

Ablation plasma transport using multicusp magnetic field for laser ion source

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Abstract. We propose a plasma guiding method using multicusp magnetic field to transport the ablation plasma keeping the density for developing laser ion sources. To investigate the effect of guiding using the magnetic field on the ablation plasma, we demonstrated the transport of the laser ablation plasma in the multicusp magnetic field. The magnetic field was formed with eight permanent magnets and arranged to limit the plasma expansion in the radial direction. We investigated the variation of the plasma ion current density and charge distribution during transport in the magnetic field. The results indicate that the plasma is confined in the radial direction during the transport in the multicusp magnetic field.

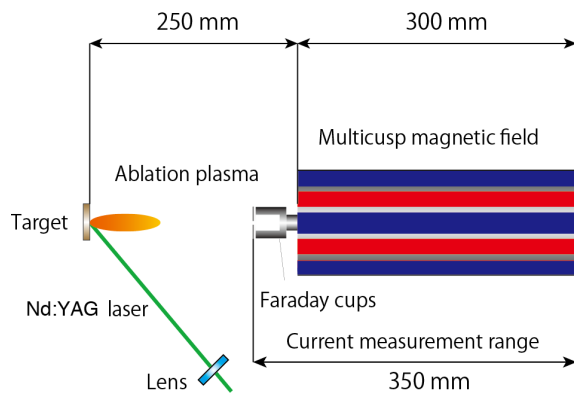
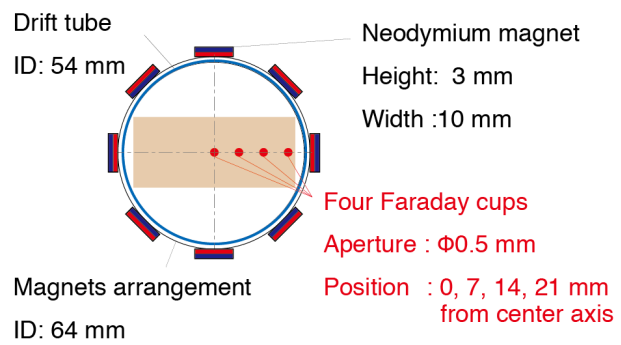
1. Introduction

Heavy ion inertial fusion (HIF) is considered as a candidate to realize power generation by nuclear fusion. The HIF requires heavy ion beams with high current to deposit sufficient energy to the fuel. For accelerating ion beams, several schemes have been considered using induction linac accelerator or recirculator[1]. For the induction acceleration scheme, ion sources, which can supply ion beams with current of 0.5 A and pulse duration of 20 μ s, are required. The current is very huge compared to conventional heavy ion beams. To realize the beams, various types of ion sources are considered [2].

A laser ion source (LIS) is expected to be one of the candidates as the injector for providing the high current ion beam [3-5]. The LIS provides ion beams with a pulse due to using a pulsed laser and the ion current waveform indicates shifted-Maxwellian distributions [6]. The duration of the beam pulse can be varied by changing the plasma drifting distance between the surface of the laser target and the ion beam extraction point. However, the current density of the ion beam decreases significantly due to the three-dimensional expansion of the plasma [7]. To maintain the plasma density, applying confining magnetic fields have been investigated [8-10].

In addition, multibeamlet scheme has been considered as the method to supply ion beams with sufficient current for HIF [11, 12]. To extract uniform ion beams with large area, uniform plasma is required. To solve this problem, we proposed multicusp magnetic guiding using permanent magnets, which has been used for confinement of plasma for electron cyclotron resonance ion sources. To investigate the effect of guiding using magnetic field on the ablation plasma, we demonstrated the transport of the laser ablation plasma in the multicusp magnetic field.



**Figure 1.** Schematic of the experimental setup.**Figure 2.** Cross section of the drift tube.

2. Experimental setup

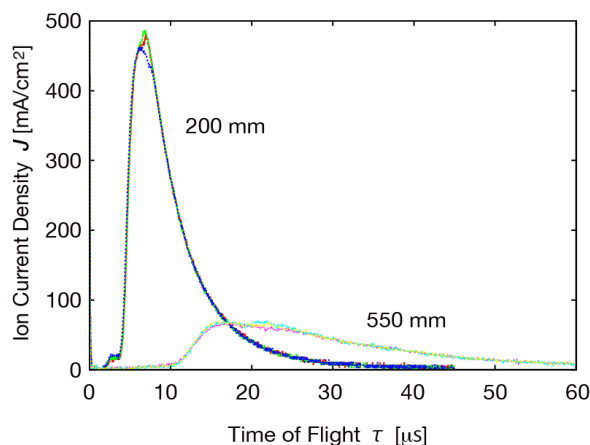
Figure 1 shows the schematic of experimental setup. A Nd:YAG laser (wavelength: 532 nm) was focused on the copper target with the incident angle of 60 deg from the line perpendicular to the target surface. The pulse duration and energy of the laser are 16-18 ns and 402 mJ, respectively. The laser intensity was 2×10^8 W/cm² estimated by measuring the irradiated spot area of 0.12 cm². In the case of producing plasmas with the laser intensity of $\sim 10^8$ W/cm², singly charged ions are dominant in the plasma and the extracted ion beams showed normalized RMS emittance of 0.025π mm.mrad [13].

The magnetic field was formed with eight neodymium magnets, which have magnetic flux density of 0.2 T on the surface and arranged around a drift tube with inner diameter of 54 mm to limit the plasma expansion to radial direction as shown in figure 2. The magnetic field is placed at 250 mm from the laser target. The distribution of magnetic field between two magnets faced each other was measured using a Gauss meter. The plasma was transported over 300 mm in the magnetic field.

The plasma ion current was measured with Faraday cups biased at -30 V to return electrons. The Faraday cups have apertures of 0.5 mm at 0, 7, 14, and 21 mm from the center axis of the drift tube. The time of flight of the plasma can be obtained by the signal from a photodiode, which detects the scattered light generated by radiation of the laser.

3. Results and discussion

The ion current was measured as a function of the plasma drifting distance from the laser target. The measurements were performed three times at same position. Figure 3 indicates the ion current signal measured at 200 and 550 mm from the laser target on the center axis of the drift tube. Both signals have waveforms like shifted-Maxwellian distribution.

**Figure 3.** Ion current density J measured on the center axis of drift tube at $L = 200$ and 550 mm from the laser target. Each condition is performed three times.

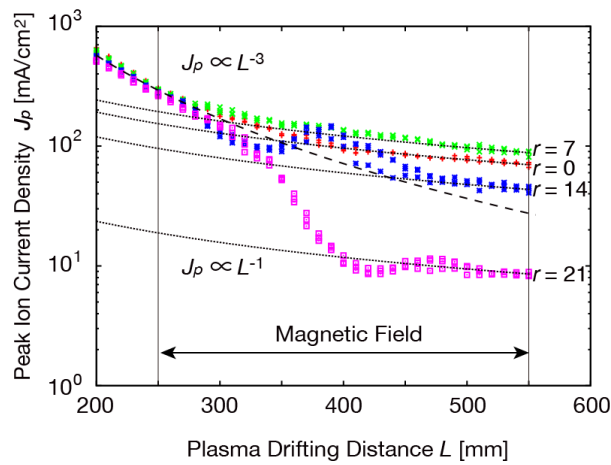


Figure 4. The variation of plasma ion current density at the peak of the waveform measured at $r = 0$ mm (red), 7 mm (green), 14 mm (blue), and 21 mm (pink) as a function of plasma drifting distance.

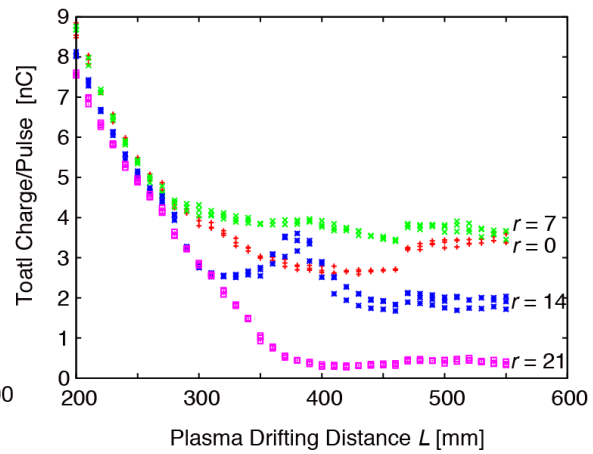


Figure 5. The variation of total charge/pulse obtained by integrating current waveform measured at $r = 0$ mm (red), 7 mm (green), 14 mm (blue), and 21 mm (pink) as a function of plasma drifting distance.

Figure 4 shows the variation of plasma ion current density at the peak of the waveform as a function of plasma drifting distance from the laser target L . The distribution of current density in radial direction is uniform without the magnetic field ($L = 200 \sim 250$ mm). In this region, the peak of the current density J_p decreases with the relation as $J_p \propto L^{-3}$ shown by the broken line. After injected into the magnetic field, current density increase compared to that without the magnetic field except for $r = 21$ mm. This implies that plasma ions move inside the drift tube from near wall where magnetic flux density is large. After going through transition region ($L = 250 \sim 450$ mm), current density decreasing corresponds to the dotted curves $J_p \propto L^{-1}$ ranging ($L = 450 \sim 550$ mm) at all radial positions.

Figure 5 shows the variation of total charge/pulse obtained by integrating ion current waveform. The variation corresponds to that of peak ion current density. The charges ranging ($L = 450 \sim 550$ mm) indicate almost constant. The results indicate that plasma expands only in longitudinal direction and laser ablation plasma can be confined in radial direction during transport in multicusp magnetic field.

Figure 6 indicates the distribution of the peak ion current density at $L = 550$ mm with magnetic flux density distribution. The plasma profile is almost consistent with the magnetic field. Although the plasma profile does not have flat top, it would be caused by the reason that the plasma profile near the center is on the way to be uniform. It is indicated that the variation of charge at $r = 0$ and 7 mm was not constant completely as shown in figure 5. To consider the effect of magnetic confinement, pressure of the plasma and magnetic field are estimated. The plasma pressure P can be derived using

$$P = (Z + 1)nkT. \quad (1)$$

Here Z is charge state of ions, k is the Boltzmann constant, T is temperature. Plasma ion density n is derived by the following equation,

$$J = Zenv, \quad (2)$$

where e is the elementary charge, v is velocity of the ions. Magnetic pressure P_B can be calculated as

$$P_B = B^2/2\mu_0. \quad (3)$$

where B and μ_0 are magnetic flux density and magnetic permeability, respectively.

Assuming $Z = 1$ and adopting the peak current density J_p as J , estimated pressures based on the values in figure 6 are shown in figure 7. As shown in figure 7, magnetic pressure is much larger than

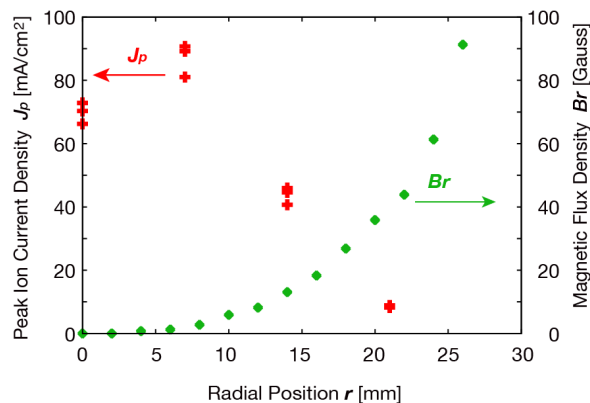


Figure 6. Distribution of peak ion current density in radial direction at $L = 550$ mm with magnetic flux density. Red and green plots indicate the current density and magnetic flux density, respectively.

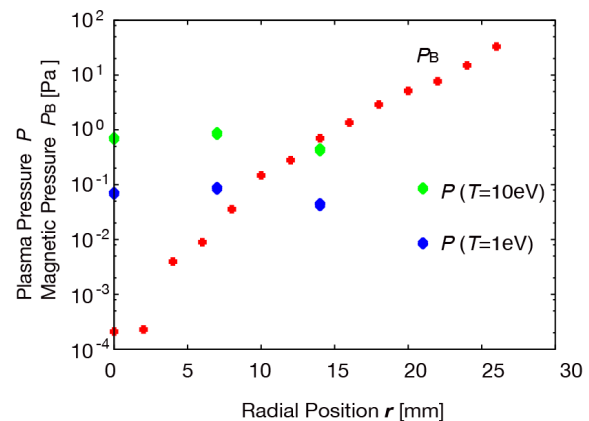


Figure 7. Comparison between plasma pressure P and magnetic pressure P_B at $L = 550$ mm. Red plots indicate magnetic pressure, green and blue plots show plasma pressure assuming temperature of 10 and 1 eV, respectively.

plasma pressure near wall of drift tube ($r = 27$ mm) and relatively uniform ion density is seen in the region of $P_B < P$.

Conclusion

To develop high current laser ion sources with large area, we demonstrated the transport of the laser ablation plasma in the multicusp magnetic field, which has much larger magnetic pressure than plasma pressure near the wall of drift tube. We investigated the variation of the plasma ion current density and charge distribution during transport in the magnetic field. The results indicate that the plasma is confined in the radial direction and expands in longitudinal direction during the transport in the multicusp magnetic field. In this study, the current density and pulse width of ~ 70 mA/cm² and ~ 20 μ s pulse duration (FWHM) at 550 mm from the target have been achieved. Although the uniform density region was realized within the diameter of ~ 10 mm Φ , we need the uniform plasma with diameter of 30 mm Φ to get 0.5 A beam. Moreover, ions should be extracted as multi-beamlet from multi-apertures and larger uniform plasma will be required. Therefore, we will try to clarify the relation between the magnetic field and plasma profile in detail and get more uniform plasma in the radial direction.

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