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Generation of disc-like plasma from laser-matter interaction in the presence of a strong external magnetic field

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Abstract
Dynamics of laser produced plasma in a strong magnetic field was studied using a 1 MA pulsed power generator coupled to an intense, high-energy laser. A 2–2.5 MG magnetic field was generated on the surface of a rod load 0.8–1.2 mm in diameter. A sub-nanosecond laser pulse with intensity of $3 \times 10^{15}$ W cm$^{-2}$ was focused on the rod load surface. Side-on laser diagnostics showed the generation of two collimated jets 1–3 mm long on the front and rear sides of the load. End-on laser diagnostics reveal that the laser produced plasma in the MG magnetic field takes the form of a thin disc as the plasma propagates along the magnetic field lines. The disc-like plasma expands radially across the magnetic field with a velocity of 250 km s$^{-1}$. An electron temperature of 400 eV was measured in the laser-produced plasma on the rod load.

Keywords: laser matter interaction, magnetic fields, plasma disc

Magnetic fields dramatically change the properties of plasmas. The study of plasmas in strong magnetic fields is relevant to basic and applied plasma physics, astrophysics, controlled fusion, and Z-pinch physics [1–6]. Multi-MG magnetic fields can be generated by magnetic-flux compression using high explosive [7] or a pulsed-power machine [8]. Magnetic fields of 10–20 MG have been applied in the investigations of solids and semiconductors and for isentropic compression. The use of strong magnetic fields can improve the ignition conditions for inertial confinement fusion (ICF). An implosion of a plasma in a magnetic field ($B > 30$ MG), compressed by the Omega laser, increased the neutron yield of a ICF target [1, 2]. The compression and heating of a magnetized plasma are basic principles of a pulsed-power approach to controlled fusion [3, 4]. The magnetized liner inertial fusion concept is based on the compression of the pre-magnetized and laser-heated plasma during the implosion of a liner driven by the Z machine at Sandia National Laboratories. Simulations show that strong longitudinal magnetic field can enhance acceleration of protons generated in laser produced plasma [5].

Isochoric heating of solid targets in a strong magnetic field was proposed in [6]. PIC simulations were carried out for a 3–5 MG magnetic field and a 0.6 ps laser pulse with an intensity of $10^{18}$ W cm$^{-2}$. It was found that the magnetic field can slow down the diffusion of fast electrons, increase the energy deposition to the target, and increase the plasma temperature.

MA Z-pinches routinely generate MG fields. However, Z-pinch plasmas also generate a powerful x-ray burst and particle beams, and are hardly reproducible due to strong instabilities [9]. This makes it difficult to perform controlled studies of magnetized plasmas.

Laser produced plasma in external magnetic fields were studied in previous publications at smaller magnetic field values $B = 0.1–0.3$ MG [10–15]. It was reported that laser
plasma expands through the transverse magnetic field due to the drift in \( \mathbf{E} \times \mathbf{B} \) fields. The collimation and focusing of the plasma plume crossing the magnetic field at laser intensity of \( 10^8–10^{17} \text{ W cm}^{-2} \) was reported in [10–12]. The formation of a diamagnetic cavity in the expanding plasma was found in both experiments and simulations [10–13]. A shock wave at the plasma front was observed in [14]. Plasma instabilities in the magnetic field were studied in the laser interaction with planar and spherical targets [15].

However, only a small number of experiments were carried out with laser produced plasmas in external magnetic fields \( >1 \text{ MG} \), so the laser-plasma interaction with MG magnetic fields has not been explored before. Laser produced plasmas in the magnetic field can be investigated at a MA-class pulsed power machine coupled with a laser beam. A 1–3 MG magnetic fields can be generated by the metal rod load 0.8–1.5 mm in diameter or by a coil if 1 MA current flows in the load [16, 17].

In this Letter we present an experimental evidence of the formation of narrow disc-like plasma around a rod load with 1 MA current. Current in the load generated a magnetic field of 2–3 MG near the rod. The plasma was produced by a 0.8 ns laser pulse with an intensity of \( 3 \times 10^{15} \text{ W cm}^{-2} \) in the focal spot. Side-on laser diagnostics showed jets on the front and rear sides of the rod load while additional information from an end-on diagnostic identified that the plasma structure was disc-like with a radial size of 3–5 mm and a thickness of 0.2–0.6 mm. A velocity of the radial drift expansion of plasma was 250 km s\(^{-1}\). The electron temperature of the Al laser produced plasma on the rod loads was 400 eV.

Experiments were carried out at the Zebra pulsed power generator. The Zebra generator produced a 1 MA current pulse with a rising edge of \( \approx 80 \text{ ns} \) from 10% to 90%. The impedance of the transmission line of the generator was 1.9 \( \Omega \). Metal rod loads 0.8–1.2 mm in diameter were used for the generation of the MG magnetic field on their surface. Rod loads were installed within a current-return cage that was 8 cm in diameter.

The 50 TW Leopard laser coupled with the Zebra generator was used for investigation of laser interaction with the plasma [18–20]. The laser operated at the wavelength of 1057 nm in the long pulse regime with the pulse duration of 0.8 ns. The laser energy on the target was 18–20 J with a contrast of 10\(^6\). Using an F/5 lens, the laser radiation was focused to a 30 \( \mu \text{m} \) focal spot on the surface of the load, giving an intensity of \( 3 \times 10^{15} \text{ W cm}^{-2} \).

Laser probes were used to diagnose the plasma properties including one and two-frame diagnostics at wavelengths of 266 and 532 nm with a duration of the laser pulse of 0.2 ns. The direction of the side-on laser probing was orthogonal to the beam of the heating laser. A laser pulse for end-on probing propagated downward through the load. This required holes above and below the load in the anode and cathode structures, respectively. Below the load, the pulse was redirected out of the vacuum chamber by a turning mirror. A hole in the side of the hollow cathode structure allowed the light pulse to escape the cathode structure. The spatial resolution of laser diagnostics was 15–25 \( \mu \text{m} \). Images were recorded by charge-coupled devices (CCD). Narrow-band interference filters blocked self-emission of plasma on CCD cameras.

X-ray diagnostics included photoconductive detectors, time-integrated spectrometers with bent crystals, and a time-integrating pinhole camera. An x-ray spectrometer with a convex KAP crystal recorded the spectra in the range of 4–12 \( \text{Å} \) with a spectral resolution of 450. A spherically bent concave quartz 10–10 crystal worked in the range of 7.1–8 \( \text{Å} \) with a spectral resolution >1300 and spatial resolution of 0.1 mm.

External MG magnetic fields were generated by metal rod loads that were 0.8–1.5 mm in diameter. Plasma with a steep density gradient and an electron temperature of 5–15 eV appeared on the surface of the rod load and slowly expanded with a velocity of \( \approx 3 \text{ km s}^{-1} \) during the current pulse [16].

Figure 1(a) presents a simplified setup for the studies of the laser plasma in the MG magnetic field. Figure 1(b) shows a side-on shadowgram of the typical plasma plume delayed by 4 ns after the laser pulse without current in the rod load. Figure 1(c) shows a side-on shadowgram of the coupled shot of the Leopard laser with the Zebra generator at 6 ns after the laser pulse. Current in the load was 0.4 MA with an estimated magnetic field on the surface of 1.3 MG. The plasma on the rod load expanded to the diameter of 1.3 mm. Side-on shadowgram (c) displays two jets: the jet marked by number 1 propagates back from the focal spot on the load. The length of the front jet can reach 3 mm at the later stage. The smaller jet, marked by 2, is seen on the rear side of the rod load. Both plasma jets were observed in Al, Cu, and Ti rod loads 0.8–1.2 mm in diameter. The laser plasma drifting in the transverse magnetic field \( \mathbf{B} = 0.1–0.3 \text{ MG} \) was observed in [10–14]. A front plasma jet crossing the magnetic field was explained by the \( \mathbf{E} \times \mathbf{B} \) drift of the plasma in the electric field produced by a separation of charges in plasma due to the Larmor shift of ions. A plasma jet on the rear side of the target was observed in the laser-plasma interaction [21] without the magnetic field but at high laser intensity of \( 10^{19} \text{ W cm}^{-2} \). The rear jet was explained by the generation of a sub-MeV electron beam. However, generation of MeV electrons in our experiment is unlikely due to much lower laser intensity. A
small amount of MeV electrons can be generated at laser intensity of $3 \times 10^{18}$ W cm$^{-2}$ (see [22]) but they cannot produce plasma jets.

The rear jet can be explained by generation of a disc-like plasma structure around the load due to the plasma propagation along the magnetic field lines. Some of the features in the shadowgrams can be linked to the large size of the plasma in the direction of the side-on laser probing. First, plasma jet images in all shadowgrams demonstrate a diffraction structure which may be explained by a large horizontal size. Second, the plasma images are the same at wavelengths of 266 and 532 nm despite the large differences in plasma absorption and refraction [9]. The end-on laser probing was applied to reveal the structure of the plasma jets. Figure 2(a) presents an optical schematic for end-on and side-on probing at 532 nm in one shot. End-on shadowgraphy did not show any plasma jets. This means that the areal density of plasma was small in the vertical direction and plasma is distributed in a wide area. The more sensitive end-on dark-field schlieren diagnostic indicated gradients of the electron density in plasma. It showed that plasma is distributed along the magnetic field lines and has a disc-like shape in figure 2(b). White circles in the image of figure 2(b) show plasma gradients. Shock-like ring structures are seen in the image of plasma. The plasma disc is not symmetric with a longer radial size and higher density of the front plasma. The formation of the disc-like plasma is a feature of the expansion of plasma in the presence of a MG azimuthal magnetic field. Plasma expansion is observed up to 12 ns after the laser pulse. An x-ray image (f) of the laser plasma with current in the load is horizontally elongate compared to image (e) taken without current. Spatial resolution of the pinhole camera is 0.1 mm. A line of sight view of the pinhole camera shows that a tail of the x-ray spot can be explained by the better collimated plasma in the magnetic field. A smaller size, $\sim$0.5 mm, of the x-ray jet in figure 2(f) compared to 1–2 mm jets in shadowgrams can be linked to the fast radiative cooling of the expanding plasma. A plasma density is smaller in the rear part of the disk-like plasma as it is shown in side-on shadowgrams. Rear plasma is difficult for observation in end-on images and absent in the x-ray image in figure 2(b).

The expansion velocity of the front plasma near the Al rod load is calculated from the data plotted in figure 3. A plot shows the radial size of the front plasma as a function of the delay of the diagnostic pulse. The data are taken from shots with the load current in the range of 0.8–1 MA. The average velocity of the radial expansion of plasma in the plot is $250 \pm 30$ km s$^{-1}$. An electron density of plasma of $(1–3) \times 10^{18}$ cm$^{-3}$ was measured by the end-on interferometry at the 6 ns delay at the distance 1.5–2.5 mm. The density decreases with a plasma expansion. Shock-like rings with increased plasma density and gradients were seen on the main plasma of the disc. The electron density in the plasma ring was $7 \times 10^{18}$ cm$^{-3}$.

Figure 4 shows the laser plasma generated on the Ti load 1.6 mm in diameter taken with a 2 ns delay. Laser intensity is the same as for the data in figure 3 but current and the magnetic field are smaller, 0.2 MA and 0.7 MG respectively. The front plasma, marked by 1 in the side-on magnified shadowgram (b), exhibits a more complicated structure compared to those in figures 1–3 and consists of symmetric sub-jets in the plane of the image. This difference may be linked to the different regime of interaction at the sub-MG magnetic field. A plasma object numbered by 2 in figure 4(a), on the rear side in shadowgram, consists of the plume and a narrow jet in the plume. Magnified image (c) shows a zone with the enhanced plasma instability, numbered by 3, on the front surface of the load in the vicinity of the focal spot. The vertical size of the zone of the laser-initiated instability on the load is $\pm 1.3$ mm. This zone is clearly seen on the smooth plasma surface of the rod at currents $<$0.7 MA when
the magneto-Rayleigh–Taylor instability has not had time to develop on the load yet. This instability zone can be linked to a propagation of the shock wave along the load surface. The velocity of motion of the instability zone in the axial direction is 200–250 km s$^{-1}$. This velocity is close to the velocity of the radial motion of plasma to vacuum.

X-ray spectroscopy was used in the Al K-shell range to measure the temperature of Al laser plasmas with and without current in the rod loads. Pinhole camera images in figures 2(g) and 2(h) show hot plasma only in the close vicinity of the focal spot. Cold plasma of the disc body is not seen in the sub-keV x-ray range of the spectrometers. The current produced plasma on the surface of the rod load, with a temperature of 10–15 eV, does not radiate in the keV range, therefore, it cannot impact spectral measurements of the laser plasma. First, the electron plasma temperature was calculated from the relative intensities of He$\alpha$ and satellites (j + k) as in [23]. The satellites were resolved by the quartz crystal spectrometer. Second, Al K-shell spectra from the convex KAP crystal were fit by the synthetic spectra calculated with a PrismSpect program. Details of calculations are presented in [24]. The electron temperature in the range of 395–405 eV was calculated from spectra in shots both with and without current in the load. Intensity of x-ray radiation of laser produced plasma was higher when current flowed in the rod load. This may be explained by plasma on the load surface which was already created by current before the interaction with the laser pulse.

To explain the experimental results presented above let us first note that for the maximum magnetic field values in our experiment the electron Larmor frequency is larger than the electron-ion collision frequency. For the electron density $n_e = 2 \times 10^{18}$ cm$^{-3}$ and the magnetic field $B = 2$ MG the Hall parameter is equal to 7.3 (assuming the electron temperature of 0.4 keV, $Z = 11$ and the Coulomb logarithm of 6). Therefore the electron transport in the directions perpendicular to the magnetic field (radial and axial directions) is limited by the magnetic field, and the plasma takes a disc-type shape due to the fast motion of particles along the magnetic field lines. The Debye length for these plasma parameters is equal to 0.1 $\mu$m and is smaller (although not by a large margin) than the Larmor radius which is equal to 0.24 $\mu$m. The oscillatory velocity of electrons in the laser field with the intensity of $3 \times 10^{18}$ W cm$^{-2}$ is equal to $1.5 \times 10^{3}$ km s$^{-1}$ and is comparable to the electron thermal velocity of $8.4 \times 10^{3}$ km s$^{-1}$. The energetic electrons generated in the focal spot can move along the magnetic field lines in the azimuthal direction and cause the corresponding change in the ion density.

It was found that the velocity of the radial expansion and the velocity of the axial propagation of the instability zone along the load are close to each other pointing to the similar expansion mechanism in both directions. The theoretical analysis of the plasma expansion into vacuum in an external magnetic field can be performed for a half-space [25], and it includes the magnetosonic waves that depend on the relation between the two characteristic velocities: the ion-acoustic velocity $c_{ia}$ and the Alfven velocity $v_A$. For our Al plasma with the electron temperature of 0.4 keV, $Z \sim 11$, and the electron density $n_e$ on the order of $10^{19}$ cm$^{-3}$, the ion-acoustic and Alfven velocities are: $c_{ia} = 130$ km s$^{-1}$, and $v_A = 440 \times B$(MG)/(ne(10$^{19}$ cm$^{-3}$)$^{1/2}$)(km s$^{-1}$). When $n_e = 7 \times 10^{18}$ cm$^{-3}$ and $B = 0.7$ MG, the Alfven velocity $v_A = 370$ km s$^{-1}$. The magnetic $\beta$-parameter is $\beta = 2(c_{ia})^2/ (v_A)^2$, and for the maximum magnetic field values in our experiments $\beta$ is smaller than unity. The velocity of plasma expansion in the Cartesian half-space geometry [25] is close to the fast magnetosonic velocity $v_M S = ((c_{ia})^2 + (v_A)^2)^{1/2}$. For $v_A$ and $c_{ia}$ estimated above, $v_M S = 390$ km s$^{-1}$ and is comparable to the average plasma expansion velocity in our experiment $v = 250$ km s$^{-1}$. The difference can be attributed to the spatial inhomogeneity of the external magnetic field and the cylindrical geometry in the experiment. A detailed modeling of the plasma dynamics in the MG field will be performed in the future with a 3D MHD code.

In conclusion, the experiments presented in this Letter show that laser-produced plasma in the presence of an external MG azimuthal magnetic field takes the unique form of a thin disc expanding in the radial direction.

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