Proton spectra calculation from Radiochromic Film stacks with high-energy proton correction

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Introduction

Laser accelerated ion beams have received attention over the past few years [1,2] since they offer a compact, cost effective alternative to conventional accelerators for scientific and health care applications [3–5].

In laser plasma experiments it is important to fully characterise the ion beam that is generated. Radiochromic Film (RCF) is frequently used for characterising the beam, as a single film gives a two-dimensional ion beam profile [6]. RCF is often layered into a stack with metal filters. Low energy ions are stopped early in the stack whereas high-energy ions deposit little energy in the front layers of RCF due to their energy deposition pattern dominated by a Bragg peak, as seen in each curve in figure 1. Hence the ion beam profile in any given layer is dominated by ions close to their stopping range in that piece of RCF. With sufficient layers of RCF a spatially resolved ion spectrum can be retrieved. Typically, protons are the only ions to propagate beyond the very front of the stack due to their lower rate of dose deposition, and so RCF stacks are useful in characterising large energy spread proton beams.

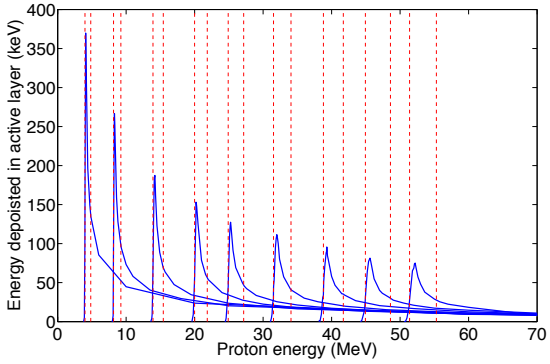

Figure 1. Energy deposition curves for the stack design as shown in figure 1. Each curve shows the energy deposited in the active layer of one of the layers of RCF, the Bragg peak for each curve is unmistakable. The red lines show where each distribution was concatenated in the BPD approximation. A total of 192 simulations were run to make this plot.

Typically though, when retrieving a spectrum from an RCF stack, it is assumed that only protons with a range equivalent to the depth of a specific film within the stack contribute to the dose deposited in that film. Or stated alternatively, that an ion deposits all its energy at the point in the stack where it stops. However this of course neglects the (mostly due to electronic) dose that an ion deposits in RCF layers that it traverses before finally being stopped at the film at it's Bragg peak dominated (BPD) range. In this report, the dose deposition by high-energy protons in RCF layers at the front of the stack will be addressed. This correction to the spectrum reduces the apparent number of low-energy protons.

Method

The general method of using a stack diagnostic is well known, but is summarised here for completeness. A typical stack design used on an experiment is shown in figure 2. As protons propagate through the stack, they deposit in the material they are travelling through. When energy is deposited in the active layer of an RCF, it reacts to form a blue coloured polymer. An example film, scanned using a Nikon Super Cool Scan 9000 ED transmission scanner is shown in figure 3, this layer of RCF has a BPD range of 14.7 MeV. The protons in this shot were accelerated from a 500nm thick plastic target with a 392J, 1ps Vulcan Petawatt laser pulse focused down to a 9µm spot. The type of radiochromic film used in the experiment and referred to in this paper was GafChromic HD-810.

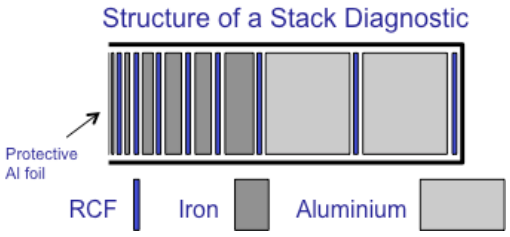

Figure 2: The stack design used on an experiment on the Vulcan Petawatt Facility. Layers of Radiochromic film were layered between metal filters so that the signal each layer of RCF is dominated by protons from a narrow energy band.

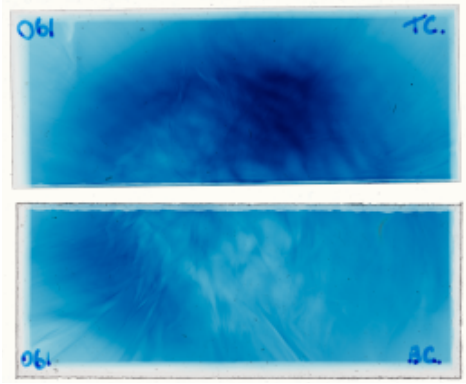

Figure 3: An irradiated layer of radiochromic film from a Vulcan Petawatt laser experiment. The blue colour is from a polymer that is formed when the active layer of the RCF absorbs energy from particle beams, the darker blue corresponds to higher dose deposition. The split in the stack was to allow the particle beam to pass to further downstream diagnostics. The corresponding proton energy of this RCF layer was 14.7 MeV and the protons in this shot were accelerated from a 100nm thick plastic target with a 392J, 1ps laser pulse focused down to a 9µm spot.

A calibration of HD-810 film was carried out at the Birmingham synchrotron by irradiating different films with known doses of protons. The films were scanned and calibration curves of dose as a function of pixel value were obtained, as shown in figure 4. The Nikon Super Cool Scan 9000 ED transmission scanner was used to scan the calibration pieces for continuity, which has red, green and blue channels. As figure 4 shows, the RCF becomes opaque to red light at only 300Gy, whereas the blue channel is transparent up to the highest dose of the calibration at 150kGy. To obtain a calibration curve for use at all doses, the blue and red channels were summed together as shown in figure 4. Since the red channel has high sensitivity at lower doses and the blue channel allows a greater dynamic range to be obtained.

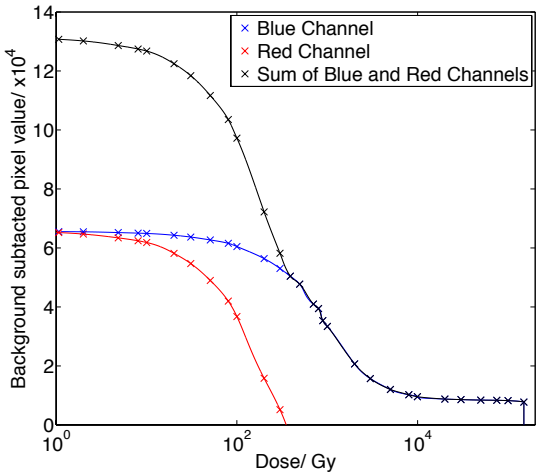

Figure 4: The relationship between the pixel value of a scanned film of HD-810 and the dose deposited within the active layer of the film. The scanner has 3 channels, red, green and blue with the red and blue channels shown. Large doses create more polymer within the RCF. When the RCF is scanned less light is transmitted through the RCF resulting in a lower pixel value recorded by the CCD.

Thus the total energy deposited on an RCF was calculated by converting all the pixel values from one scan into dose using the calibration in figure 4. A particular area of film for analysis can then be chosen to obtain a spatially resolved energy spectrum, or simply the entire observed beam can be used. The total dose for the selected area is summed and converted to energy deposited by simply multiplying by the mass of the active layer for the given film area.

To calculate the number of protons passing through the stack, we start with the relation that the total energy deposited in a layer of RCF is the number of protons incident on a film, per energy band, $\frac{dN}{dE}$, multiplied by the energy deposited by one proton of that energy, E_d, integrated over all energy.

$$Total\ Energy_d = \int_0^\infty \frac{dN}{dE}(E)\, E_d(E)\, dE \qquad (1)$$

Both the number of protons incident on a film per energy band, and the energy one proton deposits in the film, are dependent on incident proton energy. The second of these is calculated Stopping Range of Ions in Matter (SRIM) Monte Carlo simulations [7]. Figure 1 shows that the energy that a proton deposits in a given layer of RCF is strongly dependent on incident proton energy.

The conversion from total energy deposited in a layer of RCF to the number of protons in an energy band is non trivial, since the information needs to be extracted from the integral in equation 1. The first method, which includes two assumptions, is detailed below, followed by a description of a second, more advanced, method required to retrieve the correct spectrum.

All the deposition curves in figure 1 follow the same general shape, so to extract the spectrum from the integral it is common to make two assumptions. Firstly that $E_d(E)$=0 outside of the 1/e values, E_1 and E_2, of the curve, which will be referred to as the Bragg peak dominated (BPD) assumption. Secondly that the number of protons passing through the RCF per energy band is constant in this range. Both these assumptions are poor, but are a useful starting point. Equation 1 then can be rearranged to,

$$\frac{dN}{dE} = \frac{Total\ Energy_d}{\int_{E_1}^{E_2} E_d(E)\, dE} \qquad (2)$$

Equation 2 gives one point in the spectrum for each layer of RCF, and multiple layers give a sampled spectrum.

The goal of this article is to show that the assumptions above are poor ones, and result in large changes in total proton number of up to a factor of 2. The main correction comes from the long high-energy tail seen in figure 3; high-energy protons do not pass through the first few layers of RCF without depositing energy.

The correction routine uses equations 1 and 2 in a loop that works from the back of the stack forwards, since the correction is due to higher energy protons than the Bragg peak energy for that peak of a particular layer. The routine is shown schematically in figure 5.

Results and Discussion

Figure 6 shows the initial spectrum and the corrected spectrum for a 100nm thick plastic target irradiated by a 392J, 1ps pulse focussed to a 9µm spot, and the same shot as the RCF layer in figure 3. The corrected spectrum is reduced since the BPD assumption made attributes the entire signal on the front layers of RCF to protons around that layer's Bragg peak, when in fact a subset of the apparent dose is due to high-energy protons that have propagated through. So the real dose due to the Bragg peak protons is given by:

$$\boldsymbol{Real\ Dose = Total\ Dose - Dose\ due\ to\ high\ energy\ ions}$$

This shift in the spectrum significantly changes the total number of protons accelerated and therefore the beam energy and conversion efficiency. The beam temperature is also affected.

For the shot shown in figure 4 the number of protons is reduced from 1.9×10^{13} to 8.0×10^{12}, a factor of 2.4. The beam energy was consequently reduced by a factor of 2.2, which means that the conversion efficiency, from laser energy to beam energy, was naturally reduced by the same factor from 8.9% to 4.0%, a very large correction especially when the conversion efficiency of a laser plasma accelerator is used as a strong measure of it's quality.

A test of the reliability of the code was to initialise the spectrum with arbitrary values, for example a flat spectrum at 10^{11} protons MeV^{-1}. The corrected spectrum was the same as when starting from the approximated spectrum.

There are a number of limitations with this method. Firstly there is an uncertainty of where the high-energy cut off of the beam is. Ideally there is a layer of RCF at the back of the stack with no signal, so it can be assumed that there are no protons of energy higher than the Bragg peak energy for the layer before this. Secondly this method requires more SRIM simulations than when making the Bragg peak deposition assumption, since simulations need to be done up to the highest proton energy

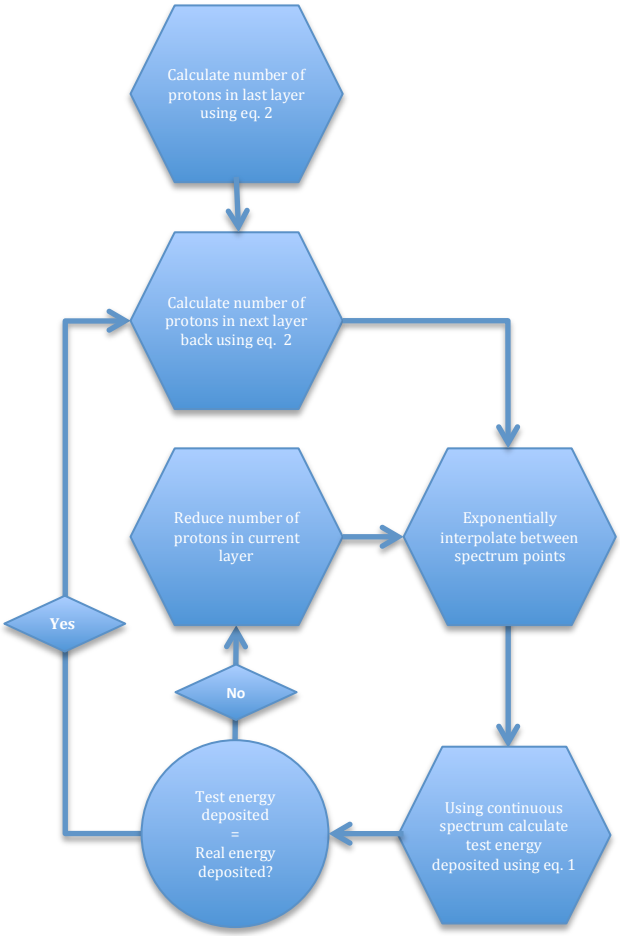

Figure 5- a schematic diagram of the computational process to extract the true spectrum from radiochromic film

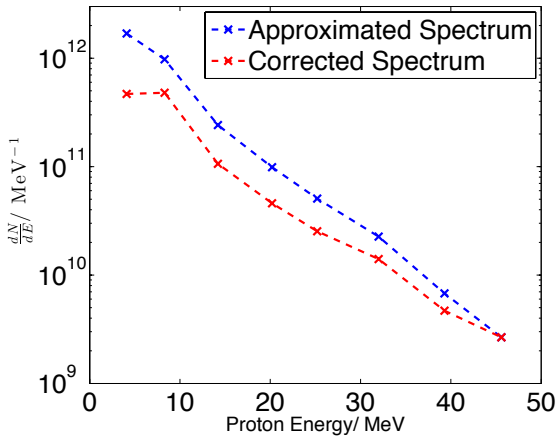

Figure 6: The original approximate spectrum, and the spectrum after being corrected using the computational process summarised in figure 5. The protons were accelerated from a 100nm thick plastic target irradiated by a 392J 1ps pulse focussed to a 9μm spot.

detected, rather than just around the Bragg peak. The routine also does not take into account carbon species, which deposit energy in the very earliest layers. This effect should be limited to those layers, but would artificially increase the proton numbers. A routine to correct this would either use information on the carbon spectrum from other diagnostics, or an assumption that for every proton accelerated of a particular energy there are a certain number of carbon ions with a certain energy.

The spectrum beyond the detection limit must be estimated. Assuming a worst case, where the spectrum falls exponentially from the detection limit to zero, we estimate the error from higher energy protons to be 4% on the total number of protons and the error on the total beam energy to be 17%. In reality, the protons would have a definite cut off energy, and so the errors are likely to be lower than that.

Conclusions

This method can be used to correct proton spectra from radiochromic film stacks. The correction is required because the assumption that the energy deposition by high-energy protons, as they propagate through the front layers of RCF, is not negligible.

The correction can be as large as 2.4 for the total proton number and 2.2 for the conversion efficiency from laser energy.

A summary of the code is provided and information on the whole process from experiment to spectrum is detailed.

Acknowledgements

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