

Article

Multi-Point Sensing via Organic Optical Fibres for FLASH Proton Therapy

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Abstract: Optical fibres are gaining popularity for relative dosimetry in proton therapy due to their spatial resolution and ability for near real-time acquisition. For FLASH proton therapy, these fibres need to handle higher dose rates and larger doses than for conventional proton dose rates. We developed a multi-point fibre sensor embedded in a 3D-printed phantom which can measure the profile of a FLASH proton beam. Seven PMMA fibres of 1 mm diameter were embedded in a custom 3D-printed plastic phantom of the same density as the fibres. The phantom was placed in a proton beam with FLASH dose rates at the TRIUMF Proton Therapy Research Centre (PTRC). The sensor was exposed to different proton energies, 13.5 MeV, 19 MeV and 40.4 MeV, achieved by adding PMMA bolus in front of the phantom and three different beam currents, varying the dose rates from 7.5 to 101 Gy/s. The array was able to record beam profiles in both transverse and axial directions in relative agreement with measurements from EBT-XD radiochromic films (transverse) and Monte Carlo simulations (axial). A decrease in light output over time was observed, which might be caused by radiation damage in the matrix of the fibre and characterised by an exponential decay function.

Keywords: optical fibre scintillator; FLASH radiotherapy; proton FLASH; multipoint; fibre array; proton radiotherapy; multipixel photon counter; photodetector



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1. Introduction

FLASH radiotherapy, the ultra-high dose delivery of ionising radiation, is currently being investigated worldwide for its potential as a superior option in radiotherapy. FLASH is not an acronym but a reflection of the timescale for dose delivery. The extremely fast irradiation at extremely high dose rates—over 40 Gray per second (Gy/s) and up to hundreds of Gy/s compared to the standard dose rates of 0.05–0.1 Gy/s—has been shown in some cases to reduce normal tissue toxicity while achieving tumour control comparable to current standard treatments [1–4]. Studies are underway to determine exactly if and why the ultra-high dose rates have a sparing effect on normal tissue; tissue-sparing processes could include hypoxia protecting the normal tissues—although recent studies do not support this being the likely or only mechanism [5,6]—as well as the reduced time spent irradiating the circulating blood and lymph during treatment (due to full treatment being achievable in under 1 s) [7].

To date, preclinical and limited clinical studies have been successfully undertaken in electron, X-ray, and proton FLASH experiments [1,3,8–12]. With FLASH being an emerging treatment possibility, it is important to develop the tools necessary to deliver the treatment safely and maximise the effectiveness of the modality.

For proton FLASH radiotherapy, it has been suggested that passive delivery systems could be an advantage for applying this modality [13], while pencil beam scanning (PBS) systems deliver modulated doses to small areas in turn over the irradiation using the high-dose advantage of the Bragg peak, a passively scattered beam with a static ridge filter can deliver a large dose to a considerable area in the FLASH radiotherapy timescale [14], which could be preferable to PBS. The relative simplicity of passively scattered systems could also be advantageous in biological mechanism research in that there is a reduced number of beam parameters to affect biological systems. Some proposed ideas for proton FLASH include “Transmission FLASH” and “Conformal/Bragg Peak FLASH”. Transmission FLASH sacrifices some conformality for higher dose rates by directing protons through the patient, while Conformal FLASH can apply energy modulation devices, stopping the beam in the patient and providing distal conformality [15].

Measurements and trials of proton FLASH have agreed that further investigation into certain aspects of the modality would be valuable for advancing proton FLASH to a clinical radiotherapy option. Necessary improvements to the field of knowledge include “...time structures and large volume coverage in short timescales commensurate with the FLASH effect” [14], as well as needed advancements in beam delivery validation involving more accurate and instantaneous dose rate information, quality assurance and patient positioning [9].

The former clinical proton therapy centre at TRIUMF (Vancouver, BC, Canada), used from 1995 to 2019 for proton radiotherapy of ocular melanomas [16,17] and now used in research applications as the Proton Therapy Research Centre (PTRC), is one such passively scattered system, and has been successfully modified to deliver FLASH dose rate protons [18]. The facility is capable of providing proton dose rates over 100 Gy/s, a passively scattered beam with custom static ridge filters (a polymer insert made up of pins and valleys) [19], and has the required features to examine many of the aforementioned elements requiring further investigation.

Optical fibres have been used extensively, primarily as light guides, for relative proton dosimetry and have proven to be very effective tools for this purpose [20–23]. Plastic scintillators and fibres have also been tested in proton FLASH studies [24,25]; however, pure plastic, like polymethyl methacrylate (PMMA), is only very rarely explored in a non-scintillator-coupled or undoped state as the primary sensor. In the case of protons, the fluorescence induced by proton interactions—generally called radio-induced luminescence (RIL)—has the potential to act as a quenching-free means of relative dosimetry [26,27]. Quenching in RIL, experienced by scintillators and other materials, occurs in regions of high linear energy transfer (LET), such as in the Bragg peak of the proton depth dose, where quenching results in underestimating the actual dose based on measurement of the RIL signal.

In proton radiation, the fluorescence created in PMMA is expected to be the combined result of damage-induced “photodarkening” and activation caused by damaging ionising radiation, which can result in an increased signal in the fibre [28]. Čerenkov contributions, though now understood to be not entirely absent from the light induced in PMMA during lower-energy proton irradiations, have been shown to be insignificant in comparison to induced fluorescence, particularly in the Bragg peak region [27]. One suggested reason for quenching-free RIL measurements in PMMA for proton dosimetry could be the lower density of RIL-creating centres in the fibres themselves [29], resulting in lower RIL generally.

In a gamma radiation study of PMMA by O’Keeffe et al., the effect of the radiation on the fibres reduced light transmission through the affected area considerably over the course of irradiation (known as radio-induced attenuation or RIA) but began recovery immediately after [30], similarly to a study by Kovačević et al. [31], suggesting that there could be a reduction in RIL over time, likely due to radio-induced damage to the material. Similar results have been characterised in neutron and proton radiation but with different organic fibre [32].

Preliminary testing of a well-seasoned PMMA fibre (it is estimated this fibre has received several hundreds of thousands of Gy prior) at FLASH dose rates at the PTRC showed dose rate linearity as determined by a single-channel multipixel photon counter (MPPC) (model C11208-350), made by Hamamatsu Corporation (Hamamatsu City, Shizuoka Pref., Japan), shown in Figure 1 [18]. No overresponse or attenuation of RIL was measured.

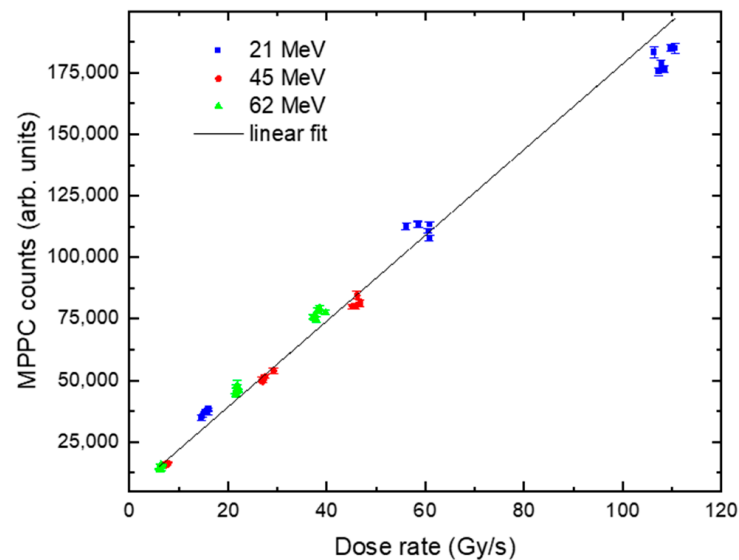


Figure 1. Light output from PMMA measured by the MPPC photodetector as a function of average dose rate over 4–6 trials at three different energies. Good linearity was established [18].

To continue exploring the potential of PMMA fibres, we fabricated a one-dimensional (1D) multi-point PMMA optical fibre array to quickly interrogate the FLASH proton beam and to determine if this detection system could be expanded to a two-dimensional (2D) or three-dimensional (3D) array to deliver near-instant detailed beam characteristics in the future.

Transverse and axial profiles of the FLASH beam were measured, as well as the dose rate and energy dependence of the optical fibre response with custom-built phantoms and a multichannel MPPC. We also investigated RIL attenuation with a pristine fibre and single-channel MPPC. Profile comparisons were made to radiochromic film measurements and FLUKA (a Monte Carlo package) simulation.

2. Materials

2.1. Sensors

The array was composed of seven fibres, 15 m in length, of Eska Premier 1 mm diameter Simplex Optical Fibre (Mitsubishi Chemical Corporation, Chiyoda City, Tokyo, Japan). The fibres were jacketed to a total outer diameter of 2.2 mm each. The fibres were machine-cut and polished at both ends by the vendor and terminated by hand: the interrogated ends with a 2.2 mm black PMMA jacket, and the photodetector-coupling ends with SMA905 connectors (Thorlabs, Newton, New Jersey, United States). The fibres were coupled to a Hamamatsu 16-channel multipixel photon counter (MPPC) module (model C13369-3050ED-04) via a 150 mm PMMA extension permanently attached to a custom faceplate via the method described by Penner et al. [33] in a study to determine if a five scintillator array would be suitable for conventional dose rate proton beam characterisation (Figure 2).

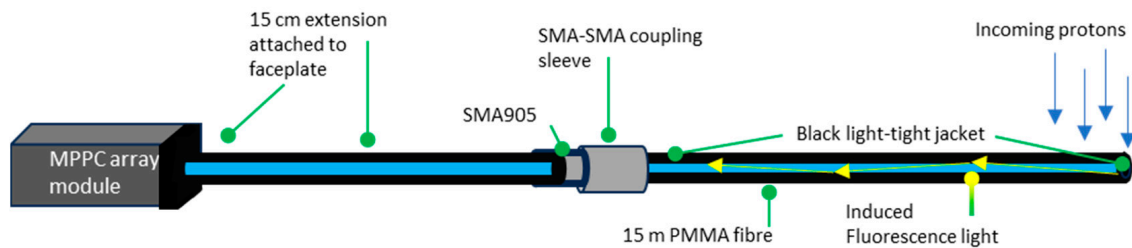
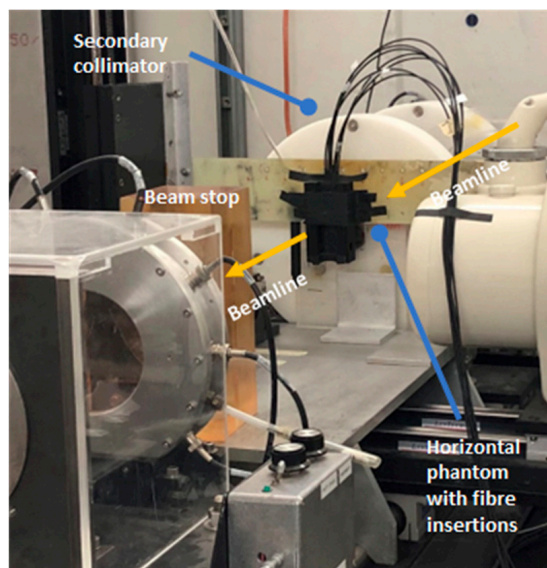


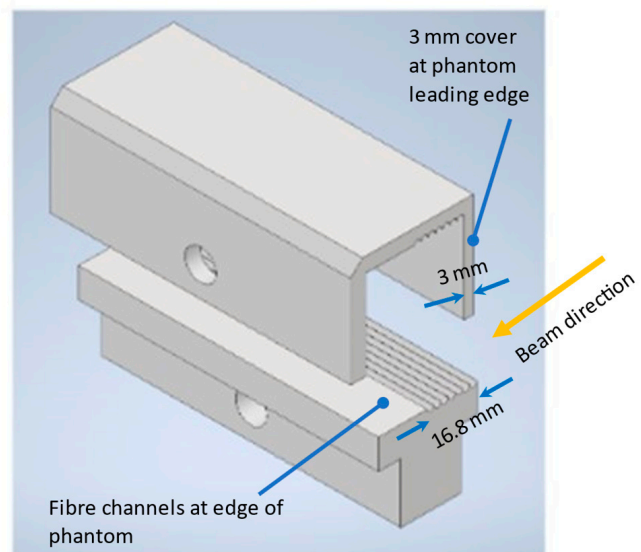
Figure 2. Schematic showing one channel of the seven channels used in this study, including sensing fibre, fibre extensions and proton irradiation direction.

2.2. Phantoms

Two phantoms were custom designed for the seven sensors, 3D printed with an Elegoo (Shenzhen, Guangdong, China) Mars Pro LCD 3D printer from a near-PMMA-equivalent black resin (Anycubic plant-based UV resin, density of 1.1 g/mL) to reduce noise from ambient light. The phantom for transverse measurements had seven channels across the centre of the phantom, each 2.4 mm from channel centre to channel centre, to hold the fibres in place during the irradiations. The front of the phantom was a 3 mm thick cover to both eliminate ambient light and simulate a 3 mm depth of water; the phantom was positioned with the face at 90 degrees to the beam direction, see Figure 3a. The axial phantom also had seven channels at 2.4 mm intervals, but rather than being across the centre of the phantom, they were situated to one side of the phantom, with a 3 mm cover over the “first” channel (Figure 3b); the phantom was positioned so the fibres were arranged in line with the beam direction.



(a)



(b)

Figure 3. (a) Beamline showing transverse phantom attached to the 2D stage, 60 mm downstream from the secondary collimator. (b) Axial phantom design with fibre channels at the leading edge.

2.3. Photodetector

The 16-channel MPPC module was fitted with a specialised faceplate to guide light to the centre of the 3 mm × 3 mm MPPCs, as described by Penner et al. [33]. Seven channels were selected for their repeatability and consistency over different thresholds and gate times; all channels were set at a threshold of 1.5 photon equivalent (p.e.) and a gate time of 1000 μ s.

3. Methods

3.1. Irradiation Conditions

All irradiations were carried out at the TRIUMF PTRC, where beamline 2C is operating at FLASH dose rates. Operation of the 74 MeV beamline in FLASH mode was as described by Bélanger-Champagne et al. [18], achieving dose rates from 7.5–101 Gy/s. Irradiations were set to deliver a prescribed number of monitor counts (MC)—measured by a diagnostic ion chamber upstream of the fibre placements—which can be related to dose via a calibration with a T1 ionisation chamber (Standard Imaging, Middleton, WI, USA). Each irradiation was followed by a dark measurement without a beam for background subtraction. For each irradiation, measurements were background subtracted, and the net signal was normalised, either to the total MC delivered or to the exact beam current during each second of irradiation. The transverse phantom was placed 6 cm behind the secondary collimator, upstream of the beam stop (Figure 3a). Transverse measurements were taken with the fibres lined up across the beam spot at 90 degrees to the beam direction.

Axial phantoms were placed 6 cm behind the secondary collimator, with the fibres lined up in the direction of the beam behind the 3 mm PMMA cover (Figure 3b). Axial measurements, where PMMA slabs were used to simulate depth in water, were performed with the PMMA slabs directly downstream of the secondary collimator.

All array irradiations were performed with the same set of fibres. All fibres had experienced photon irradiation to under 100 Gy total and were left unirradiated for over 1 year prior to proton FLASH measurements.

3.2. Transverse Measurements

3.2.1. Corrections and Correction Factors

Although every effort was made to ensure all the fibres were identical, each fibre was terminated by hand and then coupled to an extension to guide the light to an individual MPPC; therefore, correction factors were necessary to calibrate the signal from each sensor. To this end, the fibres were attached to a remote-controlled 2D stage (designed and manufactured in-house), the horizontal centre of the beam was found by moving the array, and then the individual sensors were cycled one at a time into the same position by moving the stage horizontally in 2.4 mm increments, first in one direction, then the other. By this method, the signal from each fibre was obtained in the centre position. All fibre signals were normalised at this position, and the correction factor obtained was used for all subsequent data analyses.

3.2.2. Energy and Dose Rate Dependence

Irradiations of the phantom were carried out by energy: 13.5, 19, and 40.4 MeV at three different set beam currents: 2, 6, and 10 nA, in that order, for durations of 10,000 MC at 2 nA, 25,000 MC at 6 nA, and 50,000 MC at 10 nA to ensure similar irradiation durations. Each current at each energy was measured three times. The extracted beam current was set to a fixed value, but over the course of each irradiation and between irradiations, it varied; thus, for each irradiation, during the signal processing stage, the fibre outputs were normalised to the exact number of MC and, in some cases, to the exact beam current recorded second-by-second. The signal was background subtracted, and the net signal was then summed and divided by the total MC delivered in that irradiation to show the signal intensity per monitor count. A comparison of the 2 nA dataset was made to GAFCHROMIC™ EBT-XD radiochromic film (Ashland Specialty Ingredients, Bridgewater, NJ, USA) irradiated under the same conditions.

3.2.3. Radiation Hardness

To explore radiation hardness, a previously unused single fibre was interrogated at an energy of 19 MeV and a current of 9 nA using the single-channel MPPC (Hamamatsu, model C11208-350) with an attenuator, as this MPPC is more sensitive than the 16-channel MPPC used in the array measurements. To ensure the single fibre was situated in the centre

of the beam, an EBT-XD film was placed at the irradiation depth and irradiated. The film began to develop immediately, and the region of highest dose could be estimated visually. The single fibre was attached over this area (Figure 4), and the assembly was replaced with the fibre being in the central beam region.

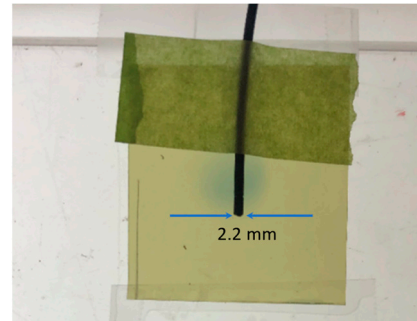


Figure 4. Film showing beam transverse profile and fibre placed over the beam central region.

The integration time for the single-channel MPPC was set to 1000 μ s at a threshold of 0.5 p.e. Irradiations were carried out in approximately 21,221 Gy (or 1,000,000 MC) iterations with 1–2 min of recovery between each irradiation. After just over 127,000 Gy (around 6,000,000 MC) of “seasoning” at a 9 nA beam current, 2 nA and 6 nA measurements were each compared to the 9 nA results: the rate of attenuation and signal intensity at different dose rates were assessed. All results were background subtracted, and the signal-per-second data were divided by the exact current measured for each corresponding second to account for current fluctuations over the course of each irradiation.

3.3. Axial Measurements

Depth Dose

Axial measurements were carried out by placing the phantom and seven fibres with the fibres directed such that each fibre was situated 2.4 mm deeper than the previous; 50,000 MC were delivered at 10 nA for three trials each. The beam energy was varied over a series of irradiations where progressively more PMMA degrader plates were placed upstream of the phantom. The fibres in the phantom thus sampled different parts of the Bragg peak for each beam energy and can be combined to characterise the full Bragg peak. Measurements at 73 MeV were performed with no PMMA slabs and only 3 mm depth due to the phantom geometry, 40.4 MeV with 24.6 mm of PMMA buildup, and 19 MeV with 33.6 mm of PMMA buildup. Results were compared to a FLUKA simulation in water at a fixed source-to-surface distance but not to the films due to the films’ severe saturation in the high LET conditions of the Bragg peak and resultant under-response.

3.4. Analysis of Films

To compare the results of the radiochromic films to the fibre results, we employed a nearly identical method to our earlier work in [33]. The images were scanned with a Xerox2 (Altalink C8170, 600 dpi) scanner, processed using the image-processing software Fiji ImageJ2, and profiles were then generated in a custom Python script. To convert the scanned radiochromic film profiles from pixel value to dose in Gy, calibration data were obtained with known doses applied at conventional proton therapy dose rates. The four-parameter Rodbard function

$$D = d + \frac{a - d}{1 + \left(\frac{x}{c}\right)^b} \quad (1)$$

determined the dose in Gy for each pixel value x using the calibrated constants of best-fit a , b , c and d (Table 1) [34,35].

Table 1. Constants of best fit for the four-parameter Rodbard function applied to the calibration data, where x is the pixel value and D is the dose in Gy; the maximum pixel value at which data points were capped is also shown. With these constants, the values of the radiochromic film images can be converted from pixel value to Gy.

Parameter	a	b	c	d	Max. Pixel Value
Value of Best Fit	0	1.319	2.716	121.247	115

Here, the calibration trials ranged between 1.38 Gy and 34.26 Gy, which corresponded to pixel values of 39 and 115, respectively; thus, the maximum pixel value for the films in our analysis was capped at 115, which is the maximum pixel value allowed in Equation (1) as the film saturates at doses above 40 Gy.

To match the geometry of the fibre for accurate comparison, film data were integrated over regions of 18 mm $\times$ 1 mm at the location of the fibres. The 18 mm vertical dimension was chosen as it is long enough to include the entire vertical range of each beam spot. The integrals are simply the dose received by the films, summed over a rectangle, representing the 2D area in which the fibres would have been measuring dose.

4. Results and Discussion

4.1. Transverse Measurements

4.1.1. Correction Factors

Although seven fibres were measured, the fibre positioned between 2.4 and 7.2 mm (in position 4.8 mm) suffered damage during the setup, which rendered the fibre measurements unusable. The fibre continued to occupy its channel in the phantom, so there were no air gaps or other density inconsistencies. The fibre located at position -4.8 mm was chosen arbitrarily as the reference fibre, and correction factors were obtained for the other fibres as described in Section 3.2.1; results are shown in Table 2.

Table 2. Correction factors calculated for each fibre sensor. Position 0 is the central fibre position of the phantom as well as the midpoint of the beam spot.

Fibre Position (mm)	-7.2	-4.8	-2.4	0	2.4	7.2
Correction Factor	1.082	1.000	1.200	1.127	1.533	1.253

4.1.2. Dose Rate and Energy Dependence

Results for measurements at the three dose rates tested are shown in Figure 5: 2 nA in Figure 5a, 6 nA in Figure 5b, and 10 nA in Figure 5c. The results from dose rate measurements show that the array can measure the beam profile at all dose rates tested (shown in Table 3). There is a noticeable increase in signal as the dose rates increase from 2 to 10 nA, indicating dose rate dependence. Due to dose rates being partly determined by energy (the lower energies shifting the high LET Bragg peak region closer to the centre of the fibres), it can also be inferred that the RIL in the fibres is energy dependent.

Table 3. Dose rates as measured by energy and current.

	13.5 MeV	19 MeV	40.4 MeV
2 nA	20.3 Gy/s	15.4 Gy/s	7.5 Gy/s
6 nA	60.8 Gy/s	46.3 Gy/s	22.4 Gy/s
10 nA	101.4 Gy/s	77.1 Gy/s	37.4 Gy/s

The comparison between the film and fibre profiles at the 2 nA current is shown in Figure 5d–f. Film and fibre data (for the second trial at 2 nA) were both normalised to 1 at position -2.4 mm. The film and fibre data agree very well at 40.4 MeV, with less than a 5% difference in the central four fibre positions, although there is a possibility of saturation

experienced by the films at 19 and 13.5 MeV due to their higher relative dose rates and the fact that those profiles appear slightly wider compared to the fibre profiles. At 13.5 MeV, there is up to a 45% difference between the film and two penumbral fibre signals and up to a 13% difference in the central four fibre positions.

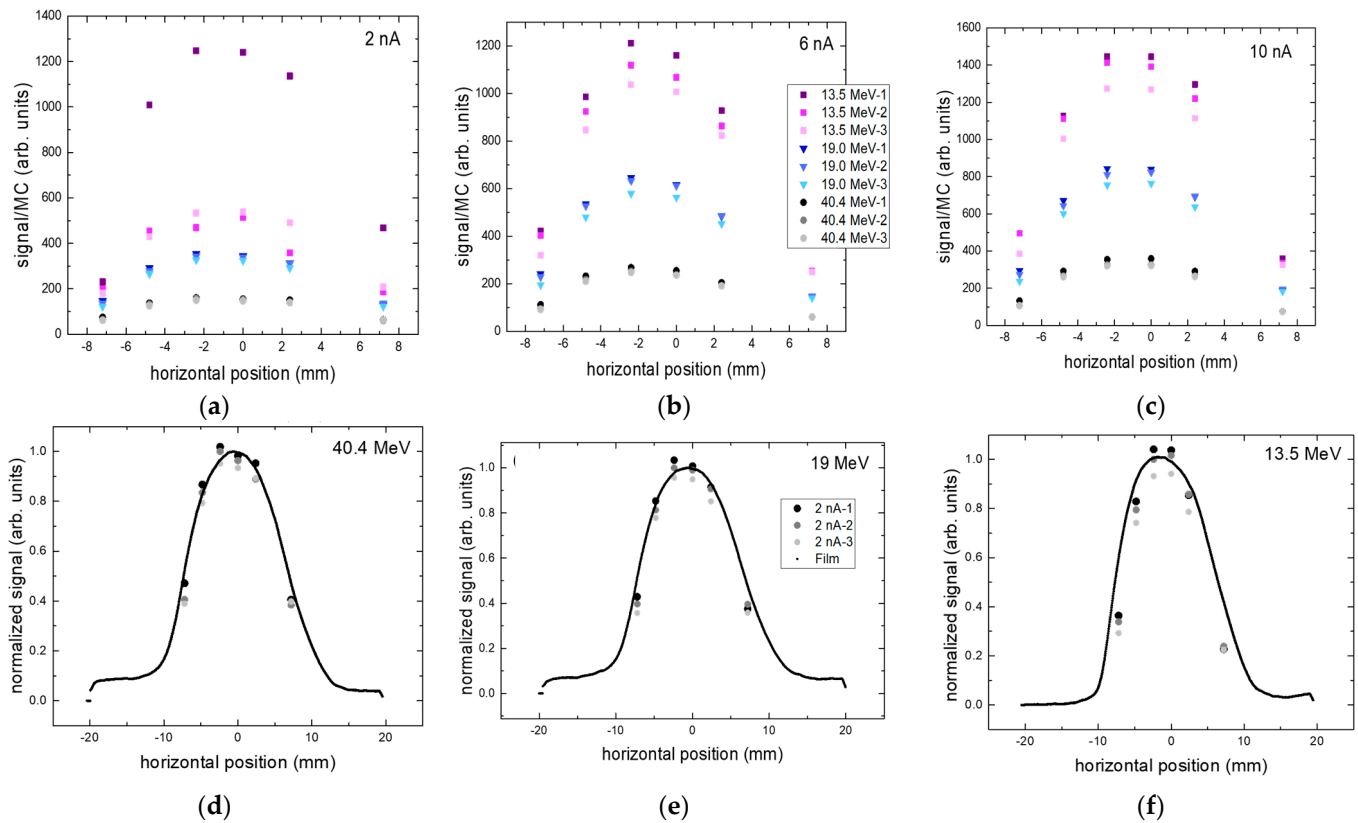


Figure 5. (a–c) Each current for the three energies tested, with the individual measurements at each energy shown as 1, 2, and 3. There is a noticeable decrease in signal from one series of irradiations to the next. Position 0 mm is the most central fibre position; however, the fact that the beam itself is not perfectly symmetrical is evident in all profiles. (d–f) Comparison between film and fibre response at 2 nA for all three energies. Results for the film and fibres are normalised to 1 at their peaks of the second irradiation. Film profiles appear to widen relative to the fibres as energy decreases below 40.4 MeV in (e) and even more so in (f). This could be a result of saturation in the films in the peaks at the lower energies—an expected result considering the dose levels received at these energies.

There was a noticeable decrease in signal from the first to the third trial at each energy—most noticeably between the first and second 13.5 MeV (2 nA) irradiations in Figure 5a. Notably, the first 13.5 MeV irradiation performed was at 2 nA. The decrease varied from over 50% between the first and second 13.5 MeV (2 nA) irradiations to an average of 4.8% for the remainder of the data points. All variations observed are due to systematic signal decrease from irradiation 1 to 3. The signal reduction observed prompted further study into the radiation hardness: RIL attenuation as a function of dose, as discussed in Section 4.1.3.

4.1.3. Radiation Hardness

Figure 6a shows six full and one partial irradiation at a 9 nA current and 19 MeV. The partial irradiation is the result of an unplanned cyclotron accelerator outage. In each of the irradiations, exponential decay in RIL, then partial recovery during the break, is observed. We found that with 1–2 min of recovery between each irradiation, the partially recovered fibre continued to exhibit average exponential decay described by the exponential decay

equation ($y = m \cdot e^{-n \cdot t}$), where m (as shown in Table 4) is the initial intensity, n is the decay constant, and t is the duration of the irradiation in seconds.

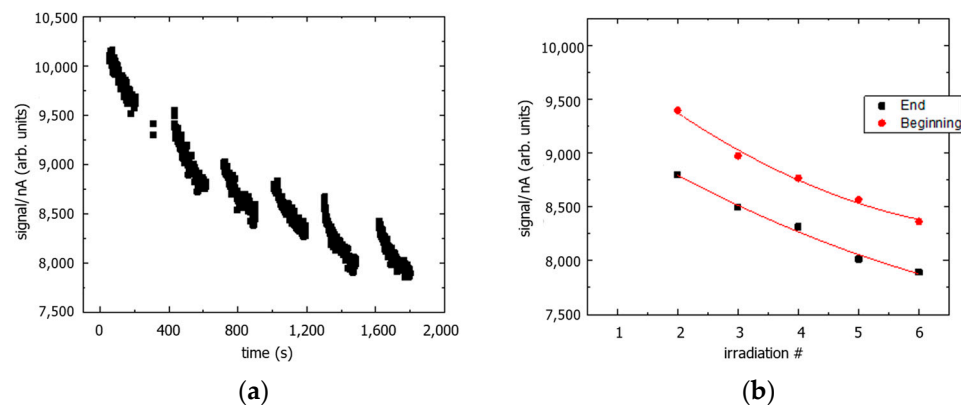


Figure 6. (a) Six irradiations of a pristine portion of PMMA optical fibre with a current of 9 nA at 19 MeV. The Figure includes recovery time between irradiations. (b) The beginning and end signal/nA for the five irradiations with virtually identical irradiation durations. The fits shown are polynomial functions to show the consistency of the attenuation from subsequent 1,000,000 MC (around 21,000 Gy) irradiations. Data are normalised to the current-per-second during each irradiation.

Table 4. Trial number with equations of best fit for each trial.

Trial	Decay Constant (n) (1/s)	R-Squared	% Difference between y -Intercept and y ($t = 0$)
1	0.00034	0.9194	0.00
2	0.00036	0.9071	1.49
3	0.00030	0.9073	0.77
4	0.00031	0.9434	0.38
5	0.00033	0.8763	1.21
6	0.00030	0.8913	1.05
Average	0.00032 ± 0.00002 *		

* indicates the standard deviation in the decay constants of the six trials.

The average signal over the first and last 10 s for five of the six trials is shown in Figure 6b. Irradiations 1 and 2 are not included in Figure 6b due to the second, truncated irradiation being only 2 s in duration and irradiation 1 being several seconds short of the full duration.

As evidenced by the fits for both the beginning and end irradiation signal strengths, each irradiation experienced nearly the same amount of RIL attenuation over its course. The consistent differences between the beginnings and ends of irradiations indicate a consistent decrease in RIL over the delivered doses. After seasoning the PMMA fibre with over 127,000 Gy of dose, the 6 nA and 2 nA tests performed afterwards with the same fibre showed continued RIL attenuation, suggesting more seasoning would be necessary to achieve a linear response in these fibres.

The 6 nA and 2 nA currents were tested both for RIL attenuation as well as for dose rate dependence. This was performed by leaving the PMMA bolus in place to maintain the energy of the protons while varying only the current. Ratios between the 2 nA, 6 nA, and 9 nA dose rates are shown in Table 5. The ratios are slightly higher than expected, even though the applied dose rates were normalised to the set dose rates of 2 nA, 6 nA, and 9 nA. The ratio between 9 nA and 6 nA was very close to the expected value; however, the ratios between 9 nA and 2 nA and between 6 nA and 2 nA were both higher than expected. These results support the assumption that RIL attenuation had not yet reached a plateau—an expected result due to linear response in the seasoned fibre [18]. Notably, when

the comparison irradiations were performed, the order of irradiations was first 9 nA, then 6 nA, and finally 2 nA—causing the 2 nA irradiation to yield the lowest normalised signal.

Table 5. Ratios of outputs between different dose rates of 2 nA, 6 nA, and 9 nA compared to expected values. Error was calculated as the standard deviation in each dataset, then propagated to the ratios between sets.

Current Rates	9 nA:6 nA	9 nA:2 nA	6 nA:2 nA
Experimental Ratio	1.51 ± 0.02	5.20 ± 0.1	3.33 ± 0.07
Expected Ratio	1.50	4.50	3.00

4.2. Axial Depth Dose Results

Figure 7 shows the comparison between the FLUKA simulation [18] of the depth dose for a 73 MeV beam as compared to the axial measurements taken with five fibres at three different energies, associated with three different positions along the Bragg peak, in the axial phantom. The sixth fibre (the one in the shallowest position, at a 3 mm depth) reported an extremely low signal for all three energies—an unexpected result considering that fibre had been in the penumbral region for transverse measurements and would have been expected to report a high signal due to a total lower dose received than the fibres in the centre of the beam. We hypothesise that the fibre had either shifted in the phantom or in its connection to the MPPC. This being the case, the fibre and its position were not included in the axial results.

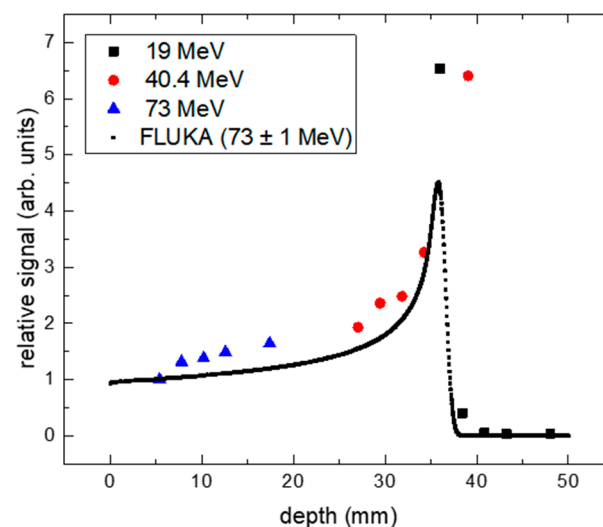


Figure 7. Depth dose comparison of five fibres at three energies of protons to the FLUKA simulation at 73 MeV. The overall beam shape and Bragg peak position are in very good agreement.

Both the simulation results and fibre signals are normalised to 1 at a depth of 5.4 mm. The depth of the Bragg peak and subsequent drop-off are in excellent agreement. The “bump” seen in the 40.4 MeV data points, around the 25–32 mm depth range, is a known characteristic of this beam [20]. Compared to the FLUKA simulation, the fibres show an overresponse in the Bragg peak; this could be due to some fibres (particularly those on the periphery) not having received the equivalent amount of seasoning to those in the central channels and thus possibly displaying higher than expected RIL in the high LET Bragg peak compared to the lower LET regions. As suggested by the single-channel RIL attenuation study (Figure 6a), the RIL signal does not appear to be entirely recoverable over the short resting durations tested; thus, the non-uniformly irradiated fibres—the same ones used in the transverse study (Section 4)—could be susceptible to non-uniform response. Furthermore, the shallowest fibre at 19 MeV and the deepest fibre at 40.4 MeV would appear to indicate a very wide BP between 35 and 38 mm of depth, which could be a result

of the figure representing the BP as point signals while the fibres were 1 mm in diameter and nearly 1 cm in length.

Due to the saturation of the films in the high LET region of the Bragg peak, we did not perform a film comparison for the axial measurements.

5. Conclusions

PMMA optical fibres have the potential to be a real-time means of monitoring FLASH dose rate proton beams by measuring the RIL induced in the fibres. Although the phantom and measurements were designed for a seven-fibre array, one fibre was irreparably damaged in the preparation for measurements. Nevertheless, we demonstrated a multi-point 1D array of six fibres to show beam transverse profiles with an accuracy of at least 95% in the central four fibre positions when compared to radiochromic films. Axial measurements presented beam features in agreement with the FLUKA simulation and other depth dose measurements from this beam.

A single fibre was shown to continue to exhibit dose rate dependence when measured with a single-channel MPPC after seasoning with over 100,000 Gy of dose. RIL attenuation was observed throughout measurements as well as at varying dose rates but appeared to begin recovery immediately after each irradiation, a phenomenon observed in gamma-radiation RIA studies of PMMA fibres. The recovery is thought to be a result of "... spontaneous reforming of the polymer bonds that are damaged during irradiation" [31]. Measurements at 9 nA and 19 MeV followed a predictable RIL attenuation trend, with a decay constant of $(3.2 \pm 0.2) \times 10^{-4} \text{ s}^{-1}$.

Overall, there is potential to use RIL attenuation as a measure of absorbed dose with future characterisation.

6. Outlook

To make the detector dosimetrically viable, investigations are needed to characterise the signal loss (both permanent and recoverable) with repeated irradiations and to improve data for RIL attenuation at varied currents and dose rates. Additionally, future experiments should explore if sufficient seasoning, perhaps with doses on the order of MGy, could cause the plain PMMA fibres to reach a damage "plateau", from which no further RIL attenuation is possible—leading to linear (i.e., without RIL attenuation and recovery) dose and dose rate response [36]. Further, where scintillator quenching is LET (therefore energy) dependent, it would be worthwhile to explore whether this is the case with RIL attenuation.

Our multi-fibre array is capable of beam monitoring and profile characterisations; expansion to a 2D or 3D array is possible due to 16 available channels and custom Python code.

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