An Alternating Electric Field Accelerator for Laser-Ablation Plasma Acceleration

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A fundamental study of a laser-electrostatic hybrid propulsion system with alternating electric field applied to an acceleration electrode was conducted, in which laser-induced plasmas were induced through laser beam irradiation onto a solid target and accelerated by electrical means instead of direct acceleration using only laser beam. In the laser-induced plasma generated from a solid target irradiated with a nanosecond laser pulses exceeding an ablation fluence, it was shown that electrons, primarily absorbing the laser energy, were emitted earlier and faster from the target and then ions follow. In this study, to accelerate the temporally shifted particles, an alternating electric field accelerator, rather than a static field accelerator, was developed, which can firstly accelerate electrons with a negative electric field pulse and then secondly accelerate ions with another positive electric field pulse. Characterization of the generation of alternating short pulse voltages typically of 1μs duration between two electrodes was conducted. The acceleration characteristics of electrons and ions using alternating fields were evaluated by a Faraday cup.

Key Words: Laser ablation plasma ,Electrostatic acceleration ,Alternative electrostatic field generation

Nomenclature

A : Plasma current
V_1 : Voltage of a first acceleration electrode
V_2 : Voltage of a second acceleration electrode

1. Introduction

Small-sized onboard laser plasma thrusters are under significant development with rapid evolutions of compact but high power laser systems[1.2.3]. 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[4.5.6]. 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.

1.1 Laser-Electrostatic Acceleration Thrusters

Schematics of laser-electric hybrid acceleration systems are illustrated in Fig. 1. The basic idea of this systems is that laser-ablation plasmas, induced through laser irradiation on a solid target, are additionally accelweerated 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 can be used for the propellant. Therefore, the system employing this technique can be very simple and compact. As the laser-ablation plasma has the directed initial velocity, which is further accelerated by electrical means, significantly high specific impulses can be expected.

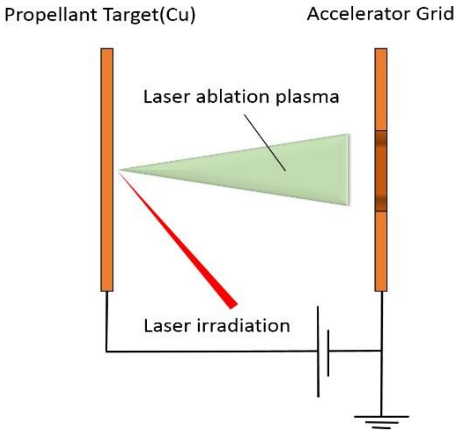

Fig 1.Schematics of laser-electric hybrid thruster.

A preliminary investigation on a laser-electrostatic hybrid acceleration thruster is being conducted, in which a laser-ablation plasma is accelerated by an electrostatic field. 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. In this study, those 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.

1.2 Laser Ablation Plasma

Generation of a laser ablation plasma induced through an interaction of an intense focused pulsed laser and a solid target is a short-duration event. Plasma temperature and density dramatically change with time and in space. Figure 2 shows a typical output signal measured by a Faraday cup (FC) fixed at 100 mm from a Cu target, showing temporal changes of electron current (negative signals, or below zero ampere) and ion current (positive signals, or over zero ampere) measured in a laser ablation plasma. This figure shows that negative signals of electrons, primarily absorbing the laser energy inside and outside of the target, are reaching to FC earlier than positive signals of ions, since electrons are emitted earlier than ions from the target surface.

Then, ions follow foregoing electrons. Namely, a wavefront of a laser ablation plasma consists of two layers of electrons and ions, or a double layer[7]. From the figure, a difference of arrival times of electrons and ion can be assumed as a gap between negative and positive peaks, which is about 10μs.

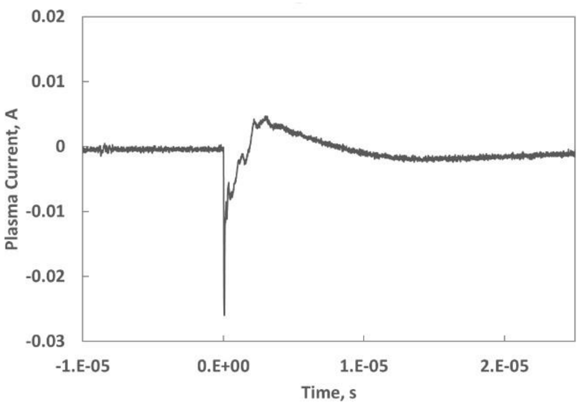

Fig 2.Temporal changes of electron and ion currents measured in a laser ablation plasma current.

2. Experimental Apparatus

Temporal evolutions of the plasma current were measured by a Faraday Cup, as shown in Fig.3. The Faraday Cup consists of three electrostatic grid and one collector grid. It was placed at 100 mm away from the thruster (target plate position) along the centerline. Temporal changes of the plasma currents were acquired by an oscilloscope (Tektronix, spectral width 300 MHz, maximum sampling rate 2.5GS/s). Since the transient probe data were highly reproducible, it was possible to obtain the current-voltage. The plasma current was estimated from the time of signal arrival to the Faraday cup. Pulse generator (DG-535) was used to transmit a signal to the IGBT and the Nd:YAG laser. It synchronize the switching circuit with the Nd:YAG laser.

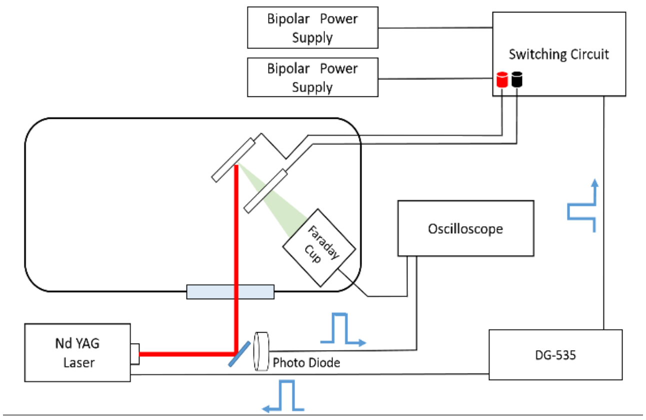

Fig 3. Experimental setup.

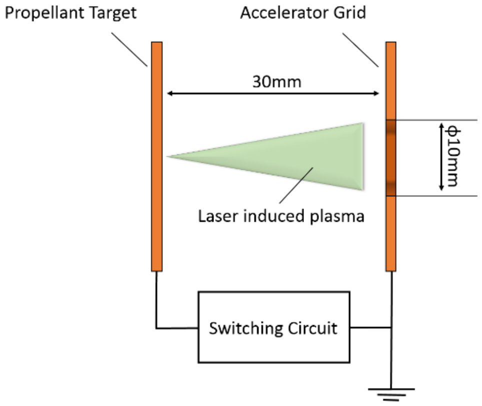

Fig 4. A schematic illustration of a laser-electrostatic hybrid thruster

2.1. Accelerator Electrodes

A schematic illustration of a laser-electrostatic hybrid thruster is shown in Fig.4. The hybrid thruster consists of a Cu target (propellant), an acceleration electrode, and a laser oscillator. The propellant target and accelerator electrode are connected to a switching circuit. This circuit provides alternating voltages (positive and negative voltages) between the target and the acceleration electrode. The Cu target was mounted on an X-Y stage to refresh irradiating spots of the target surface. For the laser oscillator, an Nd:YAG laser (wavelength: 1064nm, pulse energy: 340mJ/pulse, peak power: 0.17GW, pulse width: 5ns, repetition rate: 10Hz) was used. Laser ablation plasmas or ions were accelerated by the acceleration electrode made of a 0.3 mm-thick Cu plate with a hole of 10 mm in diameter. To evaluate the effects of the electrostatic field, effects of arbitrary delays and durations for the application of applied voltages to the target and acceleration electrode on ion emission characteristics were investigated.

2.2 Switching Circuit

To induce alternating pulse voltages to the electrodes, we have developed a switching circuit, shown in Figure.5. In this figure, V1 and V2 are bipolar power sources. V1 provides a negative pulse voltage. On the other hands, V2 provides a steady positive bias voltage. By combing these negative pulse voltage and steady positive bias, alternating voltages to the electrodes can be generated. In this circuit, IGBT and capacitor (1µF) were used to generate a pulsed voltage wave. This pulsed voltage wave was transmitted to a secondary circuit through transformer (1:1) and applied to the electrodes. A typical output signal of alternating pulse voltages applied to the electrodes synchronized with a laser pulse is shown in Fig.6. The voltages and durations can be controlled to optimize acceleration conditions.

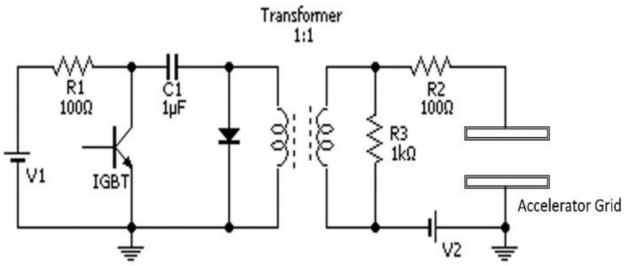

Fig 5. Configuration of switching circuit

This switching circuit can generate a short pulse voltage, in which pulse width is less than 10µs. V2 provides positive voltages to electrodes. On the other hands, V1 provides negative pulse voltages.

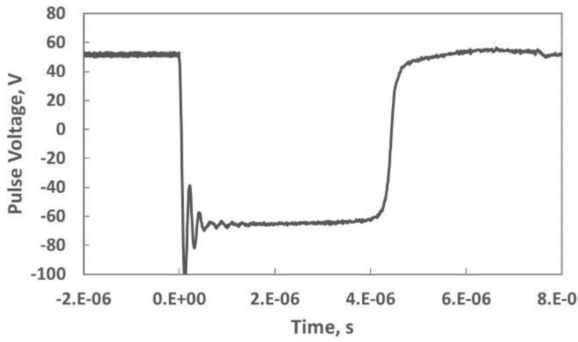

Fig 6. Pulse voltage applied to accelerator grid

This figure shows an example of alternating pulse voltages applied to electrodes. Pulse width is 5µs. V1 provides pulse voltage (-100V) and V2 provides constant bias (+50V).

3. Result and Discussion

Temporal changes of plasma (electron and ion) current were observed by Faraday cup measurement.

The pulse voltage applied to electrodes were delayed from 0 µs to 28 µs relative to a laser pulse. The temporal changes of plasma current were plotted in Figs.8 to 15.

Figures 8 and 9 show current waveforms with constant acceleration voltages applied to electrodes. Figure 8 shows the current with a steady acceleration voltage of +50V. A negative current was mainly observed, and most of the positive sides are very low. Figure 9 shows the current with a steady acceleration voltage of -50V. Conversely, in the case of -50V, a positive current waveform was observed, and most of the negative sides were very low.

Figures 10 to 15 show current waveforms with pulsed acceleration voltages applied to acceleration electrodes at different delays from laser pulse irradiation.

It can be seen that the positive current increases with the increase of the delays of less than 12 µs. The maximum positive current is observed at a delay of 12 µs, and the peak value is higher than that obtained in the steady bias case shown in Fig.9. After the delay of 12 µs, the positive current decreases with increasing delay.

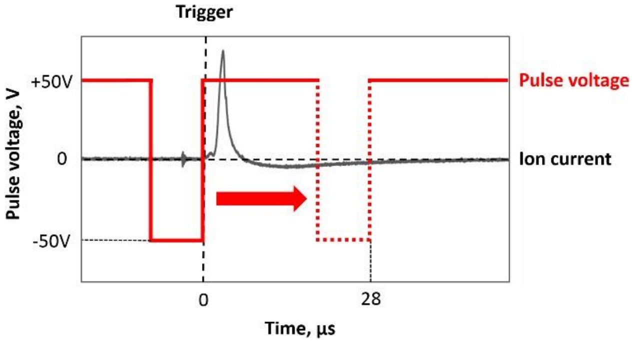

Fig 7. Schematic of the pulse voltage being delayed from 0µs to 28µs relative to a laser pulse.

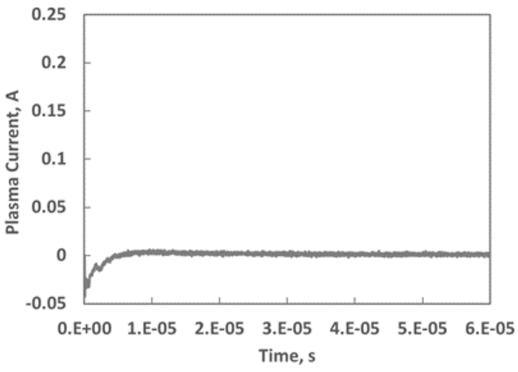

Fig 8. Temporal changes of plasma current (constant bias +50V).

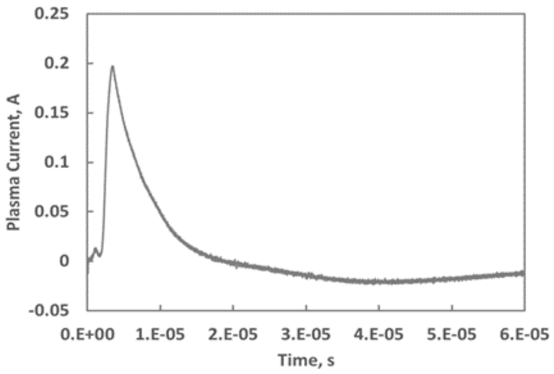

Fig 9. Temporal changes of plasma current (constant bias -50V).

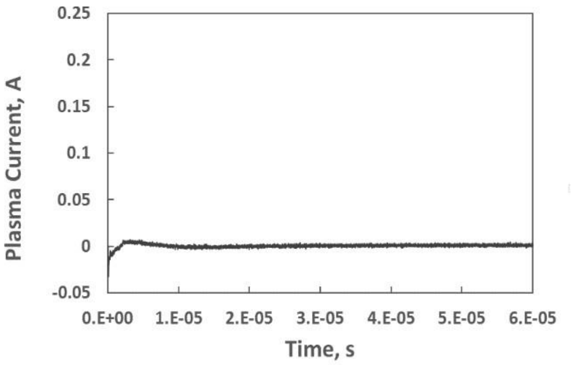

Fig 10. Temporal changes of plasma current at 0μs.

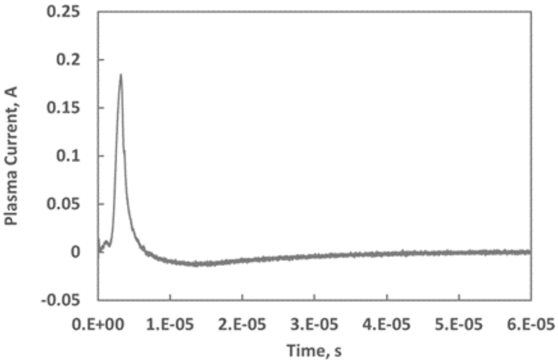

Fig 11. Temporal changes of plasma current at 4μs.

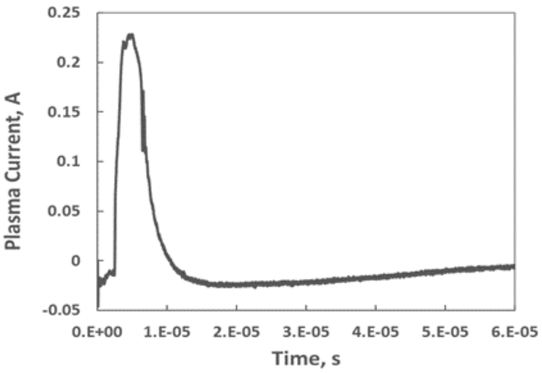

Fig 12. Temporal changes of plasma current at 8μs.

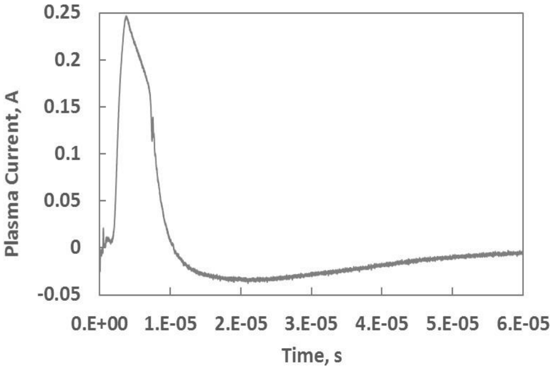

Fig 13. Temporal changes of plasma current at 12μs.

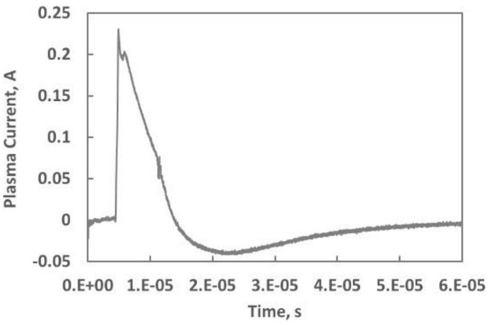

Fig 14. Temporal changes of plasma current at 16μs.

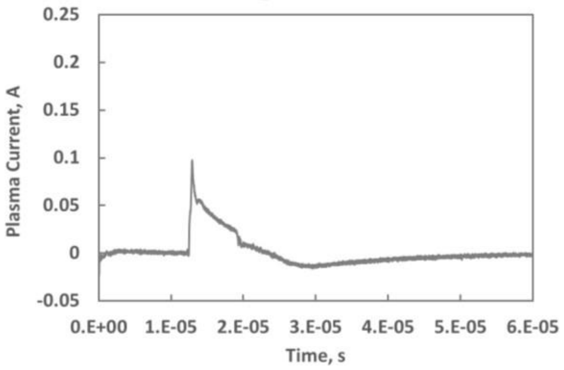

Fig 15. Temporal changes of plasma current at 24μs.

4. Conclusion

A preliminary investigation of an alternating electric field accelerator for a laser-electrostatic hybrid thruster was conducted, in which a laser ablation plasma was accelerated by an alternating electrostatic field. A newly developed pulse generating circuit successfully generated alternating pulse voltages between electrodes. In order to find the optimum timing of the alternating pulse voltages, the temporal changes of ion and electron currents were

evaluated by a Faraday cup. It was shown that the positive current increased with the increase of the delays of the pulse voltage of less than 12 μs. The maximum positive current was observed at a delay of 12 μs, and the peak value was higher than that obtained in the steady bias case. After the delay of 12 μs, the positive current decreased with increasing delay.

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