Observed Suppression of Self-Generated Magnetic Fields in a Laser-Driven Cylindrical Implosion

P. V. Heuer,[1] L. S. Leal,[1] J. R. Davies,[1] E. C. Hansen,[1] D. H. Barnak,[1] J. L. Peebles,[1] and A. Birkel[2]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Plasma Science and Fusion Center, Massachusetts Institute of Technology

The spontaneous generation of magnetic fields in plasmas is responsible for the creation of astrophysical magnetic fields from the primordial universe to stellar environments. Self-generated magnetic fields are also key features of many laboratory experiments on subjects ranging from laboratory astrophysics to inertial confinement fusion. Once generated, these fields can substantially alter particle and energy transport in the plasma, fundamentally modifying the plasma dynamics. Accurate computational modeling of magnetic-field self-generation is therefore crucial to correctly simulating these systems.

Many systems of interest require large simulation volumes and/or resolutions that are only computationally tractable using magnetohydrodynamics (MHD). However, recent theoretical articles[1,2] comparing MHD and Vlasov–Fokker–Planck (VFP) kinetic simulations have predicted that kinetic (nonlocal) effects neglected in MHD could lead to a substantial overestimate of self-generated magnetic fields in MHD simulations. This discrepancy could result in substantial errors in MHD simulations that include regions of low collisionality (where kinetic effects are non-negligible). This is particularly (but not exclusively) significant for laboratory experiments with laser-produced plasmas, which self-generate magnetic fields within the relatively low-density ablated plasma.

Results from a cylindrical implosion experiment on the OMEGA Laser System recently provided the first experimental evidence directly demonstrating the suppression of self-generated magnetic fields relative to MHD simulations in an inertial confinement fusion experiment. This measurement is made using oblique proton radiography, which allows axially resolved measurements of self-generated azimuthal magnetic fields that are undetectable at normal incidence. Comparisons to synthetic radiographs generated using simulated fields show that the observed field is a factor of ~0.4× smaller than predicted by MHD. Simulation results also indicate that nonlocal effects are likely responsible for this discrepancy.

The experiment utilizes a platform[3] initially developed for studying laser-driven magnetized liner inertial fusion (MagLIF)[4] on the OMEGA Laser System. The target is a gas-filled (11 atm D_2) parylene-N cylinder (CH, 20 μm thick, outer diameter of 580 μm) imploded using 40 beams (1.5-ns square pulse length, 16-kJ total energy) with an overlapped intensity of 10^{14} W/cm^2. Prior to compression, an axial beam (180 J) blows down a thin window on the end of the cylinder and preheats the D_2 gas. A set of external coils driven by MIFEDS (magneto-inertial fusion electrical discharge system)[5] provides an axial magnetic field (B_z = 9 T) for one shot but is inactive for a second unmagnetized shot. Proton radiography[6] is used to diagnose the self-generated magnetic fields.

The multiphysics radiation-hydrodynamics code *HYDRA*[7] is used to perform two 3-D simulations of the unmagnetized experiment with different flux limiters (f = 0.15 and f = 0.05) and one simulation of the magnetized experiment (f = 0.15). Varying the flux limiter tests the extent to which it affects the Biermann battery mechanism by modifying the electron temperature gradients.[2] The unmagnetized simulation results (Fig. 1) show a coronal plasma expanding away from the axis as the cylinder implodes. Steep density and temperature gradients are present within the ablated plasma and the cylinder. The dominant electromagnetic field components are a radial electric field $E_r \sim 10^7$ V/m and an azimuthal magnetic field $B_\varphi \sim 50$ T. The orientation of this mag-

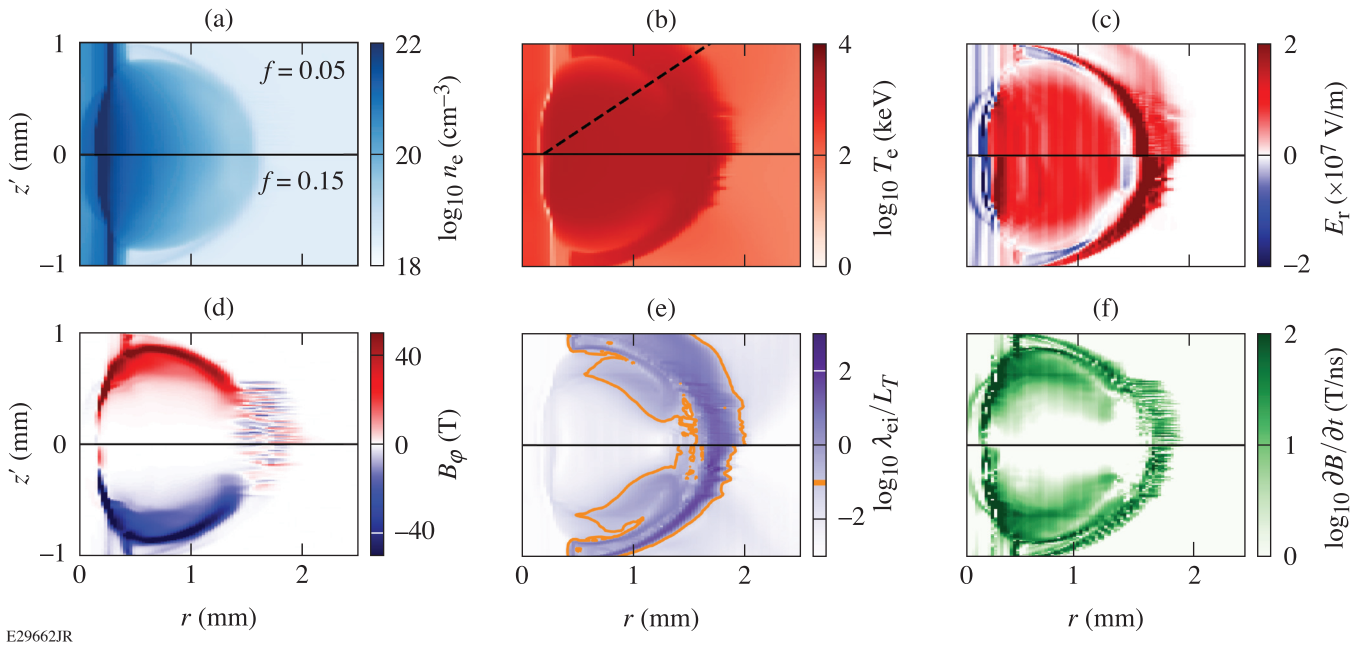

Figure 1
HYDRA outputs of the (a) electron density, (b) electron temperature, (c) radial electric field, (d) azimuthal magnetic field, (e) nonlocality parameter λ_{ei}/L_T, and (f) MHD Biermann battery source term at $t = 0.9$ ns. The top and bottom halves of each plot show the $f = 0.05$ and $f = 0.15$ unmagnetized simulations, respectively. An orange contour in (e) marks the region $\lambda_{ei}/L_T > 0.1$, where nonlocal effects are expected to be significant.

netic field is consistent with it being generated by the Biermann battery mechanism due to nonparallel temperature and pressure gradients in the coronal plasma. The magnetized simulation is comparable, but it also includes a compressed axial magnetic field at the center of the cylinder. The self-generated magnetic field is found to be insensitive to the choice of flux limiter.

To determine the possible impact of nonlocal effect on thermal transport, the nonlocality parameter λ_{ei}/L_T is calculated from the *HYDRA* results, where $L_T = T_e/\nabla T_e$ is the gradient length scale of the electron temperature T_e and λ_{ei} is the electron ion mean free path; and $16\pi\varepsilon_0^2 T_e^2/Z n_e e^4 \log\Lambda$, and where ε_0 is the permittivity of free space, n_e is the electron density, and e is the fundamental charge. The mean ion charge is $Z = 4$ and the Coulomb logarithm is $\log\Lambda = 8$. Significant nonlocal effects are expected when $\lambda_{ei}/L_T > 0.1$ (Ref. 8). The MHD Biermann battery source term, $\partial B/\partial t = \nabla T_e \times \nabla n_e/e n_e$ is also calculated. Comparing these quantities [Figs. 1(e) and 1(f)] shows that substantial Biermann growth is predicted within the region of the ablated plasma where nonlocal effects are expected to be significant.

The primary feature observed in the experimental proton radiographs is a bell-shaped region of depleted proton flux [Fig. 2(a)], from which 15-MeV protons have been deflected in z by at least 0.1 rad (since a corresponding peak is not visible on the radiograph). This deflection is in the nonlinear regime,[6,9] so a linear inversion to recover the integrated field is not possible. However, as an order-of-magnitude estimate and assuming a length scale of ~1 mm, an electric field of $E \sim 10^9$ V/m or magnetic field of $B \sim 50$ T is required to reproduce the observed deflection. Comparing these values to those predicted by the MHD simulation ($E_r \sim 10^7$ V/m, $B_\varphi \sim 50$ T) indicates that the azimuthal magnetic field must be responsible.

To directly compare *HYDRA* 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.[10] Direct comparisons show that the synthetic radiographs reproduce the bell feature observed in the experimental radiographs [Fig. (2a)]. To make a quantitative comparison, a horizontal lineout is taken through the center of the bell region [averaging in z over the shaded region in Fig. 2(a)]. The normalized intensity lineout comparisons in Fig. 2(b) show that the bell-shaped depression in the synthetic radiographs is

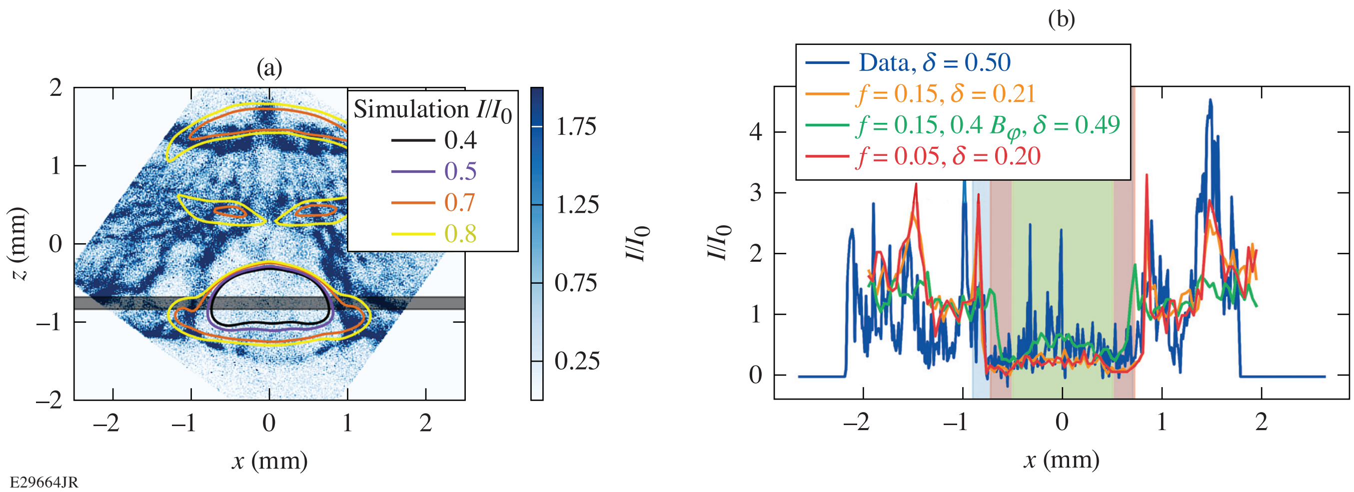

Figure 2
(a) A synthetic radiograph created using the fields from the unmagnetized $f = 0.15$ simulation (contours) qualitatively reproduces the bell-shaped depression observed in the 15-MeV proton radiograph from the unmagnetized experiment (image). (b) Lineouts through the gray-shaded region in (a), normalized to their mean. The $f = 0.05$ and $f = 0.15$ simulations are identical, but both overpredict the measured depletion [δ = mean $\left(I/I_0\right)$ averaged over the shaded region in (b)] by a factor of ~2. Reducing the simulated B_φ by a factor of ~0.4 reproduces the depletion of the experimental radiograph.

twice as deep as measured in the unmagnetized experiment. This result implies that the azimuthal magnetic field measured in the experiments is significantly weaker than predicted by the MHD simulation. Similar comparisons with different flux limiters as well as the magnetized shot support the same conclusion.

We hypothesize that this discrepancy is the direct effect of a non-Maxwellian distribution on the Biermann battery source term. The measured reduction in the self-generated magnetic field is consistent with previously published work comparing Biermann battery growth in MHD and VFP simulations.[1] This measurement constitutes experimental evidence for the previous theoretical prediction that nonlocal effects result in the overprediction of self-generated fields in MHD simulations.

This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

1. M. Sherlock and J. J. Bissell, Phys. Rev. Lett. **124**, 055001 (2020).
2. C. P. Ridgers *et al.*, Phil. Trans. R. Soc. A **379**, 20200017 (2021).
3. J. R. Davies *et al.*, Phys. Plasmas **24**, 062701 (2017).
4. S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010).
5. G. Fiksel *et al.*, Rev. Sci. Instrum. **86**, 016105 (2015).
6. N. L. Kugland *et al.*, Rev. Sci. Instrum. **83**, 101301 (2012).
7. M. M. Marinak *et al.*, Phys. Plasmas **8**, 2275 (2001).
8. A. R. Bell, R. G. Evans, and D. J. Nicholas, Phys. Rev. Lett. **46**, 243 (1981).
9. A. F. A. Bott *et al.*, J. Plasma Phys. **83**, 905830614 (2017).
10. PlasmaPy Community *et al.*, PlasmaPy (Version 0.6.0), Zenodo, Accessed 14 March 2021, http://doi.org/10.5281/zenodo.4602818.