An Active Multi-Channel Ion Beam Profiler for Laser-Driven Ion Beams

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Abstract

An optical imaging system for an ion beam profiler was designed and successfully tested on an experiment at Vulcan Petawatt. Several different optical components were tested as well as different designs for the optical setup to maximise the resolution. The spatial resolution that can be achieved by the optical system itself was $\sim$ 4 lp/mm. Several scintillator stack designs were used throughout the experiment for comparisons of brightness and resolution. It was found that out of commonly used plastic scintillators, EJ 260 was the brightest, yet it was still an order of magnitude dimmer than Gadox-based Phosphor screens, viz. the Lanex screen and P43 screens. The response of the P43 screen was calibrated against RCF, giving a conversion factor of $\sim$ 170 counts/Gy.

1 Introduction

High energy proton beams have a number of applications from oncology, generating secondary radiation sources to damage testing for materials. Conventionally protons are accelerated by RF accelerators, however, laser driven ion sources have recently emerged as compact and cost-effective alternatives to conventional accelerators [1]. Where the laser interacts with the target a plasma is created at the front surface and electrons are accelerated to relativistic energies. The relativistic electrons propagate through the target creating very strong electric fields which ionise atoms and accelerate the ions [1]. Over the last two decades, several mechanisms were investigated for efficient acceleration of the ions to high energies. To comprehend the underlying physics of driving protons to high energies, it is important to characterise the spectral and spatial profiles of the laser-accelerated beam.

Current methods to investigate the spatial profile of ion beams often use passive detectors such as image plates, Radiochromic films (RCFs) and CR39. An issue with these detectors is their single-shot usage that they need to be replaced after every shot, which combined with the fact that they need to be scanned for digitalisation of data, makes these detectors infeasible to study ion acceleration at a high repetition rate. In this context, using scintillating screens for the detection of ions is a promising alternative which can provide a number of benefits. For example, the data can be viewed immediately after the shot and the detector does not need to be accessed or changed in between shots. This later point eliminates the need to let up the chamber, meaning active ion diagnostics can be used at a higher repetition rate. The development of active ion diagnostics is timely and of significant importance as an increasing number of PW-class lasers capable of operation $\geq$ 1 Hz, for example, the upcoming EPAC laser system at the CLF, is becoming operational.

In previous works, Green et al [2] and Schwind et al [3] demonstrated the use of a stack of plastic scintillators to investigate the spatial profiles of laser-driven proton beams. The work presented in this report aims to optimise the imaging system of a multi-channel ion beam profiler and compare the brightness of light output of different scintillating screens. In the first part of the experiment, a stack of coloured scintillators was deployed, as the ions deposit most of their energy in the Bragg peak depending on the properties of the material it propagates through, each scintillator corresponds to an energy band. By separating the scintillating light into three channels, a beam profile at different proton energies was obtained. In comparison to a stack of RCF which contains numerous layers of RCF, only a couple of scintillators are stacked, so fewer energies are imaged. Moreover, the scintillators are thicker than a layer of RCF so there is less precision in the energy imaged. The light output from plastic scintillators was compared with Phospor-based scintillating screens such as P43 and Lanex. The data indicates that for a proton energy band, the light output from both the P43 and Lanex screens was an order of magnitude higher than the plastic scintillators.

2 Experimental Setup

The ion beam profiler was deployed on an experiment at Vulcan Petawatt, where, a 300 J laser pulse of duration $\sim$ 1 ps was focused by F/3 parabola on the 15 μm thick gold (Au) target. The profiler was placed 22.5cm away from the target and looked at ions accelerated from the front surface of the target as shown in Fig 2 (a).

2.1 *Setup of the Ion Beam Profiler*

The scintillator stack usually consists of a thin aluminium filter at the front to block any light and debris

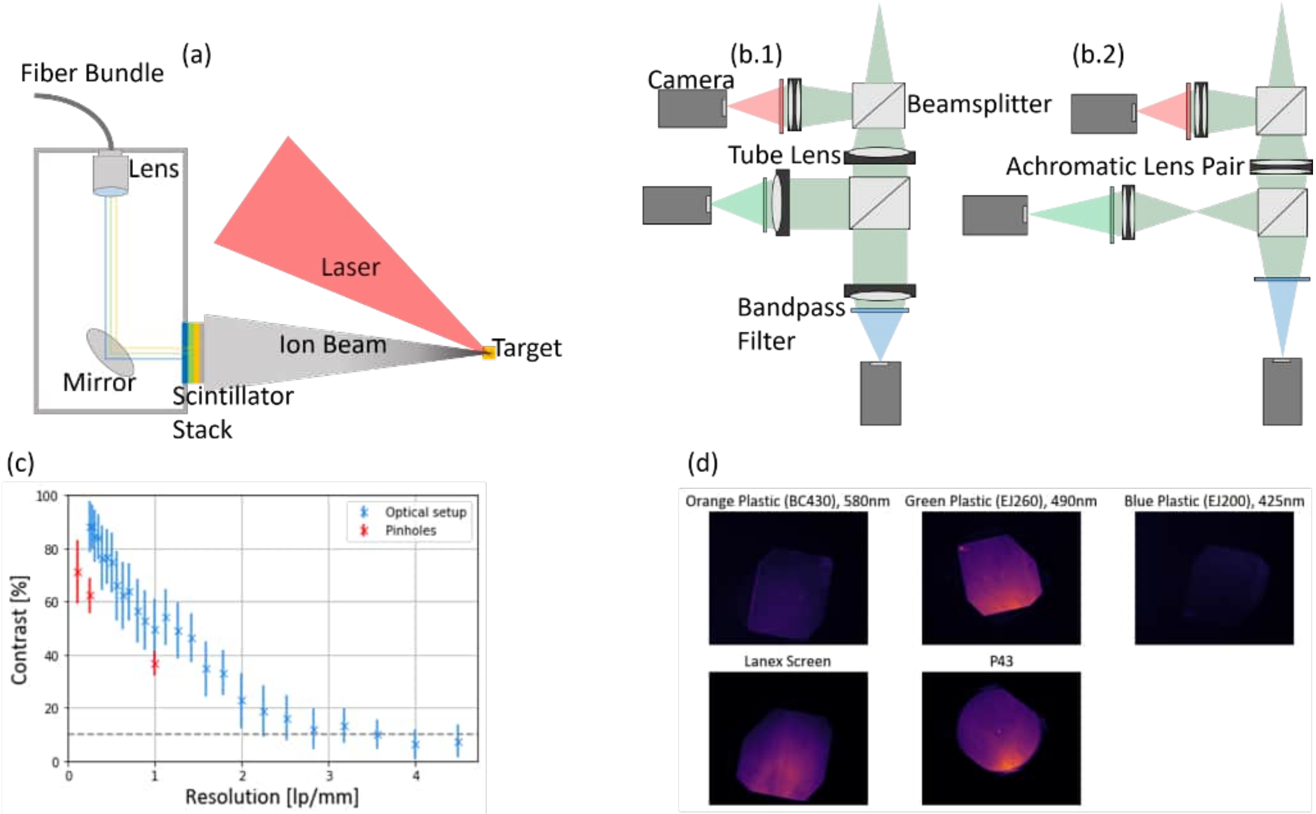

Figure 1: (a) Illustrates the setup of the ion beam profiler inside the vacuum chamber, the image was transported away from the interaction region using a fiber bundle. (b.1) and (b.2) Are two schematics for optical systems that were designed and tested to successfully split the image into 3 channels. (c) Shows the deterioration of contrast against resolution for when the optical system was considered in isolation and when using pinholes on the experiment. (d) Shows examples of raw images of each scintillator used, for the plastic scintillator images the brightness increased to improve clarity.

coming from the interaction followed by a stack of different coloured scintillators; protons will propagate through the scintillators and will deposit their energy in them if their Bragg peak is within the scintillator, so further towards the back of the stack higher energy protons will deposit their energy. The scintillators will then emit visible photons of the wavelength of that scintillator. The scintillators may be be separated by glass filters such that protons of a higher energy will have their Bragg peaks in the scintillators. A graph representing a scintillator stack is shown in Fig2 and also contains plots of proton Bragg peaks, found using SRIM [4].

The light produced by the scintillators, after reflection from a metallic mirror, is collected by an EHD 250-85C lens, which was coupled to a SCHOTT fiber bundle (4.57m long, imaging area 10x8 mm) for relaying the image to the outside of the chamber as illustrated in Fig 1(a). Outside of the chamber the fiber bundle connects to a vacuum feedthrough flange. In a simple 1-channel setup a relay lens would relay the image directly to the camera, in this case, an Andor NEO sCMOS. To split the

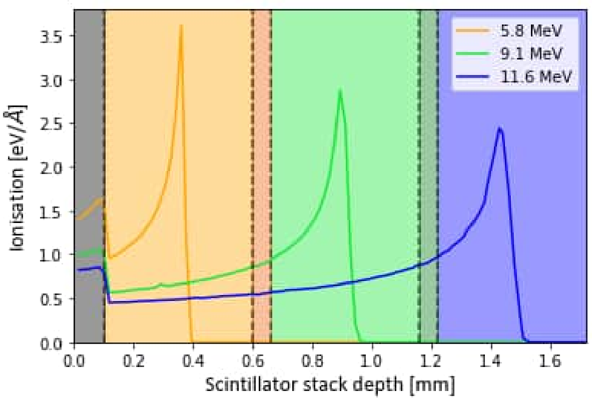

Figure 2: An example of a scintillator stack deployed in the experiment. The thick vertical bars are the plastic scintillators of different colours, the coloured lines are the simulated Bragg peaks of protons of certain energies which will deposit their energy in the scintillator. The thin grey bar represents the aluminium filter and the two thin coloured bars are plastic colour filters included in the stack.

image into 3-channels, a relay lens (Schott IG-1660) after the feedthrough flange, followed by a series of beam-

splitters (Edmund Optics 54-823), achromatic lens pairs (ThorLabs MAP10100100-A) and tube lenses (ThorLabs TTL200-A), were used. A different combination of setups was trialled using the different optics to split the image into 3 channels. Spatial considerations have to be made to keep the setup as compact as possible but allow enough space for Andor cameras. Two successful designs were tested and schematics of these designs are shown in Fig 1(b). Due to time constraints, only one of the imaging setups could be tested on the experiment, which is shown in Fig 1 (b.2). In front of each camera, there is a bandpass filter so each camera sees a restricted band of wavelengths. The filters were chosen such that each filter included the peak wavelength of one of the scintillators. The three cameras were triggered 50ms before each shot with an exposure time of 200ms.
Images of a 1951 USAF grid were taken to quantify how the contrast will deteriorate with resolution. By taking the counts of individual line pairs, the contrast for a given resolution could be calculated. This can be plotted to produce a modulated transfer function (MTF). The third sub-figure in Fig 1 shows the MTF found when considering the optical system in isolation. In addition, it also shows some data points of the contrast for certain resolutions that were found using pinholes during the experiment, and are thus subject to additional effects that worsened the contrast. From this graph it can be determined that the limiting resolution of the 1-channel optical system is 4 lp/mm.

3 Experimental Results

Initially, the three different coloured plastic scintillators (EJ200, EJ260 and BC430) were used in the scintillator stack. Different types of scintillating screens, like, P43 and Lanex screens, were used in place of the plastic scintillators for comparing the light output from scintillators. Throughout the experiment different filters at the front of the scintillator stack were used. One of these filters had a series of variously sized pinholes, which could be used as a means to find the resolution of the full proton imaging system. On several of the shots iron filters of varying thickness covered different sections of the scintillator stack. This meant that each scintillator would be split, and for each section, there would be a different stopping energy for the protons as there are different thicknesses of iron to propagate through. This means that, under the assumption that the ion beam is reasonably uniform across the whole scintillator, one scintillator can detect multiple energies; improving the energy resolution of the ion beam profiler by sampling more proton energies. During the experiment colour filters were added after each scintillator to stop forward emission from scintillators at the back of the stack affecting the scintillators in front. The bandpass filters in front of the cameras were changed depending on the scintillator used. At the end of the experiment, the response of the P43 screen was calibrated against the RCF calibrated using conventional accelerators.

The brightness of different scintillators was compared

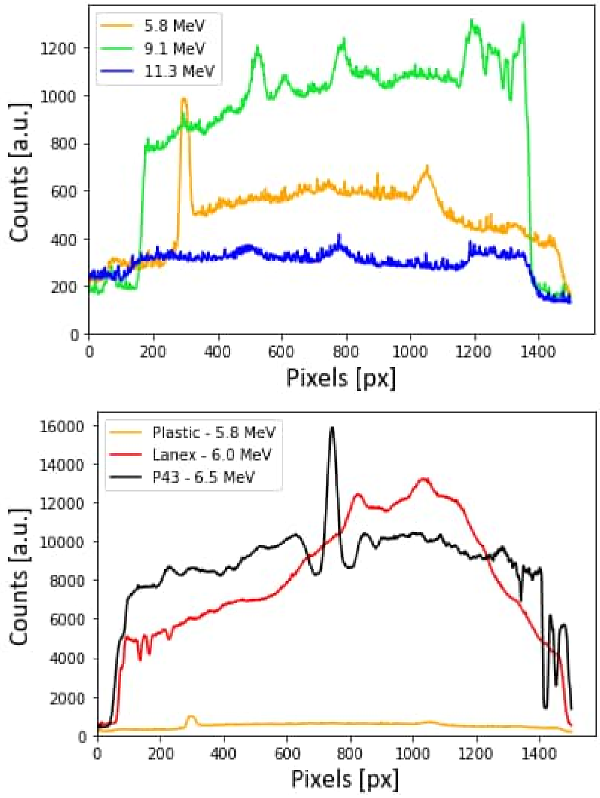

Figure 3: The graphs show a comparison of the brightness of light output from the scintillators. The top graph compares the different coloured plastic scintillators and the bottom graph compares different types of scintillating screens for a certain range of proton energies. The energy of the protons that have their Bragg peaks in the centre of the scintillator are mentioned on the graph .

by taking line-outs across the data collected for different scintillating screens. It is clear from the data shown in Fig. 3 that the EJ260 (green emitting scintillator) is by far the brightest of the plastic scintillators used, but it is still by an order of magnitude dimmer than P43 and Lanex. Plastic scintillators having a fraction of the emission when compared to other scintillators is an issue when considering the necessity of having different coloured scintillators for the ion beam profiler. Both plastic scintillators and P43 were calibrated against calibrated RCFs.

3.1 RCF Cross-Calibration

To cross calibrate, the scan of the RCF was analysed in tandem with the image in one of the channels. On the RCF scan a small section near the edge of the scan was selected and the mean counts recorded. In the image from the channel a corresponding small section was selected outside of the RCF, on the other side of the edge that the RCF section was taken. This process was repeated for a number of sections around the perimeter of the RCF. Fig. 4 helps illustrate this process by showing the two images with the corresponding sections highlighted. By averaging the mean counts across these sections a conversion factor was calculated to be 170 counts/Gy. It is important to note that this conversion rate is specific to this channel's optical setup, by changes to the scintillator stack or a change of bandpass filter would affect this conversion factor.

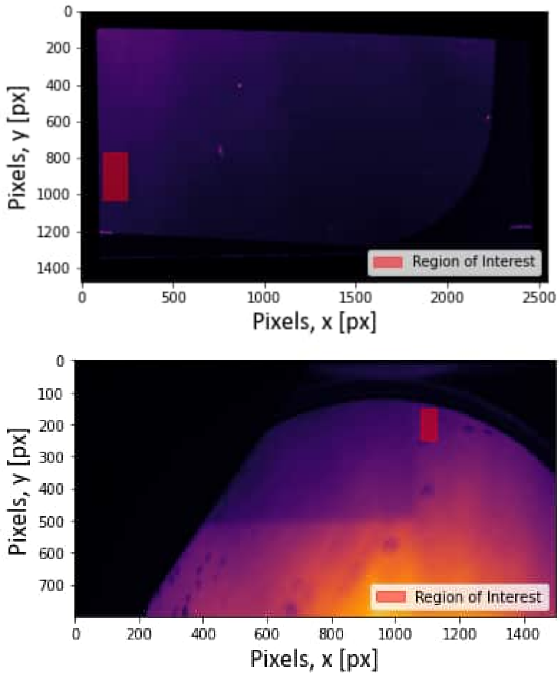

Figure 4: The top image shows the proton image recorded by the RCF, the bottom the image. Highlighted on both images is an example of the corresponding regions of interest.

One of the filters that was used during the experiment was a 2mm thick aluminium filter with a series of holes drilled into it. These holes were covered with slits of various widths, which can be treated as half of a linepair for the sake of investigating the resolution. By considering the contrast at each slit, some insight into how the contrast deteriorated with resolution can be found. The data from the pinholes make up what is the true modulated transfer function of the entire imaging system and the data points are plotted alongside the MTF found by considering to optical system in isolation in Fig 1(c). As expected the contrast of the full imaging setup is worse than just the optical system and this can be explained by additional factors needing to be considered when regarding proton imaging, for instance the scattering of ions, the effect of which is greater the greater the distance between the filter and the detector. Another factor to consider is that the scintillator stack has considerable thickness (several mm thick) and as a result the collecting lens can't focus on every layer of the stack, resulting in a de-focusing effect.

4 Conclusions

A multi-channel ion beam profiler was designed and employed in an experiment at Vulcan Petawatt for characterising laser-driven proton beams. A systematic study of different scintillating materials showed that the light output from phosphor-based scintillating screens viz. P43 and Lanex screens, for ~ 6 MeV protons, is an order of magnitude higher than plastic scintillators, which agreed with results obtained using high-energy proton beams by conventional accelerators [5]. The promising high scintillation efficiency of phosphor screens makes them a suitable candidate for transverse beam profiling of laser-driven ion beams, which, for example, by combining the 3D differential filtering mask described in [6], can be used for spectral characterisation of beams. Further investigations to understand the dynamic range, linearity between the incident particle flux and the light output, as well as, radiation hardness to laser-driven ion beams, are required.

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