Acceleration of a projectile with a high-power laser-produced magnetic field

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We report a new technique to accelerate a projectile with a high-power laser system with the output energy of ∼2 kJ. A large current is produced in a coil with a small capacitor irradiated by the laser pulse to generate a large magnetic field of ∼1 kT. A metal projectile is accelerated due to the interaction between the eddy current on the surface and the external magnetic field. We discuss the achievable velocity with this technique from the experimental results and numerical estimations.

Nomenclature

L	= Inductance
R_0	= Resistance of the coil
R_1	= Resistance of the projectile
d	= Distance between the coil and the projectile
r_0	= The radius of the coil
r_1	= The radius of the projectile
δ	= penetration depth
ρ	= Electric resistivity of the projectile
j	= Induced current on the surface of the projectile
F	= Lorentz force
B_z	= Magnetic field on z axis
B_r	= Magnetic field on r axis
μ_0	= Magnetic permeability
m	= Mass of the projectile
v	= Velocity of the projectile

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I. Introduction

Techniques for accelating projectiles can be applied to various uses such as high density material science, plasma physics, and space propulsions. Kadono *et al.* have reported the acceleration of a flyer at the maximum velocity of 11.2 km/s by laser-ablation in a laboratory,[1] and Ohno *et al.* have demonstrated vapor production as a result of an impact of a flyer accelerated with the same technique.[2] At Z machine facilities, the accelerations of flyer plates have been studied with pulsed-power-produced $\boldsymbol{j} \times \boldsymbol{B}$ force, and the maximum velocity of this technique is above 20 km/s. The high velocity flyer permits the study of the equation of state at high pressure above MBar.[3,4] In order to apply these technique to spacecrafts, projectiles should be accelerated with little power loss and with small damage on it. Therefore, the acceleration with electromagnetic force is suitable for spacecraft application.

Recently, Fujioka *et al.* have achieved nearly 1 kT magnetic field with high-power laser irradiation of double metal foils (capacitor) connected with a short conducting wire.[5] Though the duration of the field is only a few tens of nano seconds, its large $\boldsymbol{B}$ and $d\boldsymbol{B}/dt$ create large eddy current on the surface of the metal placed in the field. This current ($\boldsymbol{j}$) and $\mathbf{B}$ make a large propulsion on the projectile due to $\boldsymbol{j} \times \boldsymbol{B}$ force. This acceleration have been demonstrated by Saito *et al*[6] with a capacitor coil and a gold sphere. In this research, a projectile was disappeared from the field of view and the minimum velocity was estimated as 10 m/s.

In this paper, we propose a technique to accelerate a projectile with laser-produced large magnetic field and show the experimental demonstration. The maximum velocity is estimated from an assumed magnetic field shown in Ref.[5] The acceleration is demonstrated with high-power laser system Gekko-XII with a molybdenum disk target as a projectile. We modified the coil shape and the projectile from the experiment previously reported[6] to increase the projectile velocity.

II. Numerical estimation

Figure 1 shows the design of the acceleration target with a coil. As reported by Fujioka *et al*, a high-power laser with the laser intensity of $\sim 5\times10^{16}$ Wcm^{-2} enable us to generate ∼1 kT magnetic field in nano second time-scale.[5] The current produced in a coil is estimated as ∼1 kA using the coil diameter of 500 μm. Figure 4(b) shows the simulated time-variation of the magnetic field at $d = 0.2$ mm from the coil center assuming the current of 1 kA and $L/R_0 = 17$ ns, where R_0 and L are the resistance and inductance of the coil shown in Ref.[5]

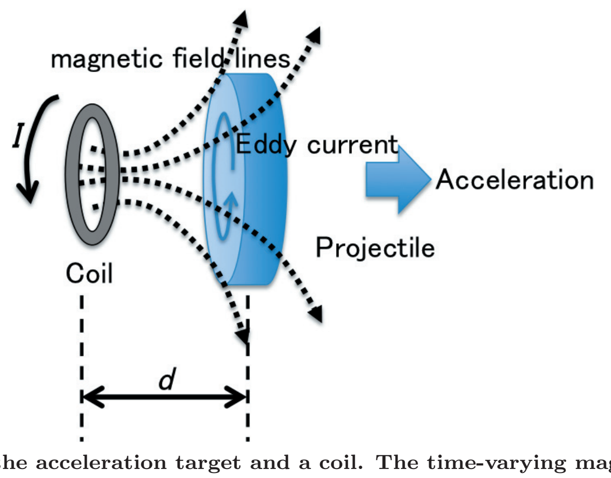

Figure 1. The design of the acceleration target and a coil. The time-varying magnetic field produces an eddy current on the surface of the projectile. As a result, the projectile is accelerated due to the $\boldsymbol{j} \times \boldsymbol{B}$ force.

The resistance of the projectile is written as

$$R_0 = \rho \frac{L}{A} \sim \frac{2\pi r_1}{\delta r_1} \quad (1)$$

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}, \tag{2}$$

where $r_1 = 250$ μm is the radius, $\rho = 2.21 \times 10^{-8}$ Ωm is the electric resistivity, $\omega \sim 2 \times 10^9$ is the frequency of the current in this experiment, and μ is the magnetic permeability. The induced current can be estimated using the resistance as follows:

$$j \simeq \frac{2\pi r^2}{R_1}\frac{dB_z}{dt} \tag{3}$$

Therefore, the repulsive force on the projectile is expressed as

$$\begin{aligned} F &= \oint jB_r dl \\ &\simeq \frac{dB_z}{dt}\frac{2\pi r_1^2}{R_1}B_r \cdot 2\pi r_1 \\ &= \frac{4\pi^2 r_1^3}{R_1}\frac{dB_z}{dt}B_r, \end{aligned} \tag{4}$$

and the time-evolutions of the induced current and the resultant Lorentz force are shown in Figs. 2(a) and 2(b), respectively. The velocity is calculated as follows:

$$v = \int \frac{F}{m} dt, \tag{5}$$

where $m = 4.0$ mg and is shown in Fig. 3 as a function of the time.

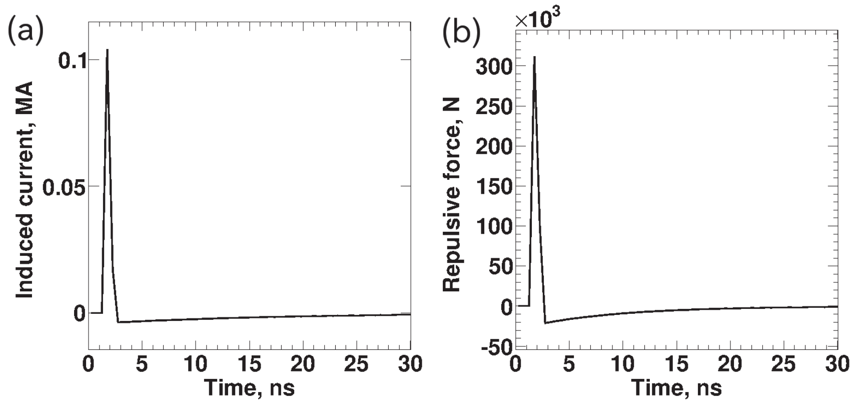

Figure 2. (a) The induced magnetic field and (b) the repulsive force estimated using Eqs. (3) and (4).

III. Experiment

We performed a model experiment of the acceleration of projectiles with high-power laser system Gekko-XII at Institute of Laser Engineering, Osaka University. The magnetic field was generated with the capacitor coil target made of copper. One of the capacitor foils was irradiated with three laser pulses which deliver 1.4 kJ in total in 1.3 ns with the wavelength of 1053 nm to generate hot electrons as shown in Fig. 4(a). These hot electrons are captured on the other disk, resulting in a potential difference between two disks.[5]

The projectile was located at 100–200 μm from the capacitor coil to generate the large eddy current on the surface. The accelerated projectile was observed with shadowgraphy using intensified charge-coupled devices (ICCDs) cameras and a high-speed camera (NAC Image Technology Inc.: ULTRA Cam HS-106E).

IV. Results and Discussion

Figures 5(a)–5(d) show the shadowgraphy images obtained before and after 10 μs, 14 μs, and 18 μs the laser irradiation, respectively. As indicated with a white arrow in Fig. 5(a), the disk is attached below the

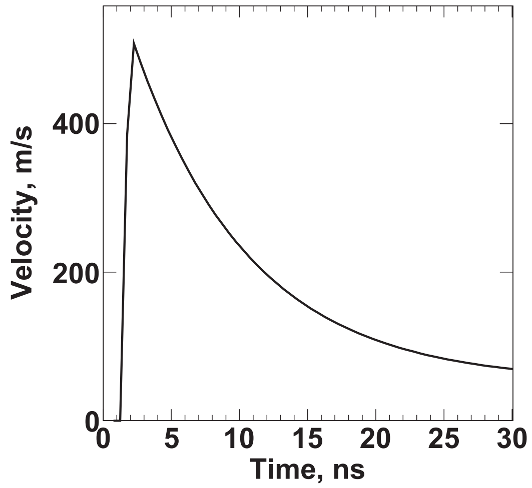

Figure 3. The velocity of the projectile as a function of time calculated from Eq. (5).

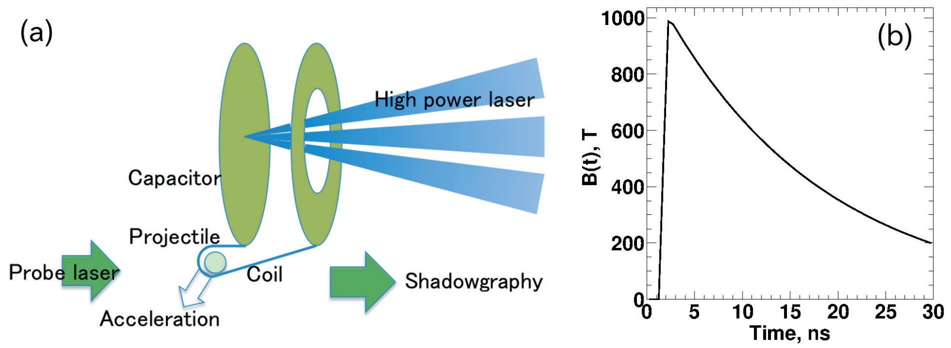

Figure 4. (a) The experimental setup and (b) the simulated magnetic field at the projectile.

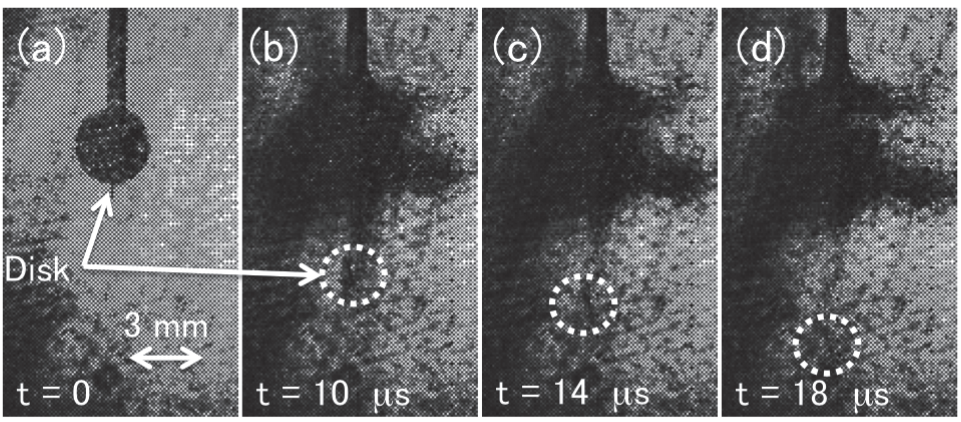

Figure 5. Shadowgraphy images at (a) t = 0, (b) 10 μs, (c) 14 μs, and (d) 18 μs.

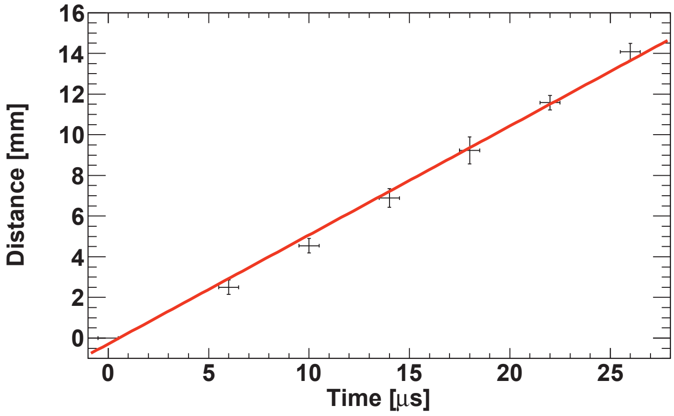

Figure 6. the projectile positions as a function of time. The solid line shows the linear fitting.

capacitor coil. As time passes, the disk moves downwards as shown with white circles in Figs. 5(b)–5(d) while the plasma around the capacitor is more or less in a same shape in $t \sim 10$–18 μs.

Figure 6 shows the distance of the projectile from the initial position as a function of time. The velocity of the projectile is obtained from fitting these points as $v \simeq 540 \pm 18$ m/s and shown with a solid line.

As we estimated in the section II, the projectile should be accelerated in the direction perpendicular to the coil (Left-hand side in Fig. 5). However, the experimental results show the acceleration in the downward direction as previously reported by Saito *et al.*[6] This suggests another force arising at the top of the projectile. The projectile is attached to a glass stalk with glue at the top, and the glue and/or glass stalk can be ionized by self-emission from the laser-produced plasmas. Therefore, this plasma can produce a large pressure on the projectile, resulting in a downward acceleration.

The acceleration by the magnetic field is not detected in the present experiment. This can be explained in the following reasons. First, the acceleration is proportional to both dB_z/dt and B_r as shown in Eq. 4. In this experiment the distance between the coil and the projectile was too close to produce large B_r and the repulsive force might be small even if the term dB_z/dt is large. Second, the duration of the magnetic field shown in Fig. 4(b) may not be enough to accelerate the projectile. The duration depends on the resistance R_0 and the inductance L of the coil. Therefore, we should optimize the coil and the capacitor for the acceleration.

V. Summary

We preformed the experiment to accelerate a projectile with a large magnetic field with a high-power laser system Gekko-XII. The trajectory of the projectile was observed by a high-speed camera and this result shows the velocity of 540 m/s. However, this acceleration is not explained by the magnetic field because the acceleration direction is different from the numerical estimation. For future work, we need to optimize the capacitor, coil, and laser conditions to generate appropriate field structure and the projectile design as well.

Acknowledgments

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