NUKLEONIKA 2012;57(2):231–235

ORIGINAL PAPER

Can laser-driven protons be used as diagnostics in ICF experiments?

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Abstract. Point projection proton backlighting was recently used to image a cylindrical imploding target at Rutherford Appleton Laboratory (UK). Due to the relatively low energy and to the very large mass densities reached during implosion, protons traveling through the target undergo a very large number of collisions which reduced the resolution. Here, we present a simple analytical model to study the proton radiography (PR) performance as a function of the main experimental parameters. This approach leads to define two different criteria for PR resolution describing different experimental conditions.

Key words: laser-driven protons • inertial confinement fusion (ICF) • proton radiography (PR) • HiPER • radio-chromic films (RCF)

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Received: 12 November 2011
Accepted: 19 December 2011

Introduction

Transverse point projection proton radiography (PR) has been used to measure the target density during the compression in many inertial confinement fusion (ICF) experiments. These were performed in the framework of the experimental road map of HiPER. Proton beam source can be generated by fusion products in exploding-pusher implosions of D3He-filled glass-shell, providing monoenergetic beam with energy ~ 15 MeV [6, 10] or by laser-target interaction providing multienergetic beam with a peak energy ~ 60 MeV [3, 15]. The multienergetic proton spectrum also allows probing the target implosion at different times in a single shot, thanks to the difference in proton time of flights. PR using laser-generated protons, and radio-chromic films (RCF) as detectors, has already been used, in a recent experiment at Rutherford Appleton Laboratory (RAL) in 2006, to probe the implosion of a spherical shell; experimental results were analyzed and compared with Monte Carlo (MC) simulations and the results are reported in Ref. [7]. However, this analysis is based on the usual approach to proton imaging, in which, the proton energy loss during the target penetration is neglected and a direct correspondence between time of flight and stopping range of proton inside the detector is assumed. This approach has proven to be very successful in the detection of electric and magnetic fields in plasmas [1, 2] but it fails if applied to the typical ICF conditions in, which protons penetrating thick and dense targets, suffer severe multiple scattering (MS) and energy losses.

PR technique has also been used in ulterior experiment at RAL in 2008 to study fast electron propagation in cylindrical compressed target [8, 11]. Experimental results were analyzed in Refs. [12–14] by considering the whole time evolution of the target implosion and comparing them with a time dependent MC simulations in which the plasma nature of the medium has been taken into account. In these papers we present a basic review of the classical scheme of PR discussing on the main physical effects, such as the stopping power and the MS of the protons traveling into the compressed target. These effects reduce the PR performance because they are connected to the variation of parameters (density, temperature and ionization degree) during target implosion. Hydrodynamical codes CHIC (2D) and MULTI (3D) have been used to produce density, temperature and ionization degree profiles to be used as initial conditions for PR MC simulations. We also show that MS effects are dominant in the high density regions of the target and to do this we have developed a simple analytical model to consider the performance of PR as a function of initial experimental parameters in that regions.

In this paper we would like to summarize our previous work [12–14] by introducing two criteria for PR resolution: the first is called "strong condition" and is based on a strong requirements in terms of energy of the beam to be satisfied; the latter is called "weak condition" is less stringent, but gives only partial information on the target density profiles. These two criteria are based on geometrical considerations and are obtained assuming that the MS processes is the main responsible for the deterioration of the PR resolution. At the same time, MC simulations have been performed to validate the theoretical prediction.

Experimental setup

Proton beam can be generated irradiating a thin metal layer (usually gold or titanium) using an ultra-short and ultra-high intensity 10^{19} W/cm^2 laser beam according to the TNSA process [3, 15] the accelerated protons are characterized by a small source, high degree of collimation, short durations and exponential decreasing energy spectrum. In this section we introduce typical ICF experimental conditions showing briefly the setting of two important experiments which have been performed at the Vulcan Peta-Watt Laser at RAL one in 2006, to study the compression of a spherical target [7], and the latter in 2008, to study electron beam propagation in a cylindrical compressed target [8, 11]. In both these experiments PR technique has been used to study density profiles and compression degree of the imploding target.

Plastic (spherical-cylindrical) target has been compressed using long pulses (ns) and high intensity (10^{16} W/cm^2) laser beams. In the experiment performed in 2006 six laser beams, in a spherical configuration, have been used to compress a 500 μ radius spherical target, while in the experiment performed in 2008, 4 laser beams have been used to compress a 220 μ diameter cylindrical target. The proton beam were generated using the ps laser pulse focused on a 20 μ-tick gold foil at normal incidence and far enough from the target such that the generated proton beam behaves as point-like source. The maximum proton beam energy reached was, respectively 7 and 10 MeV. The same detector, a stack of RCFs, has been used in both experiments. Hydrodynamic and MC simulations have been performed before (to design the PR setup) and after (to validate the experimental results). Due to the very large mass densities reached during target implosion, protons traveling into the target undergo a very large number of collisions which induce a mean deviation of protons from the straight trajectory. This phenomena reduce significantly the PR performance. In fact, in both experiments PR images appeared much enlarged compared with theoretical predictions; this apparent paradox has been addressed and solved in Refs. [13, 14]. In this paper, we recall the main point of the corresponding interpretation, and provide its analytical framework, validate by simulations. The path which have been lead to a right interpretation of the experimental results has been long and is well explained in the above-mentioned publications, here we would like present only a final PR scheme which can be useful for experimental users.

Proton radiography

A typical PR setup is shown in Fig. 1; protons, generated via laser-target interaction, probing the imploding target will be collected by the RCF stack in which particles are stopped as a function of their energy. If the proton beam is multienergetic, then protons with different energy arrive at different time (time of flight, TOF) to probe the target and are stopped at different positions inside the detector. Moreover, due to the Bragg peak properties protons deposit most of their energy at the end of its travel inside the matter. Due to this fact, it is possible to arrange the position of the films inside the stack in order to associate each film with a given detected proton energy. Finally, if the target is dropped, leaving free space between the source and detector, the obtained proton spectrum is a decreasing exponential with energy, and the contribution of higher-energy protons in a given RCF can be neglected. Consequently, each RCF can be associated with a single instant of the implosion history. This scheme has been used many times to infer the proton beam spectrum starting from the RCFs analysis by using a deconvolution technique [14]. Unfortunately, in ICF experiments the energy spectrum of the protons going out from the probed sample, change drastically with respect to the spectrum of the incoming protons. The direct relation between TOF and stopping range of protons is no longer true and the signal on the single RCF layer is no longer due to a monochromatic contribution as in the "ideal case" (no target).

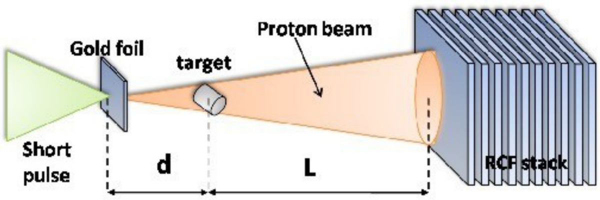

Fig. 1. Scheme of proton radiography. In RAL experiment d = 1 cm and L = 4.5 cm giving a magnification factor M = 4.5.

Analytical framework

It is important to perform an analytical evaluation of MS because it is really the main cause for the observed larger size of the proton images. This allows to evaluate the right object size and also to evaluate the necessary conditions for getting good proton radiographies. We can estimate the effect of MS on the detected size of the cylinder, by defining the blurring factor as

$$\xi = L\,\theta_{MS}$$

$$\theta_{MS}[\text{rad}] = \frac{E_s[\text{MeV}]}{2}\sqrt{\frac{1}{L_R[\text{g/cm}^2]}}\frac{\sqrt{A[\text{g/cm}^2]}}{E[\text{MeV}]} \tag{1}$$

$$A = \int \rho(x)dx$$

where A is the areal density, L is the cylinder-detector distance, E_s = 15 MeV and L_R is the radiation length and θ_{MS} is the mean angular scattering of a proton with energy E traversing a material with density ρ as obtained in Ref. [9]. Starting from MS formula we introduce two criteria to estimate the PR resolution.

Proton radiography conditions

Strong condition

In a previous work [13, 14] we have shown that the mechanism of PR in warm dense matter is quite different from that in cold matter due to the presence of a large number of collisions. A criterion to estimate the resolution degree of the system starting from the parameters and the experimental setup can be defined starting from a typical experimental setup (see Fig. 1). A point-like particle source irradiates a finite size object by creating a projected negative image on the detector. In principle, if the MS is negligible, i.e. for neutral particles, then the projected image on the detector will appear enlarged by a factor $M = (L + d)/d$ which corresponds to the geometrical magnification.

In particular, defining δx a part of the sample, the projection on the detector becomes $\Delta x = M\delta x$. Nevertheless, using charge particles the effect of the coulomb MS is never negligible and the protons passing through the object are deflected by a mean angle θ_{MS}, giving a mean transverse displacement $\xi = L\cdot\theta_{MS}$ which can be estimated by using Eq. (1). Therefore, the projected image on the detector will appear enlarged by an additional factor μ with respect to that would appear, if there were no scattering, i.e. by a factor μM with respect to the initial size δx where μ is defined as follows [5]:

$$\mu = \sqrt{1+\left(\frac{\bar{\xi}}{\delta x}\right)^2}\,;\ \bar{\xi} = \xi / M \tag{2}$$

Starting from the above considerations we can infer that the blurring coefficient must remain less, or of the same order, than the resolution that we would like to obtain δx in order to avoid the crossover between different single proton trajectory and to prevent a consequent loss of the initial spatial target information's carried out by protons. The above-mentioned condition can be written in terms of blurring coefficient (i.e. ξ/M is the resolution of our system in analogy with Rayleigh's criterion in optics

$$0 \le \xi \le \delta x \vee 1 \le \mu \le \sqrt{2}. \tag{3}$$

If the strong condition is satisfied, then the PR resolution is under control, similarly as for X-ray radiography, and the gray scale level obtained by the RCF analysis will be proportional to the density gradient of the probed target. A simple estimation of the μ parameter can be done considering the protons passing through the dense core in RAL-08 experiment: the size of the core is ~ 60 μm and we look for a resolution δx ~ 20 μm (1/3 of the FWHM); the blurring coefficient can be estimated assuming the maximum reached energy for protons (~ 10 MeV), probing an area density A ~ 0.06 g/cm^2 (M = 4.5). The result obtained using Eq. (1) is μ ~ 7 which is larger than the minimum required value confirming that the relatively small energy (~ 10 MeV) reached in these experiments seems not sufficient to satisfied the "strong condition" which remains unattainable for the maximum energy reached at the moment (~ 60 MeV). At these energies, protons are not able to probe the dense core of the imploding target. The only way to decrease the MS effects is to decrease the areal density contribution to the Rossi formula. On the other hand, considering protons passing through the plasma corona, the areal density fall into a value which is about A ~ 0.002 g/cm^2 (density 0.05 g/cc over a distance of ~ 400 μm) and, in the same conditions, we obtain μ ~ 2 which corresponds to an acceptable resolution no larger than 20 μm.

Weak condition

The above considerations suggest that "strong condition" is unattainable at the moment. We are intending to search for a less stringent condition for PR. In order to do this we must come back to the aim of the PR. What we would like to know about imploding shell during experiments? PR should gives us information about the density profiles through the areal density parameter which is defined as the product of the peak density and the FWHM of density profile. Starting from the evidence that PR of a sharp density profile is energy--independent, we can infer that the slope of the density profile play an important rule on the PR performance. As example the radiography of a flat-top profile is given by the external protons only which travel in vacuum and is energy-independent. In this case the obtained image cannot gives us density information. Since in ICF experiments the density profiles are never truly flat, then we adopt super-Gaussian profiles which allow us to describe both flat-top and smooth profiles. As just explained before protons which on passing through the dense core are stopped or diffuse while those passing through the corona (low density region) are deviated by a small scattering angle. Thanks to the sharp profiles the differences in areal density between the protons passing through the external and the internal region become very huge giving an high contrast and then an acceptable resolution. Here we developed a criterion to estimate the resolution of the system in the above-mentioned condition as a function of the sharpness of the target profile and we refer to this criterion as "weak condition". Let start assuming a 2D super-Gaussian density profile:

$$A_{x,y}(\gamma) = \rho_p \exp\left[-\ln 2\left(\frac{x^\gamma + y^\gamma}{w^\gamma}\right)\right] \tag{4}$$

where $w_x = w_y$ = FWHM/2 and γ is the degree of the super-Gaussian function. Protons arriving by the x-direction will probe certain density profiles $A_y(\gamma)$ as a function of their y position:

$$\begin{aligned} A_y(\gamma) &= \int_R A_{x,y}(\gamma)dx = A_x(\gamma)\exp\left[-\ln 2\left(\frac{y}{w}\right)^\gamma\right] \\ A_x(\gamma) &= \rho_p \int \exp\left[-\ln 2\left(\frac{x}{w}\right)^\gamma\right]dx \end{aligned} \tag{5}$$

the resulting Blurring coefficient will be

$$\xi_y(\gamma) = \frac{\Gamma c\sqrt{A_y(\gamma)}}{E_p} = \frac{\Gamma c\sqrt{A_x(\gamma)}}{E_p}\exp\left[-\frac{\ln 2}{2}\left(\frac{y}{w}\right)^\gamma\right]; \tag{6}$$

$$\Gamma = \frac{L}{M} = \frac{Ld}{L+d}; \quad c = \frac{E_s}{2\sqrt{L_R}}$$

Following the scheme in Fig. 2 "weak condition" can be written following these conditions: (I) The blurring occurring by protons passing through the plasma corona (region of the density distribution outside the FWHM $\xi_{(w+2\eta w)}(\gamma)$ must be of the same order of the resolution $\delta x = 2\eta w$ (where $0 < \eta < 1$) which we would like to obtain (the resolution must be a fraction of the FWHM). (II) The blurring occurring by protons passing through the plasma core (region of the density distribution inside the FWHM $\xi_{(w-2\eta w)}(\gamma)$ must be larger two times with respect to the target density profiles FWHM. The I conditions depend on the experimental parameters (ρ,E,ω,γ) and on the geometry of the target density profiles (γ,ε) it gives us the resolution of proton radiography for all the protons passing outside of the core limited by the FWHM. The II conditions depend on the geometry of the target density profiles only (γ,ε) and it guarantees that the protons passing through the core do not participate in forming the image on layer (but the background only). Of course, in the "weak condition" regime we cannot avoid the loss of geometrical information about the target internal core of the target; we can look at the target size only. From experimental point of view, the super-Gaussian degree γ is not easy to estimate then we can use the relation between the Gaussian degree γ and the slope of the density profiles calculated in $w/2$.

Validation using simulations

Finally, we have tested the analytical prediction with Monte Carlo simulations performed using the MCNPX Monte Carlo program [4] (for simplicity the plasma effects have not been taken into account; these effects do not change the "relative" results of our analysis), changing the density profiles only. In Fig. 3 are shown the results of simulations performed by assuming a monoenergetic proton beam E = 10 MeV probing a spherical target with a variable (γ = 2, 4, 6) Gaussian density profiles (ρ_p = 6 g/cm^2, w = FWHM/2, w = 100 μm) which correspond to a peak areal density $A(y = 0) \sim 0.12$ g/cm^2. The images below show the results of radiography as usually appears in the RCF layer.

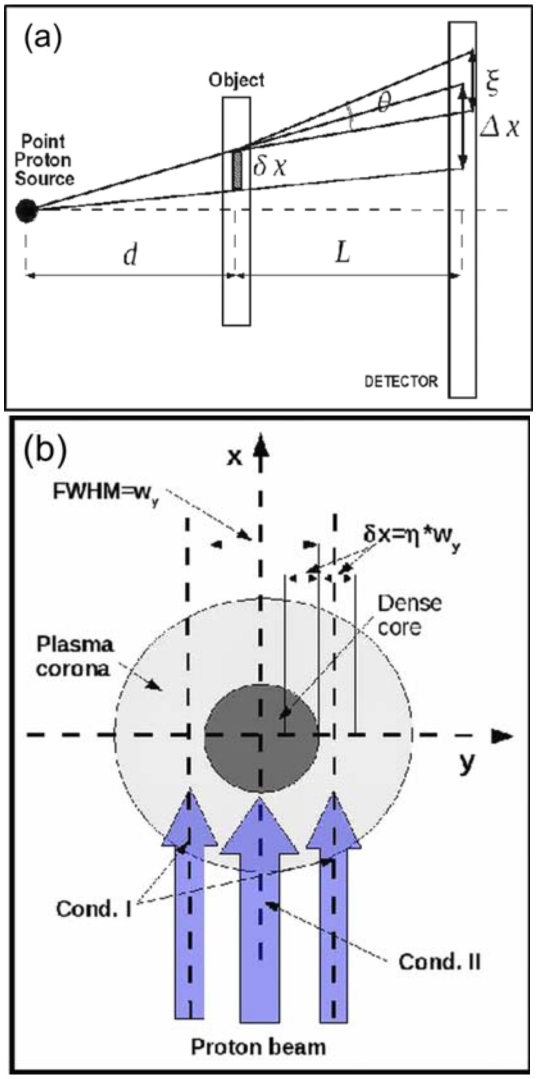

Fig. 2. Scheme of PR resolution. (a) "strong condition" lateral point of view, (b) "weak condition" top point of view.

Simulation results confirm the analytical prediction giving resolution values δx very close to that obtained analytically.

Summary and conclusions

PR has been used to diagnose the hydrodynamic evolution of imploding target. The information carried out by protons passing through the dense core is lost because they are scattered more than the protons passing through the plasma corona. The last ones then form the images on detectors "in negative". Declining proton radiography resolution is due principally to the enhancement of the scattering of protons traveling

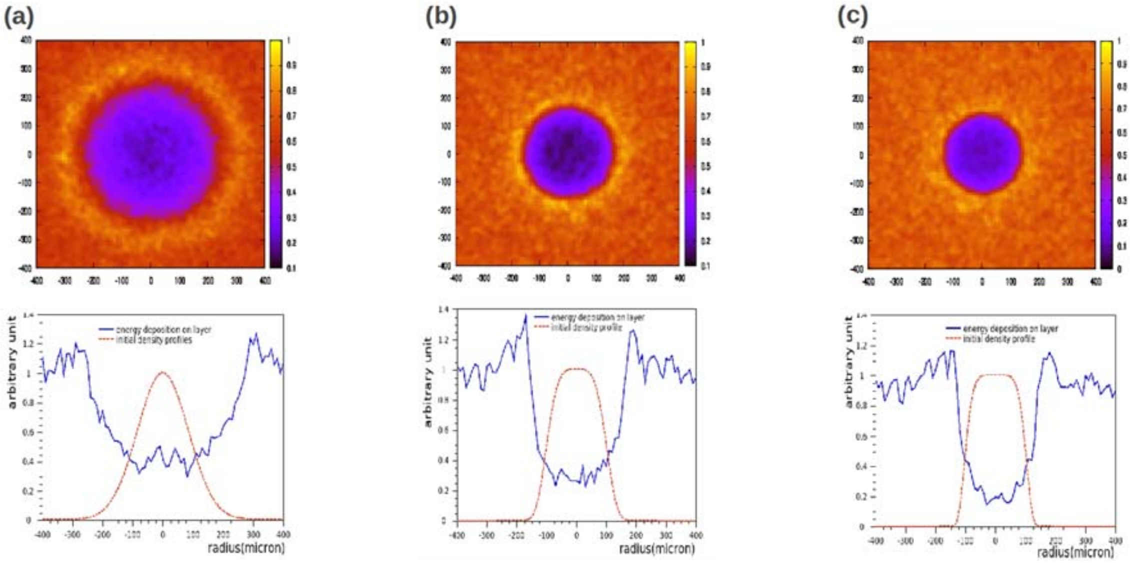

Fig. 3. Monte Carlo simulations of the PR of a spherical target represented by three different super Gaussian density profiles; the probe beam is given by 10 MeV monoenergetic proton point-like source. 2D-maps view of the probed target (top pictures) and 1D-profiles obtained from line out of 2D map compared with initial density profiles a function of the slope *g* (bottom diagrams).

inside the highest density regions of the target. MS is reduced for high-energy protons and, with respect to this problem, we have deduced two different criteria: the first, "strong condition", cannot never be satisfied to date while "weak condition" give us the possibility to applied PR with a reasonable resolution efficiency but it cannot be useful to give us exact informations about density profiles of the imploding target. The formulation of the "weak condition" suggests to introduce a new parameter which is defined as the ratio between the peak density and the FWHM.

PR could be a valid imaging tool for high density measurement if we are able to provide to calculate the resolution as a function of experimental parameters, and if we are able to give correct interpretation of the experimental results. This paper provides all the information to identify the region of parameters in which PR can be used according to the required resolution in such a way to make proper use of this diagnostics.

Acknowledgment. This work was realized at the Università degli Studi di Milano-Bicocca in Italy and at the CELIA – Université de Bordeaux 1 in France.

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