MEASUREMENT OF BEAM CHARACTERISTICS FROM C^{6+} LASER ION SOURCE

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Abstract

A C^{6+} laser ion source has been developed for a heavy ion accelerator. A graphite target is irradiated with a Q-switched Nd:YAG laser (1064nm of wavelength, 1.4J of maximum laser energy, 10ns of pulse duration) to generate carbon ions. The characteristics of the ion beam from the laser ion source were studied using the time-of-flight method, and the accelerated ions by Tokyo Institude of Technology (Tokyo Tech) RFQ linac were measured. Results of the experiments are presented.

INTRODUCTION

Highly charged ion sources have been developed for nuclear physics, heavy-ion fusion, and heavy-ion cancer therapy [1]. A laser ion source is effective for these ion sources because it can produce a highly charged, high-intensity heavy ion beam with a simple operation. In general, the ion beam is transported and accelerated by a radio-frequency quadrupole (RFQ) linac. However, it is difficult to transport a high-intensity heavy ion beam to the RFQ because of its strong space charge effect. To overcome this problem, a direct plasma injection scheme has been developed for accelerating a high-intensity heavy ion beam [2–5]. We have previously employed this scheme in developing a compact, highly charged C^{6+} ion source and reported some fundamental experiments [6]. In that study, we examined the characteristics of the C^{6+} ion beam accelerated by just an extracting electrode, that is to say, without using an RFQ linac.

The ion beam from this ion source consisted of carbon ions in every charge state. The ratio and number of extracted C^{6+} ions are important factors in providing a high-intensity C^{6+} ion beam. It is possible to evaluate the number of ion groups from the time-of-flight (TOF) spectrum [7,8]. We applied the TOF method to study the ratio of carbon ions from single-shot laser irradiation and estimated the C^{6+} ion count from the laser ion source.

In addition, acceleration experiments of the generated C^{6+} ions were conducted using the Tokyo Tech RFQ linac. We measured the transmission of the C^{6+} ions, one of the important parameters of ion sources, and the emittance of the C^{6+} ions. We modified the laser ion source to adapt it for the Tokyo Tech RFQ linac and conducted acceleration experiments.

CHARACTERISTICS OF C^{6+} BEAM FROM LASER ION SOURCE

Experimental setup

Figure 1 shows the experimental setup. A Q-switched Nd:YAG laser was used to create a plasma. The wavelength was 1064 nm, the maximum laser energy was 1.4 J, and the pulse duration was 10 ns full-width at half-maximum (FWHM). The laser beam entered a vacuum chamber through an antireflection-coated BK7 window and was focused onto a graphite target by a convex lens with a focal length of 150 mm. The graphite target was in a box that had a hole allowing the laser beam to pass through. A high-density plasma containing carbon ions was produced by laser irradiation and was guided through a nozzle to an acceleration electrode at a distance of 0.2 m from the graphite target. An electrostatic potential barrier electrode was employed to eliminate unnecessary plasma and other charged particles [6]. It was set up in the middle of the nozzle and was charged with a positive voltage compared to the extracting voltage. The carbon ions were accelerated by a high electric field between the nozzle and the extracting electrode at a maximum extracting voltage of 40 kV. The nozzle and the extracting electrode had holes 6 mm in diameter at the centre for the beam to pass through. TOF mass spectroscopy was used to evaluate the accelerated C^{6+} ions. An ion collector was placed at distances of 1.0 m, 1.5 m, and 2.5 m from the graphite target.

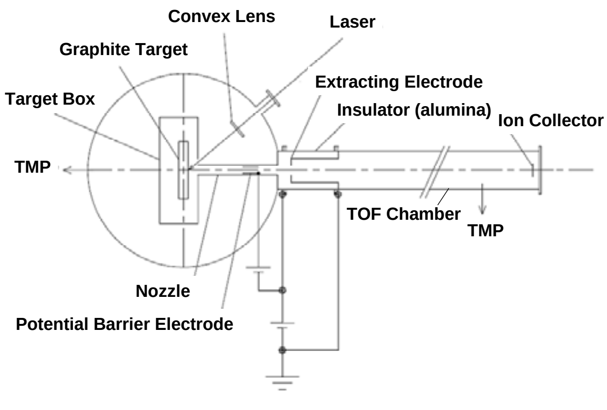

Figure 1: Experimental setup.

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Results

Figure 2 shows the single-shot TOF spectrum with the potential barrier electrode. The laser energy was 1.4 J, the distance from the graphite target to the ion collector was 2.5 m, and the extracting voltage was 20 kV, which was close to the injection energy for the Tokyo Tech RFQ linac. The first peak was identified as the C^{6+} peak [8]. From time-integration of the C^{6+} current and the current of all charged states, the ratio of C^{6+} current to the total current was 20%.

The dependence of the C^{6+} ratio on the distance from the graphite target is shown in Fig. 3. Here, the laser energy was 1.4 J, and the extracting voltage was 20 kV. The C^{6+} ratio was constant at about 20%.

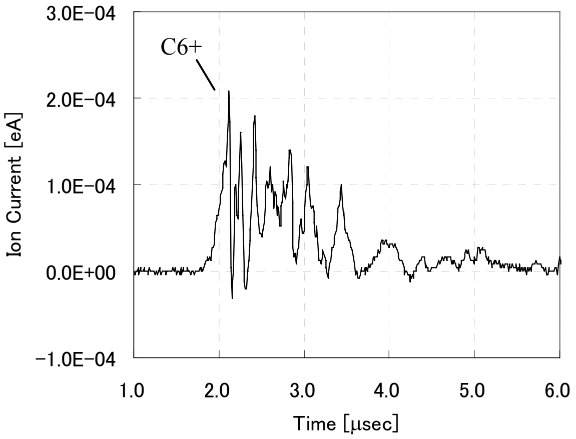

Figure 2: Single-shot TOF spectrum with potential barrier electrode. Laser energy 1.4 J, target to ion collector distance 2.5 m, and extracting voltage 20 kV.

Figure 4 shows the single-shot total current with the ion collector plate placed at the position of the acceleration electrode. The distance from the end of the nozzle to the ion collector was 10 mm, and the extracting voltage was 20 kV.

To estimate the count of C^{6+} ions at the extracting electrode, the time-integration of the measured current from 0.5 μsec to 2.0 μsec in Fig. 5 was estimated to be 9.7×10^{-8} A·sec. Using a C^{6+} ratio of 20% and a charge number of 6, we obtained a C^{6+} count of 2.0×10^{10} counts per shot, as follows:

$$N_{C^{6+}} = 9.7 \times 10^{-8} \times 0.2 / 6 / (1.602 \times 10^{-19}).$$

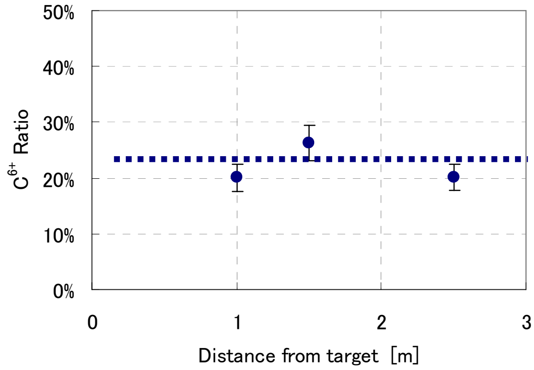

Figure 3: Dependence of C^{6+} ratio on distance from target. Laser energy 1.4 J, and extracting voltage 20 kV.

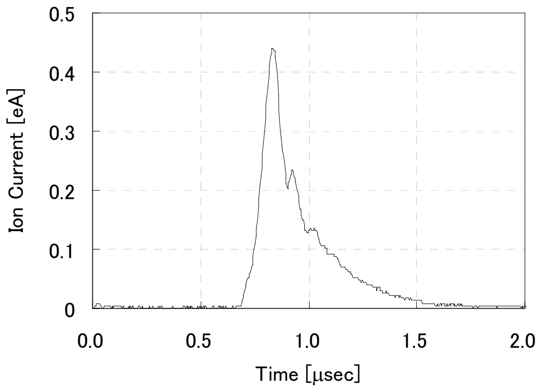

Figure 4: Single-shot current at acceleration electrode. Target to acceleration electrode distance 10 mm, and accelerating voltage 20 kV.

C^{6+} BEAM ACCELARATION EXPERIMENT

C^{6+} acceleration experiments were conducted using the Tokyo Tech RFQ linac. A photograph of the experimental set-up is shown in Fig. 6. Since the laser ion source and the RFQ linac had to be combined directly, the laser ion source was modified by making chamber compact to allow it to be placed on the HV stage. The distance from the carbon target to the RFQ linac was 370 mm. In this experiment, the laser ion source used a convex lens with a focal length of 200 mm and did not use the potential barrier electrode. The main parameters of the Tokyo Tech RFQ linac are given in Table 1.

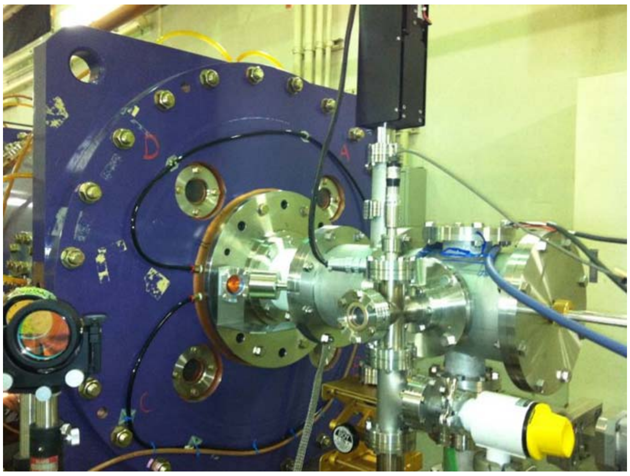

Figure 5: Photograph of the Tokyo Tech RFQ linac and the modified laser ion source.

Table 1: Main parameters of the Tokyo Tech RFQ (design values).

Charge to mass ratio	≥16
Operating Frequency (MHz)	80
Input energy (keV/amu)	5
Output energy (keV/amu)	214
Normalized emittance (100%) cm mrad	0.05π
Vane Length (cm)	422
Total number of cells	273
Characteristic bore radius, r_0 (cm)	0.466
Synchronous phase (degree)	-90 to -20
Intervane voltage (kV)	78.9
Maximum field (Kilpatrick)	2.2
Calculated Q value	20000
Wall loss (kW)	89
Shunt impedance (MΩ/m)	29.5
Transmission (mA) for q/A=1/16 beam, 10 mA input	6.84

The accelerated beam current was measured using Faraday cups. The Faraday cup just after the RFQ linac was applied to measure the total current of the accelerated beam. To identify each charge state, we used an analyzing dipole magnet after the RFQ linac, and the Faraday cup with a beam slit.

Figure 6 shows the total current signal at an injection energy of 12 kV to the RFQ linac. The first peak current was 5.5 mA. It consisted of accelerated carbon ions including at least C^{6+}, C^{5+}, and C^{4+} ions. An example of the analyzed C^{6+} signal is shown in Fig. 7. We confirmed that the C^{6+} ions were accelerated by the Tokyo Tech RFQ linac.

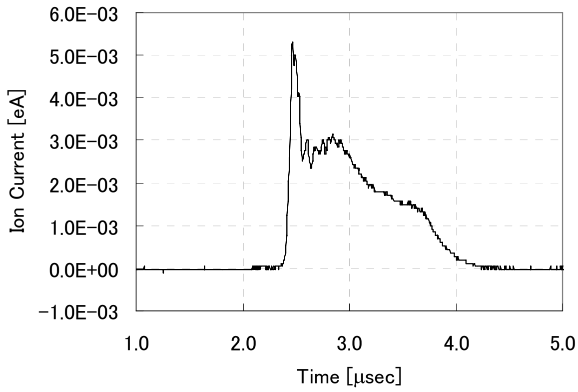

Figure 6: Accelerated carbon ion beam signal by the Faraday cup.

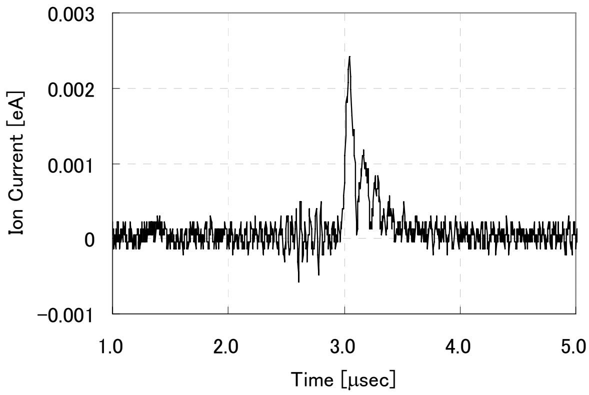

Figure 7: Analyzed C^{6+} signal by the Faraday cup after the dipole magnet.

CONCLUSION

The C^{6+} ratio and the C^{6+} count from the laser ion source were estimated by the TOF method. Using a potential barrier electrode, the C^{6+} ratio of the total current was about 20% at an extracting voltage of 20 kV. From the total current at the position of the acceleration electrode, we obtained a C^{6+} count of 2.0×10^{10} counts per shot.

We studied the characteristics of the generated ion beam when accelerated by the Tokyo Tech RFQ linac. The peak of the accelerated ion beam was 5.5 mA. From analysis of the dipole magnet, it was confirmed that the C^{6+} ions were accelerated. We are planning additional acceleration experiments in the future to examine the effect of the potential barrier electrode, the C^{6+} counts dependence of the focal length of the convex lens, and the injection energy to the RFQ linac.

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