

## PRaVDA

PRaVDA Consortium

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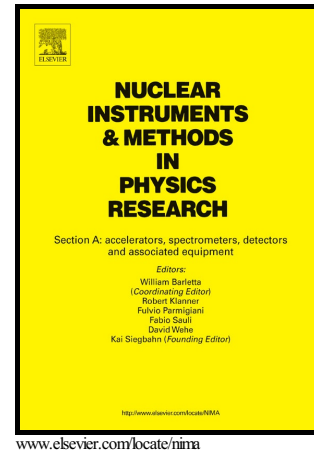
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# Author's Accepted Manuscript

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Computed Tomography

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## PRaVDA: High Energy Physics towards proton Computed Tomography

T. Price<sup>a,b,\*</sup><sup>a</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK*<sup>b</sup>*On behalf of the PRaVDA Consortium***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  
*PACS:* 11.30.Rd, 87.55.Gh, 87.57.Q-, 87.55.-x

**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  $\pm 1$  %. 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  $60^\circ$  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  $150 \mu\text{m}$  thick n-in-p silicon with a strip pitch of  $90.8 \mu\text{m}$ . 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  $93 \times 96 \text{ mm}^2$  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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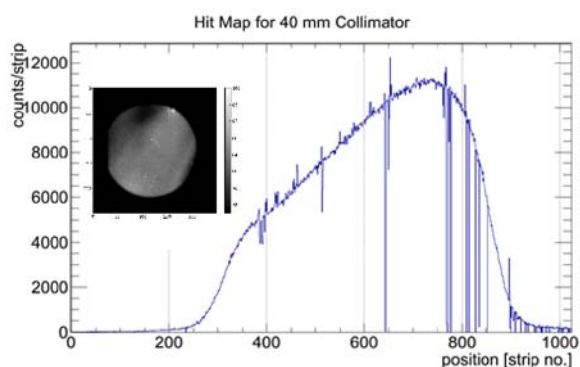


Figure 1: Channel by channel count of the number of detected proton signals per strip. Inset is a scanned GaFChromic film normalised to maximal dose used to measure the beam profile.

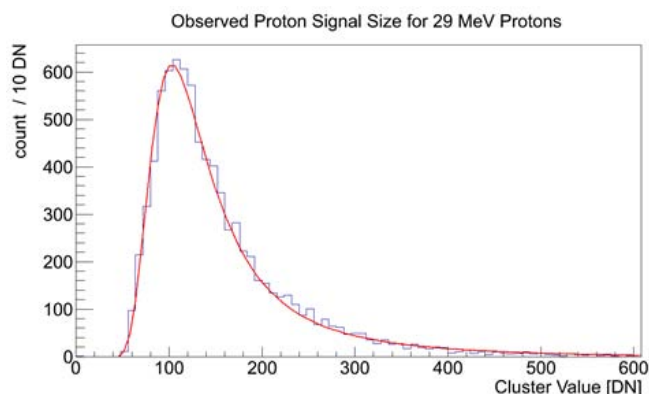


Figure 2: The reconstructed signal size (Cluster Value) for all 29 MeV protons which caused more than one pixel to fire.

61 Full CMOS capability is achieved due to the use of deep-well 98  
 62 technology as developed for HEP devices such as those proposed 99  
 63 for digital calorimetry at the ILC [4] or the ALICE ITS 100  
 64 upgrade [5]. The proton's position is measured in each layer 101  
 65 whilst a finite amount of its energy is also lost. The final layer 102  
 66 in which a proton is detected before it stops will yield the residual 103  
 67 range (and therefore the energy) of the proton. The CMOS 104  
 68 layers can be interleaved with Perspex sheets to increase the total 105  
 69 range of the RT. PRaVDA have demonstrated the ability of 106  
 70 using CMOS to track protons between layers [6][7], and measure 107  
 71 an increasing proton signal as the proton energy falls [8]. 108

72 The CMOS APS developed by PRaVDA is known as *Priapus* 109  
 73 *priapus*. Priapus has an active area of  $50 \times 100 \text{ mm}^2$  with a pixel 110  
 74 pitch of  $194 \times 194 \mu\text{m}^2$ . The wafer is  $750 \mu\text{m}$  thick with a sensitive 111  
 75 epitaxial layer of  $18 \mu\text{m}$ . Each pixel contains five diodes to 112  
 76 maximise the charge collection efficiency. A full frame readout 113  
 77 rate of 1000 frames/s is possible and the RT will unambiguously 114  
 78 track more than 1000 protons per frame. Priapus is three 115  
 79 side butttable yielding the potential of a single RT layer to have 116  
 80 a total sensitive area of  $10 \times 20 \text{ cm}^2$ . 117

81 The pixel values are represented in arbitrary units of Digital 118  
 82 Number (DN). The first beam test with a single second generation 119  
 83 Priapus sensor in May 2015 demonstrated a sensor gain of 120  
 84  $45 \text{ e}^-/\text{DN}$  and a noise floor of 4 DN ( $180 \text{ e}^-$ ). Figure 2 shows 121  
 85 the detected signal size for 29 MeV protons when the cluster 122  
 86 size is greater than one pixel. A SNR of 25 has been observed. 123

#### 87 4. Geant4 Model

88 A Monte Carlo simulation (SuSi) has been developed using 123  
 89 Geant4.10 with readout implemented using ROOT. It contains 124  
 90 realistic beam line models for the two proton sources where 125  
 91 the device will be tested (iThemba LABS, SA and University 126  
 92 of Birmingham, UK), full device geometry, and realistic read 127  
 93 out for both the strip and CMOS sensors. Each component of 128  
 94 the simulation has been verified against data. The simulation 129  
 95 allows our device parameters to be optimised to achieve the best 130  
 96 possible pCT with our technology and the testing of our novel 131  
 97 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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