Modeling Magnetic Confinement of a Laser-Generated Plasma in Cylindrical Geometry Leading to Disk-Shaped Structures

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Strong magnetic fields can play a pivotal role in the dynamics of a plasma.[1,2] Understanding the interactions in plasmas in strong fields is important for many areas of plasma physics, ranging from basic and applied plasma physics to astrophysics, controlled fusion, and Z-pinch experiments.[3–8] Understanding plasma dynamics and transport in laser-produced plasmas in strong external fields has become an important area of research in inertial confinement fusion after the demonstration of fusion yield enhancement in laser-driven implosions[9] and the most recent demonstrations of the magnetized liner inertial fusion concepts at Sandia National Laboratories.[10,11] Recent work from Lawrence Livermore National Laboratory[12] showed that by increasing the initial seed field to 60 T or 0.6 MG, the compressed field in National Ignition Facility implosions can reach hundreds of megagauss, reduce heat losses, and even confine the alpha particles. For an effective alpha-particle confinement, the compressed B field must be large enough that the thermal and magnetic pressures become comparable, as is the case in experiments of laser-generated plasmas in strong external magnetic fields.[13,14] Modeling of these experiments can lead to a broader understanding of plasma dynamics and transport. Recent experiments at the University of Nevada, Reno[13,14] have shown that laser-produced plasmas in strong magnetic fields generated by pulsed-power machines form localized structures that have unique plasma characteristics and exist for many nanoseconds after the end of the laser pulse. The experiments produced a plasma by shining a laser with a 1.056-μm wavelength and 0.8-ns pulse duration at an intensity of ~3×10^{15} W/cm^2 with a 30-μm spot size on an Al rod. The rod had a 1-mm diameter and 0.8 to 1 MA of current driven by the Zebra pulsed-power machine. A low-density, cold plasma was initially formed on the rod surface from the current and generated a magnetic field that was measured through Faraday probes to be 200 to 300 T. The laser ablated plasma of the rod surface and within nanoseconds after the laser pulse, the plasma formed a disk-shaped structure that expanded in the radial direction. Measured values using laser probing and x-ray spectroscopy showed the plasma had electron densities of the order of $n_e \sim 10^{18}$ cm^{-3}, average electron temperatures $T_e \sim 400$ eV, and an expansion velocity of $v \sim 250$ km/s. In modeling this interaction, further insight can be gained of the magnetohydrodynamic effects in laser-generated plasmas in strong magnetic fields.

A series of *HYDRA* simulations are discussed here with parameters similar to the conditions of experiments at the Zebra facility.[13] Current driven through an Al rod generates azimuthal $B_\theta \sim 3$ MG at the surface of the rod. In experiments the current pulse time is hundreds of nanoseconds—much longer than the laser pulse and interactions leading to the generation of the disk. In the simulations, the external magnetic field is set by the boundary conditions generating the current in the rod and the 3-MG field at the surface of the rod is similar to what was detected in experiments. A laser with wavelength $\lambda = 1.057$ μm illuminates the rod surface once the magnetic field has been initialized, ablating plasma with a pulse duration of 0.8 ns. The laser is injected through the *HYDRA* laser ray-trace package and enters from the large radius boundary in simulations. The simulations are 2-D with symmetry around the vertical axis. Without an external magnetic field, the ablated plasma is ejected in all directions away from the target rod. The presence of the MG magnetic field greatly affects the dynamics of the ablated plasma. The structure formed by the ablated plasma is well confined in the axial direction but continues to move in the radial direction at velocities of 300 to 600 km/s. Figure 1 compares simulation results at 3 ns after the end of the laser pulse for the plasma generated by

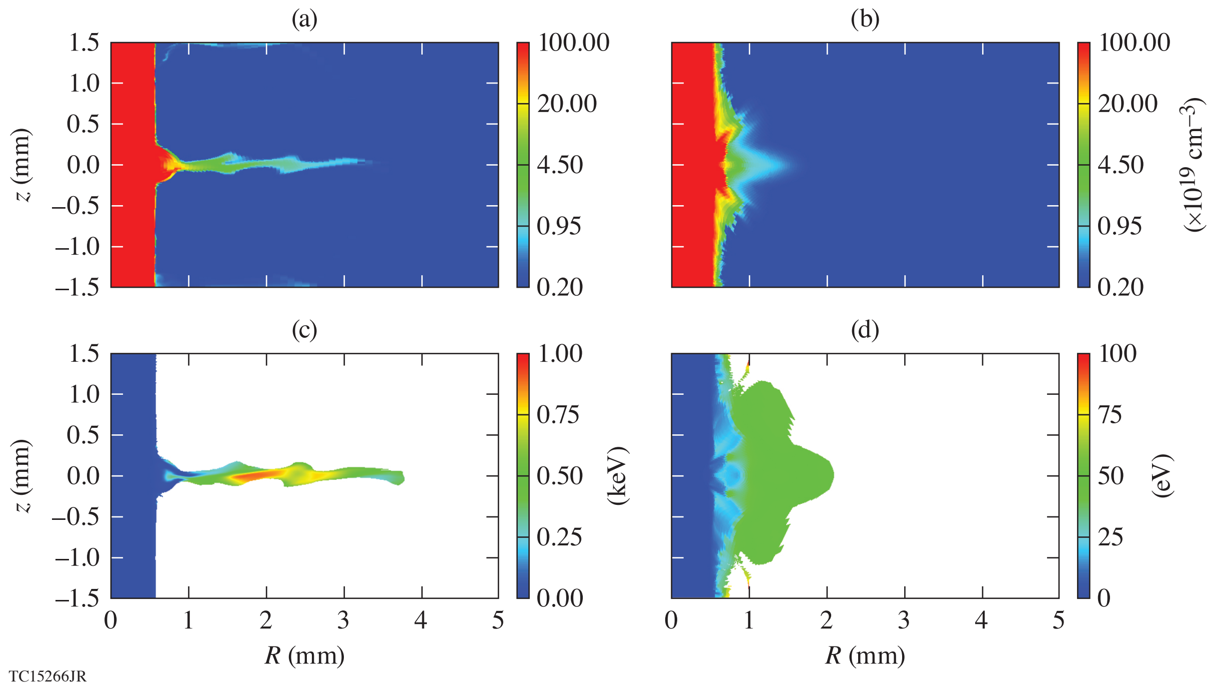

Figure 1
Electron density and temperature of laser-ablated plasma in the case [(a) and (c)] with and [(b) and (d)] without the external magnetic field, respectively, at 3 ns after the end of the laser pulse.

the laser for two cases: with current flowing through the rod (generating the 3-MG field) and without current flowing through the rod. The electron density and temperature in Fig. 1 illustrate the overall structure of the expanding plasma. For the plot of electron temperature, only the area of the ablated plasma is shown, not the "vacuum" region, which in simulations is a very low density plasma that does not affect the overall expansion of the disk plasma but can exhibit numerical noise. It can be seen from Fig. 1(a) that the plasma in the disk is underdense to the laser in the range of $n_e \sim 10^{18}$ to 10^{19} cm^{-3} but more dense and much more extended than in the unmagnetized case [Fig. 1(b)]. The plasma is fully ionized and is contained within the width of 0.1 to 0.2 mm. This collimated plasma structure, when rotated around the axis, would resemble a disk. The plasma of the disk is also much hotter than the plasma without an applied external B field. A feature seen in experiments is the presence of rings in the disk similar to Fig. 1(a) if it is rotated azimuthally.

The 2-D modeling is an important step in comparing with experimental results. The motion of the plasma following the field lines around the rod appears to be a 3-D effect of the plasma being pinched in the axial direction and leading to spreading in the azimuthal direction. The external magnetic field in the MG regime is strong enough to apply magnetic pressure that reshapes the structure of the ablated plasma, as seen in both experiment and simulation. Simulations are able to demonstrate that the strong external magnetic field outside the formed plasma provides plasma confinement in the axial direction. Interaction of laser-generated fields with the external magnetic fields leads to asymmetry of the magnetic field inside the disk. As we have shown, applying strong external fields to laser-generated plasmas leads to complex plasma structures that can be used to study fundamental plasma physics and astrophysical phenomena. The large variation in the Hall parameter also allows one to study how plasma transport properties vary as weakly magnetized plasmas transition into strongly magnetized plasmas.

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