Towards 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

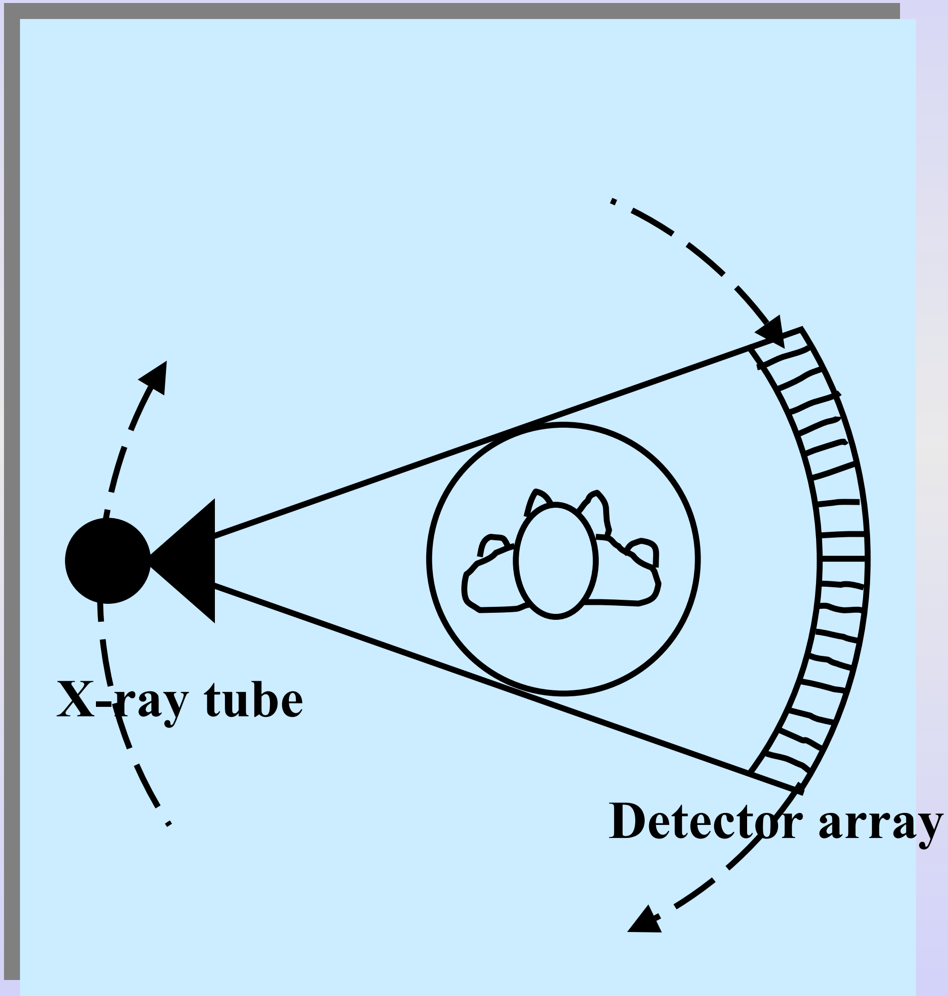
Computed Tomography (CT)

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**
- **reconstruct mass density (ρ) distribution instead of electron distribution**



Radiography: X-rays vs. Protons

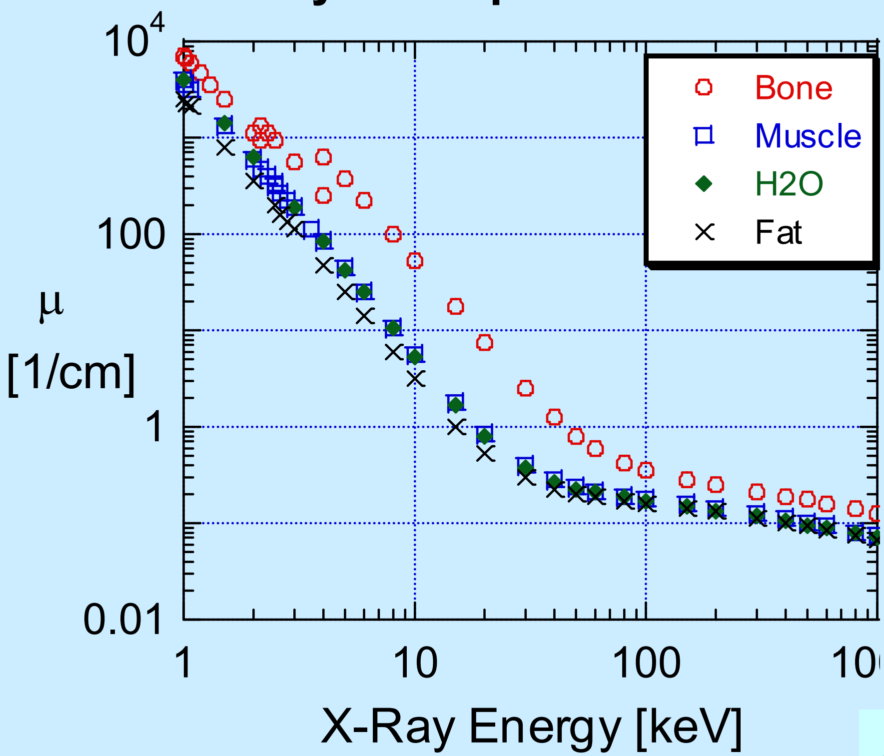
Attenuation of Photons, Z

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

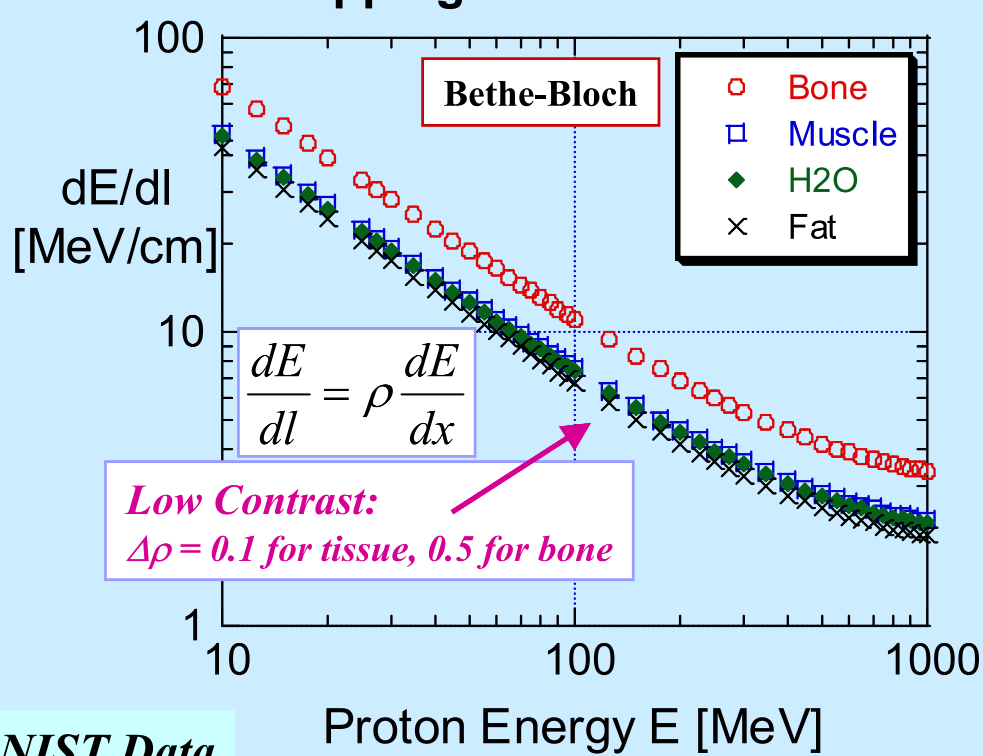
Energy Loss of Protons, ρ

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

X-Ray Absorption Coefficient



Stopping Power for Protons



NIST Data

Measure statistical process of X-ray removal

Measure energy loss on individual protons

Negative Slope in the Bethe-Bloch Formula

- **Relatively low entrance dose**

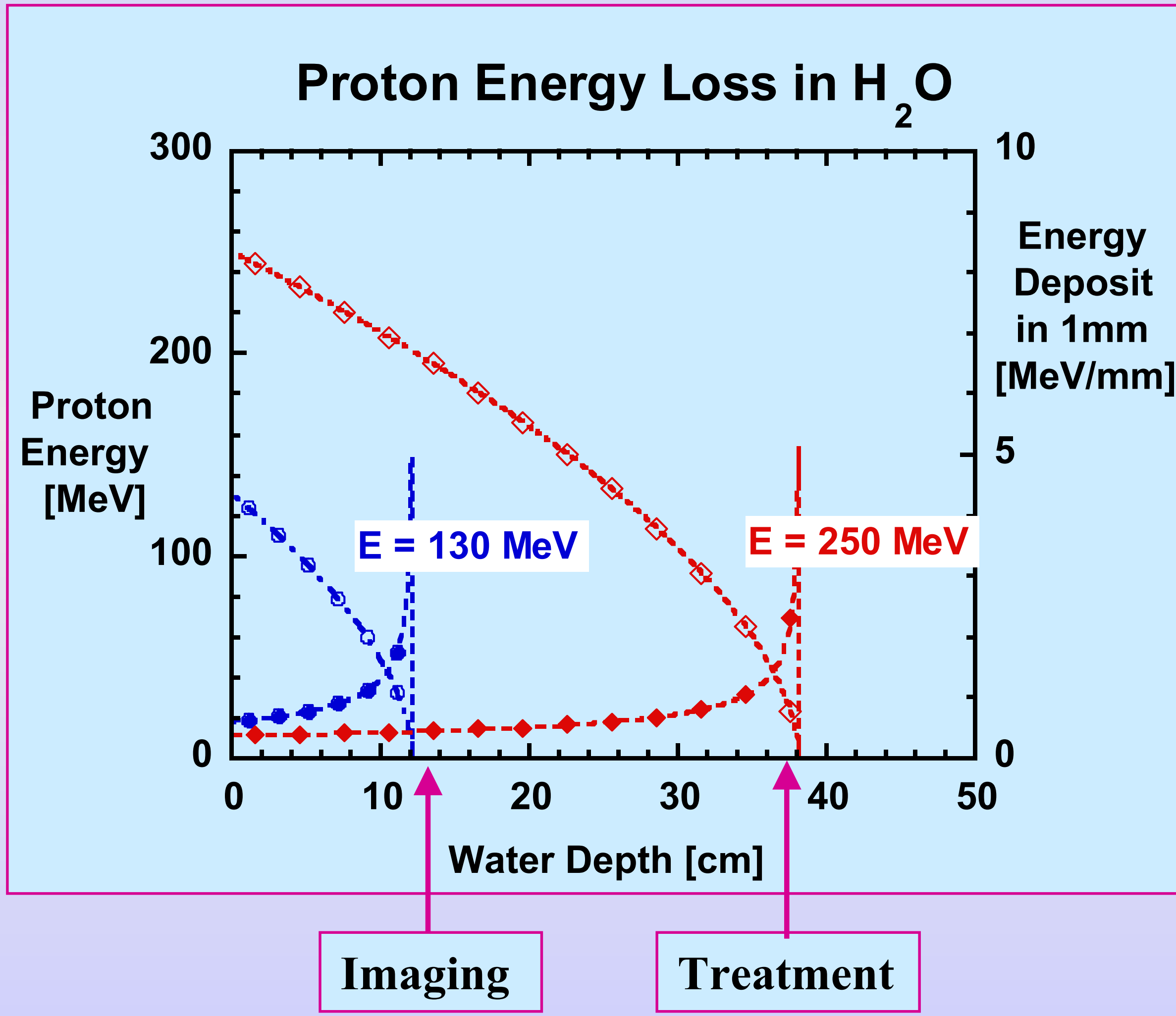
  (plateau)

- **Maximum dose at depth**

  (Bragg peak)

- **Rapid distal dose fall-off**

- **RBE close to unity**



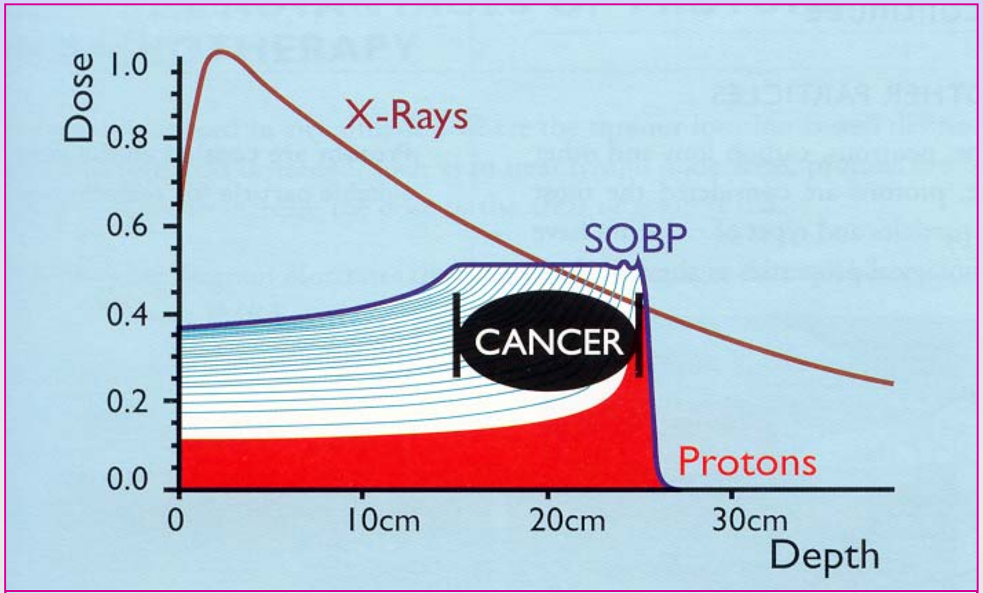
Protons vs. X-Rays in Therapy

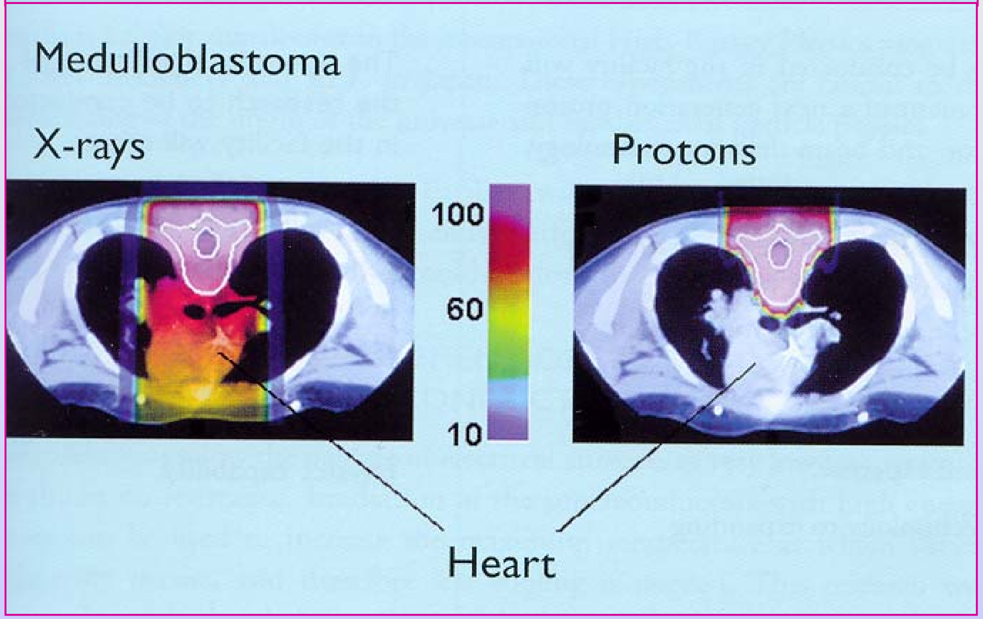
Protons:

- **Energy modulation spreads the Bragg peak across the malignancy**

X-rays:

- **High entrance dose**
- **Reduced dose at depth**
- **Slow distal dose fall-off leads to increased dose in non-target tissue**



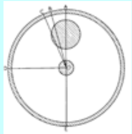


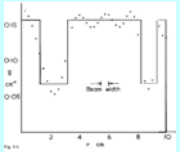
Milestones of Proton Computed Tomography

- **R. R. Wilson (1946)**

  Points out the Bragg peak, defined range of protons

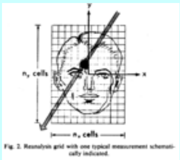
- **A. M. Cormack (1963)**





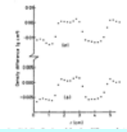
  Tomography

- **M. Goitein (1972)**



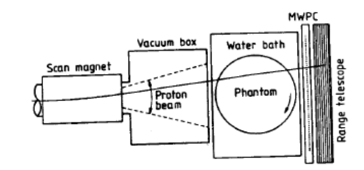
  2-D to 3-D, Simulations

- **A. M. Cormack & Koehler (1976)**



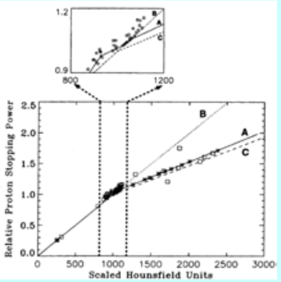
  Tomography, $\Delta\rho \approx 0.5$ %

- **K. M.Hanson et al. (1982)**



  Human tissue, Dose advantage

- **U. Schneider et al. (1996)**



  Calibration of CT values,
  Stoichiometric method

- **T. J. Satogata et al. (Poster M10-204)**

  Reduced Dose of Proton CT compared to X-Ray CT

What is new in pCT ?

- **Increased # of Facilities with gantries etc.**
  See the following talk by Stephen G. Peggs)
- **2 Ph.D. Theses at PSI and Harvard Cyclotron**
  (U. Schneider & P. Zygmanski)
- **Existence of high bandwidth detector systems for protons**
  - **semiconductors**
  - **high rate data acquisition (> MHz)**
  - **large-scale (6"wafers)**
  - **fine-grained (100's um pitch)**
- **Concerted simulation effort**
  - **Exploitation of angular and energy correlations**
  - **Support of data analysis**
  - **Optimization of pCT set-up (detector, energy, ..)**
  - **Dose calculation**

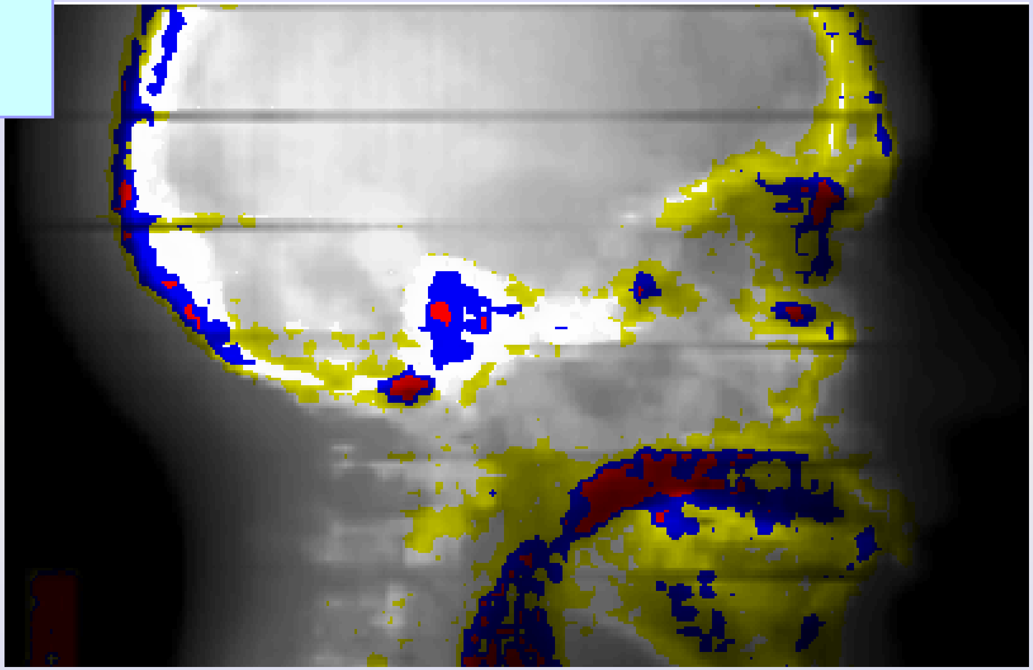
Potential of Proton CT: Treatment Planning

X-ray CT use in proton cancer therapy can lead to large uncertainties in range determination

Range Uncertainties (measured with PTR)

- Black: > 5 mm
- Blue: > 10 mm
- Red: > 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

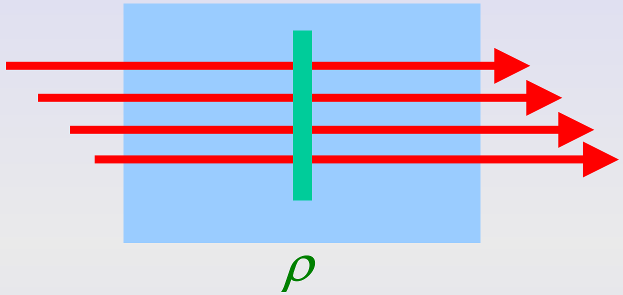
Proton CT can measure the density distribution needed for range calculation.

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

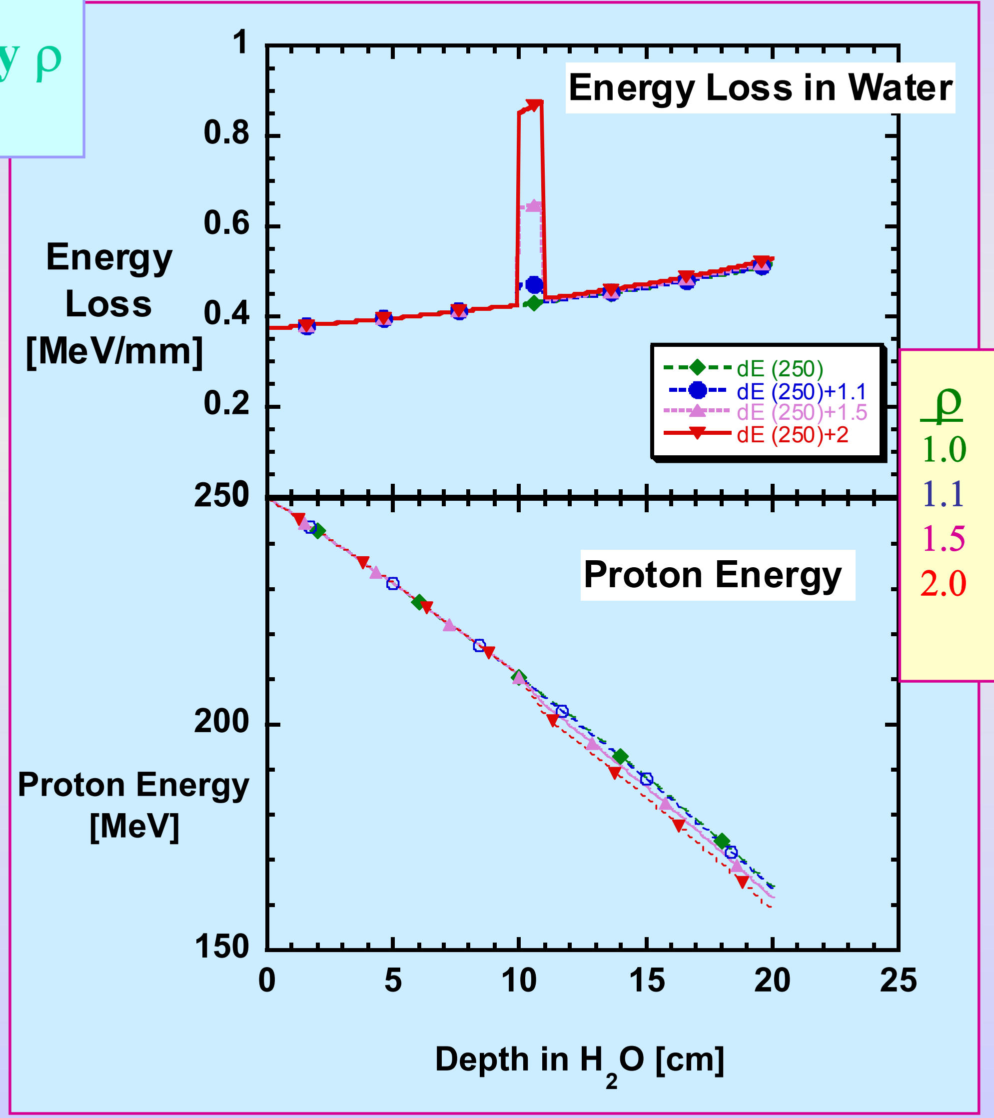
Low Contrast in Proton CT

Sensitivity Study:

Inclusion of 1cm thickness 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 much better than a degree**
  Multiple Coulomb Scattering $\Theta_{MCS} \approx 1^o$

$$\theta_{CMS} \approx \frac{13.6MeV}{\beta \cdot p} z\sqrt{l / X_0}$$

- **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**
  N/A = Fluence
  (for Voxel with diameter d = 1mm
  10^5 protons of 200 MeV = 7 [mGy])

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

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

$$\sigma_E \approx 1\%$$

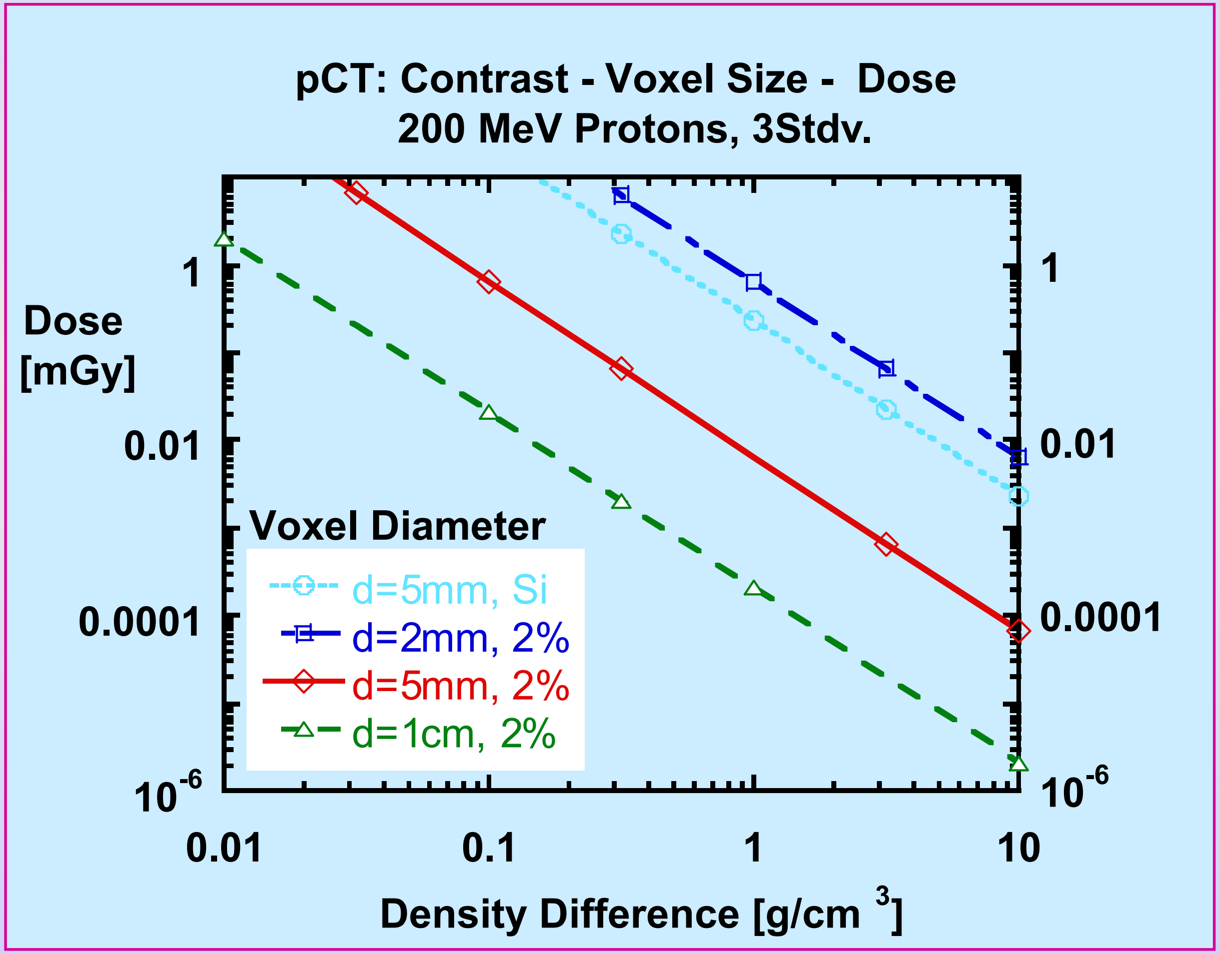
Dose vs. Voxel Size for pCT Measurements

Trade-off between Voxel size and Contrast (Δρ) to minimize the Dose

Define voxel of volume d^3
Dose in voxel = D_v
Take n =20cm/d settings
Total dose D = n* D_v

Require 3σ Significance

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

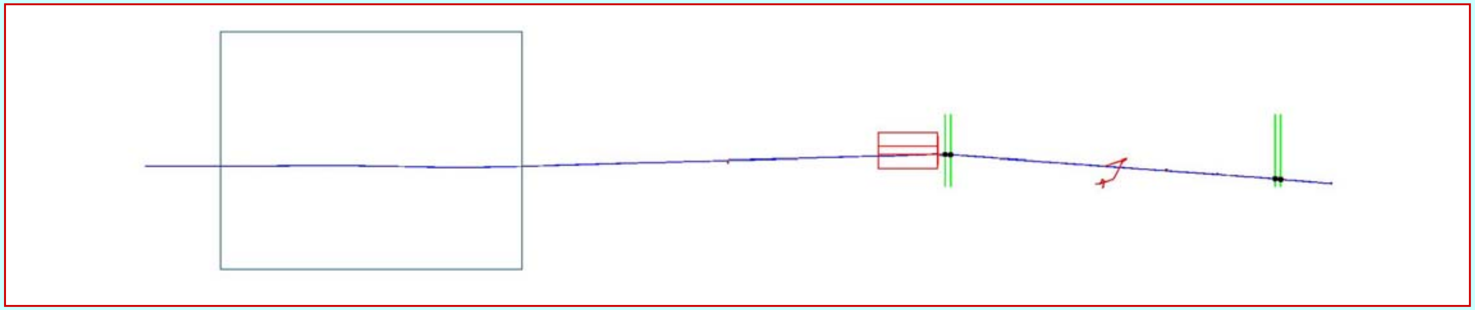


Studies in Proton Computed Tomography

Collaboration Loma Linda University Medical Center – UC Santa Cruz

- Exploratory Study in Proton Transmission Radiography
  - Silicon detector telescope
  - Simple phantom in front
  - Understand influence of multiple scattering and energy resolution on image

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



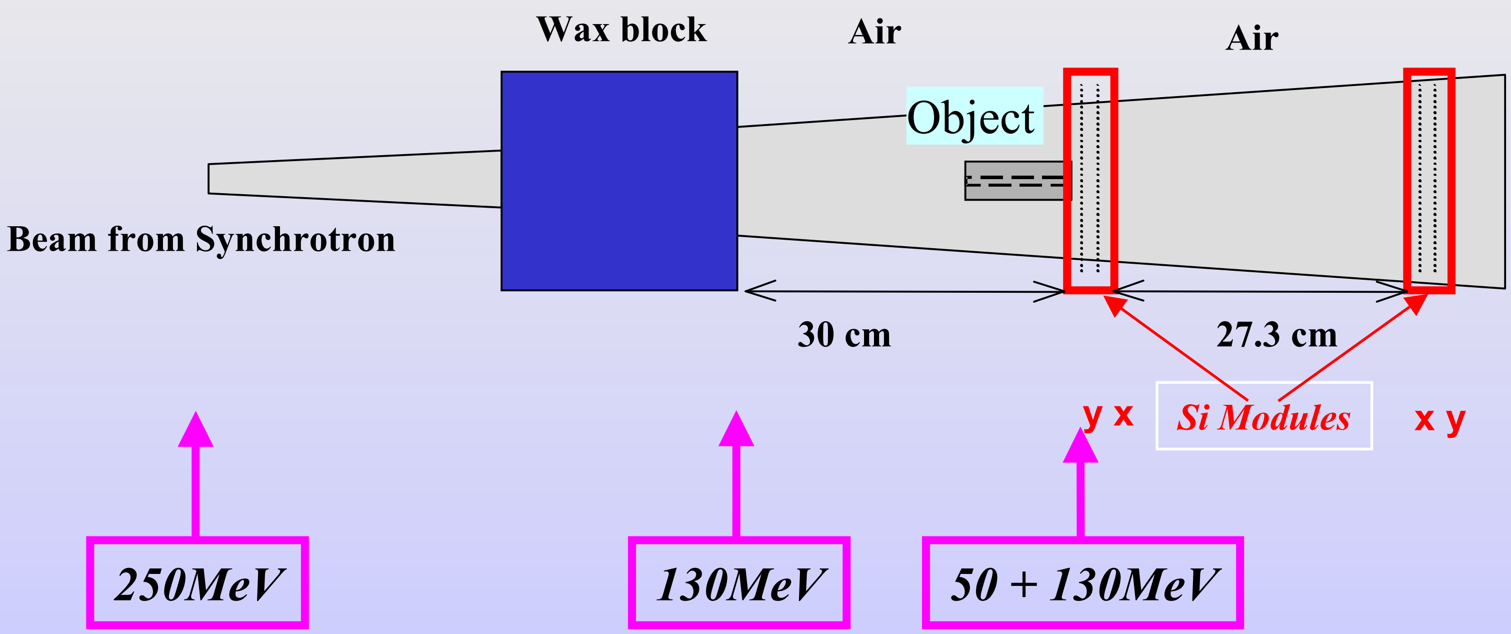
Exploratory Proton Radiography Set-up

Proton Beam from Loma Linda University Medical Ctr @ 250 MeV

Degraded down to 130 MeV by 10” wax block

Object is aluminum annulus 5 cm long, 3 cm OD, 0.67 cm 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



Silicon Detector Telescope

Simple 2D Silicon Strip Detector (SSD) Telescope of 2 x-y modules

built for Nanodosimetry

- **2 single-sided SSD / module**

  measure x-y coordinates

- **GLAST Space Mission developed SSD**

  194 µm pitch, 400 µm thickness

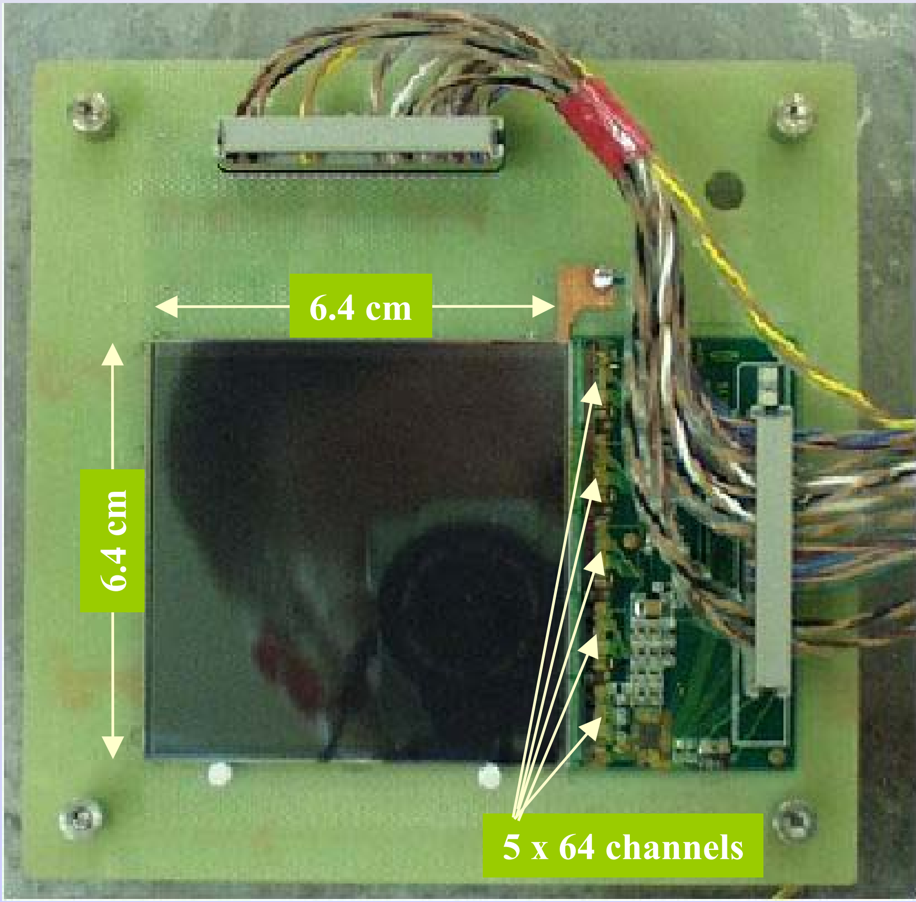
- **GLAST Readout**

  1.3 µs shaping time

  Binary readout

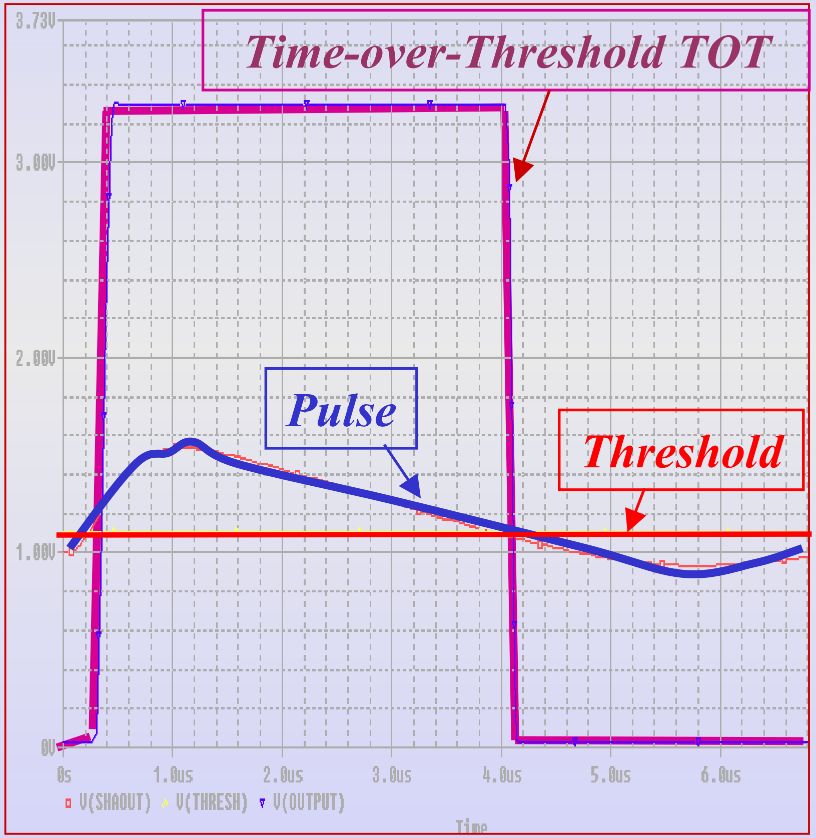
  Time-over-Threshold TOT

  Large dynamic range

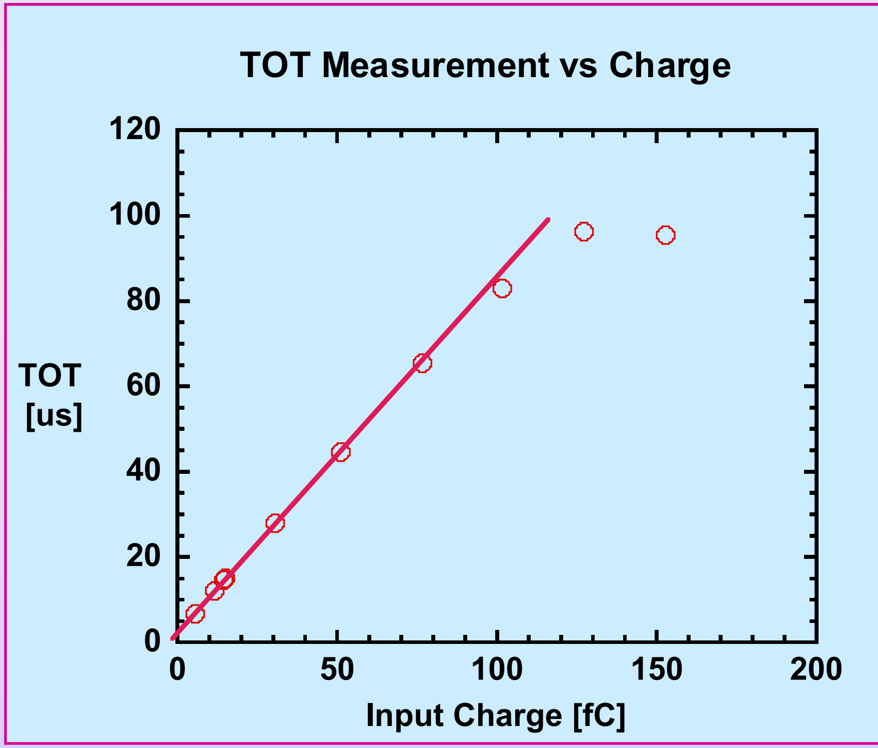


Time-Over-Threshold ~ Energy Transfer

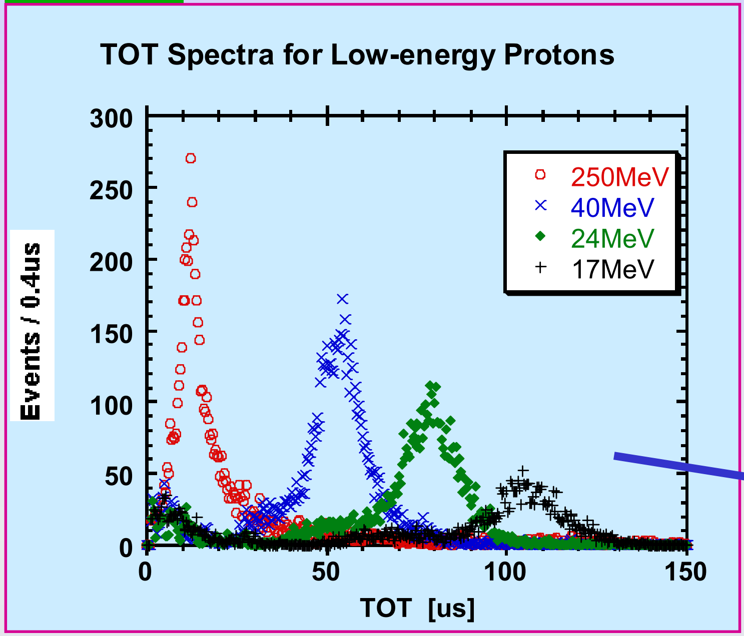
Digitization of position (hit channel) and energy deposit (TOT)



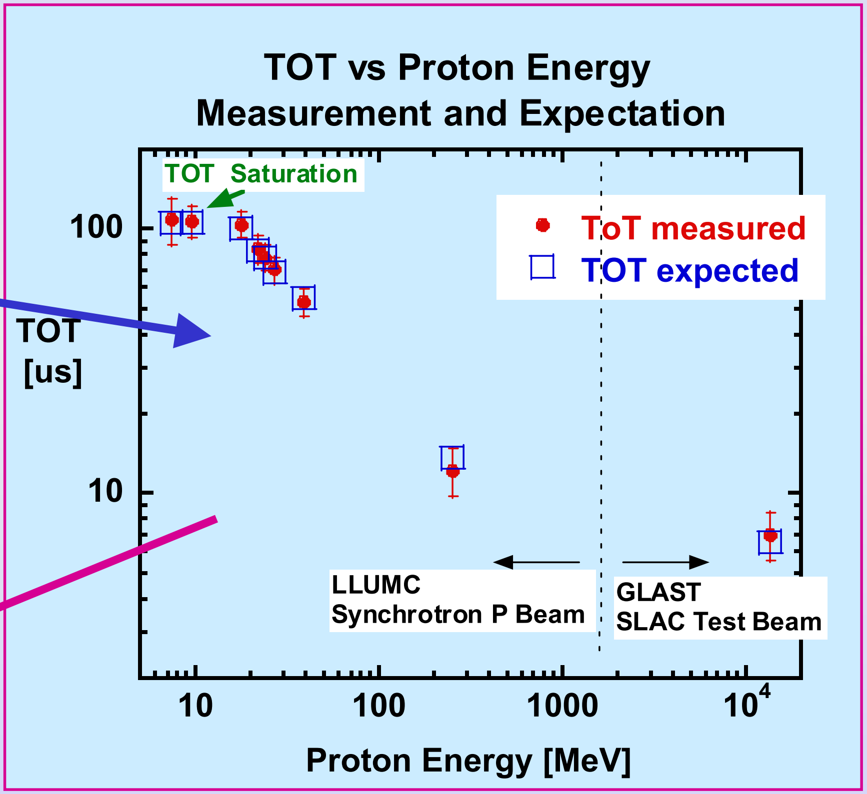
TOT ∝ charge ∝ LET

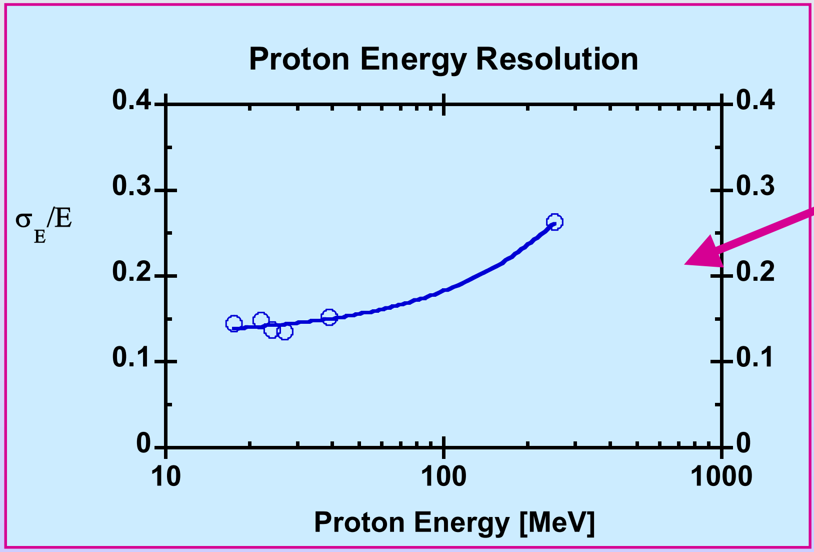


Calibration of Proton Energy vs. TOT



Good agreement between measurement and MC simulations





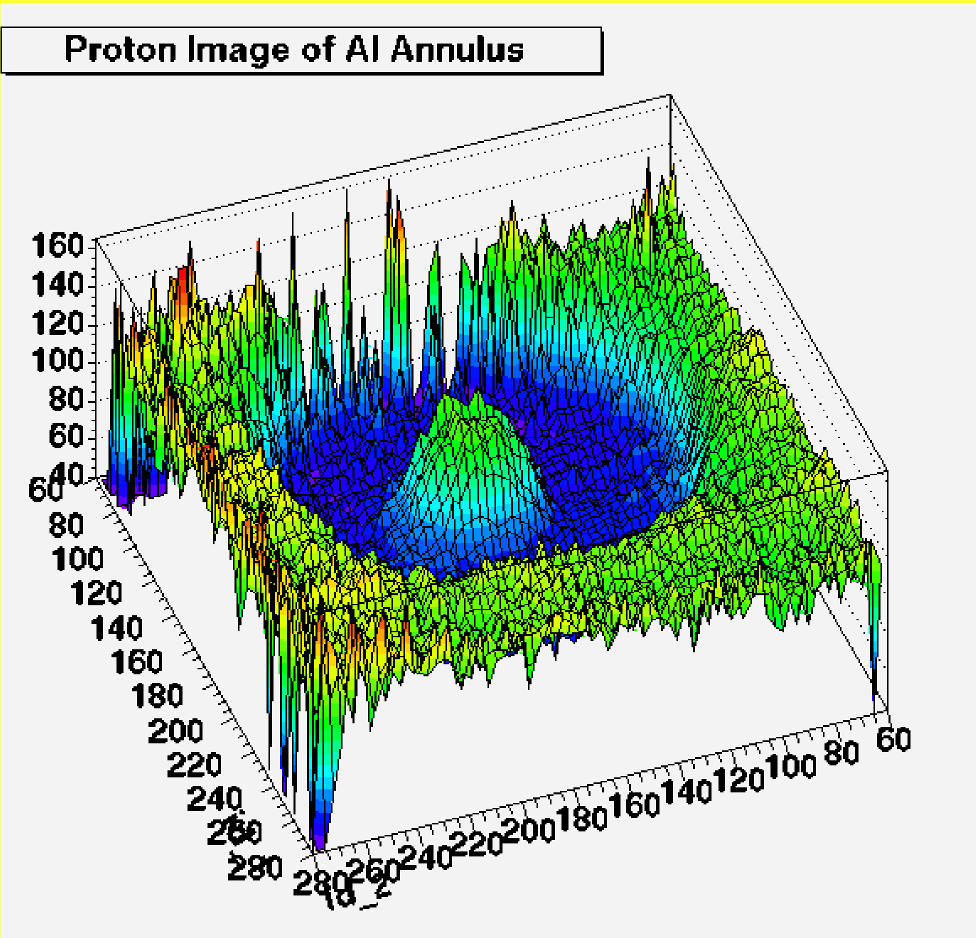
Derive energy resolution from TOT vs. E plot

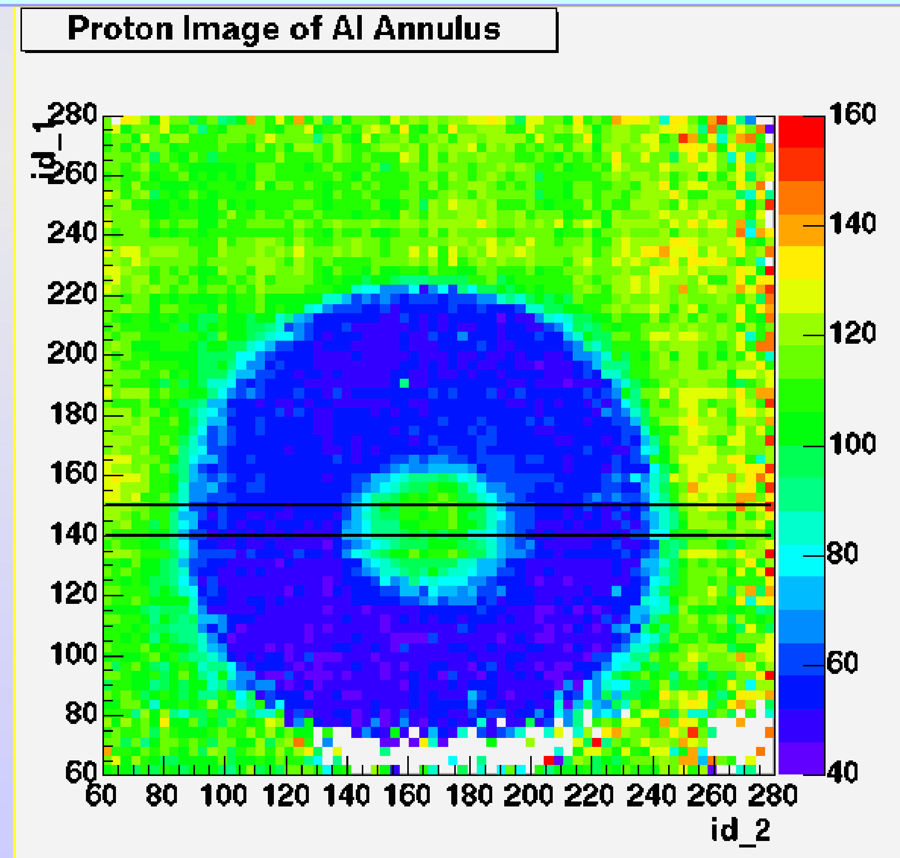
Image of Al Annulus

Subdivide SSD area into pixels

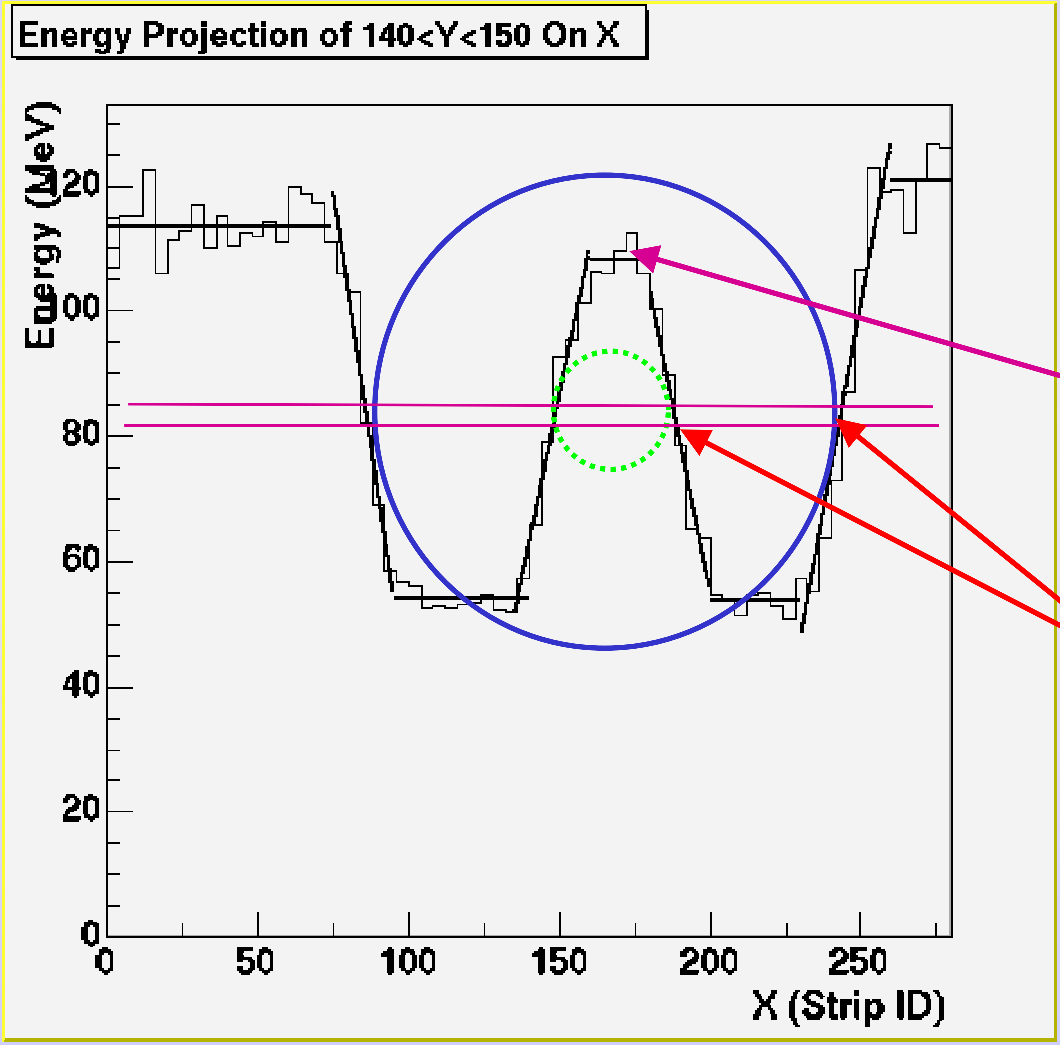
1. **Strip x strip 194um x 194um**
2. **4 x 4 strips (0.8mm x 0.8mm)**

Image corresponds to average energy in pixel





Energy Resolution => Position Resolution



Slice of average pixel energy in 4x4 pixels
(need to apply off-line calibration!)

Hole "filled in"

"Fuzzy" Edges

Clear profile of pipe, but interfaces are blurred

Multiple Scattering: Migration

Image Features:

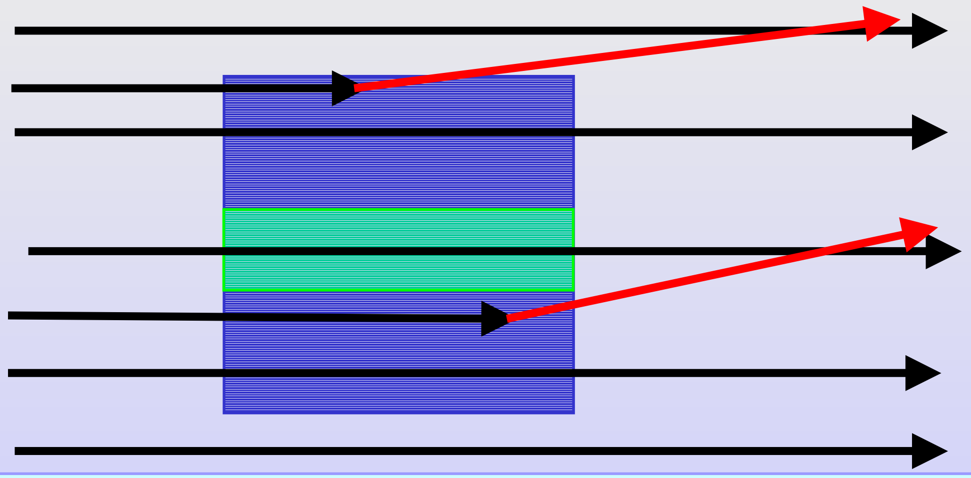
Washed out image in 2nd plane (30cm downstream)

Energy diluted at interfaces

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

Migration of events

are explained by Multiple Coulomb Scattering MCS



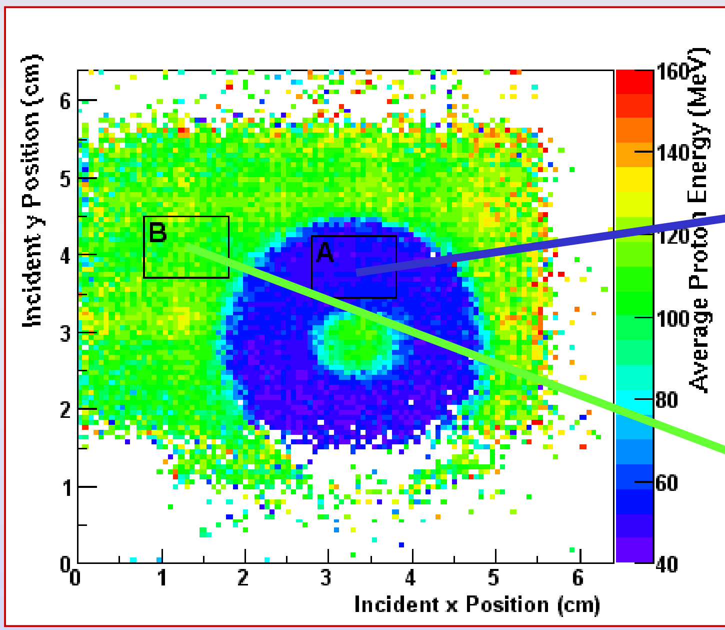
Protons scatter OUT OF target (not INTO).

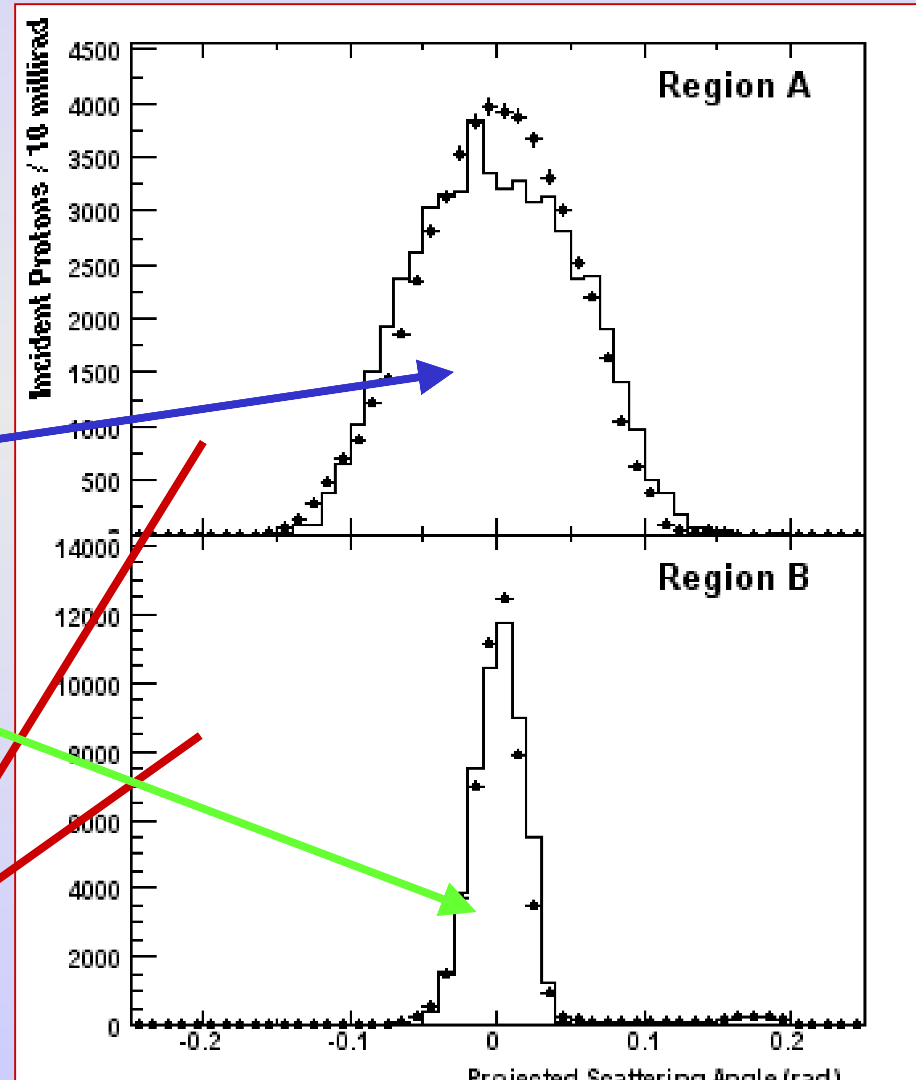
Scatters have larger energy loss, larger angles, fill hole, dilute energy

GEANT4 MC: Use of Angular Information

Si Telescope allows reconstruction of beam divergence and scattering angles

Select 2 Areas in both MC and Data
A = inside annulus : Wax + Al
B = outside annulus : Wax only



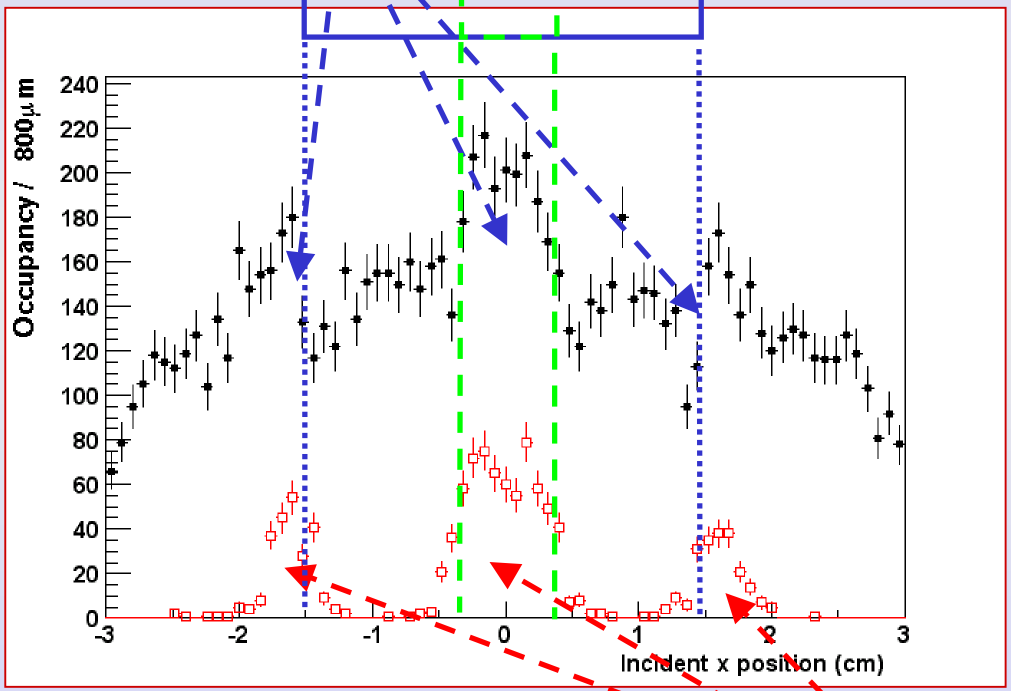


Angular distributions well understood

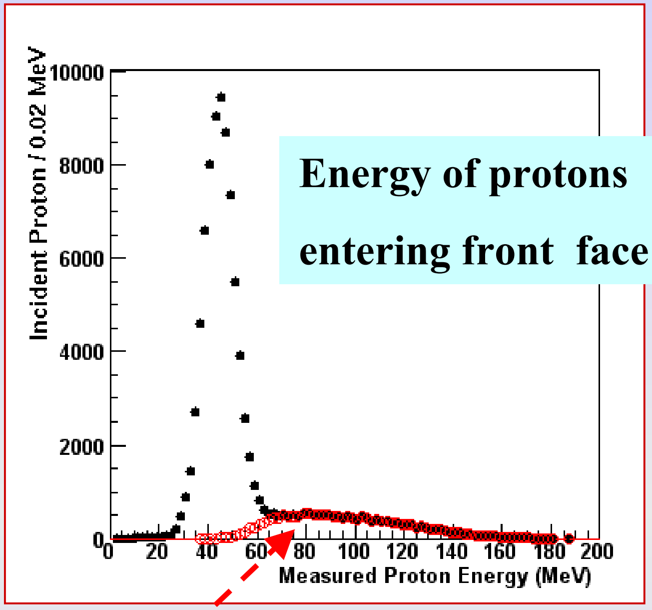
GEANT4 MC: Migration

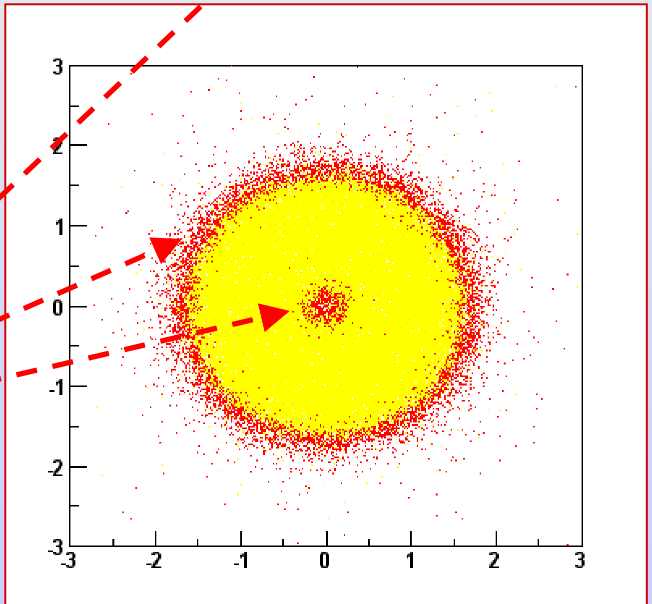
Beam profile in slice

Migration out of object



Energy of protons entering front face

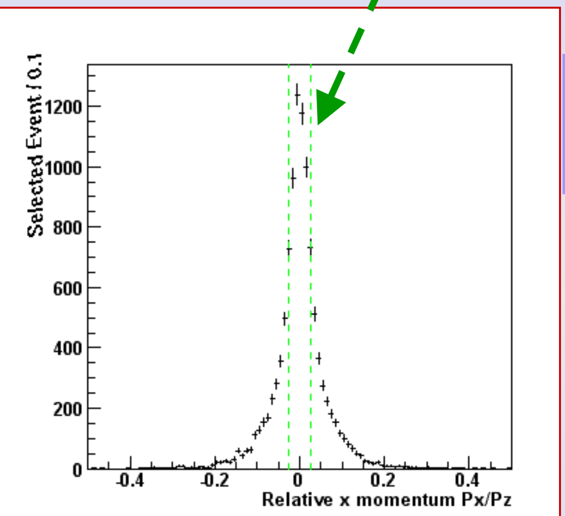




Protons entering the object in front face but leaving it before the rear face

GEANT4 MC: Use of Angular Information

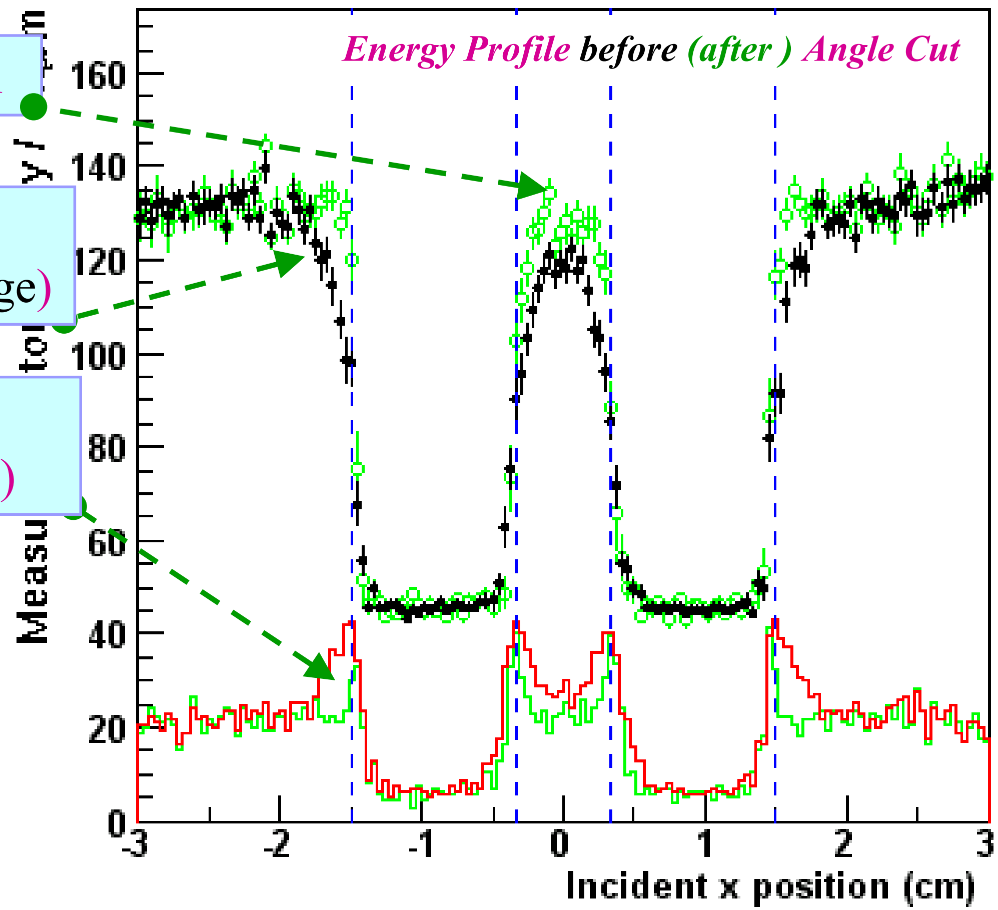
Angular Cut at Θ_{MCS} of the Wax



Less Migration

Sharp Edges
(Energy Average)

Sharp Edges
(Energy RMS)



Energy RMS before (after) Angle Cut

Angular cut improves the contrast at the interfaces

Conclusions

Present status of pCT:

- **Long tradition, increased interest with many new proton accelerators**

  (see next talk by Stephen G. Peggs)
- **pCT will be useful for treatment planning**

  (reconstruction of true density distribution)
- **Potential dose advantage wrt X-rays**

  (see Poster M10-204 by Satogata *et al.*)
- **Use of GEANT4 simulation program aids in planning of experiments**

  (correlation of energy and angle, "migration")

  (see Poster M6-2, L. R. Johnson *et al.)*

Our future plans:

- **Optimization of beam energy**
- **Investigation of optimal energy measurement method**
- **Dose – contrast - resolution relationship on realistic phantoms**