# Diagnosing Magnetic Fields in Cylindrical Implosions with Oblique Proton Radiography

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Cylindrical implosions can be used to amplify an applied axial magnetic field via flux compression, which can be used to study fundamental plasma physics in high magnetic fields[1] and is a key feature of the magnetized liner inertial fusion (MagLIF) energy scheme.[2] Previous experiments on the OMEGA Laser System have measured flux compression in cylindrical implosions using proton radiography.[3,4] These experiments were followed by the development of the laser-driven MagLIF platform,[5] which uses smaller-diameter cylindrical targets with a higher maximum convergence that reach maximum convergence more quickly. However, attempts to use proton radiography with this platform to measure the compressed axial magnetic field in the same manner as previous work have so far been unsuccessful, primarily due to the impact on the radiographs of other strong electric and magnetic fields near the target. This summary analyzes the results of two recent experiments that attempted to measure the compressed magnetic field in a cylindrical implosion using the laser-driven MagLIF platform and demonstrate how the measurement is obscured by the presence of self-generated magnetic fields.

Two experiments were conducted [hereinafter Exp. 1 and Exp. 2 using the setup shown in Fig. 1(a)]. In both experiments, the target is a plastic (CH) cylinder imploded using 40 beams (1.5-ns square-shaped pulse, total energy 16 kJ) with an overlapped intensity of $10^{14}$ W/cm$^2$. In Exp. 1 the target is gas filled (14 atm $H_2$), which is preheated by an axial beam prior to compression as in MagLIF. In Exp. 2 the cylinder interior is initially vacuum but soon fills with CH plasma when the shock driven by the compression beam breaks out into the interior. A set of external coils driven by MIFEDS (magneto-inertial fusion electrical discharge system)[6] provides an axial magnetic field (9 T in Exp. 1, 5 T in Exp. 2). An unmagnetized shot (with the coils in place but not energized) was taken in Exp. 1. Experiment 2 was identical except for the thickness of the cylinder and the addition of a foil to block some of the protons [visible in Fig. 1(d)].

Proton radiography[7] is used to diagnose the fields. A D$^3$He backlighter capsule 11 mm from the cylinder is imploded by 16 beams to produce 3-MeV and 15-MeV protons. The protons pass through the target cylinder walls with negligible scattering (verified on the unmagnetized shot) but are deflected by electric and magnetic fields in the vicinity of the target. The protons are then recorded on two CR-39 plates (shielded by 7.5 $\mu$m of tantalum and separated by 200 $\mu$m of aluminum to differentiate between the two proton energies) at a distance of 270 mm. In both experiments, the timing of the proton source is chosen to match the peak convergence of the implosion (which is also the peak of neutron production, or "bang time") at $t = 1.5\pm0.1$ ns. Due to the target chamber geometry, in both experiments the proton radiography axis is tilted relative to the target normal by an angle $\theta_T$, making this "oblique" proton radiography.

To directly compare simulations to experimental results, synthetic proton radiographs are generated using an open-source particle-tracing algorithm that was developed for the PlasmaPy project as part of this work.[8] Three-dimensional simulations of the experiment, including the coronal plasma produced by the compression beams, were performed using the multiphysics

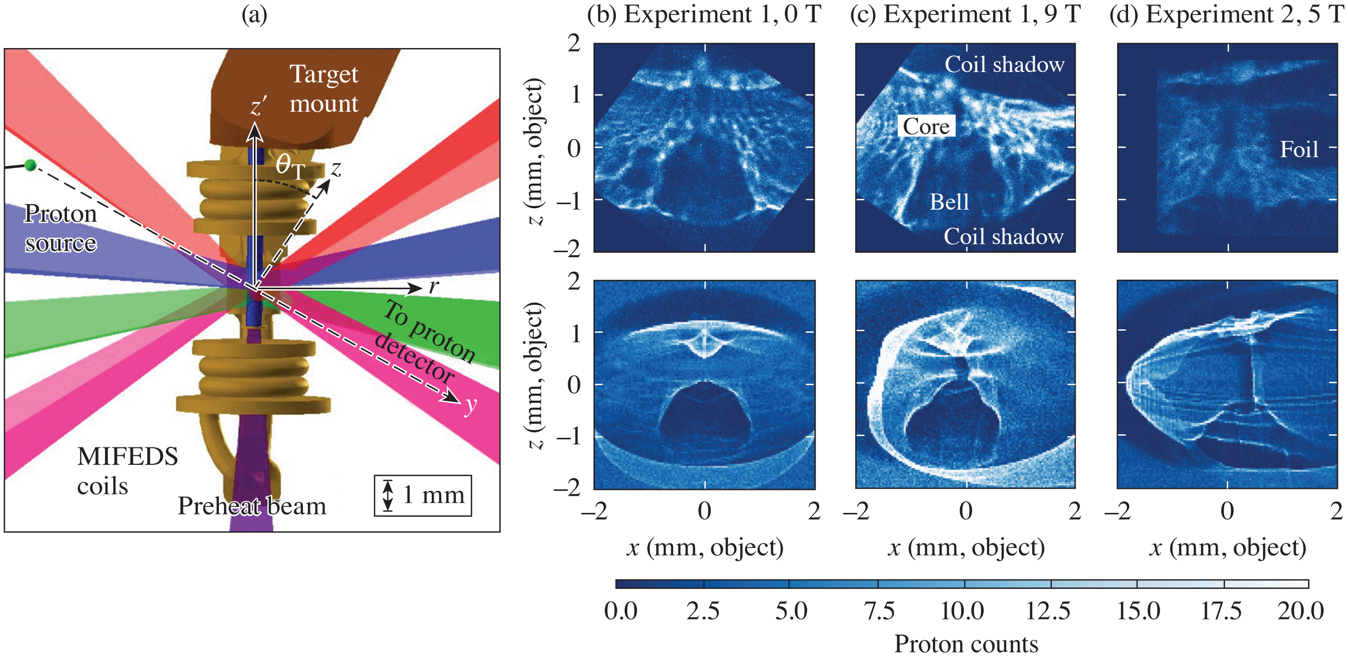

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Figure 1
(a) A diagram of the setup for Exp. 1, with only a subset of the compression beams shown for clarity. (The setup for Exp. 2 is similar.) [(b)–(d)] Experimental proton radiographs (top row) for both experiments and the corresponding synthetic radiographs (bottom row) show good agreement.

radiation-hydrodynamic code *HYDRA*. A population of test protons was then traced through the simulated electric and magnetic fields and onto a detector to create synthetic radiographs. The resulting radiographs for Exp. 1 are shown in Figs. 1(b)–1(c) and Fig. 1(d) shows the radiograph for Exp. 2. All radiographs contain similar features. The “bell”-shaped feature is created by self-generated azimuthal magnetic fields in the coronal plasma produced by the drive beams, while the “core” feature visible on the magnetized radiographs is due to the compressed axial field. Small ripple features on the experimental data are not reproduced in the synthetic radiographs: this “small-scale structure” is likely due to kinetic effects such as instabilities or charge-separation fronts. Shadows are visible at the top and bottom of the experimental radiographs where protons are blocked by the MIFEDS coils.

Several approaches, including direct inversion algorithms, are applied to try and recover the line-integrated magnetic field from the experimental radiographs. However, while these techniques work reasonably well with the synthetic data, the loss of protons in the shadows of the MIFEDS fields and the presence of the small-scale structure prevent them from working with the experimental data. It is concluded that these experimental radiographs are consistent with the presence of a compressed axial field, but that a measurement of the compressed field is prevented by the self-generated azimuthal magnetic fields in the coronal plasma and the small-scale structure fields.

These results are compared to previous experiments on the OMEGA Laser System,[3,4] which successfully measured the compressed axial magnetic field in a similar cylindrical implosion. Comparing the design of this experiment to the current work provides guidance for the design of future work, suggesting that the radiography angle $\theta_T$, target dimensions, laser pulse duration, and coil geometry are important parameters that determine the feasibility of this type of measurement. In many experiments, the ability to change these features is limited by other design considerations. However, future attempts to measure compressed axial magnetic fields in cylindrical implosions should include among these considerations the potential impact of self-generated fields on the measurement.

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