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sub-nanosecond laser***

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Low charge state heavy ion production with sub-nanosecond laser^{a)}

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We have investigated laser ablation plasma of various species using a nanosecond and a sub-nanosecond laser for both high and low charge state ion production. We found that with sub-nanosecond laser, the generated plasma has long tail which is low charge state ions determined by an electrostatic ion analyzer even when the laser irradiation condition for highly charged ion production. This can be caused by insufficient laser absorption in plasma plume. This property might be suitable for low charge state ion production. We used a nanosecond laser and a sub-nanosecond laser for low charge state ion production to investigate the difference of generated plasma using Zirconium target.

I. INTRODUCTION

Recently, a laser ion source (LIS) for low charge state ion production has been intensively studied though the development of the LIS for heavy ion production was historically driven by the demand of highly-charged intense heavy ion beam for particle accelerators. To generate laser produced plasma containing low charge state ions, the laser power density on a solid state target is required to be less than about 10^9 W/cm².¹ The ion current can be enhanced by a solenoid field applied in a plasma expanding region.² The LIS for low charge state heavy ion beam is used as an external ion source for an Electron Beam Ion Source (EBIS) or an Electron Cyclotron Resonance Ion Source (ECRIS) for further ionization. A LIS is suitable for this purpose because the LIS produces ions easily from almost all solid state materials, and ion species can be switched rapidly by changing the target position. At Brookhaven National Laboratory, the LION source has been used to provide multiple species of ion beam for the Relativistic Heavy Ion Collider-EBIS for NASA Space Radiation Laboratory and RHIC for user operation.³ Historically, lasers with the pulse width of nanosecond order, such as CO₂ lasers or Nd-YAG lasers, have been used for the LIS development.^{4,5} This is because those lasers had suitable performances for particle accelerator applications, such as repetition rate, laser energy, and stability. However, recently lasers with shorter laser pulse with adequate performance has been

nanosecond laser for the high-charge state ion production showed that there was a low velocity tail containing low charge state ions.⁶ This result indicated that the use of sub-nanosecond laser could have an advantage for low charge state ion production. To verify the difference of the laser pulse width for low charge state ion production, the plasma properties produced by both nanosecond and sub-nanosecond were compared experimentally.

II. EXPERIMENTAL SETUP

The experimental setup was similar to the one shown in ⁷. Two Nd:YAG lasers were used. The THALES laser SAGA230 (6 ns, maximum energy 2.3 J) was used as a nanosecond (ns) laser, and the Ekspla laser SL330 (170 ps ~ 570 ps, maximum energy 0.5 J) was used as a sub-nanosecond (sub-ns) laser. The wavelength of both lasers is 1064 nm. The Ekspla laser uses Backwardstimulated Brillouin scattering (SBS) to compress the laser pulse. The pulse width of 570 ps was used throughout the experiments shown below. A 0.25 mm thick Zirconium (Zr) foil with the dimension of 25 mm by 25 mm was used as a laser ablation target. The laser was focused by a focusing lens in a vacuum chamber onto the target with an incident angle of 20 degrees. The spot size on the target was 4.8 mm and 4.6 mm in diameter with the ns laser and the sub-ns laser, respectively. The ablation plasma generated by the laser irradiation adiabatically expands towards normal direction to the target surface. Because of the expansion, the ion current density decreases and the ion pulse width increases by following relations.⁴

$$j \propto L^3 \quad (1)$$

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commercially available and started to be used for the LIS development. The experimental result with sub-

$$\tau \propto L \quad (2)$$

where j is current density, L is a distance from the target, and τ is an ion pulse width. Total current of ions was measured by a Faraday Cup (FC) placed at 2.4 m from the target. The FC had a 10 mm in diameter opening and equipped with a mesh biased at -3.5 kV to extract ions from plasma and suppress secondary electrons from the cup. The charge state distribution was measured by an electrostatic ion analyzer (EIA) and a secondary electron multiplier (SEM) located at 3.8 m from the target. The vacuum pressure was kept at about 10^{-4} Pa. The FC signal was used to convert the signal of each charge state analyzed by the EIA and SEM to beam current, assuming that the electron multiplication factor of the SEM is proportional to the ion charge

III. RESULTS AND DISCUSSION

The charge state distribution irradiated by the ns laser (1.0 J) and the sub-ns laser (0.10 J) were measured to compare the difference of the laser pulse width under the condition with the similar laser power density. The laser power density on the target with the ns and sub-ns laser was 9.3×10^8 W/cm² and 1.0×10^9 W/cm², respectively. The same spot on the target was used in an experiment. The FC signal was checked before and after each experiment to ensure there was no significant change of the plasma properties.

We observed Zr, H, C, and O ions. The results of the charge state measurement and the FC signal are shown in Fig. 1, and the ion yield of each ion species is shown in Fig. 2. In the figures, the measured charge state distribution and the FC signal were converted to those at 1m from the target with 1cm² area using Eqs. 1 and 2. The first small peak of the FC signal consisted of light ions mainly H⁺, and C and O ions were found at the rising edge of the FC signal. The lower charge state distribution of Zr ions (95.9 % (Zr¹⁺), 4.1 % (Zr²⁺), and 0.01 % (Zr³⁺)) was observed with the sub-ns laser irradiation, than that with the ns laser (84.7 % (Zr¹⁺), 14.8 % (Zr²⁺), and 0.5 % (Zr³⁺)). The beam pulse width with the sub-ns laser (71 μ s for Zr¹⁺ at 10 % of the peak current) was longer than that of the ns laser (53 μ s for Zr¹⁺ at 10 % of the peak current). In addition to Zr ions, Oxygen, Carbon, and Hydrogen ions were detected as impurities. To achieve the similar charge state distribution as the ns laser, the laser power density of the sub-ns laser was increased to 3.0×10^9 W/cm² by increasing the laser energy from 0.10 to 0.28 J. The result of the increased laser power density with the sub-ns laser is shown in Fig. 3. The amount of Zr ions was 83.1 % (Zr¹⁺), 16.2 % (Zr²⁺), and 0.7 % (Zr³⁺). The pulse width of the plasma was 59 μ s for Zr¹⁺ at 10 % of the peak current. The charge state distribution and the pulse width were almost same as the ns laser experiment.

FIG. 1. Charge state distribution of Zr plasma produced by (a) ns laser (9.3×10^8 W/cm²) and (b) sub-ns laser (1.0×10^9 W/cm²).

FIG. 2. Ion yield of each ion species produced by (a) ns laser (9.3×10^8 W/cm²) and (b) sub-ns laser (1×10^9 W/cm²).

With the similar laser power density of about 1×10^9 W/cm², the sub-ns laser produced the lower charge state distribution and longer plasma than that of the ns laser. These results indicate that the plasma temperature was lower with the sub-ns laser than that with the ns laser. This can be because the laser pulse width is too short to develop the ion charge states in the plasma. With the increased laser power density of the sub-ns laser, the similar charge state distribution and the ion pulse width were observed. The plasma production process could be the same between the sub-ns and ns lasers with the adjusted laser power density. However, the sub-ns laser produced more ions of the impurities. These impurities were originated from the surface contamination. The first peak of the FC signal consisted of H⁺. The ratio of the first and second peak of the FC signal should be a measure of the amount of impurities. The ratio of the first and second peak current was 2.7 and 5.4 for the increased sub-ns laser and ns laser experiment, respectively. This suggested that the laser energy was more absorbed by the surface contamination than the Zr target. The ns laser was more efficient to generate Zr ions. The laser irradiation conditions are summarized in Table I.

TABLE I. Laser irradiation condition used in the experiments.

Name	Power density (W/cm ²)	Laser Energy (J)	Pulse width (ns)	Spot size in diameter (mm)
ns laser	9.3E8	1.01	6.0	4.8
sub-ns laser	1.0E9	0.10	0.57	4.6
sub-ns laser (increased power density)	3.0E9	0.28	0.57	4.6

IV. CONCLUSION

The laser ablation plasma of Zr generated by a sub-ns laser and ns laser was experimentally compared to see the difference of the laser pulse width for low charge state ion production. The results showed that with the same laser power density at about 1×10^9 W/cm² the sub-ns laser produced the lower charge state distribution and longer plasma than that of the ns laser. By increasing the laser power density of the sub-ns laser, the similar charge state distribution was obtained though more impurities were observed. For low charge state ion production, a ns laser can generate target ions more efficiently than a sub-ns laser.

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FIG. 3. Charge state distribution and ion yield produced by sub-ns laser with increased laser power density (3.0×10^9 W/cm²).

- ¹K. Kondo, T. Kanesue, J. Tamura, and M. Okamura, Rev. Sci. Instrum. 81, 02A511 (2010).
- ²K. Takahashi, M. Okamura, M. Sekine, E. Cushing, and P. Jandovitz, AIP Conference Proceedings 1525, 241 (2013).
- ³T. Kanesue, M. Okamura, J. Alessi, E. Beebe, A. Pikin, D. Raparia, C.J. Liaw, R. Lambiase, V. LoDestro, M. Costanzo, R. Lehn, L. DeSanto, R. Olsen, A. Steszyn, Proceedings of IPAC2014, Dresden, Germany 15-20 June, 2014, p.1890.
- ⁴B. Sharkov, and R. Scrivens, IEEE Transactions on plasma science, Vol. 33, No. 6, December 2005, p.1778.
- ⁵M. Okamura, T. Takeuchi, R. A. Jameson, S. Kondrashev, H. Kashiwagi, K. Sakakibara, T. Kanesue, J. Tamura, and T. Hattori, Rev. Sci. Instrum. 79, 02B314 (2008).
- ⁶J. Badziak, P. Parys, A. B. Vankov, J. Wolowski, and E. Woryna, Appl. Phys. Lett. 79, 21 (2001).
- ⁷M. Kumaki, S. Ikeda, Y. Fuwa, D. Cinquegrani, M. Sekine, N. Munemoto, T. Kanesue, M. Okamura, and M. Washio, Rev. Sci. Instrum. 85, 02B925 (2014).