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Contribution of material's surface layer on charge state distribution in laser ablation plasma

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To generate laser ablation plasma, a pulse laser is focused onto a solid target making a crater on the surface. However, not all the evaporated material is efficiently converted to hot plasma. Some portion of the evaporated material could be turned to low temperature plasma or just vapor. To investigate the mechanism, we prepared an aluminum target coated by thin carbon layers. Then we measured the ablation plasma properties with different carbon thickness on the aluminum plate. The results showed that C^{6+} ions were generated only from the surface layer. The deep layers (over 250nm from the surface) did not provide high charge state ions. On the other hand, low charge state ions were mainly produced by the deeper layers of the target. Atoms deeper than1000 nm did not contribute to the ablation plasma formation.

I. INTRODUCTION

Laser ablation plasma is produced by high power laser irradiation of a solid target. A Laser Ion Source (LIS) utilizes the laser ablation plasma to provide ion beams extracted from the plasma and injected into accelerators[1,2]. For example, a low charge state LIS has been used as a seed ion injector for the Electron Beam Ion Source (EBIS) at Brookhaven National Laboratory[3,4]. However, the laser ablation process has not yet been fully understood. When the laser beam is tightly focused on a target, a crater is observed after the irradiation. It is not clear whether all of the missing material is converted to a laser ablation plasma plume[5,6]. To investigate the relationship between the depth of the target material and plasma formation, we prepared aluminum targets with two different thicknesses of carbon coatings. The prepared carbon thicknesses were 250and 1000 nm. The plasma properties were measured for both thicknesses of carbon.

II. Experimental Setup

A sub-nanosecond laser beam was focused using a f = 100 mm plano-convex lens and irradiated a carbon coated aluminium target. The angle of incident was 20 degrees. The laser irradiation of the solid target makes an ablation plasma which contains multi charged ions. The laser system, Ekspla SL334 [7], emitted a pulse with a wavelength of 1064 nm and duration of 270 ps. The energy per pulse was 304 ± 10 mJ. The focused spot size on the target is estimated to be >100 µm, which is the size of the crater on the target surface. This energy and spot area correspond to power density of< 2.2×10^{13} W/cm^2. A current of produced ions were detected by a Faraday cup located 2.4 m away from the target. To measure the velocity distribution of each charge state, an electric ion analyzer was used. By scanning the voltage applied to the analyzer, ions were separated according to species and charge state. The selected ions were detected with a secondary electron multiplier which is placed 1.4 m after the Faraday Cup (FIG 1). Using the setup, it is difficult to distinguish different ion species with the same charge to mass ratio. In this experiment, C^{4+} and Al^{7+} were indistinguishable. Also, C^{5+} and Al^{11+} were too close to separate.

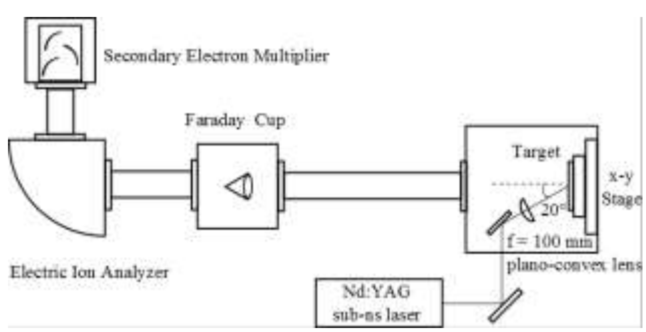

FIG. 1. Plasma analysis beam line

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III. Carbon coated aluminium Target

The thin carbon layer on the aluminum substrate could be made relatively easily by the sputtering technique. However, if a thick carbon film (> 500 nm) was sputtered, the substrate would be heated due to the radiation form the electron gun. After cooling down, the coated carbon layer may begin to peel off the aluminum substrate even if the target was preserved in vacuum. Therefore, we used the plasma arc deposition technique which could keep the substrate at a low temperature during the coating process [8]. The thicknesses of deposited amorphous carbon layers was measured during the deposition process to be 250 nm and 1000 nm with a quartz crystal monitor. The carbon coated aluminum targets were mounted on a 2-axis linear stage and moved after every laser shot to prevent the same spot being exposed twice.

FIG. 2. Plasma arc deposition equipment (left).
Al targets with a 250 nm thick C layer (right-top) and that with a 1000 nm thick C layer (right bottom) after laser irradiation.

III. Result and Discussion

Figures 3 and 4 show the analyzed results of current distributions for the 250 nm and 1000 nm thickness carbon coated targets respectively. The vertical scales were scaled at 1 meter from the target with a 1 cm^2 of sensing area. The scaling law used is,

$$I \propto L^{-3}, \quad (1)$$

where, I and L are ion current and plasma drift distance respectively. The horizontal axises were also scaled at 1 m from the target assuming the constant expanding ion velocities.

The measued plasma with the 250 nm coated target shows that predomitnantly alminium ions and only a small fraction of carbon ions were observed in the plasma. The Al^{9+} curve, which could potentially be C^{4+}, has the highest peak around 3.0 μs and the recorded maximum charge state reached was Al^{12+}. We also measured the charge state distriution and current profiles using a solid aluminum target. In fact, the observed result from the aluminum target almost coincided with the aluminum curves in Fig. 3 which was from the 250 nm coated target. The carbon layer contributions were only observed in the higher velocity part of the plasma. Also lower charged carbon, C^{1+}, C^{2+} and C^{3+} were not detected. The fast C^{6+} ion was detected at 1.7 μs which is the same as detected in the 1000 nm coated target plasma. This may indicate that the temperature of both plasmas are similar.

On the other hand, the 1000 nm coated target provided only carbon ions. As explained previously it was impossible to distinguish some charge state of aluminum ions from carbon ions. However we concluded no alminum ions were produced from the thick coated target, since no other distinguishable aluminum ions were detected. Material below 1000 nm depth of the carbon target do not contribute to the ablation plasma formation.

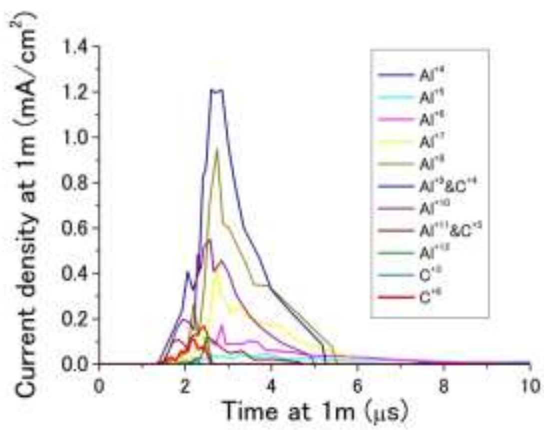

FIG. 3. Current distribution of each charge state of C and Al ions for a 250 nm thick carbon coated target on a thick Al substrate. Laser was irradiated from the carbon side.

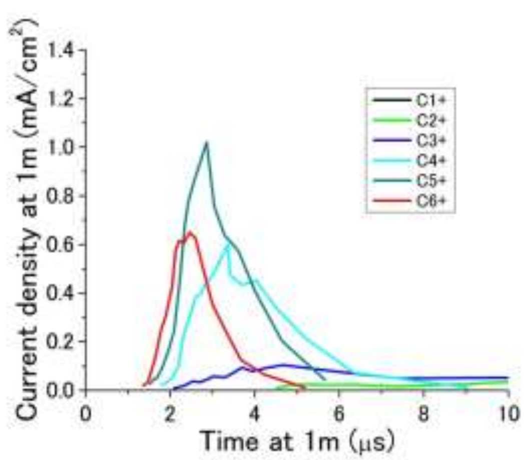

FIG. 4. Current distribution of each charge state of C and Al ions for a 1000 nm thick carbon coated target on a thick Al substrate. Laser was irradiated from the carbon side.

To compare the results more clearly, the integrated abundances of alunimum and carbon were plotted in Figs 5 and 6. Figure 5 shows that the aluminum charges were distributed from Al^{1+} to Al^{12+} for the 250 nm coated target. As mentioned, the two indistinguishable charge states were observed from the thick target, but those are assumed to be carbon ions, since the neighboring aluminum charges were not detected.

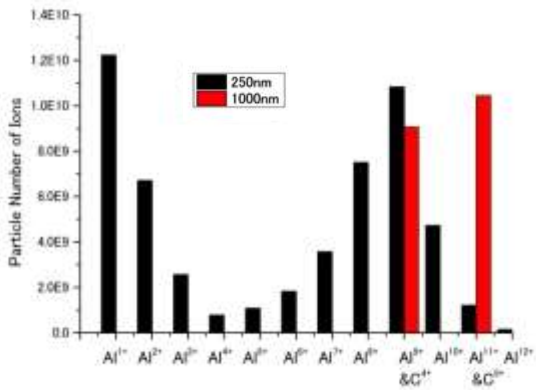

FIG. 5. Total number of aluminum ions at 1.0 m with 1.0 cm of sensing area for 250 nm thick (black) and 1000 nm thick (red) carbon coated targets.

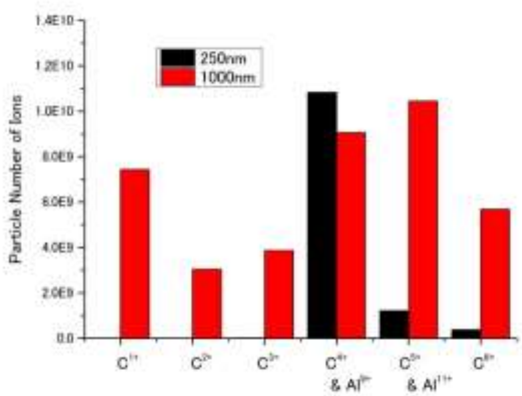

FIG. 6. Total number of carbon ions at 1.0 m with 1.0 cm of sensing area for 250 nm thick (black) and 1000 nm thick (red) carbon coated targets.

Figure 6 indicates that the plasma from the 1000 nm coated target included all the charge state of carbon ions. The thin coated target had some amount of higher charge states. Let us note again that the C^{5+} and C^{4+} ions are indistinguishable from certain charge states of aluminum ions. However the lower charge state carbon ions were not clearly observed with the thin coated target. This may imply that the ablated plasma was not relaxed enough to have a uniform temperature distribution. The surface layer contributes only the high temperature region in the plasma. The lower temperature part of the plasma was mainly formed from the layer that is deeper than 250 nm. The uniformity of the plasma and the laser exposure time seem to be correlated. Also the carbon thickness is close to the laser wave length. This may influence the formation of the plasma as well. To clarify these effects, further investigations will be required.

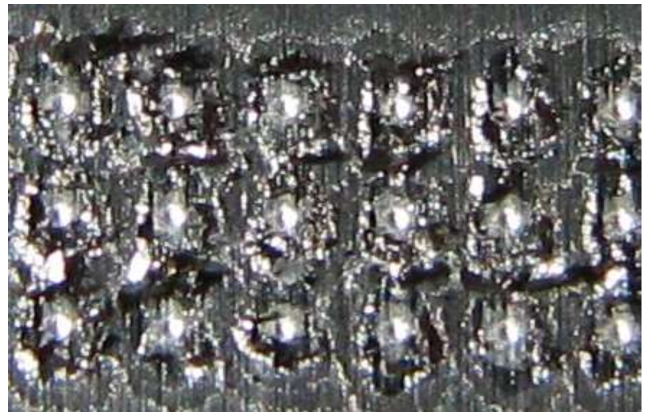

FIG. 7. Target surface of a 1000-nm-thick carbon on Al substrate from carbon side. Each crater on the photo was produced by one a laser shot. The target was moved 1 mm after each laser shot.

Figure 7 shows the closed up photo of the used 1000 nm coated target. The crater obviously reached aluminum substrate layer, however no aluminum ions were detected. This indicates that layers deeper than 1000 nm do not contribute to the ablation plasma formation. The removed aluminum seems to have become vapor without ionization.

IV. Conclusion

We measured the ablation plasma properties with two different carbon thickness on an aluminum plate. The results showed that C^{6+} ions were generated only from the surface layer and that layers deeper than 250nm from the surface did not provide C^{6+} ions. Low charge state ions were mainly produced by the deeper layers of the target. Above 1000 nm depth, the target substrate was evaporated and formed a crater, but did not contribute to plasma formation.

V. Acknowledgement

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