BNL-112221-2016-CP

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Presented at the 16th International Conference on Ion Sources
New York Marriott Marquis Hotel, New York, NY
August 23 – 28, 2015

May 2016

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

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Iron Plasma Generation using a Nd:YAG Laser Pulse of Several Hundred Picoseconds[a)]

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(Dated: 23 August 2015)

We investigated the high intensity plasma generated by using a Nd:YAG laser to apply a laser-produced plasma to the direct plasma injection scheme. The capability of the source to generate high charge state ions strongly depends on the power density of the laser irradiation. Therefore, we focused on using a higher power laser with several hundred picoseconds of pulse width. The iron target was irradiated with the pulsed laser, and the ion current of the laser-produced iron plasma was measured using a Faraday cup and the charge state distribution was investigated using an electrostatic ion analyzer. We found that higher charge state iron ions (up to Fe^{21+}) were obtained using a laser pulse of several hundred picoseconds in comparison to those obtained using a laser pulse of several nanoseconds (up to Fe^{19+}). We also found that when the laser irradiation area was relatively large, the laser power was absorbed mainly by the contamination on the target surface.

I. INTRODUCTION

We have studied high intensity heavy ion beams generated by the direct plasma injection scheme (DPIS).[1] In the DPIS, high intensity plasma, which is produced by irradiating a solid target with a pulsed laser, is directly injected into a radio frequency quadrupole (RFQ) linac.[2] In 2011, the DPIS was applied to an iron plasma and approximately 10 mA of iron beams were accelerated by the RFQ linac. At that time, the most abundant charge state among the laser-produced iron plasma was Fe^{13+} and the highest charge state was Fe^{19+}.[3] For ion generation, we used a Nd:YAG laser (Thales SAGA230) with an energy and pulse width of 1.5 J and 6 ns, respectively. The focal length of the final focusing lens was 100 mm which gave around 10^{12} W/cm^2 on the iron target surface. Iron plasma production using this Nd:YAG laser has been well established.[4]

Considering the beam acceleration efficiency of the following accelerating structure, it is desirable to generate high charge states in the ion source. In the laser ion source, the capability of generating higher charge state ions depends strongly on the power density of the laser irradiation. Therefore, we focused on using a higher power laser to generate an iron plasma comprising higher charge state ions. As a matter of course, laser properties such as pulse-to-pulse stability and an easy-to-use optical system are required for an accelerator application. We adopted a Nd:YAG laser (Ekspla SL334) for which the energy and pulse width were 400 mJ and 170 ps, respectively. We generated an iron plasma using the pulsed laser and investigated the charge state distribution of the plasma.

II. EXPERIMENTAL SETUP

The charge state distribution of the laser-produced iron plasma was examined with an electrostatic ion analyzer (EIA). The experimental setup for the plasma analysis is shown in Fig. 1. The pulsed laser was focused onto the iron plate target at 70° to the target surface. The spot size was adjusted by shifting the position of the plano-concave lens with 100-mm focal length. To provide a smooth target surface for the laser irradiation, the iron target was moved in a vertical direction to the analysis line shot-by-shot. The laser-produced iron plasma moved vertically to the target, and its charge state was analyzed with the EIA where positive and negative voltages were applied to the 90° bending electrodes. Ions were bent along a radius of curvature of 100 mm that was determined by the ion's charge-to-mass ratio and velocity in addition to the applied electrode voltages. The analyzed ions, i.e., only ions that passed through the gap between

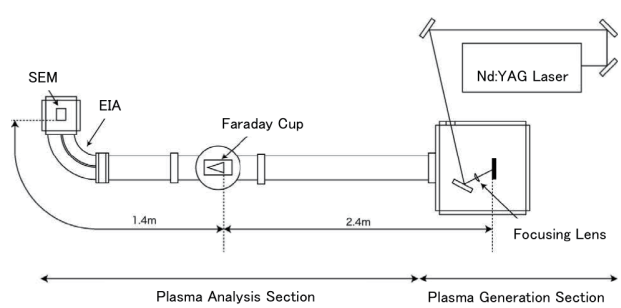

FIG. 1. Charge state analysis line.

[a)] Contributed paper published as part of the Proceedings of the 16th International Conference on Ion Sources, New York City, NY, August 2015.

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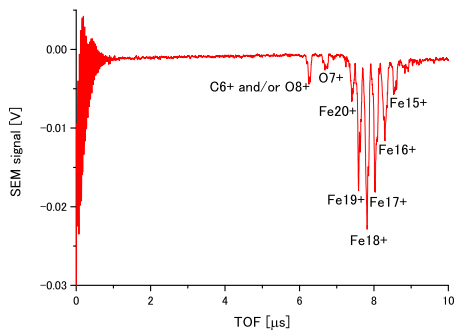

FIG. 2. Typical signal detected with a secondary electron multiplier.

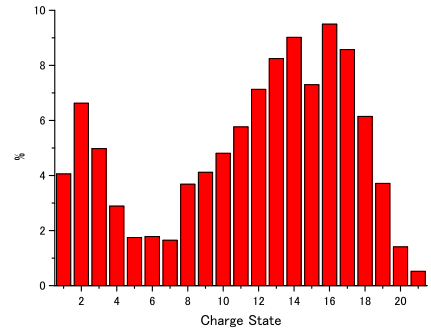

FIG. 3. Charge state distribution.

the two electrodes, reached the detector and produced an electrical signal. Therefore, it was possible to determine the charge state by observing the time-of-flight (TOF) of each signal peak. A typical waveform taken in this experiment is shown in Fig. 2. The small signal of the analyzed ions was amplified with a secondary electron multiplier (SEM) at the end of the electrodes. Subsequently, by scanning a certain range of applied voltages, the charge state distribution in a single plasma pulse was derived.

In addition to the charge state analysis, the ion current of the plasma pulse was measured with a Faraday cup at 2.4 m from the target. The plasma pulse was collimated by a 10-mm diameter hole, and the Faraday cup detected the collimated beam. The applied voltage to suppress the electron scattering from the Faraday cup was -3.5 kV.

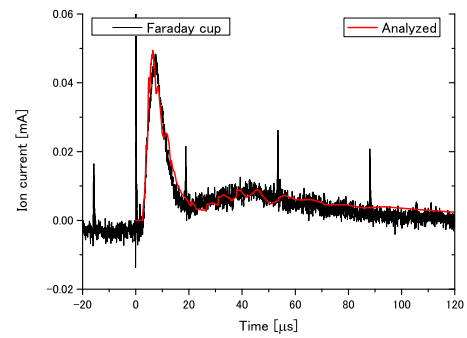

FIG. 4. (Color online). Ion current measured with the Faraday cup and pulse profile constructed using the charge state analysis.

III. RESULTS

A. Charge state distribution under focal point irradiation

To generate as high charge state as possible, we focused our attention on the rising time of the plasma pulse measured using the Faraday cup. Higher charge state ions have higher kinetic energies in plasma generated by laser ablation, as it has been experimentally obtained. Therefore, the charge state distribution was investigated at the position of the focusing lens where the earliest onset of the increasing plasma pulse occurred. The laser power density on the target with this lens position was estimated at a range of 10^{13} W/cm^2.

The highest charge state obtained using a laser pulse of several hundred picoseconds was Fe^{21+}, whereas it was Fe^{19+} when the laser pulse was of several nanoseconds. The integrated charge state distribution is shown in Fig. 3. The most abundant charge state is Fe^{16+}, whereas Fe^{13+} was the most abundant when the laser pulse was several nanoseconds. agreement with each other.

The total pulse profile was constructed by totalizing the pulse structures of each charge state. The pulse profile constructed by the charge state analysis along with the ion current measured with the Faraday cup is shown in Fig. 4. In this figure, the TOF of the configured pulse profile was normalized to that of the Faraday cup position (2.4 m/3.7 m). The height was also normalized to the peak ion current measured using the Faraday cup. Although the SEM signal amplification factors depending on ion's kinetic energy and charge state was not taken into account, these two pulses were in good

Notably, the intensity of the obtained laser plasma was lower than that with 1.5 J and 6 ns laser pulse, although the higher charge state was obtained. The intensity of the laser plasma was inversely proportional to the cube of the drift length. If the beam was extracted from the plasma shown in Fig. 3 at 30 cm from the target, the peak ion current would be 25 mA. This is nearly two orders of magnitude less than what was applied to the DPIS. Consequently, more studies focused on increasing the Intensity are needed.

B. Charge state distribution out of the focal point.

It was observed that the peak ion current measured with the Faraday cup increased when the target was out of the focal point of the focusing lens. Ion current measured with the Faraday cup with the focusing lens 10 mm from its focal position (closer to the target) is shown in Fig. 5. In this lens position, the spot size of the laser irradiation was estimated as 2 mm. Under this laser irradiation condition of spot size and laser power, it had

been considered that the pulse shape obtained by the second laser shot at the same position of the target did not differ greatly from that of the first shot. However, the pulse shape with the second shot was different as shown in Fig. 5. The peak ion current was reduced, and the

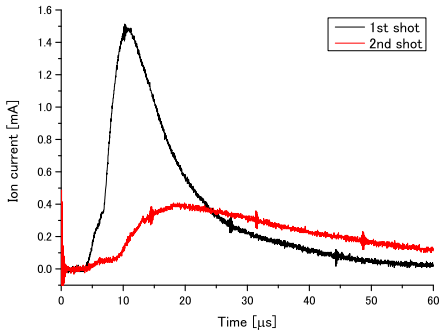

FIG. 5. (Color online). Pulse shape of the laser plasma at the first and second shot.

intensity at the rear section was higher. To investigate the cause of the pulse shape difference, the charge state distribution was examined. The pulse structure of each constitutive ion for the first and second laser shot are shown in Fig. 6 and Fig. 7, respectively. The main components of the plasma pulse generated by the first shot were contaminating ions, such as hydrogen, carbon, and oxygen, whereas the plasma pulse generated by the second shot mainly comprised iron ions. According to our interpretation, at the first shot, the laser energy was absorbed by the contamination on the target surface and these contaminations were removed by the laser irradiation. Then, at the second shot, the laser energy was absorbed by the iron target. In view of a paltry amount of contaminating ions in the laser plasma generated under the focal condition, we believe that the removal of the contamination on the target surface is more important for the target that was outside of the focal point.

IV. SUMMARY

An ion generation experiment was performed using a pulse laser to apply higher charge state ion beams for the DPIS, To generate higher charge state ions, we irradiated an iron target using a Nd:YAG laser pulse of several hundred picoseconds. We found that higher charge state iron ions (up to $Fe^{2}1+$) were obtained using a laser pulse of several picoseconds in comparison to those obtained using a laser pulse of several nanoseconds (up to Fe^{+19+}). By irradiating the same spot and analyzing the produced plasmas (1st and 2nd), we determined that when the laser irradiation area was relatively large, the laser power was absorbed mainly by the contamination on the target surface. We believe that the removal of the contamination on the target surface is more important for targets outside of the focal point.

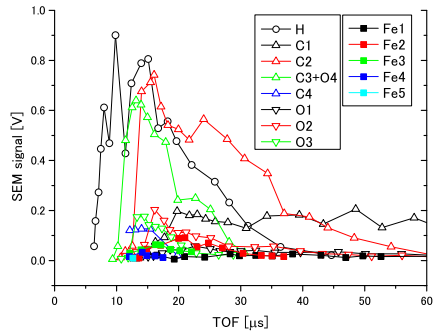

FIG. 6. (Color online). Constitutive ions of the laser plasma at the first shot.

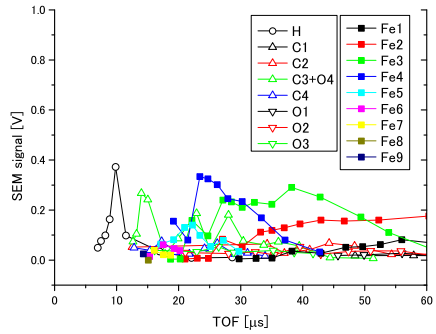

FIG. 7. (Color online). Constitutive ions of the laser plasma at the second shot.

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