PRaVDA

PRaVDA Consortium

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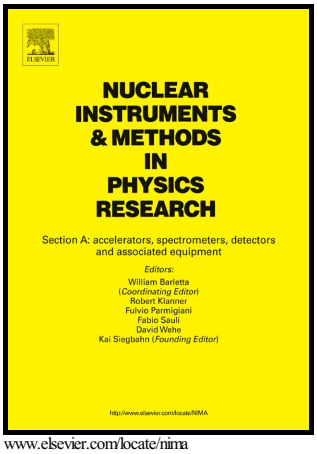

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PRaVDA: High Energy Physics towards proton Computed Tomography

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Abstract

Proton radiotherapy is an increasingly popular modality for treating cancers of the head and neck, and in paediatrics. To maximise the potential of proton radiotherapy it is essential to know the distribution, and more importantly the proton stopping powers, of the body tissues between the proton beam and the tumour. A stopping power map could be measured directly, and uncertainties in the treatment vastly reduce, if the patient was imaged with protons instead of conventional x-rays. Here we outline the application of technologies developed for High Energy Physics to provide clinical-quality proton Computed Tomography, in so reducing range uncertainties and enhancing the treatment of cancer.

Keywords: Tracking detectors, Proton radiotherapy, CMOS, High Energy Physics, Proton Computed Tomography, Applications
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1. Introduction

Proton radiotherapy uses beams of protons, typically with energies between 70 and 230 MeV, to treat cancer. Compared to conventional x-ray radiotherapy, proton radiotherapy can deliver a larger dose to the tumour region with a reduced dose to the healthy surrounding tissue due to the Bragg Peak (BP). To ensure that the protons stop within the target volume it is essential to know the proton stopping powers of the body tissues traversed by the beam on the way to the tumour. Conventionally, this information is acquired using an x-ray Computed Tomography (CT) scan. Conversions to proton stopping power from Hounsfield Unit can lead to a typical uncertainty on the proton range of 3.5 % [1] and could lead to sub-optimal patient treatment. Performing a CT scan using protons, a proton CT (pCT), would allow the stopping power to be measured directly and the range uncertainties greatly reduced.

The PRaVDA Consortium, funded by the Wellcome Trust, are developing a proof of principle pCT instrument. In order to reconstruct a pCT the input and output trajectories of every single proton must be measured alongside the residual energy of the proton once it has interacted with the patient. We envisage that $3.5{\times}10^9$ reconstructed protons and a delivered dose of 2 cGy per image will allow uncertainties on the stopping power of ±1 %. High speed readout electronics are required in order to keep data acquisition times at clinically feasible scales. Full details of the required specifications for pCT are given here [2]. PRaVDA aim to fully reconstruct more than 1M protons/s by using technologies developed for High Energy Physics (HEP). This would yield a total scan time of 60 minutes. The remainder of these proceedings will outline: the strip sensors used for proton tracking (Section 2); the CMOS sensors used to measure the residual energy (Section 3), and the Geant4 model developed to optimise the PRaVDA instrument (Section 4). Finally the future scope of the project will be discussed (Section 5).

2. Strip Tracking Sensors

The PRaVDA tracking system uses silicon strip detectors developed by the HEP group at the University of Liverpool and fabricated with high yield by Micron Semiconductor Ltd. The tracking system consists of four modules, two before the patient and two afterwards. Within each module, three sensors are rotated at 60° relative to each other to allow the reconstruction of proton tracks in an x-u-v co-ordinate system. This configuration vastly reduces ambiguities at higher beam fluences. The strip detectors are 150 μm thick n-in-p silicon with a strip pitch of 90.8 μm. The sensor is split in half, with a strip length of 48 mm to enable a maximum readout rate of 104 MHz. A total active area of 93×96 mm^2 is achieved using 2048 strips, read out by 16 ASICs (8 for each strip half). A double threshold readout further assists in the untangling of ambiguities caused by multiple protons being collected in the same strip. Further information can be found here [3]

A single layer of strips were tested using the University of Birmingham MC40 cyclotron with 36 MeV protons. The measured 1D profile for a 40mm diameter beam (Figure 1) is in good agreement with the delivered beam.

3. CMOS Range Telescope

Pixelated sensors allow multiple protons to be tracked simultaneously and can offer a reduced image acquisition time compared to scintillators. The CMOS Range Telescope (RT) is a stack of large scale CMOS Active Pixel Sensors (APS).

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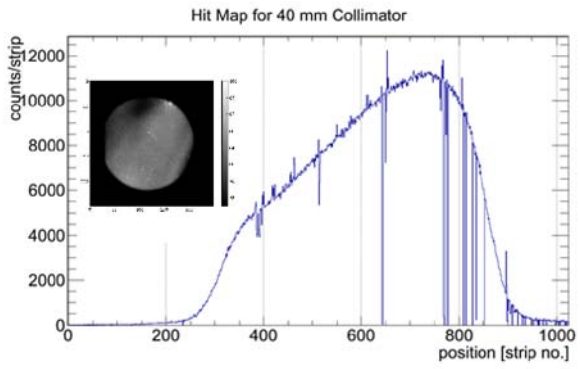

Figure 1: Channel by channel count of the number of detected proton signals per strip. Inset is a scanned GaFChromic film normalised to maximal dose used to measure the beam profile.

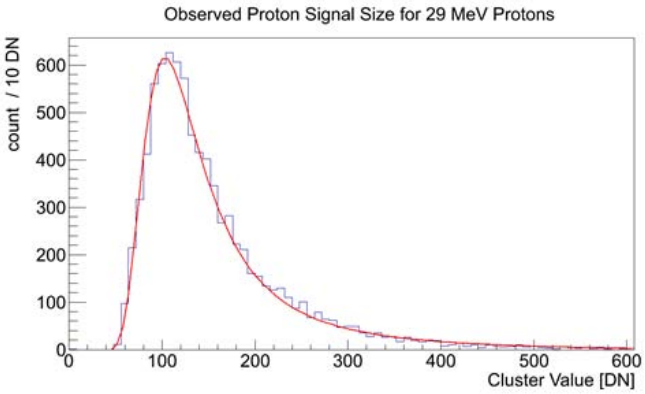

Figure 2: The reconstructed signal size (Cluster Value) for all 29 MeV protons which caused more than one pixel to fire.

Full CMOS capability is achieved due to the use of deep-well technology as developed for HEP devices such as those proposed for digital calorimetry at the ILC [4] or the ALICE ITS upgrade [5]. The proton's position is measured in each layer whilst a finite amount of its energy is also lost. The final layer in which a proton is detected before it stops will yield the residual range (and therefore the energy) of the proton. The CMOS layers can be interleaved with Perspex sheets to increase the total range of the RT. PRaVDA have demonstrated the ability of using CMOS to track protons between layers [6][7], and measure an increasing proton signal as the proton energy falls [8].

The CMOS APS developed by PRaVDA is known as *Priapus*. Priapus has an active area of 50×100 mm^2 with a pixel pitch of 194×194 μm^2. The wafer is 750 μm thick with a sensitive epitaxial layer of 18 μm. Each pixel contains five diodes to maximise the charge collection efficiency. A full frame readout rate of 1000 frames/s is possible and the RT will unambiguously track more than 1000 protons per frame. Pripaus is three side buttable yielding the potential of a single RT layer to have a total sensitive area of 10×20 cm^2.

The pixel values are represented in arbitrary units of Digital Number (DN). The first beam test with a single second generation Priapus sensor in May 2015 demonstrated a sensor gain of 45 e$^-$/DN and a noise floor of 4 DN (180 e$^-$). Figure 2 shows the detected signal size for 29 MeV protons when the cluster size is greater than one pixel. A SNR of 25 has been observed.

4. Geant4 Model

A Monte Carlo simulation (SuSi) has been developed using Geant4.10 with readout implemented using ROOT. It contains realistic beam line models for the two proton sources where the device will be tested (iThemba LABS, SA and University of Birmingham, UK), full device geometry, and realistic read out for both the strip and CMOS sensors. Each component of the simulation has been verified against data. The simulation allows our device parameters to be optimised to achieve the best possible pCT with our technology and the testing of our novel reconstruction algorithm [9].

5. Outlook

We have demonstrated the ability to detect protons in a single layer of both our new strip sensors and CMOS devices. Following on from this work the strip detector modules are being assembled and tested using both radioactive sources and the University of Birmingham cyclotron to illustrate the ability to fully reconstruct beam profiles in x-u-v space. Multiple strip modules will then form proton tracks which will be projected into the Priapus sensors. By the end of 2015 we aim to have a fully instrumented device which will allow us to acquire a pCT of an animal phantom on a clinical timescale using technology adapted from the HEP community. Finally, (we hope) the knowledge accumulated through this project will lead to a commercialised device which will be routinely used in a clinical environment, reducing the uncertainties on proton radiotherapy treatments and aiding the treatment of cancer.

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