Development of a Range Counter with SiPM readout for Proton CT

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***Abstract*– We report on the development of a range counter to be used in a new head scanner developed for proton Computed Tomography (pCT) in support of proton therapy treatment planning. The scanner consists of two silicon telescopes which track the proton before and after the phantom/patient, and an energy detector which measures the residual energy or range of the proton to reconstruct the Water Equivalent Path Length (WEPL) in the phantom. The optimization of the range counter is based on a simulation using GEANT4 and tests of hardware prototypes both in proton beams, beta source, and cosmic rays in the laboratory. Using 3.75 mm thick polystyrene tiles with a silicon photomultiplier (SiPM) attached directly to the 40 cm long scintillator, excellent efficiency and very low thermo-electric noise were observed in the 200 MeV proton beam.**

I. Introduction

Proton Computed Tomography is intended to provide a 3D map of relative stopping power for planning of the proton radiation treatment. Potentially, the pCT will provide more accurate data on the Water Equivalent Path Length (WEPL) than current technique based on scaling of the X-rays tomography results.

The pCT detector system consists of tracking subsystem and energy detector. The tracking system is designed to provide sub millimeter precision for proton tracks before and after the phantom. Silicon strip sensors, wire chambers and scintillating fibers are options which were tested or which are considered for future prototypes.

II. Energy Detector options

The final goal of the energy detector is to provide the WEPL of the proton in the phantom. Proposed and existing prototypes explored different calorimeter options like crystal calorimeter [1] and multi-stage plastic scintillator calorimeter. The calorimeter is required to provide good energy resolution of about 1% over the large area. This resolution has to be maintained by regular calibrations. The calorimeter also should be calibrated in the terms of the WEPL [2]. An additional requirement is an ability to sustain high input rate, up to 2 MHz. Usage of the conventional vacuum photomultiplier tubes for the readout complicates the problem due to the possible presence of the magnetic fields in the clinical environment.

The range detector provides a direct measurement of proton range. It consists of a stack of the thin scintillating tiles. The tile in which proton was stopped gives the proton range with accuracy of $t/\sqrt{12}$ where t is a thickness of the tile. The tile is required to exceed the threshold set well enough above the noise level. The range detector provides essentially provides a digital readout of the proton WEPL. Silicon photomultipliers are well suited as photodetectors for the range counter. Some of their advantages are low bias voltage and insensitivity to magnetic fields. On the negative side the SiPMs are relatively expensive; the temperature dependence also needs additional studies.

A GEANT4 study of interaction of therapeutic proton beams of 200 MeV in both a phantom and a stack of polystyrene plates has been performed to understand the effect of plate thickness on range counter resolution. Cost and complexity argue for as large a thickness as possible. Assuming 100% efficiency in the plates, (which might not be achievable for large thin plates) we determined the range resolution as a function of the thickness of a polystyrene degrader, representing the effect of the phantom/patient. As shown in Fig. 1, a nearly constant range resolution of close to 4 mm is achieved for plate thicknesses varying between 1 mm to 4 mm. The reason for this effect is that for a fixed beam energy, the range straggling in degrader and range counter add up and determine the resolution, until the intrinsic resolution due to the plate thickness/$\sqrt{12}$ takes over for large thicknesses (which is about 2 mm for 6 mm thick plates).

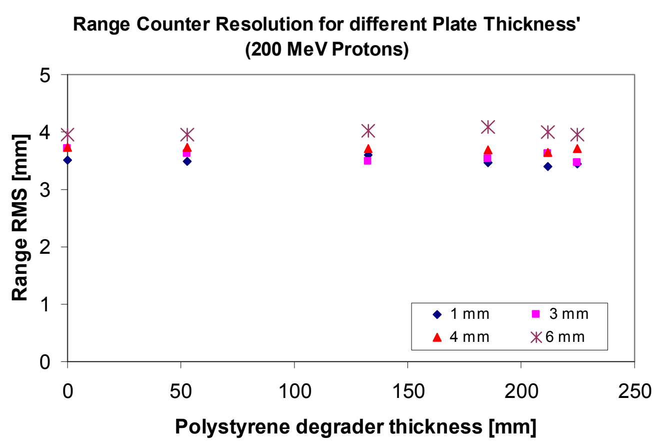

Fig. 1. GEANT4 prediction of the resolution of the range counter for various plate thicknesses.

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III. EXPERIMENTAL MEASUREMENTS

In this work we studied a direct readout of a large area scintillating tile with the photodetector coupled in the corner of the tile. The tile has dimensions 40x15 cm with thickness of 3.75 mm. Optical grease was used to improve the optical contact. The edges were polished and the tail was wrapped in Tyvek. We chose Hamamatsu silicon photomultiplier MPPC S10362-33-050C with size 3x3 mm for the photodetector. It matches well to the tile thickness, and its spectral sensitivity corresponds to the scintillator peak emission at about 420 nm.

We applied the bias voltage of 72.0 V, which is 2 V above the breakdown voltage. We estimated the single electron dark current rate at this voltage to be about 5 MHz. A threshold of 20 mV will keep the dark current rate under the 50 MHz.

A. Light yield uniformity

Fig. 2 shows an example of the pulse height distribution measured at the 200 MeV proton beam. The distance from the beam spot to the photodetector was 30 cm. The red arrow shows the threshold value. This value allows maintaining the 100% registration efficiency for the protons. Slowing down of the proton because of energy losses in the phantom or in the range counter material additionally improves the signal-to-threshold ratio.

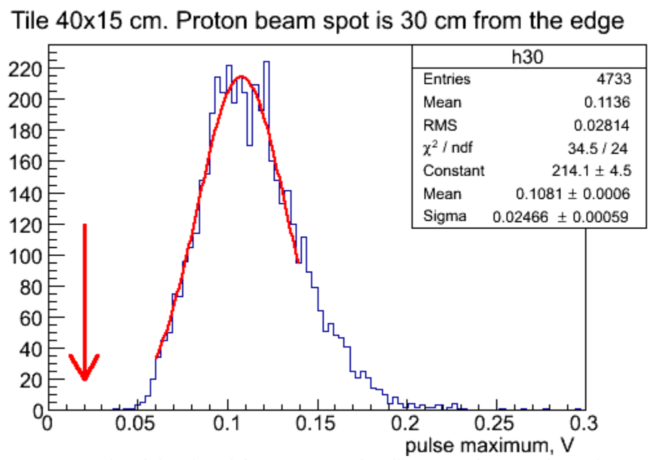

Fig. 2. Example of the signal from protons for distance of 30 cm from the photodetector. The red arrow shows the threshold value to keep the dark current rate below 50 kHz.

Fig.3 shows the light yield uniformity measured with ^{90}Sr radioactive β-source and with the proton beam of the Loma Linda University Medical Center. The pulse height ratio for protons and β-source agrees with the ratio of the stopping powers for these particles, a factor of about 3. We estimated the proton signal at the plateau of about 24 photoelectrons. The response of the tile is flat for the distances between the beam spot the photodetector are large than 15 cm. The response near the photodetector is 60% higher than at the plateau. This excess does not create additional problems with the readout.

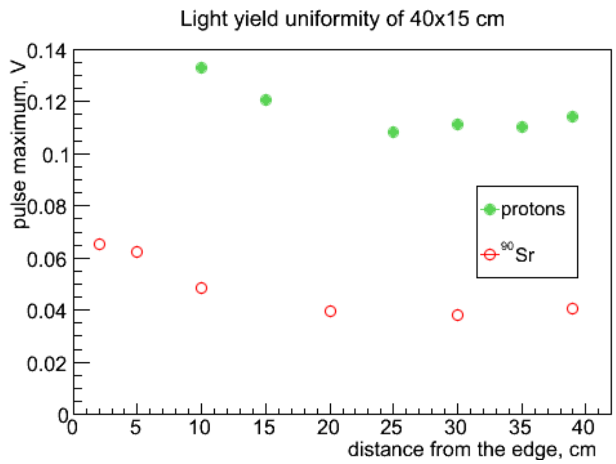

Fig. 3. Light yield uniformity measured with the β-source ^{90}Sr (open circles) and the proton beam (closed circles).

B. WEPL resolution

We measured WEPL resolution using the proton beam at the Loma Linda University Medical Center. The proton energy was 200 MeV. The experimental setup (Fig. 4) consisted of variable thickness polystyrene degrader calibrated in mm of WEPL, 100 mm thick trigger counter ("BULKY"), detector under test ("DUT"), 4 mm thick scintillator detector with SiPM readout ("REF"), and 4 mm scintillator detector with conventional photomultiplier readout ("PMT"). The detectors were read out with DRS4 digital oscilloscope board [3].

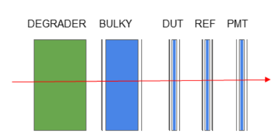

Fig. 4. Experimental setup for the WEPL resolution measurements.

We varied the degrader thickness from 137.37 mm to 162.88 mm to move the position of the Bragg peak through the detectors. For each degrader thickness we selected events in which given detector was last. For each event we identified "the last" detector: the detector which absorbed the proton. A detector was considered the last when the signal from the downstream detector fell below the established threshold. An example of the distribution for the degrader thickness 149.66 mm is presented in the Fig. 5. Each bin shows the number of events when a proton stopped in the given detector. We fit the distributions of the last detectors for each degrader thickness.

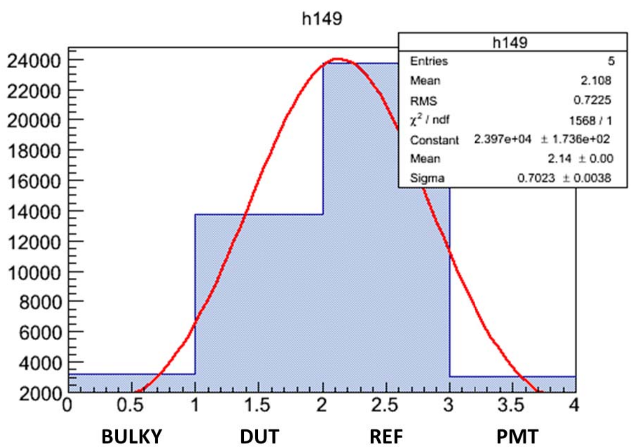

Fig. 5. Example of the fit to the distribution of the last counter events for the degrader thickness 149.66 mm.

The experimental WEPL resolution of the detector under test, 40x15 cm tile is presented in the Fig. 6. The resolution 3.0 ± 0.1 mm WEPL does not depend on the threshold value in the wide range from 5 mV to 20 mV (with an attenuator of 20 dB which we used for the WEPL resolution measurements). The GEANT4 simulation of the beam test setup gives a similar value of 2.9 mm WEPL resolution.

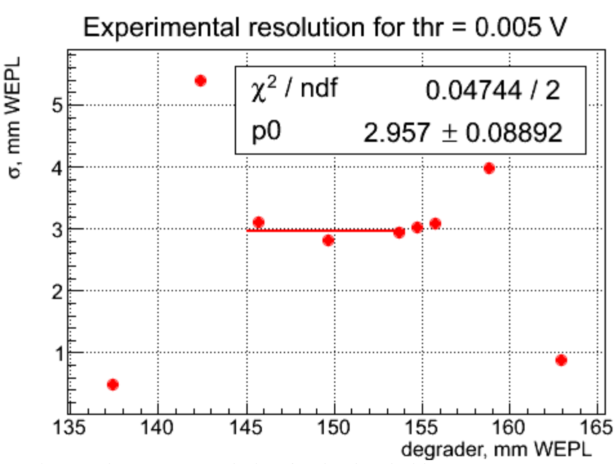

Fig. 6. The WEPL resolution for the threshold 5 mV.

IV. Summary

The direct SiPM readout for the scintillating tile of large size of 40x15 cm and thickness of 3.75 mm is a good option for the range detector. The readout provides uniform response for 200 MeV protons with excellent efficiency and noise performance. The achieved resolution of 3.0 ± 0.1 mm is limited mostly by proton range straggling.

Appendix

We evaluated the new Hamamatsu silicon photomultipliers MPPC S10931-100P with higher fill factor, 78.5%. We studied the noise rate (Fig. 7) and response from the radioactive source ^{90}Sr. The signal-to-threshold ratio for is presented in the Fig. 8. This ratio will be scaled to about 15 for the 200 MeV protons. This is a factor 3 higher than in the reported beam test.

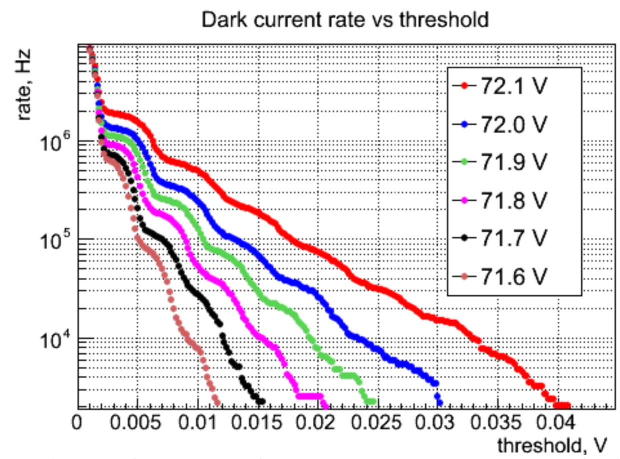

Fig. 7. Dark current rate for Hamamatsu MPPC S10931-100P for different bias voltages.

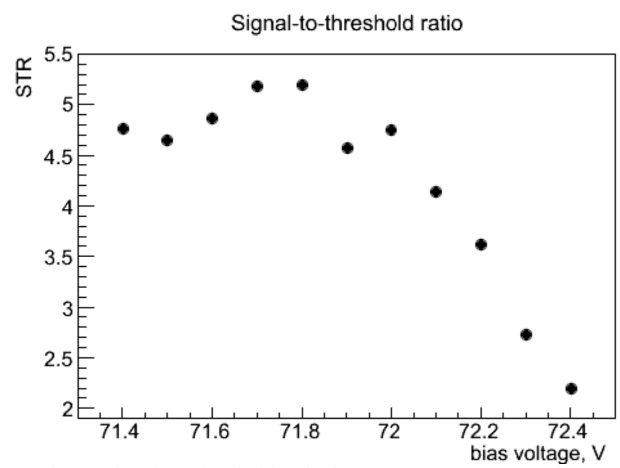

Fig. 8. Signal-to-Threshold ratio for Hamamatsu MPPC S10931-100P for the β-source ^{90}Sr data.

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