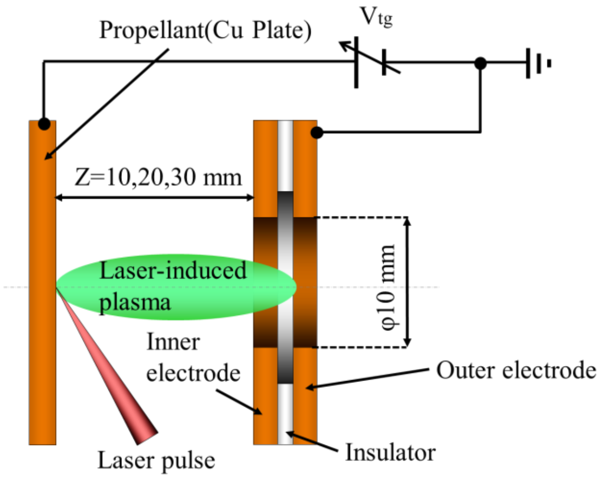

Figure 3. Laser-electrostatic hybrid thruster A

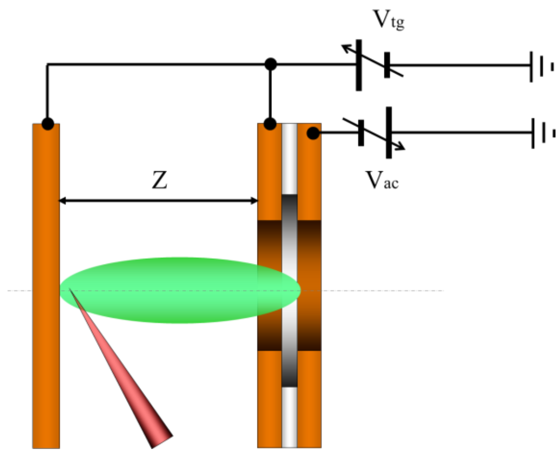

Figure 4. Laser-electrostatic hybrid thruster B

Schematic illustrations of laser-electrostatic hybrid thrusters are shown in Fig. 3 and Fig. 4.The hybrid thruster consists of a Cu target (propellant), a pair of electrodes, and a laser oscillator. The Cu target was mounted on an X-Y stage to refresh irradiated surfaces. For the laser oscillator, an LD-pumped Nd:YAG microchip laser (JDS UNIPHASE, PowerChipNanolaser, wavelength: 1064 nm, pulse energy: 50 µJ/pulse, pulse width: 250 ps, repetition rate: 1 kHz) was used. Laser ablation plasmas or ions were accelerated by the acceleration electrodes made of 0.1 mm-thick Cu plates with a hole of 10 mm in diameter.

Based on our previous measurement[7] of electron temperatures and densities of a laser ablation plasma from the same configurations, a range of distance (*Z*, target-acceleration electrode gap) and separation (0.1 mm) of the electrodes were determined for effective electrostatic acceleration of ions. In the thruster A (Fig. 3), the first electrode (inner electrode) was electrically floated enabling its potential to follow a plasma potential. The second electrode (outer electrode) was biased from 0 to -500 V relative to the target potential. On the other hand, in the thruster B (Fig. 4), the inner electrode was electrically connected to the target to give the same potential. The outer electrode was biased from 0 to -500 V relative to the target and inner potential.

III. Results and Discussion

The ion velocities of thruster A measured by Faraday cup are plotted in Figs. 5 and 6, where positions of the Faraday cup are placed at 50 mm and 80 mm away from the target, respectively. In both cases, acceleration voltages Vtg, or voltages of the target relative to the outer electrode, increased from 0 to +500 V toproduce a negative electrostatic field to accelerate positive ions for various electrode locations of Z = 10 to 30 mm. Differences in ion velocity profiles between Figs. 5 and 6 are probably due to the misalignment of the axis of the Faraday cup to that of ion beams.

In Fig. 5, measured at 50mm, the ion velocities increase with the increase of acceleration voltages for all Z cases. Typical ion velocities were 17 km/s and 30 km/s for Vtg = 0 V and 500 V, respectively at Z = 20 mm.

In Fig. 6, measured at 80 mm, similar tendencies of the ion velocities were observed. From the figure, typical ion velocities were 16 km/s and 32 km/s, respectively for Vtg = 0 V and 500 V at Z = 20 mm. Although some scatters of data can be seen, the reproducibility of these data was within 10%.

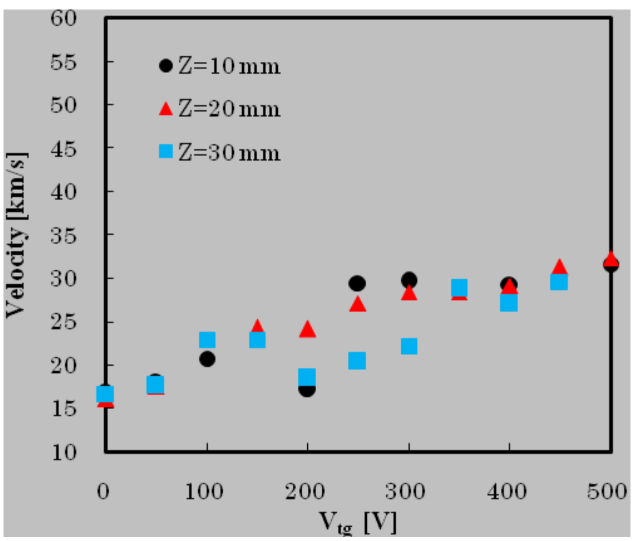

Figure5. Variations of ion velocity of thruster A with acceleration voltages measured with Faraday cup placed at 50 mm away from the target.

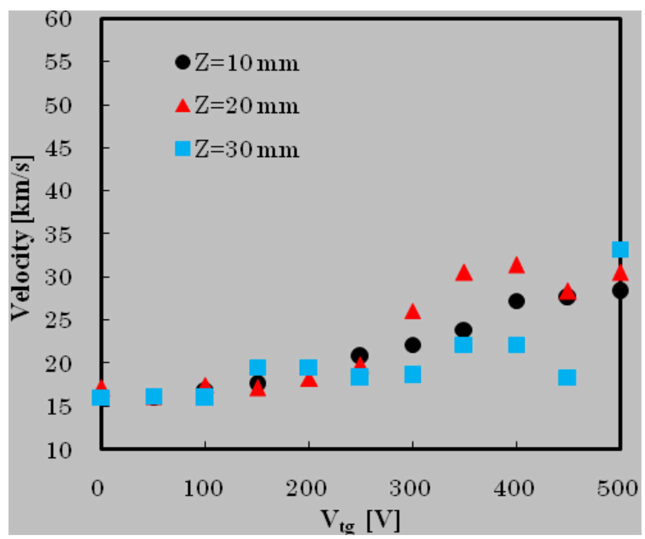

Figure6. Variations of ion velocity of thruster A with acceleration voltages measured with Faraday cup placed at 80 mm away from the target.

Variations of ion numbers with acceleration voltages measured by Faraday cup are plotted in Figs. 7 and 8, where positions of the Faraday cup are placed at 50 mm and 80 mm away from the target, respectively. In both figures, ion numbers decreased with the increase of acceleration voltages in all Z cases. This is probably the enhanced diffusion of the ions due to higher potential of acceleration electrode. In addition, ion numbers decreased with the increase of distance of the Faraday cup. When the electrode gap Z increased, the ion number decreased. Since the plasma diffuses in radial direction at larger Z, number of ions running through a hole of the acceleration electrode decreases.

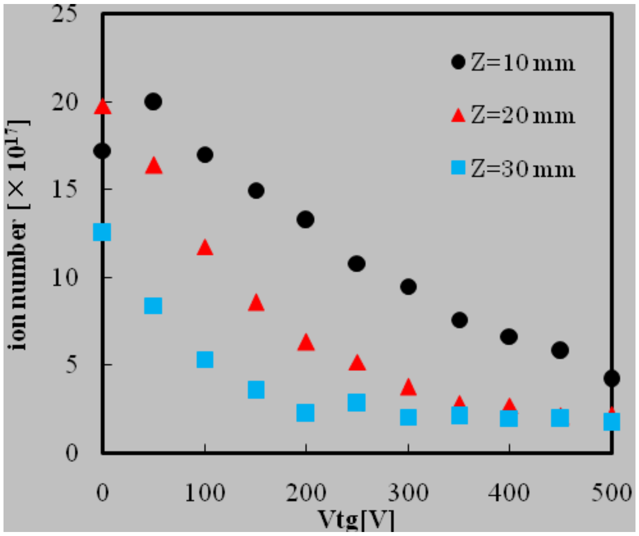

Figure7.Variations of ion number of thruster A with acceleration voltages measured with Faraday cup placed at 50 mm away from the target.

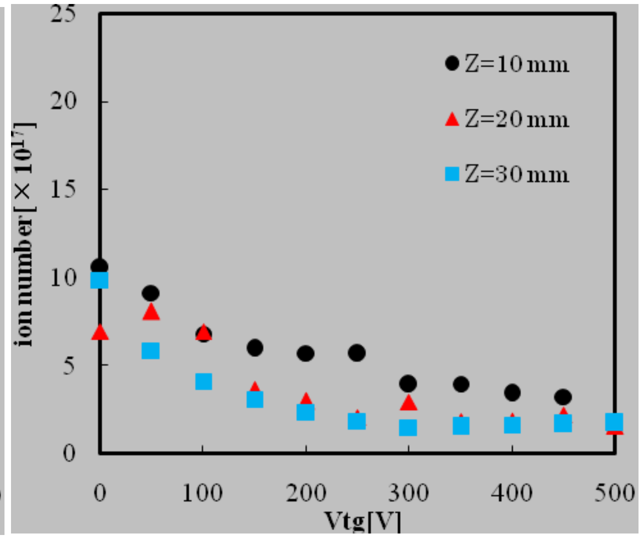

Figure8.Variations of ion number of thruster A with acceleration voltages measured with Faraday cup placed at 80 mm away from the target.

Results of ion velocities and numbers for thruster B are shown in Figs. 9 and 10. In these figures for thruster B (Fig. 4), voltages of the outer electrode, V_{ac}, were changed from 0 V to -150 V, those of target, V_{tg}, from 0 V to 500 V. Comparing the values of ion velocities of Fig. 9 to Figs. 5 and 6 of thruster A, the increase of ion velocities of thruster B (Fig. 9) with V_{tg} are less apparent than those of thruster A. Moreover, variations of Z in thruster B (Fig. 9) influenced more significantly than those of thruster A shown in Figs. 5 and 6. In thruster B, at V_{tg} = 200 V and V_{ac} = -100 V, typical ion speeds were 15 km/s and 21 km/s for Z = 10 and 30 mm, respectively. Values of ion numbers of thruster B shown in Fig. 10 were about a half of those of thruster B shown in Fig. 7.

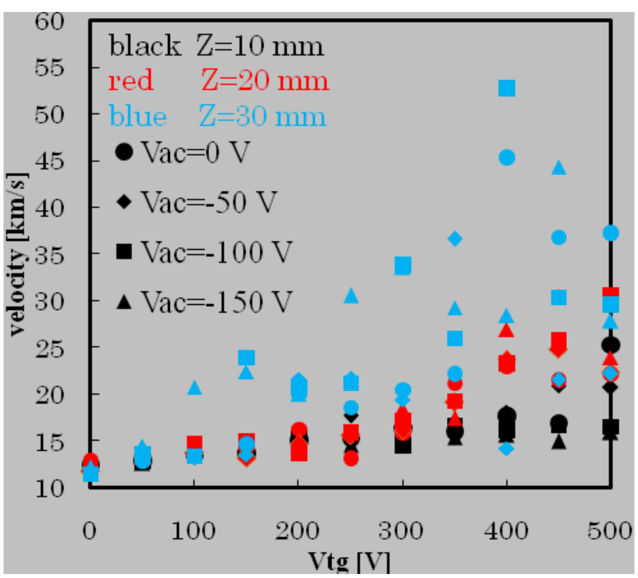

Figure9.Variations of ion velocity of thruster B with acceleration voltages measured with Faraday cup placed at 50 mm away from the target.

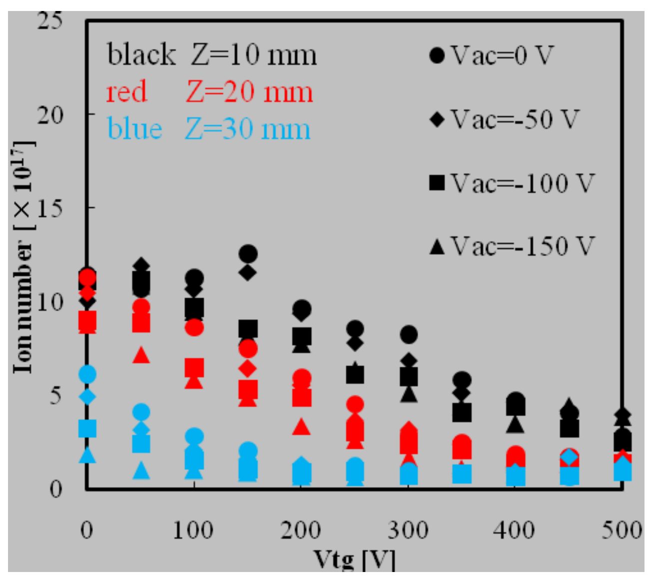

Figure10.Variations of ion number of thruster B with acceleration voltages measured with Faraday cup placed at 50 mm away from the target.

IV. Conclusion

To find the optimum electrode geometry of a laser-electrostatic hybrid thruster, speed of ions and number of ions were experimentally estimated with a Faraday cup for various electrode configurations.

It was shown in thruster A that, in a case of 10-mm-diameter electrodes placed at 20 mm away from a laser ablation target, the speed of ions increased with the increase of acceleration voltages. Typical ion speeds, measured at 80 mm away from the target, were 16 km/s and 32 km/s for the acceleration voltages of 0 V and 500 V, respectively, with electrode gap of 20 mm.

In addition, ion numbers decreased with the increase of acceleration voltages in all electrode gap cases. In addition, ion numbers decreased with the increase of distance of the Faraday cup. Moreover, with larger electrode gaps, the ion number decreased.

In thruster B, at V_{tg} = 200 V and V_{ac} = -100 V, typical ion speeds were 15 km/s and 21 km/s for Z = 10 and 30 mm, respectively.

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