University College London

Department of Physics and Astronomy

PHAS0097 Term 1 Progress Report

# Design of a Detector for Fast Treatment Plan Verification in Proton Radiotherapy

*Author*
Saad Shaikh

*Supervisors*
Dr. Simon Jolly
Prof. Ruben Saakyan

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# 1 Birmingham Experimental Run (25-26th October 2018)

The aim of the first experimental run was to test the use of the single-module calorimeter alongside the PRaVDA silicon strip tracker with a 36 MeV proton beam, improving on the previous run by having the tracker trigger the calorimeter and by performing data collection in small bursts. The intention was to perform measurements of proton energy and position through increasing thickness of absorber (PMMA), and with different types of collimators. Proof-of-principle for the simultaneous use of the two detectors would come from reproducing the 3D dose-deposition distributions of the different collimators (see below), and by demonstrating the shift in the peak of energy spectra of protons through increasing thickness of PMMA absorber.

The calorimeter was placed on a level stand downstream of the proton beam to the tracker, with the windows of both aligned by careful measurement and markings placed on the calorimeter case. Experimental runs were conducted across two days with: a Caen high voltage supply providing -900V to the photomultiplier tube (PMT), the LeCroy oscilloscope operating on a positive edge trigger set at a threshold of 70 mV, and a beam current on the order of 10 kHz ($\sim$160 pA). The oscilloscope had a time-base of 20 ns/div, a trigger delay of 80 ns and the vertical scale set to 50 mV/div. These were set by monitoring the input for some test protons, such that the pulse was centred with sufficient tail visible. The tracker trigger was sent into channel 2 of the oscilloscope; a square wave of amplitude $\sim$400 mV and period $\sim$15 ns, which triggered channel 1 (the output of the calorimeter) for data collection. The output of the PMT was split between the oscilloscope and the Caen digitiser, the latter was used to take independent measurements of proton energy spectra for verification with the oscilloscope.

Due to technical difficulties with the proton beam, limiting the time available for data acquisition, and recording of the incorrect channel on the oscilloscope, the run on the 25th failed to provide useable data. However, the remote desktop configuration (used to operate the oscilloscope and digitiser remotely in the control room), calorimeter, digitiser, oscilloscope and tracker were all tested to be functional. The oscilloscope was found to successfully receive a trigger from the tracker; measurements were made of the waveform trace of the trigger both directly from the tracker, and when split between the oscilloscope and the digitiser (where it was also attempted to trigger from the tracker). The traces revealed an expected $\sim$50% drop in amplitude when split, however it was found that the amplitude was too small to trigger the digitiser, which only accepts triggers on the order of $\sim$V. From the reconstructed hit distribution in 2D, the tracker was also found to be slightly off-centre. This was corrected before data acquisition the next day.

The run on the 26th proved more fruitful, where a 36 MeV beam was delivered for a longer period of time. Data collection was performed in 5 second bursts, where the tracker fed triggers to the oscilloscope and the digitiser was set to trigger on its own. The oscilloscope recorded the output of the PMT with a maximum of 50000 pulses in one file, which was much greater than the number of triggers delivered in 5 seconds. After each run, the trace of the oscilloscope was saved to disk, and each test configuration was repeated 3 times. The digitiser recorded one spectrum continuously for each 3 repeats of data collection with the oscilloscope. The test configurations were:

- A centred 2 mm collimator with no PMMA, used to confirm that the oscilloscope was being triggered appropriately by the tracker. The number of pulses was analysed after this run, and it was found that both the tracker and calorimeter recorded approximately the same numbers of events.
- A centred 2 mm collimator with increasing thickness of PMMA: 0.95 mm, 2.01 mm, 2.96 mm, 3.95 mm, 4.90 mm, 5.70 mm. Each thickness was repeated 3 times.
- A 2 mm collimator offset by 6mm in the positive $x$-direction, with no PMMA and with 5.70 mm of PMMA.
- A 2 mm collimator pair, with centres apart by 12 mm, with no PMMA and with 5.70mm of PMMA. An extra set without the PMMA was performed at a lower current rate.
- A 2 mm collimator pair, with centres apart by 12 mm in the $x$-direction, with one hole covered by 3.95 mm of PMMA. An extra set was performed at a lower current rate.
- Measurements with only the calorimeter in front of the beam were also planned but were unsuccessful due to technical difficulties with the proton beam and time constraints.

## 2 Development of Analysis Tools

The first stage of analysis was to reconstruct the proton energy spectra recorded by the LeCroy oscilloscope for all test configurations and compare with the equivalent spectra recorded by the digitiser. Code was first written to import and plot digitiser .txt files in histograms, for comparison with LeCroy spectra. Development of the analysis tools used the high-current half-covered collimator pair configuration as a test data sample, as it would be the most difficult to reconstruct, and would ultimately yield the proof-of-concept. The spectrum produced by the digitiser for this configuration is shown in Fig. 1:

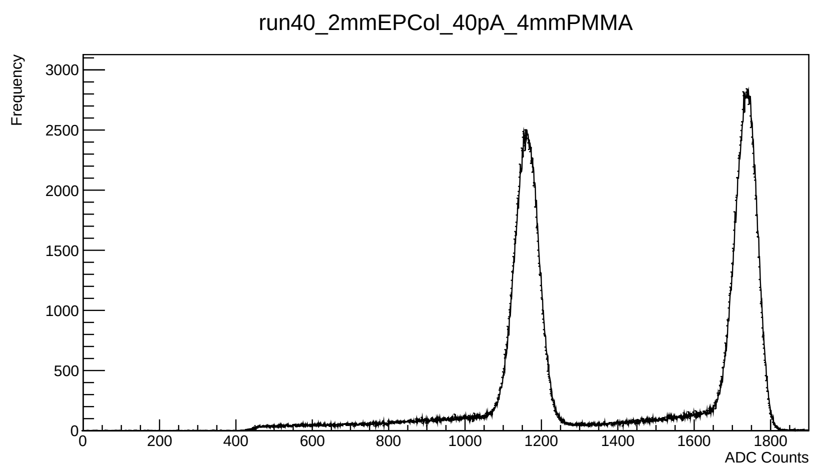


Figure 1: The reconstructed spectrum from the Caen digitiser for the half-covered collimator pair configuration. The digitiser records data into bins of size 1 mV•ns

The original version of the code for LeCroy data analysis operated on the assumption of a fixed pulse position within the acquisition window, due to the oscilloscope being triggered by the pulse at the time. This is no longer the case. The tracker now tells the oscilloscope when to record an acquisition, so the pulse could be anywhere within an acquisition (or not at all). Initially, the fixed-position parameters were adjusted to give the best spectrum possible, which were found to be: an integration length of 150 ns, a horizontal offset of -120 ns (i.e. where integration starts relative to 0 ns), and a maximum baseline sigma of 20. An example of the resulting spectrum, for one repeat of the half-covered collimator pair configuration is shown in Fig. 2

Comparison of Fig. 1 and Fig. 2 showed that the two peaks (one for each collimator) were recovered with approximately correct relative peak heights. However, a large number of events appear in a Gaussian-like shape around 0 in Fig. 2, which is indicative of acquisitions with no pulses. To rectify this, and improve pile-up filtering, the baseline testing method was overhauled.

As before, 9/10 of points before 0 ns are tested. If the test is passed then another test takes place that searches for a negative potential difference value (indicative of a pulse somewhere) in the acquisition and if this also passed, then the acquisition is labelled as "good". If the initial test is failed, the program will then test 9/10 of the points after 0 ns, in case the pulse happened to be in the first half. If this test is passed, and a negative potential difference is recorded, then an acquisition may also be labelled as "good". This baseline testing method is more robust than the previous version however, the issue of pulses close together still presides. Also, if the first baseline test is passed, then

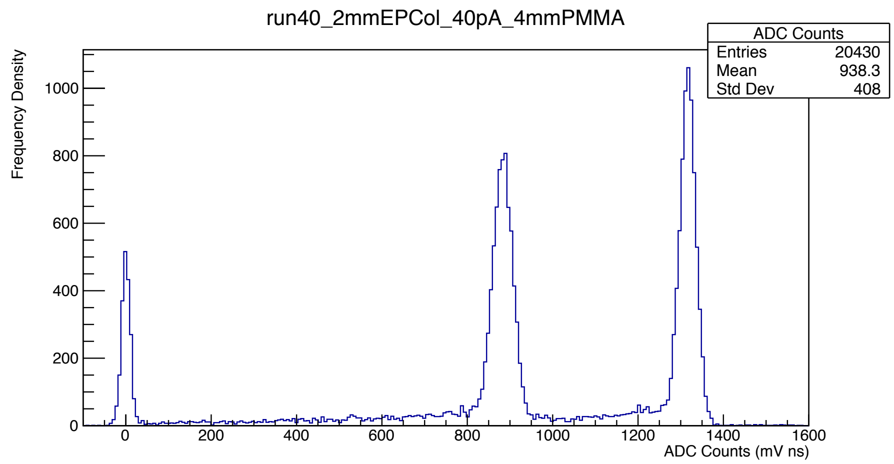


Figure 2: The reconstructed spectrum from the LeCroy oscilloscope for one repeat of the high-current half-covered collimator pair configuration using a fixed integration window. Data placed into 100 bins.

any extra pileup towards the end of the acquisition will not be taken care of. In practice however, these two issues do not appear to cause any major problems.

By locating the largest negative value recorded in the acquisition (after baseline tests), the location of the integration window is now dynamically allocated instead of having a fixed position. This removes the need for the offset parameter, meaning less guesswork for the user. It was also found that constraining the maxima baseline sigma any more than the (generous) value of 20 would ruin the spectrum in Fig. 2 entirely, such that no peaks were observed. It was realised that most pulses arrived at roughly -120 ns, which meant that choosing 9/10 of the points before 0 ns in the baseline test was including some of the actual pulse. Shortening the testing region to 8/10 improved the spectra considerably: the maximum baseline could be constrained to 5 and the location of the peaks shifted closer to those in the digitiser data. The improved version of Fig. 2, combining the 3 repeats and with all the above changes is shown in Fig. 3, demonstrating a much closer resemblance to Fig. 1.

By comparing the positions of the peaks across the digitiser and final LeCroy spectra, routines were written to scale and plot both onto a single graph. This is shown in Fig. 4. A very close match is observed but this is to be hopefully improved further by calculating the scale factors by minimising the chi-square between the plots, to take into account features of the entire plots.

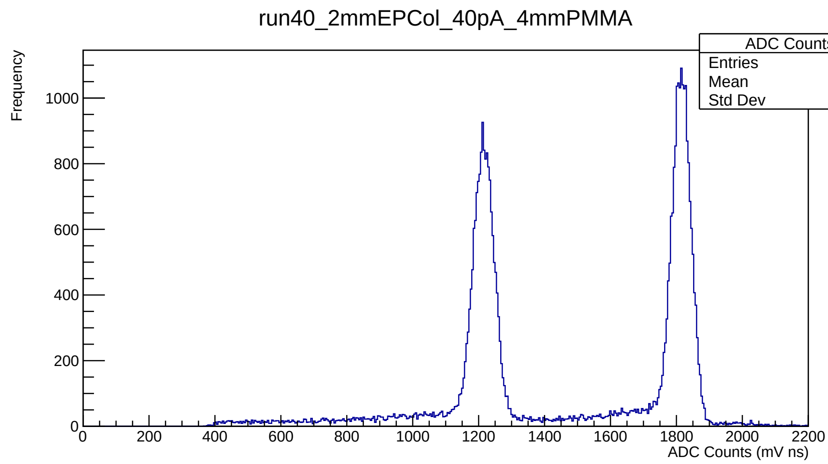


Figure 3: The reconstructed spectrum from the LeCroy oscilloscope for 3 repeats of the high-current half-covered collimator pair configuration, now using a dynamic integration window, a shorter baseline test region, and checking for empty acquisitions. Data placed into 500 bins.

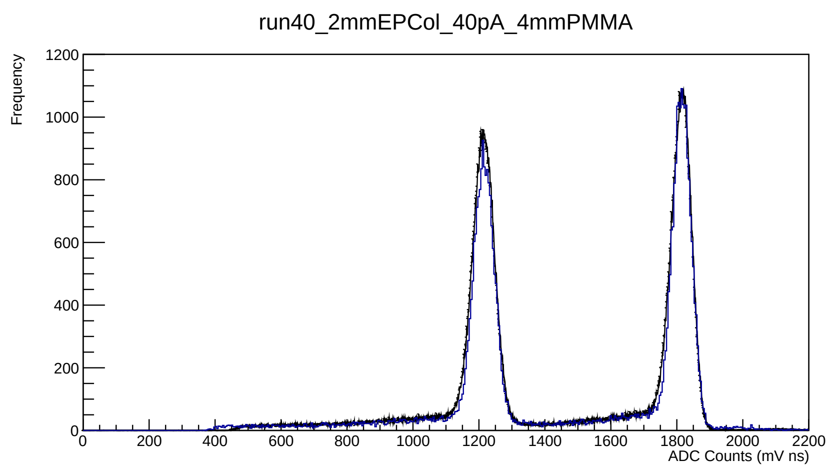


Figure 4: Scaled plot of the reconstructed Caen and LeCroy spectrum for the half-covered collimator pair configuration. Scale factor found by comparing the location of the highest value recorded in the second peak.

# 3 Matching of Tracker and Calorimeter Data

Routines were written to plot tracker data in a 2D histogram. The tracker plot of the collimator pair configuration is shown in Fig. 5. The unit consists of 4 trackers, which can record up to 5 protons each, each with 3 position coordinates. For the purposes of this experiment, a tracker event is considered to be "good" if only one proton is recorded.

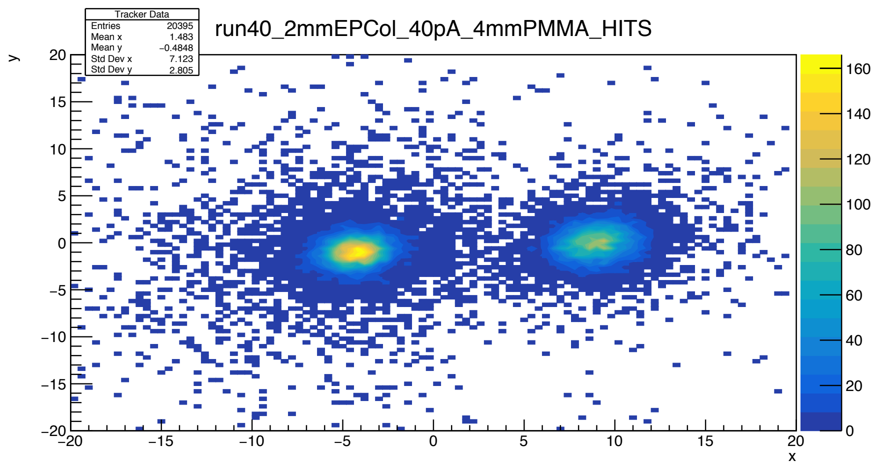


Figure 5: A 2D histogram of the $x$-$y$ distribution of hits recorded in the tracker for one repeat of the half-covered collimator pair configuration. Data placed into 100×100 bins. The collimator in the positive $x$-direction is covered with PMMA.

It was noted that the tracker is capable of much faster data collection than the LeCroy scope, which is limited primarily by the length of an acquisition (i.e. it cannot record data faster than the length of an acquisition, which was 1000 ns, sufficient to record a proton pulse fully). This resulted in the tracker recording protons at finer intervals than the LeCroy, but was dealt with by looking to map each LeCroy event onto the first tracker event that satisfied the matching criterion. Initially, it was attempted to match events with timestamps within 500 ns of each other (smaller than the resolution of the LeCroy to avoid cross-matching), but this resulted in very few matchings. It was then realised that the clocks of the tracker and LeCroy drift further apart as time progresses, likely due to an inaccuracy in the clock of the tracker (which is believed to operate at exactly 26 MHz). By plotting the time difference between the closest events, a straight-line equation was found to correctly increase the matching tolerance as time progresses. This is shown in Fig. 6. In future tests, steps will be taken to ensure both detectors operate on the same clock.

Re-matching events with the increasing tolerance window produced an ac-

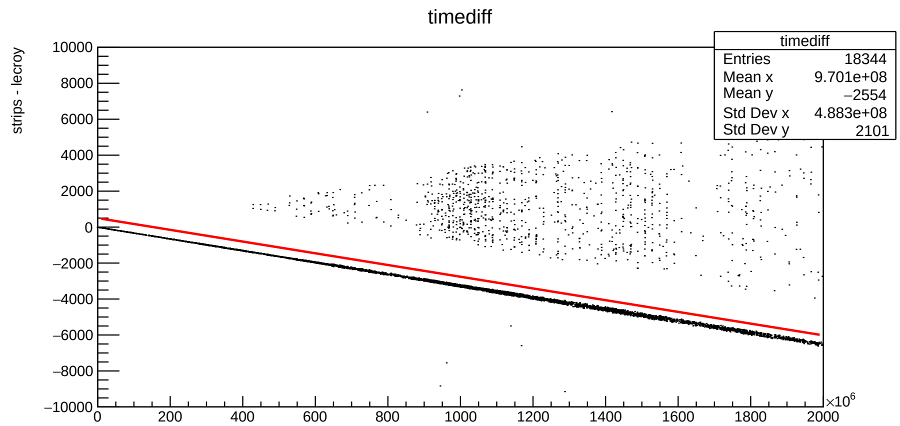


Figure 6: A plot of the difference between consecutive timestamps recorded in the tracker and LeCroy oscilloscope for one repeat of the half-covered collimator pair configuration. Points away from the line correspond to false triggers from the tracker. The red line corresponds to the equation $y = 500 - (3.42 \times 10^{-6})x$ and increasing the tolerance window according to this gives acceptable matching of events. Plot provided by T. Price, Birmingham University.

ceptable number of matchings. Roughly 20% of the events are discarded after both LeCroy and tracker data sets are filtered to contain only "good" events, and then the remaining events matched. ROOT is limited in its functionality to plot 4D histograms ($x$, $y$, energy & counts), but a summary of the 3D reconstructed dose depositions is provided in Fig. 7-9. These demonstrate the expected results: i.e. protons travelling through the covered collimator have less energy. Code has been written to output the matched event coordinates/energies in a text file, for plotting in MATLAB, which should provide greater functionality to plot 4D histograms.

# 4 Plan for Term 2

- Match LeCroy and Caen spectra with $\chi^2$ fit. Plot energy spectra, and match tracker and calorimeter data for the remaining configurations from first Birmingham trip. Plot 4D histograms in MATLAB (2 weeks).
- Measure the LeCroy scope deadtime between acquisitions (trigger rearm time) (2 days).
- Second trip to Birmingham for 2 days on the 14th of January for follow-up measurements with the proton beam. It is planned to conduct tests with higher beam currents, to investigate how the LeCroy copes. An additional

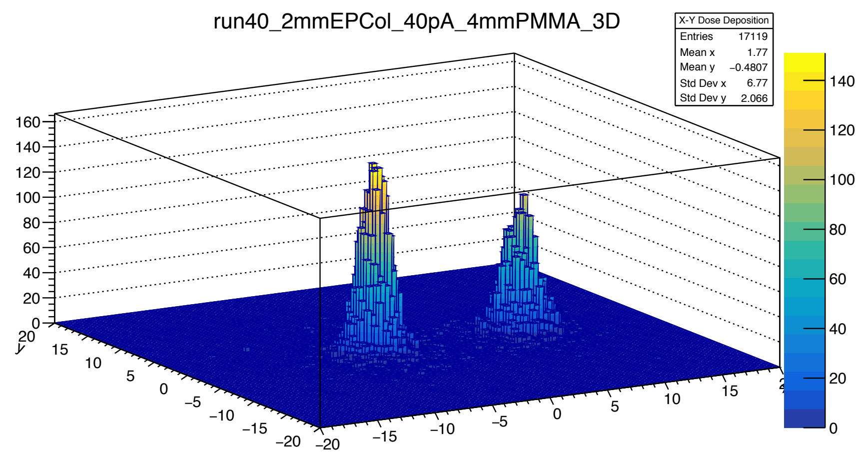


Figure 7: A 3D version of Fig. 5, showing the number of particles recorded in each bin by the tracker with bars. Data placed into 100×100 bins.

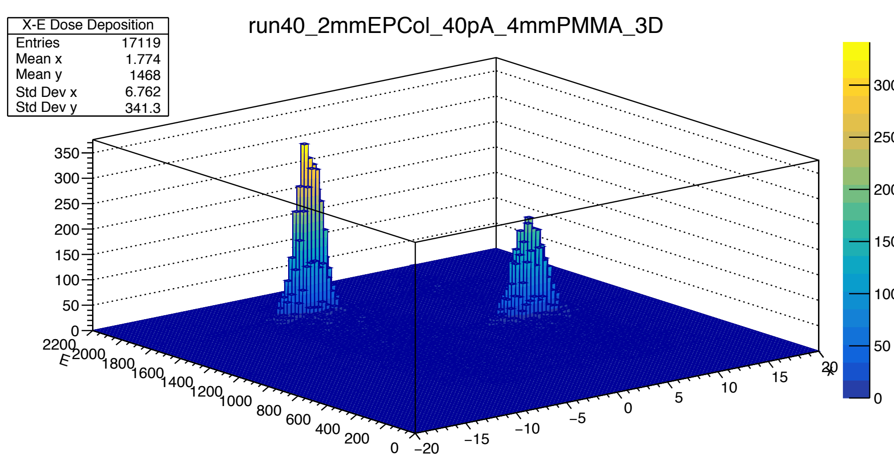


Figure 8: 3D reconstructed dose deposition, showing the dependence of energy on $x$. Recall that the collimator in the negative $x$-direction was uncovered. The energy of particles emerging in the negative $x$-direction is larger than those emerging in the positive $x$-direction. Data placed into 100×100 bins.

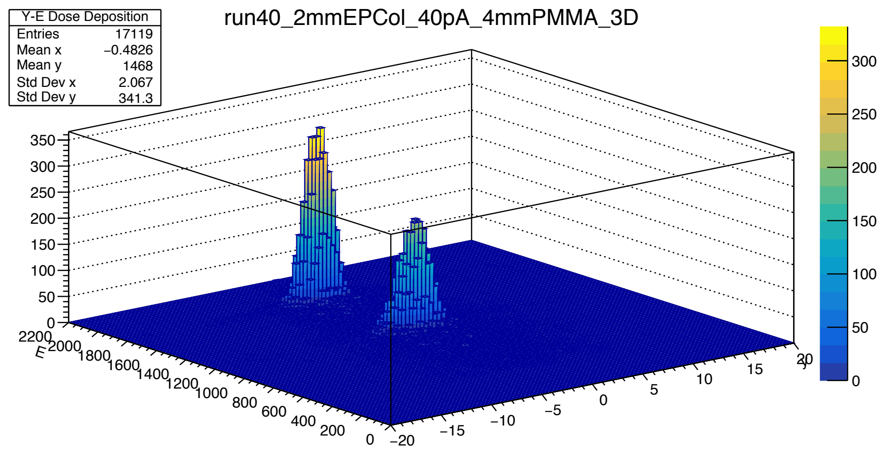


Figure 9: 3D reconstructed dose deposition, showing the dependence of energy on $y$. The collimators do not have different $y$ coordinates, therefore it is expected to see no dependence on $y$. Data placed into 100×100 bins.

scintillator block is to be tested, modified to reduce light output (e.g. by wrapping in black paper instead of foil), should the PMT become saturated under the larger current (3 days incl. prep).

- Analyse data from the second trip (2 weeks).
- Pending acceptance, deliver a short oral presentation on findings at the 5th Proton Physics Research and Implementation Group workshop, which will be held at the National Physics Laboratory from the 7th to the 8th of February (1 week incl. prep).
- Write final report and prepare presentation (4 weeks).