RCF imaging spectroscopy of laser-accelerated proton beams at Vulcan Petawatt

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Introduction

Proton acceleration by ultrashort (t < ps), high-intensity ($I > 10^{18}$ W/cm^2) laser pulses interacting with thin foils attracted high attention in recent years and has been widely examined both experimentally and theoretically. Large numbers of protons, of the order of 10^{13} per laser pulse, are accelerated from the rear side, present as hydrocarbon contaminants on the target surface, reaching energies in the multi-MeV-range [1-5]. These beams have many advantages in comparison to conventionally accelerated proton beams, including low transverse emittance and high brightness as well as short pulse duration [6-8]. For further applications e.g. in medicine or as a new particle source and pre-accelerator, it is important to have a full characterisation of these beams. Properties like proton distribution function (energy and space resolved), divergence, source size, and transverse emittance characterize the quality of this kind of beams.

In this article we present measurements with radiochromic films (RCF) and microstructured gold foils to quantify these parameters with a method called RCF imaging spectroscopy [9].

Experiment

The experiment was carried out on the Vulcan Petawatt laser (setup see figure 1). A chirped pulse amplified (CPA) laser pulse of 1 ps duration (FWHM) with energies of up to 140 J on target at 1053 nm was used for proton acceleration. A plasma mirror [10] was positioned in the focusing beam to suppress the ASE and achieve a pulse intensity contrast ratio (peak-to-pedestal) of 10^9. The laser pulses were focused to a spot size of 5 μm (FWHM) under an incidence angle of 5° with respect to the target normal achieving peak intensities on the order of 3.5×10^{20} W/cm^2.

Roth *et al.* [11] have shown the imprinting of the target rear-side microstructure into the intensity profile of the proton beam. This proton intensity modulation is observable in the RCF image detector and can be used to determine proton beam and source parameters. The targets for this experiment were 25 μm thick Au foils with equidistant grooves on the non-irradiated rear surface. The grooves with a line spacing of 10 μm have a depth of 1 μm, see figure 1 right.

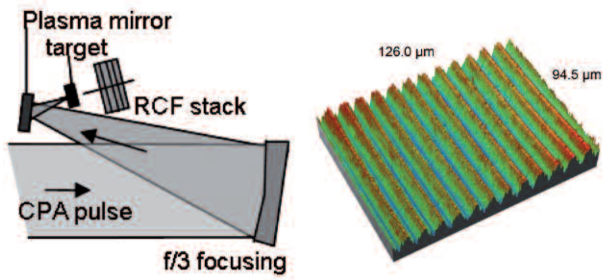

Figure 1. (Left) Experiment setup. A short high intensity CPA pulse, focused using a f/3 parabola, was used for proton acceleration. The plasma mirror placed in the CPA beam path enhanced the contrast of the short pulse. (Right) Interferometric surface measurement of the 25 μm Au target rear side. Whereas the front surface of the foil is flat, the rear surface was microstructured. The profile of the inserted structure corresponds to a sinusoidal function with maximum amplitude of 0.5 μm and a period of 10 μm.

The proton detector consisted of calibrated radiochromic films [9] in stack alignment. These dosimetry films measure radiation dose, in this case from the proton energy deposition. RCF stacks provide an energy as well as a space resolved measurement with high spatial resolution.

Results

Four different beam parameters will be discussed: the beam envelope or angle of beam spread, real and virtual source size as well as the normalized transverse emittance. The method and more details will be published in F. Nürnberg *et al.* [9]

Figure 2 shows the angle of beam spread as a function of the proton energy scaled to the maximum energy in each shot. The angles are calculated by the proton beam spot

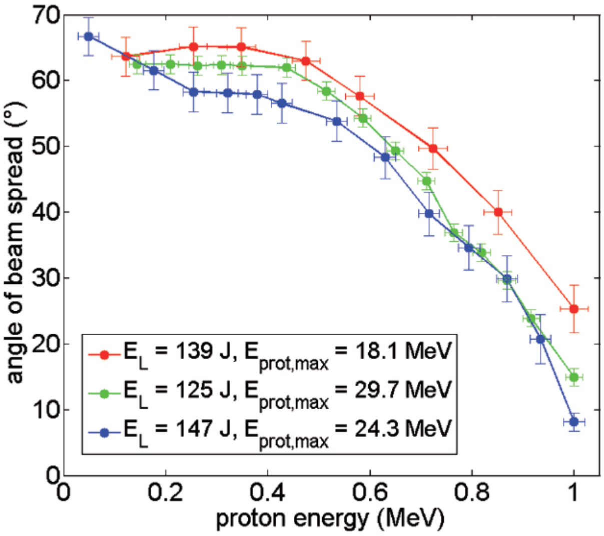

Figure 2. Angle of beam spread for the laser-accelerated proton beams scaled to the maximum energy in each shot.

size and the distance from RCF to the target. The angle of beam spread has a parabolic dependence on the proton energy. It is very similar for each shot, demonstrating that the Vulcan Petawatt laser produces very uniform and similar proton beams.

The imprinted line pattern in the RCFs (figure 3), imaged from the target rear side, allows a determination of the real source size, the area on the rear side of the target where the protons originate. The values are calculated by counting the lines in the RCF and multiplying their number with the groove spacing (figure 4). For increasing proton energies, the real source size diameter decreases from ~600 µm to ~100 µm, so the high energetic protons are accelerated from the centre of the source, where the electric field strength of the TNSA mechanism[2,4] peaks. Decreasing the laser intensity should decrease the electron divergence angle[12] and hence the real proton source size. The source size, however, is also a function of the focal spot size. We find that when we decrease the laser intensity by two orders of magnitude by increasing the laser focal spot, we observe an increase in the source size of about 100 µm for all proton energies.

A second series of measurements about pre-plasma scale length dependence of the source size can be found in McKenna *et al.*[13].

Due to the propagation behaviour of the protons and imaging properties of the real source size, a virtual source size $S_{virtual}$ in front of the target with the same mapping properties can be found. For an ideal beam, the proton trajectories extrapolated to the region in front of the target should cross in a single point. At Vulcan Petawatt $S_{virtual}$ is measured to be between 10-20 µm. The position of the virtual source in front of the target matches very well with previous published values[14]. For different proton energies the position of the virtual source size in front of the target differs. At an energy of 6.2 MeV $S_{virtual}$ is sitting between 300-400 µm and for 17.2 MeV protons between 150-200 µm in front of the target.

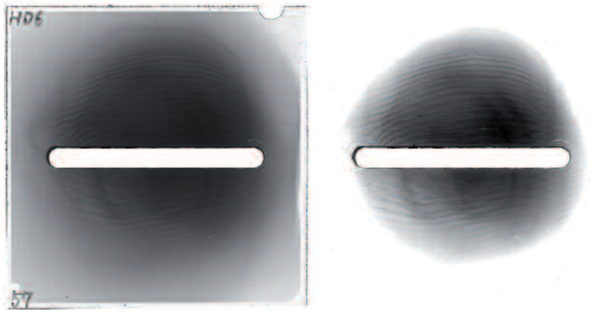

Figure 3. RCF image of 7.3 MeV protons. (Left) original scan, (right) modified image to get a better contrast for line counting. A slot machined in the RCF stack provides a line of sight to an array of Thomson ion spectrometers to measure the energy distribution.

The quality of the laser-accelerated proton beam can be characterised by the normalised, transverse emittance $\varepsilon_{norm,trans}$. The emittance describes the expansion or the parallelism of single particle trajectories and is given by the ellipse of minimal area including the proton beam in the space-divergence phase space divided by π or approximated by a parallelogram[15]:

$$\varepsilon_{norm,trans} = \frac{\beta\gamma}{\pi}\iint dx\,dx' \approx \beta\gamma\, S_{virtual}\,\Delta\varphi$$

β and γ are the relativistic parameters for the energy normalisation and Δφ is the angular error of the proton trajectories. The angular error relates to the width of the lines in the detector. For increasing proton energies an increasing line thickness is observed (for 6.2 MeV protons: ~20 mrad, for 17.2 MeV protons: ~40 mrad). The normalised, transverse emittance for proton beams produced at Vulcan Petawatt is in the order of 0.011 π mm mrad (6.2 MeV) and 0.030 π mm mrad (17.2 MeV). Typically we find that the Vulcan PW laser produces proton beams with a higher transverse emittance than other higher energy laser systems e.g. 100TW-LULI[6], which produces proton beams with a measured transverse emittance of 0.001 π mm mrad for >10 MeV. One possible explanation

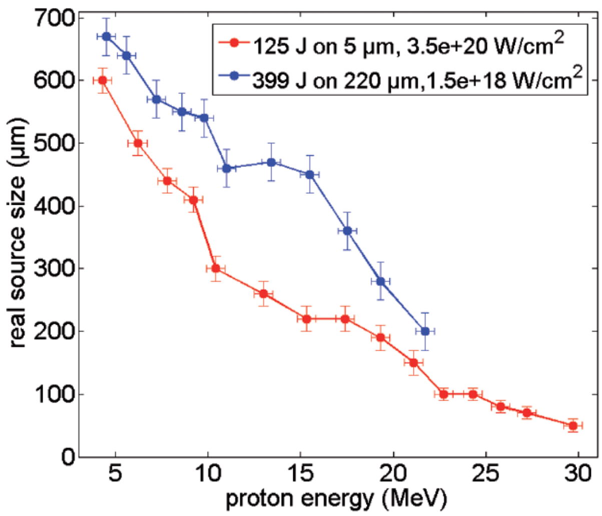

Figure 4. Energy resolved real source size measurement for laser-accelerated proton beams.

could be the 5-times higher laser energy or the factor of 2 in the pulse duration. Further investigations are required.

Conclusions

We have performed an experimental investigation on the parameters proton beams accelerated with the Vulcan Petawatt laser system. With the help of RCF stack detectors and microstructured target foils the angle of beam spread, the real and virtual source sizes and the normalized transverse emittance have been determined. Compared to other laser systems, the angle of beam spread is similar, but the source size and the emittance values are one order of magnitude higher. This will be subject for further analysis and publication [9].

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