Initial Studies in Proton Computed Tomography

L. R. Johnson, B. Keeney, G. Ross, H. F.-W. Sadrozinski, A. Seiden, D.C. Williams, L. Zhang

Santa Cruz Institute for Particle Physics, UC Santa Cruz, CA 95064

V. Bashkirov, R. W. M. Schulte, K. Shahnazi

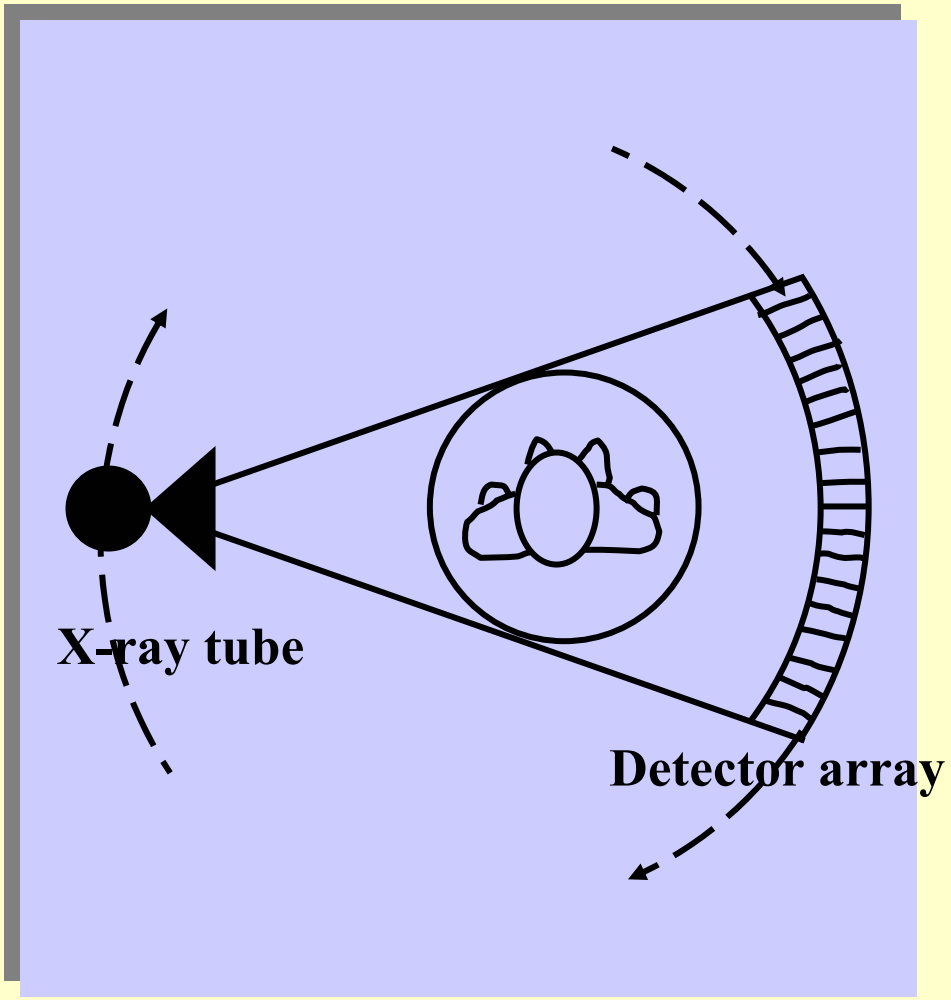
Loma Linda University Medical Center, Loma Linda, CA 92354

- 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 (ρ) distribution



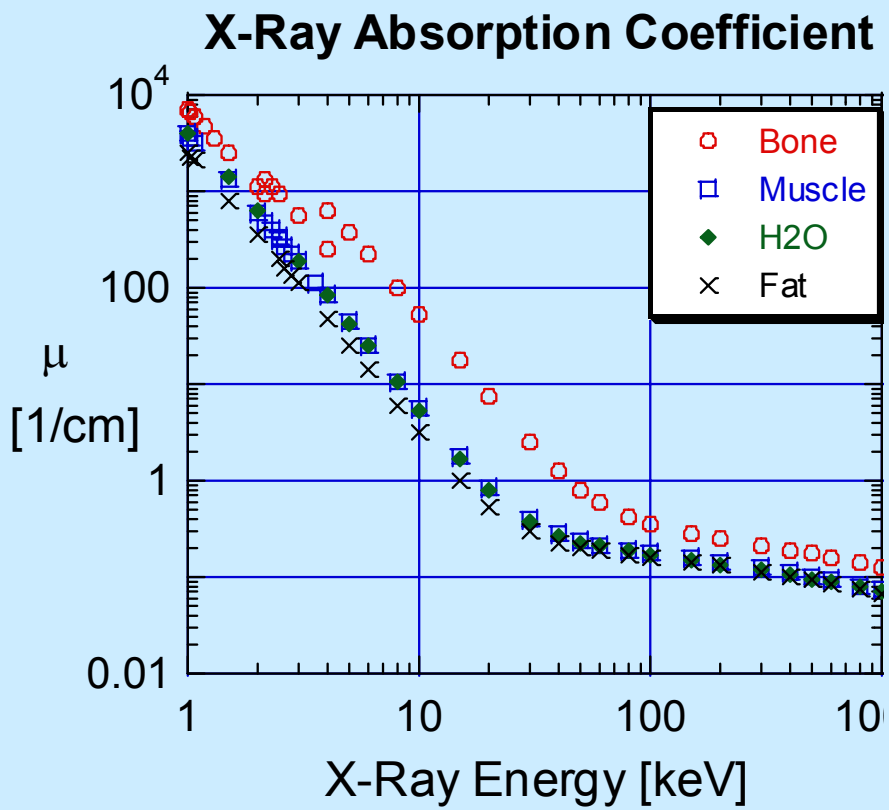
Radiography: X-rays vs. Protons

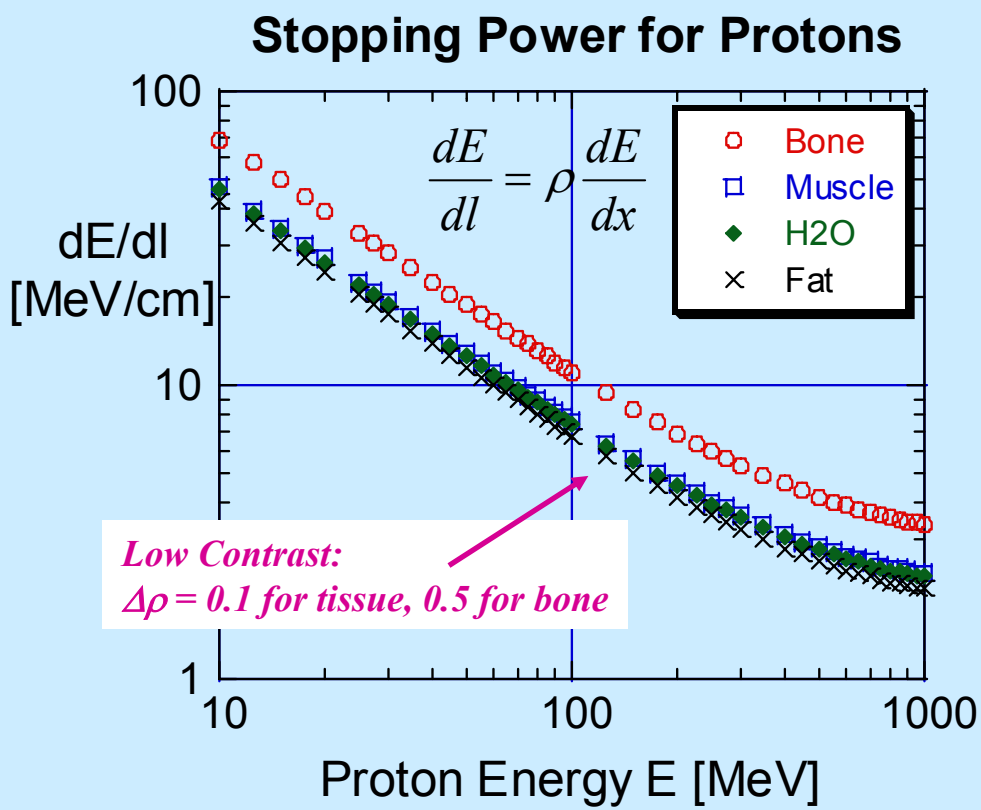
Attenuation of Photons, Z

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

Energy Loss of Protons, ρ

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



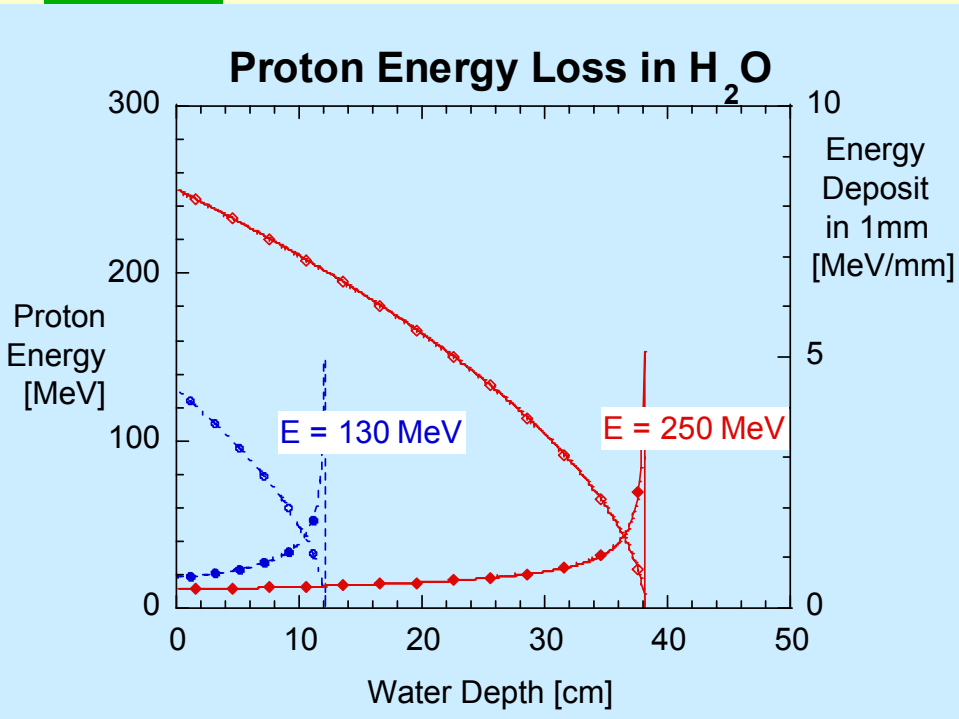


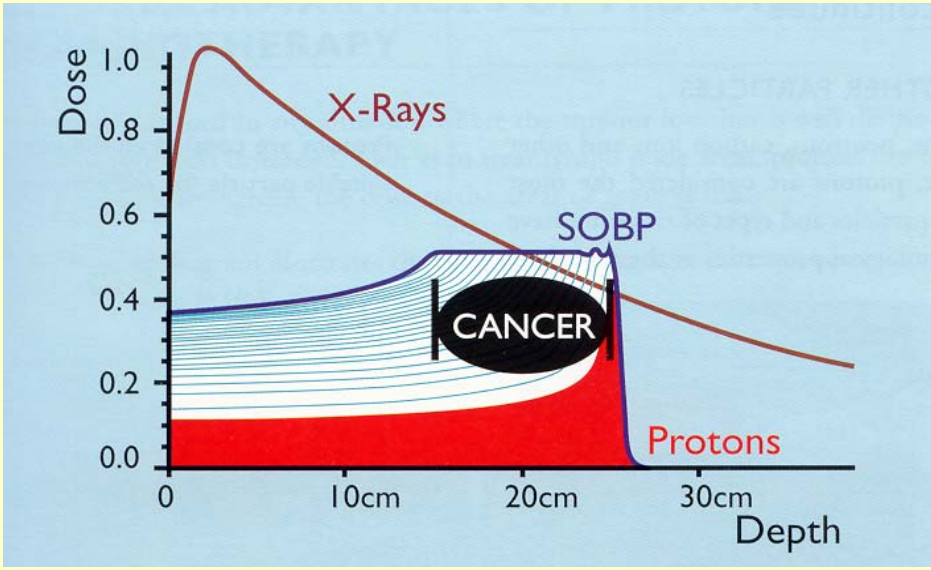
Measure Statistical Process of X-rays Removal

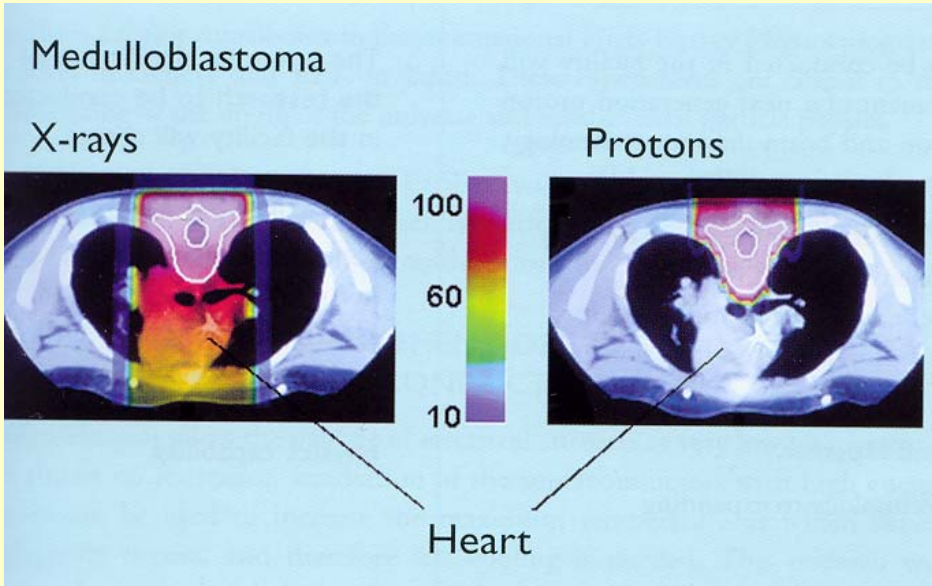
NIST Data

Measure Energy Loss on Individual Protons

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

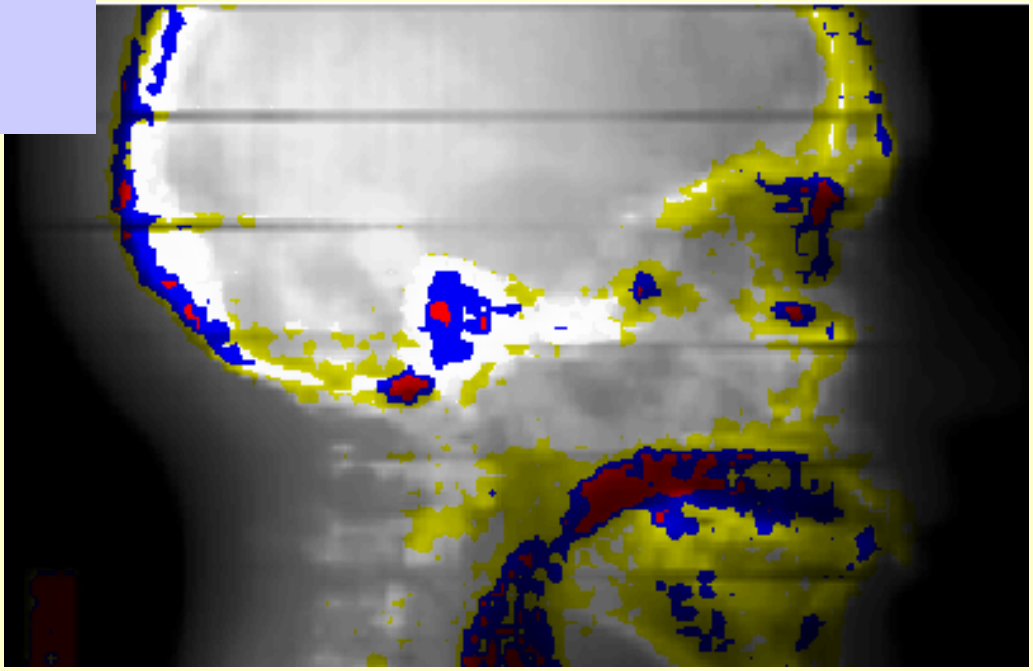
Potential Use of Proton Beam CT: Treatment Planning

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

Schneider U. & Pedroni E. (1995), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.

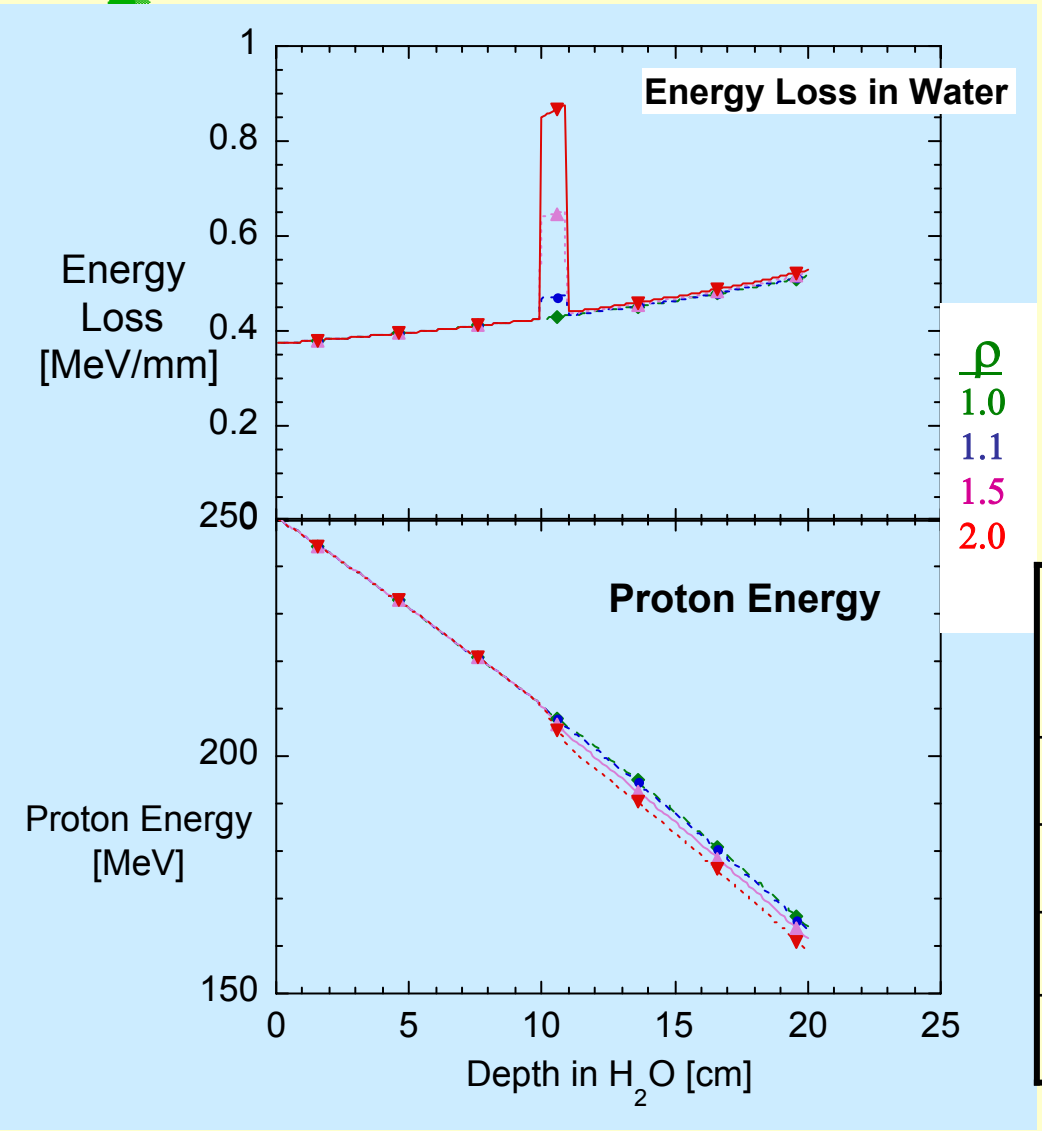


Alderson Head Phantom

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

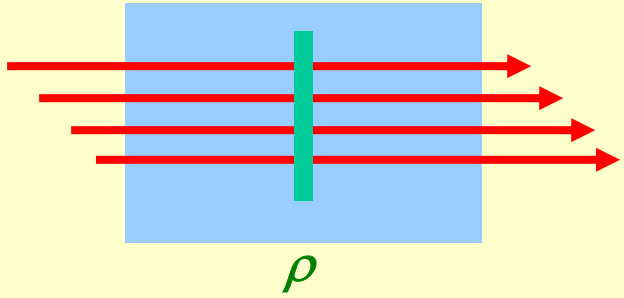
There is an expectation (hope?) that with pCT the required dose can be reduced.

Low Contrast in Proton CT



Sensitivity Study:

Inclusion of 1cm depth and density ρ at midpoint of 20cm H_2O



ρ*l [g/cm²]	Energy [MeV]	Range [cm]	TOF [ps]
1.0	164.1	38.2	1309
1.1	163.6	38.1	1311
1.5	161.5	37.7	1317
2.0	158.9	37.2	1325

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

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

- Average Proton Energy <E> to better than %

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

- Improve energy determination with statistics
- Issue: Dose D = Absorbed Energy / Mass
  Voxel with diameter d = 1mm
  10^5 protons of 200 MeV = 7 [mGy]

$$\mathrm{D} = \frac{\mathrm{N}}{\mathrm{A}} \cdot \frac{dE}{dx}$$

$$\mathrm{D} \sim \frac{\sigma_E^{\ 2}}{\Delta^2 \rho \cdot d^5}$$

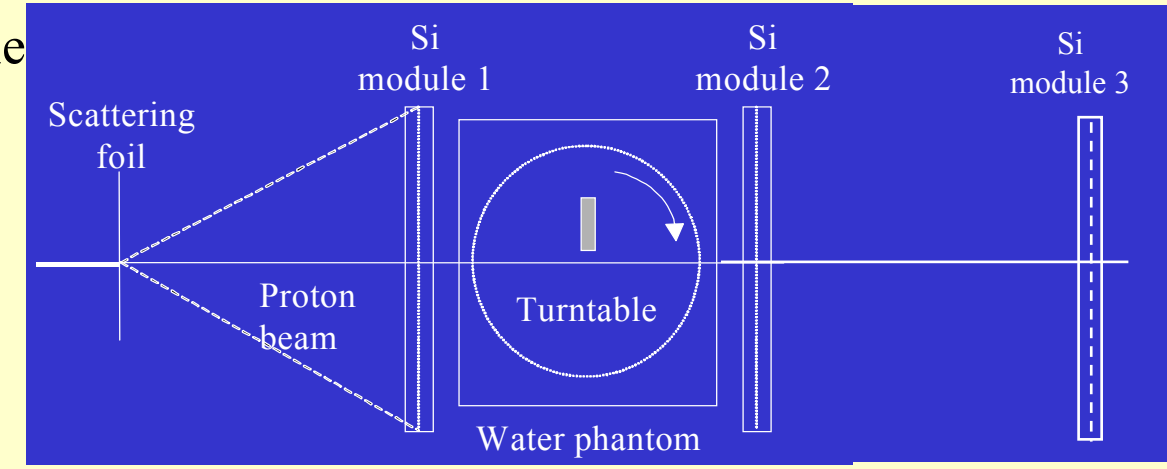
- In order to minimize the dose, the final system needs to employ the best energy resolution! Energy straggling is 1- 2 %.

$$\sigma_E \approx 1\%$$

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
  - H_2O 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

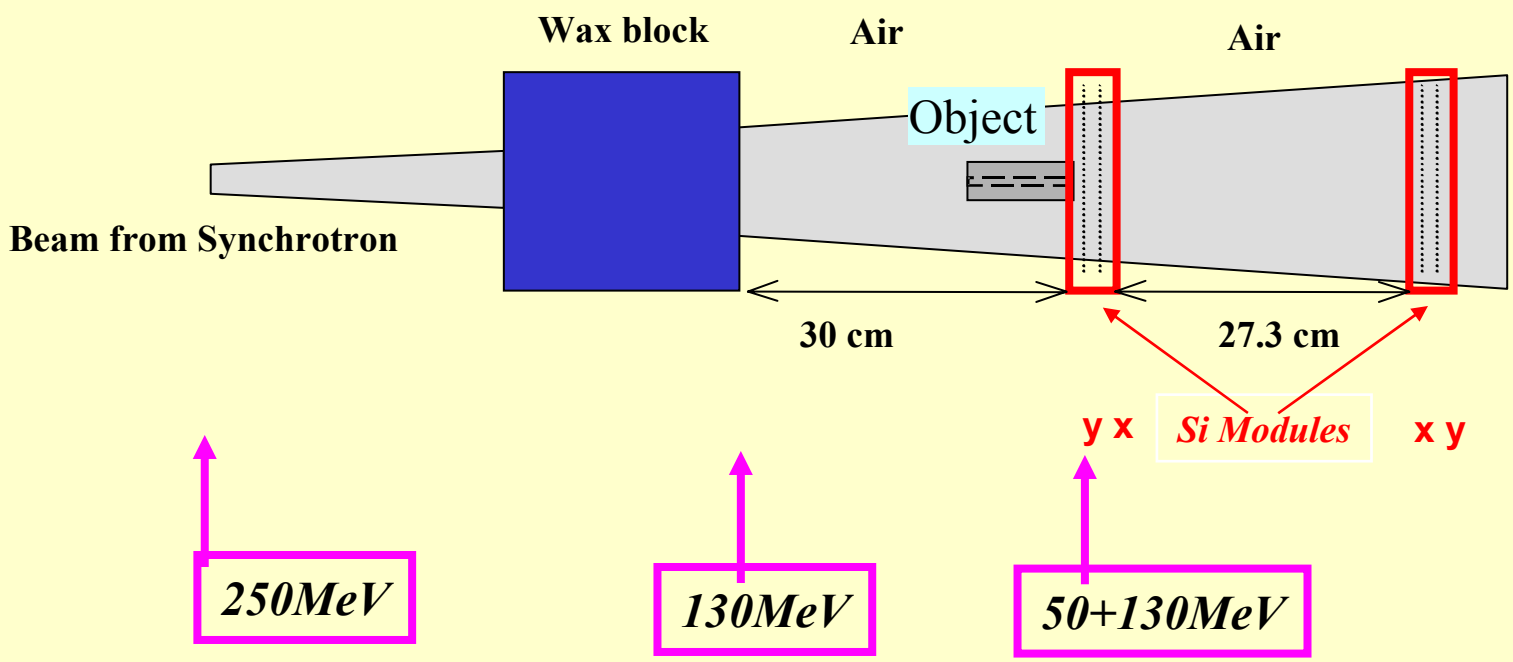
Object is Aluminum pipe 5cm long, 3cm OD, 0.67cm ID

Very large effects expected, $x = \rho * l = 13.5\ g/cm^2$

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

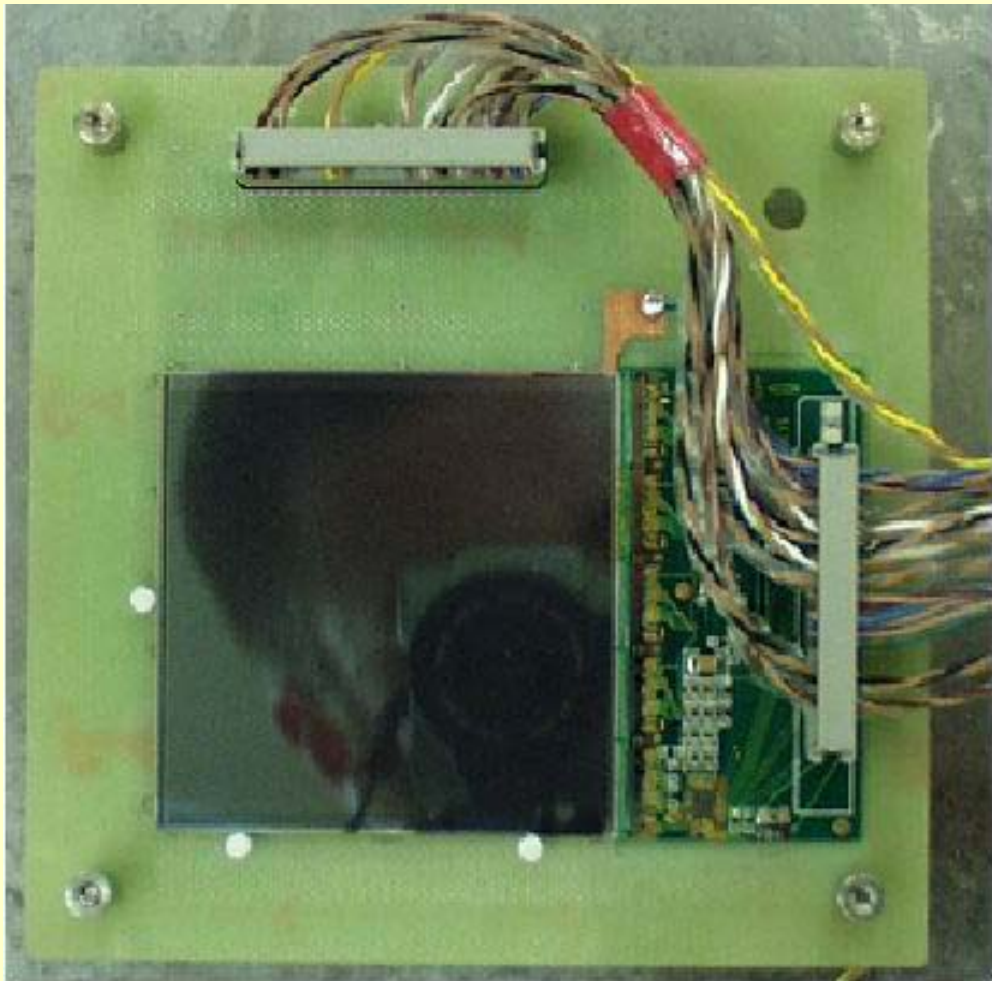
1.3us shaping time

Binary readout

Time-over-Threshold TOT

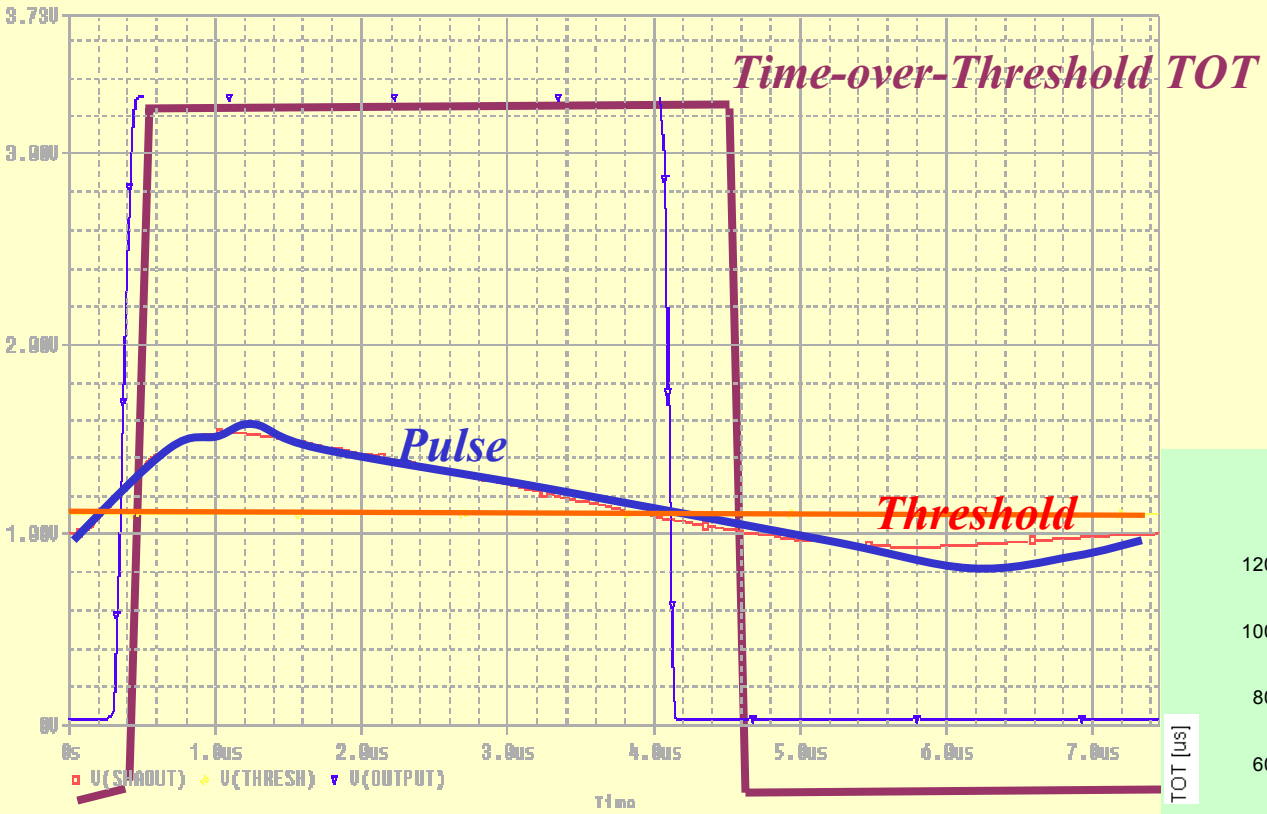
Large dynamic range

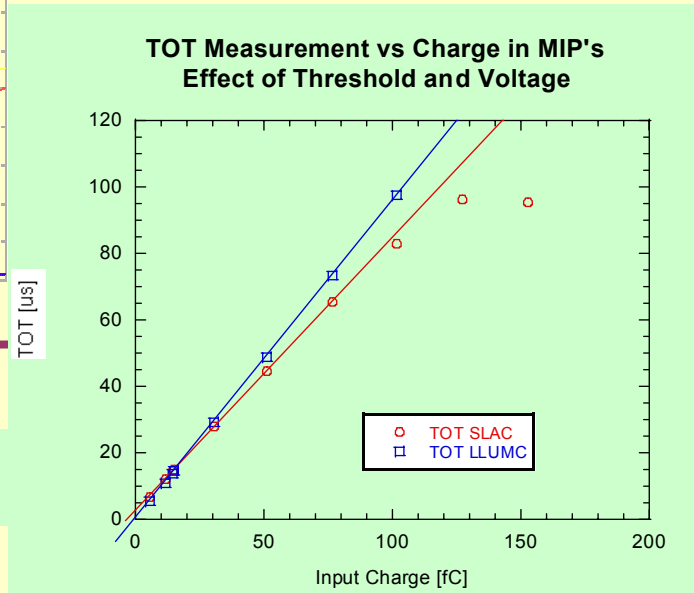
Measure particle energy via LET



Time-Over-Threshold (TOT) ~ Energy Transfer

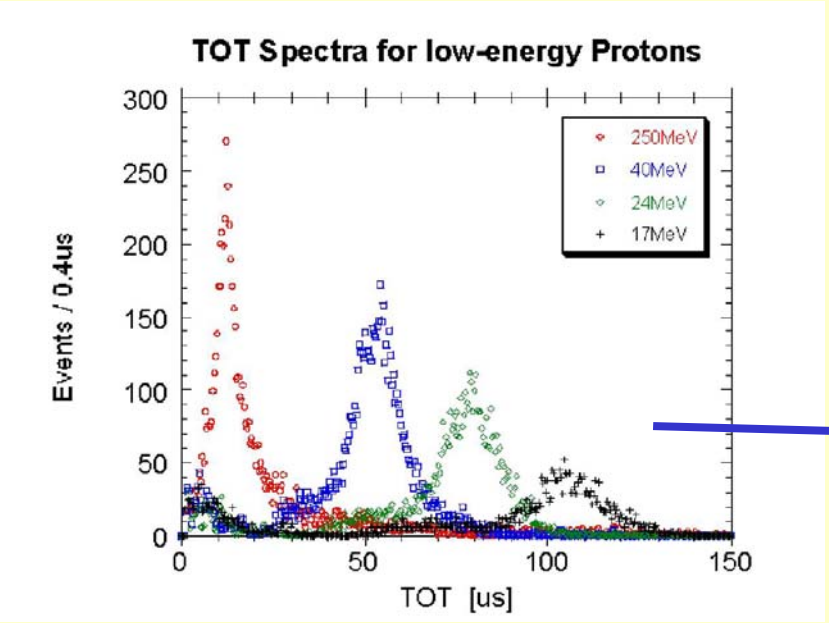
Digitization of Position and Energy Deposit with large Dynamic Range



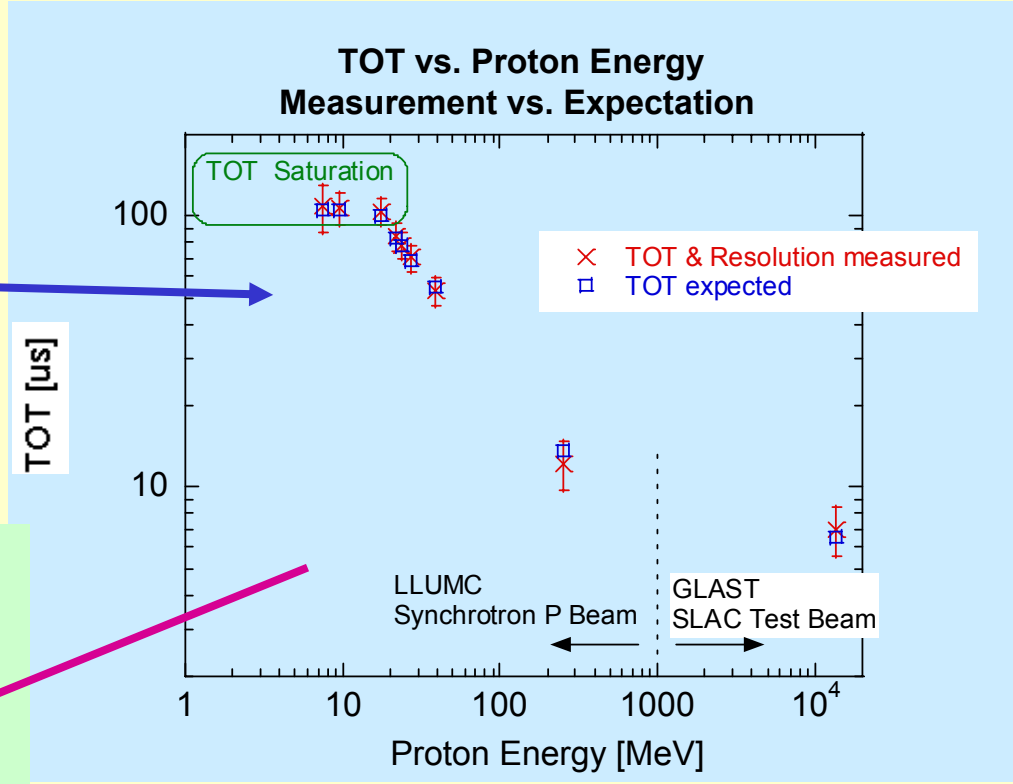


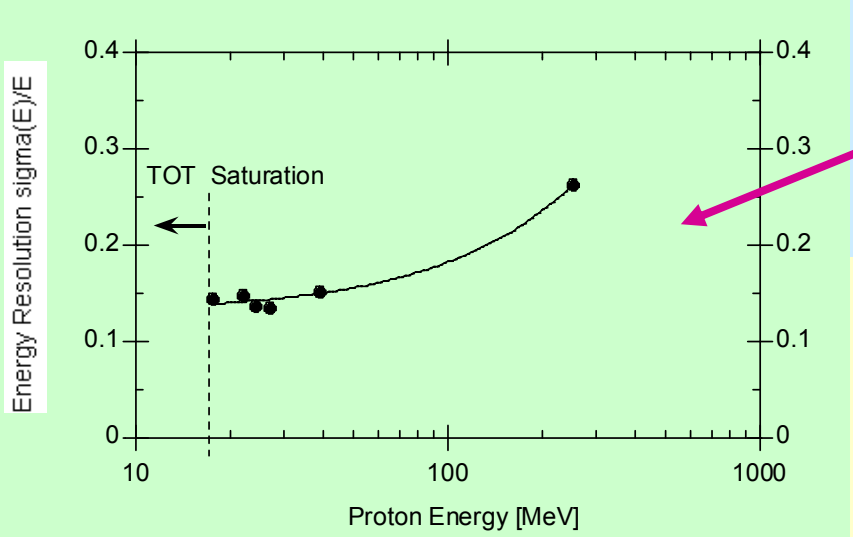
TOT ∝ charge ∝ LET

Proton Energy Measurement with LET



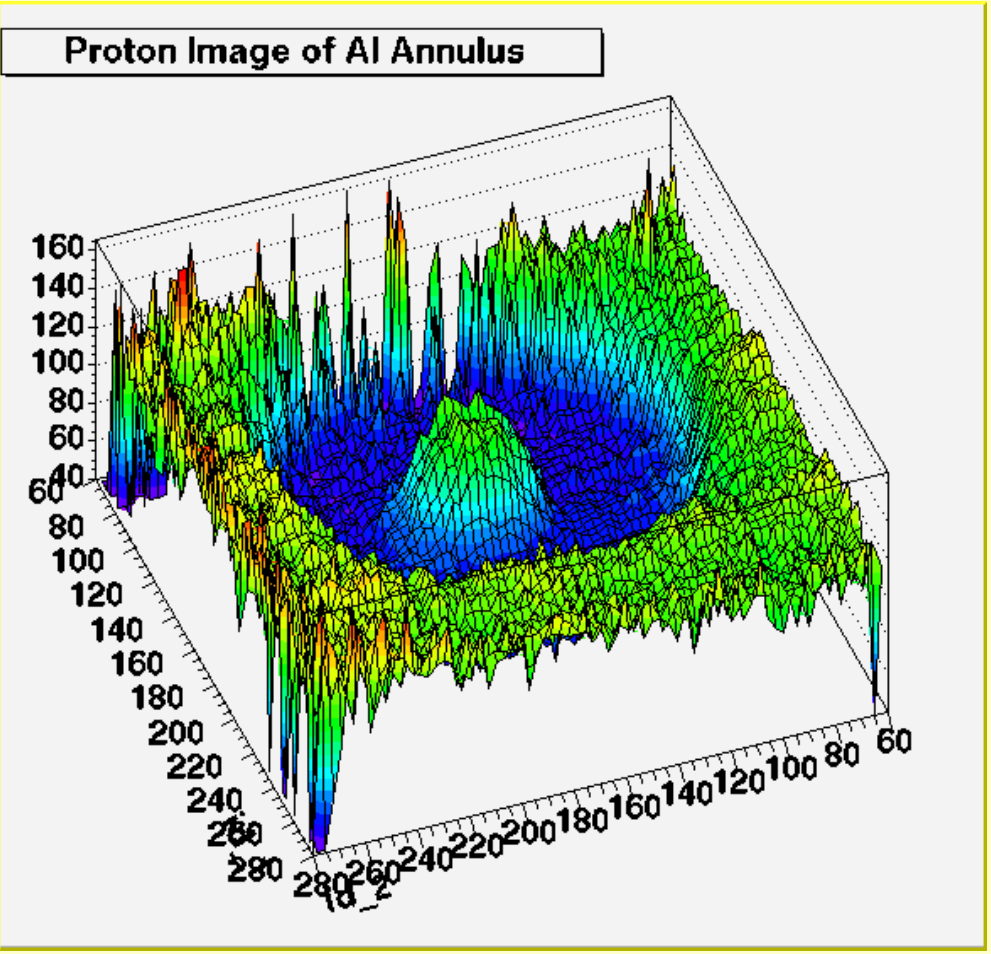
Good agreement between measurement and MC simulations





Derive Energy Resolution from TOT vs. E Plot

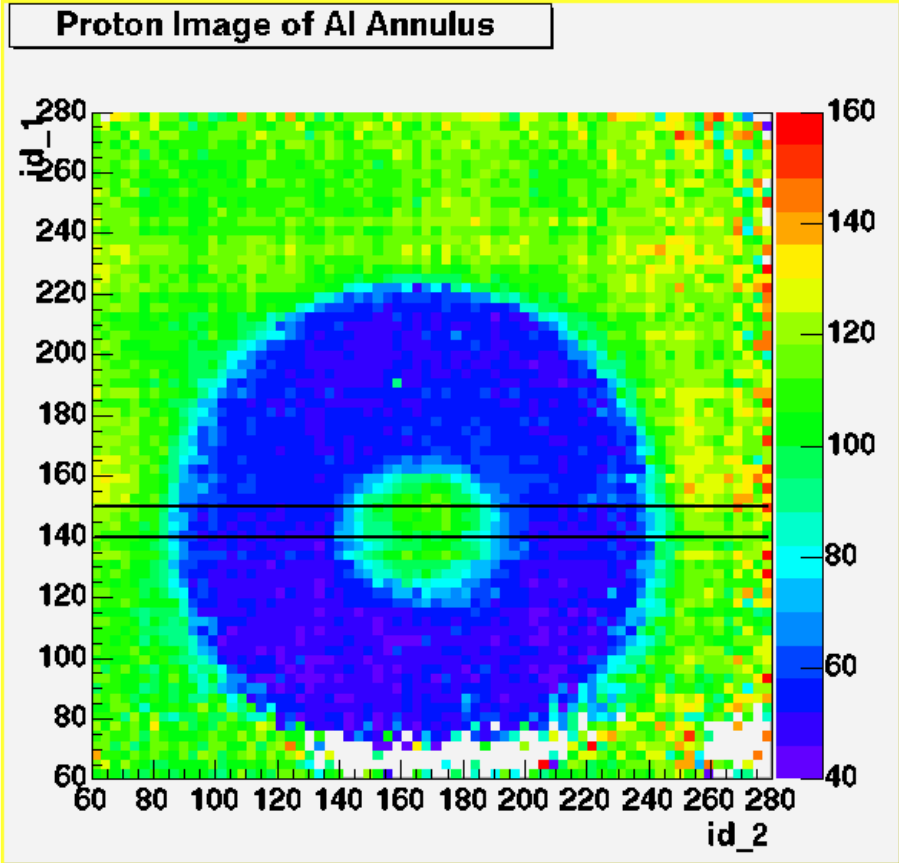
Image !



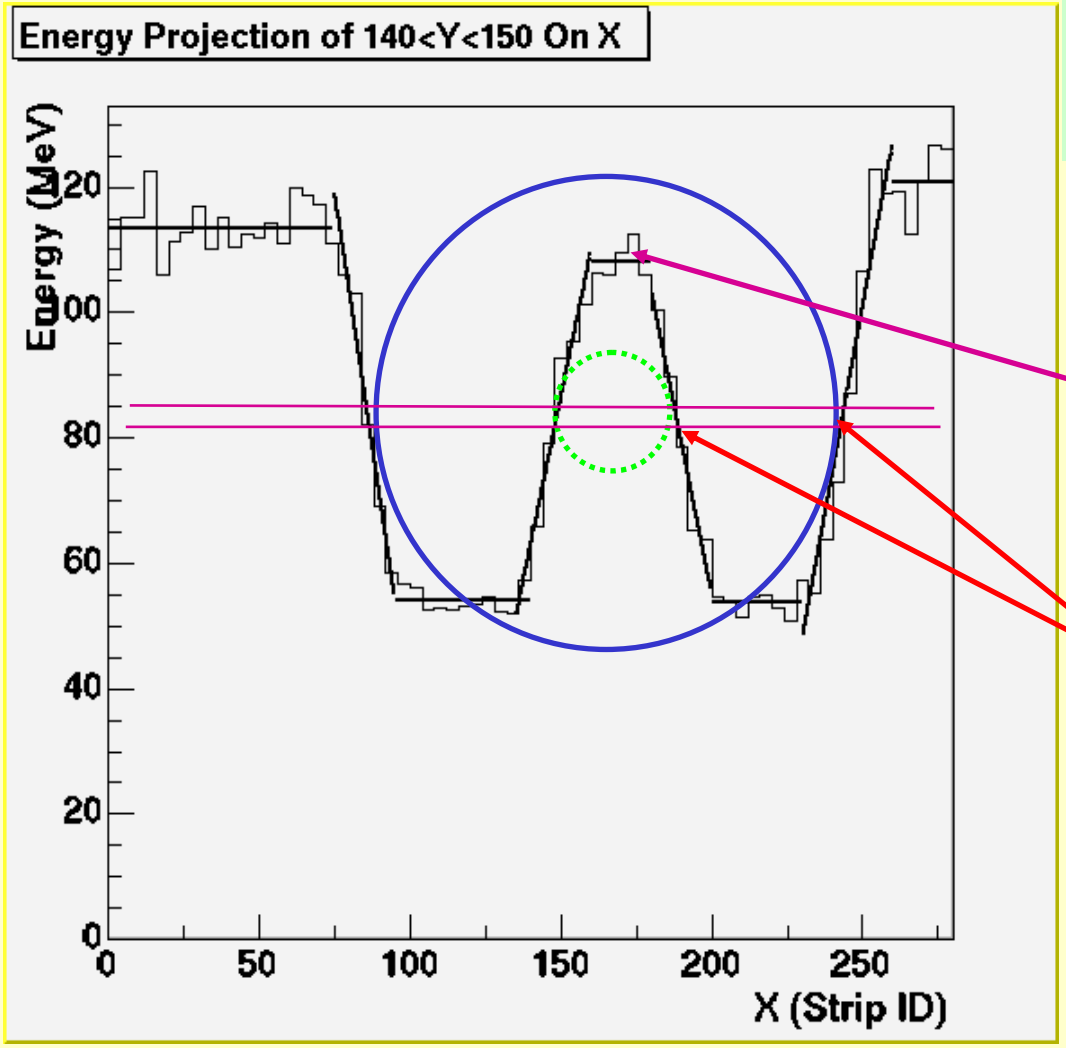
Subdivide SSD area into pixels

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 => Position Resolution



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

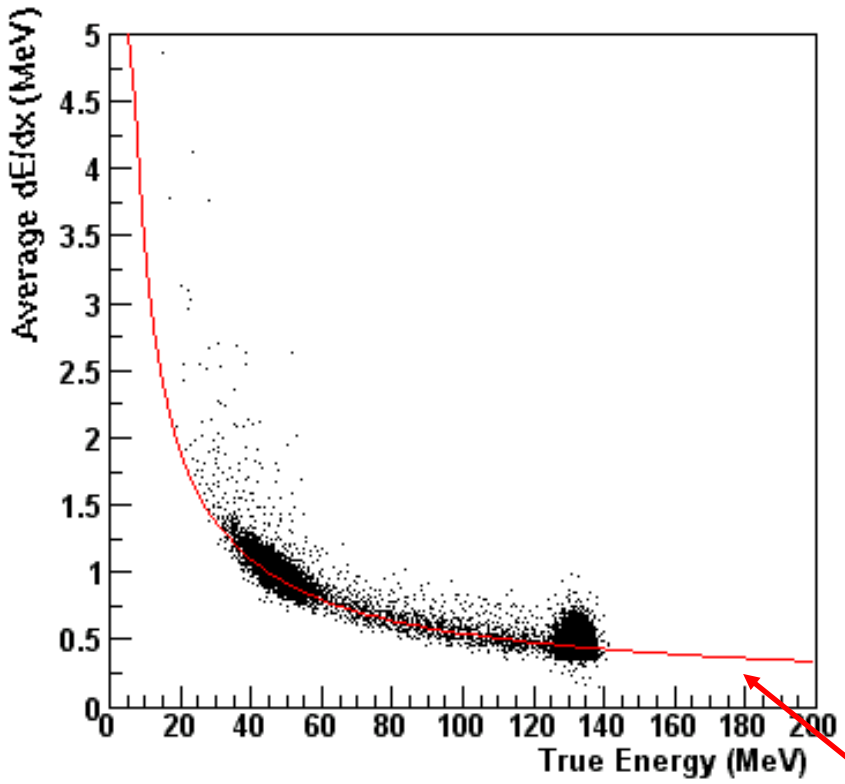
Clear Profile of Pipe, but Interfaces blurred.

Hole "filled in"

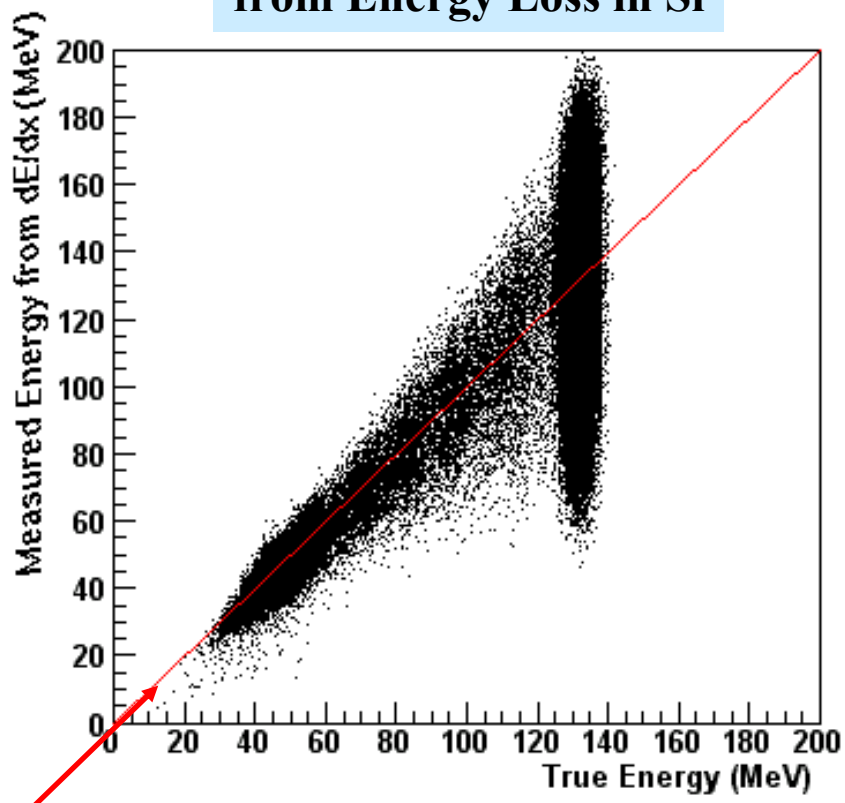
"Fuzzy" Edges

GEANT4 MC: Energy Reconstruction

Energy Loss in Si



Energy Reconstructed from Energy Loss in Si

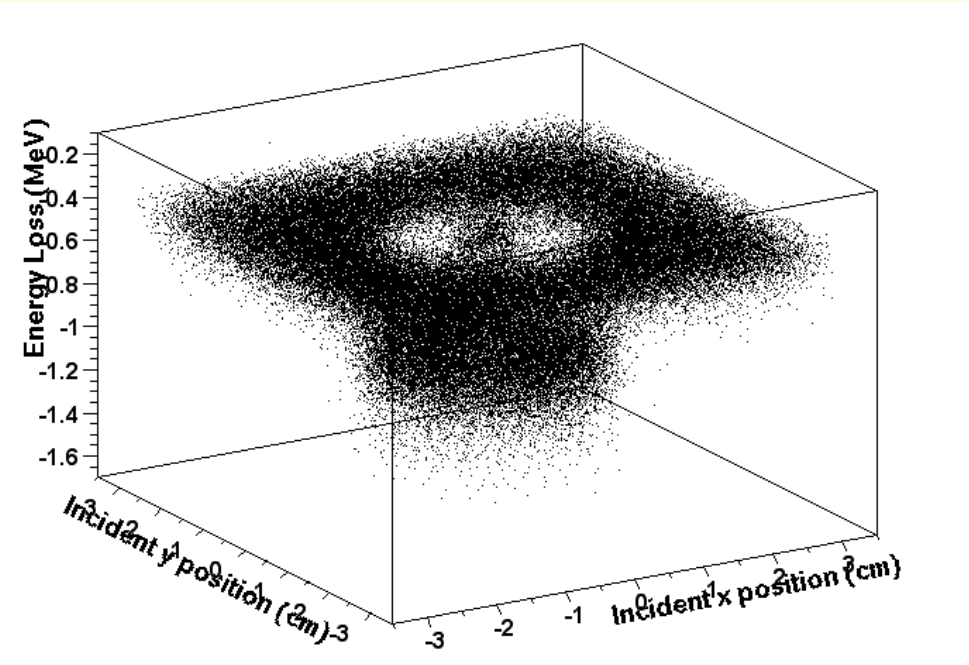


NIST Data

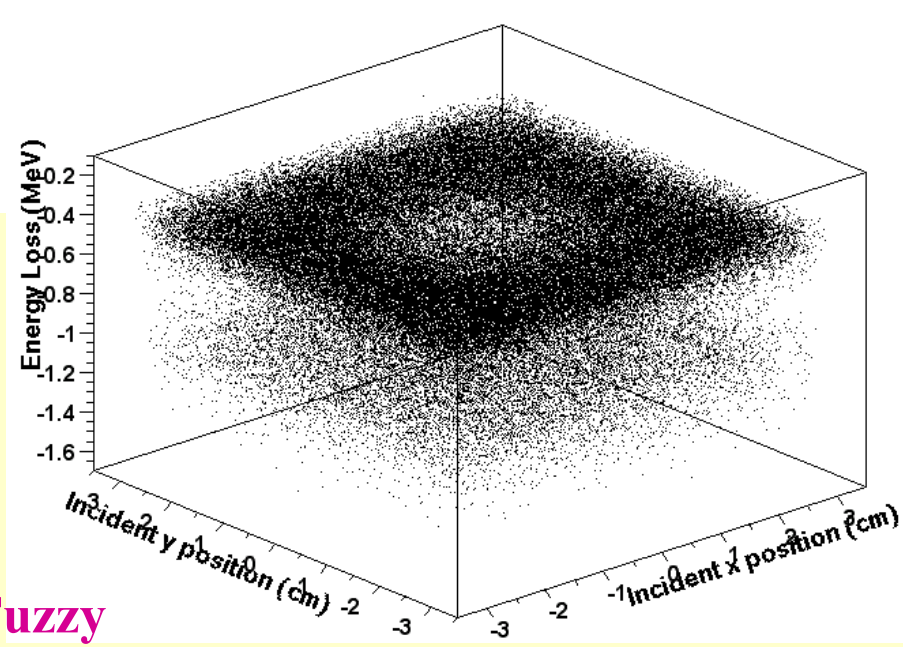
Energy Scale of Data ok to 10% BEFORE of-line calibration

Angular distribution narrower in the data!

GEANT4 MC: Loss of Resolution in Back



First Plane, 2cm behind Object



Second Plane, 30cm behind Object: Fuzzy

Multiple Scattering: Migration

Image Features:

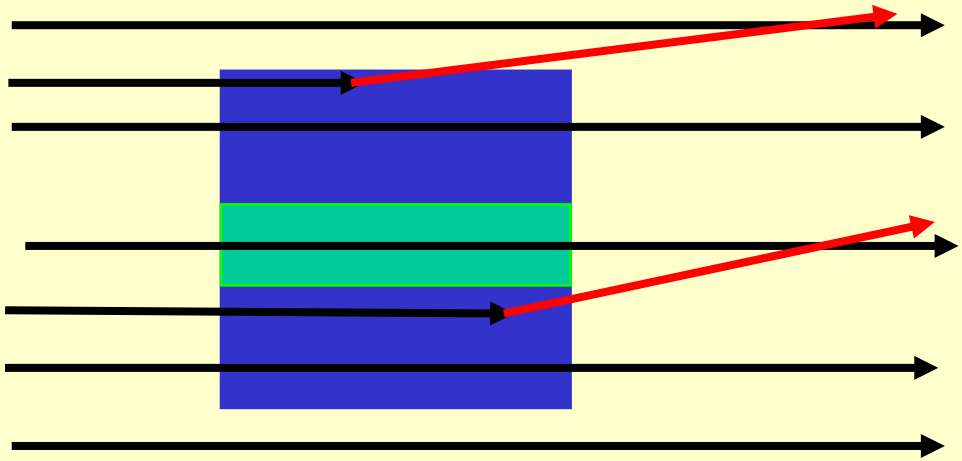
Washed out image in 2nd plane (30cm downstream)

Energy diluted at interfaces

(Fuzzy edges, Large RMS, Hole filled in partially)

Migration of events

are explained by Multiple Coulomb Scattering MCS

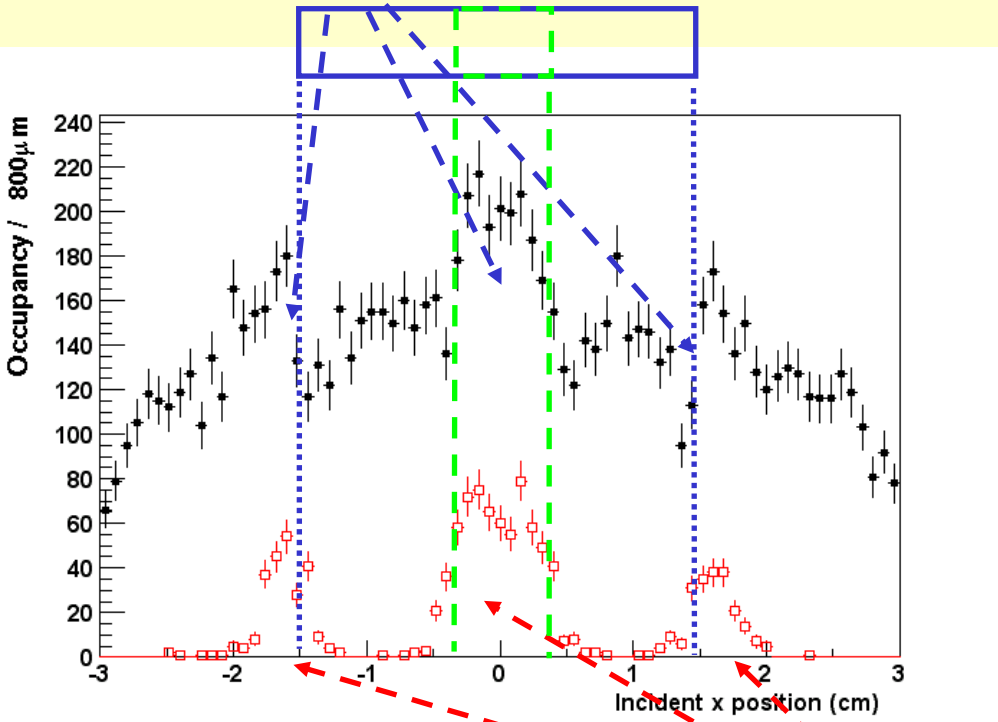


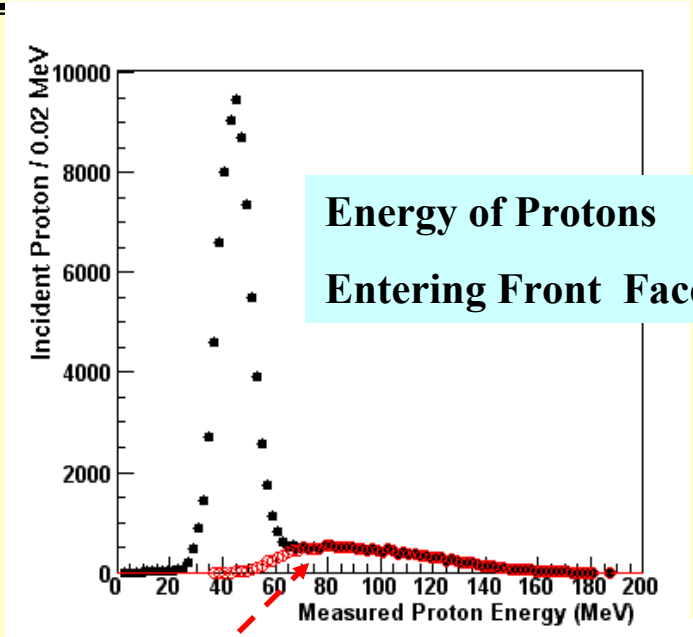
Protons scatter OUT OF Target (not INTO).

Scatters have larger energy loss, larger angles, fill hole, dilute energy

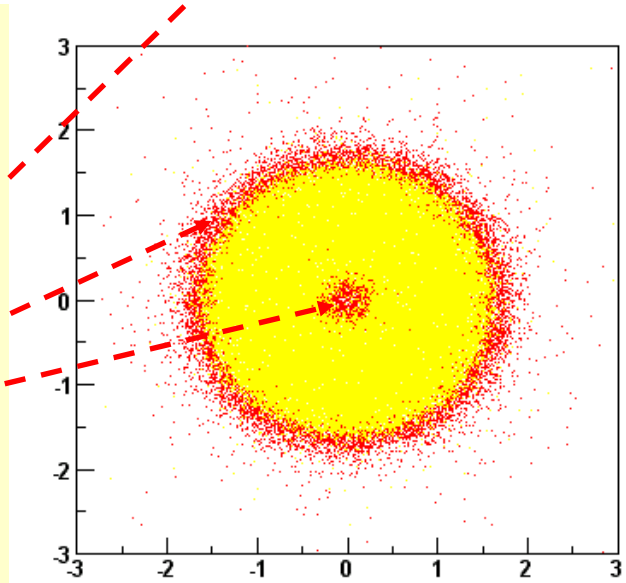
GEANT4 MC: Migration

Beam Profile in Slice shows Migration out of Object





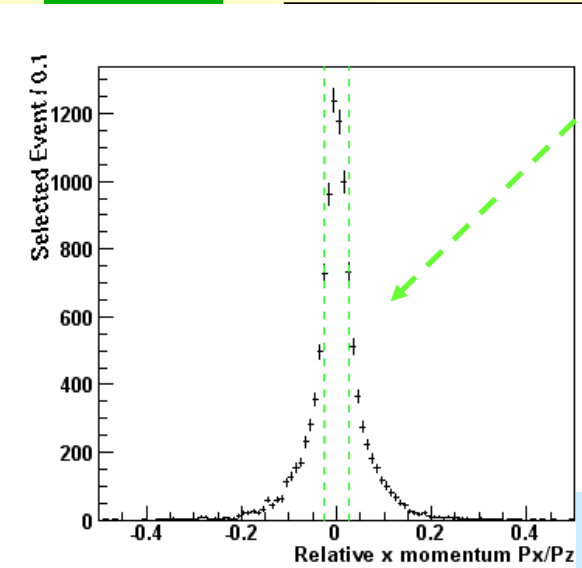
Energy of Protons Entering Front Face



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

GEANT4 MC: Use of Angular Information

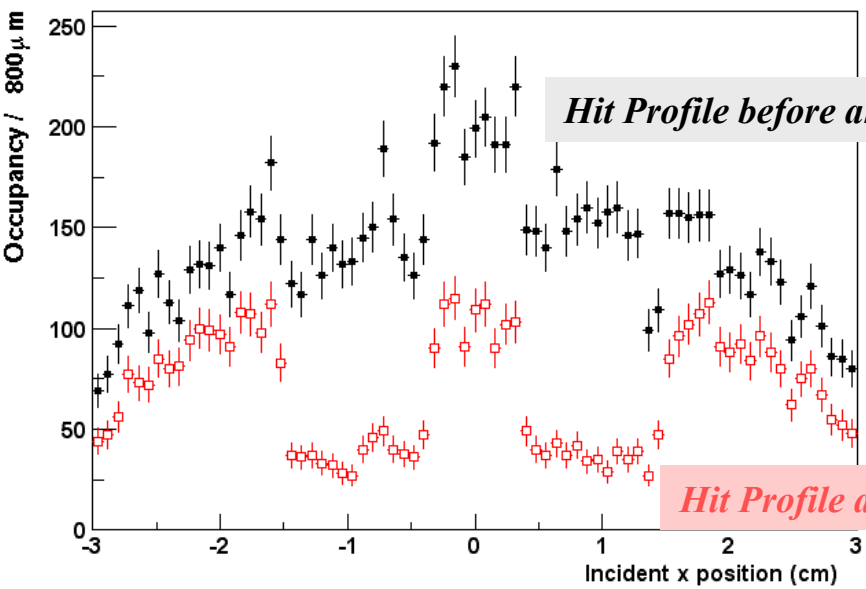
- **Effect of Angular Cut: Energy more uniform**



Less Migration

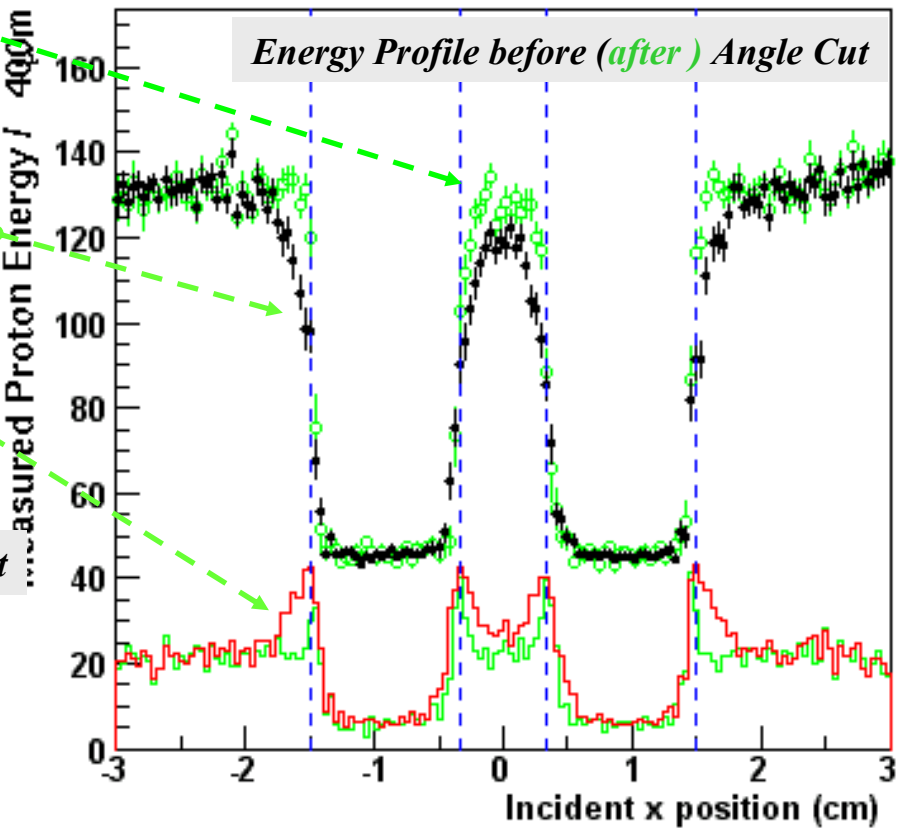
Sharp edges (Energy Average)

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

Mahalo

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