Control of Laser Ablation Plasma with Longitudinal Magnetic Field

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We investigated the interaction of a laser ablation plasma with a longitudinal magnetic field, intending to create a directional moving plasma for laser ion source. To study the plasma dynamics, time-of-flight measurements of ion flux were made as a function of laser intensity and the magnetic field. The results indicate that the ion current density in the forward direction is strongly affected by a moderate (~0.2 T) magnetic field. Results also indicate that the longitudinal magnetic field can control the ion flux as well as degree of ionization of the moving plasma by reducing the transverse expansion and setting on the recombination process during the interaction.

Keywords: laser-produced plasma, longitudinal magnetic field, transverse motion, directional plasma, recombination

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The dynamics of laser ablation plasma in longitudinal magnetic field are of interest for the development of high-flux and low-emittance ion sources. The laser ablation process is widely used in applications such as laser-induced spectroscopy, pulsed-laser deposition of thin films, and laser ion sources [1]. Magnetic field effects on ablation plumes have already been reported. However, the discussion of plasma dynamics has been rather phenomenological. To deepen our understanding of plasma dynamics in a magnetic field, we have started an interaction experiment of the laser ablation plasma with longitudinal magnetic field in this study.

We produce the plasma by laser ablation of copper in a longitudinal magnetic field. The plasma expands adiabatically, eventually converting its internal energy into kinetic energy. During its expansion, the temperature and density decrease as a function of the density-temperature history and some ions recombine. This decrease of density leads the plasma to a collisionless state [2, 3]. Throughout this process, if a longitudinal magnetic field is present, the transverse magnetic pressure or Lorentz force constrains the transverse motion of the plasma. If the transverse motion is held with colliding, the confinement directs the plasma in the longitudinal direction. In addition, the confinement controls the plasma density decrease and hence could set on the recombination by increasing the collisional frequency.

While the plasma expands and is collisional, the interaction may be described by the MHD equation. The particles of the collisionless plasma undergo Larmor motion in the presence of magnetic field. In contrast, the interaction of the plasma, whose parameter are between these states, can not be quantitatively well described. In general, available intensity of magnetic field (B) is ~10 T at most. Subsequent to the production of the plasma, the pressure of the magnetic field (~ 10^7 Pa) is much less than the plasma kinetic pressure (~ 10^{10} Pa, at $n \sim 10^{20}\,\mathrm{cm}^{-3}, T \sim 1\,\mathrm{eV}$). Therefore, subsequent to its expansion, the magnetic field should affect the plasma motion for plasma with a lower density ($n \sim 10^{17}\,\mathrm{cm}^{-3}$). The interaction occurs mainly in the intermediate-parameter region.

When the transverse motion with the laser-produced plasma is constrained by such a magnetic field, the interaction of the plasma with magnetic field is of most significance in the intermediate-parameter region.

We must exploit the expansion process to control velocity distribution by uniforming the direction and degree of ionization by setting on the recombination process of the laser-produced plasma through a longitudinal magnetic field. However, calculating the interaction of the plasma with the magnetic field is difficult. Therefore, an experiment is necessary to elucidate the effect of a longitudinal magnetic field on laser-produced plasmas.

To investigate qualitatively the effect of a magnetic field on the transverse motion of laser produced plasma, we measured the plasma flux through a longitudinal magnetic field as a function of x and z. The aim of this study is to control the direction and degree of ionization of the plasma, which can be applied to high power ion sources.

Figure 1 shows a schematic of our experimental setup. A Q-switched Nd:YAG laser with a power density of ~ $10^9\,\mathrm{W/cm}^2$ at the focal spot on the surface of the Cu target, created the ablation plasma. The pulse length of the laser (15 nsec) was sufficiently small compared with the time scale of the plasma motion (~ μs) through the magnetic field.

A biased Faraday cup measured the plasma flux

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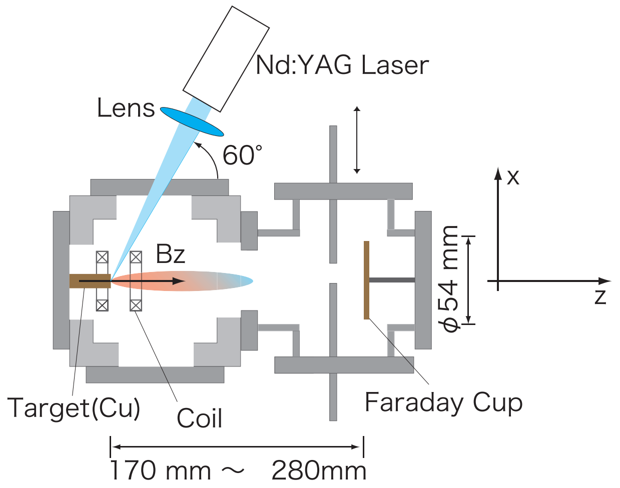

Fig. 1 Schematic of experimental arrangement.

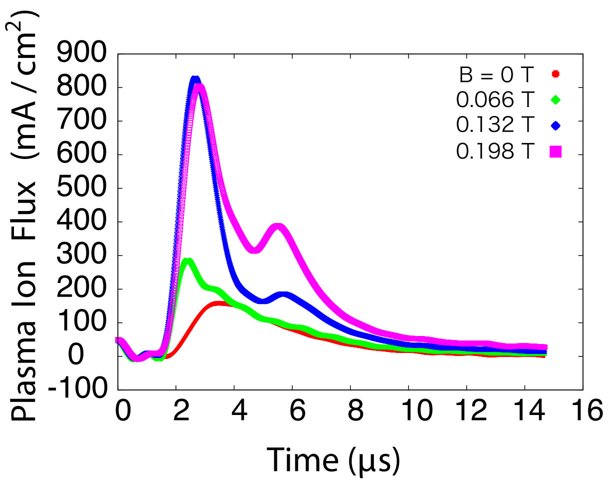

Fig. 2 Signals of biased Faraday cup located at z = 170 mm, and x = 0 mm (Laser intensity $E_L = 9.5 \times 10^8$ W/cm^2).

through the longitudinal magnetic field produced by solenoid coil, 10 mm in diameter and 30 mm in length. Prior to the measurement, the target surface was cleaned of contaminants in-situ (i.e., in the vacuum chamber) by the laser which greatly improved the reproducibility of the flux signal. A 1-mm-diameter aperture was placed in front of the plasma collector and be moved transversely.

Figure 2 shows the change in the plasma flux at z = 170 mm between the target surface and Faraday cup and for several magnetic field intensities. The result show that, in the presence of a magnetic field, the the plasma flux and number of collected ions is 7~8 times larger than those in the absence of a magnetic field.

In the presence of a magnetic field, the plasma-flux waveform exhibits two peaks. We attribute this result to a magnetic field setting on the recombination during plasma propagation. If recombination is set on, strongly ionized ions are converted to weakly ionized ions and the Faraday cup signal decreases. The combination of this effect with an increase in the directional flux from lateral confinement of plasma may be responsible for this waveform structure.

Furthermore, this waveform becomes steeper with an increasing magnetic field, which means that a significant

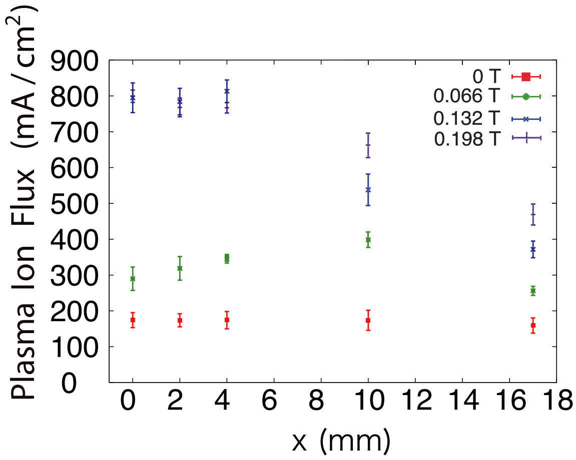

Fig. 3 Transverse distribution of the plasma flux ($E_L = 9.5 \times 10^8$ W/cm^2, z = 170 mm).

number of ions gain kinetic energy and hence travel faster. This extra kinetic energy may have come from the ionization energy that is returned to plasma by the recombination process.

Figure 3 shows the transverse distribution of the plasma flux for several magnetic field intensities. The results show that the distributions in the presence of a magnetic field is sharper than that in the absence of a magnetic field. In general the angular distribution can be described as $\cos^p \theta$, where the parameter p in the absence of a magnetic field, has been determined in a previous research is 10~30 [4]. However, in our experiment the angular distribution at B = 0.132 T is well described by $\cos^{250} \theta$. This result indicates that the magnetic field can strongly direct the plasma along the target normal.

To create highly directional plasma, a better understanding of plasma dynamics is required. Toward the end, we observe laser ablation plasma through a longitudinal magnetic field. The experimental results indicate that peak flux and its temporal structure are strongly affected by the application of a moderate magnetic field (~0.2 T). In addition change in waveform may be attributed to the magnetic field influencing the relaxation process in the intermediate-parameter region of the interaction.

Further investigations of plasma dynamics are needed for better understanding of all the features observed here. The experimental results indicate that a longitudinal magnetic field can control the ion flux as well as degree of ionization, which would be advantageous for developing high-flux and low-emittance ion sources.

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