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Drift distance survey in DPIS for high current beam production

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In a laser ion source, plasma drift distance is one of the most important design parameters. Ion current density and beam pulse width are defined by plasma drift distance between laser target and beam extraction position. In direct plasma injection scheme (DPIS), which uses a laser ion source and Radio Frequency Quadrupole (RFQ) linac, we can apply relatively higher electric field at the beam extraction due to the unique shape of a positively biased electrode. However, when we aim at very high current acceleration like several tens of mA, we observed mismatched beam extraction conditions. We tested three different ion current at ion extraction region by changing plasma drift distance to study better extraction condition. In this experiment, C^{6+} beam was accelerated. We confirmed that the matching condition can be improved by controlling plasma drift distance.

I. INTRODUCTION

Direct Plasma Injection Scheme (DPIS) is a method to produce and accelerate a high current, highly charged heavy ion beam using a laser ion source and Radio Frequency Quadrupole linear accelerator (RFQ linac). The laser ion source can produce plasma, which contains highly charged, heavy ions from any species of solid state target. Since ions are generated from a solid state target, initial ion density is much higher than gas-based ion sources. The feature of RFQ linac is that it has strong focusing force in a low energy region. In DPIS, a laser ion source is directly attached to RFQ linac and ions are extracted just at the entrance of RFQ linac. After extraction, ions are immediately captured by the RF focusing field. So intense heavy ion beam can be captured and accelerated efficiently. Up to now, 38 mA of C^{4+} beam[1] and 17 mA of C^{6+} beam[2] using a CO_2 laser and a Neodymium-doped yttrium aluminum garget (Nd:YAG) laser, respectively, were accelerated using DPIS. However, it is indicated by a simulation study that injection efficiency decreases when ion current density at the ion extraction region is extremely high.[3] We studied the relations between ion current at the ion extraction region and accelerated beam current using C^{6+} beam.

A. Laser ion source

A laser ion source uses a pulsed high power laser and a solid state target. Laser light is focused onto the solid state target by a convex lens. The target surface is heated, evaporated and ionized. The produced plasma has initial velocity towards the normal direction of the target and simultaneously expands three dimensionally. During laser irradiation of the order of several nanoseconds, electrons are heated by the laser light and highly charged ions are produced by these hot electrons. The charge state distribution highly depends on laser power density. To produce highly charged ions, more than 10×10^{10} W / cm^2 or 10×10^{11} W / cm^2 of laser power density is required depending on the target species. As the plasma plume expands, ion current density becomes lower and ion pulse width becomes longer according to the relations

$$\Delta t \propto L \qquad (1)$$

$$j \propto L^{-3} \qquad (2)$$

where Δt is ion pulse width and j is the ion current density at a distance of L.[4]

B. Direct Plasma Injection Scheme

The advantage of the laser ion source is its capability of providing high intensity heavy ion beam on the order of hundreds of milliamperes of current with high charge states. However, it is difficult to transport ion beam between the ion source and the first accelerator once it is extracted, especially in a low energy region because of the strong space charge effect.

To avoid this problem, plasma is generated in a high voltage cage inside a vacuum and expands by its expansion velocity up to the entrance of the RFQ linac through the biased nozzle, which has the same potential as the high voltage cage in DPIS. An ion beam is extracted between the nozzle and RFQ electrodes. After the extraction, ions are immediately captured by a RFQ electric field, so ions can be captured and accelerated efficiently. However, experiments and simulation studies show that when the ion current density is very high, extracted beam diverged due to plasma meniscus shape. This causes a mismatched condition

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between the injected beam emittance and the RFQ linac acceptance which causes a large beam loss to occur. To study beam loss due to a mismatched condition, different plasma drift distances were tested.

II. DRIFT DISTANCE SUVEY EXPERIMENT

A. Experiment setup

A Nd:YAG laser with a wavelength of 1064 nm was used. The laser energy and pulse duration at the full width at half maximum (FWHM) are 0.91 J and 7.1 ns, respectively. Figure 1 shows the schematic view of the ion source chamber. The setup consisted of three sections which were a laser ion source, RFQ linac, and beam diagnostic line. In the laser ion source part, an isolated target cage was placed inside a vacuum chamber. A graphite target plate was placed inside the cage. The dimension of the target was 55 mm in width, 95 mm in length and 5 mm in thickness. Laser light was injected into the target cage through vacuum windows, which was focused onto the target using a plano-convex lens with 100 mm focal length and plasma was generated. A metal tube was attached to the insulated cage toward the RFQ linac. At the end of the tube, a pipe which had an inner diameter of 6 mm was attached into the RFQ linac. The target cage, target and pipes were electrically connected and isolated from the ground potential. Plasma produced at the target expanded and was injected into the RFQ linac through these spaces. Ions were extracted between the end of the nozzle and the RFQ electrodes. The distance between the nozzle and the edge of the electrodes was 10 mm.

A high current, heavy ion RFQ linac developed for DPIS was used. Table 1 shows the main parameters of the RFQ linac.

In the beam diagnostic line, a current transformer (CT) was installed at the exit of the RFQ linac to measure a total beam current. After the CT, a cylindrical, 90 degrees electrostatic ion analyzer (EIA) and a Faraday cup were used to analyze charge state distribution inside the beam. We tested the plasma drift distance of 30 cm, 62.5 cm and 91 cm.

B. Result and discussion

FIG. 1. Schematic view of ion source chamber and injection region of RFQ linac. Bold line shows the high voltage biased area. Plasma produced by the laser expands toward RFQ linac and ions are extracted just at the entrance of RFQ.

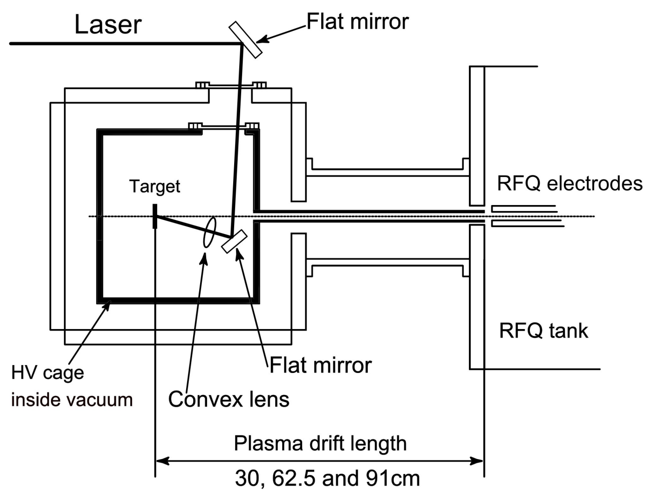
TABLE I. Main parameters of the RFQ linac.

Frequency	100 MHz
Total length	2.0 m
Input energy	20 keV / amu
Output energy	100 keV / amu
Modulated vane length	1.42 m
Limit of intervene voltage	120 kV
Aceptance	0.14 cm rad
Aperture	0.655 cm

At first, the experimental setup was adjusted for C^{6+} acceleration. The extraction voltage was set at 40 kV to match the nominal injection energy of this RFQ linac (20 keV / amu). The most suitable input power to the RFQ linac for C^{6+} acceleration was identified by changing the rf power at constant EIA applied voltage for the measurement of C^{6+} with 100 keV / amu, which is the nominal output energy of the RFQ linac. The rf input power with highest ion yield after the EIA was chosen for this experiment.

Figure 2 shows a total beam current after the RFQ linac measured by CT with the plasma drift distance was 30 cm, 62.5 cm and 91 cm, respectively. Figure 3 shows the analyzed results of the charge state in the beam with the drift distance of 30 cm by changing the EIA voltage. The EIA voltage of +-10 kV, +-12 kV and +-15 kV corresponds to that to allow C^{6+}, C^{5+} and C^{4+} beams to go through, respectively. This result shows that about 90 % of the accelerated beam was C^{6+}. The results with the drift distance of 62.5 cm and 91.0 cm also showed that about 90 % of the accelerated beam was C^{6+}.

Current and time of the signal measured by CT with the drift distance of 62.5 cm and 91 cm was scaled to the signal with 30 cm of plasma drift distance by applying Eq. (1) and (2). Figure 4



shows the experimentally obtained beam of the 30 cm drift distance and the scaled signals of 62.5 cm and 91 cm. The scaled signals mean the expected signals after the RFQ linac under the assumption of the same total beam loss for each drift distance, where the total beam loss includes the beam loss at the injection region and that during acceleration by the RFQ linac. A peak current of the scaled signal of the 62.5 cm and 91 cm drift distance was about 100 mA. However, only 30 mA was accelerated with the 30 cm of drift distance. This means the total beam loss of the 62.5 and 91 cm drift distance case was almost same while the total beam loss of 30 cm drift distance experiment was larger than that of longer drift distance case. This is because the extracted beam from the plasma with a 30 cm plasma drift distance diverged because the current was very high. As a result, the mismatched condition between emittance of extracted beam and RFQ acceptance occurred and fewer beams were accelerated. The mismatched condition at the entrance of RFQ linac is discussed more in ref.[3] It was found that the matching condition can be improved by reducing current density at the RFQ injection region. This means that the plasma drift distance should be selected carefully by considering a balance between the improvement of matching condition and the effect of total ion yield reduction to obtain a maximum accelerated ion yield.

IV. CONCLUSION

We experimentally confirmed that the mismatched condition at the injection point of RFQ linac can be improved by controlling the plasma drift distance, which determines ion current. So plasma drift distance should be selected carefully in LIS design.

V. ACKNOWLEDGEMENT

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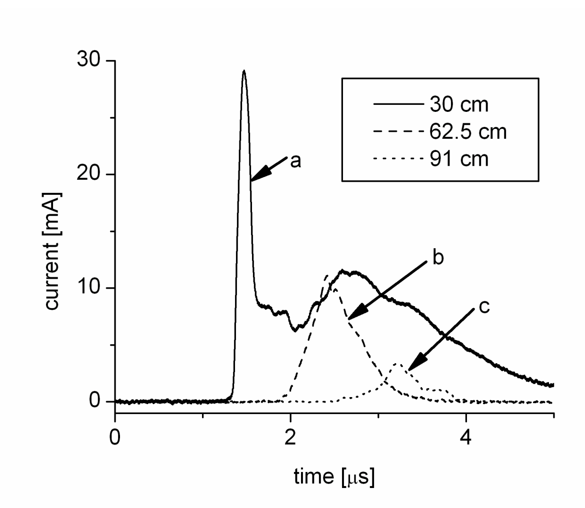

FIG. 2. Total beam current after the RFQ linac measured by CT with plasma drift distance of (a) 30 cm, (b) 62.5 cm and (c) 91 cm, respectively.

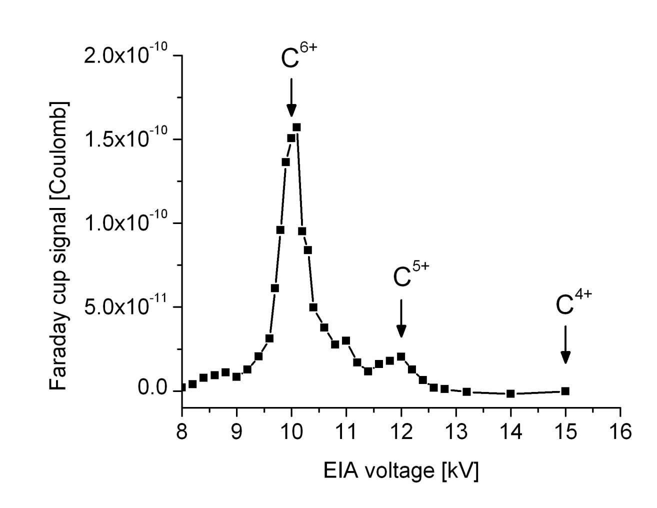

FIG. 3. Analyzed result of accelerated beam with drift distance of 30 cm. Horizontal axis is EIA voltage per an electrode. EIA voltage of +-10 kV, +-12 kV and +-15 kV corresponds to that to allow C^{6+}, C^{5+} and C^{4+} beams to go through, respectively.

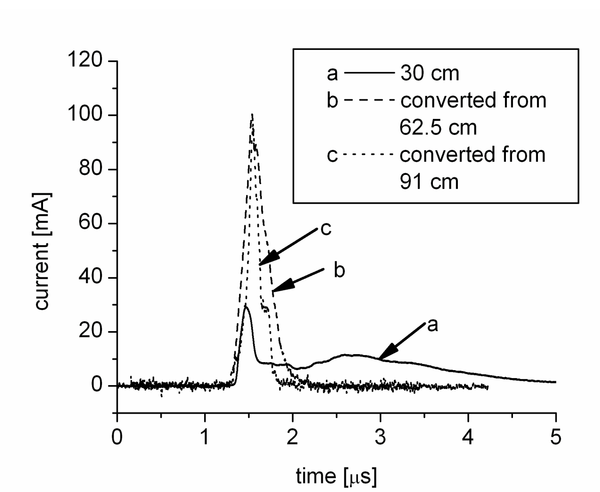

FIG. 4. Measured CT signal with 30 cm drift distance. To compare this signal, expected signals calculated from CT signals measured with 62.5 cm and 91 cm drift distance under the assumption of the same beam loss between RFQ injection and extraction for each condition using a ratio of plasma drift distance and relations of Eq. (1) and (2)