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Magnetic reconnection driven by Gekko XII lasers with a Helmholtz capacitor-coil target

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We demonstrate a novel plasma device for magnetic reconnection, driven by Gekko XII lasers irradiating a double-turn Helmholtz capacitor-coil target. Optical probing revealed an accumulated plasma plume near the magnetic reconnection outflow. The background electron density and magnetic field were measured to be approximately $10^{18}$ cm$^{-3}$ and 60 T by using Nomarski interferometry and the Faraday effect, respectively. In contrast with experiments on magnetic reconnection constructed by the Biermann battery effect, which produced high beta values, our beta value was much lower than one, which greatly extends the parameter regime of laser-driven magnetic reconnection and reveals its potential in astrophysical plasma applications. © 2016 AIP Publishing LLC.

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I. INTRODUCTION

Producing strong magnetic fields in a laboratory by using lasers is advantageous for doing research in various fields of physical science such as materials science,1 atomic and molecular physics,2 plasma and beam physics,3 and astrophysics.4–7 One example of its use is simulating plasma phenomena such as plasma magnetic reconnection (MR).8–13 MR, a topological rearrangement of magnetic field lines, is a fundamental physics process that occurs in many plasma phenomena such as solar flares, Earth’s magnetosphere, star formation, gamma ray bursts, and laboratory-produced fusion plasma.14–17 The most important feature of MR is that it can efficiently convert stored magnetic energy into kinetic energy by accelerating and heating plasma particles, leading to a new equilibrium configuration at a lower magnetic energy. MR has been observed in detail in experiments such as disruptions of tokamak discharges, and the relaxation processes in reversed field pinch and spheromak plasmas.16,18,19 Moreover, laser-driven MR experiments, mostly done by inducing a self-generated magnetic field on the surface of the laser target through the Biermann battery effect, have been widely performed in recent years.8–13 These experiments have revealed many notable features consistent with MR, such as magnetic field annihilation,9,13 jet formation,8,10–12 electron energization,12 and the stretched current sheet.13 However, because high-energy-density laser plasmas have complex three-dimensional effects, laser-driven MR still has issues, including the production of high-speed jets, the competition of thermal-plasma collisions, and the reconnection dissipation. The required conditions for laser-driven MR are an explicitly controlled magnetic field and a low-beta plasma environment, meaning that the magnetic pressure is dominant.

Producing a magnetic field by focusing laser beams on a planar foil target has many generation mechanisms,20 and compared with this magnetic field, the magnetic field produced by a coil is simple and explicit. Recently, Fujioka et al.21 reported that a $B$-field near 1.5 kT can be produced by driving a 1-kJ laser into a millimeter-scale capacitor-coil target, as first proposed by Daido et al.22 Building on this work, here we produced magnetic reconnection by using double-turn Helmholtz capacitor-coil targets, making our experiment quite different from earlier ones.8–13

Here, we use a Helmholtz capacitor-coil target consisting of two Ni disks connected by two Ni wires bent into circles. Adding photoionized and Joule-heated plasma near the two wires moving toward each other, together with the magnetic fields, could induce magnetic reconnection. Optical probing revealed an accumulated plasma plume near the magnetic reconnection outflow. Contrasting the most recent laser-driven MR experiment, which produced a high plasma beta value, our design produced a plasma beta value of much lower than one, which might be similar to the environments of some astrophysics plasmas such as the magnetosphere.

II. EXPERIMENT SETUP

Our experiments were performed at the Gekko-XII Laser Facility. Figure 1 shows the experimental setup and target configuration. The target, made of Ni, consisted of two disks

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connected by two U-turn coils. The distance between the two disks was 600 μm, and the thickness was 100 μm. Both the thickness and width of the U-turn coils were 100 μm, the distance between the connecting coils was 600 μm, and the length of the straight-line portion of the U-turn coils was 900 μm. We used laser beams to ablate the rear disk of the target through a hole in the front disk with a diameter of 1600 μm.

These experiments employed a laser configuration of two beams with wavelength of 1.05 μm, total energy of ~1.0 kJ, pulse duration of 0.5 ns, and a ~300-μm-diameter focal spot. With an irradiance of ~3 × 10^{15} W/cm², the laser beams ablated the rear disk, producing hot electrons with energies exceeding 10 keV in front of the rear disk, contributing to the electrical potential between the two disks; this potential difference drove two synchronized currents in the two U-turn coils. According to the Biot–Savart law, strong magnetic fields are generated near the coils. The magnetic field between the two coils is antiparallel and moves towards each other along with low-density plasmas, which were produced from the coils by X-ray radiation from the disks and Joule heating. The pulsed, oppositely directed B-fields along with those expanded plasmas encounter at the middle plane where the MR can occur, as shown in the inset of Figure 1.

The evolution of the plasma was investigated with optical probing, including shadowgraphy and interferometry, with a 10-ns probe laser beam (λ₀ = 0.532 μm). The B-field was measured by assessing the Faraday rotation of the polarization direction of the probe laser beam. The laser probe was incident along the coil axis and passed through a 0.5-mm-thick birefringent terbium gallium garnet (TGG) crystal with a Verdet constant of V = 11.35°/T mm) placed 3.6 mm from the middle plane of the two coils. To protect the TGG crystal from the X-ray radiation of the disks, we placed a 100-μm-thick Ta shield plate between the disks of the target and the TGG. The Faraday effect was assessed by measuring the two perpendicular components of the probe beam intensity, separated by a Wollaston prism and recorded by a time-resolved optical streak camera. The MR occurred between the two coils, and the self-emission of the reconnection outflow was also imaged by an intensified charge-coupled device (ICCD) camera.

III. RESULT AND DISCUSSION

The Faraday rotation angle θ is linearly proportional to the magnetic field component in the direction of the probe beam incident according to \( \theta = L \times V \times B \), where \( L \) is the length of the optical path in a birefringent medium: \( L = 0.5 \text{ mm} \) in our experiment. Figure 2(a) shows the streak image used to measure the magnetic field and gives the evolution of the horizontal \( I_H \) and vertical \( I_V \) components of the probe beam, from which we could determine the intensity ratio as \( I_H/(I_H + I_V) \). Figure 2(b) shows the variation of the intensity ratio.

First, the large variation, as noted by the dashed box in Fig. 2(b), was caused by the main lasers and the probe light overlapping with the main lasers during 7.0–7.5 ns. Then, after the lasers irradiated the target, the intensity ratio varied twice, as noted by the black and red triangles in Fig. 2(b), which we believe, were caused by Faraday rotation. The two rotations occurred are probably because the circuit currents in the two U-turn coils were synchronized, so both of the rotations were caused by the hot-electron current produced by the electrical potential of the two disks. Alternatively, the first rotation was caused by the synchronized circuit currents in the two coils, and the second rotation was caused by the...
reconnection electric field accelerating the electrons, which we will explain later.

Using the first variation of the ratio and the relationship between the ratio and the angle of the magnetostatic plane $I_H / (I_H + I_V) = \cos \theta / (\cos \theta + \sin \theta)$, we determined the rotation angle $\theta = 1.67^\circ$. In addition, even though the optical probe first passed through some plasma, the density of the plasma was too low to affect the probe’s rotation. Thus, the rotation of the optical probe within the plasma can be neglected. Using $\theta = L \times V \times B$, we calculated the $B$-field where the TGG is placed as 0.29 T.

Using the value of the $B$-field at 3.6 mm from the middle plane of the two coils, we easily obtained the $B$-field distribution of the double-turn coils by using Radia code. This code can simulate the initial shape of the double-turn coils with the same dimensions and material as the actual target. Figure 3(a) shows the $B$-field distribution computed in the X-Y plane of the double-turn coils. The simulated magnetic field lines at the middle plane of the coils ($Z = 0$) have opposite directions, and along the coil direction, the $B$-field is zero. The calculated $B$-field at 0.25 mm from the coil center reaches as high as 60 T.

In Figure 2, the magnetic field first develops at $\sim 1.5$ ns after the lasers fire, which agrees with a previous experiment that used only one coil. In the present case, after the magnetic field was produced first, the plasmas from the ionization of the two coils move towards the reconnection region, which is 300 $\mu$m from the coils. As mentioned before, the second Faraday rotation may have been caused by the electrons’ directional movement accelerated by the reconnection electric field. After magnetic reconnection occurred, the magnetic field changed quickly and induced the electric field, which was perpendicular to the magnetic reconnection plane and exactly along the U-turn coil, as shown in Figure 3(b). The electrons accelerated by the electric field moved along the U-turn direction and then induced the magnetic field, which caused Faraday rotation again. The inflow plasma velocity is assumed from interferometry.

In our experiment, we measured the evolution of the plasma around the coils by using interferometry, changing the optical probing beam’s delay time to 1, 2, or 3 ns. At 1 and 2 ns, the plasma around the coils was almost not produced. At 3 ns, the fringes shifted obviously, as shown in Figure 4(a). Based on the displacement distance of these fringes, $\sim 300 \mu$m, and the time interval of 1 ns, we deduced the velocity of the inflows to be $\sim 300$ km/s. The magnetic reconnection will occur after 1 ns, which is consistent with the experimental result shown in Figure 2. The second rotation component is the first time an induced electric field has been measured in a laser-driven magnetic reconnection experiment.

Figure 4(a) shows an optical Nomarski interferometry image, taken at 3 ns after laser irradiation. The coils of the target become expanded because of the X-ray radiation from the disks and the Joule effect; the probe beam could not pass through them, but the fringes outside the coils shifted dramatically, which indicates a change in density. The electron density outside the coils, $n_e$, can be inferred from the interferograms. To extract the phase data from the interferograms, we used the Interferometric Data Evaluation Algorithms (IDEA) suite of tools. While the expanding plasmas are not perfectly symmetric, we used the cylindrical symmetry approximation to approximate the electron density profile based on the Abel inversion technique. Figure 4(b) shows the two-dimensional electron density map, calculated by Abel inverting the interferogram; the electron density outside the coils (noted by the yellow arrow) is on the order of $10^{18}$ cm$^{-3}$. Considering symmetric expansion, the density of background plasma inside and outside of the coils should be on the same order.

Figure 5 shows typical shadow images and self-emission images (450 nm) of the Helmholtz target experiments. At a delay of 10 ns, the coil becomes expanded, as shown in Figure 5(a), just like in the interferometry image in Figure 4(a). The outflows accumulated at the interior of the coils, which appears from the two orthogonal directions shown in Figures 4(a) and 4(b); in this region, there is also strong self-emission, as shown in Figure 5(c). When magnetic reconnection occurred, the outflows moved towards the interior of the coils, collided with each other, and produced the accumulated plasma plume at high temperature. While the outflow plasmas spread quickly outside the coil, it is difficult to measure because its density becomes too low.

The magnetic field near the coils has been estimated by simulations to be tens of Tesla. When a low-density plasma expands from the surfaces of the Ni coils, two bent magnetic fields move together with a surrounding plasma. By magnetic reconnection process, the stored magnetic energy dissipated and released to accelerate and heat the plasma particles. Because the reconnection outflows in the coil can interact...
with the plasma from the disks, it produces an outflow with much greater density and energy. Moreover, the reconnection outflows will accumulate gradually inside the coils and eventually form the structure shown in Figure 5. Additionally, we estimate the plasma beta value near the coil as 

$$\beta = \frac{n_e (B^2/2\mu_0)}{\rho_e} = n_e k T_e (B^2/2\mu_0),$$

where the electron density is $n_e = 10^{24} \text{m}^{-3}$, the Boltzmann constant is $k = 1.38 \times 10^{-23} \text{J/K}$, and generally the electron temperature from the coils is $<100 \text{eV}$. Even if we choose an electron temperature of $T_e = 100 \text{eV} = 1.16 \times 10^6 \text{K}$ and a $B$-field of 50 T, the estimated plasma beta value is $\sim 0.016$, and it will be even smaller at a lower electron temperature. This low beta value indicates that in such a plasma environment, the plasma magnetic pressure dominates the plasma thermal pressure, causing a fast magnetic reconnection.

At the bottom of the coils, the magnetic reconnection x-point structure should have occurred when viewed from the Z–Y plane. However, we did not observe such a structure because the electron density outside the coils was too low. In a future experiment, we would add a foil away from the bottoms of the coils to produce additional magnetized low-density plasmas.

IV. CONCLUSION

This is the first laboratory-scale experimental study of magnetic reconnection with an explicitly controlled magnetic-field environment produced by a double-turn Helmholtz capacitor-coil target. Using the Faraday effect, we measured a $B$-field of 60 T around the coil. We also measured in this strong magnetic field an accumulated plasma plume, which appeared near the magnetic reconnection outflow. The observed Faraday rotation indirectly proves the existence of a reconnection electric field in a low beta magnetic reconnection, which suggests potential applications in astrophysics and plasma physics, such as in studying reconnection in solar flares and magnetotail.

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