Monte Carlo Studies on Proton Computed Tomography using a Silicon Strip Detector Telescope

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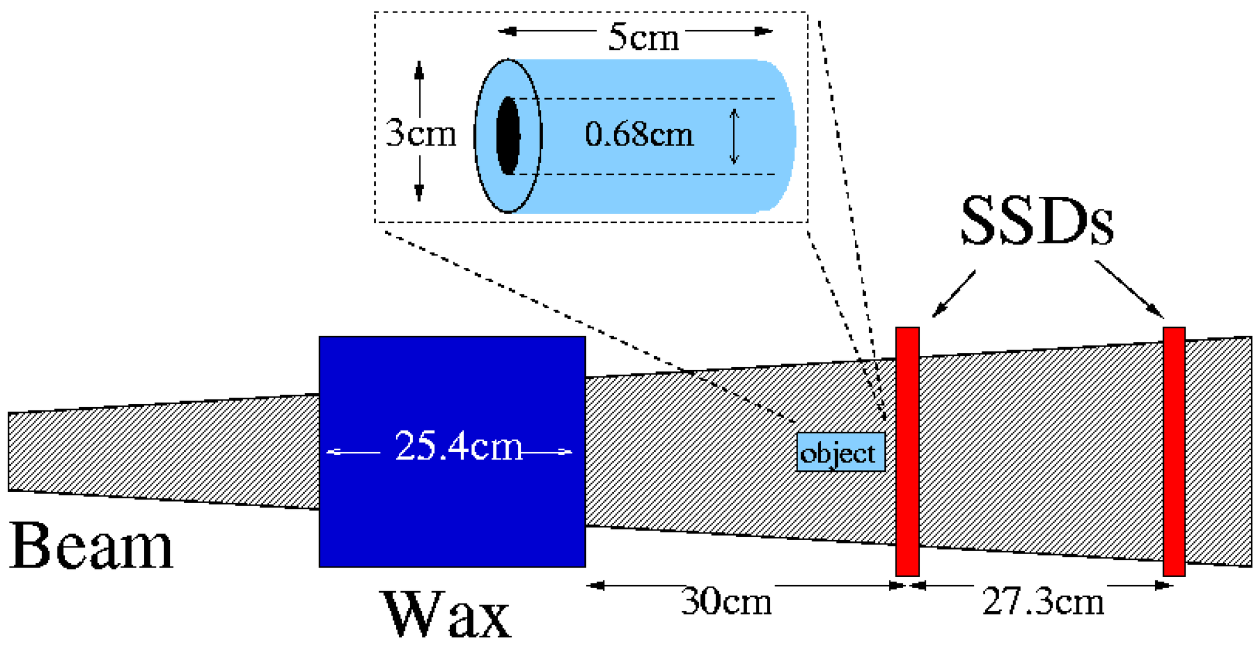
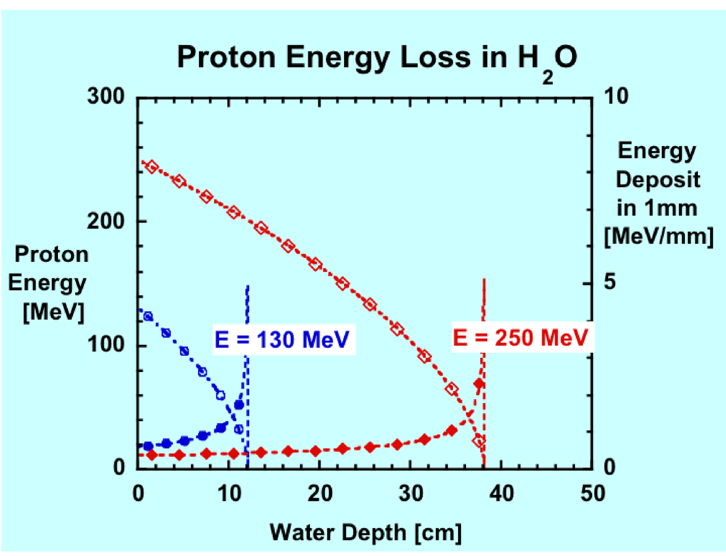
Introduction

Computed tomography (CT) has become an important tool in medical imaging. However, traditional CT scans using X-rays as probes have a disadvantage of a relatively high radiation dosage. A possible alternative is **proton computed tomography (pCT)**, an imaging technique that substitutes protons for X-rays. Imaging with protons could have the advantage of providing similar quality reconstruction with much less dose. First, it is important to understand the proton transmission images seen in the lab. An accurate analysis of laboratory data requires the use of detailed computer simulations. GEANT4 is a good tool for this purpose.

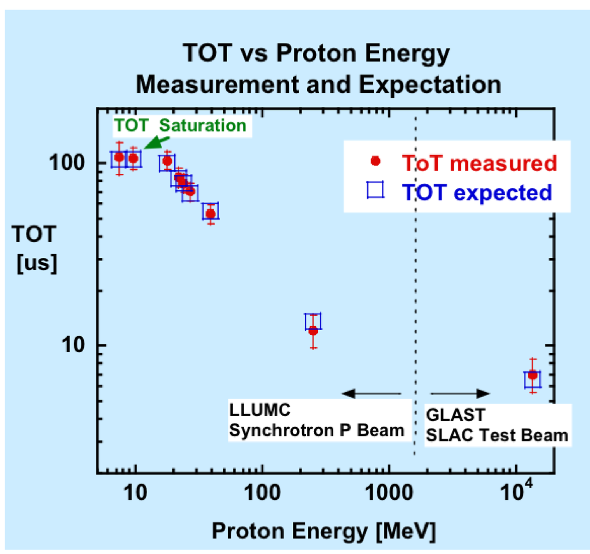
Experimental Setup



Shown Above is the set-up for our initial experiments, performed using the medical proton synchrotron at Loma Linda University Medical Center. A monochromatic beam of 250 MeV protons is degraded by a wax block. The protons then pass through a long aluminum tube resting on a polystyrene holder and placed 25 cm behind the wax block. The protons are then detected by two sets of silicon strip detectors (SSD), one placed directly behind the tube, and the second further back. Each SSD consists of a pair of single-sided silicon strip detectors. These detectors measure the trajectory of the protons (incident x and y position and direction) as well as their energy. The first is determined from strip-hit information, and the latter by measuring the charge deposited in the detector.



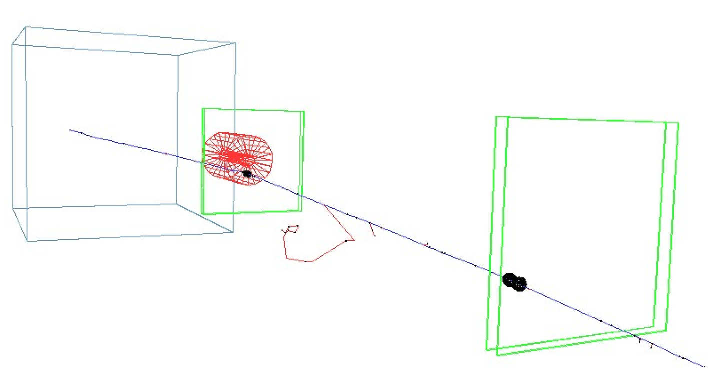
The above plot shows proton energy loss and energy deposition in water as a function of depth. The small energy deposition through along most of the path is a property that makes protons ideal for pCT, provided the energy loss can be measured accurately.



As protons pass through the SSD, they deposit energy in the silicon that depends on the energy of the proton. By using specific proton energies and measuring the corresponding time over threshold (TOT), **this experimental calibration curve** was obtained. It was used to calculate the proton energies from TOT in our experiment.

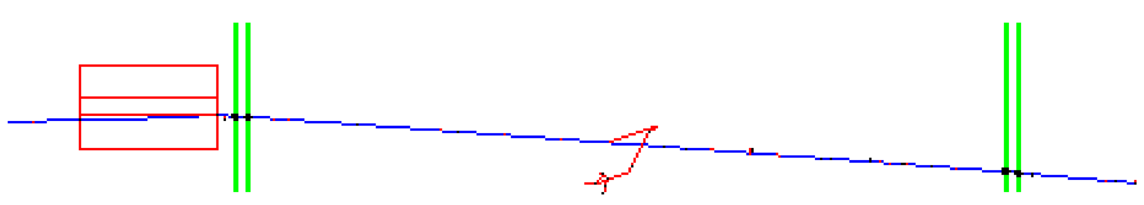
Simulation

The Monte Carlo simulation program **GEANT4** was used to model our simple experimental setup. Although GEANT4 was primarily intended (and tested) for the simulation of high-energy physics experiments, it can be applied to a wide variety of applications, including medical physics. The parameters for the simulation were matched to the physical setup described above.

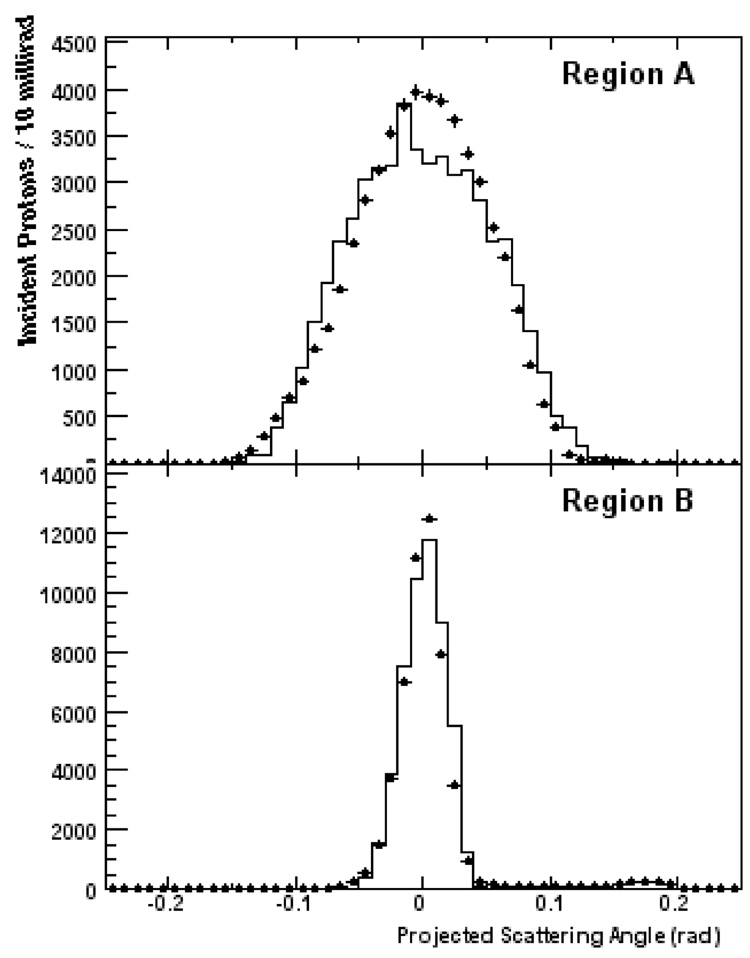


Above is a 3-D image of one simulated proton being scattered by the wax and aluminum tube, generated using GEANT4. The wax is the large box, the SSD's are shown in green, the aluminum tube in red, and the points where the proton impacted the detectors are shown in black. Red lines are secondary particles created by GEANT4 (delta rays).

Below is a 2-D side view of the same event shown above. It is easy to see the angle of deflection between the incident proton and the final path after it has pased through the aluminum tube.



Multiple Scattering Comparison

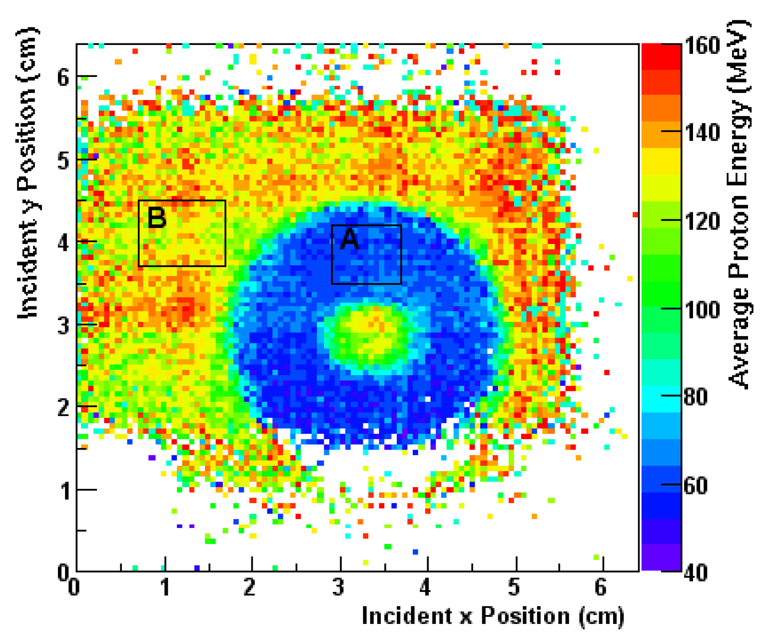


We compared scattering data for protons that passed through the aluminum tube separately from scattering data for protons that did not pass through the aluminum tube (regions A and B in color figures below).

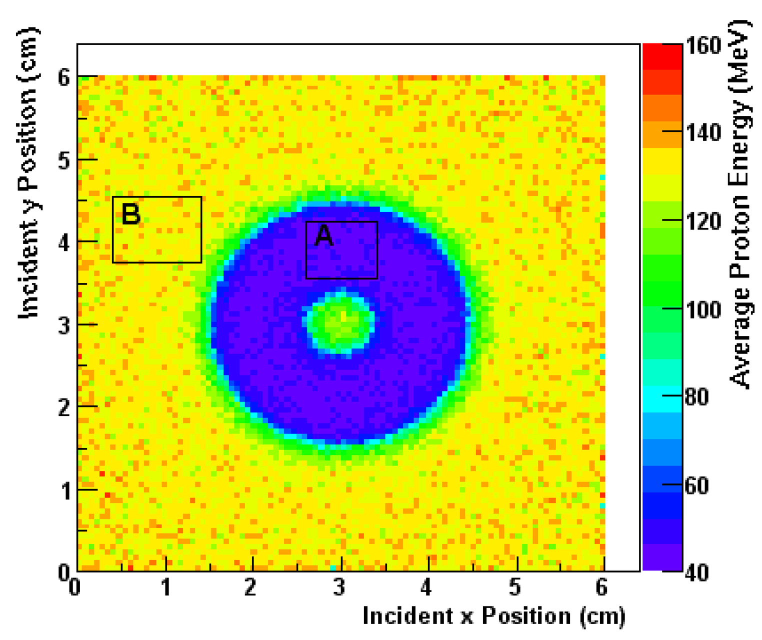
The figure on the left shows a comparison of the scattering angles of exiting protons for experiment (points) and simulation (histogram) in regions A and B. The area under the histograms were normalized to correspond to the area of the experimental curves.

There is good agreement between the experimental and simulated results. Both distributions are roughly Gaussian in shape, and centered at zero. The spread in scattering angles in region A is significantly wider than the spread in region B. This is expected, since the scattering angle depends on the amount and density of material traversed. GEANT4 appears to accurately simulate multiple scattering for protons at these energies.

Energy Comparison



Experimental proton energy, converted from the measured TOT values, including one-hit cuts. Notice the slightly enlarged inner diameter. This indicates some beam divergence.

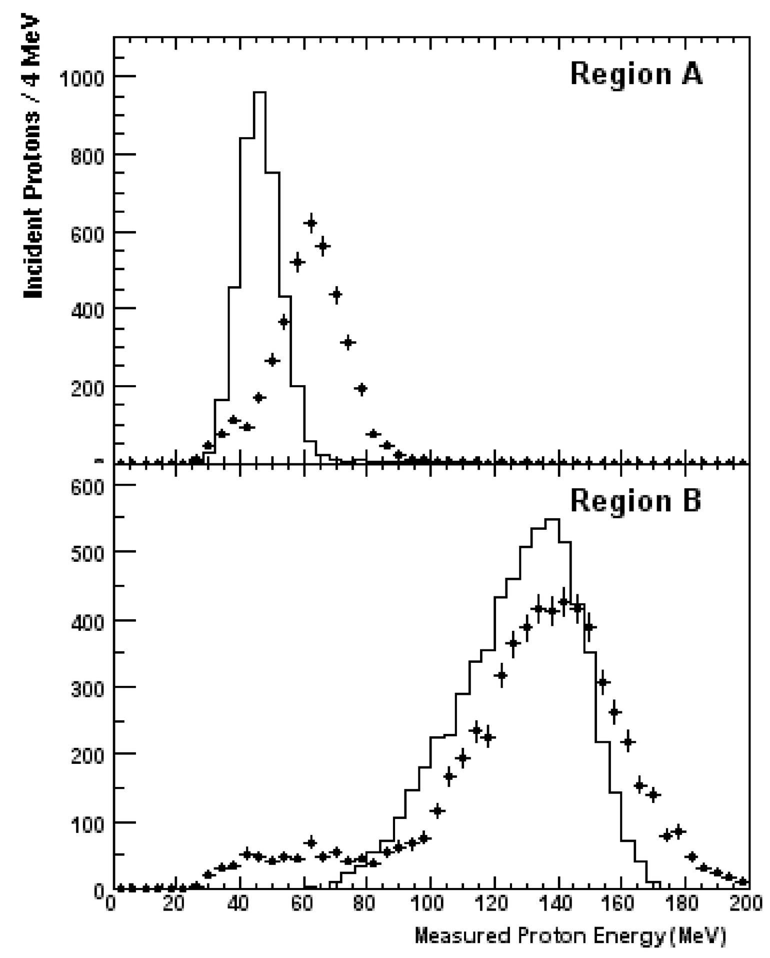


Simulated proton energy, converted from the TOT values, without cuts. Notice the overall color (and hence energy) differences between this and the experimental plot.

The figure to the right shows a comparison of the energy of exiting protons for experiment (points) and simulation (histogram) in regions A and B as indicated in figures above. The area under the histograms were normalized to correspond to the area of the experimental curves.

It is obvious from this figure that the simulation and experimental energy data do not agree as well as the multiple scattering sets. Discrepancies could be caused by:

- Wax and aluminum are not properly treated in simulation
- Charge sharing between strips gives spurious energy readings
- Irregularities in beam energy
- TOT calibration not accurate at these energies



Future Work

In continuing this work, it is important to understand the discrepancies between the GEANT4 simulation and experiment. We plan to:

- Evaluate and Improve TOT calibration
- Examine wax and aluminum modeling
- Improve beam modeling.
- Include more complex modeling of the detectors
  - Add individual strips of silicon arranged as in the real detector
  - Include new types of detectors with better energy resolution

Once we understand these factors, we can move on to modeling more complicated experimental setups. Eventually we would like to simulate a more complicated phantom, with smaller embedded objects and perhaps with very small density fluctuations like those that appear in the human body.