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Observations of Electromagnetic Fields and Plasma Flow in Hohlraums with Proton Radiography

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We report on the first proton radiography of laser-irradiated hohlraums. This experiment, with vacuum gold (Au) hohlraums, resulted in observations of self-generated magnetic fields with peak values $\sim 10^6$ G. Time-gated radiographs of monoenergetic protons with discrete energies (15.0 and 3.3 MeV) reveal dynamic pictures of field structures and plasma flow. Near the end of the 1-ns laser drive, a stagnating Au plasma ($\sim 10$ mg cm$^{-3}$) forms at the center of the hohlraum. This is a consequence of supersonic, radially directed Au jets ($\sim 1000$ $\mu$m ns$^{-1}$, $\sim$Mach 4) that arise from the interaction of laser-driven plasma bubbles expanding into one another.

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A high-Z enclosure, i.e., hohlraum, creates an environment filled with a nearly blackbody (Planckian) radiation field when irradiated by high-power lasers or energetic ions [1,2]. The cavity generates intense thermal x rays at a radiation temperature ($T_r$) of hundreds of eV. Hohlraums have been extensively used as radiation sources or platforms for a wide range of basic and applied physics experiments. In studies of laboratory astrophysics and high-energy-density (HED) physics [3,4], for example, hohlraums are used for creating and simulating various extreme HED conditions, including those of stellar and planetary interiors. The hohlraum radiation field is used to compress spherical capsules, through capsule ablation, to high temperature and density in indirect-drive inertial confinement fusion [1,2].

The use of hohlraums requires an understanding of physics details, such as coupling efficiency, plasma conditions, instabilities, radiation uniformity [1,2,5,6], and cavity shape [1,2,7,8]. Electric ($E$) and magnetic ($B$) fields generated by several processes may have important effects on hohlraum physics and overall performance [9]. $B$ fields inside a hohlraum can reduce heat flow, since cross field thermal conductivity is modified by a factor of $(1 + \omega_{ce}^2 \tau^2)^{-1}$, where $\omega_{ce}$ is the electron gyrofrequency and $\tau$ is the collision time [10,11]. $E$ fields may modify the plasma conditions and, if sufficiently large, could enhance thick-target bremsstrahlung at x-ray energies well above the Planckian background.

For low-intensity laser drive, such as used in most hohlraum experiments [1–9], the dominant source for $B$-field generation is expected to be nonparallel electron density ($n_e$) and temperature ($T_e$) gradients ($\nabla n_e \times \nabla T_e$) [10,11]. The $E$ field is expected to result from electron pressure gradients ($\nabla P_e$) [10,11]. Despite such expectations, prior to this work, no direct experimental measurement and characterization of such hohlraum fields have been made.

The first observations of $E$ and $B$ fields and their evolution in hohlraums, made with time-gated monoenergetic proton radiography [12], are presented in this Letter. Coupled plasma flow dynamics were also observed. Simultaneous imaging with two discrete proton energies breaks any inherent degeneracy between $E$ and $B$.

In the radiography setup (Fig. 1) the backlighter is a D$^3$He-filled, thin-glass-shell target driven by 21 OMEGA laser beams [13], producing a $\sim 130$-ps-long pulse of 15-MeV D$^3$He protons and 3.3-MeV DD protons. Imaging detectors utilized CR-39 [14], and the backlighter isotropy allowed two experiments to be performed simultaneously. Each hohlraum had a 30- $\mu$m-thick gold wall, 100% laser entrance holes, 2.4-mm diameter, and 2-mm length. Each was driven by 10 laser beams (incidence angle 58.8°) forming a single irradiation ring with total laser energy $\sim 4$ kJ in a 1-ns square pulse. The individual beams had full spatial and temporal smoothing [15]. SG4 phase plates resulted in each beam illuminating an elliptical spot on the wall with a ratio of long-to-short axis $\sim 1.2$ and laser intensity $\sim 2 \times 10^{14}$ W cm$^{-2}$. A nickel mesh (60 $\mu$m thick, 150-$\mu$m hole-to-hole spacing, and 75-$\mu$m square holes) [12] divided backlighter protons into discrete beam-
lets to allow quantitative measurement of proton trajectory deflection due to fields. The relative timing of backlighter and subject hohlraum drive was adjusted [12] to sample the hohlraum at a desired time.

Figure 2 shows sequences of proton images obtained on three different shots, covering a time period from the beginning of the laser pulse ($t = 0$ ns) to 0.8 ns after it was off ($t \approx 1.8$ ns). At earlier times ($t \lesssim 0.9$ ns) the beamlet arrays in 15-MeV images [Fig. 2(a)] show minimal displacement by fields or plasma, but beamlets have different sizes at different times, reflecting more subtle field effects. At late times the 15-MeV beamlets show some chaotic spatial structure, indicating that their trajectories have been affected by large field and plasma effects. In the 3.3-MeV images [Fig. 2(b)], beamlet arrays are coherently distorted by $t = 0.52$ ns and disappear altogether (due to stronger deflections) at later times.

Angular deflection of each beamlet is proportional to both $\int \mathbf{B} \times d\mathbf{l}$ and $\int \mathbf{E} \times d\mathbf{l}$ (where $d\mathbf{l}$ is the differential path length along the proton trajectory), and can be determined from $\xi$, the linear displacement of a beamlet in an image from the position it would have had in the absence of deflections (we use the apparent size of the displacement scaled to the imaged subject). For certain situations with enough symmetry, the potential degeneracy between $E$ and $B$ can be broken [16,17]. Here this is overcome by near-simultaneous 3.3 and 15 MeV radiographs. Because of the Lorentz force, deflections due to $B$ are inversely propor-

![Figure 1](image1.png)

**FIG. 1** (color). Experimental setup (a), with proton backlighter, subject hohlraums, and laser beams. The distance between the backlighter and the mesh (detector) was 0.7 (27) cm. Typical energy spectrum and detector are shown in (b). Filters in the detector pack were carefully chosen so that 3.3- and 15-MeV protons were recorded on the front and back detectors, respectively, [14].

![Figure 2](image2.png)

**FIG. 2** (color online). Radiographs of a laser-driven Au hohlraum at different times, taken with 15.0-MeV (a) and 3.3-MeV protons (b), illustrating spatial structure and time evolution of proton deflection and beamlet size. Pairs of images in (a) and (b) were taken in the same shot, but represent different sample times due to different proton velocities. In each image, darker means higher fluence; the gray scale mapping is different in each image to account for the different backlighter yields.

![Figure 3](image3.png)

**FIG. 3** (color online). Lineouts indicate that the arrays of beamlets are approximately uniformly spaced in the hohlraum center re-
opposite signs, the wall, where they encounter two regions of consideration of the proton trajectories near the hohlraum. The metric requires that this apparent constriction is an artifact of the laser-generated bubble. The deflections in the experimental geometry: the electrical potential around the mesh holes (on the incoming side only, since the hohlraum acts as a Faraday cage). It can be estimated from a simple formula based on the experimental geometry: $E = \frac{4e_p q}{3} \Delta L E a^{-1} (A - a + L E)$. The electric field scale length and the scale length along their trajectory is about the transverse size of the field, or $75 \, \mu m$. The field estimates for different times are plotted in Fig. 4(b), showing that a peak field $E \sim 2 \times 10^9 \, V\, m^{-1}$ occurs at $\sim 0.37 \, ns$. Interestingly, the field decays away, a likely consequence of discharging, but while the laser drive is on [Fig. 4(b)]. Similar charging and discharging effects have been seen for (arbitrary) targets irradiated by lasers of this intensity. It is this effect that, for thin-glass-shell targets of the experiments described herein and elsewhere [19], caused a slight upshift in the nuclear fusion birth energy from $3.0 (14.7)$ to $3.3 (15.0) \, MeV$.

A striking feature in Fig. 2 is a five-prong, asterisklike pattern in the $3.3$-MeV proton images at $t \geq 1.01 \, ns$ and later. This is a direct consequence of the staggered distribution of laser beams on the hohlraum wall. The 10 beams are grouped in five pairs, with $26.8^\circ$ between two beams in each pair and $45.2^\circ$ between adjacent pairs [Fig. 5(a)]. For the experimental conditions ($T_L \sim 1 \, keV$, $T_e \sim 1 \, eV$, and $n_e \sim 0.1 \, n_c$), the plasmas have a high $\beta (=8\pi n_e kT_e B^{-2} \sim 10-100)$ and a sound speed [$C_s \sim (ZT_e n_e)^{1/2} \approx 200-300 \, \mu m \, ns^{-1}$] that sets a scale for hydrodynamic expansion [20]. With $\sim 200 \, \mu m$ between pairs of bubbles [Fig. 5(a)], it is expected that adjacent bubbles should coalesce in $\sim 0.35 \, ns$ and reach the hohlraum axis in $\sim 3-4 \, ns$. In contrast the $3.3 \, MeV$ radiograph at $1.01 \, ns$ indicates, on the basis of the five-prong asterisk pattern extending to the axis, that Au-plasma jets shoot inward at about Mach 4 ($\sim 1000 \, \mu m \, ns^{-1}$). The $3.3$-MeV radiograph at $1.43 \, ns$

![FIG. 4 (color).](image_url) (a) Lineouts from 15-MeV images [Fig. 2(a)] at two times and (b) $E$ fields estimated from measurements (solid circles).

![FIG. 5 (color).](image_url) Laser beam distribution (a), and calculated proton scattering distributions for $\alpha \sim 1 \, mg \, cm^{-2}$ Au plasma (b), showing that scattering widths for 3- and 15-MeV protons are comparable with the measured widths (c) of the stagnating plasma.
shows a more enhanced asterisk pattern. A faint outline of
the same pattern is seen in the corresponding 15-MeV
radiograph (at 1.28 ns). From this latter set of radiographs
[Fig. 5(c)], the width of the proton-fluence depletion re-
gion in a spoke of the asterisk is \(\sim 50 \ (260) \ \mu m\) for the
15 (3.3) MeV protons. If depletion is a result of scattering
in the Au plasma, its density can be estimated. Figure 5(b)
shows the effects of scattering calculated for 3.3 and
15 MeV protons in a 1-mg cm\(^{-2}\) Au plasma. As the scat-
tering width varies inversely with the proton energy [21],
the 3.3 MeV scattering profile is broader by about a factor
of 5. The observations [Fig. 5(c)] for both the 3.3 and
15 MeV protons are consistent with 1 mg cm\(^{-2}\) Au areal
density [22, 23]. Taking the scale size for the Au plasma (in
the direction of the hohlraum axis) to be \(\sim 1\) mm, the
Au density is \(\sim 10\ \mathrm{mg\ cm}^{-3}\).

To explore aspects of these intrinsic 3D phenomena,
highly resolved 1D LASNEX radiation-hydrodynamic
simulations were run with the Au-plasma bubble expand-
ing into an ultralow density vacuum. These simulations
indicate an expansion rate almost comparable to the jets. In
addition to this pure hydrodynamic expansion, the hot
electrons advancing ahead of the rarefaction expansion
could further boost the motion of the Au ions by the ion
sound speed. Work is in progress to assess whether such a
hybrid motion of the Au bubble is sufficient to generate a
nearly \(10\ \mathrm{mg\ cm}^{-3}\) stagnation density on the symmetry
axis by \(\sim 1\) ns.

In summary, we report on the first observations of self-
generated fields associated with laser-irradiated hohl-
raums. Discrete but disparate monoenergetic proton ener-
gies enable discrimination between \(E\) and \(B\) fields. Peak \(B\)
fields were \(\sim 10^6\ \text{G}\). Gold plasma (\(\sim 10\ \text{mg cm}^{-3}\) stagne-
ates on the hohlraum axis by 1 ns due to \(\sim \text{Mach 4 (}\nu \sim
1000 \ \mu m\text{ns}^{-1}\) jets that form between adjacent laser-
generated plasma bubbles. (Note that this should not occur
in an ignition hohlraum, where a gas fill would impede the
jets.) These experimental results have important implica-
tions for understanding the precise conditions and plasma
dynamics inside vacuum hohlraums and provide an impe-
tus for the further development of 3D multifluid codes with
self-consistent field generation.

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[23] The possibility that the proton depletion seen in the
asterisk spokes could be due to \(E\) fields in the Au-plasma
jets (which would require \(\sim 10^7\ \text{V m}^{-1}\), rather than scat-
tering in the jets, cannot be experimentally excluded by
comparing measured deflections of protons at 3.3 and
15 MeV because the energy scaling is the same for both
effects. But direct evidence for scattering is strong: the
3.3-MeV protons that passed through the spokes had lower
measured energies than those passing between the spokes
by \(\sim 40\ \text{keV}\), which is consistent with the 1 mg cm\(^{-2}\) of
Au required to generate the spokes through scattering.