# SuSi : A Monte Carlo model of a novel proton CT Scanner using Geant4

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## Abstract

Proton radiotherapy uses beams of high energy protons to treat cancer. It is specifically used for cancers in children and near delicate structures due to the ability of delivering a highly focused dose to the cancer volume. The PRaVDA consortium are building an imaging device to image the patients with protons and form a proton Computed Tomography (pCT) image which will reduce the uncertainties on the treatment and further enhance patient care. Here we present the results of a Monte Carlo simulation of a novel proton Computerized Tomography instrument. We will give a brief overview of our pCT system whilst primarily focusing on our Monte Carlo modelling efforts using Geant4 to develop a full scale detector model to replicate our final design, the PRaVDASuperSimulation (SuSi). We will outline the results from modelling the sensors' response and present a reconstructed proton CT image. We will also stress the importance of having a cluster such as BlueBEAR to perform these studies by illustrating the real time benefits of running the simulation compared to a single core machine.

## Introduction

Proton radiotherapy, first proposed by Robert Wilson in 1946 (1), uses external beams of high energy protons to treat cancer. Whilst the first patients were treated at Berkeley Radiation Laboratory (California, US) in 1954 (2), it was not until 1989 at the Clatterbridge Centre for Oncology (Wirral, UK) when patients were treated in a hospital environment (3). Following the initial slow uptake, the number of proton therapy centres has increased rapidly over recent years (4) with many more sites currently in the planning stages, including two centres in the UK.

The energy deposition profile of a high energy proton has a characteristic shape known as the Bragg Peak. Initially, the proton will deposit just a small fraction of its energy per unit length, known as the proton stopping power in units of MeV/cm. As the proton loses energy, the amount of energy it deposits per unit length increases. This increase is slow at first but becomes much more rapid just before the proton loses all of its energy. This leads to a large proportion of the protons energy being deposited in a very small region at a particular depth in a material. The range a proton travels in a material is dependent on two things, the initial energy of the proton and the material it is travelling through. If we know the location of a tumour within a patient and the body tissues the protons need to travel through before the tumour, it is possible to deposit a huge amount of energy in a tumour whilst sparing healthy tissues surrounding it.

To ensure that the proton stops in the tumour and not healthy tissue a patient is imaged to determine the compositions and locations of the surrounding body tissues. Conventionally, this is achieved using Computerized Tomography (CT) which uses beams of x-rays to measure the electron density of the body tissues. The underlying physical processes which govern the interactions of x-rays and protons are very different and the conversions from electron density to proton stopping powers are non-trivial. The generally accepted uncertainty on the range of the protons is 3.5 % (5) with up to 2 % arising from the conversion alone (6). If a patient could be imaged directly using protons we would be able to measure the proton stopping powers of all the body tissues directly and reduce this uncertainty dramatically. The Proton Radiotherapy Verification and Dosimetry Applications (PRaVDA) consortium are designing, building, and testing the world's first all solid state proton CT (pCT) device. Here we present the Monte Carlo model that has been developed to assist in the design of the device and predict the quality of the final images.

## The PRaVDA Device

During a pCT, the position, direction and energy of every single proton must be measured before and after the patient to maximise the resolution of the final image. This will be achieved by pairing technologies developed at the Large Hadron Collider with large CMOS sensors. An illustration of the PRaVDA device, showing the strip trackers and CMOS sensors is given in Figure 9.

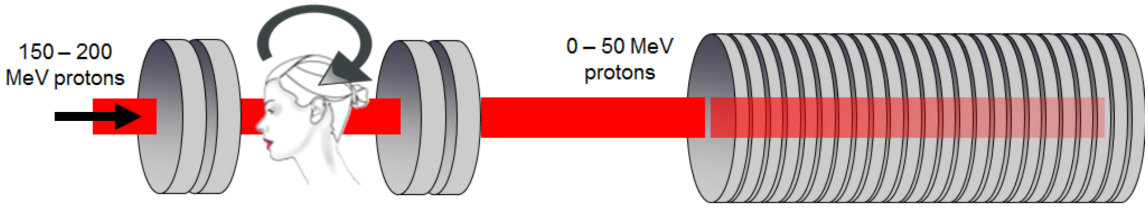

Figure 9 - Illustration of the PRaVDA device showing the strip tracking sensors around the patient (left) and the CMOS range telescope (right). The red line represents a beam of protons.

## Silicon Tracking Sensors

The positions of the protons are tracked into the patient with two banks of strips sensors. Each bank of sensors contains three strip sensors orientated at 60 degrees to each other. A strip will fire in each sensor and the location where the three strips overlap provides a hit position of the proton. The hit positions in the sensors are projected onto the patient surface to provide an input position. There are two identical banks of sensors downstream of the patient which will allow the exit location of the proton from the patient to be reconstructed using the same methodology. The incident and exit positions are used to estimate the path of the proton through the patient.

## CMOS Range Telescope

The CMOS Range Telescope is constructed of 24 layers of CMOS sensors interlaced with 1 mm of Perspex. The CMOS has a pixel pitch of 200 microns and each layer has an area of 14x10 $cm^2$. The proton track from the tracking sensors will project onto the front face of the Range Telescope and hits within the first layer will be paired up with each track. A dedicated tracking algorithm will then use the position and signal size measurements obtained from the CMOS to track each proton until it comes to a stop. The range of the proton within the Range Telescope will be converted into a water equivalent path length and the energy lost by the proton through the patient can be calculated.

Phantom Design

Until this point, the object being imaged has been referred to as the patient. Whilst this will be the case in a final pCT, during the initial proof of principle stage the patient will be a Perspex phantom. The Perspex phantom will be a spherical object which will have inserts of materials with the same compositions as human tissue to allow the performance of the device to be quantified.

## Novel Reconstruction Algorithm

In conventional CT reconstruction the image is reconstructed using a filtered back projection algorithm. This involves taking an image of the patient at multiple angles, transforming the image into fourier space, filtering out certain spatial frequencies and then projecting the resulting image back along the path the x-rays took through the patient. This is then repeated at multiple angles and an image is formed. Filtered back projection is not suited for pCT as protons do not travel in straight lines through the patient like x-rays would and this reduces the image resolution. The PRaVDA consortium have written a new algorithm, better suited for pCT known as backprojection-then-filtering as outlined here (7). SuSi allows the performance of this new algorithm to be tested.

## SuSi: An Overview

Marrying together different detector types, tracking high energy protons through 36 layers of sensors and a patient, and reconstructing an image using a novel reconstruction algorithm requires the optimisation of a huge number of properties. These include but are not limited to; the spacing between each tracking module; the size of the patient region; thresholds in the sensors; phantom design; detector sizes; readout rate required to track individual protons; the location of sensitive electronics and shielding to prevent radiation damage, and the amount of Perspex in the Range Telescope to contain the protons but not affect the image quality.

A detailed Monte Carlo simulation, namely the PRaVDASuperSimulation or SuSi for short, has been developed to fully optimise the PRaVDA device due to its immense complexity. This uses the Geometry and Tracking (Geant4) (8) software package developed, tested and validated for use in High Energy Physics. The simulation currently has 46 classes written in C++ to allow each component of the PRaVDA device to be modelled, parameters changed and optimised, and the interplay between changing different parts of the system on other aspects to be investigated.

Initial tests of the final device will be conducted using the University of Birmingham Cyclotron. This cyclotron has a maximum energy of 40 MeV and beam size of 5 cm. The final tests will be conducted at the iThemba LABS, a medical facility in SA which has a beam energy of 191 MeV used to treat patients. The infrastructure at these two facilities are very different and the protons which interact with the device have different energies, beam divergences and associated secondary particles. SuSi allows the PRaVDA device to be simulated at both of these locations, ensuring that the correct incident particle profiles are modelled.

When a particle interacts with the silicon, it will deposit some energy via ionisation. This liberates electrons from the silicon which diffuses through the sensors and is collected by the readout electronics. SuSi takes into account the differences in the charge spreading in the tracking sensors and the CMOS sensors and contains algorithms for realistic charge spreading which yields correct signal sizes and cluster sizes as collected with test sensors. The output from the simulations has been used to develop the tracking code for both the strip trackers and the range telescope and the impact on track resolution has been studied for various sensor positions.

The resulting data from the simulation allows the testing and tuning of the reconstruction algorithm. SuSi has the potential investigate the main factors which affect the reconstructed image quality by turning on and off properties such as multiple scattering, beam energy spreads, the effect of non-perfect detectors, noise in the detectors and uncertainties in the construction of the body tissues.

## Results

### Beam Line Models

The profiles of the protons have been extensively tested at both the Birmingham and iThemba locations and the simulations tuned to match the data with excellent precision. At iThemba, the range of the protons can be degraded by reducing the energy of the incident protons. This is achieved by inserting graphite wedges upstream of the final treatment nozzle. Figure 10 illustrates the excellent agreement between data and SuSi output for four proton beams where the energy has been degraded by differing amounts. Similar plots have been observed for the model describing the Birmingham cyclotron alongside excellent agreements in lateral beam profiles at both locations.

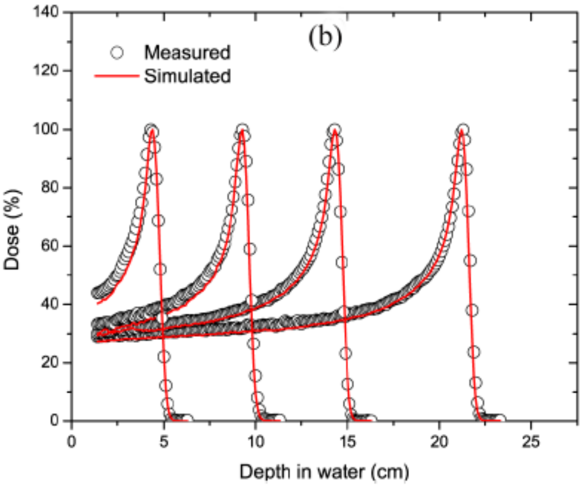

Figure 10 - Reconstructed Bragg peaks for various beam energies at iThemba showing the comparison between data and simulation.

### Strip Trackers

The signal size in the strip trackers using the full energy, 191 MeV iThemba proton beam can be seen in **Error! Reference source not found.**. The signal size is the sum of the charge collected across neighbouring strips. Also shown in **Error! Reference source not found.** is the resulting signal size obtained from SuSi using the full energy iThemba model. The difference between data and simulation is less than 10%. The 191 MeV beam will deposit the smallest signal in any of our sensors and the lower energy protons demonstrate an improved agreement. The charge spread algorithm is being refined and preliminary results yield a further improved agreement at 191 MeV.

### CMOS Range Telescope

Data taken with a 36 MeV proton beam at the University of Birmingham incident upon a single CMOS sensor close in design to the final PRaVDA CMOS sensor is compared against the output from SuSi in Figure 12. A very low current of protons were incident upon the sensor, enabling the measurement of the energy deposited by individual protons with high precision. Using realistic charge spreading algorithms, threshold functions, gain and noise parameters the output from SuSi is in excellent agreement with the data. This demonstrates the ability of SuSi to predict the behaviour of both the proton and the sensor response to the proton. This allows for a model of the full CMOS Range Telescope to be developed and optimised with high certainty and belief in the results.

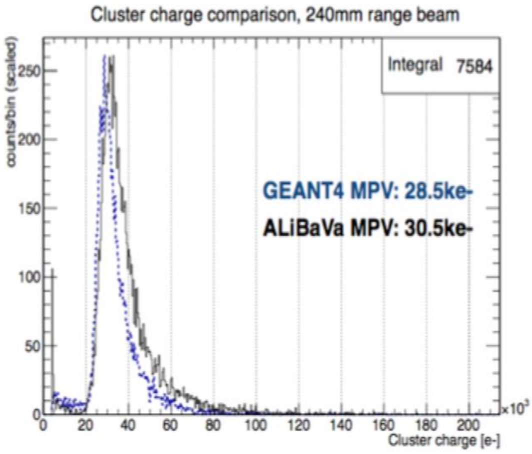

Figure 12 - Signal size in the strip tracking sensor compared to SuSi output for the 191 MeV iThemba proton beam

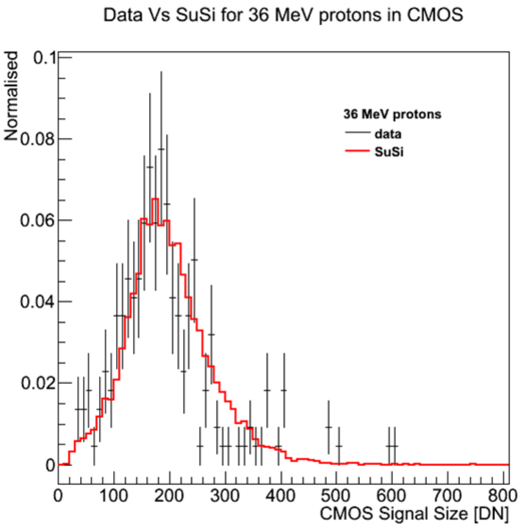

Figure 12 - Signal size in one CMOS range telescope sensor for 36 MeV protons from the University of Birmingham compared with simulation

## Reconstruction

The slice of a fully reconstructed pCT slice of our phantom using data from SuSi is presented in Figure 13. Whilst SuSi has presented the ability to accurately model the sensor responses the reconstruction uses perfect truth information with no resolution or inaccuracies on the proton positions. This was done to present an initial verification of the reconstruction algorithm and allows the effect of the introduction of the sensors onto the image resolution to be isolated and evaluated. Both SuSi and the reconstruction algorithm are still being developed this will be assessed in future work.

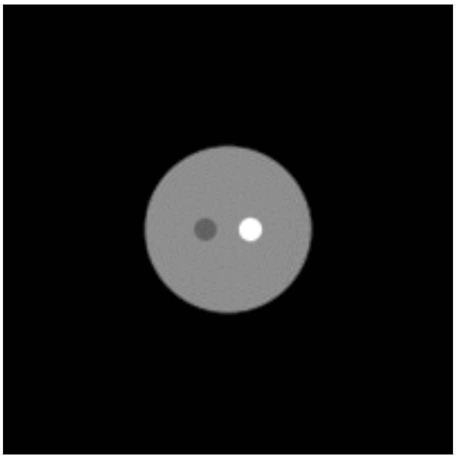

Figure 13 - Reconstructed slice of phantom using back projection filtering showing two inserts using perfect detector information from SuSi

## Run Time Statistics

It is believed that a full pCT image will require 3x$10^8$ fully reconstructed protons. Here we present the run time statistics of a pCT simulation from SuSi which yielded 10% of the required reconstructed protons.

A pCT image will require data to be taken with the patient rotated through 180 degrees in steps of 1 degree. At each of these angles 2x$10^6$ protons were generated and fully reconstructed using on average 11h34m CPU time and producing 5GB of data each. For this dataset, each angle of the simulation used a single node yielding a total of 2100 CPU hours and 900 GB of data. Using BlueBEAR these simulations were completed in just 3 days, a decrease in real time on a single CPU of 3000%.

## Discussion and Future Plans

We have presented here a fully functioning model of the PRaVDA pCT instrument and the ability to test it using two realistic sources of radiation including all secondary particles and validated initial conditions. The simulation contains realistic sensor characteristics which yield an output in excellent agreement with measured signals. This information has been used to optimise the device and test a novel reconstruction algorithm.

Whilst SuSi has demonstrated excellent results thus far it is still under development. Improvements to the charge sharing algorithms, additional components, and enhanced noise behaviour in the sensors are all planned. Alongside these changes the algorithms will be optimised for speed and the output data filtered to reduce CPU time and storage space in preparation of a full simulated dataset.

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