Nanosecond laser-target interaction for highspeed plasma emission

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Ryosuke Koyama[1], Ryo Edamura[2], Akihiro Osamura[3], Nao Akashi[4], Shigeru Yamaguchi[5], Hideyuki Horisawa[6]
Tokai University, Hiratsuka, Kanagawa, 259-1292, Japan

and
Ikkoh Funaki[7]
ISAS/JAXA, Sagamihara, Kanagawa, 3-1-1, Japan

Abstract: A temporal evolution of the plasma distribution of a laser-electrostatic hybrid thruster was experimentally evaluated to find the optimum electrode geometry for the plasma acceleration. The electron temperature and electron density profiles were obtained at positions of 10 ~ 100 mm from the ablated target. The electron temperature was in the range of about 0.8 ~ 2eV. It was shown that the peak electron density decreased toward the downstream region of the target and reached down to 50 x 10^{18} m^{-3} at 100 mm away from the target. The peak Debye length increased and reached about 360 μm at 100 mm away from the target.

I. 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 the 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 those conventional laser propulsion systems, a preliminary study on a laser-electric hybrid propulsion system was conducted.

Our laser-electric hybrid acceleration system is depicted in **Figs. 1 and 2**. The 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. Because the laser-ablated plasma has the initial velocity of about 10 km/s, if the plasma is further accelerated by an electrostatic method, specific impulses can be significantly increased.[6]

In this case, relating to electrode configuration, plasma density, electrical input-power (voltage and current), etc., acceleration schemes for the laser-ablation plasma can be classified into three types, i.e., i) electrostatic acceleration,

[1] Undergraduate student, Department of aeronautics and astronautics, ryk887estl.green@gmail.com
[2] Graduate student, Department of aeronautics and astronautics.
[3] Graduate student, Department of aeronautics and astronautics.
[4] Graduate student, Department of aeronautics and astronautics.
[5] Professor, Department of physics.
[6] Professor, Department of aeronautics and astronautics, hideyuki.horisawa@gmail.com.
[7] Associate Professor, Department of space flight system

ii) electromagnetic acceleration, and iii) electrothermal acceleration. Especially for the laser-ablation plasma, depending on laser conditions such as pulse energy, fluence, etc., plasma density distribution can be widely controlled. Moreover, this can also be increased through additional electric discharges.

Therefore, optimizing the electrode configuration for additional electric acceleration, and properly controlling a power source, or voltage and current, adapting to each acceleration mechanism, the propulsion system satisfying all the above acceleration schemes through i) to iii) can 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 with mission requirements. Each of two typical types of the acceleration schemes are currently being investigated as described in following subsections.

In this study, to reveal the acceleration mechanism of the laser-electrostatic hybrid thruster, the plasma plume near the ablation target was characterized by the Langmuir probe.

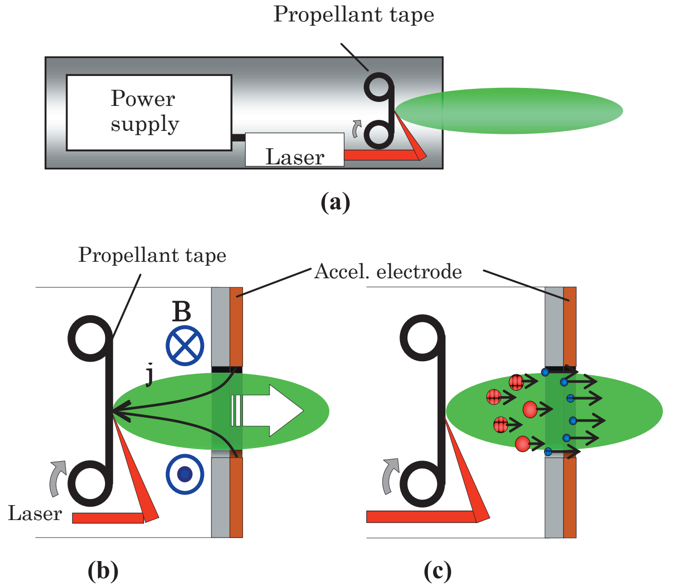


Fig. 1 Schematics of laser ablation thrusters. (a) Pure laser thruster, (b) laser-electromagnetic hybrid thruster, (c) laser-electric hybrid thruster.

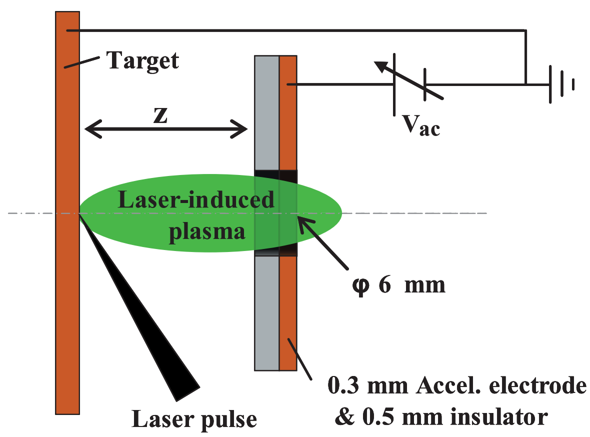


Fig. 2 Laser-electrostatic hybrid thruster.

II. Experimental Apparatus

A schematic illustration of experimental apparatus is shown in **Fig. 3**. The hybrid thruster consists of a Cu target (propellant), and a laser oscillator. The Cu target was mounted on an X-Y stage to refresh irradiated surfaces. For the laser oscillator, Nd:YAG laser (LAMBDA PHYSIK, wavelength: 1064 nm, pulse energy: 340 mJ/pulse, pulse width: 5 ns, repetition rate: 10 Hz) was used.

Temporal evolutions of the plasma plume temperatures and the plasma densities were measured by an electrostatic probe.[5,6,7] The electrostatic single-probe consisting of a tungsten rod of 0.5 mm in diameter and 5.0 mm in length was placed at 10 to 100 mm away from the thruster (target plate position) along the centerline. Temporal changes of the probe 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 characteristic at each moment by taking a temporal slice of a current-voltage characteristic. From the current-voltage curve, temporal evolutions of the plasma temperature and the plasma density were estimated based on the electrostatic probe theory.

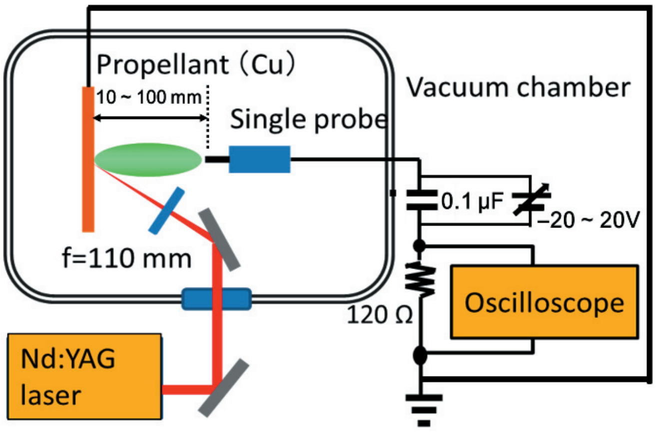


Fig. 3 Experimental apparatus.

III. Results and Discussion

Temporal evolutions of probe currents for various probe bias voltages are shown in **Fig. 4 (a),(b)**. In **Fig. 5 (a),(b)**, the probe current curves in **Fig. 4 (a),(b)** are sliced at 3.0 μs and a current-voltage curve is obtained. From the current-voltage characteristic in **Fig. 5 (a),(b)**, Electron temperature *Te*, Electron density *Ne*, and Debye length λ_D were calculated by using the following three theoretical equation.

$$T_e = -\left(\frac{e}{k}\right)\left(\frac{dV}{d\ln I_{e0}}\right) \tag{1}$$

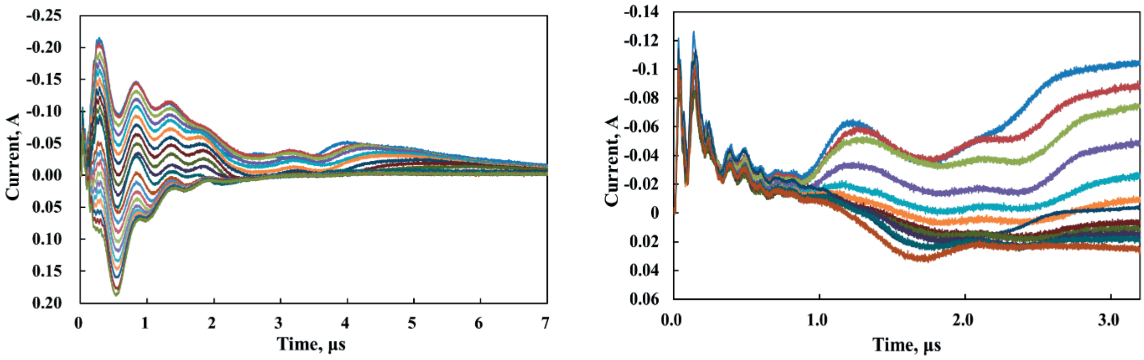
$$N_e = \frac{4I_{eo}}{eSv} \tag{2}$$

$$\lambda_D = \sqrt{\frac{kT_e}{4\pi N_e^2}} \tag{3}$$

Temporal evolutions of electron temperature and electron density are also obtained by following the same procedure to plot the current-voltage curve in **Fig. 5 (a) and (b)**. They are plotted in **Figs. 6 (a), (b) and 7 (a),(b)** for pure laser ablation plasmas; they are monitored at positions of 10 to 100 mm away from the Cu target. It is seen that the electron temperature was 0.8~2 eV. In addition, at 10 mm, the electron density had a peak value of about 1.7×10^{20} m^{-3} at 1 μs. At 100 mm, the electron density had a peak value of about 0.65×10^{20} m^{-3} at 3.2 μs.

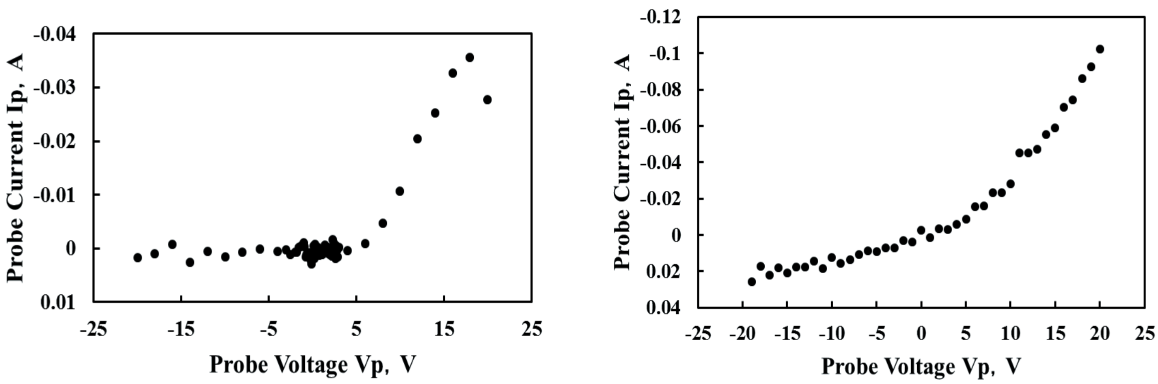
Diagnosing the temporal evolutions at several positions (10 to 100 mm away from the Cu target), a spatial distribution of the electron density and Debye length along the centerline could be obtained, as shown in **Figs. 8 and**

9. Since the plasma density drastically changes in time, only the peak values (in **Fig. 7 (a),(b)**) are selected and then are replotted in **Figs. 8 and 9**. It can be seen that the peak electron density decreased toward the downstream region of the target and reached about 50 x 10^{18} /m^3 at 100 mm away from the target. On the other hand, the peak Debye length increased and reached about 360 μm at 100 mm away from the target.



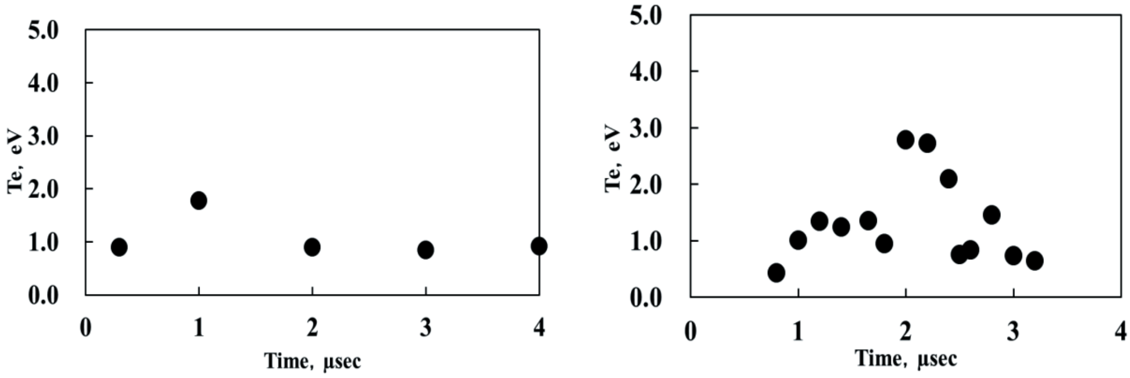
(a) Probe position = 10 mm **(b) Probe position = 100 mm**

Fig. 4 Temporal evolutions of probe currents for various probe biasing voltages.



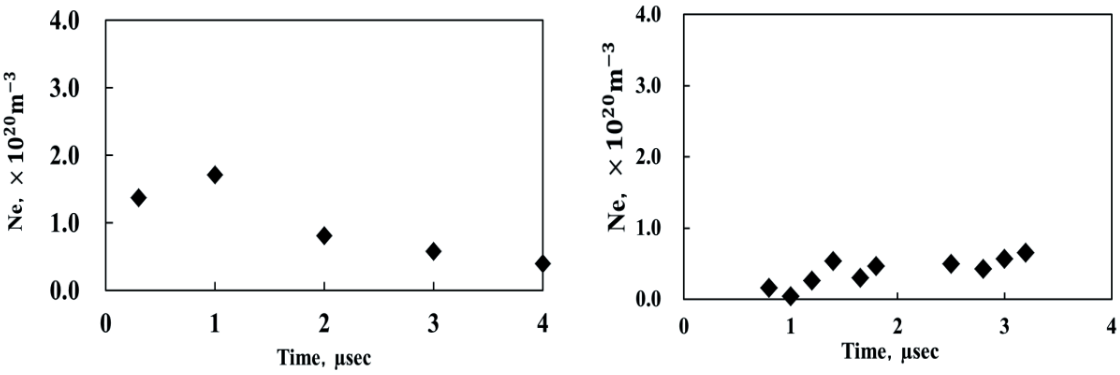
(a) Probe position = 10 mm **(b) Probe position = 100 mm**

Fig. 5 Typical plots of probe current and voltage characteristic replotted from the data (3 μs).



(a) Probe position = 10 mm **(b) Probe position = 100 mm**

Fig. 6 Temporal evolution of the electron temperature.



(a) Probe position = 10 mm **(b) Probe position = 100 mm**

Fig. 7 Temporal evolution of the electron density.

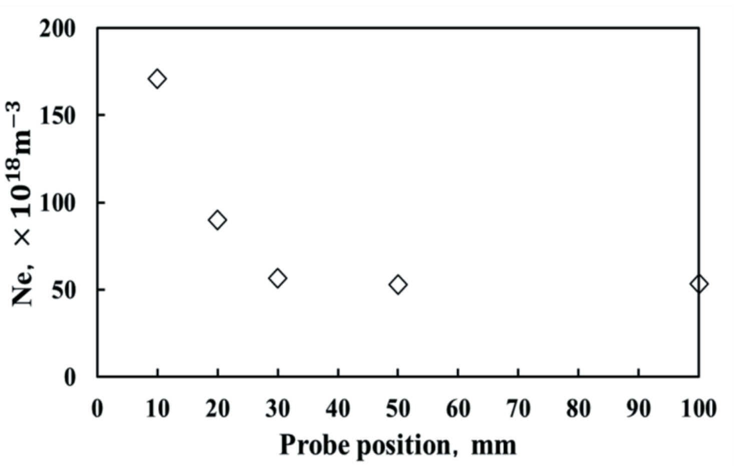


Fig. 8 Spatial distributions of Electron density for pure ablation plasma measured at several positions along the centerline (10-100 mm away from the target).

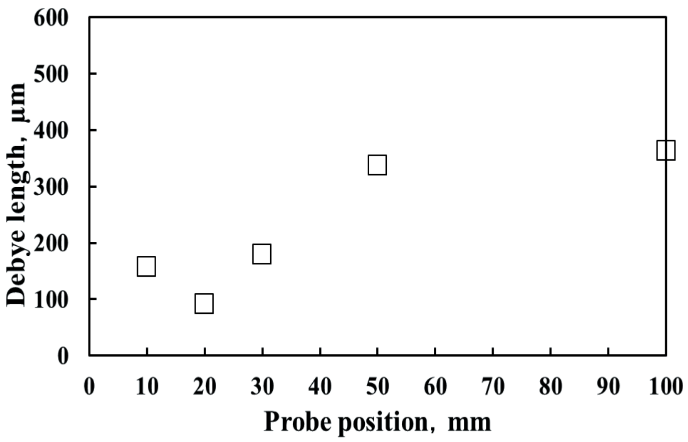


Fig. 9 Spatial distributions of the Debye length for pure ablation plasma measured at several positions along the centerline (10-100 mm away from the target).

IV. Conclusion

A temporal evolution of the plasma distribution of a laser-electrostatic hybrid thruster was experimentally evaluated to find the optimum electrode geometry for the plasma acceleration. The electron temperature and electron density profiles were obtained at positions of 10 ~ 100 mm from the ablated target. The electron temperature was in the range of about 0.8~2eV. It was shown that the peak electron density decreased toward the downstream region of the target and reached down to 50 x 10^{18} m^{-3} at 100 mm away from the target. The peak Debye length increased and reached about 360 μm at 100 mm away from the target. Although the Debye length was about 150 μm at 10 mm from the ablation target, it became much larger at downstream positions. Hence, to make the Debye length and the target-to-electrode gap comparable, the acceleration electrode should be located just in front of the ablation target. Otherwise, the electrostatic acceleration is not possible. Further optimization is required to enhance the electrostatic acceleration in the laser-electrostatic hybrid thruster because the target-to-electrode gap can be tuned corresponding to the laser-produced plasma property on the target.

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