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TRACKING AND LET MEASUREMENTS WITH THE MiniPIX-Timepix DETECTOR FOR 60 MeV CLINICAL PROTONS

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Abstract

Recent advancements in accelerator technology have led the rapid emergence of particle therapy facilities worldwide, affirming the need for enhanced characterisation methods of radiation fields and radiobiological effects. The Clatterbridge Cancer Centre, UK operates a 60 MeV proton beam to treat ocular cancers and facilitates studies into proton induced radiobiological responses. Accordingly, an indicator of radiation quality is the linear energy transfer (LET), a challenging physical quantity to measure. The MiniPIX-Timepix is a miniaturised, hybrid semiconductor pixel detector with a Timepix ASIC, enabling wide-range measurements of the deposited energy, position and direction of individual charged particles. High resolution spectrometric tracking and simultaneous energy measurements of single particles enable the beam profile, time, spatial dose mapping and LET (0.1 to >100 keV/µm) to be resolved. Measurements were performed to determine the LET spectra in silicon, at different positions along the Bragg Peak (BP). We discuss the experimental setup, preliminary results and applicability of the MiniPIX for clinical environments.

INTRODUCTION

The world's first hospital based proton beam therapy (PBT) facility is located at the Clatterbridge Cancer Centre (CCC) in the UK which has provided a successful treatment service for ocular tumours for over the past 30 years. It operates a SCANDITRONIX MC-60 isochronous cyclotron which generates a beam of 60 MeV protons at isocentre, precisely shaped and passively delivered by a double scattering system [1]. As part of efforts to completely characterise the beamline and exploit characteristics of the beam, computational approaches to model the facility in several simulation codes have been developed [2]. In particular, a model of the CCC treatment line [3, 4] was created for additional modelling capabilities for radiobiological applications. For this purpose, we examine one significant parameter which relates a physical quantity of energy deposition to radiobiological effects: the linear energy transfer.

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Linear Energy Transfer

There are several definitions of LET, as there are many considerations in order to adequately calculate and score this quantity, either analytically or with Monte Carlo methods, but in general can be expressed as Eq. (1)

$$\mathrm{LET} = \frac{d\mathrm{E}}{d\ell}. \tag{1}$$

LET is a measure of the energy loss (dE) along a track (dℓ) given in units of keV/µm. As this is dependent on the stopping power, it is defined given the contributions from electronic interactions [5]. In practice however, particles are not monoenergetic and LET can be averaged for the weighted dose contributions of individual particles. This is the dose-averaged LET ($\mathrm{LET_d}$) and can include contributions from both primary and secondary particles. $\mathrm{LET_d}$ is considered as an indicator of biological effects which result from particle interactions and is meaningful for the radiobiological work performed at the CCC beamline [6, 7].

However, it is difficult to measure LET due to several performance requirements which exceed typical capabilities of commonly used methods of detection. Primarily, the position, charge and distribution of tracks deposited by individual particles must be able to be recorded rapidly and resolved with very high spatial resolution. To provide these measurements under these conditions is challenging and has not been realised for current commercially available systems. Alternatively, the capacity of Timepix [8] to measure LET has been demonstrated in different radiation environments [9–15] and techniques for applications in ion beam therapy have been explored [16–20].

METHOD

MiniPIX-Timepix

MiniPIX-Timepix is a compact radiation camera equipped with the hybrid semiconductor pixel detector Timepix ASIC, with a 300 µm silicon sensor of 14x14 mm^2 active area [18]. Developed by the Medipix Collaboration at CERN, Timepix provides per-pixel signal processing in wide range for precise counting, energy or timing at the pixel level. The detector was held securely in a custom 3D printed case and attached to a remotely controlled, motorised rotating stand (Fig. 1).

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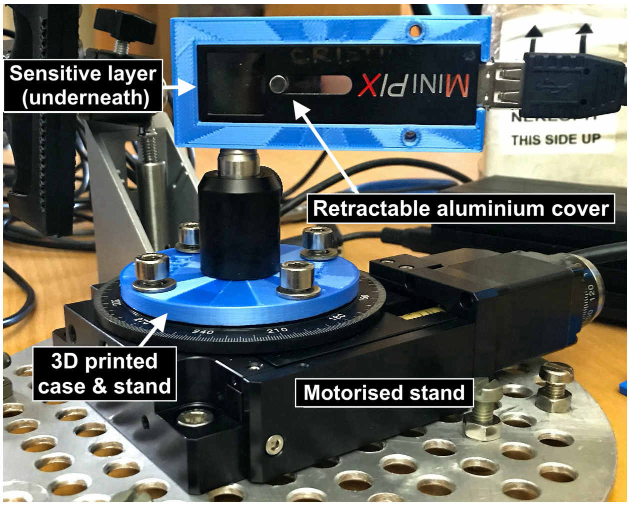

Figure 1: The MiniPIX-Timepix detector, a retractable aluminium sheath covers the chip sensitive area with the centre positioned at the the origin of the rotational axis.

CCC Measurements

As typical treatment beam settings achieve flux rates with up to 10^{10} protons/s, the beam current needed to be heavily reduced to ranges suited for MiniPIX, from $\sim 10^9$ protons/s (across the sensor) to optimally within 10^3–10^4 protons/s/cm^2. Several factors needed to be considered to account for beam uncertainties as discussed in [21]. The first few runs were performed with a sheet of lead with a 200 µm diameter pinhole and 1 mm nozzle brass collimator in front of the detector before adjustments were made to reduce the flux by several orders of magnitude and stabilise the beam. Different acquisition times were used to record hits with the detector angled at 45° and 60° in the perpendicular plane. The detector was at the same distance from the nozzle for all the runs with the different thickness blocks of PMMA placed directly upstream of the sensor (Fig. 2).

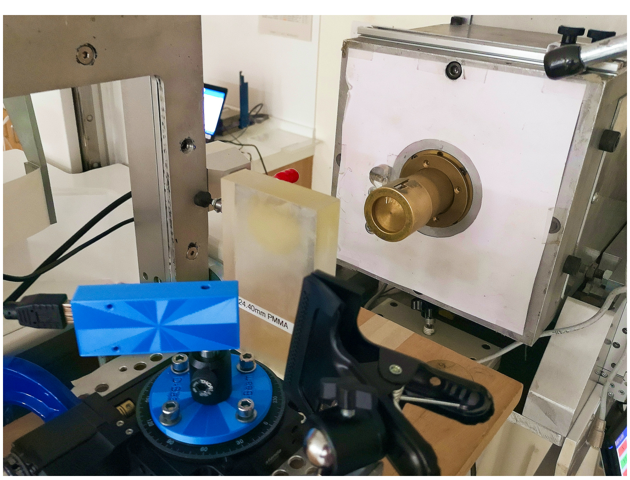

Figure 2: Experimental setup with detector angled at 45° to the beam, approximately 18 cm from the collimator. Upstream, a block of PMMA decreases the depth of the BP.

Having a tilted plane with an incidence angle of >45° has been demonstrated [20] to increase the track acceptance and measurements were also performed with the detector angled at 60° in the perpendicular plane. Furthermore, the combination of different PMMA blocks, the aluminium slider and angular rotation also changed the physical depth traversed by the protons, providing additional depth measurements.

Measurements were recorded in real time using the Advacam PIXET [22] software. An initial digitisation test showed 0 dead pixels and a recommended bias of 30 V was applied with a frame acquisition time of 10 ms. A visual check is sufficient to ensure that the chosen frame rate is suitable (single tracks appear): if this is too short, the particles are not able to deposit sufficient charge and the detector will register incomplete tracks. The detector lower measurement threshold was set to the minimum level, just above the noise for maximum sensitivity and set to measure ToT (time over threshold). There is a non-linear calibration from ToT to energy which is accounted for in the acquisition software. Data was taken for similar total acquisition times for each run, mainly to acquire adequate statistics. Cluster files reported global frame times every ~30 ms: this consists of the 10 ms open shutter time with the remaining as dead time for readout (closed shutter), approximating an effective data capture rate of 33 FPS (Frames Per Second).

RESULTS

During the 45° measurements, real-time cluster analysis indicated the most significant depths, a clear overall decrease in cluster numbers with depth and the highest cluster rate was achieved at 24.40 mm, indicating the BP (Bragg Peak). Time limitations meant that fewer measurements were possible for the second set of runs and therefore the 60° runs focused on three different depths for comparison. Similar trends in the cluster rates for both angled cases could also be seen and the positions along the BP were deduced (Fig. 3).

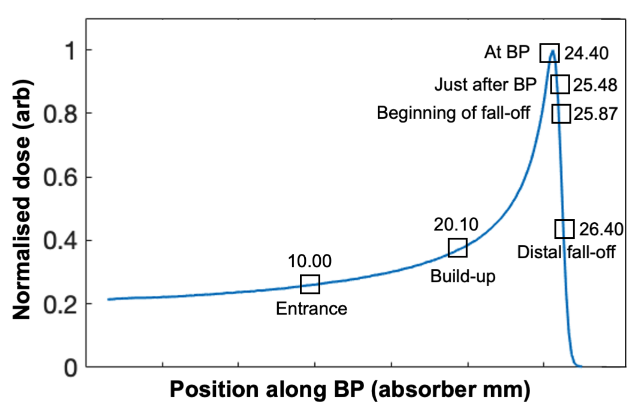

Figure 3: Observed depths along the BP for the different PMMA blocks.

Log files were processed with the readout software to generate different metrics (i.e. energy deposited, track sizes, angle etc.) for the distributions of recorded events for each run and stored as lists of clusters. These events contain the

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charge deposition produced by an individual particle. Multiple pixels may be triggered resulting in a cluster; a cluster is simply a region which contains more than one triggered pixel surrounded by zero hits. The readout software has inbuilt clustering algorithms to identify and classify clusters based on morphology, spectral and other parameters [18].

The detector can image single radiation tracks in high resolution from the size of the pixel (55 µm) to the sensor thickness (300 µm). This position and directional tracking capability combined with the timing and the energy detection for each pixel, enables measurements for track mapping and beam characterisation (profile, flux, dose rates etc.). For this work, only the properties related to the LET spectra were considered: total energy deposition, elevation angle and 3D path length. This was determined using Eq. (1) by evaluating the cluster lists and taking the cluster volume (energy deposition, dE) and cluster size (track length, dℓ) distributions. As the tracks can be recorded in any orientation, the path length was calculated given the directional angle of the incident track and the measured projected length [18–20]. The LET spectra in silicon, obtained at each depth for both angles, are shown below in Figs. 4 and 5.

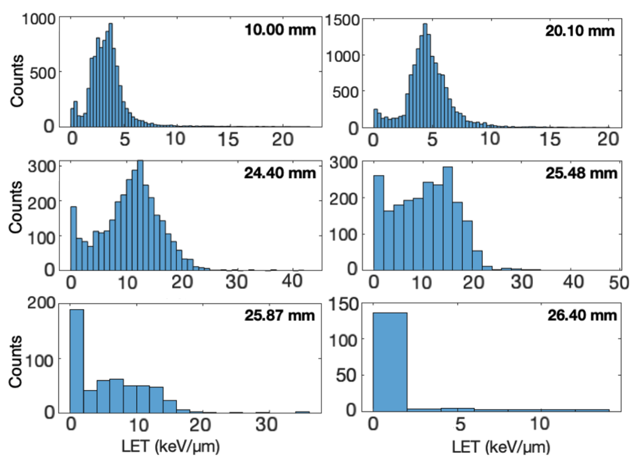

Figure 4: LET spectra with the sensor at 45°.

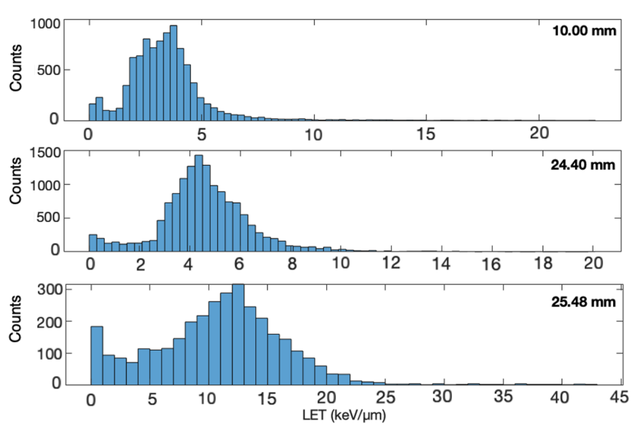

Figure 5: LET spectra with the sensor at 60°.

In general, a larger sensitive area is exposed as the change by 15° increases the effective depth of the sensor [17] and probability of detecting longer tracks, thus similar scaling differences for each cluster property were seen consistently between the 45° and 60° measurements. Greater statistics of clusters depositing larger amounts of charge, higher energy levels with a much bigger range of energy per cluster, and a multi-peaked distribution of cluster sizes were observed just before the BP. Double peaks indicate that the detector has recorded multiple particles resulting in an overlapping of tracks, distorting the true cluster size distribution. Peaks at the lower end of the LET spectra were also observed. This is due to the presence of the 1 mm thick aluminium slider which was kept closed as a protective measure. This additional layer introduces additional considerations which must be accounted for when simulating the exact experimental conditions in future. It is also unclear if limitations with preparation and beam calibration had a significant effect on device performance: it is expected that the distributions would approach better consistency given longer exposure time and increased numbers of counts.

CONCLUSION AND OUTLOOK

Experiments were performed using the MiniPIX-Timepix detector system at the CCC 60 MeV proton therapy beamline to measure relevant quantities in order to resolve the LET at different positions along the BP. Two tilt angles and various PMMA blocks provided a range of water equivalent thicknesses to vary the depth. Measurements of the deposited energy and track lengths were obtained to determine the LET spectra along the BP. Several uncertainties are noted with the experimental setup, resulting in wide distributions of cluster properties. Deeper cluster analysis and data post-processing could improve these however were out of scope of this work. Improvements in the future could be made by optimising detector settings and calibrations prior to recording data, longer irradiation times to acquire more clusters and therefore better statistics during measurements, and finally, accurate positioning of the PMMA and aluminium slider. Nevertheless, these measurements demonstrate the capability of the MiniPIX-Timepix detector to determine the LET and establish its applicability for clinical environments. The measured LET spectra in silicon at different depths along the BP, presents a basis for empirically obtained values for future simulation and radiobiological studies. Further work in this area will replicate the experimental conditions in computational models to compare simulated with detector recorded quantities and convert the LET from silicon to water, for verification of measurements and for radiobiology applications at the CCC PBT beamline.

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