A Study on the Dynamics of Laser Ablation Plasma in Vacuum

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Abstract

Dynamics of laser ablation plasma in vacuum was discussed for incident intensities less than ~ 10^9 W/cm^2. Results showed that the ablation plasma is accompanied by charge flows from the laser ablation plasma to a grounded target. The current signals, directly measured by a current monitor, developed from negative to positive depending on the dynamically evolving plasma. Results also showed that, initially the current is induced by an electron flow from the plasma plume to the surrounding wall and, after a transient phase, the current is replaced by ion flow to the wall. This result reflects a breaking of quasi-neutral state of the ablation plasma during the evolution and corroborates a generation of ambipolar electric field (double layer) during the ablation process.

Keywords: laser ablation, double layer, sheath, two-electron temperature, ion acceleration

1. Introduction

Laser ablation plasmas made by moderate irradiation level are used in a wide variety of scientific and industrial fields. Behaviors of the plasma plume in vacuum are usually estimated with the well-known solution of gas-dynamic equations [1,2]. Although the velocity distribution of ions in the plasma play an important role for high flux beam sources of charged particles [3,4], and plasma applications such as deposition of thin films and/or surface treatments, their transient behaviors are not clarified yet. In particular, the extraordinarily fast drift speed of ions has been one of the unclarified issues of the ablation plasma expanding into vacuum [5]. Although the plasma shields the laser irradiation, the plasma can interact with the target. In addition to the hydrodynamic acceleration scheme, a theoretical model of metallic target ablation considering electron emission from the hot target as well as an electric sheath produced at the target-plasma interface was proposed [6].

In connection with a study on the acceleration mechanism, transient processes induced by the evolution of ablation plasma in vacuum are of primary concern of this report. One of the purpose of this report is to show an evidence of the charge flows induced by the dynamically evolving plasma. The charge flows to a grounded target were measured directly using a current monitor and/or a charge collector probe.

2. Experimental Arrangement and Plasma Flux Measurements

A schematic diagram of the experimental arrangement for the plasma flux measurements is shown in Fig. 1. A frequency-doubled Nd:YAG laser irradiated

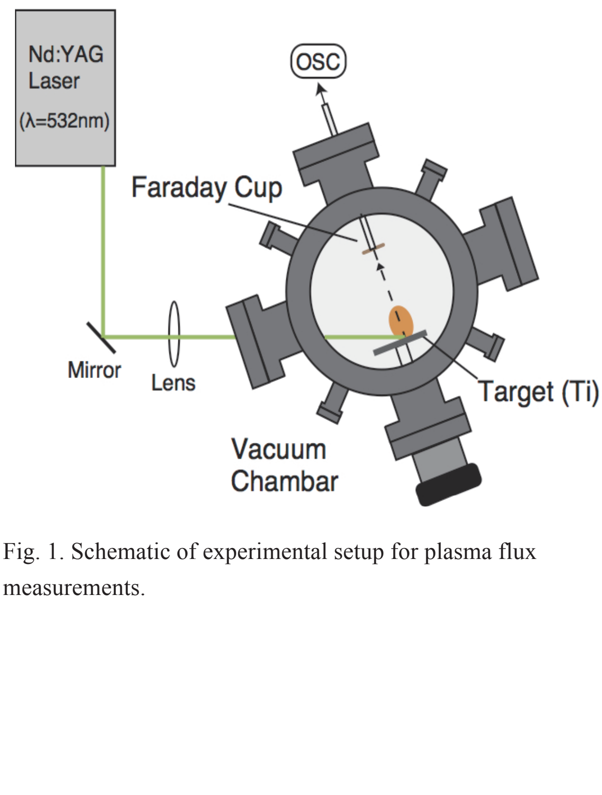

Fig. 1. Schematic of experimental setup for plasma flux measurements.

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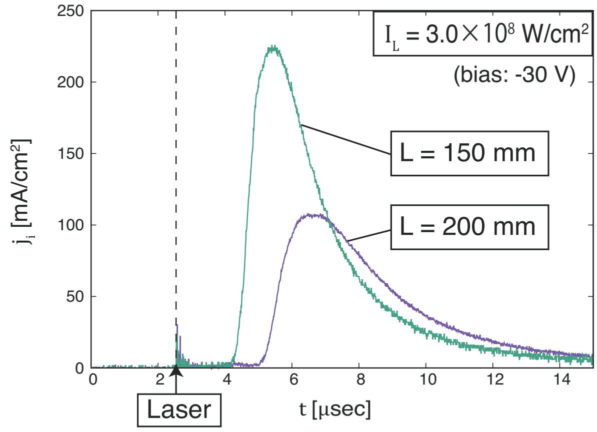

Fig. 2. Waveforms of plasma flux made by laser irradiation with I_L = 3.0 × 10^8 W/cm^2 and S = 1.73 mm^2, at L = 150 mm and 200 mm.

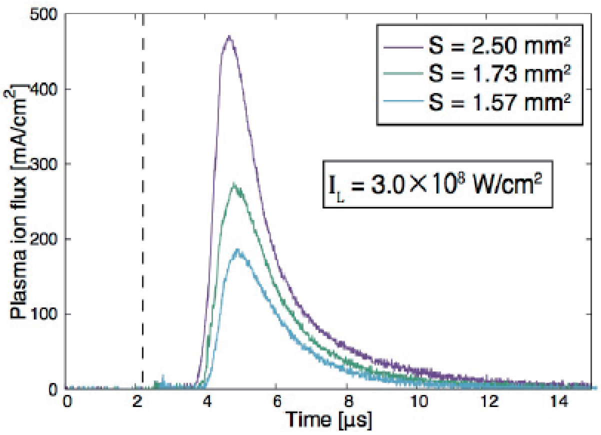

Fig. 3. Dependence of plasma flux on laser spot size with constant irradiation intensity (at L = 150 mm).

a solid titanium (Ti) plate through a lens (f = 300 mm) with a pulse energy of 115 mJ, a pulse width of 15 ns, and an irradiation power density of I_L = 1.3-3.0 × 10^8 W/cm^2. The plasma flux was measured by a Faraday cup located L = 50 mm to 300 mm downstream from the target. The background pressure of the chamber made of stainless steel was kept less than 10^{-3} Pa throughout the experiments.

Typical waveforms of the plasma flux at L = 150 mm and 200 mm are shown in Fig. 2 where the reproducibility was with the line width of the waveform. As is well known, the flux has a drifted-Maxwellian form and the plasma particles dispersed with the propagation. Then the distribution function of ions are composed of fast (drift) and thermal (random) components.

Figure 3 shows waveforms of the plasma flux at L = 150 mm where laser spot size at the target: S was changed as a parameter. As can be seen, when we increase the spot size, the rise time and the flight times for the peak values of the flux-waveforms decreased. The spot size dependence indicates that hydro-dynamical process plays a role for the dynamics of ablation plasma. The plume evolution includes two stages: in the initial stage, where the laser spot size is large enough compared with the plasma thickness, the expansion is one-dimensional, and after some time, when the plasma plume is far from the target, the expansion plume becomes three-dimensional. The transition from the 1D to the 3D behaviors depends on the distance normalized by the spot size.

In the frame of fluid dynamical theory, the ions can be accelerated, by transforming their enthalpy to kinetic energy, up-to the thermal speed at stagnation state [7,8]. This means the maximum speed: u_{max} of the particles is:

$$u_{max} \approx \sqrt{\frac{2\gamma}{\gamma - 1}\frac{RT_0}{m}} = \sqrt{\frac{\gamma}{\gamma - 1}}\,a \qquad (1)$$

where γ is the specific heat ratio, R is the gas constant, T_0 is the stagnation temperature, m is the mass of particle, and a is the sound speed. This means, in the frame of fluid dynamical theory, the ions can be accelerated up to an order of the sound speed at stagnation temperature [7].

We can estimate the attainable temperature using a simplified model, in which the power balance between the laser intensity: I_L of 10^9 W/cm^2 and the radiation power loss from the plasma is solved, without considering the latent heats for vaporization, excitations, ionization processes, and fluid-dynamical effect, the electron temperature is estimated to be 10 eV at most.

At the intensity level of this experiments, the initial temperature of the ablation plasma: T_0 is estimated to be a 10 eV at most. However, as shown in Fig. 2 and Fig. 3, the flux peak arrived the collector at L = 150 mm with time-of-flight of 3.3 µs. Then the ion energy corresponding to the flux peak is estimated to be $(1/2)m_i v_i^2 \sim 520$ eV, which is an order of magnitude larger than that predicted by the hydro-dynamical acceleration mechanism at this laser irradiation level.

3. Direct Measurements of Charge Flows from the Plasma to the Target

Figure 4 shows the arrangement for the charge flow measurements [9]. In order to measure the charge flow, the Ti target was electrically isolated from the vacuum chamber except a connection to the ground by a cable, around which a Rogowski type current monitor (R.G.) was placed. Also, to change the boundary condition for the plasma plume, a charge collector probe composed of a brass disk with 10mm in diameter was placed at L = 150-200 mm from the Ti plate.

Figure 5 shows typical signals from the current probe. As shown, the currents were negative (electron flow from

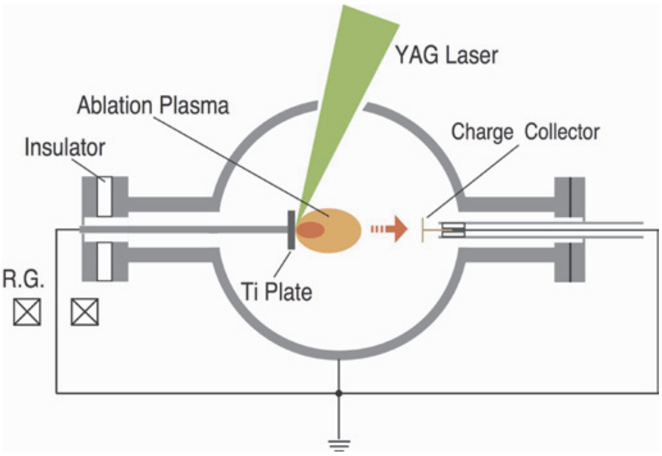

Fig. 4. Experimental arrangement for measurements of charge flow to the laser target.

the target) at the initial phase, and after that they were replaced with positive signals (ion flow to the boundary wall). The negative peak increased with increase of the laser intensity. Also the positive part slightly depended on the laser intensity. The results clearly show that the ablation plume is breaking quasi-neutrality and the plasma potential fluctuates depending on the plume evolution.

For quasi-neutral plasma, the potential ϕ satisfies the Poisson equation:

$$\varepsilon_0 \frac{\partial^2 \phi}{\partial x^2} = e(n_e - Zn_i) \tag{2}$$

where Z is the charge of ions. Then the dense plasma is separated by a sheath from the target across which the potential drop is formed.

In order to characterize spatial distribution of the charge flows, effects of conductive boundary on the current signals were investigated. For the characterization, we changed the position of charge collector probe shown in Fig. 4, and measured the dependence of the current waveforms on L. As shown in Fig.4, in these measurements, the collector probe was also directly grounded and detected the charge flux to ground potential within a narrow solid angle to the target normal.

The waveforms depended on the laser intensity and the distance between the target to the probe. Examples of the waveforms are shown in Fig.6. As shown in the figure, when we decreased the distance L, the current peak increased. These results indicate that the charge flows are induced by the dynamic behavior of the plasma plume. The sharp increase of the first peak of the current signal for smaller L is due to increase of the solid angle of the charge collector toward the plasma. The dependence of charge flow waveforms on L reflects dynamically evolving un-isotropic current distribution.

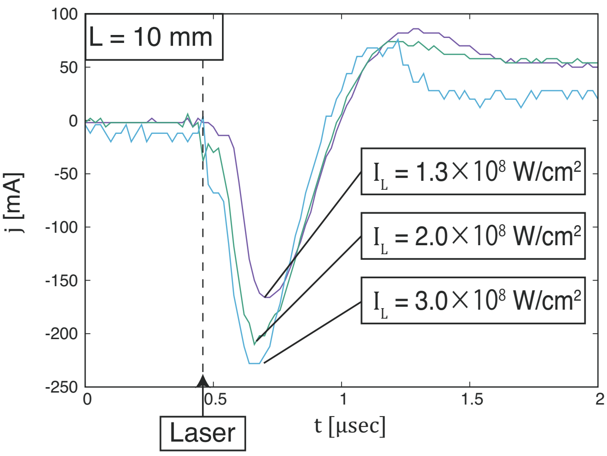

Fig. 5. Current signals through ablation target to the ground potential.

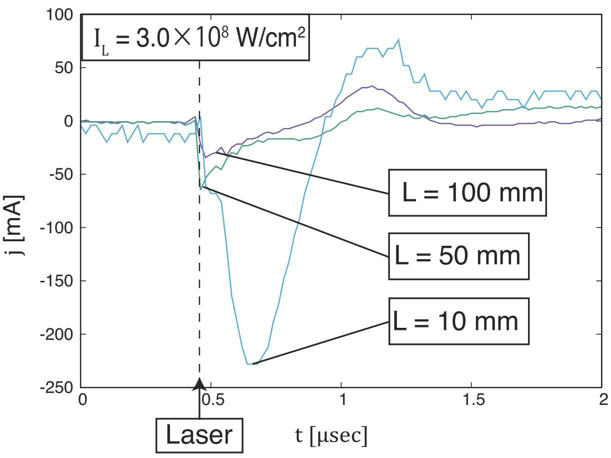

Fig. 6. Dependence of the target-to-ground current on the collector distance L.

Negative signals are probably due to energetic electrons escaping from the plume boundary and the positive signals are from ion flows induced by the potential hump induced in the plume [10]. Although a hot electron population is considered to be critical for producing double layer structure [11], electrostatic probe measurements indicated existence of the hot electron component in the laser ablation plasma under similar experimental condition [4]. Absorption of laser radiation and rapid expansion in vacuum right after the absorption, are probably essential to form the energetic electrons, two-electron temperature components, and the breaking of quasi-neutral state in laser ablation plasma.

4. Concluding Remarks

The charge separation effects in the collision-less plasma expansion into a vacuum have been studied extensively concerning high-energy ion jets from short-pulse interaction with target [12]. The effects seem to play some roles also in the plasma expansion made by moderate intensity level as has been shown in this study.

In this work, charge flows to the ground potential from the ablation plasma were measured directly using a current monitor. The current signals through the grounded target do not disturb the plasma potential. Then the results reflected the transient structure of the ablation plume in vacuum. Also the results could corroborate a breaking quasi-neutrality in the ablation plume, effect of energetic electrons, and ambipolar electric field arising during the expansion of ablation plume. Results also indicated that not only hydro-dynamical mechanism but the ambipolar electric field induced in the ablation plasma contribute the acceleration of ions in the plasma.

The final goal of this study is to clarify the acceleration mechanism of the fast ions and to derive the velocity distribution function of ions under the moderate irradiation levels (10^8-10^9 W/cm^2) which is useful for high-flux ablation type ion sources, and reliable laser triggering of pulsed discharges.

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