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***Abstract* — The properties of the proton beam can be investigated by using a stack of radiochromic film (RCF) imaging the shadows of a mesh placed within the beam path. We present results of a proton beam generated from a hemispherical shell target. The experimental data validates modeling, and leads to the understanding of proton focusing relevant to integrated proton Fast Ignition (FI) experiments.**

The advent of chirped pulse amplification (CPA) opened the way to very high intensities ~10^{20} Wcm^{-2}, which enabled the generation of protons from the rear surface of thin foil targets [1]. Accelerated hot electrons set up a sheath field on the rear surface, which ionizes and accelerates the protons normal to the sheath. The acceleration mechanism is widely known as target normal sheath acceleration (TNSA) [2]. The protons produced in these interactions have several potential applications including radiography, oncology, and Fast Ignition (FI) for Inertial Confinement Fusion (ICF).

Two parameters relevant to FI that need to be carefully studied are [3]: i) laser to proton conversion efficiency and ii) proton jet focusing. There has been significant work performed to understand the underlying physics of proton conversion efficiency and peak proton energy (ref. 4 and references within). However, investigations of proton focusing are relatively scarce. Proton jet focusing was first demonstrated using hemispherical shells [5] and was further explored to determine the optimal position of focus at a distance of 1.7*R* from the apex of the hemispherical shell, where *R* is the radius of curvature [6].

We have recently carried out experiments to study proton focusing on the Trident laser system at the Los Alamos National Laboratory. High-density carbon, 10 μm thick, hemispherical shell targets with a 300 μm radius of curvature were irradiated with the Trident ultra-short pulse laser delivering approximately 70-80J on target in 500-600fs [8]. The principal diagnostic used in the experiment to image and diagnose the proton beam was a stack of radiochromic film (RCF). RCF is a dosimetry film with an active layer that undergoes a chemical reaction when exposed to radiation changing the color of the film to blue; its intensity is proportional to the amount of radiation absorbed. Layers of RCF were alternated with aluminum filters of different thickness to create a stack, which was placed 4 cm behind the target. The experimental setup is shown if Fig. 1(a). Since protons deposit the majority of their energy at the Bragg peak, each layer of RCF corresponds to a particular proton energy [4, 7]. A copper mesh was placed in the path of the proton beam at various distances from the apex. When the proton beam is generated from the rear surface of the target, it will pass through the mesh, leaving an imprint in the beam, which is visible on the layers RCF, providing beam information for different ranges of proton energies.

Fig. 1 (b) and (c) are two layers of RCF showing the proton beam collected from a hemispherical shell target with the mesh placed 1.5 mm from the apex (position 2 in Fig. 1(a)). The mesh image on the RCF allows the proton beam to be traced back through the mesh placed in the beam path to the target using straight-line trajectories to determine the focusing characteristics of the beam (i.e. focal spot size and position). However, the calculated focal position was never beyond the equatorial plane of the hemispherical shell: much less than the previous determined 1.7*R* [6].

For further investigation, the experimental results were compared to simulations. Modeling showed that the protons have bent trajectories and do not travel in straight lines until well beyond the focus. A backward projection of the simulated particles, similar to the experimental analysis, shows that the modeling is consistent with the experimental results, which validates the modeling of the focusing process and the bending of the proton trajectories, which is seen for the first time [9].

The bending of the proton trajectories seen in the simulations is further validated by the image captured on the

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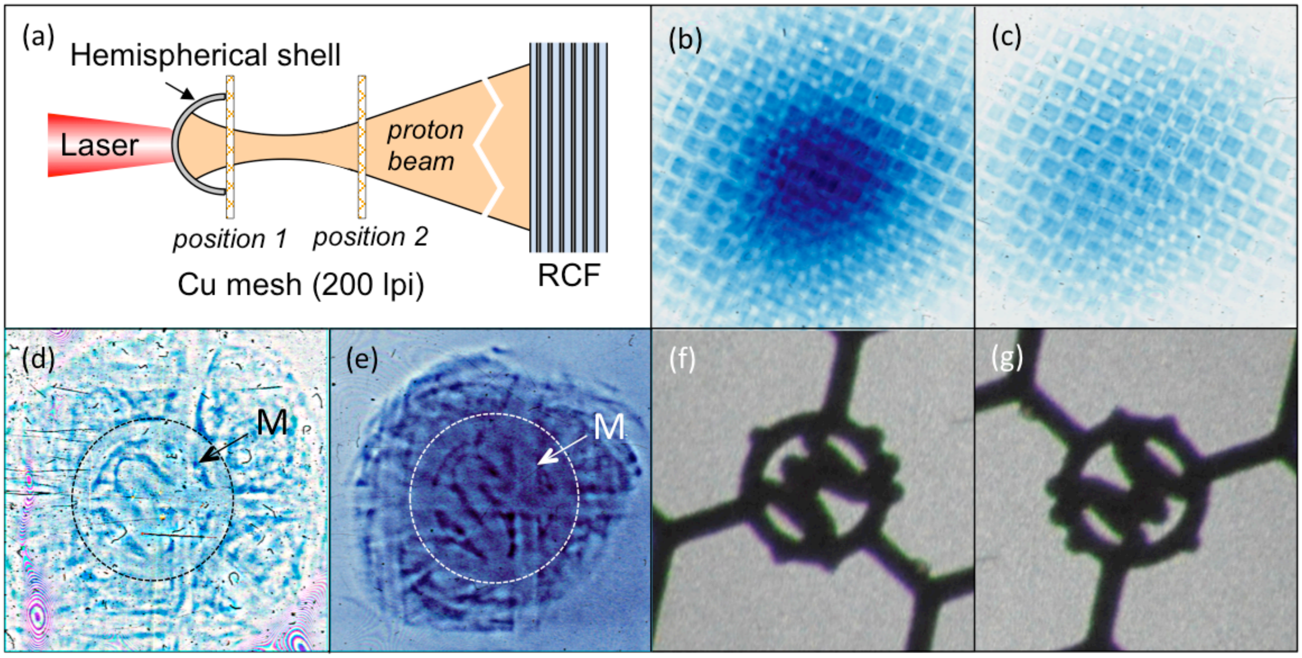

Fig. 1. (a) Schematic of the experimental setup. A proton beam passing through a mesh placed 1.5 mm from the apex of the hemispherical shell (position 2) captured on layers of RCF corresponding to the energies of (b) 7.3 MeV and (c) 11.1 MeV. Layers (d) and (e), corresponding to the energies of (d) 20 MeV and (e) 27.5 MeV, are images of a proton beam passing through a mesh at the equatorial plane with a 'M' in the center of the mesh. The dotted lines are used to guide the eye. (f) Orientation of the 'M' in the experiment as seen down the laser axis. (g) Orientation of the 'M' flipped horizontally and vertically if the proton trajectories were ballistic and passed through focus.

layers of RCF seen in Fig. (d) and (e). The proton beam passed through a mesh, with a distinctive 'M', placed 300 μm from the apex of the hemispherical (position 2 in Fig. 1(a)). The orientation of the 'M' seen in the center of the RCF is in the same orientation as in the experiment, which is shown in Fig. 1(f). If the protons moved in straight-line trajectories, then orientation of the 'M' would have been flipped horizontally and vertically as shown in Fig. 1(g). Since the orientation is not changed, straight-line approximations, assumed in a case of ballistic focusing of the proton trajectories, are not valid.

The distortion of the mesh images on the RCF in Fig. (b) and (c) provide information on the uniformity of the proton beam, which also supports the bending of the proton trajectories. The mesh image created by the higher energy protons (c) has less distortion than the mesh image produced by the lower energy protons (b). This indicates that the trajectories of the lower energy protons are affected by the plasma jet set up by the higher energetic protons, which are accelerated from the target first. Also, the outer edge of each proton beam behaves differently than the center due to the interaction of the outer protons with the protons in the center of the beam. Detailed analysis to investigate the trajectory bending mechanism(s) is underway.

In conclusion, the use of a RCF stack to image and diagnose a proton beam generated from a hemispherical shell irradiated by a short pulse laser is presented. From experimental and simulation results, proton trajectories are not ballistic and seen to bend near focus, leading to a new understanding of proton focusing relevant to Fast Ignition.

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