Laser Ablation Plasma Diagnostics for Electrostatic Acceleration

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Abstract: In this study, we aimed at establishing a system as a thruster, and carried out fundamental research for laser electrostatic accelerate propulsion system. Since this system can additionally accelerates plasmas by accelerating laser ablation plasma by an external electrostatic field, it expected to get high thrust power. Therefore, in this research, we discuss optimum electrostatic acceleration, measured the space potential of laser ablation plasma using an emissive probe. According to preliminary results to date from our research, plasma space potential shown consistently about 1.0 V. And then, when the electron temperature reached the peak value, the electron density became the lowest value. In addition, the electron density at about 20 μs from the plasma inflow is 7.3×10^{8} cm^{-3} at the peak value, the electron temperature at that time does not reach the peak value at 3.0 eV. However, when compared with the electron density at the electron temperature peak value of 4.6 eV, it is considered that acceleration by the electrostatic field is an effective time.

Nomenclature

i_C = collected current
i_E = emission current
T_E = electron temperature
T_W = filament temperature
V_F = floating potential
V_H = heating voltage
V_S = plasma potential

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I.Introduction

With the recent miniaturization of high-power laser systems, development of small laser thrusters has been widely conducted[1-4]. One of the advantages of this system is that it uses solid material for the propellant[5]. Since this eliminates the need for piping and valves necessary for gas and liquid propellants, a simple, lightweight propulsion system can be realized. Furthermore, it is possible to control the thrust performance such as total impulse and specific impulse widely by changing the fluence and repetition frequency of the laser pulse irradiated to the propellant [6]. However, the spatial structure and temporal behavior of laser ablation plasma are complex.

On the other hand, we have been developing an electrostatic acceleration system, in which ions of the laser ablation plasma are accelerated by the applied electrostatic field. To accelerate the ions efficiently, it is necessary to obtain temporal and special variation of plasma parameters of the laser ablation plasma in detail. Therefore, in this study, characteristics of laser ablation plasma using an emissive probe were examined.

II.Electrostatic acceleration by laser ablation plasma

Figure1 shows a schematic diagram of an electrostatic acceleration system of a laser ablation plasma. The thruster consists of a planar copper propellant and an acceleration electrode with a single circular hole. By focusing a laser pulse on the surface of the propellant, the propellant converted into plasma is supplied to the acceleration channel. Immediately after the laser irradiation, electrons excited by the laser are firstly emitted from the target surface, and then the remaining positive ions exert Coulomb forces, and at the same time, the ions are electrostatically attracted to the above-mentioned electrons and are accelerated[7,8].

In the method proposed in this study, laser ablation plasma with an initial velocity is additionally accelerated by generating an electrostatic field.

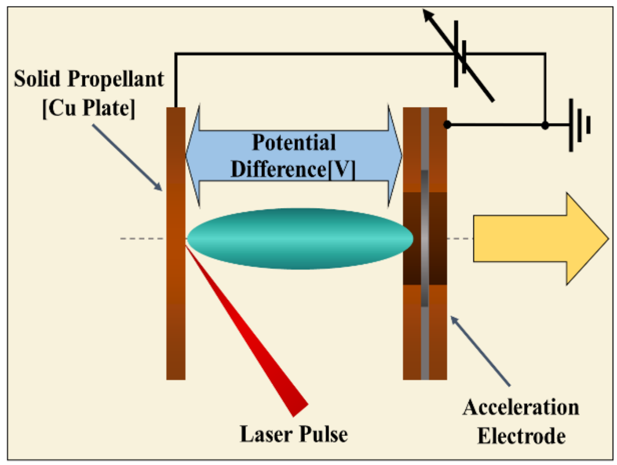

Figure 1. Schematics of laser ablation thrusters.

III.Experimental apparatus and method

In this research, our primary objective is to measure the space potential of laser ablation plasma. For this objective, an emissive probe was chosen because, (1) it’s floating potential is close to the plasma space potential, (2) less disturbing to the plasma, since no current is collected to the probe.

3.1 Emissive probe measurement

In this experiment, electrons are emitted from the filament by applying V_H to the filament within the measurement time, and changes of floating potentials at the time are measured. Application of heating voltages of the probe has ON period and OFF period. Only in the OFF period, pulse voltages are applied at high repetition rate of 200 kHz to maintain constant electron emission. The purpose of this study is to measure the space potentials of the plasmas. The values are calculated from the relations of the heating voltage V_H and the floating potential V_F[9].

3.2 Plasma diagnostics

Figure 2 shows a schematic of the experimental setup for plasma diagnostics. An Nd: YAG laser oscillator (wavelength 1064 nm, pulse energy 10^8 mJ/pulse, pulse width 5 ns) is used to generate a laser ablation plasma. Laser oscillation is triggered with a pulse generator connected to the laser oscillator. The oscillated laser light is expanded by a beam expander and then introduced into a vacuum chamber. Also, the introduced laser beam is focused on the surface of the solid propellant using a focusing lens to increase the fluence. A copper plate is used for the solid propellant. The vacuum chamber is maintained at about 10 $^{-3}$ Pa by a turbo molecular pump. Laser ablation plasma generated from solid propellant is diagnosed by placing an emitting probe on the axis perpendicular to the surface of the propellant from the focusing point. The emissive probe installed in the vacuum chamber is electrically connected to the measuring device outside the chamber through the chamber window with the copper electrodes and is applied the heating voltages from the device. In this experiment, filter frequencies of the data acquisition system were changed to confirm the suitability for laser ablation plasma measurement. This is because the phenomena of laser ablation plasma are occurring in a very short duration of tens of μs, and the differences of the measurement results in the filter frequencies are taken into consideration.

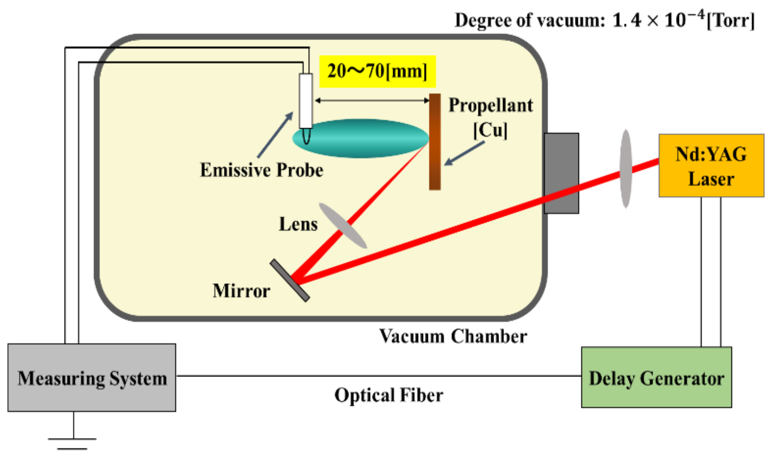

Figure 2. Experimental setup for emissive probe of LAP.

Figure 3 shows an enlarged view of the emissive probe. The emissive probe filament is a tungsten wire with a diameter of 0.03 mm, and terminals of the filament are spot-welded with nichrome wires of a diameter of 0.3 mm and electrically isolated by inserting them into a ceramic tube. In addition, an axial length of the filament is 10 mm from an edge of the insulating tube in consideration of the spatial resolution of measurement and the effect of the sheath edge.

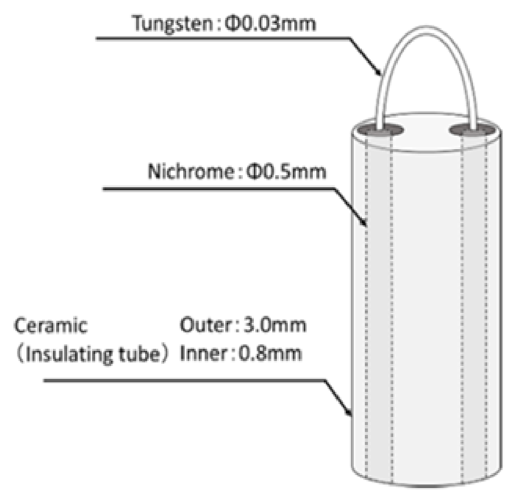

Figure 3. Schematic illustration of emissive probe.

In this study, the measurement duration is set for 20 ms, and a heating voltage is applied to the filament during this duration. A laser pulse is oscillated by the pulse generator during the light emission period of the probe measurement system. A sampling rate of the data is 5 μs according to the high frequency pulse signals applied to the emissive probe. Moreover, plasma parameters at various probe positions and at various times are estimated.

In the measurement, the voltages of the filament are monitored, which are a heating voltage and a floating potential as shown in Fig.4, respectively,

As shown in Figs.4 and 5, collected currents by the filament are monitored during switching from OFF period (V_H = 0) to ON period ($V_H \neq 0$). From the variation of the collected currents, ΔV_F is estimated. Since the heating voltages to the filament change rapidly (during ON/OFF) with high repetition rate, it can be assumed that the emission current

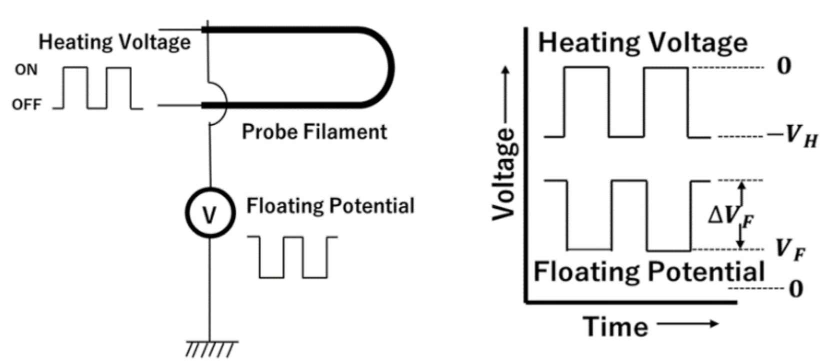

Figure 4. Schematic illustration of emissive probe filament and the electric characteristics

i_E takes a constant value, and the collected current i_C changes according to the variation of the heating voltages.

At a point in which the collected current i_C and the emission current i_E in the OFF period (V_H = 0) become equal, V_F is estimated as a plasma floating potential, and V_S in the plasma space becomes $V_F \approx V_S$ when the emission current becomes sufficient.

Therefore, it is necessary to conduct the measurement with applying the heating voltage V_H from a deceleration region to an electron current saturation region, as shown in Fig.5.

A case where the condition of $V_H + \Delta V_F \leq V_S$ is satisfied is shown in Figs.4 and 5. In the figures, the emission current i_E is shown in the opposite direction for simplicity.

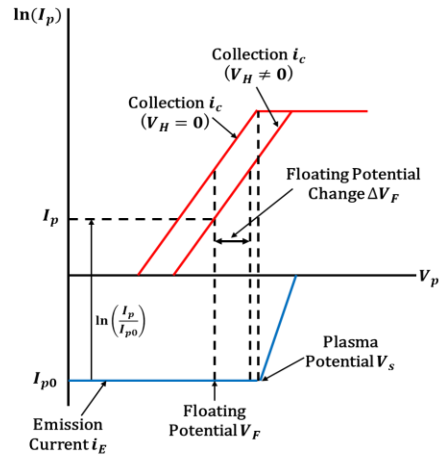

Figure 5. Schematic illustration of the equilibrium of the probe in floating

IV.Result and discussion

Figure 6 shows an example of the temporal evolutions of the floating potentials, which are displayed by different colors for various heating voltages.

The rising part of each waveform shows the inflow of laser ablation plasma. It is necessary to consider correlations of V_H - V_F to confirm the existence of unsteady plasma during the measurement period, as shown in Fig.7, in which variation of the V_H - V_F relations are shown in different colors for various times.

From Fig.6, the inflow of plasma is observed at about 980 μs after the beginning of the measurement.

Observing electron current saturation regions shown in the waveforms after 30 μs, it can be seen that plasma space potentials are about 1.0 V.

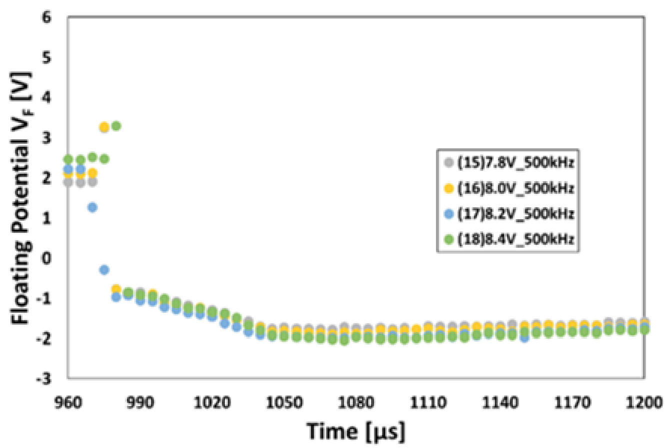

Figure 6. Temporal evolution of floating potential of each heating voltage

Next, we describe electron temperatures and densities. Electron temperatures are obtained from the following equation based on the relationship between the heating voltage V_H and the probe collection current.

In addition, temporal variation of the electron temperatures can be estimated from the ΔV_F values obtained from the measurement.

$$\Delta V_F = -\frac{kT_e}{e} ln\left\{\frac{kT_e}{eV_H}\left[1 - \exp\left(-\frac{eV_H}{kT_e}\right)\right]\right\} \qquad (1)$$

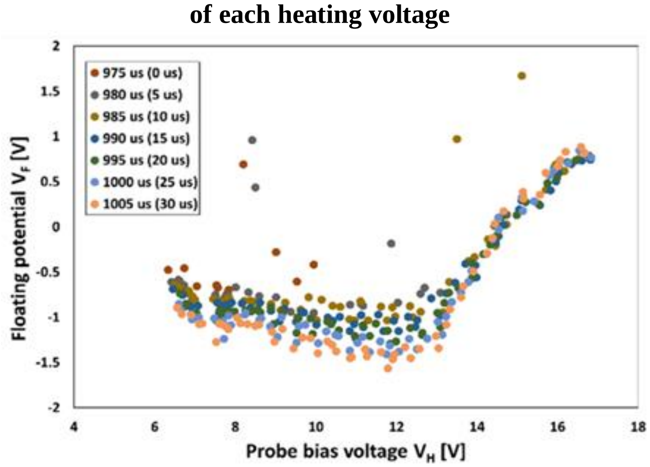

Figure 7. Temporal evolution of V_H - V_F

Electron densities are estimated under an assumption of $i_C = i_E$. Moreover, filament temperatures T_W can be obtained by calculation from the heating voltage and physical properties of the filament[9,10]).

Plasma characteristics obtained from the above mentioned procedures are shown in Figs.8 and 9.

Temporal evolution of electron temperatures is shown in Fig.8. Electron temperatures have a peak value of 4.6 eV at 45 μs from the inflow of plasma when the heating voltage is 8.2 V. At this time, from Fig.9, the electron density is 1.3 × 10^8 cm $^{-3}$.

At each heating voltage condition, electron densities decrease with the increase of the electron temperatures, and the peak value of electron temperatures are obtained at 45 μs from the plasma inflow.

In the figures, scatters of the times of plasma inflow appear for various heating voltages. Since a rapid rise of the electron density is at 985 μs for 8.2 V, the 980 μs is assumed as the origin (0 μs) of time.

The same tendencies and values are also shown under other heating voltage conditions. However, it can be seen that the electron temperatures just before the inflow of plasma show relatively low values.

This means that two different high-energy particles exist in the laser ablation plasma. Each of them seems collected to the probe, however, the high energy particles at the initial stage are not sufficiently collected within the time resolution of the device used in this experiment.

At 20 μs from the plasma inflow, the electron temperature is 3.0 eV, and the electron density peaks about 7.3 × 10^8 cm $^{-3}$.

Compared to the results obtained in previous studies, the results are consistent with the trends in electron temperatures and electron densities.

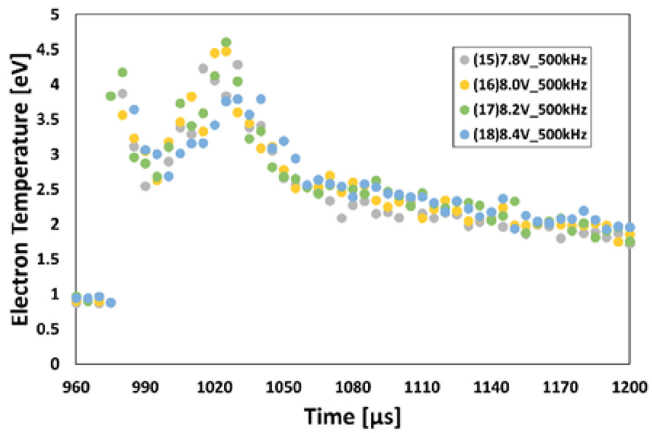

Figure 8. Temporal evolution of electron temperature (probe position = 60 mm)

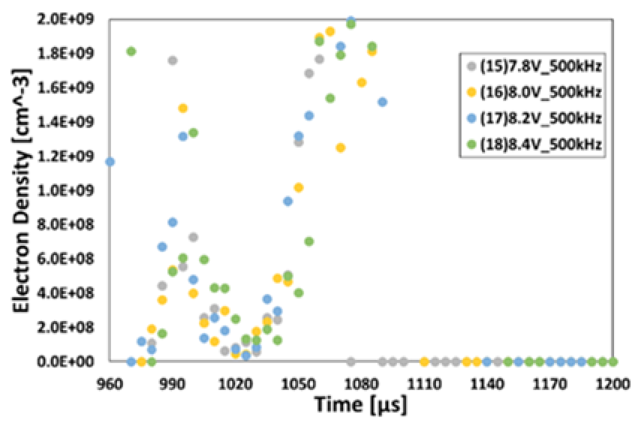

Figure 9. Temporal evolution of electron density (probe position = 60mm)

For our future electrostatic acceleration, the application timing electrostatic acceleration voltages seems effective when applied after the maximum density at 20 μs.

V.Conclusion

In this research, the measurement of space potential and other characteristics of laser ablation plasma are was conducted by using emissive probe. As the results, the followings were obtained.

(1) It was confirmed that the electron density tended to be lowest when the electron temperature reached a peak value of 4.6 eV, and it became 1.3 × 10^8 cm^{-3} at 45 μs.

(2) The electron density at about 20 μs from the inflow of plasma had a peak value of 7.3 × 10^8 cm^{-3} and the electron temperature at that time was 3.0 eV.

(3) The plasma space potential at each measurement position was found to be approximately 1.0 V consistently.

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