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Magnetic control of laser ablation plasma for high-flux ion injectors

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ABSTRACT

We investigated the interaction of a laser ablation plasma with a longitudinal magnetic field aiming to create a directionally moving plasma for high-flux and low-emittance ion injectors. To study the plasma dynamics, time-of-flight measurements and energy analysis of the plasma ion flux were made as functions of the laser intensity and the magnetic field. Moderate magnetic field (~0.2 T) directed the fast and highly charged ions in the target normal. In addition, a slow peak appeared and increased with increasing the magnetic field. These results indicated that directional electric field is formed and recombination increases by the application of longitudinal magnetic field.

1. Introduction

The application of laser ablation plasma to ion source has been discussed because the laser can easily produce a high density plasma from any solid material [1–5]. One of the possible applications is the high-flux injector for heavy ion fusion. The laser ablation plasma has a large drift velocity and a relatively low temperature after free expansion. These features are suitable for high-flux and low-emittance ion injectors. However, the plasma expansion reduces the plasma ion flux supplied to the extraction gap. Magnetic guiding of the drifting plasma is a way to increase the plasma ion flux and get a well collimated ion beam.

When the plasma propagates along a longitudinal magnetic field, the transverse magnetic pressure or Lorentz force constrains the transverse motion of the plasma. The confinement directs the plasma in the longitudinal direction. In addition, the confinement probably affects the ionization and recombination processes.

Magnetic field effects on laser ablation plasmas have already been reported [5–8]. However, the plasma dynamics in the magnetic field have not been well understood, yet. Because of the rapid expansion and large density decrease of the plasma in the magnetic field, multi-scale interaction processes need to be taken into account.

The purpose of this study is to create a directional moving plasma for high-flux ion injectors. To investigate quantitatively the effect of magnetic field on the transverse motion of laser ablation plasma, we measured the flux and energy distribution as functions of magnetic field and laser intensity [9].

2. Experimental setup

Fig. 1 shows a schematic of our experimental setup. The vacuum chamber was evacuated to $\sim 10^{-3}$ Pa. A second harmonics of a Q-switched Nd:YAG laser ($\sim 10^9$ W/cm^2) was irradiated on the surface of a Cu target. The pulse length of the laser (15 ns) was sufficiently short compared with the time scale of the plasma motion (~μs). The longitudinal magnetic field was produced by two solenoid coils of 10 mm in diameter and 30 mm in length (Fig. 2). A biased ion probe measured the plasma flux 170 mm downstream of the copper target. A 1-mm-diameter aperture was placed in front of the ion probe and moved transversely to get the spatial profile of the plasma flux.

We also analyzed the energy distribution of ions with a cylindrical electrostatic ion-energy analyzer (Fig. 3). The device is composed of cylindrical deflection electrodes and an electron multiplier. The deflection electrodes are placed coaxially and biased positively and negatively with respect to ground potential (vacuum chamber). Only ions having the same orbital radius as the mean radius of the deflectors can be detected by the electron multiplier.

The kinetic energy of the detected ions is given by the following equation equivalent to the force equation:

$$\frac{E}{z} = \frac{eU}{2\ln(R_2/R_1)} \tag{1}$$

where E is the kinetic energy, e is the charge of an electron, z is the charge state of the ion, U is the potential difference between the electrodes, and R_1 and R_2 are radii of inner and outer cylinders, respectively. The time of flight of ions from the target to the detector is

$$t = L\sqrt{M/2E} \tag{2}$$

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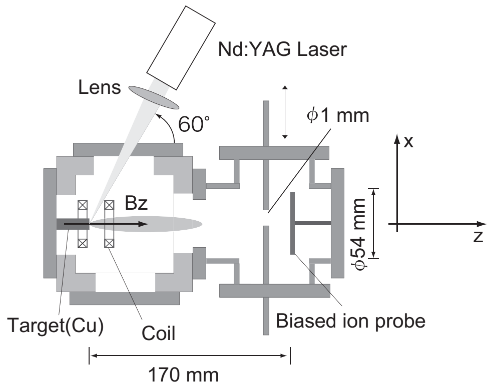

Fig. 1. Schematic of experimental arrangement.

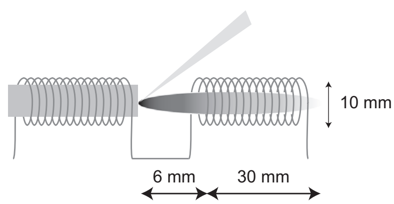

Fig. 2. Schematic of the solenoidal coil. To irradiate the target with the laser, two solenoidal coils (50 mm) connected in series were placed with 6 mm intervals.

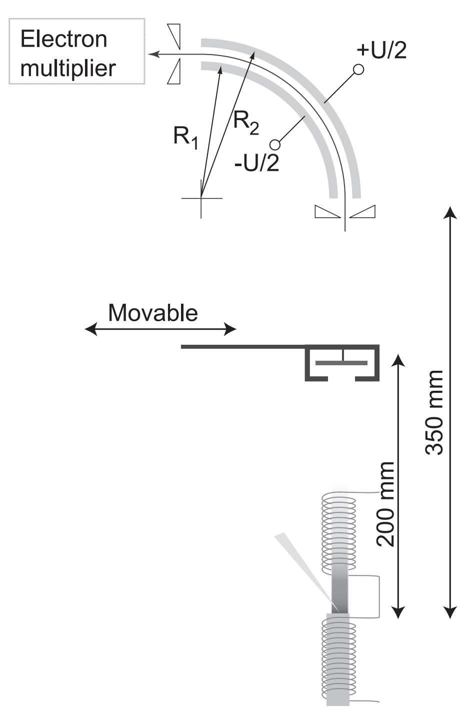

Fig. 3. Schematic of electrostatic energy analyzer.

where M is the mass of an ion and L is the path of flight. From Eqs. (1) and (2), the energy distribution of the ions having a specific M/z value can be obtained [10].

The analyzer was placed 350 mm downstream of the target surface. Here, L was 610 mm or 850 mm, R_1 was 95 mm, and R_2 was 105 mm. The biased ion probe was placed 200 mm downstream of the target for total flux monitoring.

Prior to the measurements, the contaminations on the target surface was removed in-situ (i.e., in the vacuum chamber) by the laser, which greatly improved the reproducibility of the flux signal.

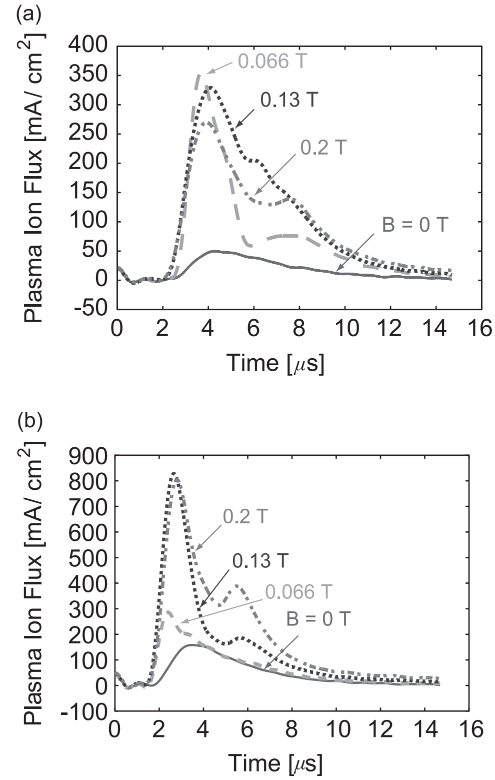

Fig. 4. Plasma ion flux at $z=170$ mm and $x=0$ mm with magnetic field density of 0 T (solid line), 0.066 T (dashed line), 0.13 T (dotted line), and 0.2 T (dot-dashed line). Laser intensities are (a) $E_L=3.2\times10^8$ W/cm^2 and (b) $E_L=9.5\times10^8$ W/cm^2.

3. Results and discussion

3.1. Plasma flux measurements

Fig. 4(a) shows the change in the plasma flux at $z=170$ mm as a function of magnetic flux density. Laser intensity was 3.2×10^8 W/cm^2. As shown in the figure, the plasma-flux waveform exhibited two peaks in the presence of magnetic field. We can see that the first peak appeared when a weak magnetic field (0.066 T) was applied as shown in Fig. 4(a). The first peak height was higher (~5–7 times) and sharper. As the magnetic field intensity increased more, the peak height decreased gradually and became wider. Meanwhile, the second peak appeared and increased with increasing the magnetic field.

Fig. 4(b) shows the change in the plasma flux at $E_L=9.5\times10^8$ W/cm^2. The changes of the flux wave form was similar to that at $E_L=3.2\times10^8$ W/cm^2 except for the magnetic flux density at which the first peak height was the largest.

The modification of the plasma flux with the moderate magnetic field and the appearance of the two peaks indicate that the effect of magnetic field on the plasma cannot be explained just by the hydrodynamic behavior of plasma. At the initial phase, the pressure of the magnetic field (~10^7 Pa) is much less than the plasma kinetic pressure (~10^{10} Pa, at n~10^{20} cm^{-3}, T~1 eV). In addition, if the plasma behaves as fluid, the magnetic field changes the shape of the plasma but does not separate two groups.

Fig. 5 shows the plasma flux measured at different positions ($x=0$, 4, 10, and 17 mm) with $B=0.066$ T and $E_L=3.2\times10^8$ W/cm^2. The value of the peak at $x=17$ mm was about 1/5 of that at $x=0$ mm. We plotted the peak flux at different positions in Fig. 6 to show that the transverse distribution of the first peak is quite sharp. If the angular distribution of ion flux follows a $\cos^p\theta$ behavior, where θ is the divergence angle of ions, the observed distribution corresponds to p~300. In contrast, angular distributions