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Extraction of ion beam from laser ion source for direct plasma injection scheme

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Abstract. Laser ion sources are expected to be used in various applications of heavy ion beam technology. The plasma direct injection scheme (DPIS) is a method in which ion beams extracted from a laser ion source are directly injected into a radio frequency quadrupole (RFQ) linear accelerator. In this study, a new shape of the plasma electrode with a concave surface for the DPIS was proposed to inject a converging beam to a cavity of RFQ accelerator. This approach allows the use of a large-diameter extraction electrode, which is not limited by the aperture of the RFQ electrode rods. The DPIS, using the concave surface electrode, was employed to accelerate C^{6+} ion beams. The results indicated that both the beam current and the number of ions increased nearly twice with the proposed electrode shape compared to values obtained with the conventional electrode. This enhancement corresponded to the increased extraction area of the beam.

1. Introduction

A laser ion source provides an ion beam from the plasma generated by irradiating the target with a laser and is expected as an ion source that can supply a large current ion beam compared to conventional ion sources employing gas discharge. It has been used to supply the ions of metal species required for high energy physics, and to evaluate the biological effects of space radiation [1]. It has also been studied for developing a carbon ion source to use for particle beam therapy [2], and a lithium-ion driver for an accelerator-driven neutron source [3-5].

Thus, laser ion sources are expected to be used in various applications of heavy ion beam technology. The plasma direct injection scheme (DPIS) is a method for accelerating high-current ion beams by directly injecting ions extracted from a laser ion source into a radio frequency quadrupole (RFQ) linear accelerator [6-10]. Traditionally, the edge of electrode for beam extraction is positioned as close to the RFQ rods as possible to avoid beam loss due to space charge effects. For this reason, the diameter of beam extraction is limited by the aperture of the subsequent RFQ. To overcome this limitation and accelerate a higher current beam, a new shape of the electrode with a concave surface was suggested to inject a converging beam into the cavity of the RFQ accelerator. This approach enables the use of an extraction electrode hole larger than the aperture of the RFQ electrode rods. We investigated the effect of the proposed electrode and compared the ion beam current extracted from the new and conventional nozzles.

2. Experimental setup

Figure 1 shows the schematic of experimental setup. In this experiment, a carbon target was used, and plasmas were generated at a pressure of 1×10^{-4} Pa. A Nd: YAG laser with a wavelength of 1064 nm, a pulse width of 6 ns, and an energy output of 978 mJ was used. The laser was focused on the target using a lens with a focal distance of 100 mm achieving a power density of the order of 10^{11} W/cm² on the target.



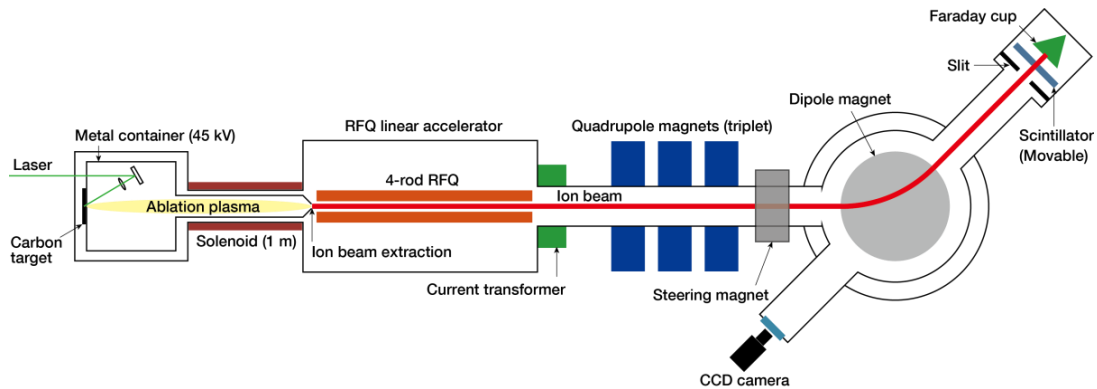


Figure 1. Schematic of experimental setup.

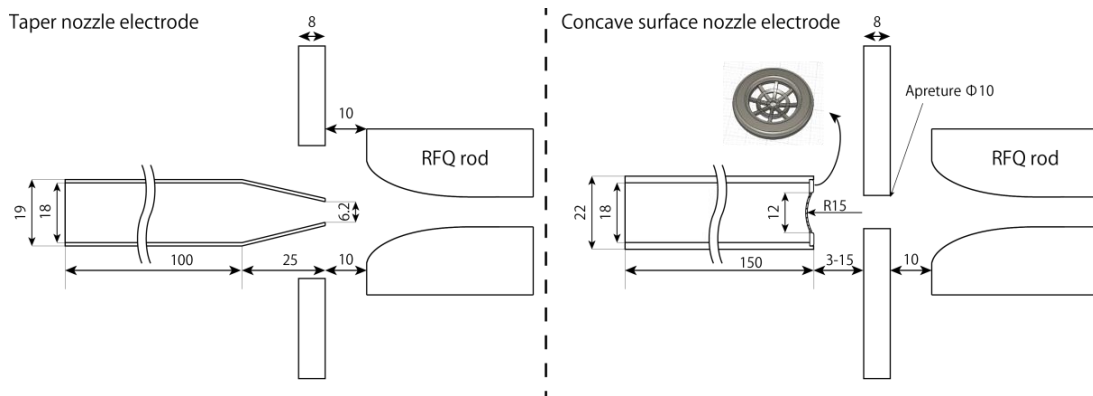


Figure 2. Conventional taper nozzle electrode (left) and proposed concave surface nozzle electrode (right) for the ion beam extraction from a plasma.

The generated plasmas were transported in a 1 m pipe with a solenoid coil. The solenoid coil can generate a magnetic field with the magnetic flux density of 105 mT. Ion beams were extracted from the plasmas with the voltage of 45 kV at extraction electrode located in the front of RFQ linear accelerator. The extracted C^{6+} ion beam was accelerated by the RFQ linear accelerator to an energy of 204 keV/u. A current transformer (CT) measured the beam current at the exit of the RFQ linear accelerator. The accelerated beam may contain impurity in addition with C^{6+} ions. Therefore, only C^{6+} ions were selected with a dipole magnet. The position and beam size of the selected C^{6+} ions were investigated using a scintillator and a CCD camera, and the beam position was controlled by triplet quadrupole magnets located between the exit of RFQ accelerator and the dipole magnet. In addition, a steering magnet located after the triplet magnet was used for the fine adjustment of the beam position. The ion beam current was measured using a Faraday cup which has an aperture with a repelling voltage of -1 kV.

Figure 2 shows the designs of electrodes used for ion beam extraction from plasmas. The left figure shows the design of the conventional taper nozzle electrode and the right figure illustrates the newly proposed concave surface electrode nozzle. Both nozzles have pipes with an inner diameter of 18 mm. The concave surface nozzle has a curvature of 15 mm and stems with a thickness of 0.8 mm. The extraction beam diameters are 6.2 mm and 12 mm, and the areas of nozzles are 30 mm² and 65 mm² for the taper nozzle and the concave surface nozzle, respectively. In the case of using the concave surface nozzle, a grounded aperture was inserted between the nozzle and RFQ electrode rods. The

structure can allow us to extract ion beams without being affected by the RF voltage applied for the RFQ linear accelerator. The nozzle was adjustable in the longitudinal position, and the gap distance between the nozzle surface and the aperture was changed to find the position for maximizing the beam current accelerated with the RFQ linear accelerator.

3. Results and discussion

Figure 3 indicates ion current waveforms obtained with the taper nozzle electrode and the concave surface nozzle electrode. Each ion current waveform was obtained by averaging 10 waveforms. Ion currents with both extraction electrodes were enhanced by applying the solenoid magnetic field. The magnetic field was varied from 0 mT to 105 mT for the taper nozzle and from 0 mT to 95 mT for the concave surface nozzle. For both cases, the magnetic flux density of 79 mT maximized the peak of current waveforms. By comparing the peaks in the current waveforms, the ion current obtained with the concave surface nozzle was almost twice as large as that obtained by using the taper nozzle.

Figure 4 shows the ion current waveforms obtained with different gap distances between the nozzle surface and the grounded aperture. The gap was varied from 3 mm to 15 mm, and the peak of current waveform was maximized at the distance of 5 mm.

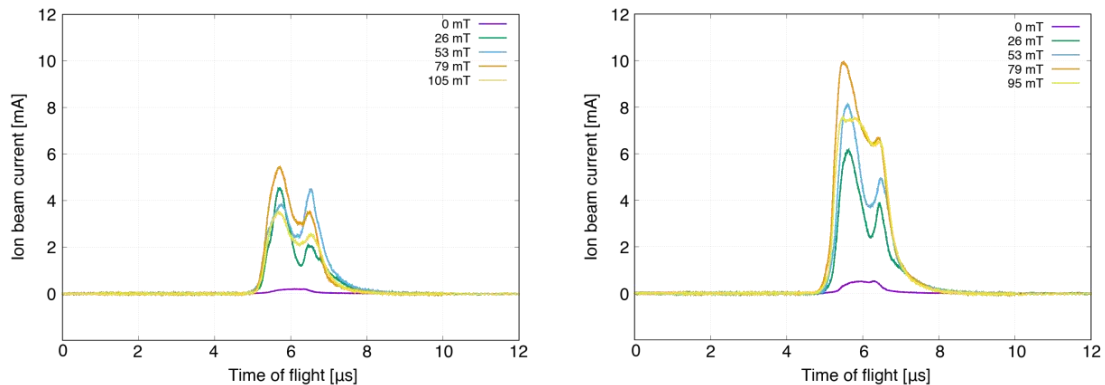


Figure 3. Ion beam current waveforms of C^{6+} obtained using (left) the taper nozzle electrode and (right) the concave surface nozzle electrode with solenoid magnetic field. The surface of the concave surface nozzle was located at 5 mm from the grounded aperture.

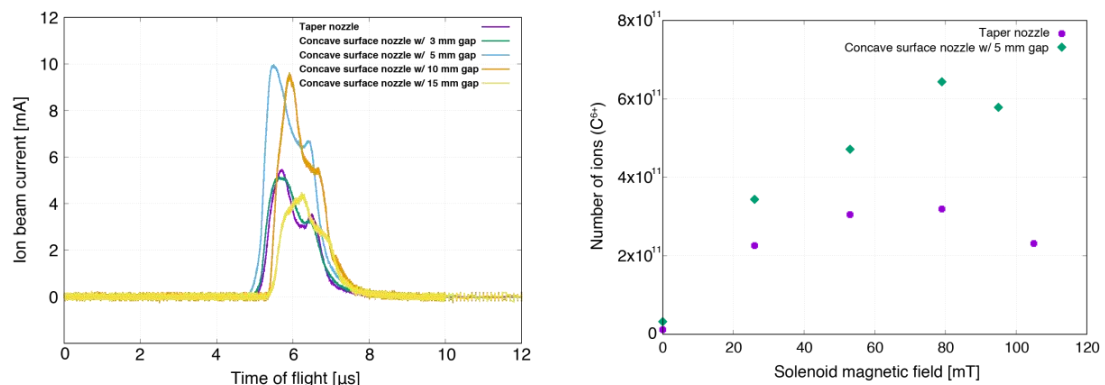


Figure 4. Ion beam current waveforms obtained with various gap distances between the nozzle surface and the grounded aperture.

Figure 5. Variation of the number of C^{6+} ions as a function of solenoid magnetic field. The points for concave surface nozzle were obtained under the condition of the gap distance of 5 mm.

Furthermore, the number of ions obtained with the concave surface nozzle under the optimal condition to obtain the highest current, that is a gap distance of 5 mm, was compared to that obtained with the taper nozzle. Figure 5 shows the variation of the number of C^{6+} ions obtained by integrating ion current waveform. This result indicates that the number of ions obtained with the concave surface nozzle was nearly twice as large as that obtained with the taper nozzle as derived in the peak current. This is reasonable because the transmission area in the concave surface nozzle is almost twice as large as that of the taper nozzle.

4. Conclusion

In this study, a new ion injection method from a laser ion source was investigated to obtain larger beam current than that using the conventional plasma electrode. The method employs a concave surface nozzle as the beam extraction electrode instead of a conventional taper nozzle. The results indicated that the proposed electrode allows for the extraction of a larger ion beam current compared to the conventional electrode. In addition, the demonstrated ion number increased in proportion to the extraction area. In the future, the matching between the phase space of injected ion beams and the acceptance of the RFQ linear accelerator will be investigated to understand the way to increase accelerated beam current furthermore.

Acknowledgments

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