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Measurement of magnetic field fluctuations and diamagnetic currents within a laser ablation plasma interacting with an axial magnetic field

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The guiding of laser ablation plasmas with axial magnetic fields has been used for many applications, since its effectiveness has been proven empirically¹⁻⁵. For more sophisticated and complicated manipulations of the plasma flow, the behavior of magnetic field during the interaction and the induced diamagnetic current in the plasma plume needs to be clearly understood. To achieve the first milestone for establishing magnetic plasma manipulation, we measured the spatial and temporal fluctuations of magnetic field caused by the diamagnetic current. We showed that the small fluctuations of the magnetic field can be detected by using a simple magnetic probe. We observed that the field penetrates to the core of the plasma plume. The diamagnetic current estimated from the magnetic field had temporal and spatial distributions which were confirmed to be correlated with the transformation of the plasma plume. Our results show that the measurement by the magnetic probe is an effective method to observe the temporal and spatial distributions of magnetic field and diamagnetic current. The systematic measurement of the magnetic field variations is a valuable method to establish the magnetic field manipulation of the laser ablation plasma.

1. Introduction

Laser ablation plasmas with magnetic guiding have been studied for many applications. In laser ion sources, magnetic guiding has been shown to enhance the beam current and extend the beam pulse width. Gray¹ showed that the peak current was enhanced by three orders of magnitude with a magnetic bottle configuration. Wolowski² observed enhancement by a factor of 2-3 by use of a Helmholtz coil. Okamura³ enhanced the ion current density by a factor of forty by using a solenoid to guide the plasma plume. For pulsed laser deposition, magnetic guiding is used to eliminate the macro-sized particles and increase the deposition rate. Tsui⁴ reported that the 20% of plasma was guided by the field in a 30-degree bended magnet. Pagano⁵ observed that the deposition rate was increased by a factor of 2.6 when the laser target and substrate were located between two ring magnets. Additionally, magnetic guiding has been studied for the formation of elongated plasma columns used in x-ray lasers⁶, for the control of laser-induced plasma micromachining⁷, and in the development of laser fusion rockets⁸.

When a plasma plume is injected into an axial magnetic field, a diamagnetic current is induced which distorts the magnetic field. Simultaneously, the plasma is subjected to radial Lorentz forces. The interaction between the magnetic field and expanding plasma flow must be predicted to achieve effective and more sophisticated guiding schemes, in order to guide larger amounts of plasma, provide well-collimated plasma flow, and tailor the temporal and spatial ion density distributions⁹.

Several experiments have been conducted concerning plasma plume dynamics. Wolowski¹⁰ observed that the angular distribution of ion current density becomes narrower in the presence of magnetic field. Using optical measurements, Pagano⁵ showed that the plume becomes cylindrical in an axial magnetic field. Takahashi¹¹ showed that the current is proportional to $L^{-1.5}$ in a solenoid, where L is the drifting distance. Although the plasma dynamics had been investigated as described, a comprehensive explanation of the

interaction had not yet been provided. This paper examines plasma dynamics and is based on the following principles and measurements: If the magnetic field is completely excluded from the plume, the difference of the magnetic pressure between the inside and outside confines the plasma radially. The interaction is described by simple snowplow model¹². However, because the laser ablation plasma has a finite resistivity, the magnetic field and the diamagnetic current are expected to penetrate into the plume during the adiabatic expansion. As a result, the diamagnetic currents are distributed as a function of depth from the surface of the plume. The current distribution is expected to have a complicated guiding effect within the plume. In order to understand the interaction, investigation of magnetic field and diamagnetic current in the plume is indispensable.

As a first step towards effective magnetic manipulation of laser ablation plasmas, we established a magnetic field measurement method using a magnetic probe and simple controlled conditions. The plasma tested was composed mainly of singly charged ions and was injected into an axial magnetic field generated by a short solenoid. We successfully measured the temporal and spatial distribution of the magnetic field, and the diamagnetic currents produced were correlated with the plasma dynamics.

2. Experimental setup

Figure 1 shows the experimental setup. An iron target was placed in a chamber evacuated to 4×10^{-4} Pa. A Nd:Yag laser pulse (1064 nm, 6 ns) was used to irradiate iron plate target with the power density of 4×10^8 W/cm². The plasma produced with such a power density has been shown to be composed of singly charged ions¹³. The target was translated slowly on a linear stage to avoid deep cratering of the target surface during successive irradiation pulses. To limit the solid angle of the plasma emitting from the exposed surface, a disk with a 14-mm diameter aperture was placed at a distance of 140 mm from the irradiation spot. The aperture defines the spatial limit of the expanding plume, and this boundary condition will aid us in deriving the diamagnetic currents.

Figure 1: Experimental setup for measurement of the magnetic field.

A short solenoid with 50 mm inner diameter and 5 mm length was placed at a distance of 260 mm from the target. The solenoid was made of two layers of copper wire windings with 14 turns each. We energized the solenoid using a DC power supply to provide a static magnetic field. The longitudinal component of the magnetic field B_z was calculated using the OPERA¹⁴ simulation code. Here, x and z are transverse and longitudinal components, respectively, of a cartesian coordinate system in which the origin is at the solenoid center as shown in Fig. 1. Figure 2 (a) and 2 (b) show B_z on the z and x axes, respectively, for a solenoid current of 1.0 A. During the experiment, the solenoid current was adjusted to induce a magnetic field with $B_z = 65$ G at the origin.

Figure 2: Calculated longitudinal magnetic field B_z on lines of (a) $x = 0$ mm and (b) $z = 0$ mm.

We measured the plasma ion current density with a detector at a distance of 740 mm from the target. The detector configuration is shown in Fig. 3. We grounded the metal mesh and applied -180 V to the copper cup to repel the co-moving electrons in the plasma that passed through a 2-mm-diameter aperture in front of the mesh. The plasma ion current density was obtained by dividing the measured ion current by the aperture area. The Faraday cup components were enclosed within a grounded stainless steel shell.

Figure 3: Configuration of current density detector.

A magnetic probe was used to measure the time varying magnetic field versus spatial position, induced by the plasma plume as it traversed the externally imposed solenoidal field. The schematic diagram of the magnetic probe is shown in Fig.4. A pickup coil with inner diameter 6.4 mm and the length of 2 mm was wound

on of an acrylic rod, flush with the front end. The coil consisted of 20 turns, in two layers of 10 turns each. Each end of the pickup coil was connected to 50 Ω BNC cables with a termination impedance of 50 Ω . We installed the probe in the solenoid to allow transverse and axial motion of the pickup coil with its axis parallel to z direction. We measured the time varying voltages on both 50 Ω termination resistors, denoted as V_1 and V_2 . The difference voltage of ($V_1 - V_2$) was integrated to map the time varying magnetic flux versus position in accordance with Faraday's law of induction. The average of the magnetic flux within the cross section of the pickup coil is obtained, and the time variation of $B_z(x, z, t)$, which we denote as ΔB_z , was obtained. The reason for measuring both of V_1 and V_2 is to subtract the common mode noise caused by the floating potential of the plasma^{15,16}. As an experimental check the probe performance, we measured the solenoidal magnetic field generated by a drive current with pulse width ($\sim 10 \mu\text{s}$). We compared the magnetic field measured by pickup coil to the calculated magnetic field estimated from the solenoid current measured by a Pearson-type current transformer encompassing one of the solenoid leads. The measured and estimated fields are displayed in Fig. 5 and show good agreement. Thus, we confirmed that the probe could properly detect temporal magnetic field variations that could be generated by a diamagnetic currents in the plasma plume as it traversed the solenoidal field. During measurements of ion current density, the magnetic probe was removed from the setup.

Figure 4: Schematic diagram of magnetic probe.

Figure 5: Magnetic field measured by the magnetic pickup coil probe (green trace), and calculated from the solenoid current as measured by a current transformer (CT) (red trace).

3. PLASMA ION CURRENT DENSITY MEASUREMENT

We measured the plasma ion density to investigate the interaction time-scale and the plasma plume dynamics. Figure 6 shows the plasma ion current density on the z axis at a distance of 740 mm from the target, as a function of the time from the laser shot. The red and the green curves show the waveforms obtained in absence and presence of the magnetic field, respectively. The red curve is a typical waveform reflecting the thermal velocity distribution of the ions. It is described by a shifted Maxwell-Boltzmann distribution¹⁷. From the waveform, the plasma ion current density at the solenoid center can be estimated by using scaling laws. Namely, the time of flight is proportional to the drifting distance L from the target and the current density is proportional to L^{-3} . The estimated waveform is shown later in this paper along with the measured magnetic field.

From Fig.6, it is found that the plasma ion current density in the head of the plume from 20 μs to 30 μs was enhanced in the presence of the magnetic field. On the other hand, in the tail of the plume the current density after 40 μs was not affected. This difference shows that the guiding effect varies between the head and the tail of the plume.

Figure 6: Plasma ion current density as a function of time at a distance of 740 mm from the target. The red and green curves were taken without and with magnetic field, respectively.

4. RESPONSE OF AXIAL MAGNETIC FIELD

Figure 7 shows typical magnetic probe signals, V_1 and V_2 . The red and green curves correspond to the signals at either end of the probe wires. Each signal was obtained by averaging ten waveforms taken with the same condition. The signals with the same polarity (observed for $t < 3 \mu\text{s}$) were common mode noise. The signals with opposite polarity (observed at approximately 10 μs) were induced by the variation of the magnetic field caused by the transit of the plasma plume.

Figure 7: Averaged magnetic probe signals at either end of the magnetic probe wires.

Figure 8 shows ΔB_z (red curve) at the center of the solenoid and the plasma ion current density (black curve) deduced by scaling from the red curve shown in the Fig. 6. As shown, ΔB_z had a minimum value at $t = 8 \mu\text{s}$ and was almost zero after $20 \mu\text{s}$. The negative value means that the magnetic field decreased. The negative peak value was -0.44 G , which was 0.7% of the external field, $B_z(x=0, z=0) = 65 \text{ G}$, at the same point. Meanwhile, the plasma ion current density increased from $6 \mu\text{s}$ to $10 \mu\text{s}$ and then decreased until $30 \mu\text{s}$. The current density profile means that the head part of the plasma plume reached the solenoid center around $8 \mu\text{s}$ while the tail part reached the center after $10 \mu\text{s}$. The comparison between the profiles of the magnetic field and the plasma ion current density shows that the decrease in magnetic field was greater when the head part of the plasma plume passed through the solenoid center than when the tail part passed by.

Figure 8: ΔB_z and plasma ion current density as a function of time at the solenoid center, $z = x = 0$.

We scanned the magnetic probe in z - x plane to obtain the spatial distribution of ΔB_z . Figure 9(a) shows distribution of ΔB_z at $z = 0$ as a function of x at times of 6, 8, 10, and 14 μs . For all the cases, ΔB_z was negative at $x = 0$ and the deviations became smaller with increase of the transverse coordinate. These monotonic variations mean that the magnetic field penetrated into the center of the plasma plume. The magnetic field decreased most greatly at 8 μs and then was gradually restored. On the other hand, the field deviation, ΔB_z , was almost zero in the range of $x > 13$ mm. This is because that the plasma was not expanded into the region due to the aperture disk placed between the target and the solenoid. Figure 9(b) shows the distribution of ΔB_z at $x = 0$ (on the solenoid axis) as a function of z for times 6, 8, 10, and 14 μs after the laser pulse. At 6 μs , ΔB_z was negative from -60 to 0 mm and smallest around -20 mm. As shown in Figure 9(a), ΔB_z did not change at all for $x > 10$ mm. This is because that the front edge of the plume was just excluded from 0 mm at this early measurement time as shown in the plasma current density waveform in Fig. 8. At later measurement times, ΔB_z was negative at $z < 0$ and positive at $z > 0$. This means that the magnetic field became asymmetric with respect to the solenoid's transverse mid-plane as illustrated in Fig. 10. In other word, the field was excluded toward outside of the plume at the upstream side while the field was dragged toward the inside at the downstream side. The distortion of the magnetic field varied with time, due to the passage of the plasma. Namely, as seen in Figure 9(b), the difference between negative and positive ΔB_z was largest at 8 μs and then became smaller.

Figure 9: ΔB_z distribution on the lines of (a) $z = 0$ mm and (b) $x = 0$ mm at $t = 6, 8, 10$, and 14 μs after the laser pulse.

From the results, it was found that spatial and temporal magnetic distributions are induced within the plasma plume during the interaction because of the field penetration into the plasma.

Figure10: Image of exclusion and dragging of magnetic field by plasma plume.

5. ESTIMATION OF DIAMAGNETIC CURRENT DENSITY DISTRIBUTION

In this section, we will consider only the induced B -field; hence we will denote ΔB_z as just B for simplicity.

5.1 Estimation method

From the experimental setup, we can assume axial symmetry. We will use a cylindrical coordinate system in which the origin is at the solenoid center, and z is along the axis as in the previous sections. In this case, the basic equation of magnetic field is described by

$$-\frac{\partial^2 A_\theta}{\partial z^2} - \frac{\partial^2 A_\theta}{\partial r^2} - \frac{1}{r} \frac{\partial A_\theta}{\partial r} + \frac{A_\theta}{r^2} = \mu_0 j_\theta, \quad (1)$$

where j_θ is azimuthal component of diamagnetic current and A_θ is azimuthal component of the vector potential.

We assumed the form of $j_\theta(r, z, t)$ as a linear combination of functions $F_n(r)$, $G_m(z)$. Namely,

$$\begin{aligned} j_\theta(r, z, t) &= \sum^{n,m} c_{n,m}(t) i_{n,m}(r, z), \\ i_{n,m}(r, z) &= F_n(r) G_m(z), \end{aligned} \quad (2)$$

where n and m are integers. $F_n(r)$, $G_m(z)$ were assumed as follows:

$$F_n(r) = \begin{cases} 0; & r > R = 20 \text{ mm}, \\ J_1\left(\frac{\nu_n r}{R}\right); & r < R, \end{cases} \quad (3)$$

$$G_m(z) = \begin{cases} 0; & |z| > L = 100 \text{ mm}, \\ \sin\left\{\left(\frac{m\pi}{2}\right)\left(\frac{z}{L} + 1\right)\right\}; & |z| < L. \end{cases} \quad (4)$$

$J_1(x)$ is the Bessel function of the first kind of first order and ν_n is n-th zero of the function. Since the system is assumed to have axial symmetry, j_θ is zero at $r=0$. Therefore, we excluded the Bessel function of the first kind of 0th order, and used the first order. R was assumed to be 20 mm because the measured magnetic field was 0 around 20 mm as shown in Fig. 9(a). Values of n were 1, 2 or 3. L was assumed to be 100 mm because the magnetic field was expected to be almost 0 for $|z| > 100$ mm as shown in the measured magnetic field distributions in Fig. 9(b). m was integers less than 13.

By substituting the Equations 2-6 in Eq. 1 and solving Eq. 1, we obtained the longitudinal magnetic flux density. The calculation region was $-300 \text{ mm} < z < 300 \text{ mm}$ and $0 \text{ mm} < r < 300 \text{ mm}$ and the number of mesh points were $K = 800$ along z direction and $L = 400$ along r direction. A_θ was defined as zero at the boundary. Then we fit the calculated magnetic field to the measured field by adjusting $c_{n,m}$ by means of the least square method. Here, we added points at $z = -100, -87.5, 90,$ and 100 mm on z axis to B_{exp} artificially. Namely, we assumed $B_{\text{exp}} = 0$ at $z = -100$ and 100 mm, and then assumed B_{exp} at $z = -87.5$ and 90 mm by linear interpolation. From the derived $c_{n,m}$ we obtained $j_\theta(z, r, t)$. Figure 11(a) shows the measured B_z and fitting curve at $z = 0$ as a function of r , and Fig. 11(b) shows those at $r = 0$ as a function of z for $t = 10 \mu\text{s}$. The figures show that the fit function represents the measured values well.

Figure 11: Measured and fitting distributions of B_z on the lines of (a) $z = 0$ mm and (b) $r = 0$ mm for $t = 10 \mu\text{s}$, which shows a good fit to the data.

5.2 Estimated current density distributions

Figure 12 shows the two-dimensional color maps of the estimated j_θ , azimuthal component of diamagnetic current, as functions of r and z at times of (a) 6, (b) 8, (c) 10, (d) 12, (e) 14, and (f) 16 μs , respectively. At 6 μs , a negative j_θ appeared around $z = -30$ mm and $r = 5$ mm. A non-zero j_θ did not exist for $z > 0$ mm because the front edge of the plasma plume at this time was just arriving at 0 mm as mentioned above. At 8 μs , the negative j_θ grew around $z = -20$ mm and $r = 5$ mm. In the radial direction, the negative j_θ was smallest around $r = 5$ mm and gradually became zero for $r > 5$ mm. A positive j_θ was induced around $z = 40$ mm. The absolute value of the positive j_θ was smaller than that of the negative one. In addition, the boundary at which j_θ changed from negative to positive was around $z = 20$ mm. After that, with increase in time from 8 to 16 μs , both the negative and positive values of j_θ dropped towards zero. Consequently, the difference of the negative and positive current became smaller. In addition, the boundary line between the negative current region and positive current region stays at the same place and created a conical shape in the plasma plume. Namely, the

transition point from negative to positive moved from $(z, r) = (0,0)$ to $(10,10)$. Moreover, the positive current region shifted to outside from $r = 5$ mm at $10 \mu\text{s}$ to $r=10$ mm at $16 \mu\text{s}$.

Figure 12: Two-dimensional distributions of diamagnetic current density at various time.

The figures show that j_θ penetrated the plasma plume from the outside as shown in the radial distribution from the plume center. Furthermore, j_θ was negative in the upstream side of the solenoid and positive in the downstream side. This shows that the diamagnetic current has a complex spatial distribution resulting from the penetration.

If we had a conductive rod, instead of the plasma plume, with uniform resistivity and velocity passing through the axial magnetic field, the diamagnetic current would be maximum at the rod surface. Meanwhile, according to the measurement, j_θ was not maximum at the plume surface but at the middle. The difference indicates that variation of the parameters of the plasma, such as the velocity, the density, and the temperature within the plume¹⁸⁻²² affects the j_θ map.

The diamagnetic current leads to radial a Lorentz force $j_\theta B_z$ on the plasma plume. At $8 \mu\text{s}$, the negative j_θ around $z = -20$ mm generates larger inward force towards the axis than the outward force generated by the weaker positive j_θ around $z = 40$ mm. As a result, the earlier part of the plasma plume coming around $8 \mu\text{s}$ is subjected to net inward force. At later measurement times when the tail of the plume passed, the net inward force decreased because the difference of diamagnetic currents became smaller.

As we observed in the Fig. 6, the plasma ion current density of the earlier part of the plume was particularly enhanced whereas the tail was barely affected. The facts mean that the head of the plume was guided by the net inward force. We checked that the impulse value by the net inward force is quite consistent with the

radial momentum of the focused ions. It was verified that the measured spatial and temporal distribution of diamagnetic current makes different guiding effects to ions depending on the plume position.

6. CONCLUSIONS

We measured the transient response of the axial magnetic field ΔB_z induced by the plasma injected into the solenoid by scanning a magnetic probe, which moved longitudinally and transversely with respect to the short solenoid axis. The results showed that the magnetic field penetrated into the center part of the plasma plume.

From ΔB_z , we derived the diamagnetic current density distribution. The results showed that the diamagnetic current was distributed from the center to the surface of the plume; the current was negative in the upstream portion and positive in the downstream portion. The diamagnetic current distribution was correlated to the plume dynamics measured with an ion probe, and showed that the distribution creates a complex guiding effect on ions within the plume.

With this study, a measurement and the estimation method with a magnetic probe scanning has been established. The probe is a powerful tool to analyze the temporal and spatial distribution of diamagnetic currents in the plume under the presence of an axially guided magnetic field. The systematic measurement of the current distribution using the probe will help us understand the interaction between the laser ablation plasma and magnetic field. The knowledge gained will help us to design more effective magnetic guiding fields to manipulate laser ablation plasmas.

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