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ARTICLE

Study on behavior of ablation plasma from liquid metal target for laser ion source

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When supplying highly charged ion beams from a laser ion source, the lifetime of a laser target is limited by its area because laser irradiation induces substantial surface damage and the position of laser irradiation needs to be changed every shot. In order to develop a target with longer lifetime, we have proposed using a liquid target for laser ion sources because the liquid target can recover its surface after being damaged by laser irradiations. In this study, we investigated the behavior of laser ablation plasma from a liquid metal target with some different laser frequencies. The employed target was a U-Alloy 60, which is an alloy composed of Bi, In, and Sn, and it was irradiated by a Nd:YAG laser with a wavelength of 532 nm. The results indicated that the reproducibility of current waveform at a laser irradiation with 10 Hz was almost the same as that obtained by single-shot experiment even when the laser was irradiated on the liquid while its surface was oscillating. This was because the amplitude of surface oscillation was not large enough to affect the laser intensity on the target surface. These results implied that a laser ion source using a liquid metal target can supply ion beams as stably as using a solid target.

Keywords: Laser ion source; Laser ablation; Ablation plasma; Heavy ion beam; Liquid metal target

1. Introduction

A laser ion source can supply high current ion beams from plasmas generated by irradiating a target with a laser. In recent years, it has been used to supply Au ions used in high energy physics experiments and various metal ions have been supplied for applications in radiobiology [1]. In addition, it is possible to accelerate higher current beams by applying the Direct Plasma Injection Scheme (DPIS) [2-6], in which an ion beam directly extracted from a plasma is injected into the RFQ linear accelerator without using a Low Energy Beam Transport (LEBT). Based on the scheme, some applications have been proposed, including particle beam therapy using carbon beams [7], and an accelerator neutron source that generates highly directional neutrons [8-10] using inverse kinematic reaction [11] with lithium beams and hydrogen targets.

One issue in using a laser ion source is the lifetime of the laser target. An actual example of using a laser ion source is the supply of low-charge-state metal ions at Brookhaven National Laboratory (BNL) in the United States. The lowly charged ions are injected into an electron beam ion source (EBIS), which is installed after a laser ion source, in order to obtain highly charged ions before the acceleration by the RFQ linear accelerator. By reducing the power density of the laser, damage to the target is minimized, and even if the same target surface is irradiated with the laser for a long time, ablation plasmas can be generated with good reproducibility over a long period of time [1].

On the other hand, when highly charged ions are required from the laser ion source alone, or when targets such as alloys or compounds containing multiple elements are used, it is necessary to increase the laser power density in order to obtain the desired ion species with high current. In such applications, the number of laser irradiation times is limited by the target area, and the lifetime of the laser target becomes a problem for steady operation of the laser ion source.

Therefore, in order to solve this problem, we have proposed a laser ion source with a liquid target that can recover the target surface. A laser was repeatedly irradiated on the liquid metal surface, and the behavior of the liquid surface and the ion current were measured to investigate the effect on the reproducibility of the ion current waveform. In this study, we investigated the behavior, especially the reproducibility in the ion current of laser ablation plasma from a liquid metal target with various laser frequencies.

2. Experimental setup

In this experiment, a laser was irradiated on the center of a liquid metal in a vessel, and plasma was generated at a pressure of 5×10^{-3} Pa in a vacuum chamber as shown in **Figure 1**. The employed target was a U-Alloy 60, which is an alloy consisting of Bi, In, and Sn with the melting

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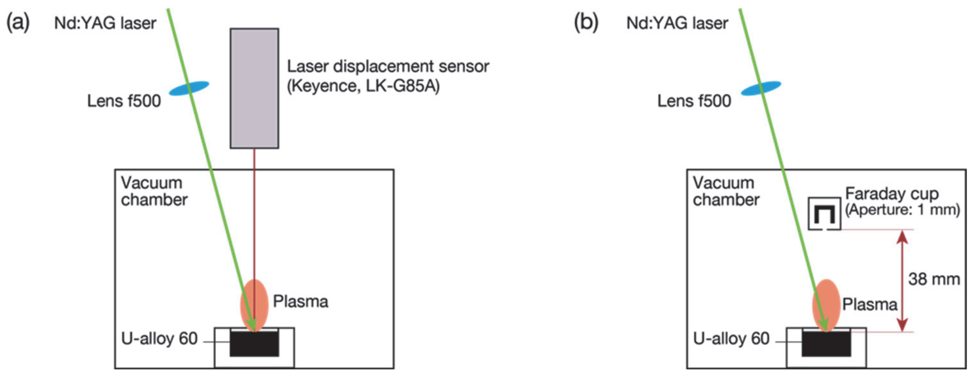

Figure 1. Experimental setups for measurements of (a) liquid surface oscillation after laser irradiation and (b) ion current of plasma.

point of 60°C, and kept to 100°C during the laser irradiation experiments. A brass vessel was heated using a film sheet heater (Tokyo Giken, FSHH-P2-50-1.1A) and contained the liquid metal with a radius of 6.5 mm and a depth of 8 mm. The temperature was measured with a K-type thermocouple attached to the vessel. The oscillation of the liquid surface was measured using a laser displacement sensor (Keyence, LK-G85A).

The laser used for plasma generation was a Nd:YAG laser, with a wavelength of 532 nm, pulse width of 16-18 ns. A lens with a focal length of 500 mm was located at 245 mm from the target surface. Ion currents were measured using a Faraday cup (FC) with an aperture of 1 mm. The FC was positioned 38 mm in front of the laser irradiation point. The Ion current was measured by applying a retarding voltage of -50 V to repels plasma electrons.

The laser power and energy were measured using a power and energy meter (Ophir, Nova II /12A-P). A photodiode was also used for detecting the timing of laser irradiation to measure the time of flight of plasma and to measure the fluctuation of laser power shot by shot.

3. Results and discussion

First, we investigated the reproducibility of laser energy for single-shot and repeated irradiations. **Figure 2(a)** shows the difference in laser energy when the frequency is changed while an identical laser flash lamp energy is used. The change in the laser frequency was performed through the internal system of the laser, which controls the frequencies of the flash lamp and the Q-switch. As shown in this figure, it was confirmed that the output laser energy varied depending on the frequency of the flash lamp, and that the higher the energy was output as the higher the frequency. In addition, since the single-shot experiments were performed at a flash lamp frequency of 10 Hz, almost the same energy as that at a laser frequency of 10 Hz was output.

Figures 2(b) and **2(c)** show the laser light signals obtained by the photodiode and the standard deviation divided by the average of the laser peak power with respect to the laser irradiation frequency. The variation became smaller as the laser frequency increased, and the variation of the peak power at 10 Hz was smaller than that of the single shot, while it was larger at 6 Hz. This variation dependent on the laser frequency could be caused by the change in the thermal condition in the YAG laser rod [12].

Then, we investigated the characteristics of the oscillation of the liquid surface after laser irradiation in order to understand the influence of the behavior of the liquid surface on plasma generation. The maximum amplitude was about 1 mm in this experiment as shown in **Figure 3(a)**, and the oscillation damped with a time constant of about 0.29 s. As a result of FFT analysis, the main component of this surface oscillation was 12 Hz. In order to investigate the factors determining the characteristics of this oscillation, we estimated the natural frequency f_{ij} (i-th mode in the azimuthal direction, j-th mode in the radial direction) of the liquid determined by the geometry of the vessel using the following formula.

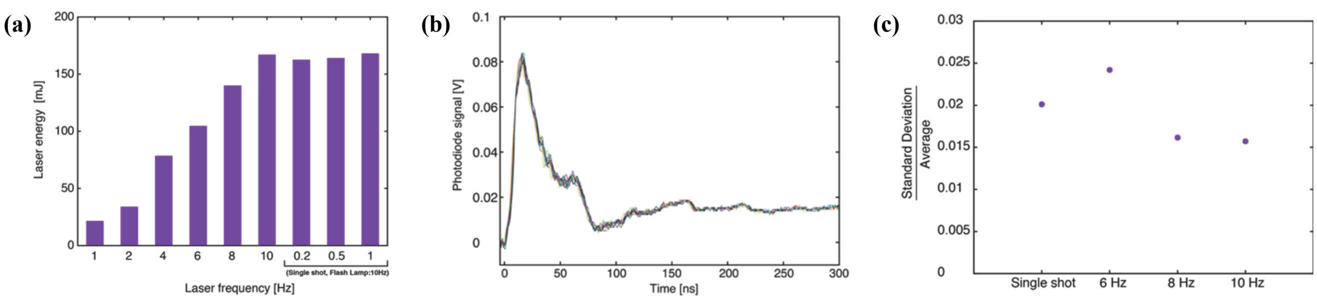

Figure 2. (a) Laser energy with respect to laser frequency, (b) the signals obtained by photodiode during repetitive laser irradiations, and (c) the standard deviations divided by the average of laser peak power.

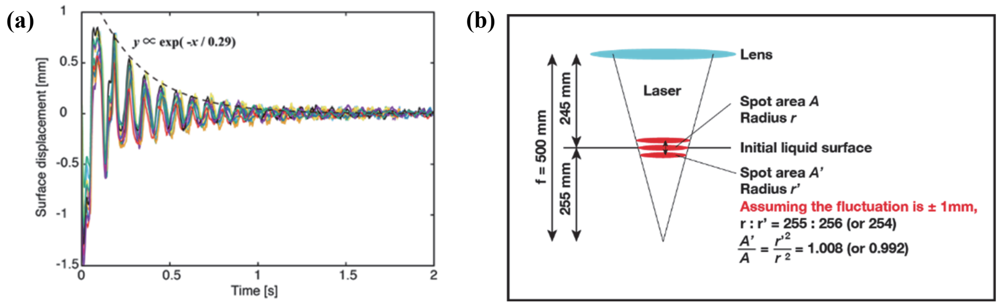

Figure 3. (a) Liquid surface oscillation after laser irradiations and (b) the estimation for variation of laser spot area due to the liquid surface oscillation.

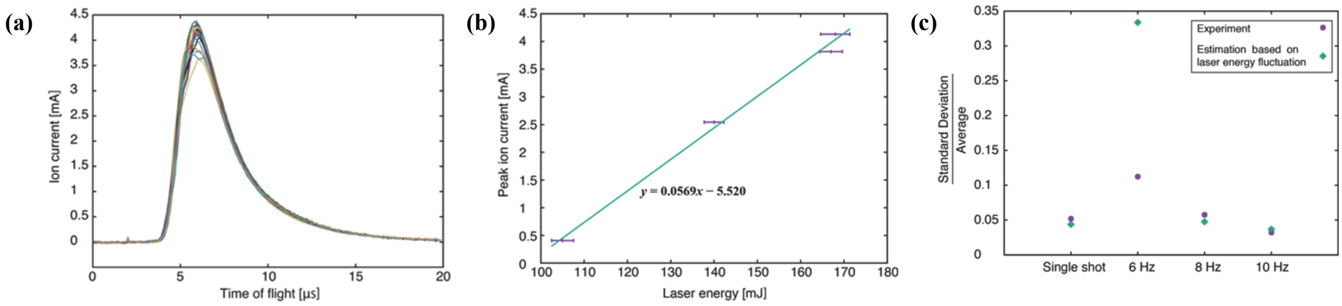

Figure 4. (a) Ion current waveforms obtained by single shot experiment, (b) the peak ion current as a function of laser energy, and (c) the standard deviations divided by the average of ion current obtained by experiments and estimation based on the reproducibility of laser power.

$$f_{ij} = \frac{1}{2\pi}\sqrt{v_{ij}\frac{g}{R}tanh\left(v_{ij}\frac{h}{R}\right)}, \qquad (1)$$

where v_{ij} is the j-th positive root of $J_i'(v) = 0$ ($J_i(v)$: i-th order Bessel function of the first kind), g is the gravitational acceleration, h and R are the liquid level from the bottom and the radius of the vessel, respectively. The analysis indicated that the frequency of 12 Hz corresponded to the natural frequency of f_{01} mode [13].

The experimental result also showed that the periods corresponding to laser frequencies of 6, 8, and 10 Hz were 0.167, 0.125 and 0.1 s, respectively, and all of them are smaller than the time constant of oscillation 0.29 s. This indicates that the liquid surface was irradiated with the laser before the oscillation of the liquid surface stops in repeated laser irradiation experiments.

In order to understand the effect of the liquid surface oscillation on the reproducibility of plasma generation, we considered the effect of the liquid surface displacement on the laser intensity, which is defined as laser power divided by laser spot area. The change in laser intensity on the target surface was estimated using the focal length of the lens and the distance from the lens to the target surface based on the principle of geometric similarity. Assuming the amplitude of ±1 mm as shown in **Figure 3(b)**, the change in laser spot area can be estimated to be ±0.008 when the spot area on the initial liquid surface with static condition is assumed to be 1. This change is small compared to the laser power fluctuation which has a standard deviation of about 0.02 shown in Figure 2(c). Therefore, this result suggests that the influence of the surface oscillations on the reproducibility of the ion current in this experimental system was not large compared to the laser power fluctuation.

Then, we investigated the reproducibility of the ion current from plasmas generated by irradiating the liquid metal with the laser. As shown in **Figure 4(a)**, it was confirmed that plasma could be generated with good reproducibility even from the liquid target similar to the case of using a solid target.

To understand the main factor which determines the reproducibility of ion current, the standard deviation of ion current based on that of laser power was estimated. As shown in Figure 2(a), the ion current can be obtained as a function of laser energy. By fitting a linear approximation to the obtained experimental results, the equation: $y = 0.0569x - 5.520$ was derived. From this equation and the standard deviation of laser power, the standard deviation of ion current was estimated. **Figure 4(c)** shows a comparison between the standard deviation of the ion current predicted by that of the laser power and obtained experimentally. The result showed they have a similar tendency and the values of the standard deviation divided by average were almost the same. This result suggests that the reproducibility in the ion current was determined due to that in the laser energy and little depends on the surface oscillation. These results indicate that ions can be stably supplied from the liquid metal target by laser irradiation at 10 Hz when the amplitude of surface oscillation does not enough large to affect the laser intensity.

Targets made of materials with lower viscosity than U-Alloy 60 may have larger surface oscillations. Nevertheless, the results show that when the variation of laser power density due to the change in the laser spot is small compared to laser energy fluctuation, plasma generation and the ion current would show good reproducibility. To maintain the stability of the laser spot size during the surface oscillation, it is effective to use a lens with a long focal length or position the laser target away from the focal point of the lens. However, in cases where the surface variation does not follow a simple damping oscillation but significant surface changes such as the so-called milk crown formation, further investigation is required to understand the recovery process and timescale.

4. Conclusion

To develop a laser ion source based on a liquid target, the reproducibility of ion current of laser ablation plasma using a liquid target of low melting point metal was investigated as a function of laser frequency (6, 8, 10 Hz and single shot operation). The results indicated that the reproducibility of current waveform for laser irradiation at 10 Hz was almost the same as that obtained by the single-shot experiment even if the laser was irradiated on the liquid while its surface was oscillating. This was because the amplitude of surface oscillation does not large enough to affect the laser intensity on the target surface. These results suggest that a laser ion source using a liquid metal target can supply ion beams as stably as using a solid target.

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