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A new algorithm for spectral and spatial reconstruction of proton beams from dosimetric measurements

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Abstract

We report on a new algorithm developed for the dosimetric analysis of broad-spectrum, multi-MeV laser-accelerated proton beams. The algorithm allows the reconstruction of the proton beam spectrum from radiochromic film data. This processing technique makes dosimetry measurements a viable alternative to the use of track detectors for spatially and spectrally resolved proton beam analysis.

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1. Introduction

When an ultra-intense laser pulse is focused on a solid target a sizeable fraction of the laser energy (up to 30%) is transferred to charged particles [1,2]. Production of energetic protons has been observed since the earlier laser–plasma interaction experiments [3]. However, generation of multi-MeV proton beams has been possible only recently, thanks to the increase in laser power allowed by the implementation of the Chirped Pulse Amplification technique. The energy and spatial features of these beams make them of great interest in view of a wide range of multidisciplinary applications. Laser-produced proton beams have been proposed as the ignition trigger in the Fast Ignitor scheme of inertial confinement fusion (ICF) [4] and, more recently as a tool for tumor treatment [5]. Moreover, due to the electric charge of the protons, these beams can be used to diagnose the electric and magnetic fields generated during the interaction of intense laser pulses with plasmas [6,7]. Proton beams have been observed even using target which nominally do not contain hydrogen (as in the case of metal targets). Recently [8] it was proved that protons originate from hydrocarbon impurities located on the target surfaces. The proton burst produced in this way

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is characterized by a short duration ($\sim$ps), a large number of particles ($\sim 10^{11-12}$ protons), a broad band energy spectrum and a moderate collimation [9–11]. A thorough investigation of the properties of these beams is required, in view of the applications described above, and in general to evaluate the promise of laser acceleration as an alternative to more established acceleration techniques. The work presented in this paper sets in the frame of the range-energy deconvolution of particle energy spectra ([12] and references therein), bringing in a novel algorithm for proton beam characterization from dosimetric measurements.

2. Proton detection

A fundamental step towards the experimental characterization of laser-produced proton beams is the development of a detection technique capable of providing good spatial and spectral resolution in single shot measurements and in the presence of the large electromagnetic noise typical of high power laser experiments. Due to noise interference, detectors based on scintillator/photomultiplier assemblies are ruled out. An alternative is offered by track detectors, such as CR39 [13]. However, the use of these detectors is not straightforward: their analysis requires post-exposure processing (chemical etching) under controlled conditions, and time-consuming track counting procedures.

An interesting alternative is the use of Radio-Chromic Film (RCF) [14]. This detector is extensively used in clinical dosimetry for detecting electrons and gamma rays, and has also been used for high-flux proton detection in several laser–plasma experiments [10,11,15–17]. In practice, detection with RCF exploits the proportionality between optical density (OD) variation of active layers and the energy locally released by the incoming particle beam (absorbed dose). The main disadvantage in the use of RCFs is that they do not discriminate between different types of ionizing particles (for this reason a detailed study of the beam composition requires the simultaneous use of different detectors [7,10]). Moreover, RCF response is only slightly dependent on the radiation energy. On the other hand RCFs provide excellent spatial resolution (~ 1 μm) and good linearity, do not require developing procedures after exposure, and are insensitive to electromagnetic noise.

3. Conceptual detection scheme

The lack of sensitivity of the RC films to the energy of the incident particles can be overcome by building a multilayered RCF detector [7,10]. A possible detector arrangement is shown in Ref. [7]. We refer here to the characteristics of the Gafchromic MD55 film, the most commonly used in laser-acceleration experiments. The film consists of 270 μm thick plastic containing a double layer of an organic dye, which reacts to ionizing radiation. The equivalent dose of energetic protons released in the film can be measured from the OD variations undergone by the film. By using RC film in a stack, each film acts as a filter for the following ones. In the case of detection of laser-produced proton beams an Al foil is placed in front of the first film to protect it from scattered laser light and debris from the target. With a 25 μm thick Al foil the minimum detectable proton energy is about 3 MeV.

The exposed radiochromic films are digitized using densitometers or scanners. The conversion factor of the OD into absorbed dose depends on the frequency of the light used to scan the film. The conversion curve is provided by the RC film manufacturer, or it can be obtained via ad hoc calibration procedures. The OD dependence from the dose is linear over an extended range of Optical Densities.

4. Description of the algorithm

The numerical algorithm presented in this paper has been developed to reconstruct the spatial and energy distributions of proton beams detected by stacks of RC films. In the following, $R(E,z)$ is the Bragg curve, i.e. the stopping power as a function of the penetration depth z for a proton of energy E. The numerical expression of $R(E,z)$, which is crucial for characterizing the response of the detector, can be computed by means of a Montecarlo simulation. We used a software package to evaluate the Stopping and Range of Ions in the Matter (SRIM) [13,18] throughout all the present work. Some SRIM outputs for mylar are shown in Fig. 1a. We point out that, within the energy range of our interest, the Bragg curves for protons of different energies can be reduced to a single numerical function by applying simple scaling laws. The final result is shown in Fig. 1b. We will exploit this useful result to reduce the number of simulations to be performed and to implement an efficient and faster algorithm. It is important to notice that, since proton deflections due to scattering in the detector are small, we can assume straight line propagation of the protons through the layers of RC films. The energy $S_k(x,y)$ released in a point of coordinates (x,y) of the kth RC film can be written as the integral of the product between the proton spectrum $f(E,x,y)$

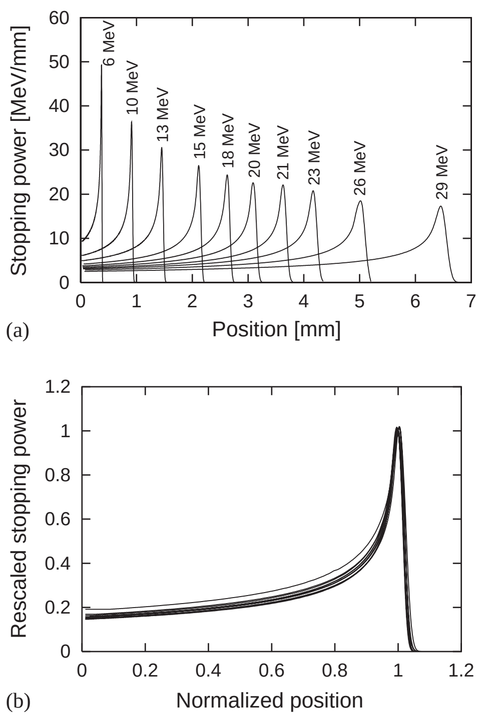

Fig. 1. Bragg curves ($R(E,z)$) for protons of various energies propagating in Mylar, evaluated using SRIM: (a) original Bragg curves plot; (b) after the rescaling law.

(defined as the proton density per energy and surface unit) and the Bragg curve $R(E,z_k)$, giving the equation

$$S_k(x,y) \simeq \int_0^{\infty} R(E,z_k) f(E,x,y)\,\mathrm{d}E \quad (1)$$

where z_k is the position of the median plane of kth RC film. The main idea behind the algorithm is that the proton beam spectrum can be always approximated with a set of function $g_i(E)$ and corresponding coefficient Np_i

$$f(E) \simeq \sum_{i+1}^{n} (Np_i g_i(E)). \quad (2)$$

The simplest choice for g_i in our case is a set of triangular functions, whose analytical form is

$$g_i(E) \simeq \begin{cases} \dfrac{E - E_{i-1}}{E_i - E_{i-1}} & \text{for } E_{i-1} < E \leqslant E_i \\ \dfrac{E_i - E}{E_{i+1} - E_i} & \text{for } E_i < E \leqslant E_{i+1} \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

So, for a given set of sampling energies $\{E_i\}$, Eq. (1) can be rewritten in a more compact form by rewriting the energy integral as a matricial operator

$$S_k = M_{ik} Np_i \quad (4)$$

where Np_i is the proton density sampled into $\{E_i\}$.

Since the detector has a finite number of layers, we can just determine the spectrum for some values of the z coordinate and then perform a linear interpolation. The number of elements of the base (i.e. the matrix dimension) is equal to the number of RC foils. At this point the solution of the problem requires a particular choice of energy sampling set $\{E_i\}$.

To this aim some considerations about the proton energy loss in the matter are necessary. Due to the characteristic form of protons' Bragg curves, the greatest contribution to the signal collected in a generic RC foil is due to the protons whose Bragg peak falls exactly within that RC foil. However, protons having Bragg peak both after and immediately before the considered RC foil will also contribute, to some extent, to the signal. By choosing the medium energy point E_{Mk} of each RC foil, we expect the matrix M to be almost triangular

$$M = T + \delta M \quad (5)$$

where T is an upper triangular matrix and δM a matrix consisting of elements below the principal diagonal.

In order to solve the system of Eq. (4) we just need now to translate the medium values ($\{E_i = E_{Mi} + \delta E_i\}$) until the condition $\delta M \ll T$ is satisfied.

5. Test of the algorithm

In order to validate the algorithm, we have developed a code that simulates the OD distribution caused by a proton beam with a given spatial and energy spectrum into a RC film detector. The reconstruction algorithm has then been used to retrieve the spatially resolved energy spectrum of the protons from the simulated set of exposed RC films.

The incident proton beam chosen in the simulation has a cylindrical simmetry with a ring-like shape with an exponential energy spectrum truncated at 20 MeV. This is qualitatively similar to the distribution of protons produced, in some experiments, during the interaction of an intense laser beam with a thick target (thicker than 100 μm) [9]. A 2-D plot of the proton distribution is shown in the upper frame of Fig. 4.

As shown in the figure, both the depth and the diameter of the ring become smaller as the proton energy increases.

We have simulated the signal corresponding to the energy deposited by such a beam for each film of the RC stack. As it is shown in Fig. 2, the simulated scans of the RC films of the stack have almost completely lost the annular structure of the impinging proton beam. These scans were built assuming a standard 8 bit digitization. In other words, we handle the simulated data with the same accuracy (for what concerns sampling and dynamic range) as in the case of digital data obtained scanning RC films with a 8 bit scanner. The optical density (OD) is obtained from the numerical matrix associated to the scans as

$$\text{od} = -\log \frac{I}{255}. \quad (6)$$

Fig. 3 shows the comparison between spatial distributions of the proton beam used in the simulation and those retrieved by the algorithm for two sampling energies of 7 and 19 MeV. The entire distribution, including the ring-like structure, is well reconstructed. Also visible in the reconstructed profile is the noise due to the digitization resolution (8-bits) used to build the simulated RC data. An overall comparison between the test distribution and the retreived one is shown in Fig. 4. In the figure, the upper half of the graph shows the 2-D gray-scale plot of the test beam (energy/space profile). The lower half shows the same profile as obtained from reconstruction with our algorithm.

The agreement between the beam parameters retrieved by the algorithm and those of the test beam is very good up to about 19 MeV. The discrepancy observed between 19 and 20 MeV is

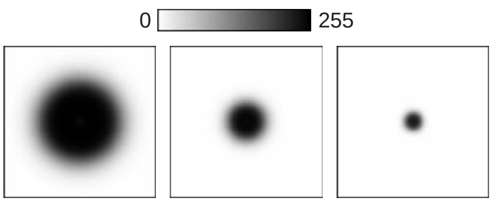

Fig. 2. Simulated digitized data for three RC films exposed to the proton beam (number 0, 5, 10): the first one is the nearest to the proton source.

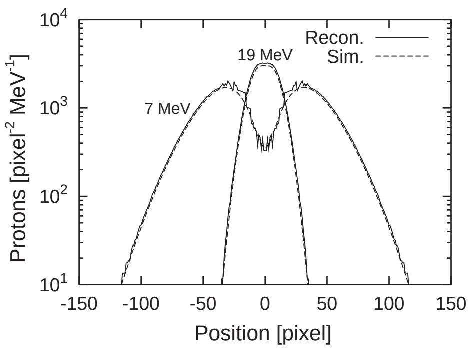

Fig. 3. Comparison between the spatial distributions of the test (dashed line) and reconstructed spectra (solid line) for two sampled energies.

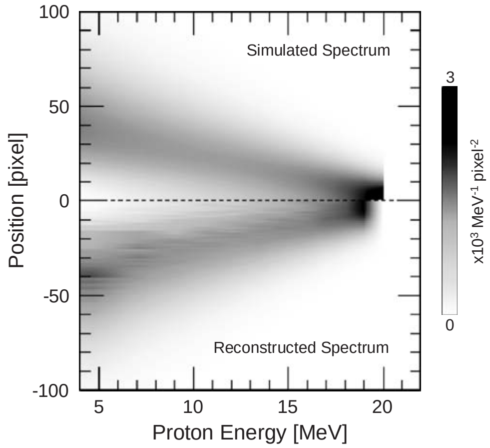

Fig. 4. Overall comparison between the simulated and reconstructed space resolved spectrum of the proton beam.

due to a reconstruction error arising from a lack of information on protons in this energy range, whose Bragg peak occurs after the last RC film with detectable signal. This is a general feature of the reconstruction algorithm due to the specific properties of energy release of protons (Bragg peak). Moreover, in our case, this effect, is emphasized, due to the truncation of the energy distribution function above 20 MeV.

6. Conclusion

A new algorithm, developed for the analysis of data obtained from dosimetric proton detection, has been described in detail. Its validation has been carried out by means of Montecarlo simulations. The algorithm has been developed in view of the analysis of the spatial and spectral properties of a proton beam produced in laser–plasma interaction experiments, where multilayered dosimetric detection is a viable and advantageous diagnostic option. Our results show that the algorithm applied to RC films exposed to proton beams enables the main properties of the proton beam to be retrieved with high accuracy. In our opinion, this results is particularly interesting in view of future developments and applications of laser-produced proton beams.

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