Generation of Strong Magnetic Fields for Magnetized Plasma Experiments on a 1-MA Pulsed-Power Machine

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Introduction

The development of techniques for the generation of strong magnetic fields provides an opportunity to investigate plasmas in megagauss (MG) fields. Strong magnetic fields change basic properties of hot and dense plasma. Studies of magnetized plasmas are relevant to basic and applied plasma physics, controlled fusion research, and astrophysics. Astrophysical magnetic fields can reach a value of 10^9 MG in magnetars[1] and a value of 1 to 100 MG in white dwarf plasma.[2] High magnetic fields also provide an increased neutron yield in inertial confinement fusion.[3] A 30- to 40-MG magnetic field plays a key role in the magnetized liner inertial fusion (MagLIF) approach to fusion.[4] Magnetic fields change the dynamics of plasma expansion,[5–7] the development of plasma instabilities, and parametric effects. Laser–plasma interactions in external magnetic fields display unusual plasma expansion such as the generation of disk-like plasma in a 2- to 3-MG transverse magnetic field.[7] Narrow plasma jets are generated in the longitudinal magnetic field.[5,6] Astrophysical magnetized plasmas can be scaled to laboratory plasmas.[5] Megaampere-class pulsed-power machines routinely generate MG magnetic fields.

Plasma in an Azimuthal Magnetic Field

Unusual dynamics of plasma expansion in the azimuthal 1- to 3-MG magnetic field of a rod load were observed in Ref. 7. Here, the results of an additional series of shots are presented. Figure 1(a) shows a scheme of the laser–plasma interaction (LPI) experiment with a laser pulse focused on the surface of the Al rod load 0.9 mm in diameter. A current in the load generates an azimuthal magnetic field. The laser intensity in the focal spot is 3 to 5×10^{15} W/cm^2. Without the laser pulse, a strong magnetic field contains plasma that arises on the surface of the load. After the laser shot, side-on laser-imaging diagnostics show the formation of two plasma jets on the front and rear sides of the load. The shadowgrams in Figs. 1(b) and 1(c) present jets of laser-produced plasma at 6 ns after the laser pulse. The magnetic field on the surface of the rod is $B = 1.3$ MG. One plasma jet propagated out from the focal spot; the second smaller jet was seen on the rear side of the rod load. Diagnostics with a tilted probe [Fig. 1(c)] explain the front and rear jets as parts of a plasma disk around the load. Plasma propagated along the magnetic field and formed a thin disk around the load with ring structures in it.

The radial size of the disk is longer and the plasma density is higher in the front half-disk, so the disk is not symmetric. Plasma expansion is observed during >10 ns after the laser pulse. The electron plasma density in the rings is 6 to 8×10^{18} cm^{-3}. The formation of the disk happens only in the presence of the strong azimuthal B field. Two-frame shadowgrams and interferograms show that the disk expands radially with a velocity of ~250 km/s. The electron temperature of the plasma is measured from the x-ray Al K-shell spectra to be about 400 eV in the area of interaction. Plasma disks were observed in LPI with Al, Cu, and Ti rod loads.

Two-dimensional cylindrical magnetohydrodynamic (MHD) simulations of the plasma in the strong transverse magnetic field were performed in Ref. 8. The simulations with the current in the rod that resulted in a magnetic field of 3 MG on the rod

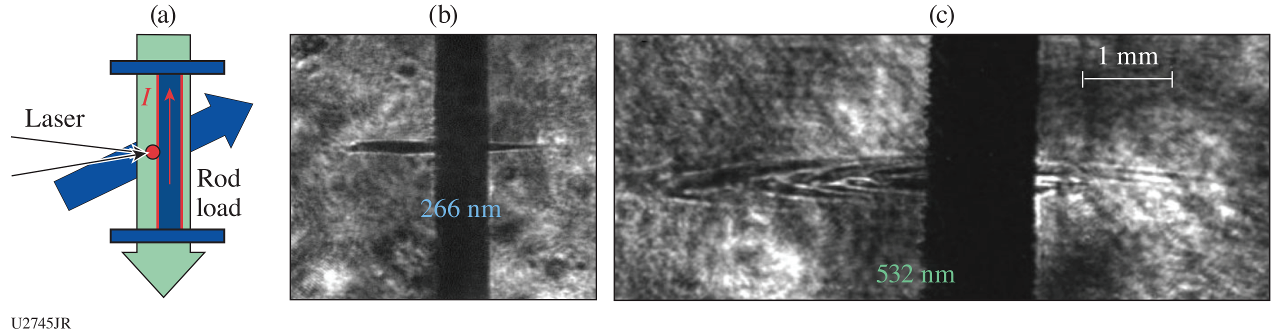

Figure 1
(a) Experimental setup; [(b),(c)] side-on shadowgrams of a plasma disk [with a tilted probe beam in (c)].

showed the formation of the density wave localized in the axial direction and moving in the radial direction. The propagation of the density wave continues after the end of the laser pulse. The azimuthal magnetic field strongly changes in time in the region of the density wave due to magnetic-field generation by crossing density and temperature gradients. The change in the azimuthal magnetic field due to the density wave is comparable to the magnitude of the azimuthal field generated by the current in the rod. The magnetic β parameter at 1 to 2 ns after the laser pulse is about 1 and decreases after the pulse. The thermal pressure is responsible for the motion of the plasma. When plasma moves in the radial direction away from the rod, the thermal pressure decreases and the magnetic pressure has the main role in the plasma expansion. The density of the plasma in the MHD simulations is shown in Fig. 2 and is in agreement with the side-on shadowgrams in Fig. 1(b).

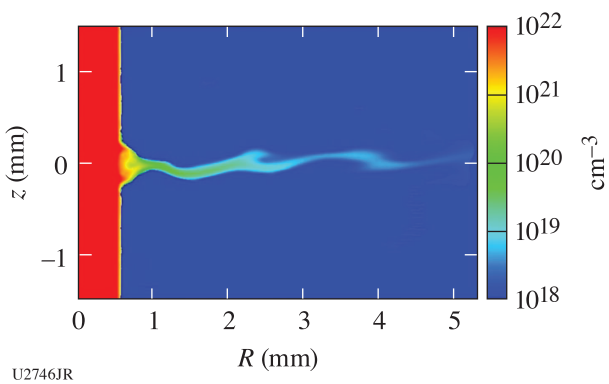

Figure 2
Density of ablated plasma in the external magnetic field of 3 MG at 4 ns after the end of the laser pulse.

Plasma in the Longitudinal Magnetic Field

Plasma takes the shape of a jet in the longitudinal magnetic field of 0.1 to 0.2 MG (Ref. 5). A 1-MA pulsed-power machine allows for the investigation of plasma jets in higher magnetic fields.[6] Plasma in the B field of the coil was produced by the Leopard laser operated with a 0.4-ps pulse. Intensity of the laser beam in the focal spot was 2 to 6 × 10^{18} W/cm^2. The laser target was placed at 1 mm from the copper coil 2.5 to 3 mm in internal diameter. The axial B field at this point was 0.5 to 0.7 MG, depending on the timing relative to the current pulse. A Si laser target was used to avoid the influence of eddy currents. The size of the target was 2 × 2 mm^2 and 10 μm thick. The interferogram and shadowgram in Fig. 3 illustrate the collimation of plasma and the formation of the long plasma jet on the front side and the shorter rear jet in the B field of 0.7 MG. A plasma plume begins focusing at ~1 mm from the target and forms a narrow jet. The velocity of propagation of the jet tip calculated is ~200 km/s. Laboratory plasma jets of this type can be scaled to the astrophysical jets.[5] In MHD simulations, plasma expands, forming a jet, and the magnetic field in the plasma is much weaker than the external magnetic field. At the same time, the magnetic field at plasma edges increases and becomes larger than the external field that results in collimation due to magnetic pressure. While the magnetic field is compressed at the edges of the jet, it is much smaller inside the jet forming the magnetic-field envelope. This

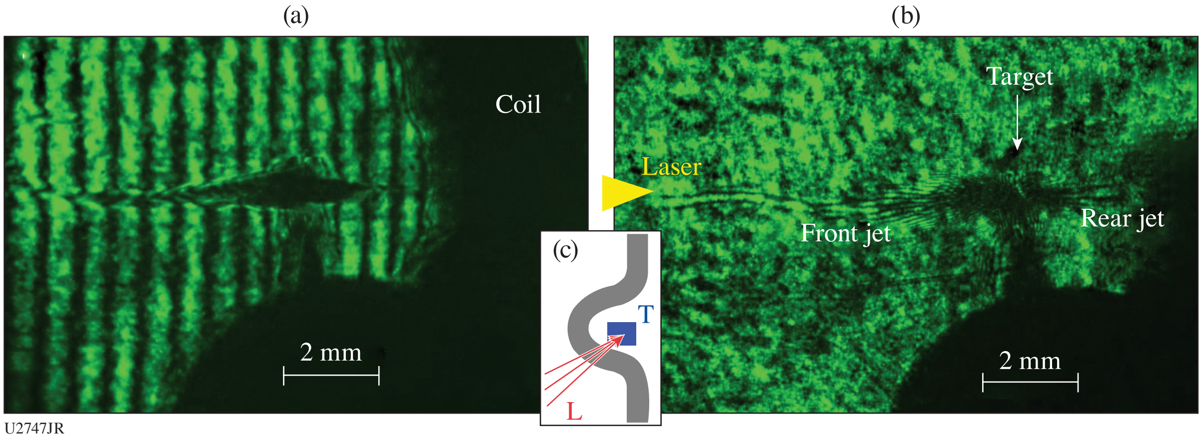

Figure 3
(a) Interferogram and (b) shadowgram of the Si target during the current and the magnetic field in the coil load at 7 ns after the laser pulse; (c) a schematic of the laser beam (L) and target (T) near the coil load.

envelope maintains the collimated jet during all its evolution. Later the diffusion of the magnetic field into the envelope makes the field inside the envelope close to the field on its edge. A plasma jet in a magnetic field depends on the magnetic β parameter being small. Figure 4 shows the expansion of the jet tip in simulations (the dashed line), and the tip positions in experiment and simulations are in a good agreement.

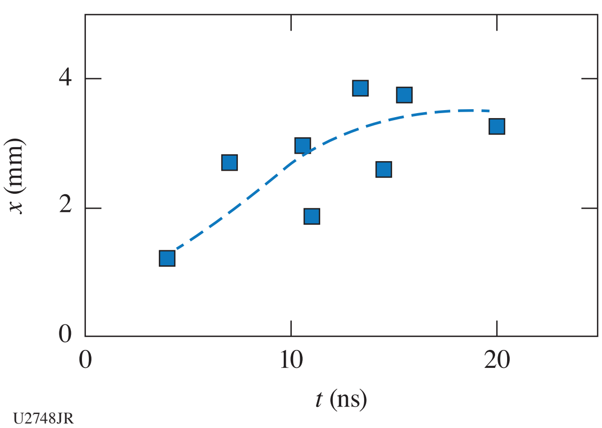

Figure 4
Positions of the jet tips (squares). MHD simulation (dashed curve).

Two-Plasmon Decay in the MG Magnetic Field

Two-plasmon decay (TPD) plays an important role in LPI. TPD occurs near one quarter of the plasma critical density n_c for the laser frequency ω_0, and the resulting two Langmuir waves (plasmons) have "blue" and "red" spectral shifts compared to the $\omega_0/2$ frequency. Wave conversion involving these two plasmons generates new light waves with frequencies around $\omega_0/2$. Wave conversion involving TPD plasmons can also generate light with frequency around $3/2\omega_0$, which easily leaves the plasma and makes a robust diagnostic. The strong magnetic field produces a shift proportional to the square of the electron Larmor frequency ω_e:~ $(\omega_{ce})^2/\omega_0$ in addition to the thermal shifts of the "red" and "blue" spectral components.[9] The narrowband Nd:glass laser used in the TPD experiments generated pulses at 1053 nm with $\Delta\lambda_0$ ~ 10 pm and an energy of 6 J at 2 ns. Al and Ni rod loads 1 mm in diameter were used to generate the magnetic field of 2 to 3 MG in the surface plasma. A laser pulse was focused on the rod surface with an intensity of 1 to 3 × 10^{14} W/cm^2. An intensified charge-coupled–device (ICCD) camera was used to record the $3/2\omega_0$ emission.

Figure 5(a) presents $3/2\omega_0$ spectra from the Al rod load. The strong 2- to 3-nm widening and 2- to 4-nm shift of "red" and "blue" $3/2\omega_0$ spectral components were observed. Both red and blue $3/2\omega_0$ components are clearly seen but the blue component is weaker. The $3/2\omega_0$ emission was not seen in Ni and Cu loads. $3/2\omega_0$ emission can be observed only if TPD instability develops, and the TPD threshold is inversely proportional to the density scale length. The strong $3/2\omega_0$ emission in Fig. 5(a) is an indication of extended plasma with a gradual density profile, and the absence of $3/2\omega_0$ emission is an indication of more-localized plasma with a steep density profile.

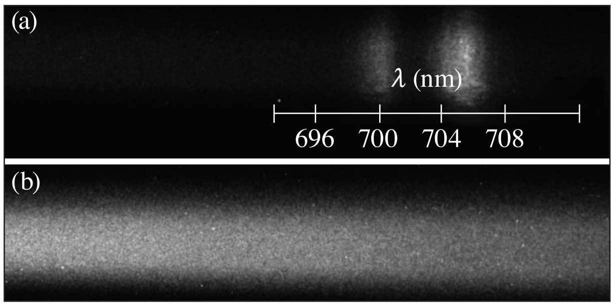

Figure 5
(a) Spectra of $3/2\omega_0$ harmonics from the Al rod load recorded by an ICCD camera with a 3-ns gate; (b) spectrum from the Ni load.

Conclusion

In this work, it was shown that the 1-MA pulsed-power machine provides a robust platform for experiments with plasma in MG magnetic fields. The dynamics of expansion of the laser-produced plasma in the strong transverse and longitudinal magnetic fields were studied with the rod and coil loads. The expanding plasma takes the shape of a thin plasma disk in the azimuthal field of the rod load. Plasma is confined in the vertical direction by the 2- to 3-MG magnetic fields. In the longitudinal magnetic field, laser-produced plasma generates narrow 3- to 4-mm jets with a density of 10^{19} to 10^{20} cm^{-3}. The TPD parametric instability generates wide and shifted "red" and "blue" components of $3/2\omega_0$ emission in the 2- to 2.7-MG field. Finally, pulsed-power technology provides a capability for the investigation of plasmas and laser–matter interaction in 1- to 4-MG magnetic fields at the university-scale machine.

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1. D. M. Palmer *et al.*, Nature **434**, 1107 (2005).
2. S. Jordan *et al.*, Astron. Astrophys. **462**, 1097 (2007).
3. P. Y. Chang *et al.*, Phys. Rev. Lett. **107**, 035006 (2011).
4. A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).
5. B. Albertazzi *et al.*, Science **346**, 325 (2014).
6. V. V. Ivanov *et al.*, Phys. Plasmas **26**, 062707 (2019).
7. V. V. Ivanov *et al.*, Plasma Phys. Control. Fusion **59**, 085008 (2017).
8. L. S. Leal *et al.*, Phys. Plasmas **27**, 022116 (2020).
9. N. G. Basov *et al.*, JETP **65**, 954 (1987).