Initial Studies in Proton Computed Tomography

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• Proton Energy Loss in Matter
• Proton Tomography / Proton Transmission Radiography
• Proton Transmission Radiography Data
• Proton Transmission Radiography MC Study
Computed Tomography (CT)

- Based on X-ray absorption
- Faithful reconstruction of patient’s anatomy
- Stacked 2D maps of linear X-ray attenuation
- Coupled linear equations
- Invert Matrices and reconstruct z-dependent features

Proton CT replaces X-ray absorption with proton energy loss to reconstruct mass density ($\rho$) distribution
Radiography: X-rays vs. Protons

Attenuation of Photons, $Z$

$$N(x) = N_0 e^{-\mu x}$$

Energy Loss of Protons, $\rho$

$$\Delta E = \int \frac{dE}{dx} \approx \sum \rho \frac{dE}{dx} \Delta l$$

**X-Ray Absorption Coefficient**

- Bone
- Muscle
- H2O
- Fat

**Stopping Power for Protons**

- Bone
- Muscle
- H2O
- Fat

*Measure Statistical Process of X-rays Removal*

*Measure Energy Loss on Individual Protons*

*Low Contrast: $\Delta \rho = 0.1$ for tissue, 0.5 for bone*

*NIST Data*
Advantages of Protons in Therapy

- Relatively low entrance dose (plateau)
- Maximum dose at depth (Bragg peak)
- Rapid distal dose fall-off
- Energy modulation (Spread Bragg peak)
- RBE close to unity
Potential Use of Proton Beam CT: Treatment Planning

X-ray CT use in Proton Cancer Therapy can lead to large Uncertainties in Range Determination

Range Uncertainties (measured with PTR)
- > 5 mm
- > 10 mm
- > 15 mm


Alderson Head Phantom

Proton CT would measure the Density Distribution needed for Range Calculation.

There is an expectation (hope?) that with pCT the required dose can be reduced.
Low Contrast in Proton CT

Sensitivity Study:
Inclusion of 1cm depth and density $\rho$ at midpoint of 20cm $H_2O$

<table>
<thead>
<tr>
<th>$\rho*1$ [g/cm$^2$]</th>
<th>Energy [MeV]</th>
<th>Range [cm]</th>
<th>TOF [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>164.1</td>
<td>38.2</td>
<td>1309</td>
</tr>
<tr>
<td>1.1</td>
<td>163.6</td>
<td>38.1</td>
<td>1311</td>
</tr>
<tr>
<td>1.5</td>
<td>161.5</td>
<td>37.7</td>
<td>1317</td>
</tr>
<tr>
<td>2.0</td>
<td>158.9</td>
<td>37.2</td>
<td>1325</td>
</tr>
</tbody>
</table>
Requirements for pCT Measurements

Tracking of individual Protons requires Measurement of:

- Proton location to few hundred um
- Proton angle to better than a degree

Multiple Coulomb Scattering

- Average Proton Energy \( <E> \) to better than \( \% \)
- Improve energy determination with statistics

- Issue: Dose \( D = \text{Absorbed Energy} / \text{Mass} \)
  Voxel with diameter \( d = 1\text{mm} \)
  \( 10^5 \) protons of 200 MeV = 7 [mGy]

In order to minimize the dose, the final system needs to employ the best energy resolution! Energy straggling is 1- 2 \( \% \).

\[
\theta_0 = \frac{13.6 \text{ MeV}}{\beta_c \rho} \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right]
\]

\[
\sigma_{<E>} = \frac{\sigma_E}{\sqrt{N}}
\]

\[
D = \frac{N}{A} \cdot \frac{dE}{dx}
\]

\[
D \sim \frac{\sigma_E^2}{\Delta^2 \rho \cdot d^5}
\]

\[
\sigma_E \approx 1\% 
\]
Development of Proton Beam Computed Tomography

Collaboration Loma Linda University Medical Center – UC Santa Cruz

- **Exploratory Study in Proton Transmission Radiography**
  - Silicon detector Telescope
  - Simple phantom in front

- **Theoretical Study (GEANT4 MC simulation)**
  - Evaluation of MCS, range straggling, and angular measurements
  - Optimization of energy

- **Future Experimental Study in pCT**
  - Three or four x-y Si planes
  - H₂O phantom on turntable
  - 3-D Reconstruction
Exploratory Proton Radiography Set-up

Proton Beam from Loma Linda University Medical Ctr @ 250 MeV
Degraded down to 130 MeV by 10” Wax Block
Object is Aluminum pipe 5cm long, 3cm OD, 0.67cm ID
Very large effects expected, $x = \rho \cdot l = 13.5 \text{ g/cm}^2$
Traversing protons have 50 MeV, by-passing protons have 130 MeV
Silicon detector telescope with 2 x-y modules:
measure energy and location of exiting protons
Proton Energy Measurement with LET in Si

Simple 2D Silicon Strip Detector Telescope of 2 x-ymodules

built for Nanodosimetry (based on GLAST Design)

2 single-sided SSD/module
-measure x-y coordinates

194um Pitch, 400um thickness

GLAST Readout

1.3us shaping time

Binary readout

Time-over-Threshold TOT

Large dynamic range

Measure particle energy via LET
Time-Over-Threshold (TOT) \sim\text{Energy Transfer}

Digitization of Position and Energy Deposit with large Dynamic Range

TOT \propto \text{charge} \propto \text{LET}
Proton Energy Measurement with LET

Good agreement between measurement and MC simulations

Derive Energy Resolution from TOT vs. E Plot
Subdivide SSD area into pixels
1. Strip x strip 194um x 194um
2. 4 x 4 strips (0.8mm x 0.8mm)

Average Energy in Pixel makes Image
Energy Resolution $\Rightarrow$ Position Resolution

Average Pixel Energy in Slice of 4x4 pixels (need to apply off-line calibration!)

Clear Profile of Pipe, but Interfaces blurred.

Hole “filled in”

“Fuzzy” Edges
GEANT4 MC: Energy Reconstruction

Energy Loss in Si

Energy Reconstructed from Energy Loss in Si

Energy Scale of Data ok to 10% BEFORE of-line calibration

Angular distribution narrower in the data!

NIST Data
GEANT4 MC: Loss of Resolution in Back

First Plane, 2cm behind Object

Second Plane, 30cm behind Object: Fuzzy
Multiple Scattering: Migration

Image Features:

- Washed out image in 2\textsuperscript{nd} plane (30cm downstream)
- Energy diluted at interfaces
  
  (Fuzzy edges, Large RMS, Hole filled in partially)

Migration of events are explained by Multiple Coulomb Scattering (MCS)

Protons scatter OUT OF Target (not INTO).
Scatters have larger energy loss, larger angles, fill hole, dilute energy
Beam Profile in Slice shows Migration out of Object

Protons entering the Object in Front Face but leaving it before the Rear Face

Energy of Protons Entering Front Face

Protons entering the Object in Front Face but leaving it before the Rear Face

Incident Proton / 0.02 MeV

Measured Proton Energy (MeV)
Effect of Angular Cut: Energy more uniform

Less Migration

Sharp edges (Energy Average)

Sharp edges (Energy RMS)

Hit Profile before angle cut

Hit Profile after angle cut

Energy Profile before (after) Angle Cut

Energy RMS before (after) Angle Cut
Conclusions:

• Imaging with protons is working!
• GEANT4 program describes the data well
  (energy and position resolution, angular distribution, migration)

Issues:

• Energy needs Optimization depending on Target
• Improve Resolution with cut on exit angle ✓
• Investigate Energy Measurement independent from Silicon Detectors
• Dose – Contrast - Resolution Relationship:
  Dose from 10,000 Protons of 200 MeV: 1 mGy

Next step: pCT
Vertex2002  

Mahalo

http://scipp.ucsc.edu/~hartmut/Kona