Calibration of the Range Stack Detector for the NIU proton CT head scanner

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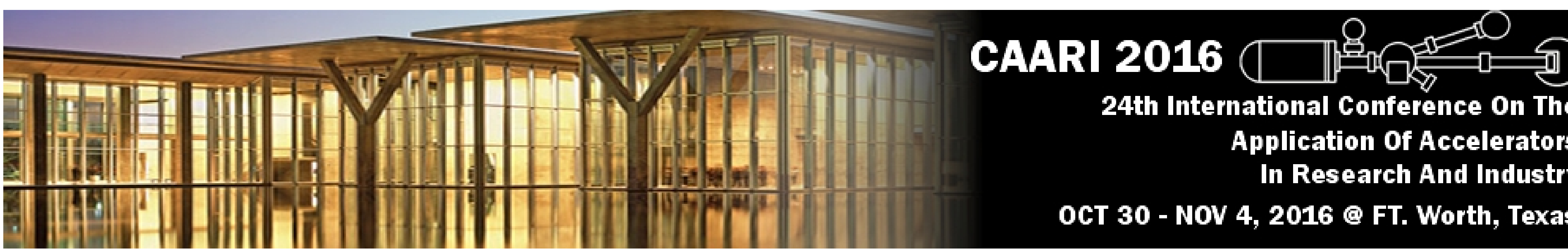
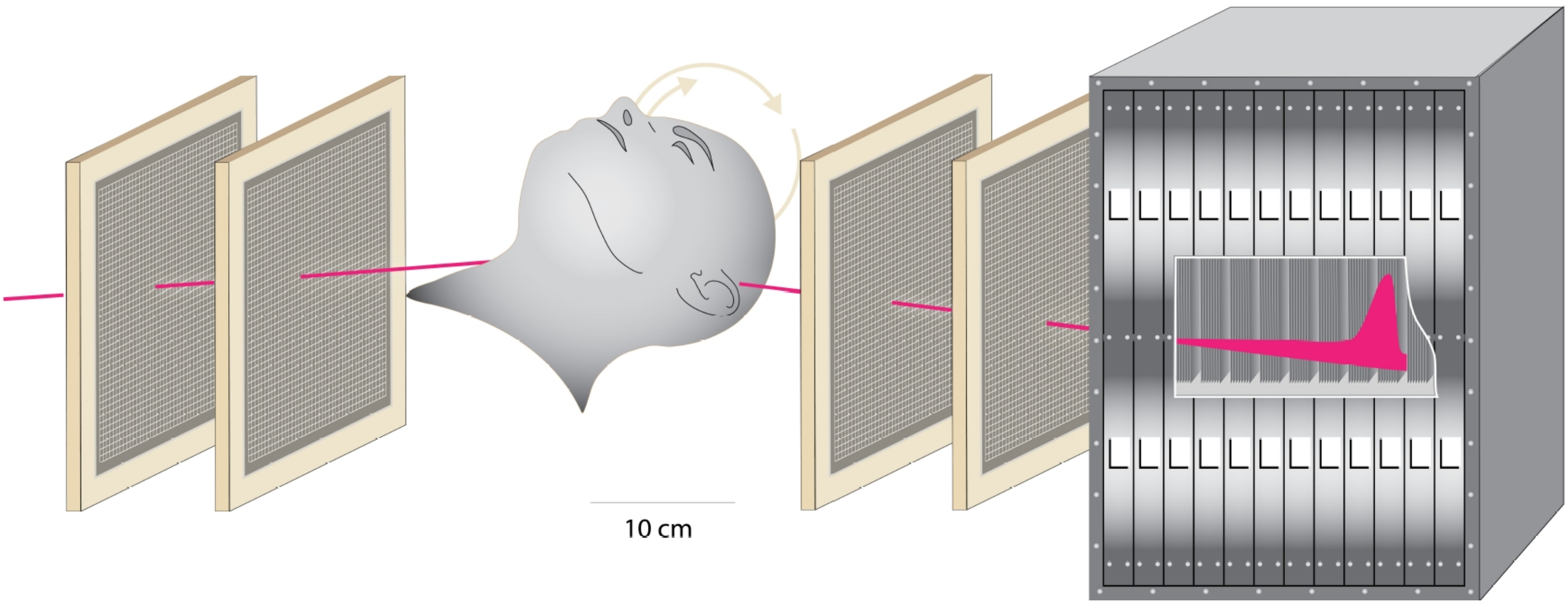


NICADD/NIU, FNAL, Dehli pCT Detector Schematic



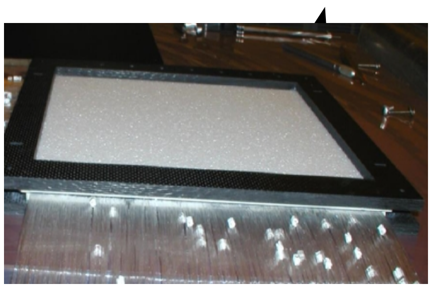
Four (X,Y) stations measure the proton trajectory before and after the patient.
A stack of 3.2~mm thick scintillator tiles measures the residual energy or range after the patient.

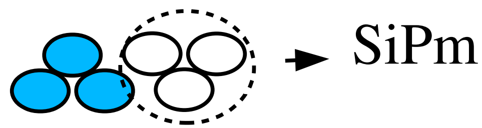
Detector components

Fiber tracker planes , 4 X-Y stations

0.5 mm scint. fibers (Kuraray)

20x24 cm (front FT), 24x30cm (back)

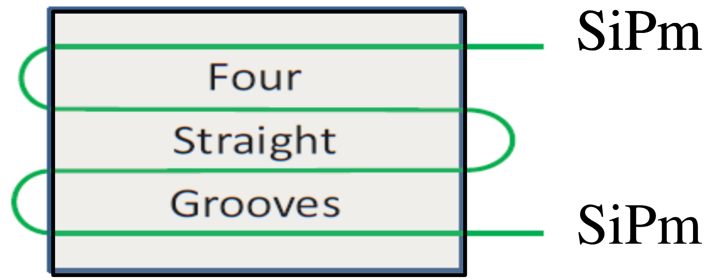




213-320 3-fiber bundles per plane

Range detector (96 scintillator tiles)

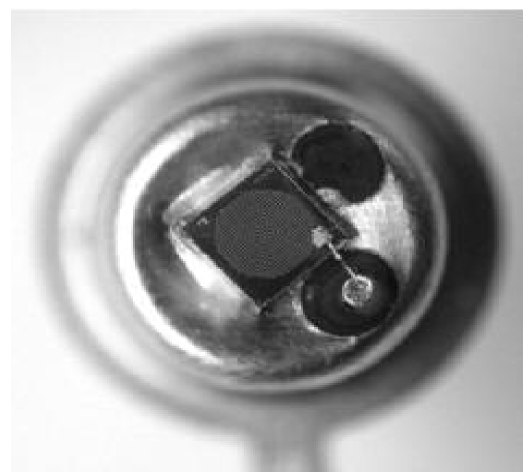
1.2mm WLS fibers in (27x36x3.2mm)



CPTA 151-30:

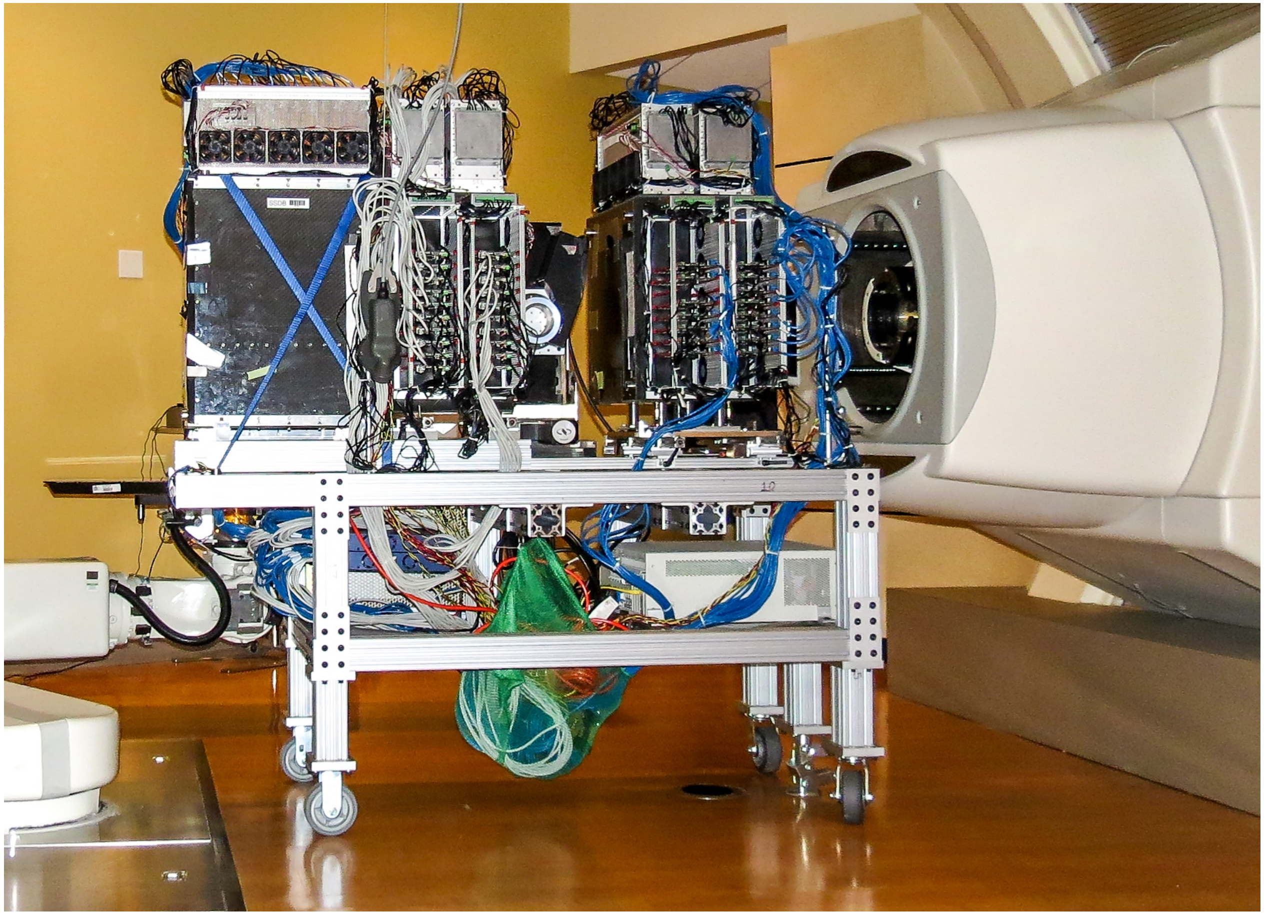
- area 1.28 mm, 796 pixels
- gain 50 ADC/photo electron

- ~2200 readout channels



SiPMs used both for the fiber tracker stations and the range detector

Fully assembled proton CT scanner at CDH Proton center.



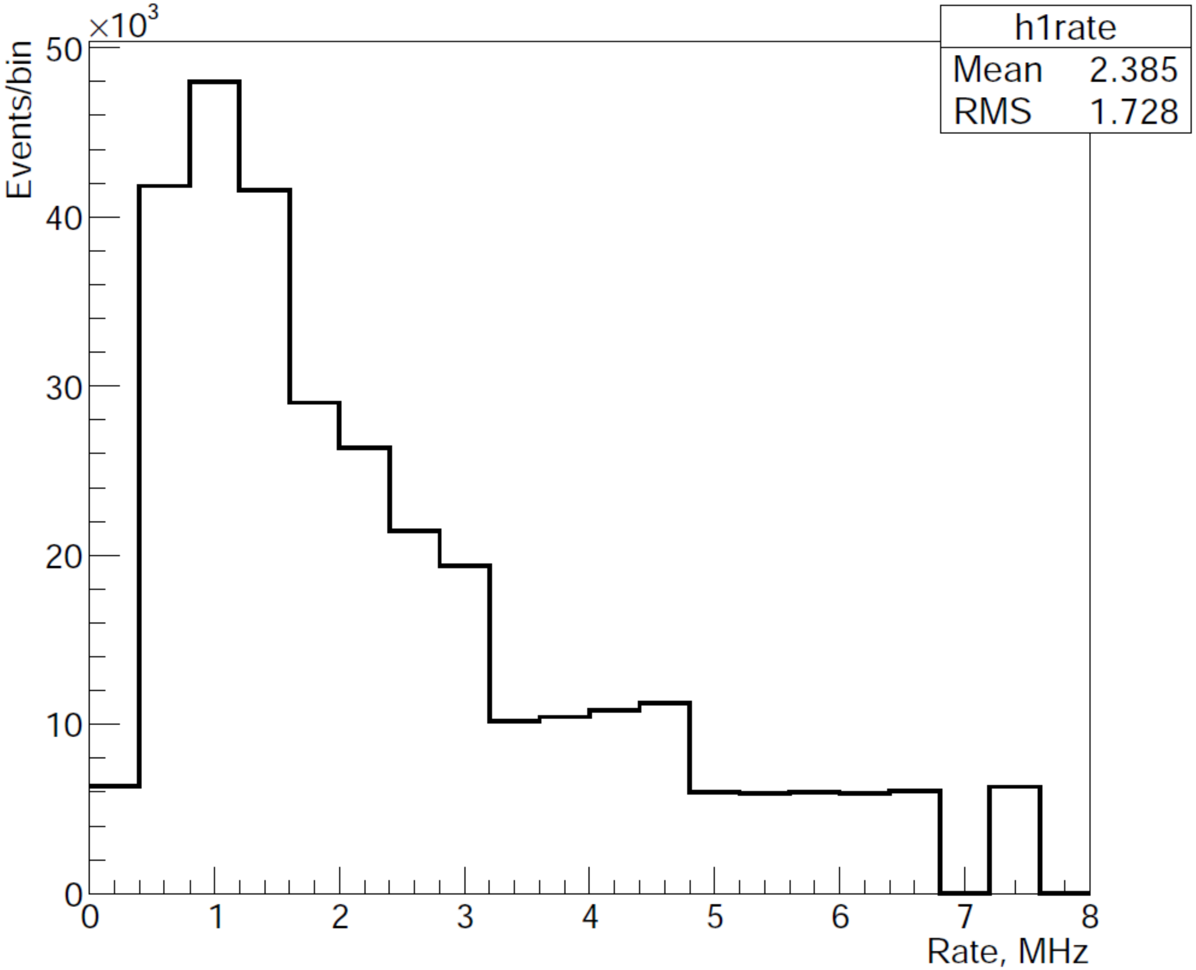
From right to left, beam enters the upstream tracker planes followed by the downstream tracker planes and finally the range stack. The gap in the middle is where the rotation stage for the head phantom in the horizontal plane is placed.

The Data Acquisition system

- Designed to operate at rate of 2 MHz.
- The 72 front-end electronics boards provide readout and digitization of the tracker (about 2100 data channels) and the range detector (192 data channels).
- The front-end data are collected by the mobile data acquisition (DAQ) computer cluster via 20 Gb/s HDMI link.
- Data are distributed between 24 data collectors running on six DAQ worker nodes. Each DAQ node is able to acquire into RAM up to 48 GB of data at a maximum rate of 240 MB/s per workstation

  The collected data are stored on a disk drive.
- Offline, through post processing of the data, the proton candidate events are formed from tracker and scintillator hits within 100 ns time window.

DAQ rate test

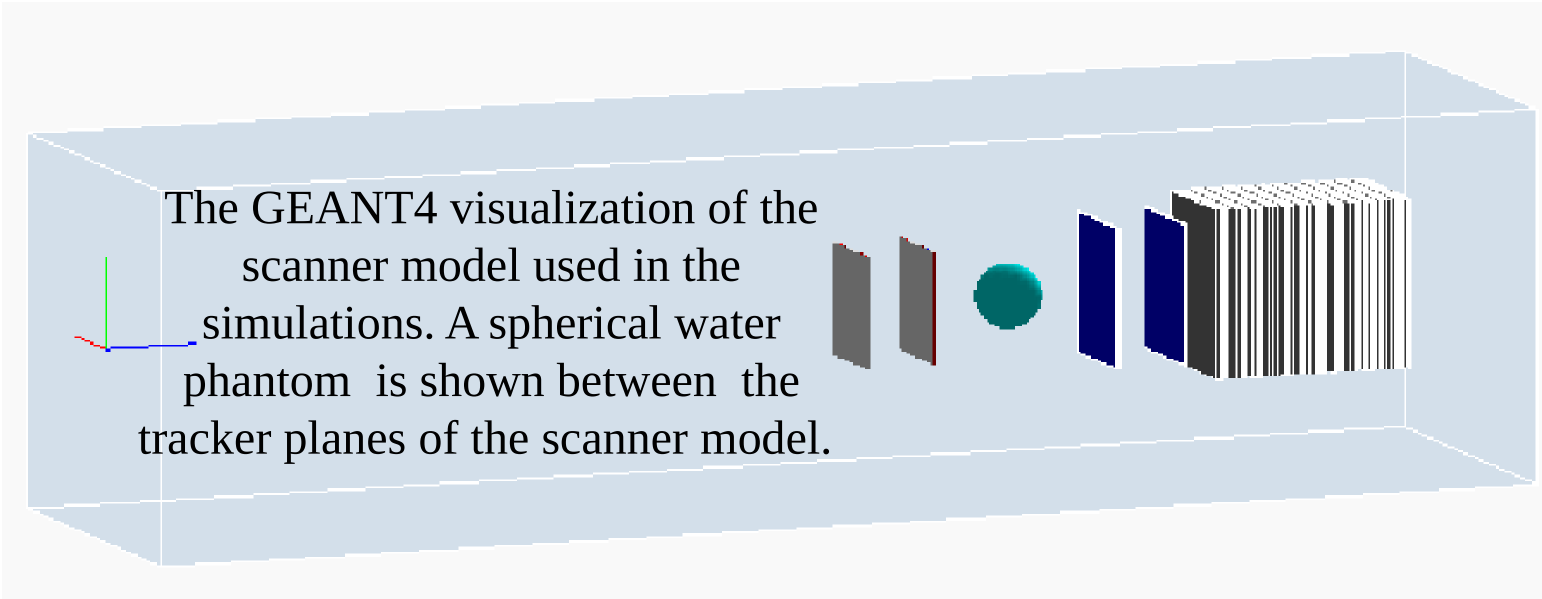


The 200 MeV proton candidates collection rate. Only events with more than five stack tiles signals above noise level are counted.

Beam tests at the Central DuPage Hospital (Warrenville, IL)

- A photo-electron (PE) calibration of the range detector and verification of the DAQ system functionality.
- Measurements of energy deposition and proton stopping position in a narrow beams of protons with energies in the range of 80-225 MeV.
- High intensity beams tests - to measure the ability to operate at the design rate.
- A detailed head model [2] exposed in a 200 MeV beam to collect data for image reconstruction.

The GEANT 4 scanner model

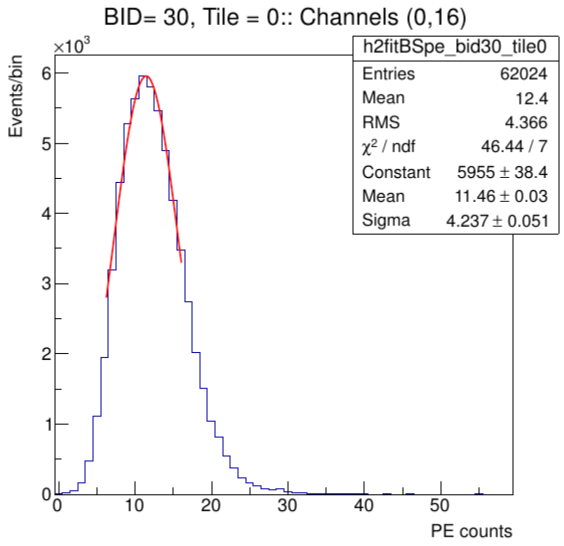


- A G4 simulation: accurate detector description; water and head phantoms; cone and pencil beam types

- to obtain energy profile (normalized to 200~MeV proton signal in Tile0) and stopping position in the range stack

- incident proton energy at CDH is given in stopping range in water; We used Ep = (Rp/0.0022)(1/1.77) conversion from energy - stopping range tables

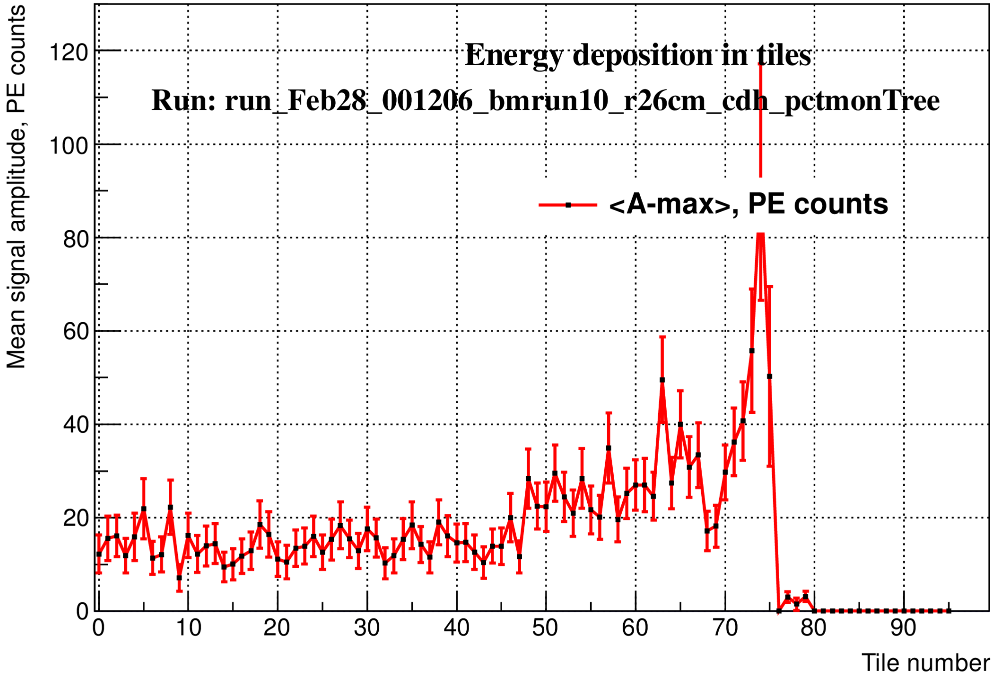
The Range Stack



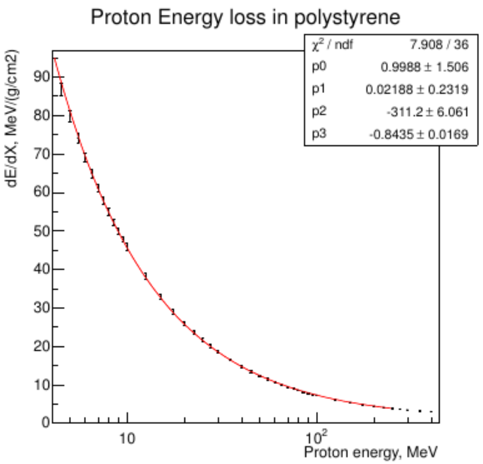
Able to measure proton energy deposition profile

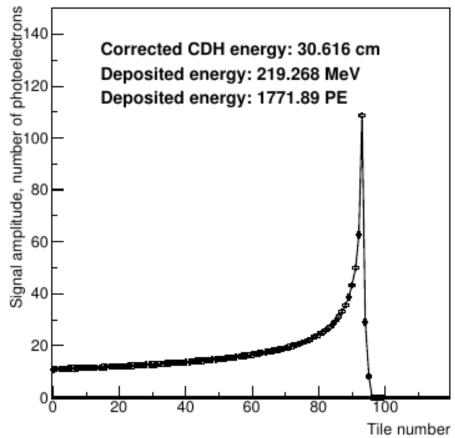
- the total deposited energy (up to 225 MeV)
- the proton stopping position (Bragg Peak)

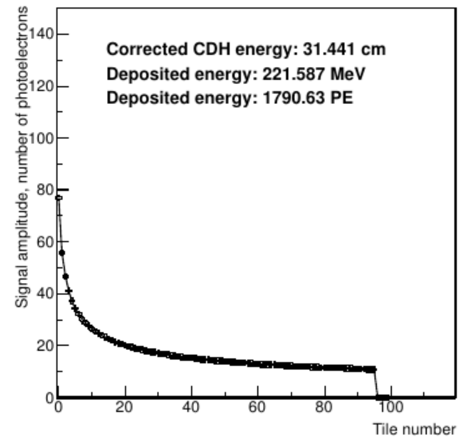
Challenge – 196 SiPMs, 96 tiles to calibrate

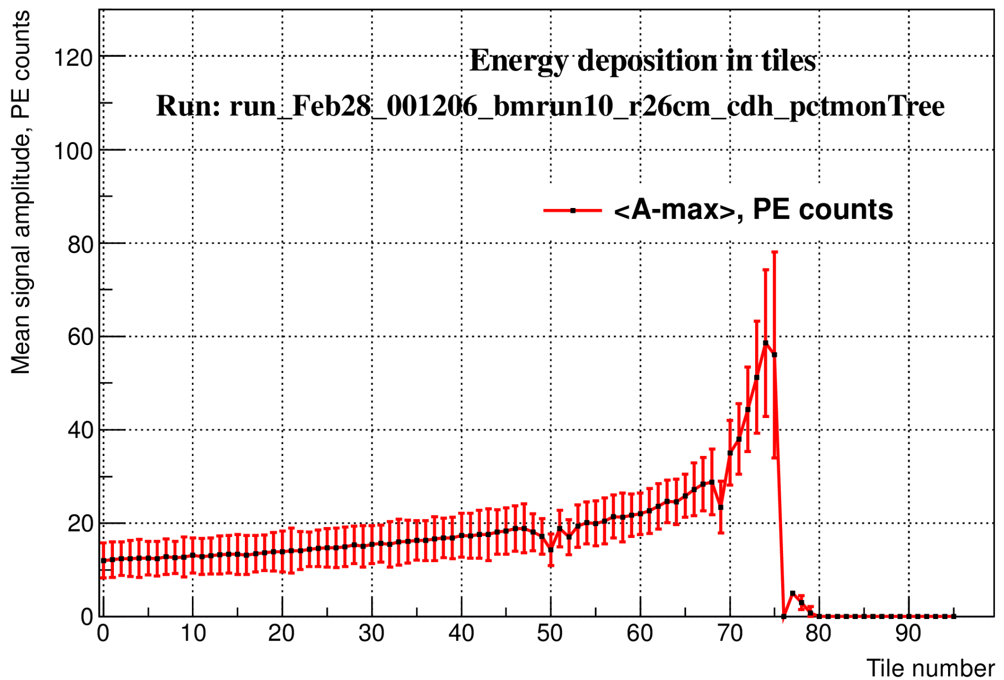


Range Stack Calibration

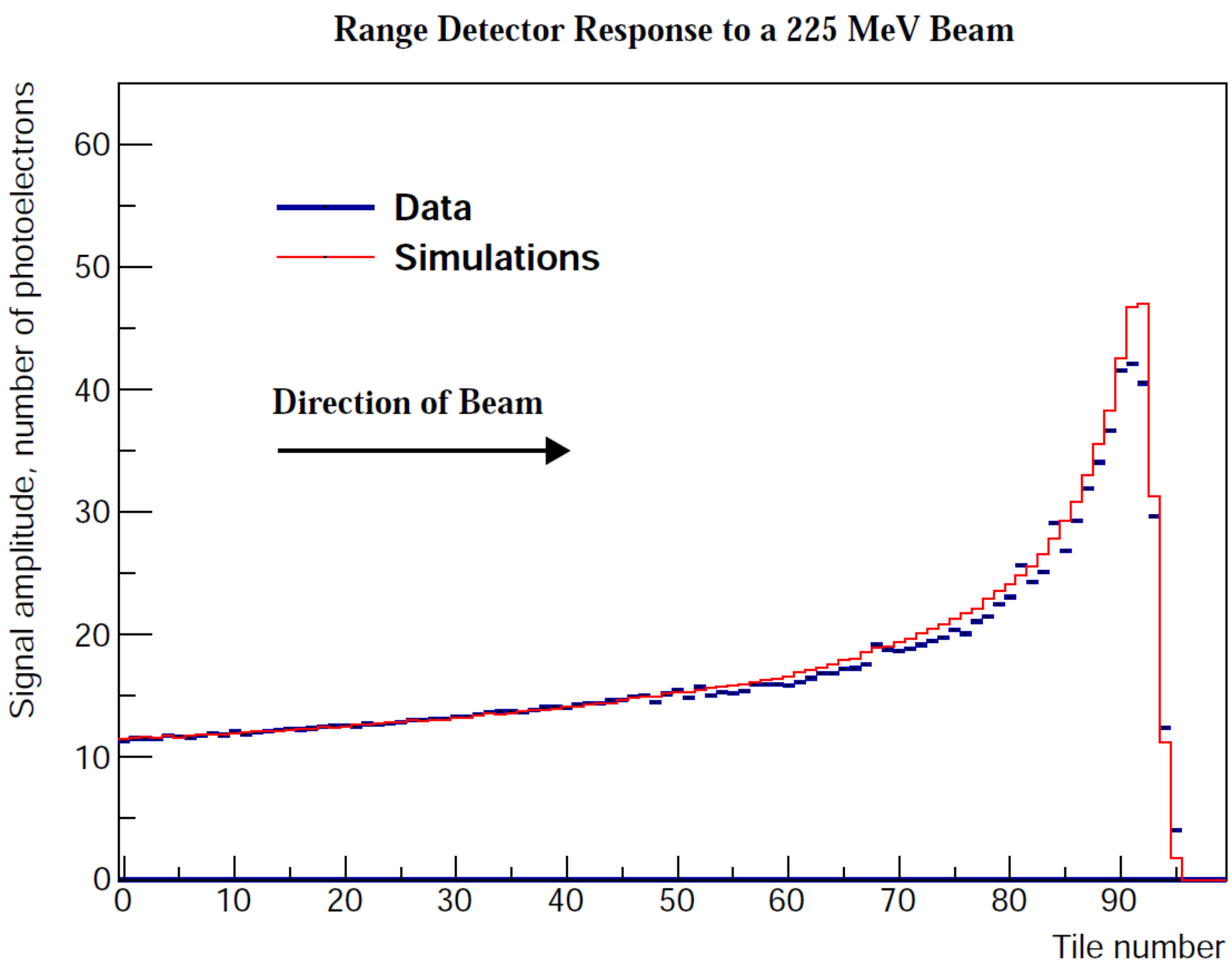








The Range Stack Energy profile



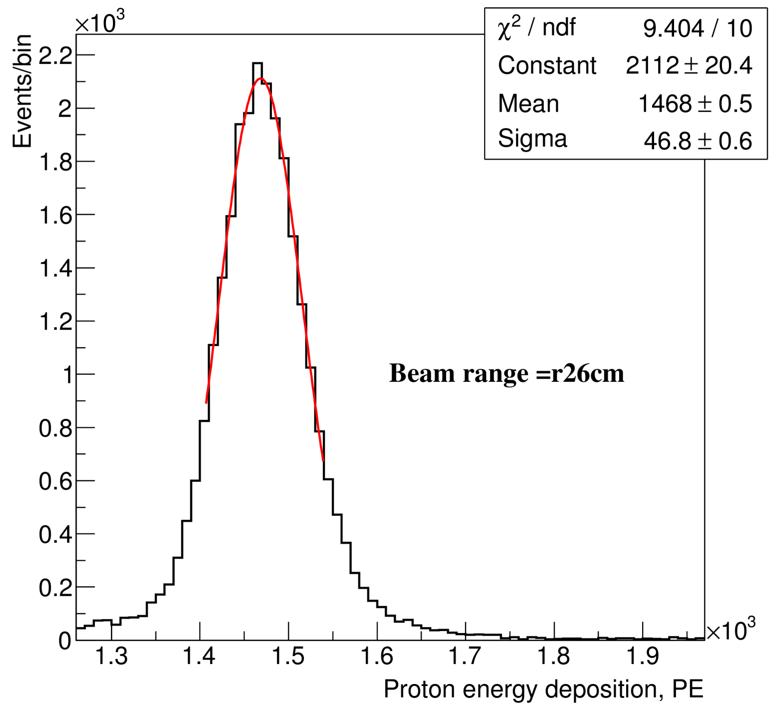
Comparison of the measured (blue dots) and expected (red histogram) signal profiles in the range stack from protons of incident energy of 225 MeV

WEPL for the Image

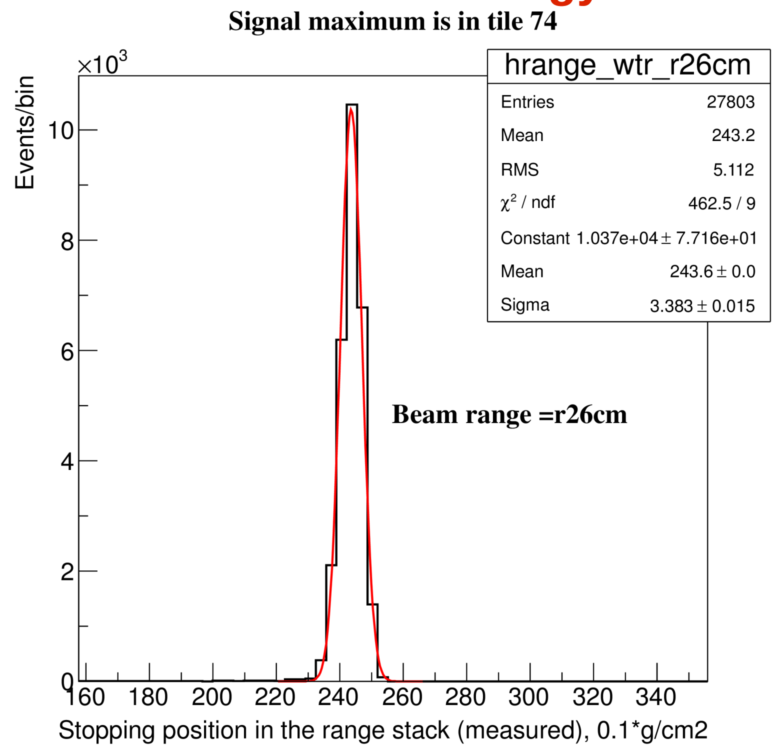
- Image reconstruction software uses WEPL of a scanned object that can be obtained from the known beam energy and WEPL measured in the range stack:

$$WEPL_{obj} = E_{beam}(cm) - \mathbf{WEPL_{rs}\ (E_{rs}\ or\ R_{rs})}$$

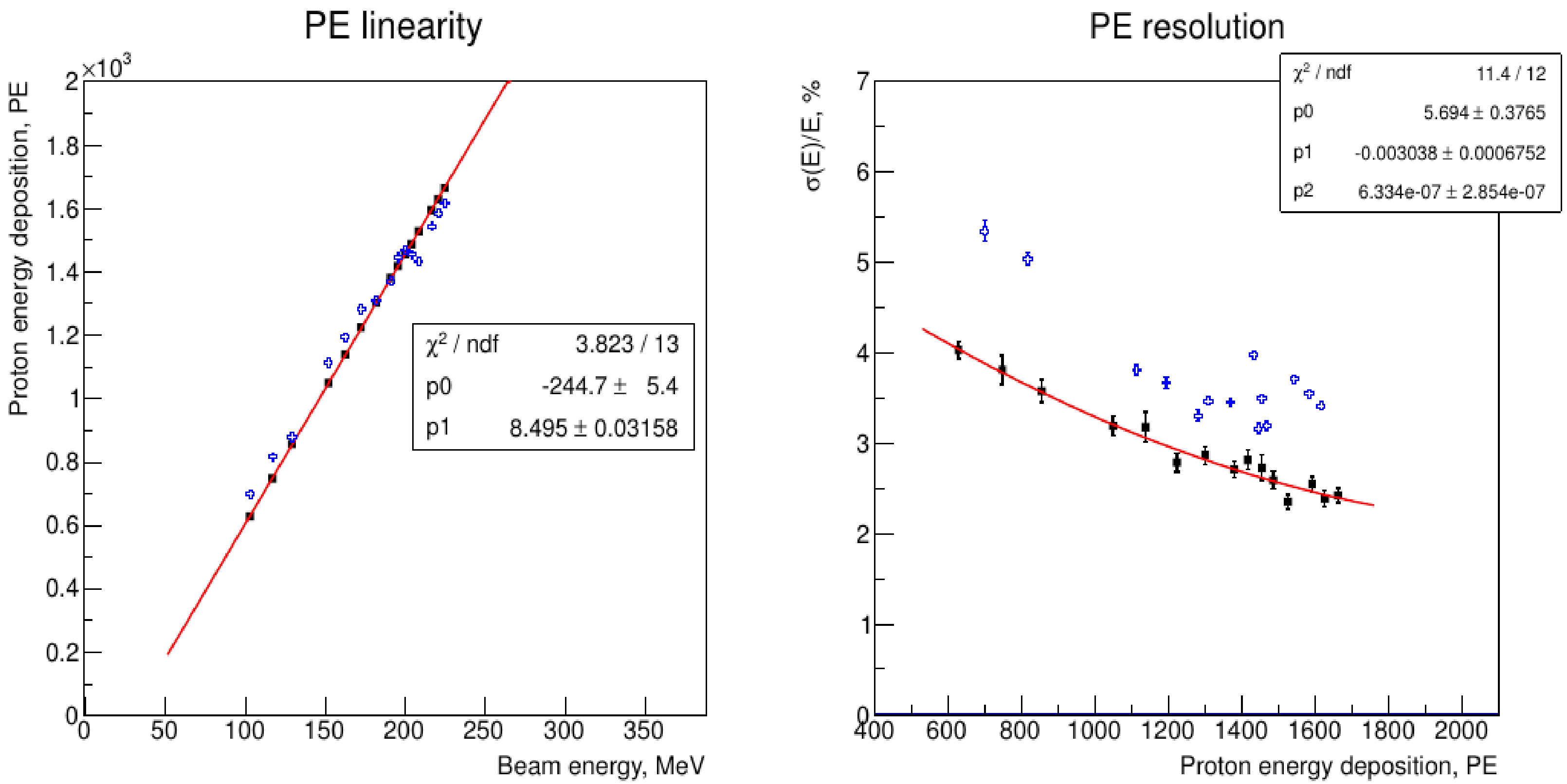
E_{rs} == Total energy measured by the Range stack



R_{rs} == stopping position calculted from the position of the tile with maximum energy

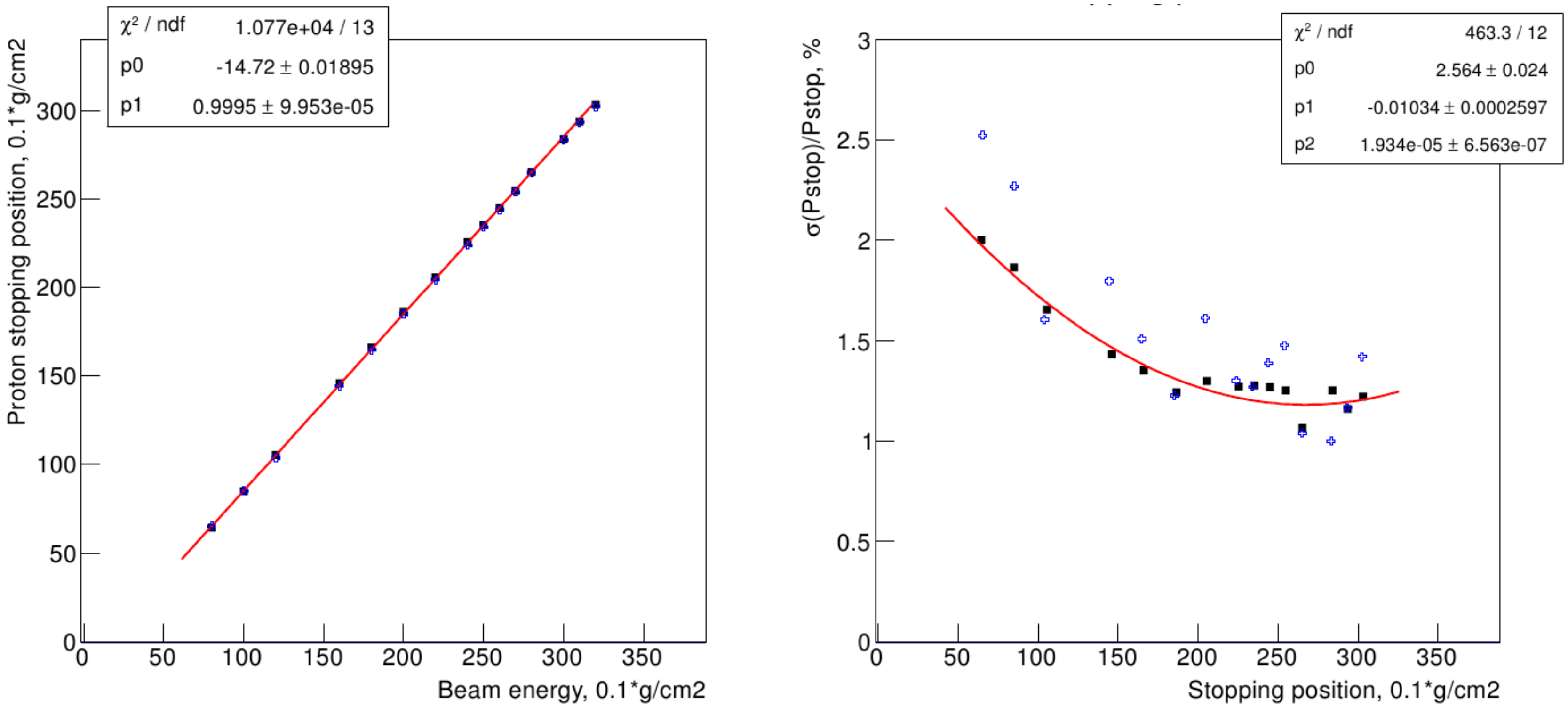


Total energy measurements



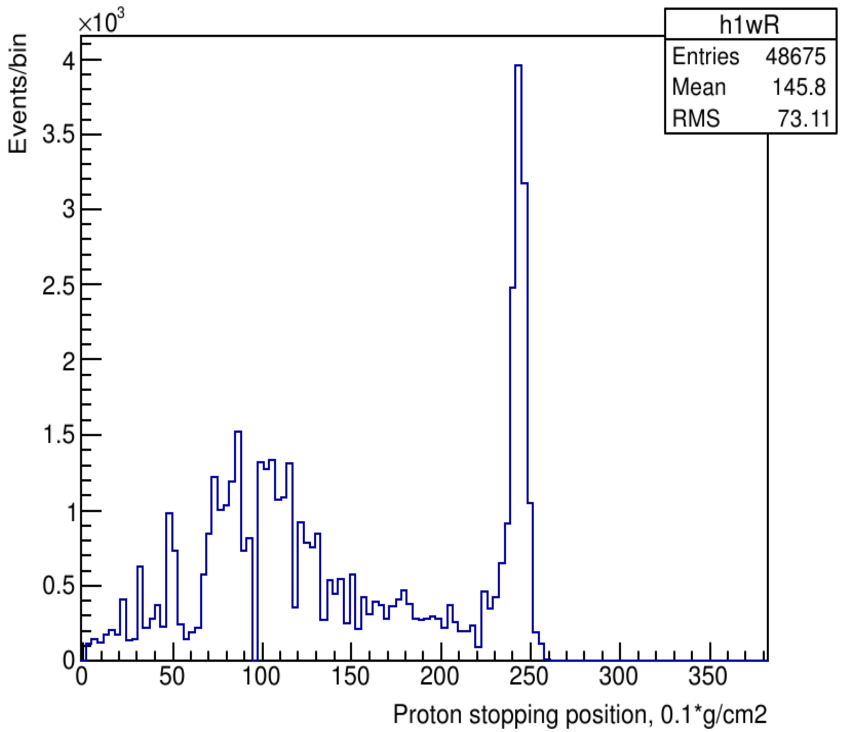
Comparison of the linearity (left) and resolution (right) of the energy measurements in the range stack in data and GEANT. Fits correspond to simulated results (black squares). Data shown as ``blue crosses``.

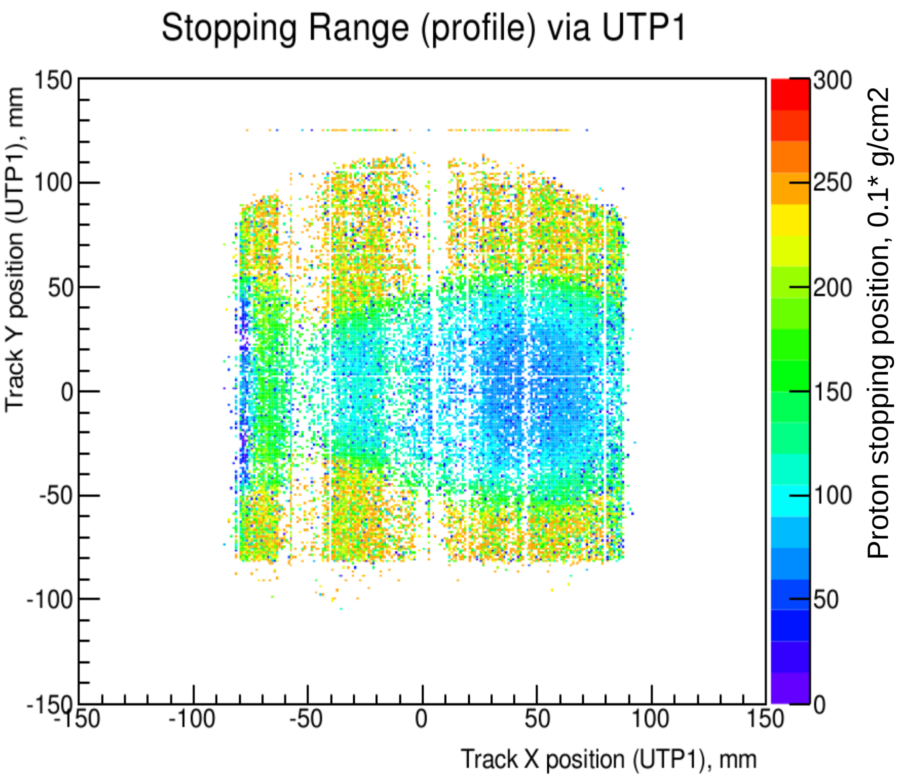
Proton stopping position measurements



Comparison of the linearity (left) and resolution (right) of the proton stopping position measurements in the range stack in data and GEANT. Fits correspond to simulated results (black squares). Data shown as ``blue crosses``.

Head phantom beam studies





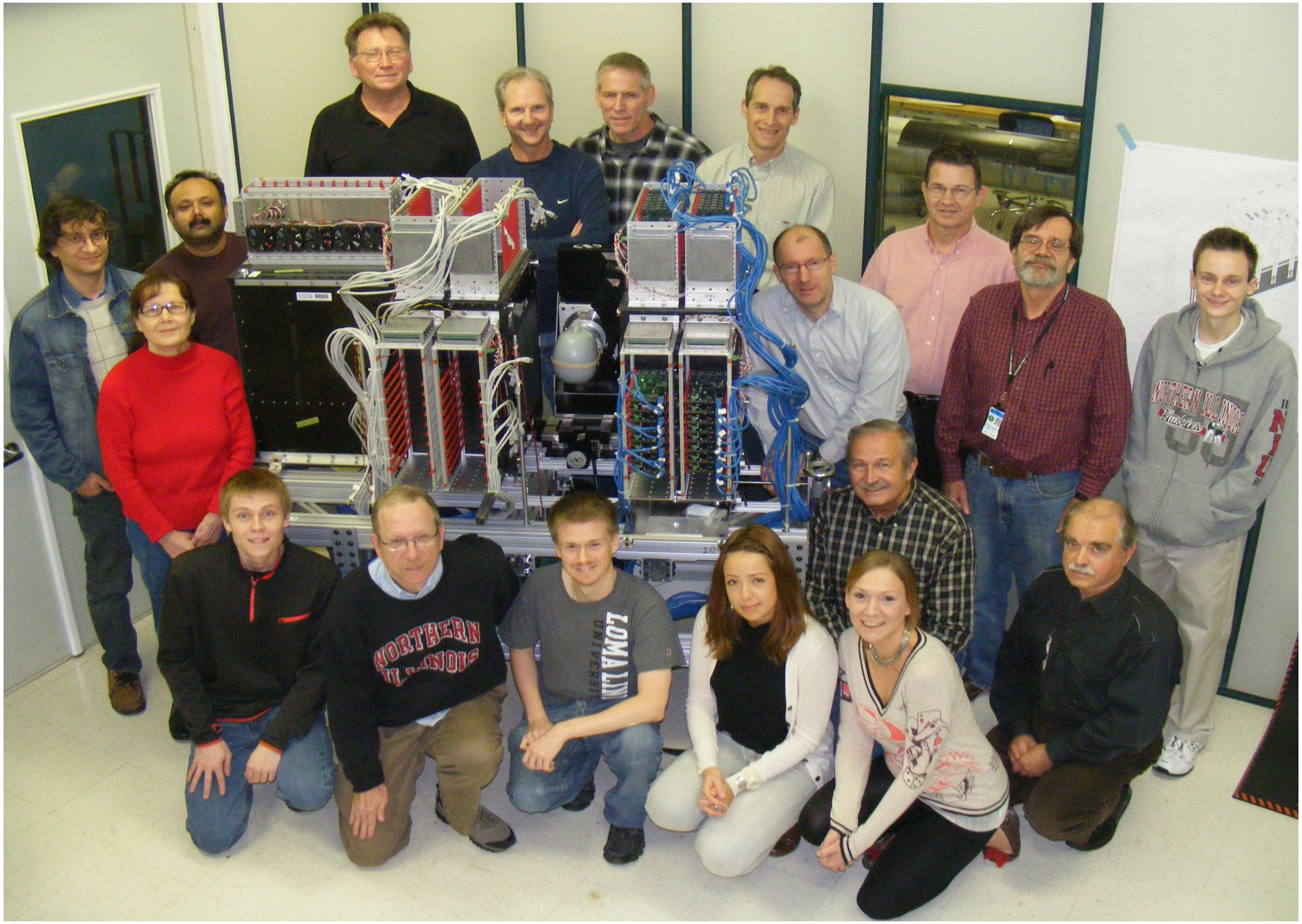
Data collected with 3D head phantom in a uniformly wobbling beam: the distribution of proton stopping position in the range stack (left) and the (X,Y) distribution of hits in the first tracker station from the reconstructed proton tracks (right).

Summary

- A proton CT head scanner based on fiber tracker and scintillator stack range detector has been developed at Northern Illinois University.
- The proton stopping position measurements have better linearity and accuracy than the energy measurements and thus are expected to provide more accurate WEPL calibration for the image reconstruction. The behavior of the range stack detector is well modeled by GEANT.
- Detailed Fermilab Technical Note arXiv:1601.00249

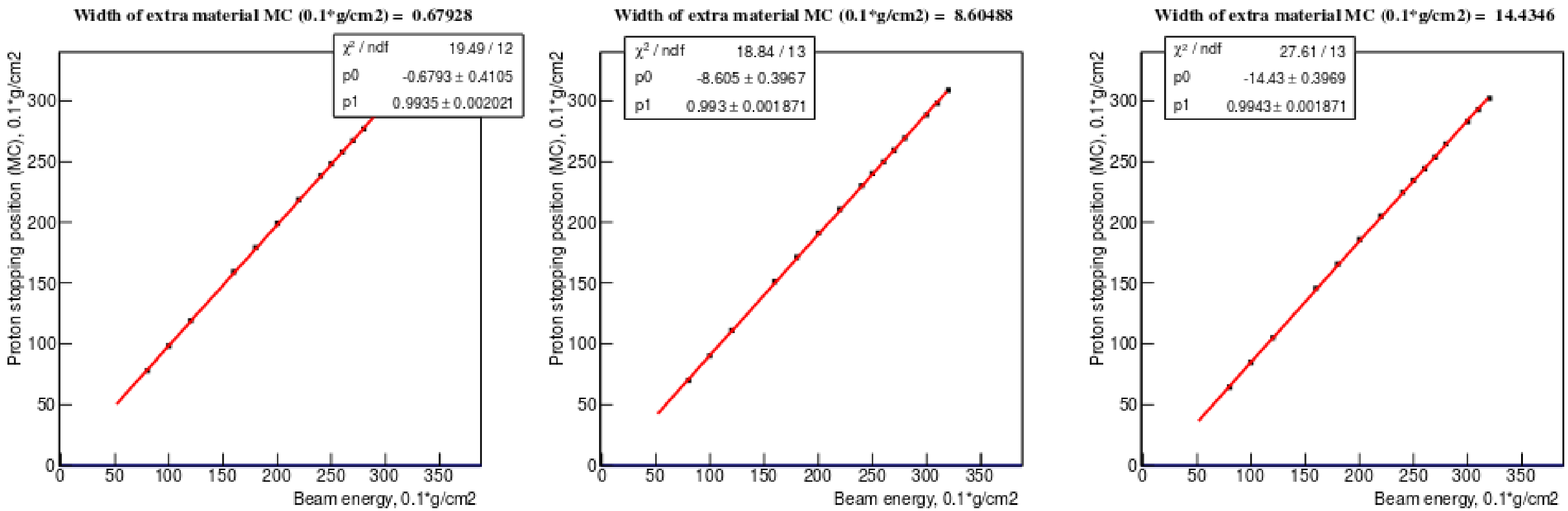
Backup

Detector assembling



NIU pCT team

MC energy correction from range measurements



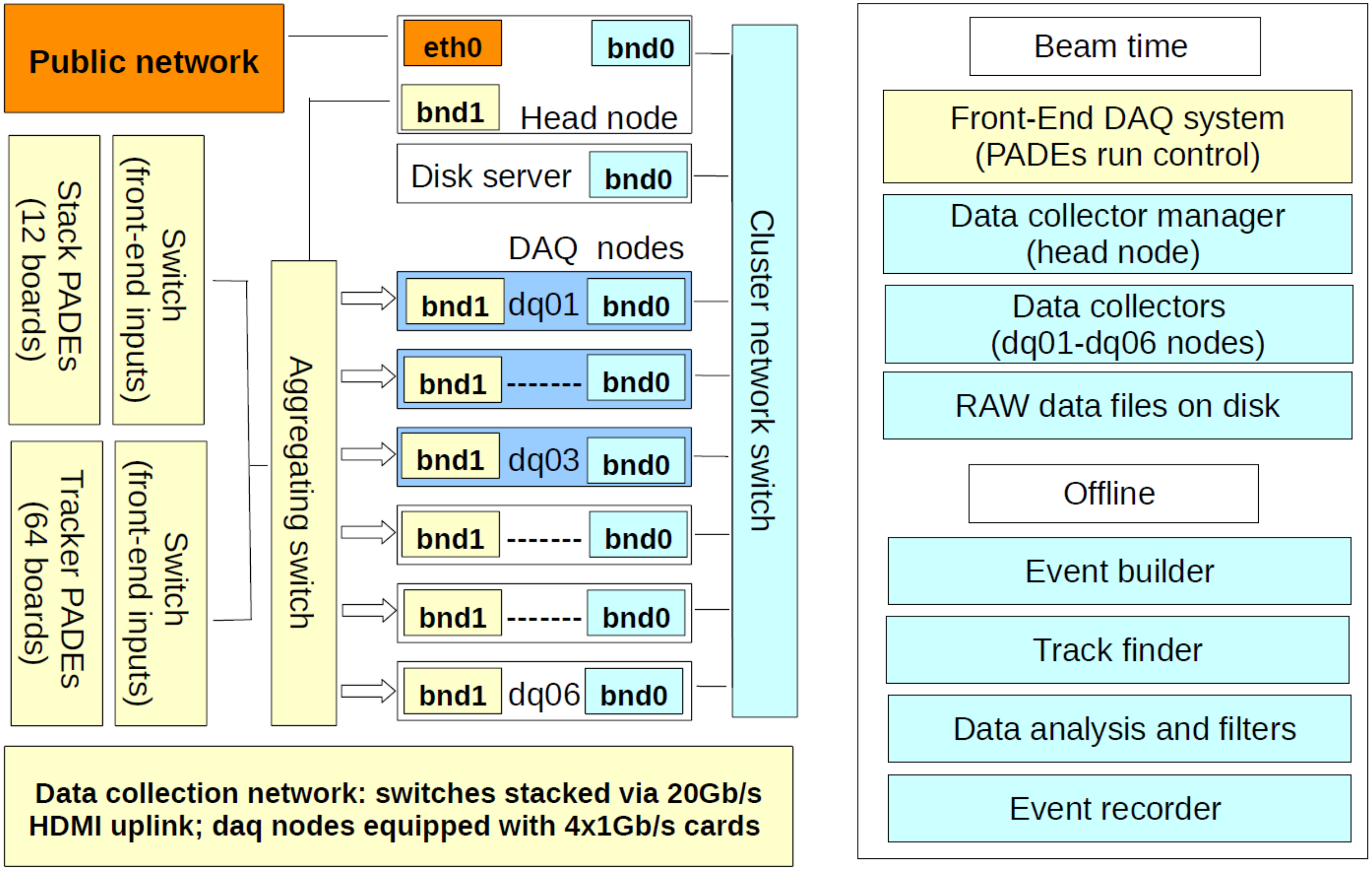
(a) (b) (c)

Figure 21: (a) the linearity of the proton stopping position measurement R_{rs} obtained with GEANT using the nominal CDH beam energy points in a configuration with no tracker before the range stack; (b) the R_{rs} linearity for nominal CDH beam energy points including the tracker; (c) the R_{rs} linearity after correcting beam energies by adding "extra material" observed in data (5.7 mm).

$$R_{total} = R_{rs} + R_{beamline} + R_{tracker} + sft\_const$$

$$R_{rs} = (nt_{stop} + 1) \times (tileW \times tileD + alW \times alD + mlrW \times mlrD) + nframe \times (alW \times alD + mlrW \times mlrD), nt_{stop} = [0, 95]; nframe = [0, 11]$$

The DAQ system



Diagrams of Back-End DAQ computer cluster (left) and data acquisition and analysis flow (right, from top to bottom).

References

[1] G. Coutrakon *et al.*, *Proceedings Intl. Topical Meeting on Nuclear Applications of Accelerators, Bruges, Belgium, (2013).*

[2] Computerized Imaging Reference Systems, Inc., www.cirsinc.com, Norfolk, VA.

[3] N. T. Karonis *et al., J. Parallel Distrib. Comput., (2013).*

[4] S. A. Uzunyan *et al., Proceedings of the IEEE conference , San Diego, CA (2015).*

[4] J. F. Janni, ”*Proton Range-Energy Tables, 1 keV-10 GeV, Energy Loss, Range, Path Length, Time-of-Flight, Straggling, Multiple Scattering, and Nuclear Interaction Probability. Part I. For 63 Compounds*”, Atomic Data and Nuclear Data Tables, 27, 147,(1982).