The application of laser-driven proton beams to the radiography of intense laser–hohlraum interactions

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Abstract. Plasma expansion following the interaction of an intense laser beam with the inner surface of gold hohlraums, emulating conditions relevant to indirect drive inertial confinement fusion (ICF), has been investigated by a radiographic technique which employs a beam of laser-accelerated protons. This probing technique has made it possible to measure the electric field distribution associated with the plasma front and its propagation throughout the interior of the hohlraum with a temporal and spatial resolution of the order of a few ps and µm, respectively. The data indicate that the expanding plasma slows down approaching the opposite walls, possibly due to the interaction with x-ray heated plasma from the non-irradiated walls. The electric field at the plasma front shows a bipolar structure, suggesting the presence of ion-acoustic soliton-like structures cotraveling with the front. Data obtained using enclosed hohlraums suggest the feasibility of this type of diagnosis in gas-filled hohlraums, as currently employed in ICF experiments.
1. Introduction

Indirect drive inertial confinement fusion (ICF) has received a great deal of attention in the last few decades as one of the most promising schemes to reach controlled fusion in laboratory [1, 2] and large laser facilities such as the National Ignition Facility [3] and MegaJoule [4], who aim to demonstrate ignition using this scheme within the next few years.

In the basic scheme a microsphere of fuel (typically a mixture of deuterium and tritium) is placed inside a metallic cavity (hohlraum) and a large number of long and energetic laser pulses are focused onto the inner surface of the cavity itself. The x-rays generated by the interaction of the pulses with the metallic walls drive the compression of the fuel until sufficient pressure and temperature to initiate ignition are reached. The more relaxed uniformity and stability requirements on the laser beams are advantages of such a scheme compared to the direct drive ICF approach [5]. However, the expansion through the hohlraum of the hot plasma created at the wall is a concern, as it can perturb and degrade the uniformity of fuel compression, mainly by moving the energy deposition spot away from the hohlraum walls to the plasma critical surface [6]; ignition target designs envisioned in order to slow down the high Z, warm plasma expansion, employ hohlraums filled with a low Z gas (typically helium) or low-density foams [7]. Plasma filling of the hohlraum and the specific details of the laser energy deposition create a complex environment, which is difficult to model in a satisfactory manner. Optimum conditions can therefore only be determined via an empirical, experimental approach. However, diagnosing plasma expansion in the interior of the hohlraum presents obvious problems due to the enclosed nature of the target, and measurements have been mainly indirect and of limited detail [1].

In this paper, we present measurements of plasma expansion in laser-irradiated hohlraum targets, obtained using a particle radiography technique employing laser-accelerated protons, which has already been applied to the diagnosis of electric and magnetic fields in a variety of interaction settings and plasma conditions (see for instance [8]–[10]). A parallel technique employing monoenergetic beams from fusion reactions [11] has also been applied to the diagnosis of plasmas relevant to inertial confined fusion as the generation of magnetic fields in both direct [11] and indirect drive configurations [12] and directly driven fuel capsule implosions [13]. Advancing these previous works, we show that broad spectrum laser-accelerated proton beams can ensure a fine temporal mapping of the interaction allowing one to extract useful information about the dynamics of the plasma front.
The data here discussed have been obtained in both open and enclosed hohlraum configurations; results for open hohlraums are compared with the enclosed (unfilled) case, proving the potential of this proton radiography technique for plasma expansion characterization for enclosed targets as employed in ICF experiments.

2. Proton probing technique

The proton probing technique (see figure 1) employs a proton beam, generated and accelerated during intense laser–matter interaction, as a charged particle probe for laser-plasma experiments. In its general setup, a short and intense laser pulse is focused onto a thin metallic foil (in the case of the present work a 20 µm thick Au foil) in order to generate and accelerate an energetic and collimated proton beam with a temporal duration comparable to the laser pulse duration. Such a proton beam is directed to propagate through the region of interaction between a second intense laser pulse and the target, and undergoes deflections due to the transverse electric field in the region of interest. Due to the high degree of laminarity of the beam, the proton source, while being physically extended, is practically equivalent to a nearly point-like virtual source placed in proximity of the target [14]. A point projection of the probed region is thus obtained with a geometrical magnification given by

$$M = \frac{L + l + l_s}{l + l_s} \approx \frac{L}{l},$$

where $L$ is the distance between the interaction target and the detector, $l$ is the distance between the foil and the interaction target, and $l_s$ is the distance between the virtual source and the foil. This approximation is consistent with the fact that $l_s$ has a typical dimension of the order of a few hundreds of microns [14] while typical arrangements of this probing technique provide $l \approx 3$ mm and $L \approx 3$ cm. After the proton beam has passed through the interaction region, it is recorded on a spectrally resolved detector, in the case of the present work a stack of dosimetrically calibrated RadioChromic Films (RCF) [15].

Figure 1. Proton probing technique general setup.
Since the proton beam is created via target normal sheath acceleration (TNSA) [16], it exhibits a broad energy spectrum resulting in different times of flight for the different energy components; the multi-layer arrangement of the RCF stack allows then for a temporal multi-frame capability of the detector even in a single shot configuration. This is because protons with different energies penetrate up to different depths in the stack and, releasing most of their energy in correspondence with the Bragg peak, give a different volumetric signal deposition; each film in the stack acts as a filter for the following ones and spectrally selects the protons whose Bragg peak is localized within the active layer.

The image is a result of a spatial and temporal averaging: calling $b$ the longitudinal size of the region where the electric field is present, $\varepsilon_p (v_p)$ the kinetic energy (velocity) of the protons and $m_p$ the mass of the protons, it can be easily deduced that the averaging temporal window, due to the finite transit time of the beam through the region of nonzero electric field, is $\delta t_t \approx b/v_p \approx b \times (m_p/(2\varepsilon_p))^{1/2}$. Then, the main parameters affecting the temporal resolution of this probing technique are: the proton pulse duration $\delta t_P$, the finite transit time $\delta t_t$ and the spread of the energy deposited within every single layer, $\delta \varepsilon_p$. At the source, the burst duration of proton beams created via the TNSA mechanism, is of the order of $\delta t_b \approx 1$ ps, while typical energy spreads within a single RCF layer are of the order of $\delta \varepsilon_p \approx 0.5$ MeV leading to a temporal uncertainty

$$\delta t_{RCF} \approx l \left( \frac{m_p}{(2\varepsilon_p)^2} \right)^{1/2} \delta \varepsilon_p \approx 1 - 2 \text{ ps.}$$  (2)

These values are extracted assuming probing proton energies in the range $\varepsilon_p \approx 5$–$10$ MeV. In this case, the minimum intrinsic temporal resolution of the technique is of the order of 1–2 ps; in case of extended plasma regions, the averaging temporal window across the plasma can exceed this value, effectively determining the temporal resolution.

As mentioned above, the imaging properties of this source are practically equivalent to those of a virtual source located in proximity of the foil; therefore, the minimum spatial precision of the diagnostic can be considered to be the transverse size of the virtual source which, for typical experimental conditions, is of the order of a few microns [14].

An analytical dependance of the proton density modulation at the detector plane on the transverse electric field distribution at the interaction plane can be derived. The protons, while passing through a region of transverse nonzero electric field $E_{\perp}$, acquire a transverse displacement $\vec{\rho}_{\perp}$ at the detector plane, that can be expressed as (calling $x$ the proton propagation axis)

$$\vec{\rho}_{\perp} = \frac{\delta v_{\perp}}{v_p} \cdot L \approx \frac{eL}{m_pv_p^2} \int_b E_{\perp} dx,$$  (3)

where $\delta v_{\perp}/v_p \ll 1$ and negligible contributions from the magnetic field are assumed (as discussed later in section 4).

Calling $n_p$ the proton density at the detector plane, $n_{p0}$ the proton density before the nonzero electric field region and $n_{pu}$ the unperturbed proton density at the detector plane, the proton density perturbation at the detector plane is defined as $\delta n_p = n_p - n_{pu}$. Moreover, $n_p$ is related to $n_{p0}$ by $n_p = n_{p0} / |J|$, where $|J|$ represents the determinant of the Jacobian transformation from the Eulerian $\vec{r}_{\perp}$ to the Langragian $\vec{\rho}_{\perp}$ transverse coordinates of the protons. Under the approximation of small angular deflection, $|J|$ can be written as $|J| \approx M^2 + M \cdot \nabla \cdot \vec{\rho}_{\perp}$, where $M$ is the geometrical magnification defined in equation (1) and $\nabla \cdot$ refers to taking the derivative with respect to the transverse coordinates $y, z$. $n_p$ can then be written as
The CPA pulse (τ = 0.5 ps, I \sim 6 \times 10^{19} \text{ W cm}^{-2}) is focused onto a 20 \mu m thick Au foil generating a proton beam with maximum energy of 20 MeV. Such a beam passes through an open gold hohlraum (inner diameter 1.5 mm, length 1 mm and thickness 26 \mu m), probing the interaction of an ns flat-top laser pulse with the hohlraum inner wall (EAST beam, E \sim 250 J, I \sim 10^{14} \text{ W cm}^{-2}), and is then recorded on an RCF stack. The images on the RCF layers are geometrically magnified by a factor of \( M \approx L/\ell = 3 \text{ cm}/3 \text{ mm} = 10 \). In the second part of the experiment, enclosing walls were inserted at the sides of the hohlraum. A radiograph of an unirradiated hohlraum is also shown in the upper-right inset.

\[ \delta n_p \approx -n_{pu}/M \nabla \cdot \vec{\rho}_\perp \] where \( n_{pu} = n_{p0}/M^2 \). Therefore, a relation between the relative proton modulation and the transverse component of the electric field distribution can be written as

\[ \frac{\delta n_p}{n_p} \approx -\frac{eL}{2e_pM} \int_b \nabla \cdot \vec{E}_\perp \, dx. \]  

(4)

Furthermore, under certain experimental conditions, the electric field variation along one of the transverse directions may be negligible with respect to the other, so that \( \nabla \cdot \approx \partial/\partial y \). In the case of the present experiment, the plasma front can be approximated to be quasi-planar near the plasma propagation axis (see figure 3 in section 4). This assumption implies that the electric field gradient is much larger along the plasma front (y-axis) than along the other transverse axis (z-axis). This approximation allows one to obtain the expression

\[ \langle E_y \rangle \approx -\frac{2e_pM}{eLb} \int \frac{\delta n_p}{n_p} \, dy, \]  

(5)

where \( \langle E_y \rangle = 1/b \int E_y \, dx \).

3. Experimental setup

The experimental campaign, carried out at the Helen facility [17] in AWE, adopted the setup sketched in figure 2. The experiment employed two different laser beams. A first, relatively long
and energetic beam (\(\tau \approx 1\) ns temporally flat-top, \(E \approx 250\) J, focal spot diameter \(d \approx 250\ \mu m\) leading to an average intensity of \(I \approx 10^{14}\) W cm\(^{-2}\), EAST beam in figure 2) was focused by a f/3 lens through the laser entrance hole (LEH) onto the inner surface of a 26 \(\mu m\) thick, 1 mm long gold hohlraum. A second, much shorter and more intense beam (\(\tau \approx 700\) fs, \(I \geq 10^{19}\) W cm\(^{-2}\), CPA beam in figure 2) was focused onto a 20 \(\mu m\) thick gold foil, with a changeable delay with respect to the EAST beam in order to create, via TNSA [16], a broad spectrum proton beam with a maximum energy of \(\epsilon_{\text{max}} \approx 20\) MeV.

Although a mesh was inserted in the proton beam path between the proton source and the hohlraum in the deflectometry arrangement [18], the features described in the text mainly refer to proton density variations in the probe beam cross section (proton projection imaging arrangement [8]).

The experimental setup was such that the proton foil–target and the target–detector distances were \(l \approx 3\) mm and \(L \approx 3\) cm, respectively, leading to a geometrical magnification of the image of \(M \approx 10\) (equation (1)).

In the case of the experimental parameters discussed in the following (\(b \approx 100\ \mu m\) and \(\epsilon_p \approx 10\) MeV), the time of flight of the protons across the structure is revealed to be approximately 3–4 ps; this will be, then, the main factor limiting the temporal resolution (see section 2).

While in the first part of the experiment open-ended hohlraums were employed, in the second part of the experiment the sides of the hohlraum were enclosed by two 1 \(\mu m\) thick gold foils in order to test this diagnostic for laser–hohlraum interactions of more direct relevance to indirect drive ICF.

4. Experimental results for open-ended hohlraums

Data exemplifying the features observed are shown in the upper row of figure 3; as a rule of thumb, the electric fields are directed from the regions of a lighter gray color compared to the background (reduced proton flux) toward the regions of darker gray color (increased flux). Different phenomena are clearly distinguishable directly from the raw data: the most evident feature is the expansion of an ellipsoidal front inside the hohlraum from the interaction region. By varying the optical delay between the CPA and EAST pulse, it has been possible to monitor the plasma front position throughout the whole nanosecond of interaction, as shown in figure 4. The data correspond to four different delays between the two pulses, while the multi-frame capability of the probing technique, as discussed in section 2, allowed extraction of different points within the same shot, with smaller temporal separation. Two different propagation regimes are clearly distinguishable: in the first stage the front propagates with a constant velocity of \(3.1 \times 10^6\) m s\(^{-1}\), whereas in the second stage the propagation velocity decreases down to \(6.6 \times 10^5\) m s\(^{-1}\).

Simulations of the interaction of the heating laser beam with a hemispherical target have been carried out using the two-dimensional (2D) Lagrangian Radiation Hydrodynamic Code NYM [19]. The results extracted from the simulations can in fact, following the propagation of electron density isocontours in time, provide a theoretical expansion velocity of the plasma into vacuum to be compared with the experimental data. As an example, the 1D projection along the interaction axis of the simulated electron density \(\approx 620\) ps after the beginning of interaction is shown in figure 5(a) and a comparison between 2D profiles and a proton radiograph is shown in figure 5(b) giving a good topological agreement. Simulation results give a theoretical
**Figure 3.** Upper row: interaction snapshots obtained by proton probing (all images shown refer to a proton energy of $\varepsilon_\text{p} \approx 10 \text{ MeV}$); the laser is focused at the entrance hole in the upper right corner. The ruler in each picture represents $500 \mu\text{m}$. The drawing on the right side sketches the relevant features that can be seen in the images. Lower row: experimental electric field distributions across the plasma front for the snapshots in figure 3 corresponding to 390, 560, 630 ps after the beginning of interaction, respectively. For all the profiles the lineout has been taken in the same position, corresponding to the geometrical center of the plasma front itself.

**Figure 4.** Position of the plasma front inside the hohlraum during the whole nanosecond of interaction. The data for the early stage of interaction (blue dots) are compared with simulated expansion velocity (blue line). Labels (1)–(3) refer to the images in figure 3. Green dashed line represents the temporal profile of the EAST beam. Error bars fall within the dots dimension.
expansion velocity of $\approx 2.8 \times 10^6 \text{ m s}^{-1}$ (blue line in figure 4) in good agreement with the measured velocity, for the first stage of propagation, of $\approx 3.1 \times 10^6 \text{ m s}^{-1}$. This suggests that the plasma ablated from the hohlraum wall initially propagates freely and is subsequently slowed down, possibly by the interaction with the cold plasma originated by x-ray heating of the opposite surface of the hohlraum wall. Simulations also show that these velocities fall within the ion-acoustic range.

It is interesting to note how, in a few hundred picoseconds, the plasma front has already reached and overtaken the center of the hohlraum (i.e. the position of the fuel capsule in an ICF target). Dewald et al. [2] report, for hohlraum targets practically equivalent to ours, a time scale to reach the highest radiation temperature inside the hohlraum of 5–10 ns in strategic experiments carried out at NIF, further proof of the necessity of slowing down the plasma expansion in order not to let it detrimentally perturb the capsule compression.

From equation (5) it is possible to extract the electric field distribution across the plasma front. We can assume here that self-generated magnetic fields arising during plasma ablation and expansion, e.g. via the $\nabla T_e \times \nabla n_e$ mechanism [20, 21], will be negligibly small at the low densities at which the front is observed [10, 22, 23], and unable to contribute significantly to the proton deflection observed at the front [10], thus allowing use of equation (5).

Thus, an example of the electric field profiles is shown in figure 3; the parameter $b$ in equation (5) has been chosen, assuming cylindrical symmetry, of the order of the longitudinal size of the plasma front [24]. As is clear from the figures, rather than the single-signed hump-like electric field distribution expected in correspondence of plasma expansion in vacuum [25], the profile highlights a bipolar nature. This can be understood by considering that, rather than expanding in vacuum, the ablated plasma expands first in a low-density plasma resulting from ionization of the residual gas present in the vacuum chamber (corresponding to $\approx 10^{-3}$ mbar [24]). Also, as mentioned before, at later stages of the expansion, the ablated plasma will also interact with a cold x-ray heated plasma expanding from the non-directly irradiated walls.
The interaction with an ambient plasma (or with a counter-expanding plasma) can trigger, via two stream instability, a double layer structure (with a single sign electric field distribution), as reported several times in the literature (see for example [26]). At later times the two stream instability is expected to evolve nonlinearly due to the interaction of the double layer with the hot plasma particles leading to the formation of ion-acoustic solitons and phase space holes in the electron and ion distribution [27]. The bipolar structure in figure 3 might then be explained by supposing that the electric field is tied either to an electronic or to an ion-acoustic soliton [28, 29]. The main macroscopic distinction between these two phenomena is the propagation velocity; the measured velocity of the order of the ion-acoustic speed is thus a clear indication of its ion-acoustic nature. Indeed, the appearance of solitons at plasma interfaces has been reported in particle-in-cell simulation studies, e.g. in work modeling the ion acceleration by double layers in the auroral upward-current region [29], and in experimental observation of plasma expansion from planar targets [24]. It is furthermore interesting to note the strong asymmetry of the electric field distribution, possibly indicative of a persistent positive potential contribution, associated to the plasma expansion. It is also worth taking into account that, due to the cylindrical shape of the target, the collision between the x-ray heated plasma and the walls takes place at different times for different points in the front. This may be the cause of the uneven and unstable evolution of the plasma front (clearly shown in the set of images in figure 3).

Besides the plasma front propagation, other phenomena are clearly visible looking at the proton probe images such as the creation of a plasma in correspondence of the LEH. Since the laser beam was focused at the entrance hole by a f/3 lens creating a Gaussian focal spot of FWHM $\sim 250 \mu m$ and the hole diameter was $\sim 350 \mu m$, the tails of the beam impinging on the walls of the hole contain $\approx 5\%$ of the total intensity (corresponding then to $I_{tail} \sim 5 \times 10^{12} \text{ W cm}^{-2}$), which is enough to produce a plasma front propagating from the hole’s periphery towards its center; one can envisage a scenario in which, after the front collapses at the center of the hole, it will subsequently expand radially outwards. Comparing the different snapshots at different times, a radial evolution of a plasma structure in correspondence of the entrance hole is indeed clearly visible.

5. Experimental and simulated results for enclosed hohlraums

In the second part of the experiment the proton probing technique is tested, with the same laser parameters, for hohlraums enclosed at both sides by two 1 $\mu m$ thick gold walls (see figure 6(a)), a more closely relevant configuration for ICF experiments [30].

The propagation of the probing proton beam through the gold walls induces a deterioration of the spatial quality of the beam itself, mainly due to the lateral spread induced by scattering of the protons inside the Au foils; this clearly yields a degradation of the spatial resolution of the image recorded on the RCF stack. An example of a proton radiography image taken in such a configuration is shown in figure 6(a). As intuitively expected, even though the main features previously detectable in the open-ended case are still visible, a significant loss in spatial resolution is evident (i.e. the image has become much more blurred, as is clear by comparing figures 6(a) and 3). In order to quantify this effect, expected to scale with the initial proton energy, simulations of proton beam propagation through the gold foils are performed using the Monte Carlo scattering code SRIM [31]. This code calculates the stopping power, propagation distance and scattering spread of pencil-like ion beams into matter using a quantum
Figure 6. (a) Proton radiography of an enclosed hohlraum interaction; the image refers again to a probing proton energy of $\varepsilon_p \approx 10$ MeV: the black ruler represents $500 \mu$m. (b) Simulated ratio between the lateral spreading at the detector plane between side-enclosed and open-ended hohlraums as a function of the initial probing proton energy for two different wall thicknesses. The transverse projections of the simulated spread, of an initially pencil-like 10 MeV proton beam, at the detector plane with and without the insertion of 2 $\mu$m side-enclosing walls are plotted in (d) and (c), respectively. (e) Related simulated proton beam tracing along the proton propagation axis.

mechanical treatment of ion–atom collisions; these calculations are made very efficient by the use of statistical algorithms which allow the ion to leap between calculated collisions, and then averaging the collision results over the propagation distance.

The resolution of the image on each RCF layer is tightly connected with the transverse size of the spread proton beam at the detector plane. For the side-enclosed hohlraums, the proton beam is spread mainly by two effects: the scattering that the proton beam encounters passing through the gold walls and the intrinsic scattering induced by the detector. Therefore, a
convenient way to evaluate the resolution degradation due to the insertion of enclosing walls for different proton energies is to calculate the ratio between the spread encountered when the side walls are applied and the spread induced by the sole detector. Simulations have been performed for both 1 µm (like those used in the experiment) and 2 µm thick gold walls (2 µm is reported as the minimum thickness required for containing thermal x-rays in proof of principle indirect drive experiments [30]). These ratios are plotted in figure 6 as a function of the initial proton energy for both wall thicknesses. The two curves show the same qualitative behavior: as expected, for the probing proton energies employed during the experiment (εp ≈ 2 to 12 MeV), the ratio between these two quantities is significantly above 1, corresponding to the blurriness visible in figure 6(a). The situation significantly improves for increasing energies and the ratio approaches 1 for εp ≈ 30 MeV, suggesting that, at such probing proton energies, no significant difference in spatial resolution can be noticed between the open-ended and enclosed hohlraum targets.

It must be noted that proton energies in the range of 30 MeV can currently be obtained routinely in PetaWatt laser–foil interactions [16, 32]. These results thus look highly encouraging for future diagnosis of ICF implosions in facilities such as NIF, where PetaWatt diagnostic beams will also be available.

6. Conclusions

Measurements via proton radiography of laser–matter interaction inside a hohlraum target in conditions relevant to ICF have been reported. The data show that such a diagnostic technique allows one to characterize, with high temporal and spatial resolution, the expansion of the ablated plasma front inside the hohlraum, obtaining not only its topology and expansion velocity, but also details of the electric field distribution at the front, which clarify the nature of the structure observed.

Data indicate, in a first stage, a free plasma expansion into vacuum followed by a slowdown, likely in correspondence to the interaction with x-ray-heated plasma from the opposite, not directly irradiated, hohlraum surface.

The electric field distributions, taken at different times, across the plasma front are a clear indication of solitary, ion-acoustic-like structures cotraveling with the plasma front itself.

The data also indicate that it is possible to probe enclosed targets and retain information even with relatively low energy protons (10–15 MeV), although at the cost of a degradation of spatial resolution. Simulation results clearly indicate that the use of more energetic proton beams (εp ≥ 30 MeV) will permit maintenance of the intrinsic spatial diagnostic resolution (of the order of few µm) even for enclosed hohlraum configurations, allowing us to investigate, for instance, gas-filled hohlraums.

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