Plasma-Density Determination from X-Ray Radiography of Laser-Driven Spherical Implosions


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The fuel layer density of an imploding laser-driven spherical shell is inferred from framed x-ray radiographs. The density distribution is determined by using Abel inversion to compute the radial distribution of the opacity $\kappa$ from the observed optical depth $\tau$. With the additional assumption of the mass of the remaining fuel, the absolute density distribution is determined. This is demonstrated on the OMEGA laser system with two x-ray backlighters of different mean energies that lead to the same inferred density distribution independent of backlighter energy.

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Inertial confinement fusion (ICF) relies on the compression of spherical targets by means of a high power driver, such as a laser, to achieve the necessary conditions of high density and temperature [1]. Areal densities of $\sim0.3$ g/cm$^2$ and temperatures of $\sim10$ keV must be obtained in the central hot spot for ignition to occur. Measurements of the target areal density provide a means of comparing the actual and predicted conditions in ICF implosions.

Previous experiments performed with the OMEGA laser [2] have been successful in inferring the areal density of the imploding capsule at the time of fusion particle production [3–5] (hot-spot formation). At this time, the hot-spot temperature is at maximum, whereas the cold main fuel layer is still evolving. The total areal density of the capsule is determined from the slowing down of protons resulting from D$^3$He fusion reactions within the fuel. These can be either primary fusion reactions from a D$^3$He gas fill or secondary reactions from a D$_2$ gas fill. This method determines the total areal density by associating proton energy loss with the amount of plasma traversed. This method is restricted to sampling the areal density at the time of fusion particle production.

In non-igniting capsules, the cold main fuel layer produces negligible fusion yield and emitted radiation. It is therefore difficult to diagnose. The problem is solved by the introduction of an outside source of radiation (backlighter) acting as a probe. Both x-ray [6] and proton backlighters [7] have been employed as plasma probes in laser-driven fusion experiments. X-ray backlighters have been extensively used for both planar experiments and spherical implosions on OMEGA. X-ray backlighters of spherical implosions on OMEGA has been restricted to experiments using fewer than 60 beams to drive the target implosion, freeing up some of the beams to generate the x-ray backlighter emission. The recent completion of the OMEGA EP laser [8] will make it possible to generate a backlighter while using all 60 OMEGA beams to drive the implosion.

In this work, it is shown that the density distribution of the plasma can be inferred from framed x-ray radiographs. With x-ray backlighter emission available during and after core formation, the time history of the main fuel layer density, and therefore the areal density, can be determined. The use of two-dimensional imaging techniques such as pinhole imaging, Kirkpatrick-Baez microscopes, and Bragg crystal diffraction are preferred since there may be significant azimuthal variation of the plasma density.

In a previous treatment of this problem [9], a Ge-doped ablator at a temperature $\ll 100$ eV was assumed to have the opacity of cold matter. The imploding shell, driven by a hohlraum, was radiographed with a nearly monochromatic Ti x-ray backlighter at conditions close to that of the Ti backlighter used in this work. The density of the pusher was inferred from the radiographs using this assumption of cold opacity and Abel inversion. It is shown here that by constraining the mass to that of the unablated shell mass, the absolute density determined is independent of the backlighter spectrum, relaxing the need to precisely know the opacity of the plasma. This is demonstrated using x-ray radiographs of polar-driven implosions [10] performed on OMEGA with an Au backlighter (broadband emission from $\sim2.5$ to 4.5 keV) and a Ti backlighter (with emission from $\sim4.7$ to 5 keV). Despite a significant difference of the magnitude of the plasma opacity resulting from these two backlighters, the method yields the same density distribution when simultaneous framed images are compared.

For a radially symmetric distribution, absorption of backlighter x rays along the line of sight, in the direction...
where \( I \) is the observed intensity, \( I_0 \) is the backlighter intensity, and \( \kappa \) is the opacity in \( \text{cm}^{-1} \) at energy \( E \) and radius \( r \) \((r^2 = y^2 + z^2, y \) is the projected radial position\). The opacity can also be expressed as \( \kappa(E, r) = \mu(E, r) \rho(r) \) where \( \mu \) is the mass absorption coefficient in \( \text{cm}^2/\text{g} \) and \( \rho \) is the density in \( \text{g}/\text{cm}^3 \). The integral in Eq. (1) is the Abel transform \([11]\) of the opacity. When the inverse Abel transform \([11]\) is applied to Eq. (1), the result is an expression for the radially dependent opacity as a function of the observed intensity at \( y \)

\[
\kappa(E, r) = \frac{1}{\pi} \int_r^\infty \frac{d}{dy} \left[ \ln \left( \frac{I(y)}{I_0} \right) \right] \frac{dy}{\sqrt{y^2 - r^2}}.
\]

The mass absorption coefficient \( \mu(E) \) at energy \( E \) can be assumed to be approximately constant through the absorbing region of the plasma if the temperature and density are sufficiently low. This has been shown to be the case in a CH plasma \([12]\) for temperatures below \( \sim 100 \text{ eV} \) and densities below \( \sim 100 \text{ g}/\text{cm}^3 \) where bound-free absorption \([13]\) by carbon \( K \)-shell electrons dominates. In such a case, the mass absorption coefficient averaged over the energy band of the radiograph \( \mu_{\text{eff}}(E) \) can be used to infer the absolute density from \( \rho(r) = \kappa(E, r)/\mu_{\text{eff}}(E) \). Uncertainties in the instrumental response or an incomplete knowledge of the spectral shape can make it difficult to determine the exact value of \( \mu_{\text{eff}}(E) \). If, however, the mass of the plasma shell \( M_{\text{shell}} \) is known, then \( \mu_{\text{eff}}(E) \) can be determined from

\[
M_{\text{shell}} = \int \rho(r) dV = 4\pi \int \frac{\kappa(E, r)}{\mu_{\text{eff}}(E)} r^2 dr.
\]

By choosing \( M_{\text{shell}} \) to be the unablated mass obtained from simulation, the absolute density is then determined. Fujioka et al. \([14]\) have shown that absorption of x rays from a Ti backlighter (one of two used in this work) by polystyrene (CH) can indeed be characterized by an effective energy-band-dependent absorption coefficient.

If the absorber is fully stripped, as is the case for a pure-hydrogen fuel layer, and is at a sufficiently high temperature, as would be expected for a D or DT main fuel layer near stagnation, the opacity is \( \propto \rho^2/T^{1/2} \) and, therefore, the optical depth is \( \propto \rho^2 R/T^{1/2} \) \([15,16]\), where \( T \) is the temperature and \( R \) is the radius. If the temperature variation of the absorber is small, the radial variation of the opacity can be determined by Abel inversion from which a functional form of the density distribution can be determined. Constraining the mass to that of the unablated shell mass allows the absolute density distribution as a function of radius to be calculated.

Experiments were performed using 40 beams of the OMEGA laser in the polar-drive illumination configuration \([10]\), emulating the conditions on the NIF (the National Ignition Facility) \([17]\) when direct-drive implosions are performed with the beams in the indirect-drive configuration. The beam pointing used was described in Marshall et al. \([10]\) (case 3, with offsets of rings 1, 2, and 3 of 90, 150, and 150 \( \mu \text{m} \), respectively) on a target with an outer radius of 433 \( \mu \text{m} \). The target consisted of a 24-\( \mu \text{m} \)-thick glow-discharge-polymer GDP (i.e., CH) shell filled with 15 atm of \( \text{D}_2 \) at room temperature. The main drive pulse consisted of a 1.5 ns pulse with a 1-to-3 (foot-to-main) intensity ratio with the foot and main part of the pulse having approximately equal durations \((\sim 0.75 \text{ ns})\). A total of 13.2 \( \text{kJ} \) was incident on the target with 1-THz smoothing by spectral dispersion (SSD) \([18]\) with polarization smoothing \([19]\) used to minimize small-scale illumination nonuniformities. This pulse shape was used to keep the main fuel layer on a low adiabat \((P/P_{\text{Fermi}} \sim 3)\) \([1]\).

Two backlighter targets were employed opposite two high-speed x-ray framing cameras \([20]\). One backlighter was a 25-\( \mu \text{m} \)-thick Au foil and the other a 25-\( \mu \text{m} \)-thick Ti foil, each with four OMEGA beams of \( \sim 350 \text{ J/beam} \), focused to diameters of 750 and 600 \( \mu \text{m} \), respectively. Each framing camera was positioned behind a \( 4 \times 4 \) array of 10-\( \mu \text{m} \)-diam pinholes producing four strips of framed images with a time-gated resolution of \( \sim 30 \text{ ps} \), \( 56 \text{ ps} \) between images, and strip times independently set to the nearest 100 ps. Absolute frame times were determined by observing the backlighter onset on the first strip and from the measured delay from strip to strip determined from an electronically recorded monitor signal.

The framing camera opposite the Au backlighter was filtered with a total of 229 \( \mu \text{m} \) of Be making it possible for x rays above \( \sim 2.5 \text{ keV} \) to be transmitted. The framing camera opposite the Ti backlighter was filtered with a \( 12.7-\mu \text{m} \)-thick Ti filter. This filter limits the transmitted spectrum of the backlighter so as to be nearly monoenergetic with a characteristic energy of 4.75 keV, corresponding to the He-like emission line of Ti \([9]\). This simplifying assumption about the backlighter spectrum will be used later in this Letter as a means of checking the accuracy of the assumed mass of the shell.

The images are recorded on film with an imposed step wedge so that relative intensity variations can be determined. The exposed images and step wedge are developed simultaneously to make possible the subsequent conversion to intensity variation from scanned and digitized film. Variations of the backlighter intensity are removed by fitting the shape of the backlighter to a super-Gaussian-plus background outside the region of the target radiograph and then extending this fit to the region of the radiograph \([21]\).

Figure 1 shows a set of these corrected radiographs up to shell stagnation, which occurs at \( \sim 2.3 \text{ ns} \). Note that all images are during the time period after the end of the laser pulse \((t \sim 1.5 \text{ ns})\) at which time all ablation has already occurred and it is assumed that the mass of the shell then remains constant. The values are presented as \(- \ln(I/I_0)\) [i.e., the optical depth \( \tau \)]; all values are \( >0 \) with the
exception of the frames from 2.32 ns and on where self-
emission from the core exceeds emission from the back-
lighter in the central region of the images. Figure 2(a)
shows the azimuthally averaged optical-depth variation
for one nearly simultaneous pair (at the mean time of \( t = 2.14 \) ns) of Au- and Ti-backlight images. The magnitude of
the optical depth is greater for the lower-energy backlighter
as expected. The dotted line in Fig. 2(a) is the Au-backlit
profile divided by 1.7 showing that the optical depths differ
only by a multiplicative constant. Applying Abel inversion
and assuming the unablated shell mass \((3.34 \times 10^{-5} \text{ g})\)
given by the 1D hydrodynamic code LILAC [22] determines
the density distributions from the observed optical depths
[Fig. 2(b)]. The inferred density distributions from the Au
and Ti backlighters are nearly identical, with only small
differences due to noise in the images.

An independent check on the accuracy of the assumed
mass can be obtained by determining the areal density of
the shell from the transmission through the center of the
shell. For the nearly monoenergetic Ti backlit image
[Fig. 2(b)], the observed optical depth near the center of
the image is 0.63. For a cold opacity of 19.72 cm\(^2\)/g [14],
the areal density is then \( \rho R = \pi/2\mu = 16 \text{ mg/cm}^2 \),
within \( \sim 14\% \) of the value obtained from the Abel inverted
profile \( (\rho R = 18.5 \text{ mg/cm}^2) \). In general, the Abel inver-
son result will average over more of the shell and hence
will be less subject to local variations of the areal density.

Figure 3 shows the density distributions determined for a
sample of these images. The densities inferred from one
additional simultaneous pair of Au- and Ti-backlit images
are included. The LILAC simulated shell density is shown
for comparison for the 2.20-ns case. Figure 4 shows the
resulting calculated shell areal densities \( \rho R_{\text{shell}} \) determined
from all Au- and Ti-backlit images plotted as a function
of frame time from the beginning of the main laser pulse
(\( t = 0 \)). For the two frames when the Au- and Ti- backlit
images occurred at the same time, the areal density values
are the same within errors. All times have an uncertainty of
\( \pm 50 \) ps. The absolute densities and, therefore, the areal
densities are assumed to be uncertain by \( \pm 10\% \) due to
uncertainty in the unablated mass. The time from \(~2.3\) to
2.6 ns corresponds to the time during which intense x-ray
emission from the core as well as fusion production occurs.
During peak emission, heat from the core moves out
through the shell and absorption by the backlighter is
momentarily obscured. Since an independent measurement
of this emission is not available (image with no back-
lighter), it cannot be corrected for and no density profiles
are determined during this time interval. Later in time, the
shell cools and absorption of the backlighter reappears.

FIG. 1. Intensity-corrected x-ray radiographs from OMEGA
shot 49331 taken with two x-ray framing cameras, one backlit by
an Au target and one backlit by a Ti target. Each image is a
400 \( \times \) 400-\( \mu \text{m} \) region corrected for backlighter intensity variation
as explained in the text.

FIG. 2 (color online). (a) The natural logarithm of the intensity
variation as a function of projected radial distance in the image
plane for a simultaneous pair of Au- and Ti-backlit images. The
profiles are azimuthally averaged about the image centers. The
dotted line is the Au profile, normalized to the Ti profile
demonstrating that they differ only by a multiplicative constant
(1.7). (b) The absolute density distributions computed from the
intensity profiles of (a) by Abel inversion with the additional
constraint of mass as described in the text.

FIG. 3 (color online). Density distributions computed from the
x-ray radiographs showing the evolution of the shell density and
position as a function of the indicated frame times.
Frames during this later time were recorded by the Ti-backlit framing camera (2.70 ns and later).

The mean neutron production time (bang time), as recorded by the neutron temporal diagnostic [23], occurred at 2.43 ns during the time interval when x-ray emission from the core is evident. The total areal density (gas-fill + shell) averaged over the time of fusion particle production was independently determined by a set of three filtered CR39 packs measuring the slowing down of the D-He\(^3\) protons [3] and yields a value of \(\langle \rho R \rangle_p = 58 \pm 5 \text{ mg/cm}^2\) (the error is 1 standard deviation of the three values). An estimate of the gas-fill (fuel) areal density \(\rho R_{\text{fuel}}\) is determined from the size of the observed core emission at stagnation (~50 \(\mu\text{m}\)) and mass conservation, yielding \(\rho R_{\text{fuel}} = 6 \pm 1 \text{ mg/cm}^2\). The proton inferred shell areal density is therefore \(\rho R_{\text{shell}} = 52 \pm 5 \text{ mg/cm}^2\) and is plotted as a single point in Fig. 4 at bang time. The value determined from the proton spectra falls closely on the trend of the x-ray measurements, giving additional credence to the results of this method. The LILAC simulation of this implosion was performed assuming flux-limited diffusion [24] with a flux limiter \(f = 0.06\). The predicted areal density is shown as a solid line in Fig. 4. The areal density measurements are seen to closely follow this prediction until the time of stagnation where significant departures from spherical symmetry can be seen in the framed images (Fig. 1).

This analysis demonstrates that with the application of an area x-ray backlighter, the shell areal density time history can be measured on a single implosion experiment from early in the implosion, up to stagnation, and again later in time after core emission has subsided. Such a determination is limited by the temporal extent of the backlighter and the requisite exclusion of target self emission. A similar measurement of the areal density time history using proton radiography [7] requires repeating the implosion, acquiring a single time measurement from each of a series of identical implosions. The x-ray radiography technique therefore offers a much less intensive use of the experimental facility, not requiring that the implosion be repeated multiple times to acquire the areal density time history. The results of this technique support the conclusion that the polar-driven direct-drive implosion exhibits near 1D performance, up to the time of core self emission, with evolving nonuniformities affecting the performance thereafter. The reader is referred to the discussion in Ref. [10] for a description of the low Legendre mode departures from spherical symmetry observed in polar-driven, direct-drive implosions that are of importance to the target performance but outside the scope of this Letter.

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