Acceleration of Laser-Ablation Plasma by Alternating Electric Fields

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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(-than ions). 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 variable pulse voltages between two electrodes was conducted. The acceleration characteristics of electrons and ions using alternating fields were evaluated by a retarding potential analyzer (RPA). Ion current, the most probable velocity and the average velocity was increased by alternating electrostatic field. The most probable velocities and average velocity increased to 39 km/s and 36 km/s at -150 V.

Key Words: Space Engineering, Electric propulsion, Double layer, Laser ablation plasma

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.

2. Laser-electrostatic acceleration thruster

Schematics of laser-electric hybrid acceleration systems are illustrated in Figure.1. The basic idea of this systems is that laser-ablation plasmas, induced through laser irradiation on a solid target, are 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 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.

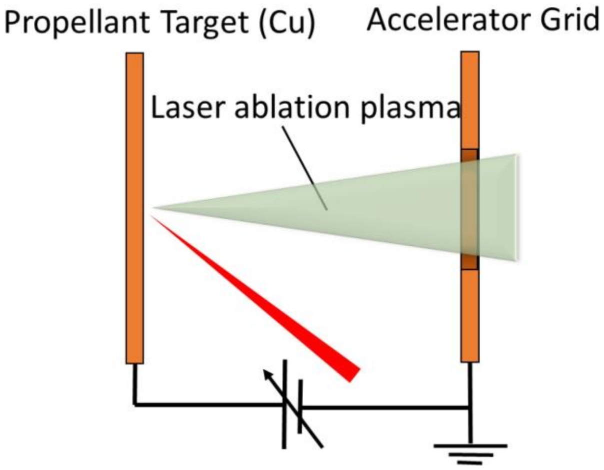

Fig. 1. Schematics of laser-electric hybrid thruster

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.

3. acceleration with alternating electrostatic field

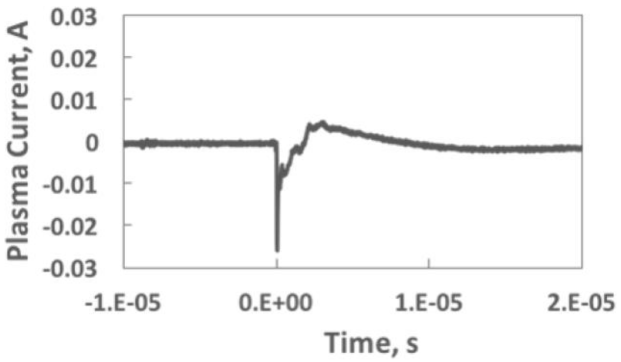

Fig. 2. Temporal changes of electron and ion currents measured in a laser ablation plasma

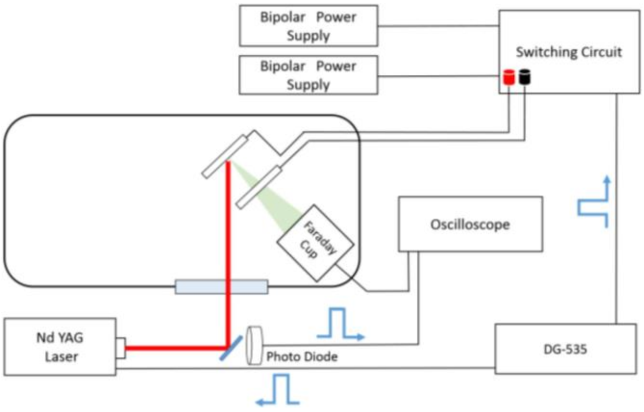

Fig. 3. Experimental setup

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 laser energy at 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 10 µs.

In this study, to accelerate both electrons and ions with negative and positive charges, alternating electric fields are applied. To accelerate foregoing electrons passing through an accelerator electrode, a negative electric field is applied. Then, to accelerate subsequent ions, a positive electric field is applied at targeted delay and in a controlled duration.

4. Experimental Apparatus

Temporal evolutions of the plasma current were measured by a Faraday cup (FC), or retarding potential analyzer (RPA), as shown in Fig.3. The RPA consists of three electrostatic grids and one collector grid. Potentials of the grids were 0 V, -15 V, and 0 to 1000 V, respectively, from its intake. The RPA 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). The plasma current was estimated from the time of signal arrival to the Faraday cup. A pulse generator (DG-535) was used to transmit a signal to a switching circuit and a laser and to synchronize them with arbitrary durations.

A schematic illustration of a laser-electrostatic hybrid thruster is shown in Fig.4 to Fig.8. 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 electrons and ions, were accelerated by the acceleration electrode made of a 0.3 mm-thick Cu plate with a hole of 10 mm in diameter.

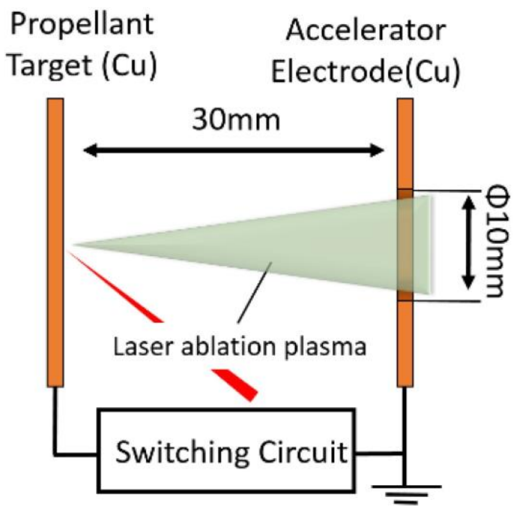

Fig. 4. A schematic illustration of a laser-electrostatic hybrid thruster

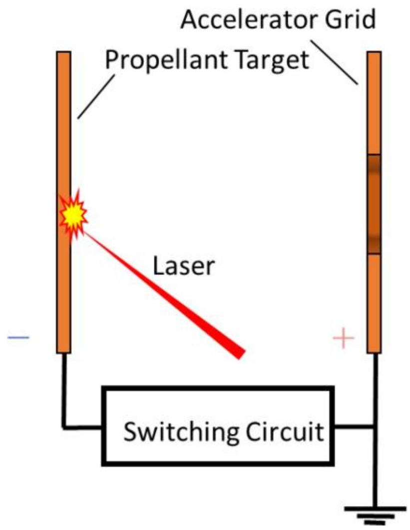

Fig. 5. First step of acceleration mechanism, Laser irradiation

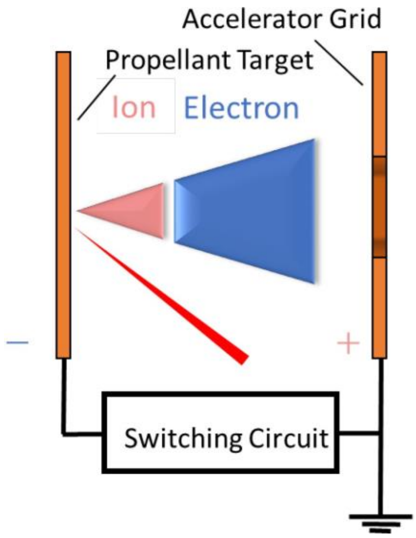

Fig.6. Second step of acceleration mechanism, double layer formation

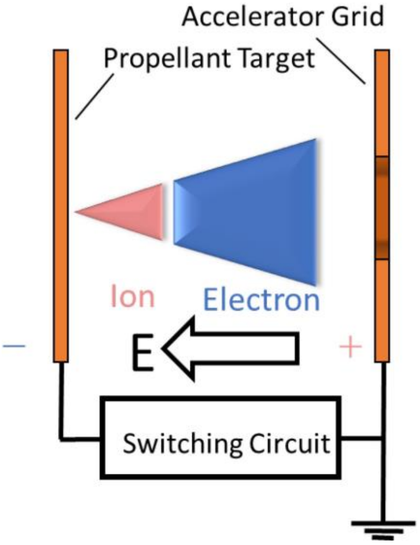

Fig. 7. third step of acceleration mechanism, electron acceleration

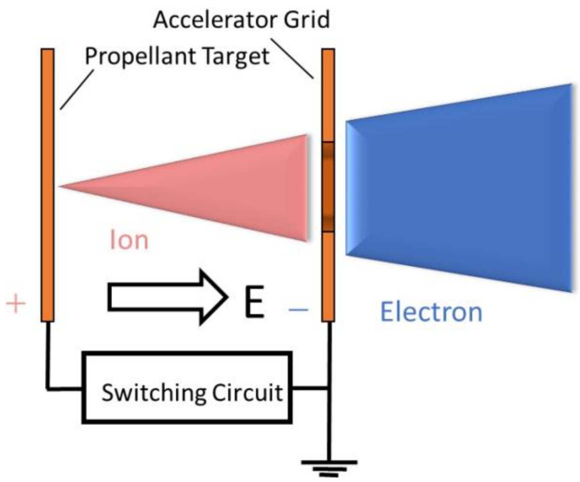

Fig. 8. fourth step of acceleration mechanism, Laser irradiation

To induce alternating pulse voltages to the electrodes, we have developed a switching circuit, shown in Fig.9. 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.10. The voltages and durations can be controlled to optimize acceleration conditions.

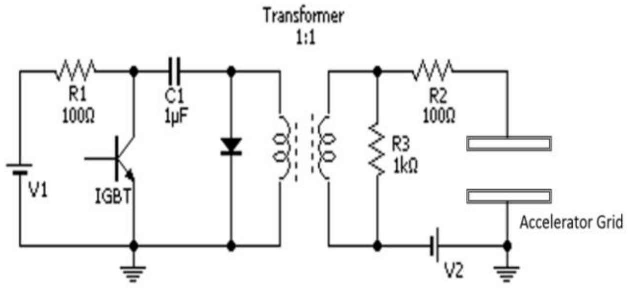

Fig. 9. Diagram of switching circuit

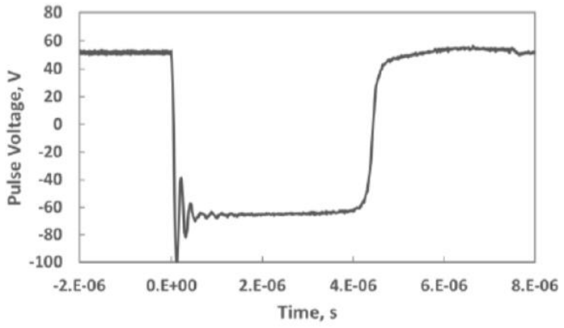

Fig. 10. Output voltage of switching circuit

5. Results and Discussions

Plots of peak ion currents versus grid voltages of RPA for various acceleration voltages are shown in Fig.11. Taking derivatives of these plots of ion currents with respect to grid voltages, or *dI/dV*, ion energy distributions, or namely ion velocity distributions, can be obtained.

Fig.12. shows the results of ion velocity distributions for various acceleration voltages of 0 to - 150 V. From the figure, it can be seen that peaks of the distributions of ion velocities, or the most probable velocities, shift toward higher velocities with increase of acceleration voltages.

Plots of the most probable velocities of ions and average velocities of ions, derived from integrations of ion velocities weighted with ion numbers, are shown in Fig.13. for various acceleration voltages. It can be seen from the figure that ion velocities increase with increasing acceleration voltages.

The most probable velocities change from 33 km/s at 0 V to 39 km/s at -150 V. In addition, the average velocities increase from 22 km/s at 0 V to 36 km/s at -150 V.

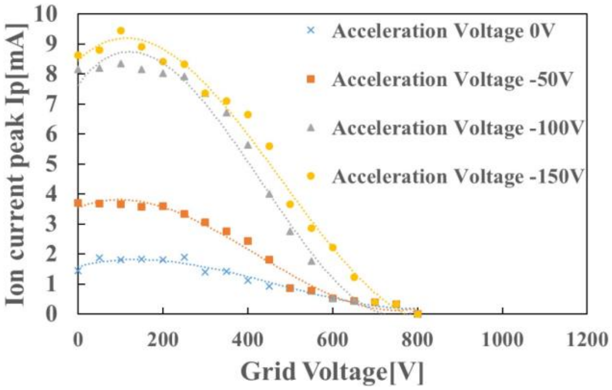

Fig. 11. Ion currents vs grid voltages of RPA for various acceleration voltages.

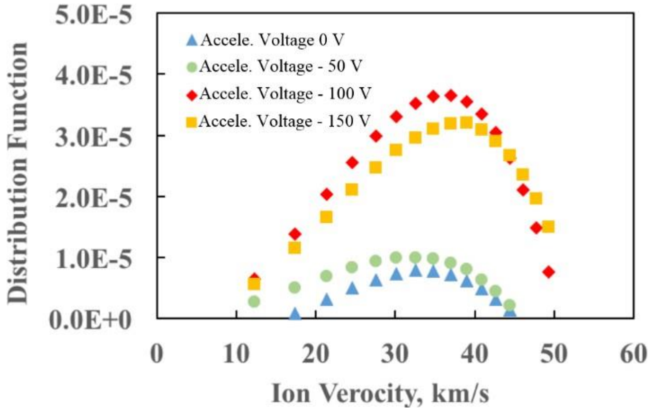

Fig. 12. Ion velocity distributions for various acceleration voltages.

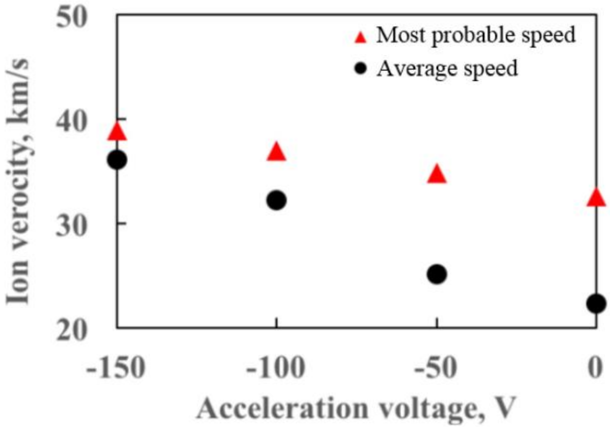

Fig. 13. Most probable and average velocities for various acceleration voltages.

6. 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. To measure temporal evolutions of the plasma currents and ion velocity distributions, a Faraday cup (FC), or retarding potential analyzer (RPA), was employed. It was shown that ion velocities increase with increasing acceleration voltages. The most probable velocities increased from 33 km/s at 0 V to 39 km/s at -150 V. In addition, the average velocities increased from 22 km/s at 0 V to 36 km/s at -150 V.

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