Measuring Magnetic-Flux Suppression in High-Power Laser–Plasma Interactions

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In high-power-laser–produced plasmas, strong magnetic fields can be spontaneously generated by a number of mechanisms, although the primary source is the Biermann battery effect caused by nonparallel temperature and density gradients $\left(\partial B/\partial t \propto \nabla T_{\mathrm{e}} \times \nabla n_{\mathrm{e}}\right)$. A detailed understanding of self-generated magnetic fields is critical to laser-fusion research because strong fields can influence thermal energy transport and potentially impact the evolution of hydrodynamic instabilities. Laser-driven magnetic fields also enable laboratory investigations of magnetized astrophysical phenomena, especially magnetic reconnection.

The extended-magnetohydrodynamics (extended-MHD) framework has been developed to describe transport of energy and magnetic fields in high-energy-density (HED) plasmas.[1] Predictive modeling used in concert with experimental observations is often essential for developing and interpreting both laser-fusion and laboratory astrophysics experiments. Although relatively simple in the broader context of HED experiments, a single laser spot interacting with a foil target can provide a powerful platform for validating extended-MHD modeling.

Using proton deflectometry to make high spatial and temporal resolution measurements of magnetic-field generation driven by moderate laser intensities (I_{L} = 10^{14} to 10^{15} W/cm^2), recent experiments demonstrated that simulations of laser–foil interactions must incorporate key physical processes such as Biermann battery field generation and Nernst advection.[2,3] By varying the target material the influence of atomic or radiation physics on transport and field dynamics can be explored. Incorporating radiation transport into extended-MHD simulations reproduced recent experimental observations of two distinct regions of magnetic-field generation around radiation-driven double ablation fronts in mid-Z targets.[4]

In that work, however, it was found that extended-MHD simulations overestimated the generated magnetic flux. It is anticipated that nonlocal effects not captured by the extended-MHD framework can suppress the rate of Biermann battery field generation in regions where the electron mean free path (λ_{ei}) approaches (or exceeds) the local temperature-gradient length scale $\left(l_T = \left|T_{\mathrm{e}}/\nabla T_{\mathrm{e}}\right|\right)$. Using empirical fits to kinetic simulations, Sherlock and Bissell[5] developed a scaling for the suppression of classical Biermann battery generation rates as a function of the ratio $\lambda_{\mathrm{ei}}/l_T$.

In this summary, experimental observations of magnetic flux are used to help validate extended-MHD simulations that include the new scaling for nonlocal suppression of Biermann battery field generation, as well as radiation transport. Experimental data are drawn from two campaigns performed with the OMEGA EP laser. Magnetic-field generation was driven by either one[4] (I_{L} = 2.2×10^{14} W/cm^2) or two overlapped[3] (I_{L} = 4.4×10^{14} W/cm^2) UV laser pulses interacting with thin foil targets. The foil material was varied between 50-μm-thick plastic (CH), 25-μm copper, 25-μm aluminum, or 50-μm aluminum coated with either 1 μm of copper (Cu + Al) or gold (Au + Al). Self-generated magnetic fields were imaged by protons in a point-projection geometry.

In both experiments a high-intensity laser pulse was used to produce a proton probe via the target normal sheath acceleration mechanism. A 1-D polar-coordinates field reconstruction technique was developed to extract quantitative path-integrated magnetic-field information from radial lineouts through the proton images.[4,6]

Experimental measurements were compared to extended-MHD simulations performed using the Gorgon code,[1] which was updated with the option to include the new scaling for suppression of magnetic-field generation due to kinetic effects (referred to throughout as "Biermann suppression"). The results for CH foil targets are summarized in Fig. 1. Proton images show the evolution of magnetic-field structures using the higher laser intensity ($2I_0$, overlapped pulses) in Fig. 1(a). Corresponding reconstructed magnetic-field profiles are plotted in Fig. 1(b). Figure 1(c) compares the evolution of the azimuthal magnetic flux from the experiment and extended-MHD simulations for both laser intensities. Simulations without Biermann suppression greatly overestimate the magnetic flux (>5×). Agreement is significantly improved by including Biermann suppression, indicating that this effect is likely influencing the field dynamics. In the simulations, the suppression results in a 3× to 4× reduction in the predicted magnetic flux.

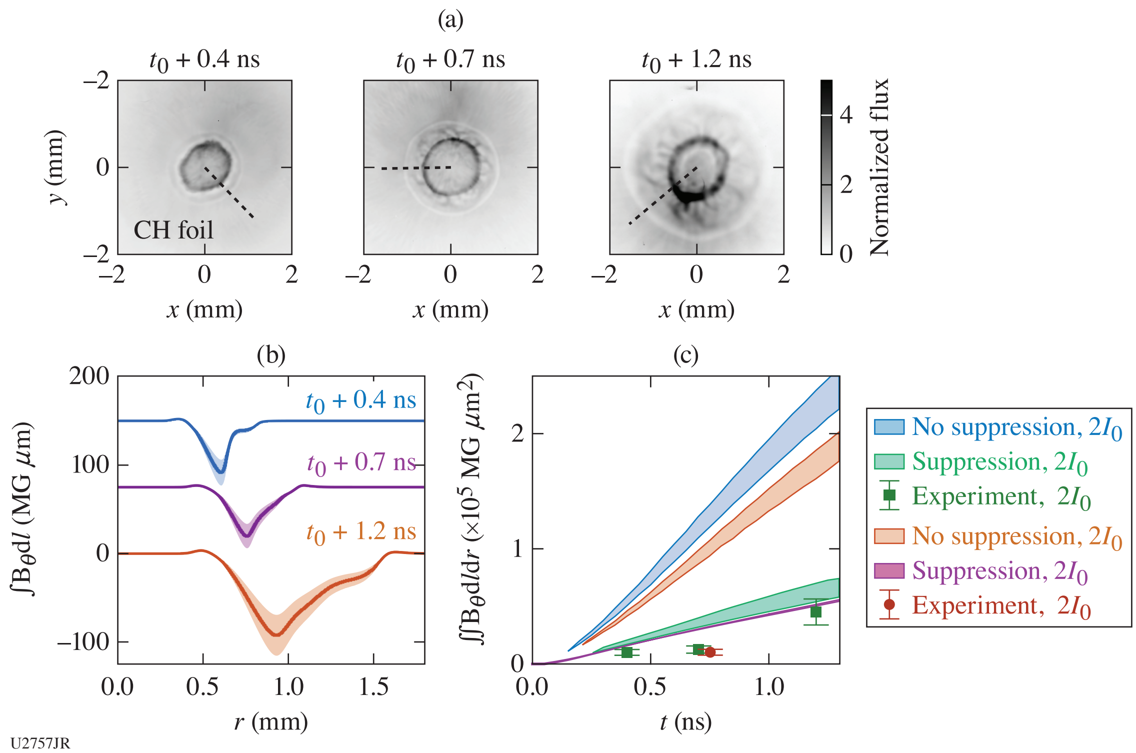

Figure 1
Comparison of experimental and simulation results for CH foils. (a) Proton images of fields driven by the higher, overlapped laser intensity ($2I_0$) taken at 0.4 ns, 0.7 ns, and 1.2 ns. Radial lineout locations are indicated by dashed lines. (b) Reconstructed magnetic-field profiles (offset vertically for clarity). (c) Magnetic-flux predictions from simulations both without and with Biermann suppression for each laser intensity are compared to experimental measurements. Upper and lower bounds on the simulation results are produced by tuning the laser energy to approximate the influence of energy-coupling efficiency (corresponding to ~90% and ~70% coupling, respectively).

Figure 2 summarizes the results for Cu foil targets with the lower laser intensity. As with CH targets, the simulations without suppression overestimate the flux, although the discrepancy is not as large. For Cu targets, however, the Biermann suppression model reduces the predicted flux below experimental observations. Overall, the simulation and experimental results suggest that nonlocal suppression effects are more significant for low-Z targets. Without Biermann suppression, simulations with Cu targets predict lower magnetic flux than the CH results, likely due to additional radiative losses at higher Z, reducing temperature gradients. In contrast, the experimental measurement of the magnetic flux increases when the target changes from CH to Cu. The same

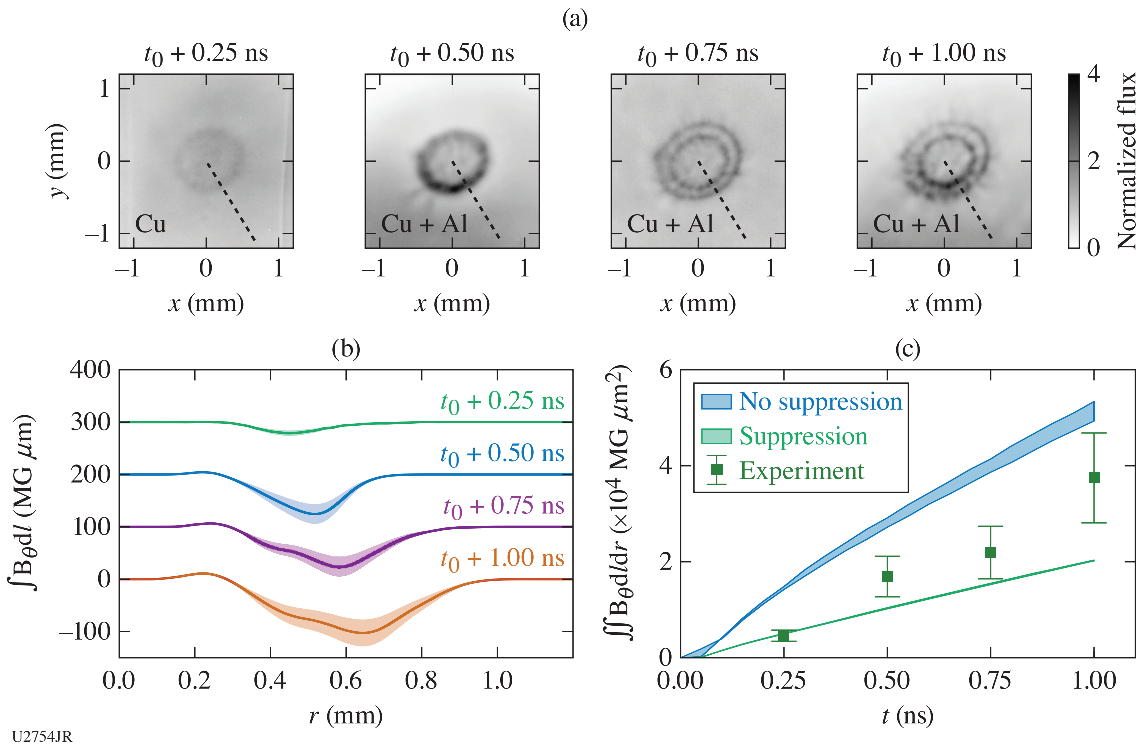

Figure 2
Comparison of experimental and simulation results for Cu foils. (a) Proton images at 0.25 ns, 0.5 ns, 0.75 ns, and 1.0 ns. Lineout locations are indicated by dashed lines. The target for t_0 + 0.25 ns was a 25-μm-thick Cu foil, and the other probing times use a Cu + Al layered target. (b) Reconstructed magnetic-field profiles. (c) Magnetic-flux predictions from simulations both without and with Biermann suppression are compared.

qualitative trend is also seen in the simulations including Biermann suppression, where the copper targets are less kinetic, due to both lower temperature gradients from radiative losses and shorter mean free paths for higher-Z plasmas.

In conclusion, quantitative measurements of magnetic flux enable detailed comparisons between experiments and extended-MHD simulations, demonstrating the need to account for suppression of Biermann battery generation due to nonlocal effects. Even with the Biermann suppression, the simulations with CH targets overestimate magnetic-flux generation. For Cu, however, while some suppression is necessary, the implementation of the suppression scaling decreases the predicted flux below experimental observations. The effects of radiation-hydrodynamics and the equation of state likely influence the details of simulations but are beyond the scope of this work. In future experiments, additional diagnostics, such as Thomson scattering and interferometry, can help constrain plasma parameters to further validate and improve extended-MHD models. Combined with the magnetic-field analysis presented in this work, measurements of the temperature and density profiles can elucidate the dynamic interplay between energy transport and field generation in HED plasmas.

This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Numbers DE-NA0003606, DE-NA0003764, and DE-AC52-07NA27344. P. T. Campbell is supported by the U.S. Department of Energy Fusion Energy Sciences Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education (ORISE) for DOE. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-SC0014664. B. K. Russell acknowledges support from National Science Foundation Award Number 1751462.

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