Manipulation of the spatial energy distribution of laser accelerated proton beams with a separate low intensity laser pulse

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Introduction

Multi-MeV ion beams generated using ultraintense (>10^{19} W/cm^2) laser pulses have attracted a lot of international interest recently [1]. Having active control over the properties of these beams would benefit the many exciting possible applications of these ion beams. Recently, it has been demonstrated experimentally that it is possible to optically change the direction of the proton beam [2,3], and it has been shown theoretically that it should be possible to change the spectral distribution of the beam by use of a double laser pulse arrangement [4].

Here we present a study on the optical manipulation of the spatial distribution of laser accelerated protons using separate low intensity laser pulses.

Experimental Method

The experiment is carried out using multiple beams from the Vulcan laser at the Rutherford Appleton Laboratory. A chirped pulse amplified (CPA) short pulse of 1 ps duration (FWHM), a wavelength of 1053 nm and energies up to 90 J is used to drive proton acceleration. This short pulse beam is focused using an off-axis f/3 parabolic mirror. A plasma mirror [5,6] is positioned in the focusing beam to reduce the intensity of the amplified spontaneous emission (ASE) on target to less than 10^{12} W/cm^2. The mirror is operated at an incidence angle of 15º, in a P-polarized geometry, and has a measured reflectivity of 55%, giving a pulse energy on target of up to 50 J. The incident angle of the beam onto target is 5º and the spot size at focus is 9 µm (FWHM), resulting in a peak intensity of up to 4×10^{19} W/cm^2. The experimental setup is shown schematically in Fig. 1.

Thin, 5µm Cu foils, with a surface roughness of ~0.7 µm, were irradiated using a low energy long pulse (<5 J, 1053 nm, 6 ns) with a temporal profile approximating a flat-top distribution. This long pulse is focused with an f/10 lens and has an incident angle of 25º and arrives at on target 3.5ns before the short pulse. The spatial distribution of the long pulse at focus is manipulated by using binary phase plates placed in the beam. The spatial distributions used are shown in Fig 2; they are an annular ring and a line focus. The phase plates are based on a fused silica substrate, on which a surface relief has been produced (using photolitography). This induces a designed phase distribution in the laser beam passing through it, leading to the desired intensity distribution in the focus.

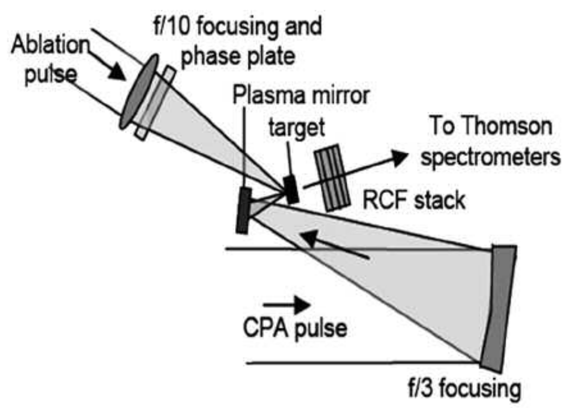

Figure 1. Schematic diagram of the experiment setup. A short high intensity CPA pulse, focused using a f/3 parabola, is used to drive the proton acceleration. The plasma mirror placed in the CPA beam path enhances the contrast of the short pulse. A separate long pulse is focused onto target at low intensities using an f/10 lens. A binary phase plate is placed in the beam path of the long pulse and is used to produce either a low intensity 'ring' focus or a line focus. The proton spatial energy distribution is measured using a stack of RCF film and ion charge and spectral distributions are measured using Thomson ion spectrometers.

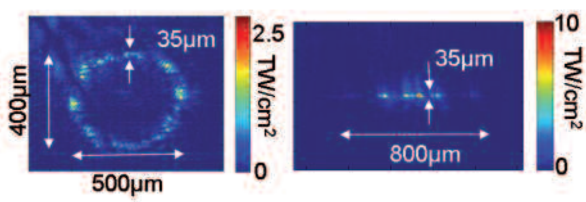

Figure 2. This shows the phase plate induced spatial intensity distributions of the long pulse used. The image on the left is an annular ring and the image on the right is a line focus.

A radiochromic film (RCF) stack positioned 30 mm from the target is used to measure the proton beam spatial distribution at different energies. RCF is preferentially sensitive to protons [7] and by introducing a periodic pattern in the proton beam by using an absorbing mesh, placed behind the target, it was confirmed that the RCF dose was predominately due to protons. Each layer of the RCF stack measures the deposited proton dose above an energy defined by the total thickness of the preceding stack layers. RCF turns blue when it is exposed to ionising radiation and the darker the colour the higher the flux that the RCF has been exposed to. A vertical slot was machined into the RCF stack so that a line of sight to the target was possible for a vertical array of Thomson ion spectrometers.

Results

When 5 μm thick Cu targets are irradiated with only the CPA short pulse a broad energy distribution proton beam emission is detected from the rear of the targets, typically reaching up to 12 MeV. The spatial distribution of the proton beam is typically characterised with disrupted edges and an uneven flux within the beam at each energy measured. These spatial variations may arise due to modulations in the short pulse laser focus, target surface quality and/or electron transport instabilities through the target [8]. A representative example is shown in Fig 3(a) and it shows clearly how the shape of the proton beam is not preserved at the highest energies.

When the target is irradiated with a long pulse prior to the short pulse reaching the target then a change is seen in the spatial distribution of the generated proton beams. The changes to the spatial distribution are also dependent on the shape of the long pulse focus. Typically, the intensity of the long pulse is between 3×10^{12} and 3×10^{13} W/cm^2.

A horizontal line focus, 800 μm long by 35 μm wide, is used for the long pulse, positioned ~30 μm below the short pulse focal spot on target. The spatial distribution of the proton beam generated is elongated along the vertical axis, see Fig 3(b), compared to the proton beam generated without the presence of the long pulse. The section of the beam containing the highest energy protons is observed at a higher position on the RCF relative to the centre of lowest energy protons of the beam.

Next an annular ring long pulse focus, thickness ~35 μm and mean diameter of ~450 μm, is positioned on the target with the short pulse focal spot at the centre. This produces a proton beam with a smoother flux distribution at each energy slice with a sharper, more defined, edge (see Fig 3(c)). The spatial distribution also stays circular in shape for all energies detected. In addition, the divergence as a function of proton energy changes – a more linear decrease in beam divergence with energy is observed.

Interpretation

The intensity of the line focus is high enough that a low temperature shockwave launched into the target, due to the ablation pressure at the front surface, is able to propagate to the rear surface of a 5 μm Cu target before the short pulse irradiates the target. The breakout of this low temperature shockwave will dynamically distort the target rear surface [2,3]. A bulging rear surface will produce a

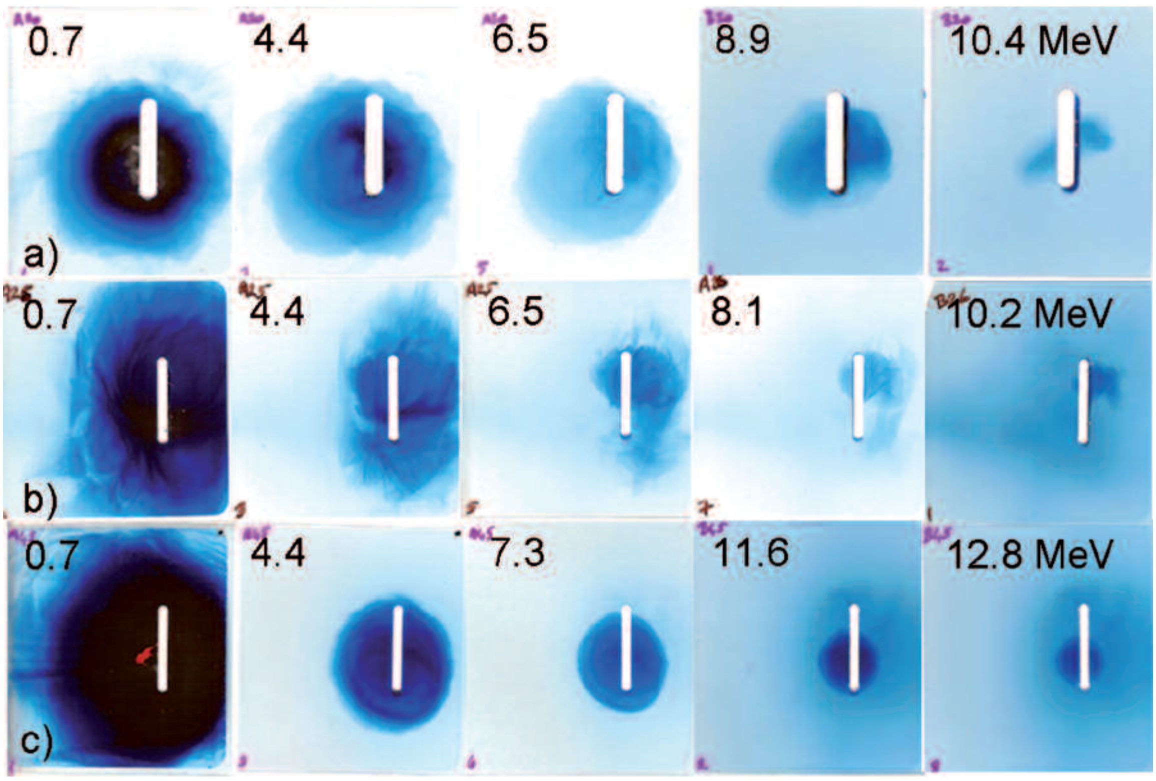

Figure 3. a) Layers of film from a RCF stack for a representative shot where the long pulse was not used. For part b) the long pulse had a horizontal line focus 30 μm below the short pulse focal spot. The images shown in c) are for a shot where the long pulse had an annular focus with the short pulse focal spot at its centre. The short CPA pulse driving the proton acceleration is the same for all three shots.

proton beam with a greater divergence perpendicular to the line focus orientation. We confirmed that the direction of the distortion changes with the orientation of the line focus, by producing a vertical line on target.

The improvement in proton beam quality observed with the ring focus is unlikely to result from the breakout of an ablation-driven shockwave because we observe the same effect with 20 micron thick targets, for which we do not expect the shockwave to have reached the rear surface by the time the CPA pulse arrives on target. Instead we interpret the result as arising from confinement of the lateral spread of the refluxing hot electron population within the target. This lateral confinement leads to a more spatially limited accelerating sheath on the target rear surface. We interpret the changes to the beam shape and divergence as arising due to a change in the shape of the sheath at the target rear surface.

Conclusion

We have performed an experimental investigation on the use of a second low intensity laser pulse to actively (optically) manipulate the properties of beams of protons accelerated by a high intensity laser pulse. We observe significant changes to the shape and divergence properties of the proton beams due to the presence of the low intensity long pulse.

When a line focus is used, the proton beam divergence increases in the direction perpendicular to the orientation of the line. The position of the highest energy protons within the proton beam have also been shifted away from the long pulse position. A long pulse with an annular ring focus irradiating the target prior to the proton accelerating short pulse gives rise to well defined circular proton beams with a more uniform flux distribution. These results point towards active control of the proton beam properties. The use of a second laser pulse, instead of preformed targets, enables active control at high repletion rates.

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