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Laser driven MeV proton beam focussing by auto-charged electrostatic lens configuration

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Introduction

Laser driven multi-MeV proton beams from the rear surface of solid targets have been the subject of significant interest in last few years, due to their potential applications in various fields of science [1]. Despite of unique beam characteristics, such as low emittance, short burst duration and high particle energies there is still need for development. The large divergence angle and the broad energy spectrum are undesirable in most applications. Significant reduction of the inherent large divergence of the laser driven MeV proton beams has been achieved by strong (of the order of 10^9 V/m) electrostatic focusing field generated in the confined region of a ’washer’ type target geometry attached to the proton generating foil. In this scheme, the self charging of the target to multi-MV positive potential [2] is exploited to form a focusing field in suitable target geometries. A significant reduction in the proton beam divergence, and commensurate increase in the proton flux has been observed while preserving low beam emittance. The underlying mechanism has been verified using particle tracking simulations.

Experimental Setup

The experiment was performed at Rutherford Appleton Laboratory employing VULCAN petawatt laser system. The laser pulse delivered $\sim$ 300J of energy on target in 500 fs FWHM duration. Using f/3 off axis parabola, the laser was focussed to 8 μm FWHM spot on the target with peak intensity $\sim 10^{21}$ W cm^{-2}. In addition to free standing Au foil targets of 15 μm thick, two ’washer’ geometries, namely rectangular and cylindrical as shown in Fig. 1(a) and (b) respectively, were fielded in the experiment. In case of the ’washer’ geometries, thin Au

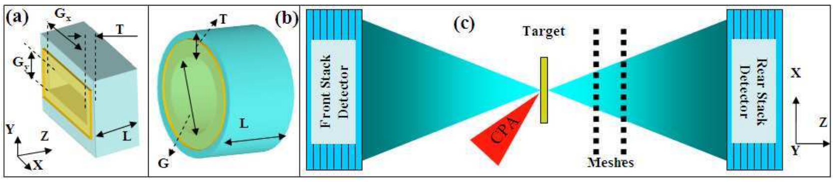

Figure 1: *Schematic of* ***(a)*** *rectangular and* ***(b)*** *cylindrical 'washer' targets fielded in the experiment.* ***(c)*** *Schematic of the experimental setup (top view).*

foil of 15 μm was in contact with one side of the washer. The laser was allowed to interact with the Au foil, close to the axis of the 'washer' geometry. Spatial and spectral profiles of the multi-MeV proton beam emitted normally from either side of the target were measured by employing stacks of radiochromic films as shown in Fig. 1(d). Multiple periodic meshes were introduced at the rear side of the proton generating target, at various distances from it.

Results

Significant (up to factor of two) reductions in the proton beam divergence angle have been observed using 'washer' targets when compared to free-standing flat foil targets. The angular divergence of the low energy part (up to 25 MeV) of the spectrum was observed to be highly reproducible ($\sim$ 56°) for the flat foil targets (typical proton beam profile is shown in Fig. 2[i][b-f]. In order to ensure that the observed effect was unambiguously due to the target geometry, rectangular 'washers' target designs (see Fig. 1(a)) were employed resulting the proton beam profile shown in Fig. 2[ii][b-d]. Instead of the typical near-circular beam profile, an elliptical profile with an major to minor axes ratio of

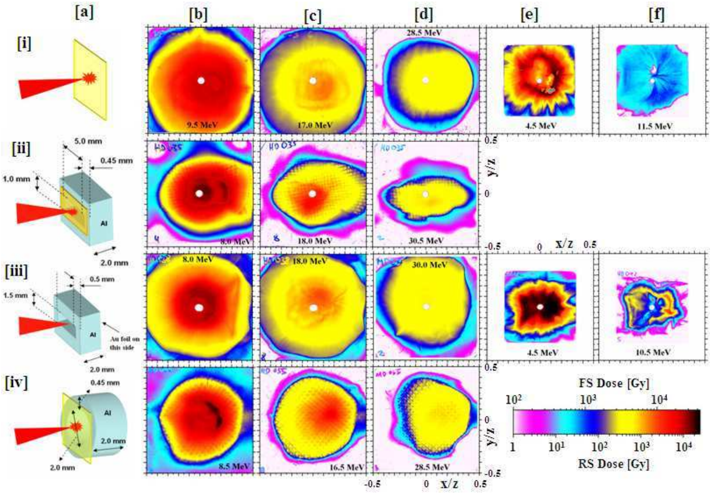

Figure 2: *Experimentally obtained RCF images for four different types of target, as shown in the leftmost column. Spatial scales of the RCF images are normalized to their distances from the proton generating foil. Energy of protons, mainly responsible for the dose deposition in a rcf, is labeled over its image. Columns [b-d] and [e-f] shows images obtained from Rear and Front stacks respectively. Color table employed to represent the dose in the RCF images is shown. Images in the figure are referenced in the text as '[α][β]', where α and β are labels of the row and column, respectively, to which it belongs.*

3:1 is observed on the RCF detectors. Mounting the 'washer' to the front surface of the proton generating foil, resulted in an elliptical spatial profile of the proton beam from front surface of the laser irradiated foil as shown in Fig. 2[iii][e-f]. As expected in this case, the proton beam from the rear side of the target has retained spatial dose profile similar to that from flat foil target (see Fig. 2[iii][b-d]). Employing 'washers' targets with cylindrical symmetry(see Fig. 1(b)), nearly-circular profile of rear side protons was observed as shown in Fig. 2[iv][b-d] with significant reduction in beam divergence as compared to the flat foil case.

Commensurate increase in the proton flux is seen in case of 'washer' targets with respect to the plain foil case. Moreover, no significant change in the proton beam cut-off energy and spectrum was found in case of the 'washer' targets in comparison to the plain foil targets. Therefore, one can conclude, without any loss of generality, that the focussing field of the 'washer' targets do not alter the proton accelerating sheath at the rear side of the laser irradiated foil. Furthermore, no significant loss of intrinsic proton beam laminarity, indicated by the pronounced proton radiographs of mesh wires, is another encouraging result from the 'washer' type electrostatic lens.

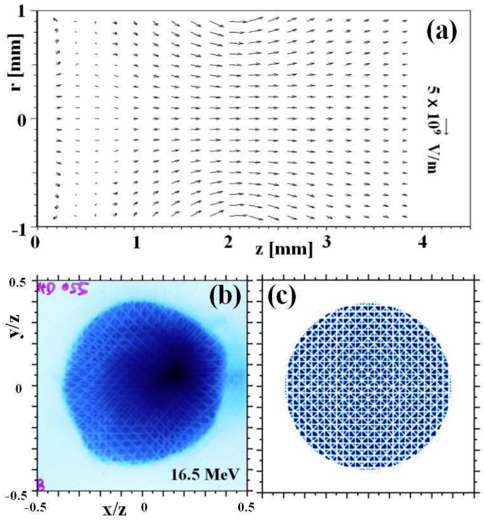

Figure 3: ***(a)*** *Longitudinal (across XZ plane) electric field profile across a cylindrical Al 'washer' target of G=2 mm, L=2 mm and T=0.5 mm. Experimental* ***(b)*** *and simulated* ***(c)*** *proton spatial dose profiles (mainly due to 16.5 MeV protons) obtained from the cylindrical 'washer' target. Spatial scales of the images are normalized to their distances from the proton generating foil.*

Characteristics and the focussing power of the electrostatic lens were studied experimentally by varying material and dimensions of rectangular and cylindrical 'washer' targets. Reduction in the proton beam divergence (as a measure of the focussing power of the elctrostatic lens) has been observed increasing with decrease in the aspect ratio [G_y/L (G/L) for rectangular(cylindrical) washer] of the 'washer' targets. The effect of material (from Aluminium to plastic) and thickness (0.5 mm to 1 mm) of the 'washer' reducing the beam collimation has also been observed in the experiment. These results anticipate the role played by a positively charged 'washer' geometry as a focussing device for the proton beam traveling through it. The amount of charge(electrons) loss, controlled by the target capacitance, is instantaneously compensated by the surrounding cold electrons in the target. The charge wave thus initiated will propagate across the 'washer' with a velocity close to the velocity of light [3] maintaining the target at MV potential. As the charge wave spreads at much higher speed than the protons, complete charging up of the target is attained much earlier than the protons leave the active focussing field region. Charging of the target is followed by discharging, mainly due to the electrons rushing from the ground via the stalk holding the target. In our case, abrupt discharging of the ’washer’ target was avoided by employing few mm thick insulating stalks. Role played by the target discharging is understood from the faster drop in beam focussing with decrease in proton energy for the case of metallic washer targets than the dielectric washer target.

3D particle tracing simulations, employing PTrace [4], were carried out in order to study the focussing mechanism due to the charging up of cylindrical ’washer’ targets. The temporal evolution of the target potential is computed by considering the self-capacitance of a charged disk. As shown in the Fig. 3(a), the steady state electric field profile due to a circular ’washer’ target fielded in the experiment resembles with that of a conventional ’Einzel’ lens, therefore act to reduce the proton beam divergence by the strong transverse field near the edge of the charged washer. It is to be noted that, for a divergent proton beam the longitudinal field also contribute towards the beam focussing. As shown in Fig. 3(b) and (c), the proton beam dimension as well as the mesh magnification obtained in the experiment were reproduced in the simulated RCFs. Indeed, further improvement in the beam collimation can be achieved by suitably modified ’washer’ target designs. For instance, reducing the wall thickness (T), employing a conical (instead of cylindrical) ’washer’ geometry and mounting the target with much thinner (few microns) insulating wires than used in the experiment. For a 30 degree conical washer with initial diameter of 0.4 mm, L=2 mm and T=50μm, simulation predicts in excess of factor of three reduction of 2 MeV proton beam divergence for the discussed experimental conditions. This implies an order of magnitude increase in the proton flux, promising for many potential applications mentioned earlier.

Conclusion

We present experimental results of a scheme in order to reduce the laser driven proton beam divergence obtained from typical flat foil targets. Employing ’washer’ geometries, auto positive charging-up of the laser irradiated targets to MV potential is exploited to set up a electrostatic lens scenario act to reduce the inherent divergence of the proton beam. Significant reductions in the beam divergence without sacrificing its laminarity are the success of the scheme. Excellent agreement to the experimental data is obtained from 3D particle tracing simulation for dynamically charged targets.

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