Characterisation of plastic scintillators for detection of laser-accelerated protons

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Introduction

In recent years an increasing number of high repetition rate, ultra-intense laser facilities have been commissioned, capable of delivering high power laser pulses on to target at unprecedented rates. High shot rates necessitate high repetition-rate diagnostics, capable of acquiring data at 1 Hz or faster in the near future, whilst maintaining the spatial and spectral resolution offered by conventional, passive diagnostics that are useable at only very low shot rates.

The placing of diagnostics in a high vacuum environment also drives the requirement for in-situ diagnostics that are remote operable by the user. We have designed a new scintillator-based ion beam profiler capable of measuring the ion beam transverse profile for a number of discrete energy ranges. The optical response and emission characteristics of four common plastic scintillators has been investigated for a range of proton energies and fluxes.

Ion beam spatial profiler

The ion beam spatial profiler [1] replicates the working principal of the RCF / CR-39 stack, using organic scintillators as an active imaging medium. By placing multiple scintillators together and exposing them to the ion beam, each scintillator will respond to a different ion energy range. By imaging the light emitted from each scintillator a 2D 'footprint' of the ion beam can be collected for multiple beam energies.

In the latest revision of the diagnostic the scintillator stack is housed in a light-shielded box which can be placed close to the laser-plasma interaction. A camera lens is used to image the scintillator stack over a distance of 5-20 cm (depending on the size of the ion beam to be imaged), and the light is coupled from the diagnostic head into an intensified CCD camera via a high resolution (800 x 800 pixels) Schott fiber optic bundle (see Figure 1). The use of a fiber optic bundle simplifies the diagnostic alignment process and reduces the risk of electromagnetic pulse (EMP) and X-ray damage to the CCD camera.

In order to distinguish between the optical signals emitted by each scintillator we have investigated the use of multiple scintillators, each with a different emission spectrum. So far we have tested four anthracene-based scintillators; BC-408 and BC-422Q manufactured by Saint-Gobain Crystals and EJ-260 and EJ-264 manufactured by Eljen Technology.

Scintillator emission spectra

Figure 2 shows that the emission spectra of the scintillators cover a range of wavelengths from 325 nm to 750 nm, with some overlap inbetween. Both the EJ-260 and EJ-264 have blue tails in their spectra which can be attributed to the wavelength shifting process in these longer wavelength scintillators. Each scintillator contains additional doping which absorbs the initial (blue) scintillated light and re-emits it at longer wavelengths. For thin (sub mm) sheets this process is not 100% efficient, however for thicker samples this short wavelength tail can be eliminated. For this reason the longer wavelength scintillators need to be placed at the front of the stack (as in Figure 1) in order to prevent absorption of shorter wavelength scintillated light from other layers.

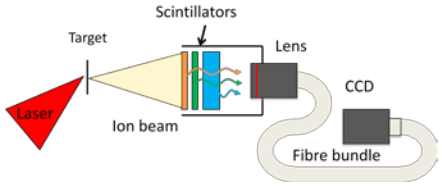

Figure 1. Schematic of the ion beam spatial profile monitor. Higher energy protons are stopped in the shorter wavelength scintillators further in the stack. The combined optical signal is collected and relayed to a CCD camera via a fiber optic bundle.

To resolve the ion beam profile at each energy range, the optical signal from each scintillator must be clearly separable in order that they can be split and imaged individually at the CCD camera. In order to achieve this a thin, polymer coloured filter is placed between each scintillator to act as a long pass filter (see modified output in Figure 3 for a three color system). By placing the longest wavelength scintillator (EJ-264) at the front of the stack, and the shortest wavelength (BC-408 or BC-422Q) towards the rear, a narrow portion of each signal can be isolated at the detector end.

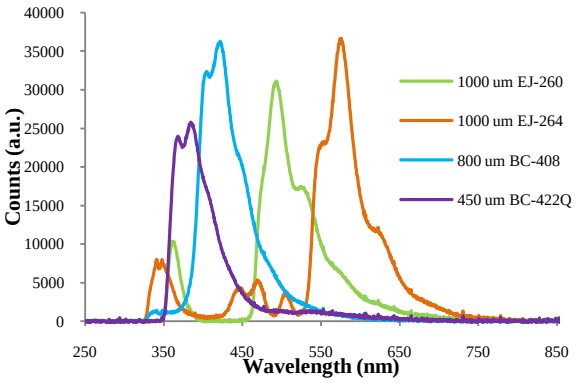

Figure 2. Optical emission spectra for BC-422Q, BC-408, EJ-260 and EJ-264 thin organic scintillators. Spectra were obtained by illuminating each scintillator with a 2.5 MeV proton beam.

Scintillator response as a function of proton energy

In order to characterise the response of each scintillator to a range of proton fluxes and energies, each material was tested individually using two tunable, monoenergetic proton sources. The light from each scintillator was collected using a fixed CCD lens and an Andor iXon intensified CCD camera. For the lowest energies (250 keV – 4 MeV) the tunable Tandetron

accelerator at the Surrey Ion Beam Centre was used. For higher energies (3 MeV – 28 MeV) calibration tests were carried out using the University of Birmingham Cyclotron. While the typical currents (1-10 nA) produced by each facility differed, we have scaled the CCD counts accordingly, having first confirmed a linear response to (see Figure 5) the fluxes being considered here.

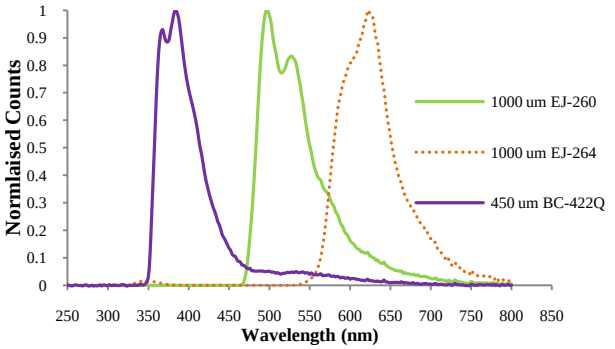

Figure 3. Predicted optical emission spectra for a combination of BC-422Q, EJ-260 and EJ-264 organic scintillators. Emission curves have been normalised as they do not take into account the incident ion flux on each layer.

The response curves for each scintillator are shown in Figure 5. The optical output of the BC-422Q and BC-408 scintillators was found to be proportional to proton energy to the powers of $E_p^{1.50\ +/-\ 0.04}$ and $E_p^{1.52\ +/-\ 0.04}$ respectively. For the Eljen Technologies EJ-260 and EJ-264 scintillators, the light output was found to scale similarly with proton energy as $E_p^{1.49\ +/-\ 0.04}$ and $E_p^{1.50\ +/-\ 0.04}$ respectively. As expected these anthracene-doped scintillator response data are consistent with those obtained by Smith et al. for anthracene crystals [2].

Care must be taken when using the above scalings when calibrating experimental results for several reasons. Firstly the response of the above plastic scintillators at low energies (< 1 MeV) appears to deviate from the quoted response, tending towards a more linear response. Secondly the response of a scintillator will change depending on the length and degree of previous exposure to ionising radiation. Continuous exposure to high fluxes of ionising radiation will reduce a scintillator's light output dramatically [3].

In order to examine the effect of high proton fluxes on scintillator response a 3 MeV proton beam was focused down to a spot size of just 1.7 mm (FWHM), using a beam current of 10 nA. The scintillator light output was then recorded at regular intervals (see Figure 6).

The scintillator response clearly falls rapidly as the incident dose accumulates, before leveling out after several minutes. The sharp reduction in light output is most likely concentrated around the Bragg peak for the incident proton energy. The drop in scintillation could be due to damage to the polyvinyltolouene base material (reducing optical transmission) or to the scintillator compound itself (reducing optical emission).

The continuous wave nature of the proton source used here might be expected to exacerbate any damage, reducing material recovery times, however future high-repetition rate laser systems might require operation on a quasi-continuous basis. Under these conditions accurate flux measurements using organic plastic scintillators would require a careful choice of illumination area, especially in the case of monoenergetic ion beams. Further studies need be conducted to quantify the effect of continuous wave and short-pulse fluxes of protons on scintillator response and to identify the nature of both the reversible and irreversible damage.

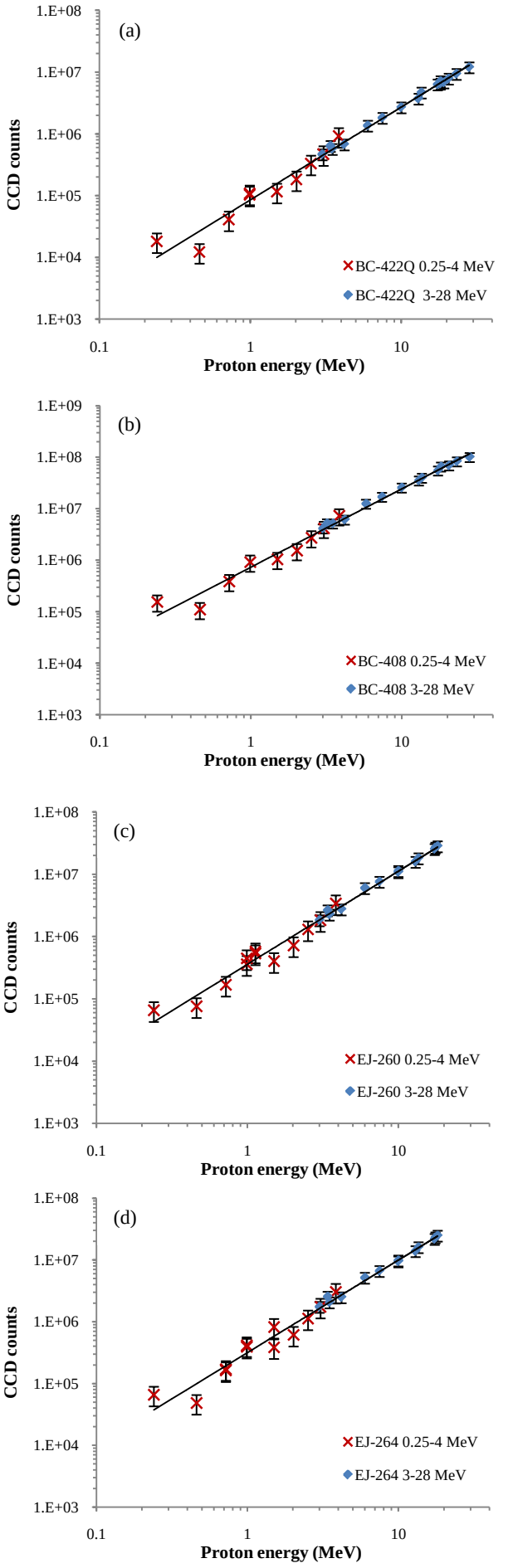

Figure 4. Proton response data for (a) BC-422Q, (b) BC-408, (c) EJ-260 and (d) EJ-264 thin organic scintillators together with empirical fits.

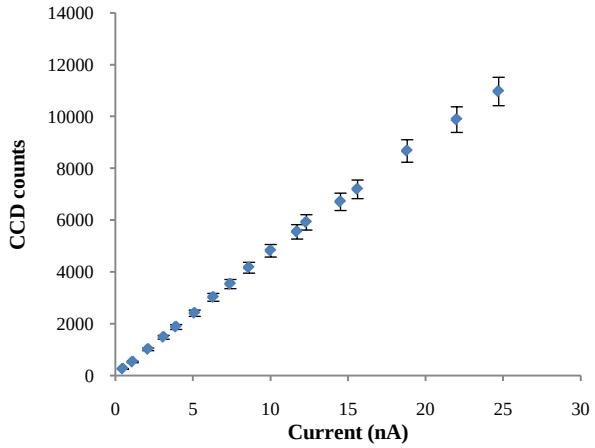

Figure 5. BC-408 scintillator response as a function of beam current.

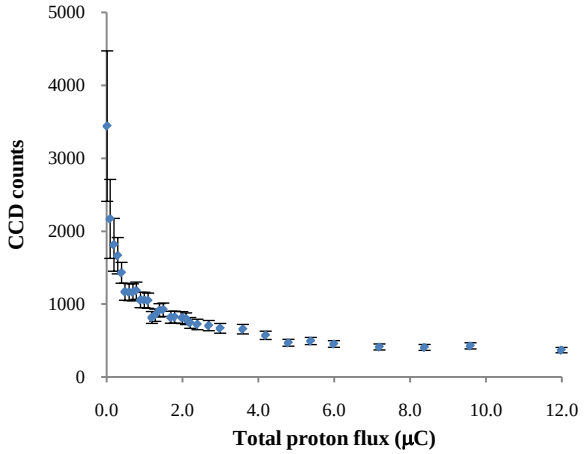

Figure 6. EJ-260 scintillator response as a function of total incident proton flux when irradiated with a focused current of 10 nA for 12 minutes.

Conclusions

Over the next few years we predict that the demand for in-situ, high repetition rate diagnostics suitable for characterising laser-generated radiation will increase significantly. The work presented here marks the initial steps towards a fully-calibrated, multi-channel ion beam imaging system suitable for deployment on a range of laser facilities. While the initial experimental results have been positive, it is clear that care must be taken when analysing any results if quantifiable data is to be extracted.

Cross-calibration of the scintillator-based beam profile monitor with existing passive media methods (e.g. RCF stacks) on upcoming ultra-intense laser-plasma experiments will act as a useful evaluation of the difference (if any) in scintillator response to a pulsed source as opposed to the continuous accelerator sources presented here. Such an experiment will also allow a direct comparison of the scintillator spatial resolution over a range of ion energies.

Additional work on the damage threshold and lifetime of plastic scintillators also needs to be undertaken, with the aim of characterising the usable dynamic range for consistent operation under the extreme conditions of a laser-plasma interaction. Indentifying the mechanisms of radiation-sourced scintillator damage will enable us to identify new preventative measures or chemical compounds that could be used to minimise any fluctuations in diagnostic operation during use.

Acknowledgements

The authors gratefully acknowledge the assistance of the Central Laser Facility staff at the Rutherford Appleton laboratory. We would also like to acknowledge the valuable facility access and useful discussions provided by the Surrey Ion Beam Centre and University of Birmingham. The work has been supported as part of the LIBRA EPSRC grant EP/E035728/1.

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Maximising the dynamic range of radiochromic film through novel scanning techniques

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Abstract

Radiochromic film (RCF) is a common diagnostic in laser driven ion acceleration studies used primarily for the characterisation of ion beam spatial profiles for a range of ion energies. Here, we report on the viability of scanning in different spectral regions to increase the recoverable dynamic range relative to greyscale scanning. In particular, Gafchromic HD810 RCF is used [1].

The recoverable dynamic range of RCF can be extended relative to greyscale scanning by analysing the film separately in the three colour channels that a commercially available flatbed transmission scanner typically records. The recoverable dynamic range of the film can be shown to increase by an order of magnitude compared to a conventional greyscale scan.

Taking this concept further we report that by using ultra violet backlighting of the film, the maximum measurable dose can be increased to at least 200 kGy, an order of magnitude greater than the three colour method and up to two orders of magnitude greater than using greyscale.

Introduction

RCF is a self developing dosimetry film with an active layer consisting of a chemical monomer which when exposed to ionising radiation reacts to form a blue, optically dense polymer. The optical density is proportional to the absorbed dose and therefore the incident proton flux.

RCF is particularly suited as a laser-ion acceleration diagnostic as the response appears to be independent of dose rate [2], but the energy response of the film for ions has been shown not to be flat [3] as it is for photons [4]. If RCF is exposed to a known dose via a monoenergetic cyclotron accelerated proton beam, the optical density of the film can be measured and absolutely calibrated, with this calibration being equally valid for laser produced ion beams.

Ions are known to deposit the bulk of their energy in a Bragg peak; a spatially small distance corresponding to a peak in energy loss just before the ions are stopped. This technique is particularly effective when used in a stack configuration consisting of multiple layers of RCF. The width of each active RCF layer may be considered to stop a narrow proton energy range; hence a full proton energy spectrum can be derived with a resolution proportional to the number of RCF layers. Other beneficial properties of RCF include its high spatial resolution, allowing the two dimensional spatial profile of a given energy to be examined.

With a limited number of shots available on the leading high power laser facilities, it is crucial to maximise the amount of data extracted from each film. This article outlines a novel method of increasing the recoverable dynamic range of RCF, extracting useful data which was previously unobtainable. Here we define dynamic range as the difference between the largest and smallest flux that can be measured above the noise level, and maintaining a monotonic relationship.

It is worthwhile making the distinction that the recoverable dynamic range is that which a specific technique is able to measure and make use of. We do not increase the intrinsic dynamic range of the film by physically altering it or the conditions it is used in, as can be done by cooling the film.

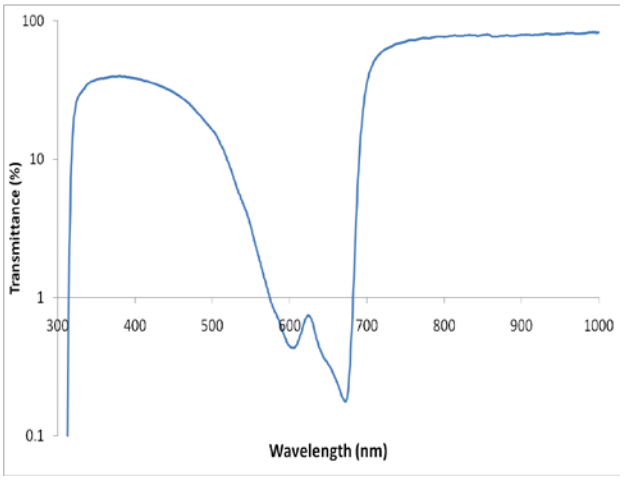

Figure 1: RCF HD810 transmission spectrum on exposure to 570 Gy.

Red Green and Blue

The advice given by Gafchromic for analysing RCF is to illuminate it with a narrow bandwidth Light Emitting Diode (LED) of wavelength around 660 nm as this coincides well with a prominent absorption peak in the film (Figure 1). This technique is recommended provided the RCF has been exposed to a dose in the range of 10 Gy to 400 Gy. However as fluxes well in excess of this are regularly generated in laser-driven ion acceleration experiments, the corresponding optical density in this region of the spectrum becomes very large before beginning to turn over. It is hence necessary to develop sensitive scanning techniques to extract data.

Another standard RCF analysis method uses a flat bed transmission scanner [5]. Here pixel values of the scanned film can be calibrated to an optical density for each pixel, and a separate calibration must be done for each individual scanner.

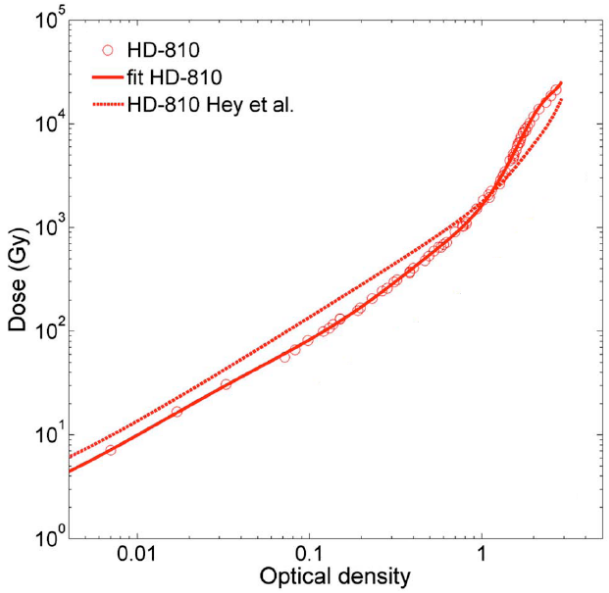

Figure 2: Greyscale calibration curve comparing [6,7].

Calibration curves for RCF analysis using this method have been shown to be effective in the range of around 40 Gy to 20 kGy in scanning in grayscale [6] and we produce results with good agreement with those in Figure 2.

It is possible to build on both of these ideas by analysing the RCF at discrete wavelengths or channels by the use of red, green and blue LEDs commonly used in flatbed scanners. For this work a *Nikon Super Cool Scan 9000 ED* transmission scanner was used.

The scanner consists of an RGB LED array on one side of a transmission tray, which is loaded with the film before being passed over the stationary LEDs. A CCD on the other side of the tray measures the transmitted intensity of the wavelengths corresponding to each LED. Analysis using a flatbed scanner and its component channels is becoming commonplace as opposed to analysis in greyscale [8].

In this method use is made of the fact that for a given dose there is a different optical density and hence sensitivity at each wavelength (Figure 1). Each colour channel has a different dynamic range, and by combining the measurements from each channel the recoverable dynamic range of the film can be significantly increased.

The optical density can be measured to provide a calibration curve in each channel and by making use of the three channels' individual dynamic ranges, accurate measurements of the absorbed dose of a test piece of RCF can be obtained over a range of doses up to an order of magnitude greater than using grey values alone for the same scanner.

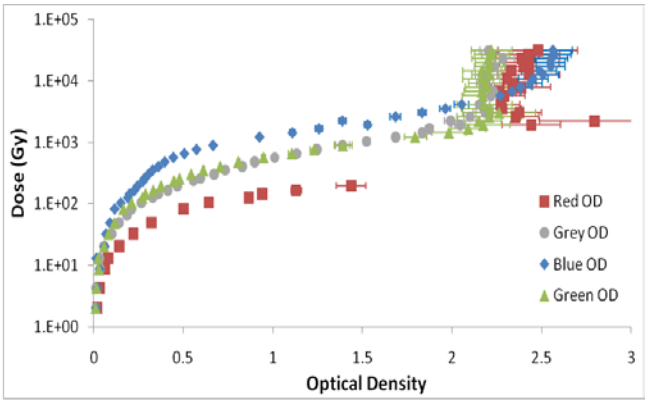

Figure 3: Nikon Super Cool Scan 9000 ED calibration of HD810 optical density with dose.

Using this method it was shown that the blue channel can be used to measure doses of up to 31 kGy where the maximum measurable dose in the greyscale is around 2 kGy. The lowest measurable dose can be shown to be at around 0.5 Gy by using the red channel of the scanner (Figure 3).

The three channel method is limited by both the scanners dynamic range, and by the inherent 'turnover' of the RCF at high dose.

As RCF is exposed to high dose the polymerisation reaction generally turns the film darker; however it is observed in practically every region of the spectrum that there exists a nonlinear threshold above which the film's response is not a monotonic function of dose. When this threshold is passed and RCF is exposed to a higher dose the optical density begins to decrease making the film appear lighter in shade and so here a specific value of absorbed dose cannot be obtained. For each wavelength the dose at which this turnover occurs varies and this is the inherent reason for there being a different sensitivity and maximum detectable dose for each wavelength.

Ultra-violet

While the three colour method is successful in increasing the recoverable dynamic range it shows the blue channel to be approaching turnover near 31 kGy and this technique cannot be used above this dose. It is therefore important to identify a region of the spectrum where the higher doses may be resolved to increase the recoverable dynamic range.

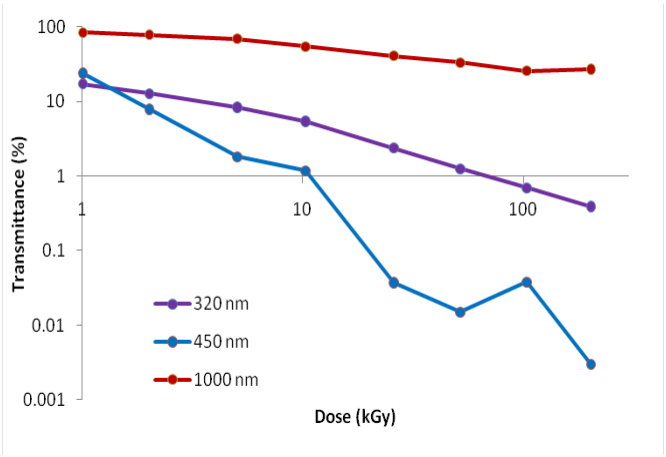

Figure 4: Transmittance against dose for RCF in three regions of the spectrum.

For this purpose RCF was exposed to a controlled dose of up to 202 kGy at the cyclotron source at the University of Birmingham. To give the best possible chance of identifying a region of the spectrum where the recoverable dynamic range may be increased, the RCF was scanned using a *Shimadzu UV-1800* spectrophotometer across the wavelength range of 190 nm to 1000 nm. It should be noted that below around 310 nm the RCF was found to become totally absorbing and so this data is omitted.

The spectrophotometer transmittance versus wavelength scans for a dose range of 1 kGy to 202 kGy revealed a region in the UV part of the spectrum from 310 nm to 390 nm, where the optical density has a monotonic relationship and scales well with dose across the full range up to and including 202 kGy (Figure 4). The maximum measurable dose in the UV region may well exceed this value but we are unable to verify this as we do not have a higher exposed dose calibrated film.

This remarkable result shows that RCF can be used to measure a maximum detectable dose of up to 500 times that quoted by the manufacturers of the film at a modest 400 Gy. In the blue region of the spectrum this work implies a maximum measurable dose of up to 25 kGy, with turnover occurring

between 25 kGy and 100 kGy (Figure 4). A set of intermediate calibrated films would be needed to find the maximum dose that varies as a monotonic function in this region. This result agrees well with the results obtained using a flatbed transmission scanner, which had shown the blue channel to be suitable for measuring doses up to around 30 kGy. However in probing the UV region the maximum measurable dose is increased almost by an order of magnitude compared with the limit of the blue channel.

Caution should be taken when directly comparing the transmittance curve obtained by spectrophotometry with the three colour method as the spectral response of the scanner LEDs is not known. Weight is given to this point when considering that the spectrophotometry shows that small changes in the wavelength used to probe the RCF will give rise to not insignificant variations in dynamic range in that spectral region.

The spectrophotometry shows that the infra-red region too has a higher recoverable dynamic range than the visible spectrum, where a maximum measurable dose of the order of around 50 kGy can be measured. The IR spectrum benefits from having particularly low optical densities in the range of OD 0 to OD 1 for the dose range shown in Figure 4. Lower optical densities are desirable as they require a lower overall sensitivity of the instruments used to measure them. This would make the IR an attractive compromise where a high dynamic range is required but where the measurement of high OD may be difficult, or indeed for most measurements where the dose does not exceed 50 kGy.

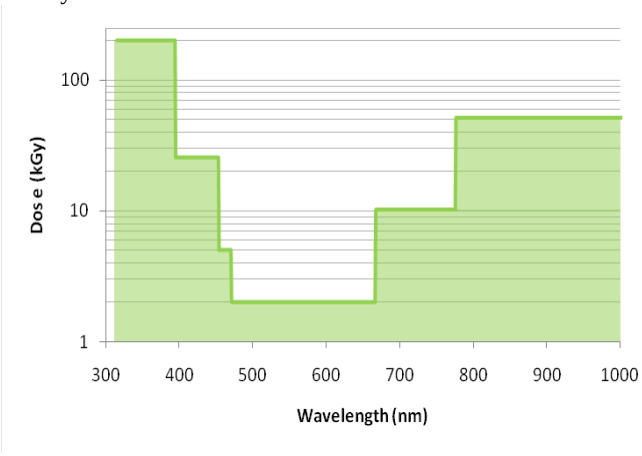

Figure 5: The shaded area gives a guide of the maximum detectable dose in each region of the spectrum.

A rough guide is given in Figure 5 for the maximum dose that would be measurable by RCF across the spectrum. It is incomplete in the sense that it is stepwise, but a great many more intermediate doses would be needed to complete the curve, but this serves as a useful guide.

From the spectrophotometry data it should be possible in principle to measure a maximum dose of at least 202 kGy over an approximate range of 310nm to 390nm, with an optimal wavelength appearing to be around 320 nm. Where a monochromatic light source is not obtainable, a (350±40) nm filter used in conjunction with a white light source as a backlight is suitable to inspect the RCF in this region. Using such a setup with an Andor iXon EMCCD camera for imaging, preliminary work has shown there to be detail in highly exposed RCF film from a recent experimental campaign. It has been found that in probing the film in the ultra violet that data can be recovered that would have otherwise been irretrievable using existing methods.

Radiochromic film has been shown to be more sensitive to ultra violet radiation [9] compared with visible and infra red light, although visible light is generally regarded to have no effect on the pigmentation of the film for low exposure times. However an investigation must first be carried out on the response of the RCF to any UV backlight over time to discover if any significant effect occurs and if such an effect should be corrected for in the cases of the already very highly exposed films this technique would be used for.

Conclusions

In the spectrophotometry it is clear that in the UV a spectral region has been identified where the recoverable dynamic range can be dramatically increased by increasing the maximum detectable dose by almost an order of magnitude of that previously obtainable using the three colour method. However these two methods may be used to complement each other to allow a dose range of a few Grays to hundreds of kilograys to be measured.

It is intended to apply these techniques to the new EBT2 film to inquire into its dynamic range, however the manufacturer quotes a higher sensitivity in the 2cGy to 800cGy range and half the spatial resolution of HD810 at 5000 dpi, it is therefore possible that it will have a lower dynamic range.

Acknowledgements

Thanks go to Benji Coles for his assistance in providing access to the spectrophotometer that was used.

This work was carried out as part of an EPSRC and STFC funded project.

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