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Modeling of laser-driven proton radiography of dense matter

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Abstract

Laser-driven MeV proton beams are highly suitable for quantitative diagnosis of density profiles in dense matter by employing them as a particle probe in a point-projection imaging scheme. Via differential scattering and stopping, the technique allows to detect density modulations in dense compressed matter with intrinsic high spatial and temporal resolutions. The technique offers a viable alternative/complementary route to more established radiographic methods. A Monte-Carlo simulation package, MPRM, has been developed in order to quantify the density profile of the probed object from the experimentally obtained proton radiographs. A discussion of recent progress in this area is presented on the basis of analysis of experimental data, which has been supported by MPRM simulation.

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1. Introduction

Theoretical and experimental studies of the properties of highly compressed matter are of fundamental interest to several branches of physics, including inertial confinement fusion (ICF), astrophysics and geophysics. For example, in the conventional, isobaric fast ignition approach, cryogenic deuterium tritium fuel has to be compressed from an initial diameter of 2 mm to a 60 μm diameter hotspot, resulting in particle density ' ρ ' ranging from 100 g/cc to 600 g/cc around the cold fuel-hot spot interface region, with an areal density ' ρR ' of 0.3 g/cm² inside the hot spot. In order to achieve these extremely high densities, the compressed core must be spherically symmetric with a relatively smooth interface between the cold fuel and central hot ignition region [1]. Diagnosing density perturbations and general deformity of the core shape

in these conditions are required in order to understand the underlying physical process. Similarly, the knowledge of 'Equation of State' (EOS) of heavily dense and compressed matter is important for several fields of physics. For instance, the evolution of the stars is mainly governed by the thermodynamic properties of matter at very high temperature and pressure. EOS of the planet cores is also a fundamental requirement for the understanding of their internal structures [2]. Moreover, success of ICF also relies on the knowledge of EOS of the extreme state of DT fuel, which is required in order to understand the phenomenon of shell pellet implosion and the final core compression.

In recent days shock-wave-EOS experiments, dense compressed matter is created by sending laser produced shock waves through matter. Measurement of the shock/fluid velocity or the density profile of the compressed medium is required, with high precision, in order to obtain the EOS values. While a few experiments have used X-ray radiography in order to obtain the density profile of the compressed low-Z materials [3], most of them [4,5] rely on the shock velocity

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measurement (via optical interferometry in transparent media or by observation of shock breakout times on steps of known thickness in optically opaque materials). In opaque high/average Z materials, it is not possible to obtain information about the density profile of the shocked sample and also to measure the fluid velocities directly. Moreover, in measurements based on velocity determination, it is impossible to have a good precision, contrary to the measurement based on density diagnosis, due to error amplification going through Rankine–Hugoniot relations [6,7]. It is a challenge to the conventional radiographic techniques to probe the above-said dense matter states. Similarly, in ICF experiments, the ideal diagnostic would penetrate densities up to 600 g/cc and resolve features of less than 5–10 μm . Imaging of neutron/proton emission from an igniting core is capable of providing such resolution during ignition shots, however, it is not certain that a target that does not reach ignition will not produce the large number of neutrons/protons required to image the core using this technique [8–10]. Another possibility, currently under development, is X-ray imaging in the range of 15–30 KeV [11]. The proton radiography technique (as will be discussed in the following section), employing proton beams driven by high power lasers, can be developed as an alternative, or perhaps complementary, technique to probe the density perturbations in highly dense materials.

The idea of using ion beams, and particularly proton beams, for radiography purposes has been circulated for several decades [12,13]. High energy ($\sim\text{GeV}$) and monochromatic beams of ions from conventional accelerators have been used for detecting the areal density variations in samples by exploiting the energy deposition and scattering of the incident particles [14]. However, the long pulse duration and high production cost of such ion pulses have been major drawbacks, in view of employing them as a particle probe in many cases, such as in high power laser–plasma experiments. On the other hand, the unique properties of high power laser accelerated multi-MeV protons [15], such as high brilliance in a very short duration, high directionality and highly laminar flow, are favorable for achieving high spatial resolution with desired magnification, when back illuminating an object with the proton beam via point-projection imaging scheme. Proton beams with substantial flux in the range of 50–60 MeV can be produced by focusing a petawatt-class laser on a thin foil target [16,17] and it is reasonable to expect that higher energies will be obtained soon due to the rapid growth in laser technology and extensive scientific research in the field. Therefore, picosecond laser-driven proton radiography appears as a potential candidate to probe dynamic events in very dense matter, such as the imploded ICF cores where particle density of about 500 g/cc can be found.

One of the attractions of the proton radiography technique is the intrinsic high spatial resolution (of a few microns [15,18]). In a point-projection imaging scheme, this would indicate emission from a source with diameter of the order of the spatial resolution, unless it is a perfectly laminar source. The results of a series of investigations on the source properties consistently showed that protons are emitted in a laminar

fashion from an area of the target much larger than suggested by the resolution tests [15,19–21]. Moreover, the magnification test suggested that the source of proton is located at few hundred micrometers behind (on the side of laser incidence) the proton generating flat foil. In summary, the imaging properties of this source are equivalent to those of a *virtual* source of very small dimension (of the order of achievable resolution) located up to several hundred microns behind the target.

Several experiments have been carried out in which laser-driven proton beams have been employed as a backlighter for static and dynamic objects (produced by laser interaction). Particularly successful has been the application of these proton beams to the detection of highly transient electric and magnetic fields generated during laser–matter interactions. The structure and dynamics of the fields is in this case typically retrieved by matching experimental proton deflection patterns to synthetic maps obtained with particle tracing codes, modeling the propagation of protons through prescribed field distributions. A description of the principles and results of this particular application can be found in Ref. [15].

Transverse (to the probe proton beam) density variations in the object can be imprinted over the detector films via modifications in the proton beam cross-section, caused by differential stopping and scattering [see Section 2]. In order to retrieve the information about the density profile of the probed object from the radiographs, a two-dimensional modeling code, based on the Monte-Carlo simulation ‘TRIM’ [22], has been developed [23]. The code is referred in the text as ‘*modeling of proton radiography of matter*’ (MPRM). Next to a brief description about the fundamentals of the proton radiography technique, the architecture of the MPRM code will be discussed.

Simulations have been performed employing the MPRM code in order to interpret the data obtained in three different experiments, discussed in this paper. The first experiment is the one (discussed in Section 4) where the proton radiographs of a static test objects (periodic meshes) were obtained by employing the laser-driven proton beams. From the data, the dimension of the *virtual* source of the probe proton beams was estimated by the help of MPRM simulations. The first “model” experiment of direct drive implosion was carried out at RAL in order to demonstrate the feasibility of proton probing in an ICF scenario. The radial density profile of the compressed core, obtained by a direct laser-driven spherical implosion of a hollow plastic micro-balloon, at its stagnation has been obtained with the help of the MPRM simulations. The details of the experiment and analysis will be discussed in the following section (Section 5). The analysis of the proton radiographs, again using MPRM simulations, obtained from an experiment probing laser-driven shock will be discussed in Section 6.

2. Fundamentals of proton radiography

Each atom in matter behaves like a scattering center for incident charged particles, due to the presence of the surrounding Coulomb potential barrier. Therefore, the final velocity

(i.e. the energy as well as the direction) of the incident particle after passing through a given object depends on the total number of scattering centers with which the particle has interacted along its way [24]. Consequently, the final velocity of the incident particle will be different after crossing different sections of a probed object having different areal densities (density $\times$ thickness). We can imagine a diverging proton beam of broad energy spectrum (example, high power laser accelerated proton beam from solid targets) as composed of many monoenergetic beamlets. When probing an object with a given transverse areal density profile, each monoenergetic incident beamlet will emerge with a certain transverse straggling (due to multiple small-angle scatterings) and energy spread (mainly due to electronic energy losses [24, Fig. 1 of Ref. 25] during scatterings) depending on the areal density of the object they experience. Information on the transverse distribution and energy of the protons emerging from the sample can be obtained employing thin sheet detectors, such as radiochromic film (RCF) [26,27], in a multilayer stack. Radiochromic films (RCFs) are self-developing ionizing radiation (e.g. electrons, ions, ionizing radiations such as X-rays and Gamma rays) sensitive detectors which change its optical density upon exposure. The main component of these films is the thin layer of radiation-sensitive material (also called *active layer*), which is sandwiched between optically transparent plastic layers, in order to provide mechanical support. The final optical density (o.d.) profile across a given radiograph thus produced will be due to the sum of the contributions from each proton passing through it. Most of the deposited dose is contributed by protons within a narrow energy band, depending upon the type of RCF and its position in the stack. This is because of the property of ions having a sharp and narrow peak, called Bragg peak, in their dose deposition curve close to their stopping range).

There has been significant interest devoted to developing analytical theories of multiple Coulomb scattering of an incident particle by matter [24]. However, due to the statistical nature of the process, these theories are only capable of providing rough estimations of scattered beam parameters, such as energy and transverse spread. For an example, the Highland's formula [28] is given by

$$\theta_{\text{FWHM}}[\text{radian}] = E_s \frac{z}{2E[\text{MeV}]} \sqrt{\frac{\rho[\text{g/cm}^2] \times l[\text{cm}]}{L_{\text{rad}}[\text{g/cm}^2]}}, \quad (1)$$

which can be used for a quick estimation of the FWHM spread (i.e. θ_{FWHM}) of a particle (of energy E and charge ze ; e is the charge of an electron) beamlet scattered by an object of density ρ and thickness l . Here L_{rad} (called radiation length) is a term dependent on the scattering material and can be found in the literature [29]. ' E_s ' in Eq. (1) is a constant according to the classical theories, which in fact depends on various parameters of the target and the incident particles. It can be properly evaluated for the interested regime of parameters, for example, employing 'TRIM' [22] Monte-Carlo simulation.

Even when the energy loss of the protons while passing through the object is negligible, changes in their directions of motion due to the multiple small-angle scatterings are sufficient to produce an imprint of the object over the detector [19,27]. The transverse straggling of probe proton beam, which depends inversely on the energy of the probe protons, determines the minimum resolvable (threshold) areal density of the object. Let us assume a Gaussian spreading of probe proton beamlets with FWHM spread angles of θ_{obj} while propagating through an infinitesimal object. If D is the unperturbed dose level of the detector, the normalized dose depression ($\Delta D/D$), at the respective magnified position of the object over the detector, will be

$$\frac{\Delta D}{D} = 1 - \sqrt{\frac{\ln(2)}{\pi}} \frac{2t}{x\theta_{\text{obj}}}. \quad (2)$$

Here, t is the transverse extent of the object and x is the distance of the detector from the object.

Depending on the dynamic range of the detector sensitivity as well as the 'noise' fluctuations in dose level, the threshold areal density for a given incident probe proton energy can be easily estimated.

Similarly, the FWHM of the resulting Gaussian dose depression profile on the detector (ξ) will be equal to the FWHM of the scattered beam from the probed object, i.e. $\xi = x\theta_{\text{obj}}$. ξ can also be seen as a blurring coefficient, because, in the case of an object with finite transverse dimension t , the FWHM size of the image over the detector will be the convolution of the ξ and the magnified size of the object. In a point-projection imaging scheme, it would correspond to $\sim \sqrt{\xi^2 + (Lt/l)^2}$, where L and l are the distances of the object and the detector from the proton source, respectively. Clearly, the transverse spread of the probe beam controls the blurring of a radiographic image. Hence increase in the probe proton energy is essential in order to reduce the blurring effect. This will also be discussed at various occasions in this paper, evident from MPRM simulations. Consequently, the broad energy spectrum of the laser-driven MeV proton beam is a suitable candidate for sampling, in a single shot measurement, small-scale density modulations at levels of different areal densities of a probe object.

An interesting factor of any diagnostic is its spatial resolution. In a point-projection radiography scheme, it represents the minimum separation between two similar objects producing a detectable modulation in the dose lineout across the detector. Fig. 1(a) shows the schematic where two infinitesimal objects A and B are being probed by a divergent mono-energetic proton beam, originated from a point source. The objects have given areal densities above the threshold corresponding to the probe proton energy. Each object will produce a dose lineout, as shown in Fig. 1(b), centered at their respective magnified position over the detector. Intuitively, one can resolve the dose depressions in the final superimposed lineout if and only if their centers are separated by more than one FWHM spread. Hence, the spatial resolution can be written as

Fig. 1. (a) Schematic of point-projection proton radiography of two similar objects. (b) Schematic of the individual (red for object A and blue for object B) and superimposed (black) dose lineout produced across the detector [for interpretation of color in this figure, the reader is referred to the web version of the article].

$$d = x_1 + x_2$$

$$= \left(1 - \frac{l}{L}\right) \left[\tan(\theta_1/2) \sqrt{x_1^2 + l^2} + \tan(\theta_2/2) \sqrt{x_2^2 + l^2} \right], \quad (3)$$

where θ_1 and θ_2 are the FWHM spread angles of the proton beam scattered by the objects A and B, respectively.

For a finite size object with unknown thickness and density profiles, it is not straightforward to retrieve the profiles from the final velocity distribution of the probe particle beam. However, an estimate for the areal density of the unknown object can be obtained by reproducing both the spatial and spectral modulations in the transmitted particle beam profiles, at a given transverse plane, while simulating for different model objects. This idea has been implemented for the analysis of the proton radiographs aiming to detect areal density modulations in dense matters. Due to the complexity and statistical nature of the multiple small-angle scattering process, the code MPRM has been developed employing the Monte-Carlo simulation ‘TRIM’ as a tool, which provides the final velocity distribution of the probe beam after passing through an object of given density and thickness. The code models the probed object with a given density profile and by the help of TRIM calculations it simulates the proton radiographs over the detector plane.

3. Architecture of MPRM

The architecture of MPRM code is based on five blocks, as shown in the flowchart in Fig. 2. They are *source*, an *object*

Fig. 2. Flowchart of the MPRM code [for interpretation of color in this figure, the reader is referred to the web version of the article].

(with three-dimensional (3D) density profile), a *detector*, an *operator* (to handle the TRIM input and output) and a *counter* (to construct the final dose profile across the detector). The first step is the probe proton source modeling. For the simulations presented in this paper, this is modeled as a point source emitting protons with a given energy spectrum in a given divergent cone. The source emits protons in small *bunches*, in which each proton has the same energy and direction of propagation. The number and the energy of protons in a *bunch* are set according to the given energy spectrum. The *bunches* propagate through a 3D *object* of given density profile. Modeling of the 3D *object* in MPRM has been done in different ways for different types of objects. For example, in the case of a hollow spherical object, protons travel through two thin layers of dense matter (see Fig. 3(a)). The thickness of the layers and their positions, as experienced by a proton *bunch* moving at an angle θ with horizontal, are obtained from the co-ordinates

Fig. 3. Schematic view (2D) of the proton beam propagation through (a) hollow spherical object and (b) slab type object.

of the points A, B, C and D (the intersection points of the line PP' with the inner and outer circumferences of the hollow sphere). Similarly, in case of a *slab* object as shown in Fig. 3(b), protons are allowed to pass through the thickness AD having density equal to the average density ' $\langle\rho\rangle$ ' along the propagation axis of protons. In this case $\langle\rho\rangle$ is evaluated numerically as the line integral of the object density along AD divided by the distance AD. By the help of a simple pedagogical test, as described below, it has been verified that there is insignificant loss of accuracy while considering an average density $\langle\rho\rangle$ of the object instead of its longitudinal density profile. For the test, two simulations were carried out by modeling an Al *slab* of 500 μm thick partly inserted in the probe proton beam. Two different longitudinal (along the probe proton beam axis) density profiles of the *slab* were chosen. The first one was a step profile as shown in Fig. 4(a). The second profile has a constant density throughout the *slab* (as shown in Fig. 4(a)), which is equal to the average of the step density profile over the thickness of the *slab*. The simulated dose lineouts across the detector for the two cases are shown in Fig. 4(b), which clearly demonstrates the agreement.

The multilayered *detector* is the third building block of the MPRM code which is modeled up to the active layer of the RCF under observation, by considering the thickness and types of previous layers. Consecutive RCF layers, before the one under observation, of the stack detector used in the relevant experiment are approximated in the *detector* as a single layer

of polyester with equivalent thickness (also taking into account the different densities of the intervened active layers in each RCF layers).

Modeling of the *source*, *object* and the *detector* provides the input parameters to the Monte-Carlo simulation of the transport of protons emitted from the source. For each step (in other words, for each *bunch* of protons emitted from the source), the *operator* starts the TRIM simulation by feeding the input parameters generated by the *source*, *object* and *detector* modules. The *operator* also provides the multilayer medium configuration to TRIM, which includes the source to object and object to detector with vacuum spacing. The vacuum regions are specified as layers of 'air' of a given density, calculated from the pressure of the vacuum chamber in the experiment. After completion of a TRIM simulation for a given bunch of probe protons, the *operator* collects final positions and energies of each proton arriving at the bounding z plane (the plane of the RCF layer under observation) and hands over the data to the last building block of the MPRM code, i.e. the *counter*. The *counter* is supplied with the spectral response curve of the RCF (amount of energy deposited in the active layer of the RCF versus incident energy of proton), in the form of a database. Using the database and by means of interpolation, the counter estimates the amount of dose deposited by each proton at its arrival position over the RCF. Finally, it calculates the dose profile across the RCF by adding up the contributions from each incident proton on the active layer.

Due to the transverse straggling of the incident proton beam while passing through the target, the MPRM simulation produces a 2D radiographic projection of a longitudinal slice of the target. In the case where the object has a spherically symmetrical density profile, the radiograph of a 3D object can readily be obtained by superimposing a large number of the 2D radiographs, obtained from the simulation, rotated in steps of small angles about its center.

One of the major issues with any simulation is its accuracy. TRIM, the main unit of the simulation, is a well known package simulating stopping and scattering of ions with $\sim 5\%$ accuracy with the available experimental scattering data [30] for most of the materials. Moreover, MPRM simulations have demonstrated their accuracy by providing perfect agreement with our experimental data obtained for many static objects with known density profiles (for example, fine meshes and plastic micro-balloons as discussed later in the paper). Accuracy of MPRM simulation is also controlled by mainly four free parameters, such as the energy steps in the incident proton energy spectrum, total number of the incident protons, number of grid points on the probed object and the width of the detector. The first three parameters also control the runtime of the simulation, hence one needs to make a compromise between the accuracy and the runtime, depending upon the problem. The simulations presented in the paper, unless stated, are done for 0.1 MeV energy steps in proton spectrum and grid points having 1 μm separation on the object. The normalization constant in the simulation controls the noise level of the output dose profile, which is corrected after the simulation by rescaling the background dose level with the experimental

Fig. 4. (a) Longitudinal (along the probe proton propagation) density profiles of an Al *slab* of 500 μm thick used in the simulation — a stepped density profile (black) and a constant density (red) corresponding to the $\langle\rho\rangle$ of the stepped density profile. The *slab* partially covers the transverse extent of the probe proton beam. (b) Comparison between the simulated dose lineout across the detector while probing the 500 μm thick Al *slabs* of (red) stepped and (black) average density profiles, as shown in (a) [for interpretation of color in this figure, the reader is referred to the web version of the article].

data. The fourth parameter is only critical for the objects lacking spherical symmetry in their density profiles, and special care is needed in such cases due to the difference in transverse straggles of the protons passing through different longitudinal slices of the object.

In case of hot and dense plasmas, there is a significant effect of density and temperature on the wavefunction and bound energy levels of outer shell electrons, which have different orbitals in hot plasmas than that in elemental matter. The bound as well as free electrons are mainly responsible for the energy loss of incident particles called electronic energy loss (see Fig. 1 of Ref. [25] and references therein). In such cases the stopping power of the plasma shows non-linear behavior and strongly depends on the plasma conditions. Several analytical and numerical approaches can be found in the literature calculating stopping ranges and scattering cross-sections of ions in hot dense plasmas [31–33], close to the conditions expected in inertial confinement fusion (ICF) experiments. In order to properly simulate the radiographs of such extreme states of matter, research is under progress aiming to incorporate a reasonable functional relationship between scattering cross-section and the plasma conditions in the MPRM code. On the other hand, when the probe object is relatively cold in comparison to the ‘extreme’ states, one may find MPRM as a useful tool for the analysis of proton radiography data, providing very good agreement with the experimental results as discussed in the following sections.

4. Proton radiography of thin periodic meshes

The data analyzed in this section were obtained in an experiment carried out at the JanUSP laser facility, located at the Lawrence Livermore National Laboratory, CA, USA [19]. The Ti:SA CPA pulse of JanUSP has $0.8\ \mu\text{m}$ wavelength and 100 fs duration. It was focused, on to the target ($3\ \mu\text{m}$ thick Al foil) by an $f/2$ OAP, down to a focal spot of $3\text{--}5\ \mu\text{m}$ FWHM, where the peak intensity was in excess of $10^{20}\ \text{W}/\text{cm}^2$. The protons emitted from the target were detected by a multilayer stack of RCF and CR-39 layers. The proton beam was used to backlight static objects (square meshes of different dimensions), using the setup shown in Fig. 5(a). The schematic of the location of the *real* and *virtual* sources of proton beam as predicted from the resolution and magnification tests is shown in Fig. 5(b). In Fig. 6(a), proton radiograph, formed mainly by 15 MeV protons, of an electroformed copper mesh grids obtained on the RCF is shown. All spatial scales presented in this section correspond to the image plane.

The propagation of 15 MeV protons through the thin (~ 5 microns) Cu wires of the meshes is a simple case of multiple small-angle scattering. It is to be noted that stopping range of 15 MeV protons in copper is about $500\ \mu\text{m}$. Protons propagating through the mesh wires acquire larger lateral spread, due to multiple small-scale scatterings, compared to the protons propagating in vacuum. Superimposition of the beamlets with different divergences produces the observed modulation in the dose profile across the detector. The schematic of the mechanism is shown in Fig. 6(b).

Fig. 5. (a) Layout of the experimental setup discussed in Section 4. (b) Schematic illustrating the *virtual* source description of the quasi-laminar emission of proton beam from the ‘real’ source located at the rear surface of a thin foil irradiated by intense laser pulse [for interpretation of color in this figure, the reader is referred to the web version of the article].

The hypothesis of the *virtual* source description controlling the imaging properties of the beam, as discussed earlier, was reported by Borghesi et al. [19] based on the series of tests performed during the experimental campaign at JanUSP. A source of hundreds of microns in diameter [19,20] needs to be perfectly laminar in order to resolve thin wires of the meshes. From the magnification test described in Ref. [19], the position of the *virtual* source was estimated as $\sim 400\ \mu\text{m}$ behind the target. As shown in Fig. 7(a), the estimated position of the *virtual* source provides a clear periodicity match between simulated (via MPRM) and experimental profiles. In this case, the Cu mesh wires were modeled as *slabs* with constant solid density of Cu. The dimensions and periodicity of the *slabs* were taken from the mesh used in the experiment. The proton source in this case was modeled as a point source, located $400\ \mu\text{m}$ behind the target position in the experiment, emitting mono-energetic (15 MeV) proton beam in a divergent cone. It can also be seen from Fig. 7(a) that there is a considerable disagreement between the shapes of the dose profiles, as if the image in the data are blurred. This indicates the possibility of a finite size, rather than a point, *virtual* source, simply because in a point-projection imaging scheme the blurring of an image is expected from an extended source. In order to observe the effect of *virtual* source size on the sharpness of the shadows, the *virtual* source was modeled (in the MPRM code) as a Gaussian line source of finite size, each point of which emits a divergent beam of fixed number of protons weighted according to its position in a Gaussian profile. The final dose deposited over the RCF for this type of extended *virtual* source was constructed by adding up the repositioned

Fig. 6. (a) Experimental data showing shadows of grid meshes (pitch: $31\ \mu\text{m}$, wire width: $10\ \mu\text{m}$, wire thickness: $5\ \mu\text{m}$) imprinted over RCF, placed at $23.8 \pm 0.5\ \text{mm}$ from the proton generating Al foil. The grid was placed $1.0 \pm 0.05\ \text{mm}$ away from the Al foil. (b) Schematic showing the mechanism of small-scale multiple scattering producing mesh radiographs over the detector [for interpretation of color in this figure, the reader is referred to the web version of the article].

Fig. 7. Comparison between experimental (blue circles) dose lineout across the shadow of the mesh in Fig. 5(a) with simulated dose lineout for (a) *virtual* point source (red), (b) *virtual* source of $d = 2\ \mu\text{m}$ (green), $d = 8\ \mu\text{m}$ (pink), $d = 20\ \mu\text{m}$ (turquoise) and $d = 40\ \mu\text{m}$ (black), and (c) *virtual* source of $d = 12\ \mu\text{m}$ (pink) and $d = 14\ \mu\text{m}$ (red). In each case, the *virtual* source is located at $400\ \mu\text{m}$ behind the target [for interpretation of color in this figure, the reader is referred to the web version of the article].

dose profiles independently obtained for every point source inside the *virtual* source. In order to have a precise estimate for the size of the *virtual* source, the *full width at 1/e maxima* (d) of the *virtual* source was adjusted until the simulated dose modulation reproduced the experimental data. In this way, the lineout obtained for a range of source sizes, as shown in Fig. 7(b), shows strong dependence of the dose profile with the source size. Close matches with the experimental data were obtained for $d = 12\text{--}14\ \mu\text{m}$, as shown in Fig. 7(c), which fairly estimate the size of the *virtual* source in our case as $13\ \mu\text{m}$. There are several possible explanations for the residual disagreement between the simulated and experimental profiles, such as the non-uniformity in the fabrication of the mesh, the error bars in the measurement of the position of *virtual* source size (due to quasi-laminarity and non-uniformity of the probe proton beam), and possibly secondary effects such as charging up of the mesh wires due to the impact of the probe protons.

The size of the *virtual* source is an important parameter, from the point of view of imaging applications, from which the degree of laminarity [34] of the source can be estimated. In the present case, the emittance of the laser-driven proton source has been estimated (using *virtual* source position and size) to be considerably smaller [19] (also agrees well with the independently reported measurements by Roth et al. [21]) than the emittance of the proton beams achievable by conventional accelerator technology.

5. Feasibility study on proton radiography of ICF compressed core

An experiment on proton radiography of dense laser-compressed matter was carried out at Rutherford Appleton Laboratory, UK [35]. Six long pulse beams of the Vulcan

Nd-Glass laser system, each of 100–150 J energy and 1 ns duration, were focused onto a hollow micro-balloon of 500 μm outer diameter and 7 μm wall thickness. The micro-balloons were made up of PAMS (poly-alpha-methylstyrene) of density 1 g/cc. The heater beams were arranged in such a way that they simultaneously illuminated the target tangentially from six orthogonal directions, providing a best symmetry for the implosion. The implosion was diagnosed using the proton beam emitted from the rear side of a 25 μm Tungsten foil irradiated by the CPA beam at an irradiance of $5 \times 10^{19} \text{ W/cm}^2$. The schematic of the experimental setup is shown in Fig. 8. The proton beam had a quasi-exponential spectrum of mean temperature 3 MeV and a high energy cut-off around 15 MeV. A 6 μm thick Aluminum foil was inserted between the proton generating foil and the micro-balloon, in order to minimize the disruption in the proton beam production caused by fast ions, scattered laser light and soft X-rays from the coronal plasma of the imploding micro-balloon, while preserving the spatial resolution in the proton radiographs. However, in presence of an imploding capsule, the proton beam had a quasi-exponential spectrum of mean temperature 1.5 MeV and a high energy cut-off around 7 MeV. The detectors used for capturing the proton radiographs consisted of a 25 μm Al foil followed by multiple layers of RCF. The distances of the proton foil from the center of the micro-balloon and the Al filter of the detector were approximately 4.25 mm and 42 mm, respectively. Spatial scales in the images presented in this section correspond to the image plane.

A static test of the point-projection proton radiography technique was obtained by backlighting the undriven micro-balloon. Fig. 9 shows radiographs of the undriven micro-balloon obtained at different RCF layers corresponding to different probe proton energies. From the dose lineout across

the radiographs, as shown right to the respective one in Fig. 9, it is clear that the micro-balloon strongly modulates the proton beam – with the highest modulation at the edges of the shell, where there is a sudden jump in the amount of matter experienced by the probe protons. The temporal evolution of the capsule density profile during the implosion was studied by varying the delay between the backlighter (beam of protons from the thin foil) and the implosion beams, as shown in Fig. 3 of Ref. [35]. These radiographs demonstrate that due to high spatial resolution and contrast, the technique provides quantitative information about the early phases of the implosion. This may be useful in ignition scale capsules for diagnosing the onset of early time instability growth such as the feed-through from imperfections in the ice surface to larger scale density perturbations in the ablation surface through the Rayleigh–Taylor instability [36].

The radiograph taken at 3 ns after the start of the peak of the driver beams is shown in Fig. 10(a). This is an expected time for the stagnation point (time of maximum compression) of the implosion for the 7 μm wall thickness shell as inferred from the hydrodynamic simulations [35]. Again the radiograph clearly resolves the imploded core. At this time the dense core has assembled just below the center point of the original capsule. The core has formed in the lower third of the original shell, due to the higher drive levels from the upper beams. This is expected as in the earlier time (shown in Fig. 3(b) of Ref. [35]) the core was found slightly elliptical in a similar fashion. It is important to note that the primary goal of the experiment was not to achieve a perfect implosion but to prove the capability and effectiveness of protons as a radiography source for dynamically evolving heavily compressed plasmas. The ultimate requirement, in order to make the diagnostic useful for such type of applications, is to obtain the density profile of the probed object. This has been estimated, with remarkable accuracy, by comparing MPRM simulated radiographs for different density profiles with the experimental one.

At first, simulations were carried out for the radiographic images of the undriven micro-balloon obtained at various layers of RCF. The purpose of the simulations was not only to reproduce the experimental data but also to verify the accuracy of the calculations done by the code. It can be seen from Fig. 9 that the simulation agrees well with the experimental data, reproducing the main features of the data, such as shape of the edge of the micro-balloon. In this simulation, the proton source was designed as a point source (the *virtual* source description was ignored as the dimension of the object and its distance from the proton generating foil is large compared to the size and distance of the expected *virtual* source from the target, respectively) emitting protons with Maxwell–Boltzmann energy spectrum at a temperature of 3 MeV. The object in the simulation was modeled as shown in Fig. 3(a), taking into account the dimension and material of the micro-ballon used in the experiment. Agreement between the simulation and experimental results confirms the role of multiple small-angle scatterings of the protons behind the formation of the radiographic image. The reproducibility of the experimental lineout also demonstrates the level of accuracy of the

Fig. 8. Schematic of the experimental setup discussed in Section 5 [for interpretation of color in this figure, the reader is referred to the web version of the article].

Fig. 9. Left column: experimentally obtained proton radiographs of cold micro-balloon in three different RCFs of the same stack. Right column: comparison between the experimental (black) and simulated (red) lineout of dose deposited in the corresponding layers [for interpretation of color in this figure, the reader is referred to the web version of the article].

modeling done in the simulation. It is to be noted that, the residual disagreement between the simulated and experimental profiles can be explained from the point of view of non-uniformity in the shape, diameter and wall thickness of the micro-balloon (often expected during its fabrication), as well as the spatial variation in the flux profile of the incident proton beam.

In order to estimate the density profile of the compressed target (as shown in Fig. 10(a)), simulations were accomplished trying to reproduce the experimental proton radiographs. The object was modeled as spherically symmetrical, made up of PAMS and having a Gaussian density profile along its diameter. Full width at half maximum (FWHM) and Peak Density (PD) of the Gaussian profile were varied, as shown in Fig. 10(b) and (c). The best fit to the experimental lineout was found for PD of 3 g/cc and FWHM of about 80 μm . The error bar in the estimation of the FWHM and PD has been obtained by comparing the simulations for different

combinations of FWHM and PD (keeping the mass of the object conserved) with the best fit as shown in Fig. 10(d). These results show that the best fit occurs between peak densities of 2 g/cc and 4 g/cc with corresponding FWHM between 75 μm and 95 μm . In other words, the results indicate that the peak density and FWHM of the compressed core are 3 ± 1 g/cc and 85 ± 10 μm , respectively, with an assumption of a Gaussian density profile. Moreover, the estimations agreed well (within 25%) with the PD and core size measurements obtained experimentally by employing picosecond duration K_α (4.5 keV) radiography of the same implosion [37].

The radiograph of the imploded micro-balloon was obtained mainly by the protons of energy from 4 MeV to 7 MeV. As the geometrical magnification in the experiment was 10.0, the FWHM core size from the radiograph over the object plane is 110 μm , whereas the best fit for the core FWHM was found for 83 μm . The blurring of the image is due to the strong scattering exhibited by the protons of energy

Fig. 10. (a) Experimentally obtained proton radiograph of a fairly symmetrical implosion of the micro-balloon closed to the stagnation. (b) Simulated lineout obtained for 83 μm FWHM at different PD such as 1 g/cc (green), 3 g/cc (turquoise) and 4.5 g/cc (black). (c) Simulated lineout obtained for PD of 3 g/cc at different FWHM such as 62 μm (violet), 83 μm (turquoise) and 126 μm (red). (d) Simulated lineout obtained for different sets of PD and FWHM (respectively), such as 1 g/cc and 120 μm (pink); 2 g/cc and 95 μm (black); 3 g/cc and 83 μm (red); 4 g/cc and 75 μm (green); and 6 g/cc and 66 μm (turquoise). In (b), (c) and (d), the blue curves are the average of few angular lineout obtained from the experimental data shown in (a) [for interpretation of color in this figure, the reader is referred to the web version of the article].

~5 MeV. Employing TRIM, the FWHM spread angle of 5 MeV protons through a PAMS object of 85 μm thickness and density of 2.2 g/cc (the average density of a Gaussian density profile of PD of 3 g/cc and FWHM of 85 μm) is found to be 37.5 mrad. Therefore, the expected size of the compressed core over the detector would be roughly $\sqrt{(38 \times 0.0375)^2 + (42 \times 0.085/4.25)^2}$ mm = 1.65 mm, or 165 μm over the object plane. This simple estimation agrees (to ~30%) with the 110 μm FWHM core size observed in the experimental radiographs. The blurring effectively results in a spatial resolution of 20–30 μm. This resolution is adequate for inferring the overall shape and uniformity of the

compressed core but not for investigating smaller scale density perturbations. Taking the PD and FWHM of the compressed core as 3 g/cc and 83 μm, respectively, it has been observed in MPRM simulation that, increasing the proton energy leads to an increase in resolution. The simulated FWHM of the core reduces from 110 μm for ~5 MeV to 90 μm at ~14 MeV, as shown in Fig. 11. This is equivalent to a better resolution less than 10 μm, due to reduction in spread angle at higher proton energies.

An ideally compressed core, for the same experimental conditions, would have a 10 μm radius core of density ~2 g/cc, enclosed by a denser (~15 g/cc) shell of 10 μm thickness. This has been obtained from 1D HYDRA

Fig. 11. Simulated lineout for the compressed core having Gaussian density profile ($83 \mu\text{m}$ FWHM at 3 g/cc PD) observed with proton beams of energy range $4\text{--}7 \text{ MeV}$ (black) and $13\text{--}16 \text{ MeV}$ (red) [for interpretation of color in this figure, the reader is referred to the web version of the article].

simulation [38] (see Fig. 12). MPRM simulations were performed probing an spherically symmetrical object with the HYDRA predicted radial density profile by mono-energetic proton beams of various energies. As shown in Fig. 12(a), it is interesting to observe that for a very high energy probe protons the density fall of the object towards its center is clearly imprinted. However, any density modulation in the coronal plasma could not be clearly diagnosed. It is simply an effect of minimum resolvable density which increases with increase in probe particle energy. Therefore, in such cases a probe particle beam with broad energy spectrum, such as a laser-driven MeV proton beam, is advantageous to obtain the density non-uniformities across the whole object. As a next step, investigations continued via MPRM simulation in order to explore the feasibility (mainly looking for suitable probe proton energy) of the proton radiography technique, diagnosing small-scale density perturbations in heavily dense ICF cores as would be created at the National Ignition Facility, USA. Similar result has

Fig. 12. Simulated proton radiographs obtained for (a) the ideal imploded capsule at RAL employing mono-energetic proton beams of energies 5 MeV (turquoise), 10 MeV (violet), 20 MeV (green), 35 MeV (blue) and 55 MeV (black) and (b) a mistimed imploded capsule at NIF employing mono-energetic proton beams of energies 50 MeV (turquoise), 70 MeV (violet), 110 MeV (green), 150 MeV (brown) and 210 MeV (blue). The red curves in (a) and (b) are the radial density profiles of respective imploded capsules, rescaled to the image plane [for interpretation of color in this figure, the reader is referred to the web version of the article].

been inferred from the study using density profile of a predicted compressed ICF shell, close to ignition conditions, obtained from 1D HYDRA simulation [38] (see Fig. 12(b)). The density conditions at the center of the core are still extreme (of density about 50 g/cc), and surrounded by a thin shell of density up to 350 g/cc located at a radial position of 50 μm . MPRM simulated dose profiles obtained for this core, scanning for probe proton energies ranging from 50 MeV to 200 MeV, are shown in Fig. 12(b). It can be seen that the density peak at 50 μm radius is clearly resolved using protons of energy above 150 MeV. The simulated dose profiles also indicate that protons in the 30–50 MeV energy range would be useful for characterizing asymmetries outside the stagnated core, but in order to resolve the inner density structure one would require proton energies in excess of 100 MeV. Theoretically, deflection of probe protons due to macroscopic electric fields driven by pressure gradients in the compressed core is negligible in comparison to the deflection by small-scale scatterings [35]. Another factor also neglected in the analysis is the effect of plasma conditions on stopping power of the compressed core in a real implosion, which is not clearly understood yet and is under investigation. However, it is reasonable to assume that the above analysis provides an order-of-magnitude estimation for the proton energy required to diagnose the small-scale density perturbation in ICF core-like scenarios. Proton beams up to 60 MeV have already been produced by PW laser systems [17], however, the generation of sufficient number of protons above 100 MeV would require a significant improvement in high power laser technology and related areas.

6. Proton radiography of shocked matter

Motivated by the capability of the proton radiography technique, an experiment intended to probe various stages of laser-driven shock waves using laser-driven MeV proton beams was carried out at the *Laboratoire Pour l'Utilisation des Lasers Intenses* (LULI), France, employing 100 TW Nd-Glass laser pulses. The long uncompressed temporally Gaussian pulse of 550 ps FWHM with an energy up to 60 J was focused down to a 300 μm FWHM spot (with $\sim 150 \mu\text{m}$ flat top spatial intensity profile) on a 15 μm thick Al foil in order to observe the shock breakthrough (released shock) at the rear side of the target. The peak intensity of the laser on the target was about $6 \times 10^{13} \text{ W/cm}^2$. The probe proton beam was produced by irradiating high intensity CPA short pulse (30 J – 350 fs – 1053 nm) on to a 15 μm thick Al foil, focused by an f/3 OAP down to a 10 μm FWHM spatially Gaussian spot leading to peak intensity of about $3 \times 10^{19} \text{ Wcm}^{-2}$. The typical proton beam had a quasi-exponential spectrum of mean temperature 1.5 MeV and a high energy cut-off around 10 MeV. The RCF stack detector was placed 22 mm away from the probed object, providing a point-projection magnification of 12. All spatial scales in the images presented in this section correspond to the image plane. More description about the experiment, collected data and their analysis (related to the diagnostics other than proton radiography) can be found in

Refs. [5,39]. In this section we shall concentrate on the proton radiography data and their analysis via MPRM simulations. It is to be noted that this experiment was the first test experiment conducted in order to study feasibility of proton radiography of shocked matter.

In the experiment, the long pulse laser was shot on a target with a quartz sliver on the rear in order to probe the shocked matter inside a solid [5,39]. However, the dose lineout across the shadow of the sliver did not show any strong modulation which could be interpreted as the location of the compressed matter produced by the propagation of the laser-driven shock wave. Modeling of the proton radiographs, using shocked matter density profile from 1D hydrodynamic simulation, revealed the inefficiency of the employed probe proton energy to produce a detectable dose modulation across the detector.

In the case of a 15 μm thick Al foil target, a high contrast boundary between vacuum and the expanding foil was observed (see Fig. 13(a)) in the radiograph taken at 7 ns after the interaction of the long driver beam. The shape of the dark region, corresponding to the piling up of the protons, as shown in the radiograph, indicates a spherical symmetry of the shock breakout. As shown in Fig. 13(a), the radius of curvature of the exploding shocked matter was obtained by fitting a circle to the dark region in the experimental data. In order to reproduce the experimental dose lineout over the detector, MPRM simulations were carried out by modeling a spherical ‘cap’ object with a given radial density profile, as shown in Fig. 13(b). The density profiles were chosen in such a way that the mass of the modeled object becomes equal to the mass of an Al disk of 15 μm thickness and diameter equal to the transverse dimension of the deformed portion of the target.

Considering the radial density profile of the plasma as obtained from a 1D hydrodynamic simulation (shown in Fig. 14(a)), carried out for a similar experimental conditions, it was not possible to reproduce the modulation in the dose lineout across the experimental data. It is shown in Fig. 14(a). Therefore, by the help of relevant (by keeping mass of the object conserved) density profiles we tried to reproduce the experimental data, as shown in Fig. 14(b)–(d). During the investigation three interesting conclusions were inferred, as mentioned below, providing blueprints for interpretation of experimentally obtained proton radiographs, in general.

- (1) A sharp increase or decrease in the object density profile gives a ‘hump’ in the deposited dose profile at the respective position (see Fig. 14(a) and (b)). This is because of the superimposition of consecutive beamlets with sudden change in divergence, similar to the case of probing a mesh wire shown in Fig. 6.
- (2) For similar reasons, a smooth increase/decrease in the density profile gives a smooth decrease/increase in the deposited dose profile (see Fig. 14(b)–(d)).
- (3) The contrast between the doses at two different points increases (in some orders) with increase in the contrast between the areal densities at the respective points (see Fig. 14(c) and (d)).

Fig. 13. (a) Proton radiograph of the released shock from rear side of a 15 μm thick Al foil, taken 7 ns after the interaction. Target holder position and the fitted plasma sphere used in modeling are shown. (b) Schematics showing transverse probing of spherically symmetrical shock breakthrough from rear surface of laser irradiated target [for interpretation of color in this figure, the reader is referred to the web version of the article].

Fig. 14. Comparisons between the experimental (red) and simulated (black) dose lineout across the detector for four different radial density profiles (blue) are shown. The radial density profiles are plotted with spatial scales referring to the image plane. The zero radial position of density profiles is the position of the rear surface of the target holder [for interpretation of color in this figure, the reader is referred to the web version of the article].

The close match to the experimental data was obtained for a density profile as shown in Fig. 14(d). The residual disagreement between the background dose levels can be explained by the typical spatially Gaussian proton flux distribution obtained in experiments. The disagreement between the best density profile reproducing the data and the density profile obtained from 1D hydrodynamic simulation could be due to some limitations in the hydrodynamic simulation describing the release state of the shock at the late times ~ 7 ns after the peak of the laser pulse.

7. Conclusion

One of the main applications of the recently discovered high power laser-driven MeV proton beams is point-projection radiography technique. The diagnostic has been employed in several experiments in order to detect the transverse density variation in probed objects. The density variation in the probed object is imprinted over the proton detectors as a result of variations in the transverse beam cross-section — caused by differential scattering and stopping of the probe protons while passing through the object. MPRM code, based on TRIM, is developed in order to retrieve the density profile of the object from the experimentally obtained optical density modulation across RCFs, a commonly used proton detector in such experiments. Reasonably high accuracy has been obtained by the MPRM simulations, which is demonstrated by comparing the simulated and experimental proton radiographs of various static objects, such as thin mesh wires and plastic micro-balloons. Simulations for the proton radiographs of periodic mesh structures provided detail information about laminar flow of the laser-driven proton beam with their extended *virtual* source, a key factor while employing the proton beam as a high resolution backlighter in a point-projection imaging scheme. In another experiment proton radiography technique was employed in order to probe various stages of a laser-driven implosion. MPRM was used to simulate the proton radiograph of the compressed core near to its stagnation. In this case the core was modeled as a spherical object of Gaussian radial density profile, where PD and FWHM are estimated with an accuracy of 1 g/cc and 20 μ m, respectively. However, better accuracy could have been obtained in the experiment by probing the compressed core with higher energy protons, as inferred from MPRM simulation. As a feasibility study of the technique, MPRM simulations predict that employing 100–150 MeV probe proton energy, proton radiography diagnostic will be capable of resolving core asymmetries in ignition scale inertial confinement fusion plasmas at the National Ignition Facility, USA. Another demanding research area in the field of high energy density physics is the study of Mbar pressure driven shock-wave propagation through matter, in order to obtain EOS of the extreme states analogous to ICF compressed core. Proton radiographs of the shocked material obtained in a recent experiment were analyzed via MPRM simulations. Deficiency in the probe proton energy behind the failure in radiographing the shocked matter was concluded from a series of simulations.

Due to the complexity and very statistical nature of particle beam scatterings by matter, it is difficult and also not adequate to employ analytical approaches for analysis of the proton the radiographs. However, for the prospective of an experimentalist, seeking for a quick understanding of the data over the experiment, simple formulas to estimate various crucial parameters, such as spread angle, threshold areal density, blurring coefficient and spatial resolution for a given probe particle energy are described. In addition, the variety of proton radiographs and their analysis discussed in the paper also provides many useful tips to obtain a rough understanding about areal density variation across the probed object from the radiographs.

While the MPRM simulation reproduces the experimental radiographs of cold dense matter, it requires updates for scattering parameters in case of objects in extreme matter states. Research in this field is under progress while the requirement of laser-driven high energy particle beam (for diagnosing ICF like cores) will be addressed.

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