# DEVELOPMENT OF CARBON 6+ LASER ION SOURCE

A. Yamaguchi, K. Hayashi, A. Osanai, K. Hashimoto, K. Sato
Toshiba Corporation, 2-4, Suehiro-cho, Tsurumi-ku, Yokohama 230-0045, Japan

*Abstract*

We developed a laser ion source for supplying a high-intensity carbon 6+ ion beam. A graphite target was irradiated by a Q-switched Nd:YAG laser (wavelength 1064 nm, maximum laser energy 1.4 J, pulse duration 10 ns). The characteristics of the ion beam were studied by time-of-flight mass spectroscopy and magnetic momentum analysis. Experimental results 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. For acceleration of a high-intensity heavy ion beam, a direct plasma injection scheme has been developed [2-5]. We applied this scheme in developing a carbon 6+ ($C^{6+}$) ion source as a compact highly charged ion source. The characteristics of the $C^{6+}$ ion beam accelerated by an acceleration electrode were studied.

The ion beam from this ion source consisted of carbon ions in every charge state. The ratio and number of accelerated $C^{6+}$ 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 of the ions [6-7]. An advantage of TOF mass spectroscopy is its ability to identify all charged ions at once from single-shot laser irradiation, if the ion current and peak separation are sufficiently high. We applied TOF mass spectroscopy to study the ratio of carbon ions from single-shot laser irradiation. Additionally, we used magnetic momentum analysis to confirm the ratio from TOF mass spectroscopy, and we estimated the accelerated $C^{6+}$ ion count.

## EXPERIMENTAL SETUP

Figure 1 shows the experimental setup. A Q-switched Nd:YAG laser was used to generate a laser-created plasma. The wavelength was 1064 nm, and the maximum laser energy was 1.4 J. 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. 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. The carbon ions were accelerated by a high electric field between the nozzle and the acceleration electrode at a maximum voltage of 40 kV. The nozzle and the acceleration electrode had holes 6 mm in diameter at the centre for the beam to pass through.

e-mail:aki.yamag@toshiba.co.jp

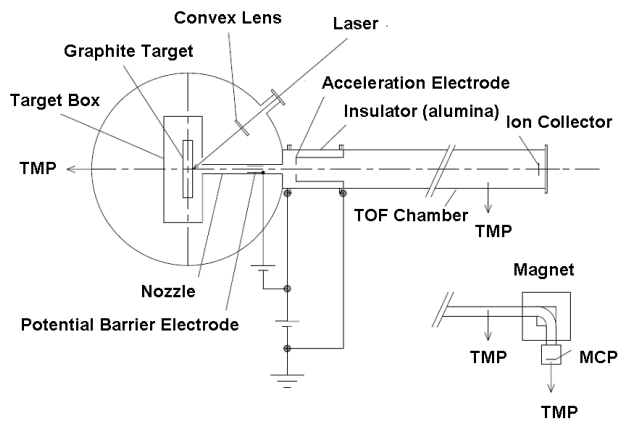


Figure 1: Experimental setup.

Two ion measurement methods were used to evaluate the accelerated $C^{6+}$ ions.

One was TOF mass spectroscopy. An ion collector was placed at distances of 1.0 m, 1.5 m, and 2.5 m from the graphite target. The TOF setup is shown in Fig. 2.

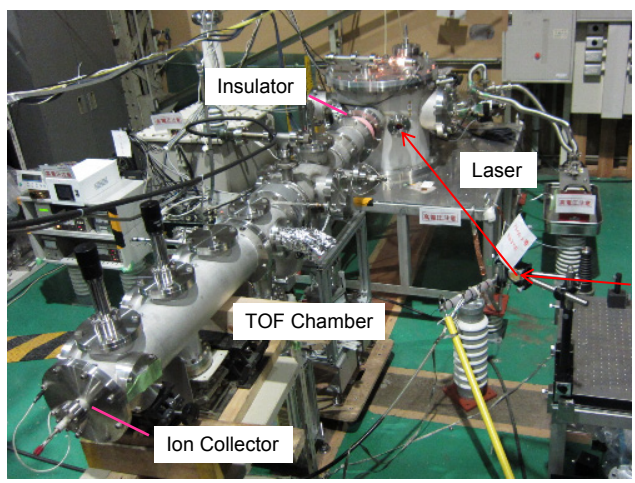


Figure 2: Photograph of the TOF setup.

The other was magnetic momentum analysis with a setup consisting of a bending magnet and a Micro Channel Plate (MCP; Hamamatsu Photonics F2221). The

gap size of the bending magnet was 20 mm, and the bending angle was 90 degree. The ions were detected by the MCP at a distance of 2.2 m from the graphite target.

## RESULTS AND DISCUSSION

Figure 3 shows the single-shot TOF spectrum without 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 accelerating voltage was 30 kV. The charged ion peaks, especially for low-charge ions, were not clear. Fig. 4 shows the single-shot TOF spectrum with the potential barrier electrode; the spectrum contains several peaks. The potential barrier was useful to eliminate plasma and charged particles other than the carbon ions.

We identified the peaks for each charge state using the results of the magnetic momentum analysis. The peak position and the momentum distribution of each charged ion were predicted from the results of magnetic momentum analysis. As a result, all charged carbon ions were observed in the single-shot TOF spectrum. From time-integration of the $C^{6+}$ current and the current of all charged states, the $C^{6+}$ ratio of the total current was 17%.

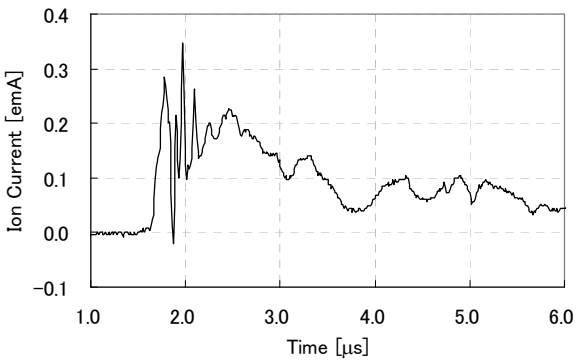


Figure 3: Single-shot TOF spectrum at without potential barrier electrode. Laser energy 1.4 J, target to ion collector distance 2.5 m, and accelerating voltage 30 kV.

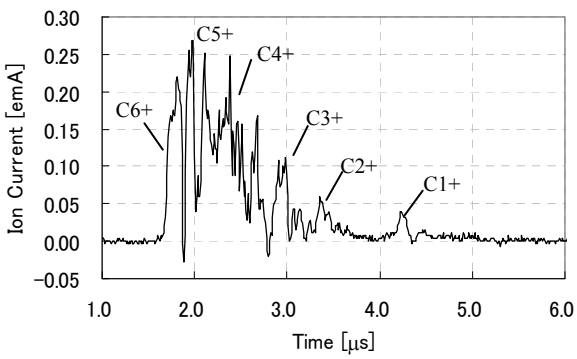


Figure 4: Single-shot TOF spectrum with potential barrier electrode. Laser energy 1.4 J, target to ion collector distance 2.5 m, and accelerating voltage 30 kV.

The integrated current ratios of each charge state obtained from the TOF spectrum and the magnetic momentum analysis are shown in Fig. 5. The laser energy was 1.4 J, the distance from the target to the ion collector was 2.5 m (the distance to the MCP was 2.2 m), and the accelerating voltage was 30 kV. The ratio of each charge state of the TOF spectrum was almost the same as in the magnetic analysis.

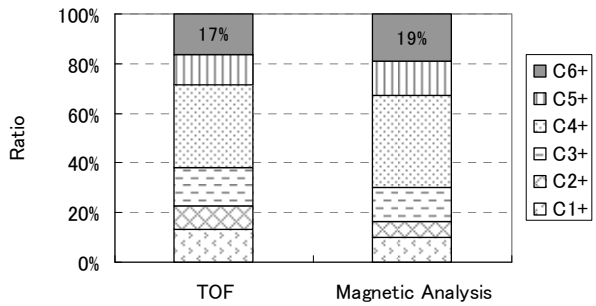


Figure 5: Ratio of each charge state. Laser energy 1.4 J, target to ion collector distance 2.5 m (target to MCP distance 2.2 m), and accelerating voltage 30 kV.

Figure 6 shows the dependence of the $C^{6+}$ ratio on the laser energy. Here, the distance from the graphite target to the ion collector was 2.5 m, and the accelerating voltage was 30 kV. The $C^{6+}$ ratio didn't extremely decrease as the laser energy was decreased. The $C^{6+}$ ratio at a laser energy of 0.2J was more than 10%.

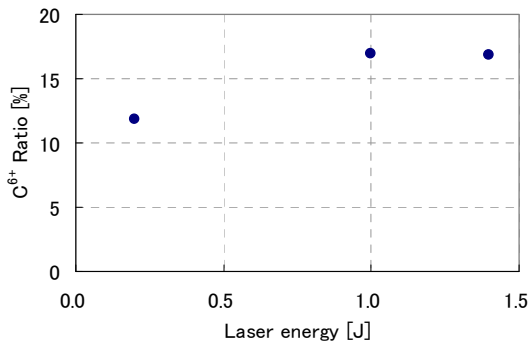


Figure 6: Dependence of $C^{6+}$ ratio on laser energy. Target to ion collector distance 2.5 m, and accelerating voltage 30 kV.

The dependence of the $C^{6+}$ ratio on the distance from the graphite target is shown in Fig. 7. Here, the laser energy was 1.4 J and the accelerating voltage was 30 kV. The $C^{6+}$ ratio didn't extremely decrease as the distance from the graphite target was increased. The $C^{6+}$ ratio at distance of 1.0m was about 20%.

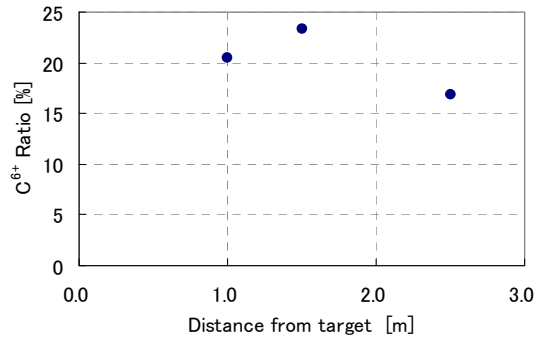


Figure 7: Dependence of $C^{6+}$ ratio on distance from target. Laser energy 1.4 J, and accelerating voltage 30 kV.

Figure 8 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 accelerating voltage was 30 kV.

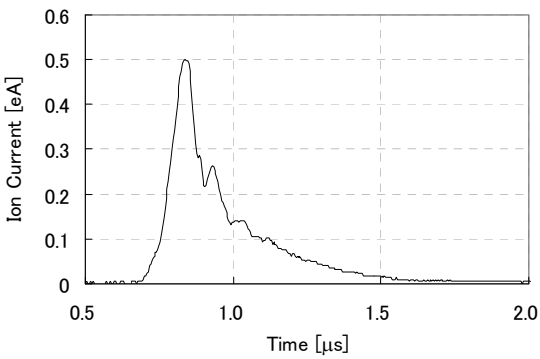


Figure 8: Single-shot current at acceleration electrode. Target to acceleration electrode distance was 10 mm, and accelerating voltage was 30 kV.

To estimate the count of $C^{6+}$ ions at the accelerating electrode, the time-integration of the measured current from 0.5 μs to 2.0 μs in Fig. 8 was estimated to be $1.0 \times 10^{-7}$ A·sec. Using a $C^{6+}$ ratio of 20% and a charge number of 6, we obtained a $C^{6+}$ count of $2.2 \times 10^{10}$ counts per shot as follows:

$$N_{C^{6+}} = 1.0 \times 10^{-7} \times 0.2 / 6 / (1.602 \times 10^{-19}).$$

## CONCLUSION

We examined the $C^{6+}$ ratio from single-shot laser irradiation using TOF mass spectroscopy, and we estimated the accelerated $C^{6+}$ ion count. Using a potential barrier electrode, the results of magnetic momentum analysis showed that all charged carbon ions were observed in the single-shot TOF spectrum, and the $C^{6+}$ ratio of the total current was around 20%. The $C^{6+}$ ratio of the total current was almost constant at laser energies of 1.0 J and greater and at distances from the graphite target of 1.5 m and less. From the single-shot total current at the position of the acceleration electrode, we obtained a $C^{6+}$ count of $2.2 \times 10^{10}$ counts per shot.

## REFERENCES

[1] B. Yu. Sharkov, A. V. Shumshurov, V. P. Dubenkow, O. B. Shamaev, and A. A. Golubev, Rev. Sci. Instrum. 63, 2841 (1992).
[2] M. Okamura, T. Katayama, R. A. Jameson, T. Takeuchi, and T. Hattori, Rev. Sci. Instrum. 73, 761 (2002).
[3] T. Takeuchi, T. Katayama, M. Okamura, K. Yano, A. Sakumi, T. Hattori, and R. A. Jameson, Rev. Sci. Instrum. 73, 764 (2002).
[4] T. Takeuchi, T. Katayama, T. Nakagawa, M. Okamura, K. Yano, A. Sakumi, S. Ozawa, S. Kondrashev, N. Mescheryakov, and B. Sharkov, Rev. Sci. Instrum. 73, 767 (2002).
[5] H. Kashiwagi, T. Hattori, N. Hayashizaki, K. Yamamoto, Y. Takahashi, T. Hata, M. Okamura, R. A. Jameson, T. Katayama, and N. Mescheryakov, Rev. Sci. Instrum. 75, 1569 (2004).
[6] A. W. Ehler, J. Appl. Phys. 96, 2961 (1975).
[7] J Krása, K Jungwirth, E Krousk, L Láska, K Rohlena, M Pfeifer, J Ullschmied, and A Velyhan, Plasma Phys. Control. Fusion 49, 1649 (2007).