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Enhanced proton flux in the MeV range by defocused laser irradiation

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\textbf{Abstract.} Thin Al foils (50 nm and 6 \textmu m) were irradiated at intensities of up to 2x10\textsuperscript{19} W cm\textsuperscript{-2} using high contrast (10\textsuperscript{8}) laser pulses. Ion emission from the rear of the targets was measured using a scintillator-based Thomson parabola and beam sampling ‘footprint’ monitor. The variation of the ion spectra and beam profile with focal spot size was systematically studied. The results show that while the maximum proton energy is achieved around tight focus for both target thicknesses, as the spot size increases the ion flux at lower energies is seen to peak at significantly increased spot sizes. Measurements of the proton footprint, however, show that the off-axis proton flux is highest at tight focus, indicating that a previously identified proton deflection mechanism may alter the on-axis spectrum. One-dimensional particle-in-cell modelling of the experiment supports our hypothesis that the observed change in spectra with focal spot size is

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due to the competition of two effects: decrease in laser intensity and an increase in proton emission area.

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1. Introduction

One of the phenomena associated with ultra-intense ($>10^{18}$ W cm$^{-2}$) laser–solid interactions that has received considerable attention is the production of beams of multi-MeV protons and heavier ions [1]–[5]. This field of laser-driven ion acceleration is being actively investigated by many groups worldwide due to its potential application in many areas, ranging from basic science and ion-driven fast ignition inertial confinement fusion [6, 7] through to medicine [8].

Currently, a number of methods for increasing the proton conversion efficiency and implementing spectral and beam control are being investigated by many groups [9]–[15]. The results of these studies will permit a realistic evaluation of the potential of laser-driven ion acceleration sources. In this paper, we report on the effect of the laser irradiation lateral size on the accelerated ion beam. We show that an enhanced regime of ion production can be attained when the diameter of the drive beam is many times the diffraction limited spot size. This novel operating regime opens up opportunities for lasers operating at low contrasts (the ratio between the intensity of the main pulse to that of the pre-pulse or pedestal) to use thinner foils to produce higher fluxes in the low-energy range (0.1–1 MeV in this experiment) than is possible at tight focus.

Experimentally, this study was performed by placing a foil target at some position away from best focus to increase the area of irradiation. As the available laser energy (500 mJ) and pulse length (40 fs) was fixed, this meant that the intensity was correspondingly decreased to as low as $\sim10^{16}$ W cm$^{-2}$ for the thinnest target foils. The region of enhanced flux occurred at intensities 100–500 times less than that at best focus, which makes the observation all the more unexpected. The observation has been interpreted as the combination of potentially four effects: a geometric enhancement in proton emission due to increasing the laser spot size and hence the ion emission zone, a change in beam divergence due to spot size, a temporal enhancement due to electrons being less likely to escape the acceleration region (the distance fast electrons can travel during the laser pulse duration being much less than the defocused spot size) and the reduction in proton emission due to decreasing the laser intensity.

This paper is organised as follows. In section 2, we describe the experimental setup employed in this study. In section 3, the results of the experimental investigation are presented. In section 4, we describe the geometric and temporal enhancement hypothesis and the numerical
Figure 1. Experimental setup. A Thomson spectrometer deflects the ions onto a piece of plastic scintillator, which is imaged using an EMCCD camera. A second sheet of scintillator images the off-axis portion (>6° off-target normal) of the ion beam.

results, and discuss/interpret the experimental results in light of this. Our findings will be summarised in section 5.

2. Experimental setup

The experiment was carried out using the Ti:sapphire Astra laser system, which produced 40 fs pulses of energy up to 500 mJ. The pulse contrast was enhanced from $2 \times 10^6$ at 1 ns to $10^8$ using a plasma mirror [16] system placed upstream of the interaction, as shown in figure 1. The plasma mirror system consisted of an anti-reflection-coated glass substrate irradiated with p-polarised light at an intensity of $10^{15}$ W cm$^{-2}$ and two F/8 off-axis parabolas (OAPs) set to recollimate the beam after reflection. The throughput of the system was measured as 50% and the quality of the reflected beam was confirmed on a regular basis by using an equivalent plane monitor, which observed a leakage. After every shot, the plasma mirror substrate was moved to a fresh location to ensure good beam quality. After every shot, the plasma mirror substrate was moved to a fresh location to ensure good beam quality. The beam was focused onto target at an incidence angle of 45°, in a p-polarised geometry, using an F/2.5 OAP capable of delivering a focal spot of $4 \times 6 \mu m$ (full-width at half-maximum, FWHM) at best focus, yielding a peak intensity of $\sim 2 \times 10^{19}$ W cm$^{-2}$. The size of the focal spot was adjusted by moving the target along the laser axis until the desired spot size was reached. The spot shape away from best focus was monitored using a focal spot camera. The spot was found to vary in close approximation to a Gaussian and had a broadly uniform structure, with 40% of the laser energy within the central FHWM, up until quite large defocus positions where the beam was seen to break up. Target foils were supported on Cu support frames and each foil was checked to ensure the surface was flat by monitoring the reflection of a 0.53 μm laser off the target rear surface, with any ripple gradients being below 4 μm mm$^{-1}$ across the central 1 mm region used in the experiment. A wheel-mounted target system was used to allow typically 20 shots per pump down cycle.
Figure 2. Logarithmic contour plot showing the target normal proton flux for 6 µm thick Al targets irradiated with varying focal spot sizes. The positive and negative values of spot diameter are used to indicate which side of optimum focus the results were obtained at, with negative referring to the target being located in the converging beam. Lineouts of the contour plot are presented across two energy bands.

The primary diagnostic was a Thomson parabola ion spectrometer, which used an absolutely calibrated scintillator [17] optically coupled to an Electron Multiplying Charge-Coupled Device (EMCCD) to give instantaneous spectra over the range of 0.15–5 MeV for protons. A scintillator screen was inserted partially into the ion beam so as not to block the beam going to the main spectrometer and the emission imaged onto a gated CCD to give an indication of the ‘footprint’ distribution [18] of the ion beam size. This scintillator was coated with a 0.2 µm layer of Al to prevent scattered plasma light entering the detector and was situated to look from 6° to 50° off-target normal. A fast decay (0.5 ns) scintillator was used and the gate time set so that the initial emission due to fast electrons and x-rays was eliminated while protons in the 0.1–1 MeV range were detected.

3. Experimental results

At high contrasts of 10^8, the maximum proton energy, P_M, was obtained when the target foil was close to best focus. For 6 µm thick Al foils this corresponds to P_M = 2.2 MeV at an intensity of I ~ 2 x 10^{19} W cm^{-2}, as shown in figure 2. As the spot size was increased to φ ~ 75 µm, P_M decreased only slightly to 1 MeV but the proton flux in the 0.1–0.5 MeV range increased significantly, as shown in figure 2. With a further increase in spot size, both P_M and the flux decreased, with no protons being detectable for φ > 150 µm corresponding to I ~ 10^{16} W cm^{-2}. For 50 nm Al foils the same general trends were observed as in the 6 µm case, but the details are different. At best focus a much higher value of P_M = 3.5 MeV was obtained and the secondary lower energy peaks were obtained for larger values of φ = 125–200 µm (see figure 3). Measurable proton signals are obtained for very large spot sizes, φ = 0.5 mm, corresponding to intensities as low as I = 3 x 10^{15} W cm^{-2}.

An asymmetry is observed in the width on the secondary ion peak in both figures 2 and 3, with a wider distribution being observed on the negative side of focus corresponding to the
target being irradiated by a converging laser beam. Future investigation will examine if this asymmetry is due to slight differences in the intensity distributions on the two sides of focus, as we believe, or is associated with the converging/diverging nature of the laser beam as it goes through focus.

At best focus, the proton spectra obtained with the 6 µm foil can be described as a simple single temperature ion distribution [19] in agreement with the results from many other groups. This is not the case with the 50 nm foil, where the distribution has a peak at 0.8 MeV and the flux levels are much higher than in the 6 µm case. The difference in spectral shape at best focus between the two target thicknesses has been attributed to a magnetic focusing effect that is more significant at the rear of the thinnest targets [20]. A strong proton focusing B-field at the target rear surface, which grows rapidly over the duration of the laser pulse, preferentially focuses a portion of the proton distribution. This results in lower energy protons being over-focused and hence deflected away from the axial point of observation. Similarly, optimal focusing of intermediate energies (around 1 MeV in this case) could lead to an enhanced on-axis signal for the same laser and target conditions and hence the clear peak observed in the ion spectra for the 50 nm case at best focus.

Hence this effect appears to be due to self-generated magnetic fields affecting the phase space of the accelerated protons so that when the pinhole of the magnetic spectrometer only samples a portion of this phase space, a peaked spectrum is observed. In contrast, other experiments have attributed their results to entirely different effects, including modification of the proton spectrum by a second ion species [21], limiting the thickness of the ion source layer [22] and limiting the transverse extent of the ion source [23].

As the footprint monitor is sensitive to all ion species and was set to sample an off-axis portion of the ion beam (to avoid blocking the primary diagnostic) it was not possible to directly measure the FWHM or central distribution of the proton beam. The Thomson parabola results showed only a weak trace of ion flux along the target normal and hence would not be expected to contribute significantly to the footprint monitor signal unless the majority of the ion flux was emitted off-axis. The footprint signal is strongest at tight focus and then gets weaker as the focal spot is increased. This general trend is observed for both thicknesses of targets studied, with the strongest emission from the 50 nm foils being ~50 times brighter than from the 6 µm foils, in

**Figure 3.** Logarithmic contour plot showing axial proton flux for 50 nm thick Al targets irradiated with varying focal spot sizes. Lineouts of the contour plot are presented across two energy bands.
Figure 4. A series of proton beam footprints, obtained over a range of irradiated spot sizes for 50 nm thick Al targets. The defocused laser spot diameter is shown above each image.

quantitative agreement with the spectrometer results. Figure 4 is a representative series of shots from the footprint monitor for the 50 nm foils, showing a clear decay in emission as the focal spot size is increased.

This would seem to contradict the data obtained from the Thomson spectrometers where peak proton flux was observed when the laser spot was significantly increased. However, the combination of two factors could explain this observed difference. Firstly, it is possible that the proton beam becomes less divergent as the spot size of the driving laser is increased. This is most likely explained by either a reduction in the level of disturbance at the target rear surface owing to a pre-pulse whose intensity, and hence disruptive effect, falls with increasing laser spot size [24], or by the presence of a more uniform sheath profile, resulting from the increased spot size, accelerating the protons in a more collimated manner. Since the footprint monitor captures the beam only over 6–50° from the target normal, any increase in the central part of the proton beam is not captured.

Secondly, the magnetic proton focusing mechanism [20], as discussed above, would be expected to deflect a significant portion of the low-energy protons away from the laser axis due to the strong focusing magnetic field present at the target rear surface for the highest intensities. Under best focus conditions, the over-focusing of the lower energy (<1 MeV) protons away from the laser axis could lead to that portion of the proton beam falling outside of the Thomson spectrometer’s narrow, on-axis, collection angle. The beam footprint diagnostic, however, would still be able to capture this deflected, off-axis, flux. Hence, the peak in proton flux seen off-axis by the beam footprint diagnostic for smaller spot diameters in figure 4 would not be expected in the on-axis Thomson measurements seen in figure 2.
4. Theoretical interpretation and discussion

One of the most salient results that was obtained in this study is the following: there is a higher flux of low energy protons (150–500 keV) at large defocus ($\phi = 50–100 \mu m$ for 6 $\mu m$ thick foils) than at best focus ($\phi = 7 \mu m$) by a factor of 2–3 detected along the target normal. Given that at this defocus the intensity has decreased by a factor 100, this is a surprising observation that demands proper explanation.

What we propose is that this is the result of a combination of effects. Firstly, by increasing the spot size, one increases the area of the rear surface of the target over which acceleration is driven. If the laser intensity were somehow to remain fixed one would expect that this would increase the proton flux, and one would expect, to first order, for the proton flux to be linearly proportional to the area of the laser spot. However, in this experiment the laser energy, not the laser intensity, was fixed. One must therefore account for the second effect: the changes in the proton energy spectrum with laser intensity. If the spot size is fixed, and the laser intensity is decreased (for a fixed pulse duration) then one expects the proton flux in all energy ranges, as well as the cutoff, to decrease.

Now suppose that one simultaneously increases the laser spot area and decreases the laser intensity (as was the case in this experiment). There is now a competition between the two effects, and one might reasonably expect the observed proton spectral flux to vary as

$$s_{\text{obs}}(I, E) = A s_f(I, E) = \frac{I_0 A_0}{I} s_f(I, E),$$

where $I$ is the laser intensity, $E$ is the proton energy, $A$ is the laser spot area, $I_0$ is the intensity at best focus, $A_0$ is the laser spot area at best focus, and $s_f$ is a function that gives the variation of the energy spectrum with intensity. One expects this approximation to work best at large spots, and that in this limit $s_f$ should be well represented by the energy spectrum as determined by a one-dimensional (1D) calculation.

In order to compare this hypothesis to the experimental results, we carried out a number of 1D PIC simulations using the BOPS code [25] for the same target over a wide range of intensities. The pulse duration was fixed at 50 fs, and the target was a 1 $\mu m$ foil consisting of protons at a density of 40 times the electron critical density. The code was operated in the ‘boosted’ mode [26] (where the simulation frame moves parallel to the target surface at a velocity $v_0 = c \sin \theta$ where $\theta$ is the laser incidence angle) to simulate p-polarised incidence at 45°. The energy spectra from these simulations were used to estimate $s_f$ for this target thickness and pulse duration. From this $s_{\text{obs}}$ was calculated and it was indeed found that there was a band of intensity around $1–5 \times 10^{17} W cm^{-2}$ in which there was a proton flux 5 times greater than the flux in the same energy range at $10^{19} W cm^{-2}$. This is shown in figure 5. Note that the function $s_f$ decreases monotonically with intensity in this intensity range, which is also shown in figure 5, which indicates that the geometric enhancement is critical to the existence of this feature.

The prediction of such a feature by this hypothesis agrees very well with the spectral measurements obtained in this study. Figure 6 shows a comparison of the spectral measurements made during the experimental campaign with the results generated from the BOPS code. It is therefore concluded that this region of enhanced spectral flux is the product of the geometric enhancement due to an increased laser spot and the intrinsic changes in proton emission caused by reducing the laser intensity.
Figure 5. Plot of $s_{\text{obs}}(I, E)$ and $s_I(I, E)$ proton energy spectra for a range of laser intensities, as modelled by the BOPS 1D PIC code. It should be noted that the apparent steps in the energy spectra visible for $s_{\text{obs}}(I, E)$ are artefacts of the data interpolation.

5. Summary and conclusions

Measurements have been made of the proton spectra produced from thin Al foils when irradiated with a high contrast laser pulse at intensities of up to $2 \times 10^{19}$ W cm$^{-2}$. The laser focal spot diameter was varied from a minimum of $4 \times 6 \mu$m (tight focus) up to a maximum of 0.5 mm. While the highest proton energies were obtained close to tight focus for both target types, a significant increase in the proton flux, in the range of 0.1–0.5 MeV, was observed when the laser spot was increased. The peak proton flux was found to occur for spot diameters of between 50–100 $\mu$m and 125–200 $\mu$m for 6 $\mu$m and 50 nm Al foils, respectively. The corresponding intensities of $\sim 10^{17}$ W cm$^{-2}$ and $\sim 2 \times 10^{16}$ W cm$^{-2}$ are significantly lower than the relativistic intensities typically used for studies into laser-driven ion acceleration.

Off-axis measurements of the proton beam footprint indicate that the strongest ion signal was obtained at best focus as opposed to defocused spot diameters. The decline in proton flux with increasing spot could have been in part due to a reduction in proton beam divergence, with an increasing proportion of the central proton beam falling outside of the off-axis collection angle of the detector. The growth of strong magnetic fields at the rear surface of the thinnest targets could also be acting to modify the emitted on-axis ion spectra, an effect not observable on the footprint diagnostic. Such a result underlines the need to take into account more than a single, narrow angular sample of the ion beam when analysing ion spectra.

While these results reaffirm the need for higher intensities in order to achieve the highest peak proton energies, the significant enhancement of lower energy proton flux through the use...
Figure 6. Comparison of proton flux for a range of laser intensities, between modelled flux from the BOPS 1D PIC code and 6 µm Al experimental data. The experimental data shown is that using a negative focus, i.e. the target was located in the converging beam.

of a defocused laser spot could be a useful technique when operating under lower contrast conditions. Thin foils, the use of which is normally precluded by disruption of the target rear surface by laser pre-pulse, could be used in the future to generate useful high flux, medium energy, beams without the requirement for contrast enhancement, providing that a sufficiently defocused laser geometry is used.

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