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Behavior of moving plasma in solenoidal magnetic field in laser ion source

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Behavior of moving plasma in solenoidal magnetic field in laser ion source[a)]

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In laser ion source, a solenoidal magnetic field is useful to guide the plasma and to control the extracted beam current. However, the behavior of the plasma drifting in the magnetic field has not been well uderstood. Therefore, to investigate the behavior, we measured the plasma ion current and the total charge within a single pulse in the solenoid with changing the distance from the entrance of the solenoid to a detector. We observed that the decrease of the total charge along the distance became smaller as the magnetic field became larger and then the charge became almost constant with a certain magnetic flux density. The results indicate that the transverse spreading speed of the plasma decreased with increasing the field and the plasma was confined transversely with the magnetic flux density. We found that the reason of the confinement was not magnetization of ions but an influence induced by electrons.

I. Introduction

Laser ablation plasma has been investigated as an ion source for heavy ion accelerator[1-3]. One of the features of the source is that almost all types of ion species that are solid in the standard condition can be produced with the relatively brief setup. A laser ion source is operated at the Brookhaven National Laboratory (BNL) providing several types of heavy ions to Relativistic Heavy Ion Collider and NASA Space Radiation Laboratory[4].

In laser ion source, the plasma produced on a solid target drifts toward an extraction electrode with spreading to transverse direction; perpendicular to the beam line. If no external field is applied, the plasma size becomes so large compared to an aperture of the electrode that only a small fraction of the plasma is injected. On the other hand, if we apply a solenoidal magnetic field, we can increase the number of the injected ions by suppressing the spread of the plasma.

The application of the solenoidal magnetic field to a laser ion source has been studied[2,5,6,7]. The researches reported that the magnetic field increased the beam current up to several tens times. These showed that the magnetic field is useful to control the beam current. However, the mechanism of the plasma guide has not been well understood. Therefore, we investigated the plasma behavior in the magnetic field by measuring the plasma ion current and the total charge within a single pulse in a solenoidal magnetic field.

II. Experimental setup

Figure 1 is a schematic illustration of the experimental device. A Fe target was placed in a chamber that was evacuated to 4 x10^{-4} Pa. Laser light (1064 nm wave length, 6 ns pulse width, and 630 mJ energy) was shot from a laser (THALES SAGA 230) and focused on the target. The spot size was 0.24 cm^2 estimated from a mark of the damage on the target surface. The incident angle of the laser to the target normal was 30°. The laser produces singly charged ions mainly[8].

A solenoid with 480 mm in length and 74 mm in diameter was placed at a distance of 320 mm from the target. The 2.1mm-diameter conductive wire was wound 226 times per layer and 2034 times totally with 9 layers. We calculated magnetic field with software (OPERA). We assumed that the solenoid was a cylinder with a 74-mm inner diameter, a 111-mm outer diameter, and a 482-mm length with a coil current density of 23 A/cm^2. The longitudinal component of the magnetic flux density is shown in Fig.2.

Plasma ion current was measured with a Faraday cup. The cup had a grounded plate with a 2 mm-diameter aperture and negatively biased (- 5 kV) metal mesh. Between the plate and the mesh, electrons were removed from the plasma and then the beam current was measured with the cup. The bias voltage was experimentally chosen to maximize the detected current. The biased mesh was also used to repel secondary electrons emitted from the

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cup. We scanned the Faraday cup to the longitudinal direction at distances between 100 mm and 400 mm from the entrance of the solenoid. In this region, as shown in the Fig.2, the magnetic field was almost uniform.

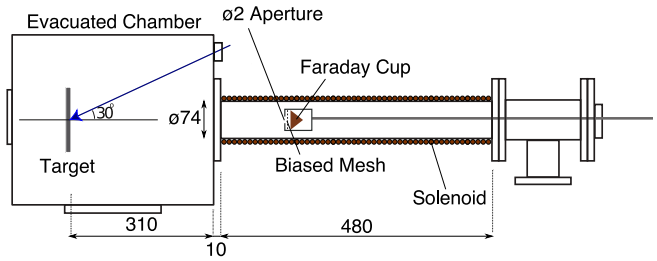

Figure 1 Experimental setup

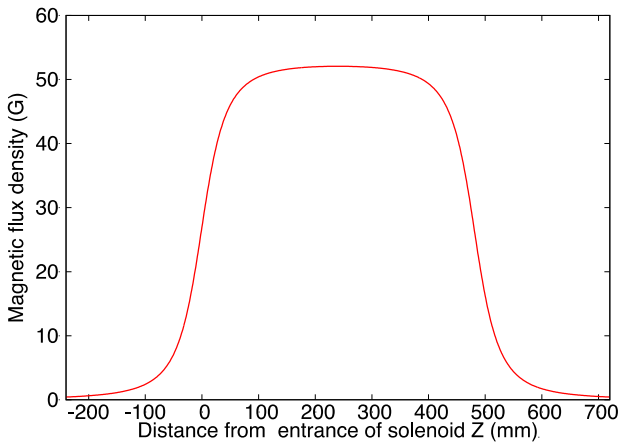

Figure 2 Longitudinal component of magnetic flux density as a function of the distance from entrance of solenoid

III. Results and discussions

Figure 3 shows the plasma ion currents as functions of the time from a laser shot. Those were measured at a distance of 240 mm from the entrance of the solenoid. The red curve is the current without magnetic field and the other curves are those with magnetic field. We obtained a typical curve without the field. The curve can be explained by assuming that the velocity distribution of the ions is described as a shifted-Maxwell distribution[9]. Right after the production, the ions collide frequently, reach a thermal equilibrium, and then adiabatically expand. Due to the expansion, the velocity distribution function of the ions becomes shifted-Maxwellian with a drift velocity in the direction perpendicular to the target surface. Then the ions continue to expand and finally become collisionless. In this case, the velocity distribution is frozen. Thus the plasma ion current at a point can be calculated from the shifted-Maxwell distribution function.

In the presence of the magnetic field, we found that the plasma ion current increased as the magnetic field was larger. When the magnetic flux density at the center of the solenoid was smaller than 55 G, the waveform was similar to that without the magnetic field. On the other hand, when the magnetic field was 55 G, a fluctuation appeared in the waveform and when the field was larger than 55 G, the fluctuation became larger and the reproducibility of the waveform was much worse. Therefore, we did not use the currents with the magnetic field larger than 55 G for the following discussion. The peak around 10 μs is composed of lighter particles, such as carbon or oxygen ions adsorbed on the target surface.

We measured the current waveforms with changing the distance from the entrance of the solenoid and then integrated the waveforms to obtain the total charges within a single pulse. Figure 4 shows the plots of the charges as functions of the distance from the solenoid. Each plot is the average of from 6 to 10 data. The red plots are the total charges without magnetic field and the other ones are those with the field. The total charge without the field decreased monotonically with increasing the distance. This means that the amount of the plasma passing through the aperture of the Faraday cup decreased with increasing the distance. Because the laser spot was much smaller than the distance of the detector, we can consider the laser spot as a point

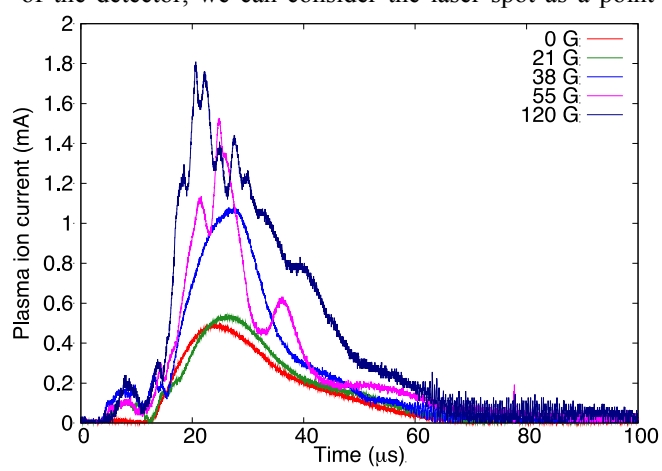

Figure 3 Plasma ion currents with magnetic field at a distance of 240 mm from entrance of solenoid

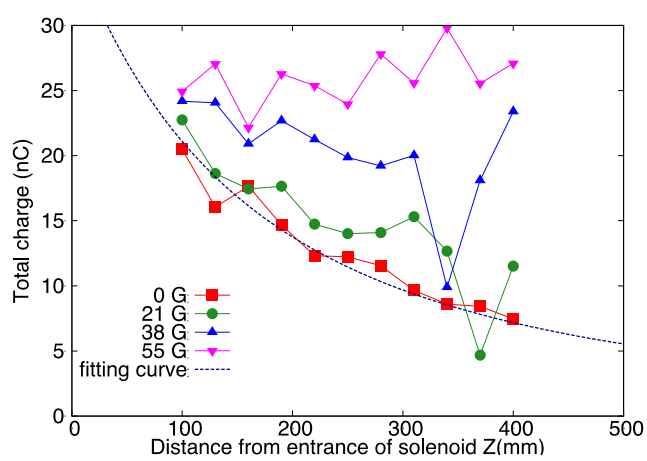

Figure 4 Total charge as functions of distance from entrance of solenoid

source. In addition, the ions are collisionless as mentioned above. Therefore, the ions can be considered to move straightly from the point source. In this case, the amount of the ions passing through the aperture is determined by the solid angle of the aperture viewed from the laser spot. Thus, the solid angle decreases with increasing the distance and the amount also decreases. The solid angle and the total charge should be proportional to the inverse square of the distance from the target. To confirm that, we tried to fit a curve proportional to the inverse square of the distance to the plots without the magnetic field. The dashed line shown in Fig.4 is the fitting curve and we can find that the charge without magnetic field is proportional to the inverse square of the distance.

On the other hand, the charges with the magnetic fields were larger than without the field. In addition, the decrease rates, that are the decreases of the charge per a distance, were smaller. This means that the ions did not move straightly but were dragged toward solenoidal axis. The decrease rate became smaller as the magnetic field became larger and then the charge became almost constant with magnetic field of 38 and 55 G. The tendency indicates that the transverse spreading speed of the plasma decreased with increasing the magnetic field and then the plasma was confined transversely with the field around 50 G.

We can estimate the effect of magnetization of the ions by comparing the cyclotron period of the ions and electrons with the time scale for the ions to pass through the solenoid. The cyclotron periods were $7.0\text{x}10^2$ μs for ions and less than μs for co-moving electrons. On the other hand, we can estimate the time scale for the passes by using the current waveform in Fig.3 and the geometry of the experimental device. As shown in Fig.3, the time of flight of the current peak was 24 μs and the distance of the Faraday cup from the target was 560 mm. Therefore, longitudinal velocity of the ion v_z was estimated to be $2.3\text{x}10^4$ m/s and the time scale to pass through the solenoid was 2.1 x 10 μs. This means that the time scale was so shorter than the cyclotron period that the ions would not move along the magnetic field. Thus, we found that the observed confinement mechanism is not the magnetization of ions but the influence of electrons.

IV. Conclusion

In laser ion source, a solenoidal magnetic field has been used to modulate a beam current, but the behavior of the plasma in the magnetic field has not been investigated. Therefore, we measured the plasma ion current and the total charge within a single pulse in a solenoidal field. The current waveform measurements showed that the current increased with increasing the magnetic field. The waveforms with magnetic field were similar to one without the field when the field was less than 55 G. On the other hand, fluctuation appeared when the field larger than 55 G.

We obtained total charges within a single plasma pulse by integrating the current waveform and then plotted the charges as a function of the distance form the entrance of the solenoid. Although they decreased with distance, the decrease of the charge along the distance was smaller as the field was larger. This means that the transverse spreading speed of the plasma decreased. Moreover, when we applied around 50 G, the charge became almost constant along the distance. This means that the plasma was confined transversely. From a comparison of the cyclotron period with the time scale for the ions to pass through the solenoid, we found that the confinement mechanism was not the magnetization of the ions but the influence of electrons.

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