Rectangular Laser-Electromagnetic Hybrid Pulsed Plasma Thruster

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Abstract: A fundamental study of a newly developed laser-electromagnetic hybrid pulsed plasma thruster was conducted. In the rectangular discharge channel, a laser-induced plasma was produced and then accelerated by electromagnetic force instead of accelerating only by laser ablation. The effects of laser energy and irradiation position on propellant surface on thrust performances were evaluated by thrust measurement using a torsion-balance type thrust stand. As the result, for a laser energy of 126 mJ, the impulse bit increased linearly from 27.1 μNsec to 48.3 μNsec for the increased charged energy. For the cathode side irradiation, in which the laser spot position is shifted by 2.5 mm from the center of propellant surface, *Ibit* increased from 27.1 μNsec to 48.3 μNsec. While, the coupling coefficient is decreased with the charged energy up, and higer *Cm* values are obtained for the cathode side irradiation (*Cm*; 15.6 μNsec/J at 2.16 J). Therefore, higher performances were obtained for the cathode side irradiation.

I. Introduction

Attempts of utilization of a laser-beam for a next generation onboad plasma thruster have attracted a great deal of attention along with the rapid evolution of high-power compact laser systems. Several potential thrusters are under significant development. One of the advantages of such laser thrusters is that they can use any solid materials as their propellant [1-5]. Therefore, the system can be very simple and small with significant controllability of thrust. To improve the thrust performance and system simplicity of conventional electric and laser propulsion systems, preliminary studies of a laser-electric hybrid acceleration system have been conducted by the authors[6-10].

Schematics of laser-electric hybrid acceleration systems are illustrated in Fig.1. A basic idea of these systems is that laser-ablation plasma induced through laser irradiation on a solid target is additionally accelerated by electrical means. Since any solid materials can be used as propellants in these cases, no tanks, valves, or piping systems are required for the propulsion system. Therefore, the system employing these techniques can be significantly simple and compact. Because laser-ablation plasma has a directed initial velocity of tens of km/sec, which will be further accelerated by electrical means, significant improvement of thrust performance can also be expected.

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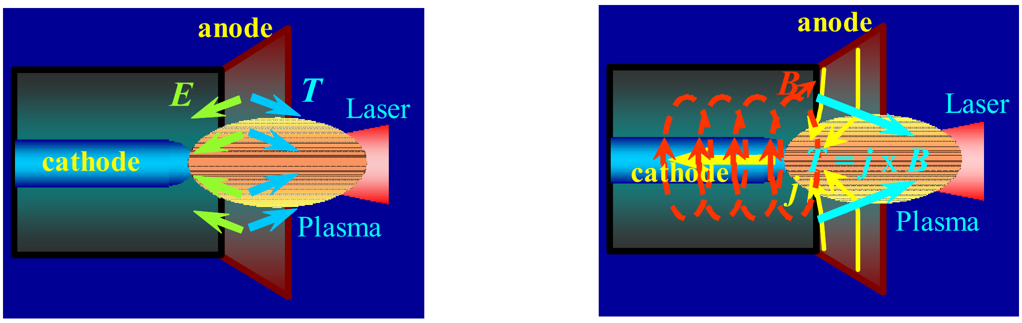
In the above hybrid regimes, depending on different factors such as electrode configuration, plasma density, and electrical input power (voltage x current), acceleration mechanisms for the laser-ablation plasma can be classified into three types, i.e., i) electrostatic acceleration, ii) electrothermal acceleration, and iii) electromagnetic acceleration, as shown in Fig.2 [11], whereas ii) usually occurs simultaneously with iii). Especially for laser-ablation plasma, depending on laser conditions such as pulse energy, fluence, etc., plasma density and velocity distributions can be widely controlled. Moreover, they can also be controlled through additional electric discharges.

Properly controlling a power source, or voltage and current, with optimized electrode configuration for additional electric acceleration, each acceleration mechanism can be adopted. Therefore, propulsion system that is able to satisfy all the above acceleration regimes through i) to iii) will be achieved with one thruster configuration. Namely, this system enables a robust conversion between high-specific-impulse operation and high-thrust-density operation in regard to mission requirements, as shown in Fig.2. Each of two typical regimes, a laser-electrostatic hybrid acceleration modes and a laser-electromagnetic hybrid accelerator, is currently under investigation independently by authors [6-10].

Regarding the forms of energy contributions, or input for acceleration, laser-electric hybrid thrusters can be classified into various operational modes. When an electric energy contribution on the acceleration process is zero compared with laser energy contribution, the thruster can be defined as being in the “pure laser propulsion mode”. If the electric contribution is smaller than the laser energy contribution, it can be defined as being in the “electric-assisted laser propulsion mode”. Also, with a greater electric contribution than the laser energy, it can be defined as being in the “laser-assisted electric propulsion mode”. Moreover, with zero contribution of lasers, it can be defined as being in the “pure electric propulsion mode”.



(a) (b)

Figure 1. Schematic illustrations of coaxial laser-electric hybrid accelerator.

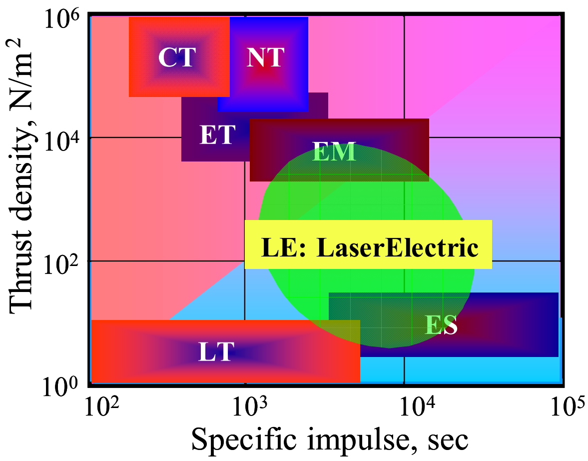


Figure 2. Classification of laser-electric hybrid propulsion systems based on thrust characteristics and energy contributions; *CT: chemical thermal propulsion, NT: nuclear thermal propulsion, ET: electrothermal propulsion, EM: electromagnetic propulsion, ES: electrostatic propulsion, LT: laser thermal propulsion, LE: laser-electric hybrid propulsion.*

II. Laser-Electromagnetic Hybrid Pulsed PlasmaThruster

In this study, plasma acceleration characteristics of the laser-electromagnetic hybrid mode are investigated. Another motivation of this hybrid acceleration mode is to improve the thrust performances of conventional pulsed plasma thrusters, PPTs. Pulsed-plasma thrusters 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 [12–14]. This low efficiency arises from the incompleteness of phase changes of the propellant surface within a short duration of a single pulse discharge. The surface of the propellant will continue to evaporate long after completion of the discharge pulse, providing mass that cannot experience acceleration to high speeds by the electromagnetic and gasdynamic forces. Since the residual vapor or plasma from the late-time evaporation of the propellant surface remains in the discharge channel, which cannot contribute to the impulse bit, it has been difficult to improve this mass loss and thrust efficiency [12-14].In order to reduce this late-time ablation and to improve thrust efficiency, authors showed the effectiveness of the utilization of a laser-pulse inducing a plasma from the 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 could be achieved [6–10]. Since the use of a shorter pulse of the laser enables a shorter duration of a pulsed-plasma in this case, significant improvement of the thrust performance can be expected.

A schematic of a rectangular laser-electromagnetic hybrid acceleration thruster is illustrated in Fig.3. 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. Then, the electrothermal acceleration effect becomes significant. When current rises up to thousands amperes, an electromagnetic acceleration effect becomes significant. Since a primary current runs from the anode plate through the plasma to the cathode plate creating a loop current, a self-induced magnetic field is induced in the perpendicular direction in the acceleration channel. Then a streamwise acceleration is provided through the interaction of the current and magnetic field, or Lorentz force [11].

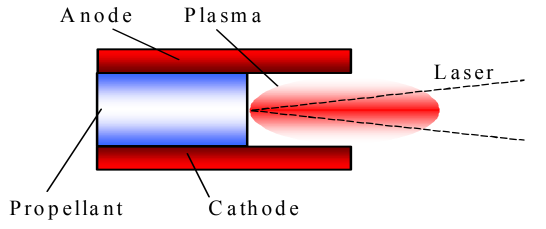


Figure 3. Schematic image of laser-electromagnetic hybrid pulsed plasma thruster.

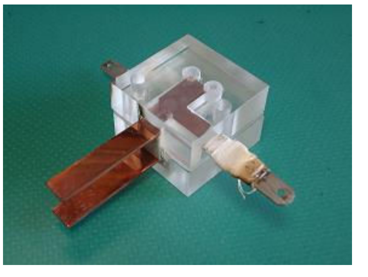


Figure 4. Photo of rectangular laser electromagnetic hybrid thruster.

Table 1 Sizes of thruster

Length	50 mm
Width	7 mm
Height	10 mm

III. Experimental Setup

For a rectangular thruster (Fig.3), copper electrodes (7 mm in width, 50 mm in length) and an alumina propellant (10 mm in height) were used, as shown in Fig.4. A schematic of experimental setup is shown in Fig.5. A Q-sw Nd:YAG laser (BMI, 5022DNS10, wavelength: λ = 1064 nm, maximum pulse energy: 1 J/pulse, pulse width: 10 nsec) was used for a laser assistance, or a plasma source. The laser pulse was introduced into a vacuum chamber (10^{-3} Pa) through a quartz window, then it was focused on a target (or a propellant), with a focusing lens (f = 100 mm). Discharge current was monitored with a current probe (Pearson Electronics, Model-7355,

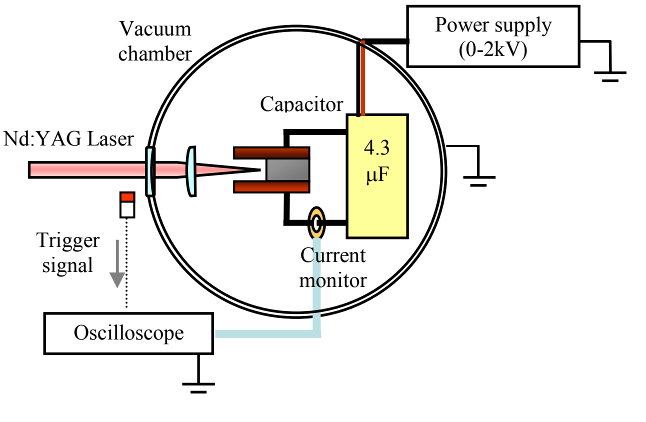


Figure 5. Schematic of experimental setup.

maximum current: 10 kA, minimum rise time: 5 nsec) and an oscilloscope (LeCroy, 9374TM, range: 1 nsec/div ~ 5 msec/div). In this experiment, the electric energy from a capacitor bank (= $CV^2/2$, where C and V are capacitance and voltage) was variable from 0 to 8.65 J for a fixed laser pulse energy of 0.13 J.

In order to estimate μNsec-class impulses, a calibrated torsion-balance type thrust-stand was developed. A schematic of experimental setup for impulse-bit measurement is given in Fig.6. The torsion-balance consists of a balance, a pair of pivots, a displacement sensor, and a counter weight. The balance is 450 mm long made of aluminum. Distance between the pivot and thruster is set to 437 mm. For the pivots, the Flexural Pivot (SDP/SI) was used. A torsional spring rate of the pivot estimated in this case is k = 4.7 x 10^{-2} Nm/rad. As for the displacement sensor, a non-contacting displacement sensor of eddy current type (EMIC, 503-F, NPA-010, maximum range: 1 mm, minimum displacement: 0.5 μm) located at 450 mm away from the pivots was used.

Calibration of the torsion-balance was conducted with known impulses using arbitrary impacts by an aluminum ball weighing 0.18 g (Fig.7). Velocities of the rod before and after the impacts on the balance were measured from values of the displacement sensor.

In this report, the effects of laser energy and irradiation position on propellant surface on thrust performances were evaluated using this thrust stand. In the case of the former, it is evaluated when the electric energy of a capacitor bank was varied from 2.16 J to 8.65 J in laser pulse energies of 1 J or 126 mJ. In the latter case, the irradiation position is the center of propellant surface (Fig.8(b)), or is slightly shifted from the center to the anode side or the cathode side positions (Fig.8(a),(c)).

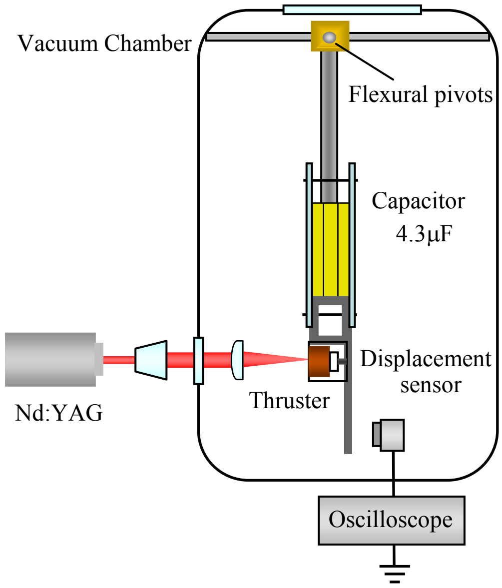


Figure 6. Schematic of a torsion balance type thrust stand.

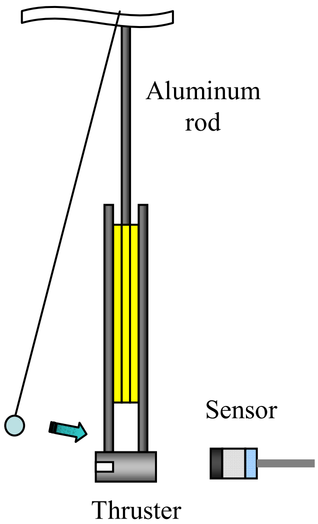
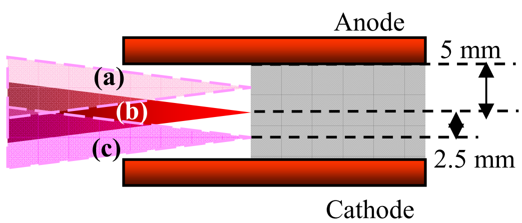


Figure 7. Calibration method.



Figuer 8. Irradiation positions;
(a) anode side,(b) center, and (c) cathode side.

IV. Results and Discussion

Plots of impulse bit measured with the torision-balance type thrust-stand for various energies charged to capacitors are shown in Figs.9 and Fig.10, showing the effects of laser energy and the laser spot position. Deviations of the plots are due to those of laser pulse energies and misalignments of mechanical and optical elements at each operation. Mass shots were estimated with an electronic-balance (SHIMADZU, LIBROR AEX-200G) for cases of 266 shots and 401 shots with a charged energy of 8.65 J. An averaged value of the mass shot per pulse, almost independent of pulse numbers, was 1.02 μg/pulse [8-10].

As shown in Fig.9a, for a laser energy of 1 J, the impulse bit increases linearly from 35.3 μNsec to 54.0 μNsec when the energy is increased up to 8.65 J. While, for a laser energy of 126 mJ, it increases from 27.1 μNsec to 48.3 μNsec. It is shown that higher performance is obtained for a higher laser energy.

Variations of momentum coupling coefficient, C_m, which is a ratio of impulse bit to total energy input (laser pulse energy + charged energy) with charge energy are shown in Figs.9b and 10b. As shown in Fig.9b, for a laser energy of 1 J, the coupling coefficient decreases from 11.2 μNsec/J to 5.60 μNsec/J when the energy is increased. For a laser energy of 126 mJ, it decreases from 11.8 μNsec/J to 5.50 μNsec/J. It is shown that there seems no significant difference in momentum coupling coefficient between different laser energy cases.

Figure 10a shows the relations between the impulse bit and the charged energy for various laser irradiation positions. For the cathode side irradiation, the impulse bit increases linearly from 35.8 μNsec to 87.7 μNsec when the charged energy was enlarged to 8.65 J. For the anode side irradiation, it increases from 32.3 μNsec to 60.5 μNsec. It is shown that higher performance is obtained when the irradiation position is shifted to the cathode side. As shown in Fig.10b, for all cases, the coupling coefficient decreases with the increasing electric energy. Among three different irradiation positions, the cathode-side laser-focal point resulted in the highest *Cm* values.

According to our previous study [10], at 0 J, which corresponds to pure laser ablation with a laser energy of 126 mJ, impulse bit is about 3.36 μNsec. Since the impulse bit is increased with increasing charged energy, it is expected that the plasma is subsequently accelerated by an electromagnetic field after given a directed initial velocity through the laser ablation in the initial phase.

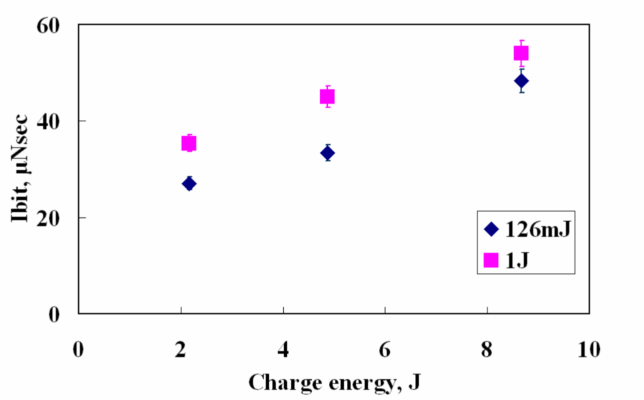


Figure 9a. Charge energy vs. impulse bit; *effect of laser energy.*

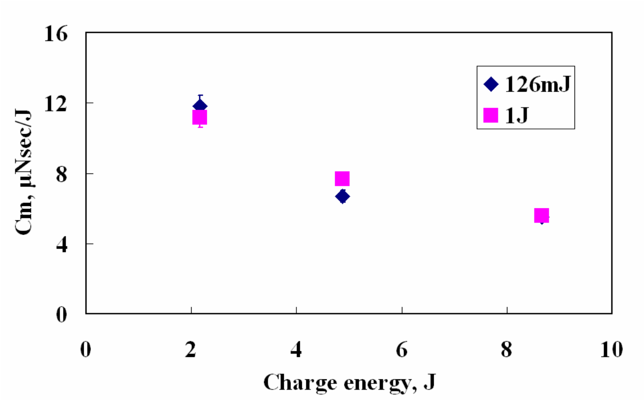


Figure 9b. Charge energy vs. coupling coefficient; *effect of laser energy.*

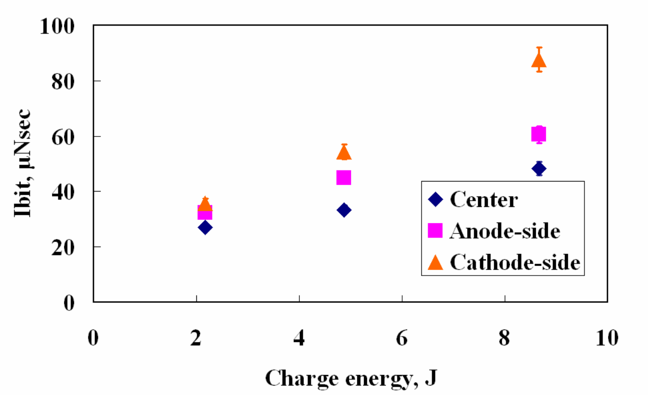


Figure 10a. Charge energy vs. impulse bit; *effect of laser irradiation position.*

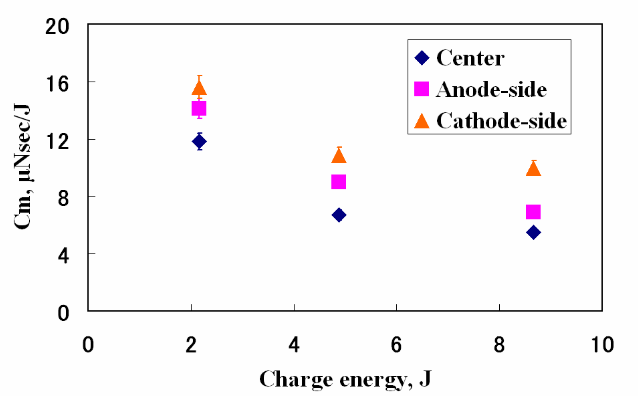


Figure 10b. Charge energy vs. coupling coefficient; *effect of laser irradiation position.*

Specific impulse for various charged energies to the capacitors are shown in Fig.11. An increase in specific impulse for an increased energy can be seen in this figure. *Isp* of conventional PPTs is 800 sec at 2 J [13 15]. While, for this laser-electric hybrid thruster, at 2.16 J, *Isp*: 3600 sec, which is significantly higher than those of conventional PPTs, was obtained for the similar energy levels. Also, this table shows that higher *Isps* are obtained when the laser beam is irradiated on the cathode side position.

Relationship between thrust efficiency (= [kinetic energy]/[(charged energy) + (laser energy)] and charged energy are shown in Fig.12. In these cases, a laser pulse energy of 0.13 J was added to the charged energy to estimate the total energy (denominator). As shown in this figure, thrust efficiency slightly decreases with energy charged up. Also, it is shown that thrust efficiency is significantly higher than those of conventional PPTs. Moreover, higher efficiency are obtained for the cathode side irradiation.

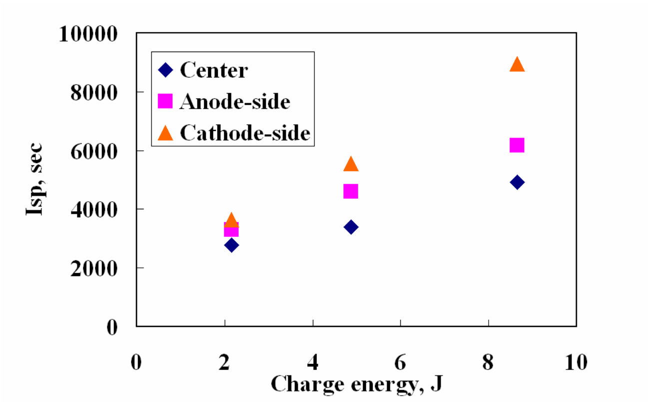


Figure 11. Charge energy vs. *Isp*
effect of laser irradiation position.

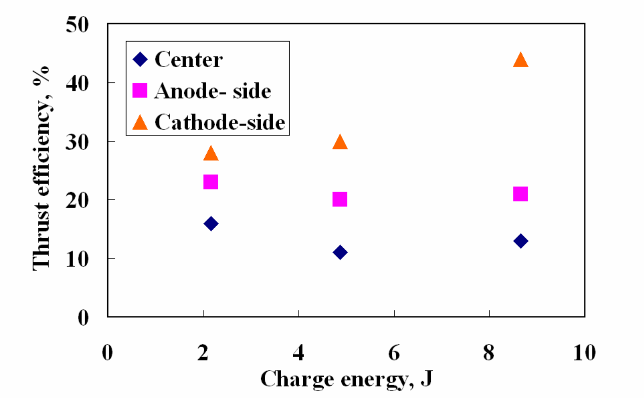


Figure 12. Charge energy vs. Thrust efficiency
effect of laser irradiation position.

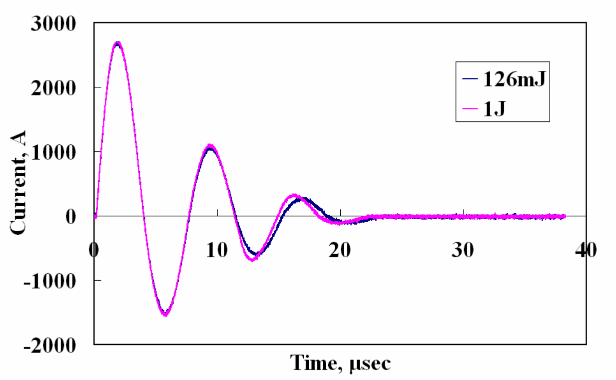


Figure 13. Temporal variation of discharge current;
effect of laser energy.

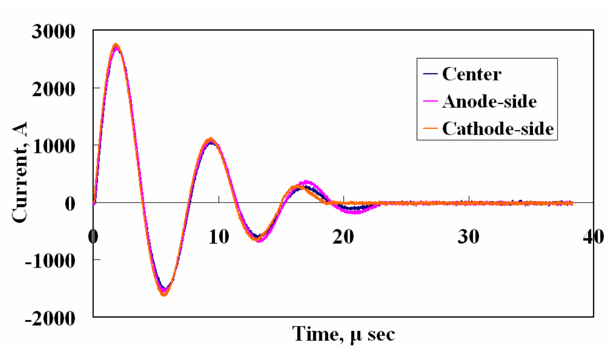


Figure 14. Temporal variation of discharge current;
effect of laser irradiation position.

Temporal variations of discharge current for high-voltage cases are given in Fig.13 and Fig.14. As shown in Fig.13, for the charged energy of 8.65 J and the laser energy of 1 J or 126 mJ, the current wave damps as time passed for higher voltage conditions; this is generally observed in conventional PPTs. From this figure, for a laser energy of 1 J and 126 mJ, the current wave shows nearly the similar result, for example, an abruptly current rise is followed by a maximum value of 2700 A at 2.0 μsec. After that, the current falls down to a minimum value of –1500 A at 6.0 μsec, converging to zero at about 24 μsec. It seems that the current wave does not depend on the laser energy.

From Figs.13 and Fig.14, it is concluded that the current wave form dose not depend on the laser energy level or the laser irradiation position, while the thrust performance increases in these case. The acceleration of plasma must be mainly electrothermal and electromagnetic, and these acceleration must depend upon the discharge current. However, an increase in thrust, seen in Figs.9a and 10a, cannot be attributed to these current patterns of Figs.13 and 14. A primary cause of these increases in the performance is still unknown. Although a significant difference of mass shot among these cases was not observed, further detailed measurements of mass-shot, plasma behaviors, etc., should be conducted for the next step.

V. Conclusions

A fundamental study of a novel laser-electromagnetic hybrid pulsed plasma thruster was concluded to elucidate its discharge and thrust characteristics. Inducing a short-duration conductive plasma between electrodes with certain voltages, short-duration switching or discharge was achieved.

With a newly developed trsion-balance type thrust-stand, it was shown that the impulse bit linearly increased for increased energy. On the other hand, the coupling efficient decrease with increased energy showing a maximum value at 0 J, corresponding to the pure laser ablation case. In case of the laser energy changed, higher performance was obtained in higher laser energy. At 8.65 J discharge energy, the impulse bit was 54.0 μNsec for a laser energy of 1 J. While, in case the irradiation position is sifted, the thrust performance is increased. The higher performance was obtained for the cathode side irradiation, and its impulse bit was 87.7 μNsec.

From the discharge current measurement, it was shown that the current wave form did not depend on the laser energy level or the laser irradiation position. While the thrust performance increased in these cases. The acceleration of plasma must be mainly electrothermal and electromagnetic, and these acceleration must depend upon the discharge current. However, an increase in thrust performance cannot be attributed to these current patterns. A primary cause of these increases in the performance is still unknown. Although a significant difference of mass shot among these cases was not observed, further detailed measurements of mass-shot, plasma behaviors, etc., should be conducted for the next step.

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