Instrumentation for Proton Computed Tomography

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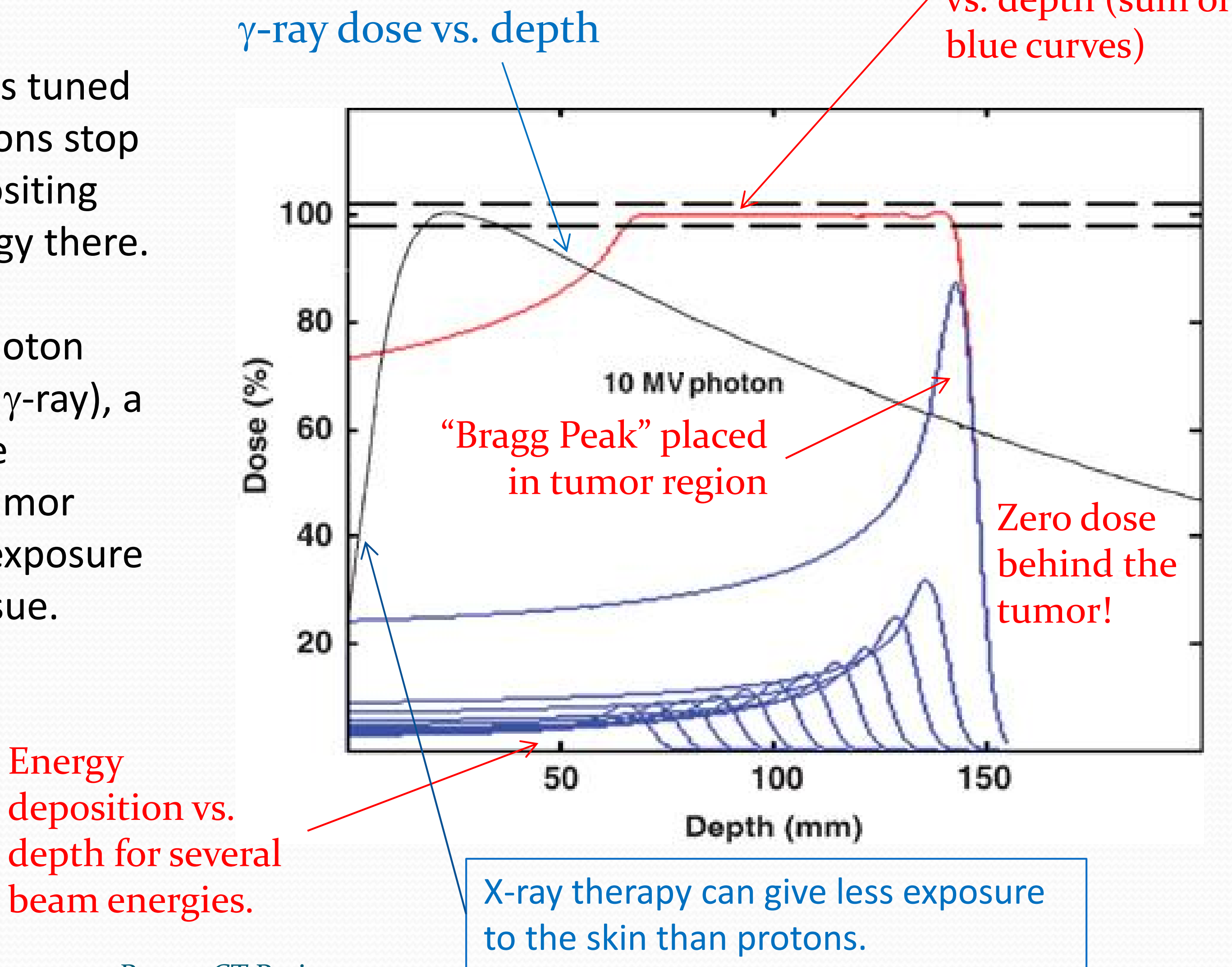
Physics 205

February 10, 2014

Proton Radiation Therapy

The proton beam is tuned such that the protons stop in the tumor, depositing most of their energy there.

Compared with photon radiation (X-ray or γ-ray), a higher does can be delivered to the tumor while minimizing exposure to surrounding tissue.



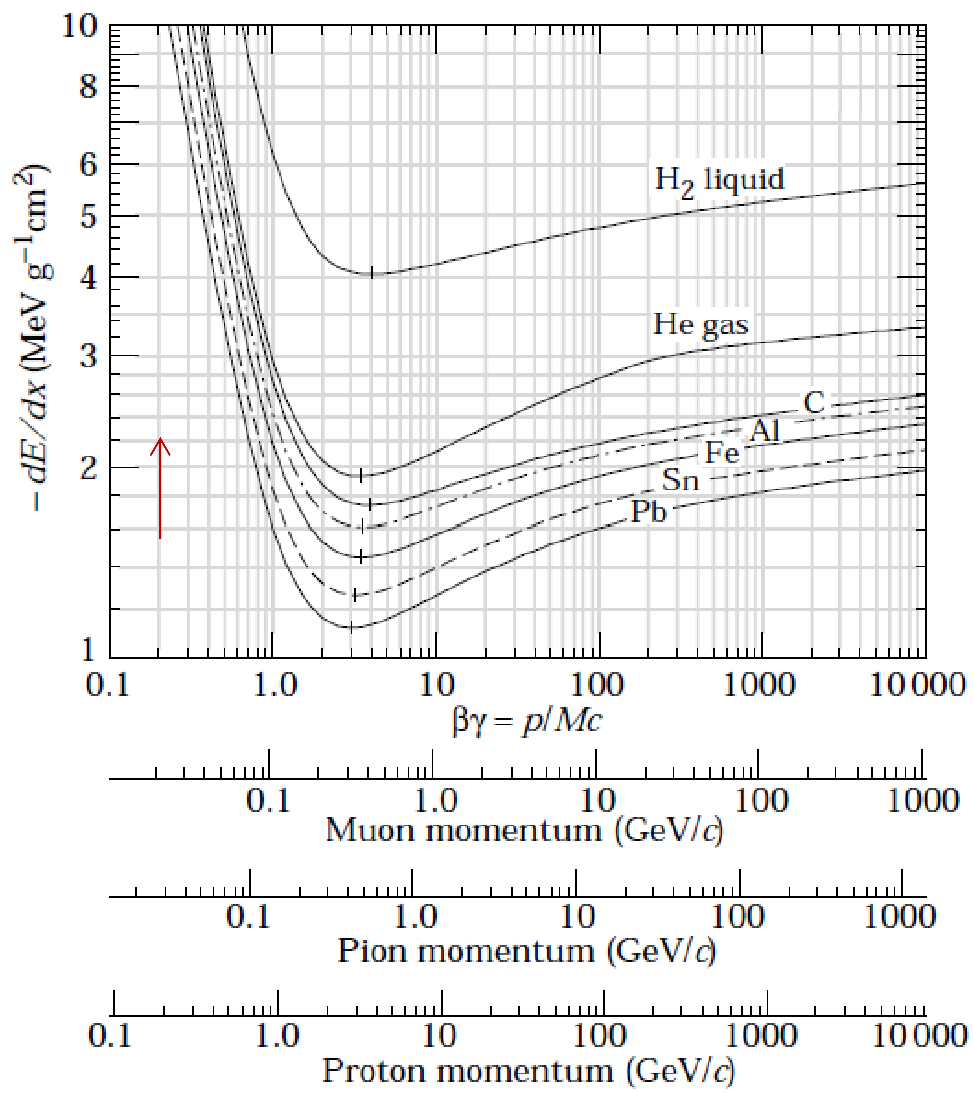
Interaction of Protons with Matter

dE/dx is the amount of energy lost per unit length by ionization as the particle passes through the material.

Here the values read from the vertical scale need to be multiplied by the density of the material in g/cm³ to get the energy loss rate in MeV/cm.

For non-relativistic protons (*p*<GeV/*c*) the energy loss rate increases rapidly (~1/*v*²) as the particle slows down.

Therefore, most of the energy is lost in the last several mm of travel.



History of Proton Therapy

- First proposed by Robert Wilson in 1946
- The first treatments were performed at particle physics labs, such as LBL and Los Alamos, starting in 1954.
- The Massachusetts General Hospital used the Harvard Cyclotron to treat 9,116 patients between 1961 and 2002.
- In 1990 a dedicated proton accelerator was installed in a hospital (Loma Linda Medical Center) for the first time.

The Loma Linda accelerator being built at Fermilab in the late 1980s.

Today 11 hadron (p + heavy ion) therapy centers operate in the USA, with 39 worldwide.

Based on synchrotrons or cyclotrons.

Where Proton Therapy is Well Suited

- Delivery of high, localized doses of radiation to tumors that respond well to such doses (i.e. are destroyed).
- Delivery of radiation doses to tumors while minimizing exposure to surrounding tissue
  - This has shown especially good results in pediatric treatments, with significant reduction in long-term damage to the child's developing organs.
  - The single most common target, however, has been prostate cancer (about 26% of all treatments worldwide). Here the improvements with respect to other treatments have been less clear.
  - Treatment of ocular tumors by protons is very important (e.g. UC Davis), but is a somewhat special case, as beams of only 70 MeV are required (the LLUMC beam goes as high as 250 MeV).

Example Facility

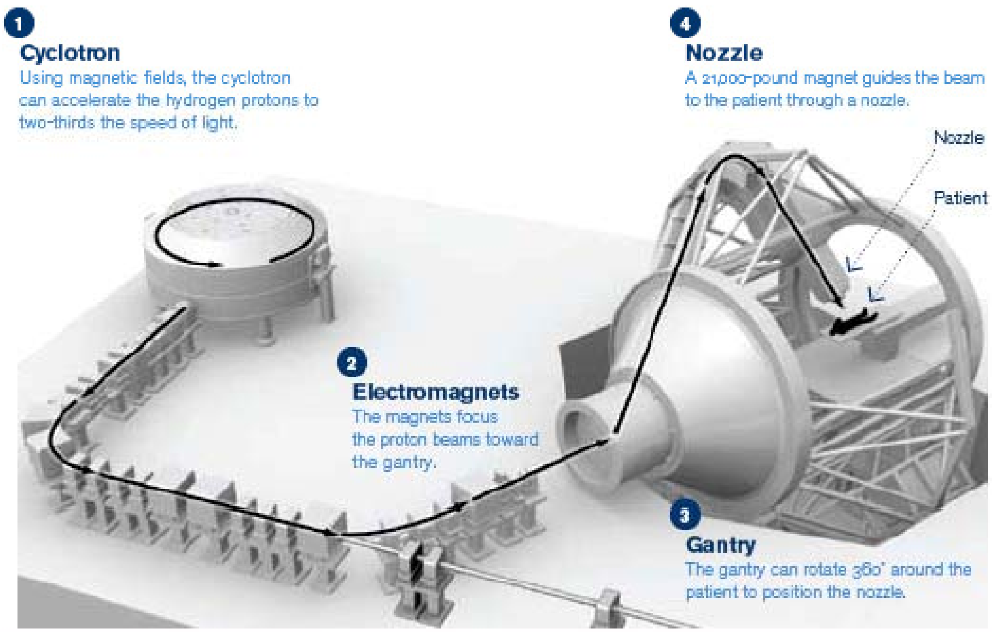
This facility at the University of Florida cost $125 Million to build and can serve up to 150 patients per day.

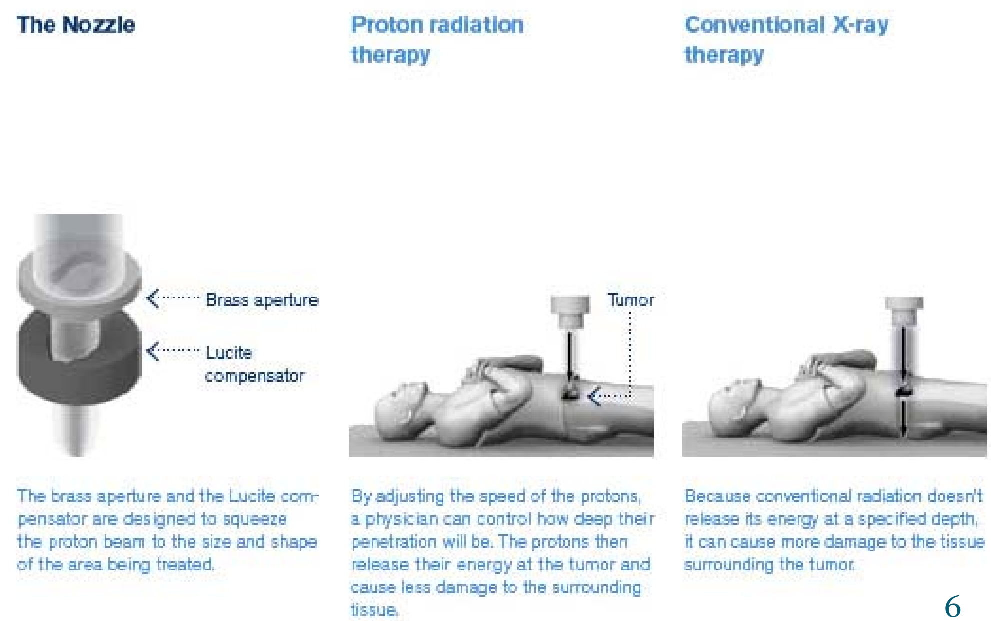
The high cost of such a facility is the main point of criticism of this type of treatment.

- Costs are offset by reduction in collateral damage and the ability to succeed in few treatments.
- New facilities no longer need to be custom designed.

New, compact (cheaper), accelerator technologies are being developed for proton therapy.

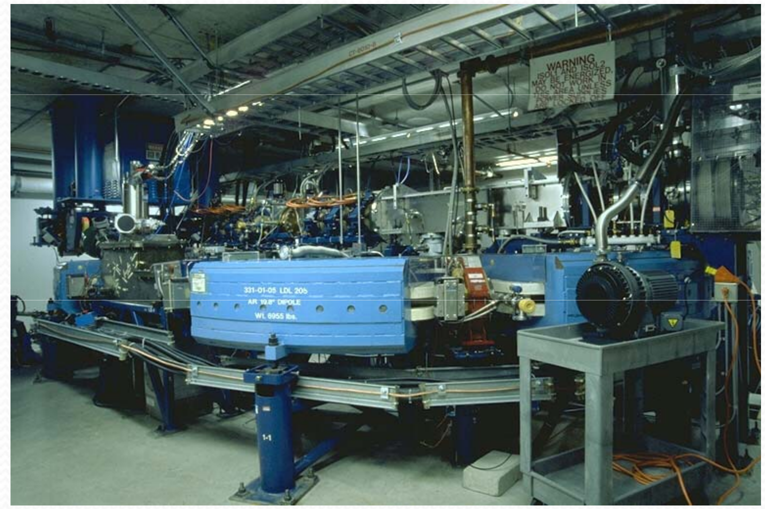
- Small superconducting cyclotrons.
- Dielectric Wall Accelerator.





LLUMC Proton Treatment Center

Hospital-based facility

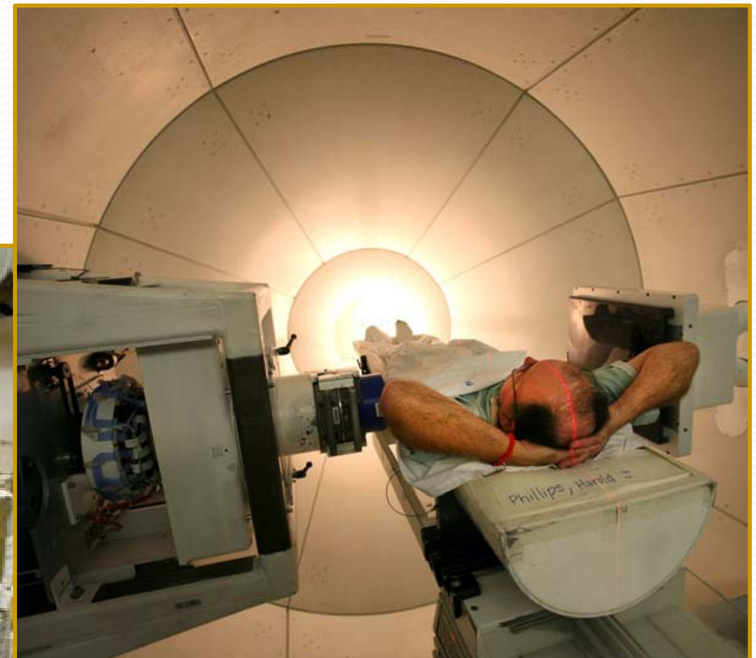


40-250 MeV Synchrotron

Gantry beam line

Fixed beam line

Views from the business end of *p* therapy



M.D. Anderson Cancer Center, University of Texas

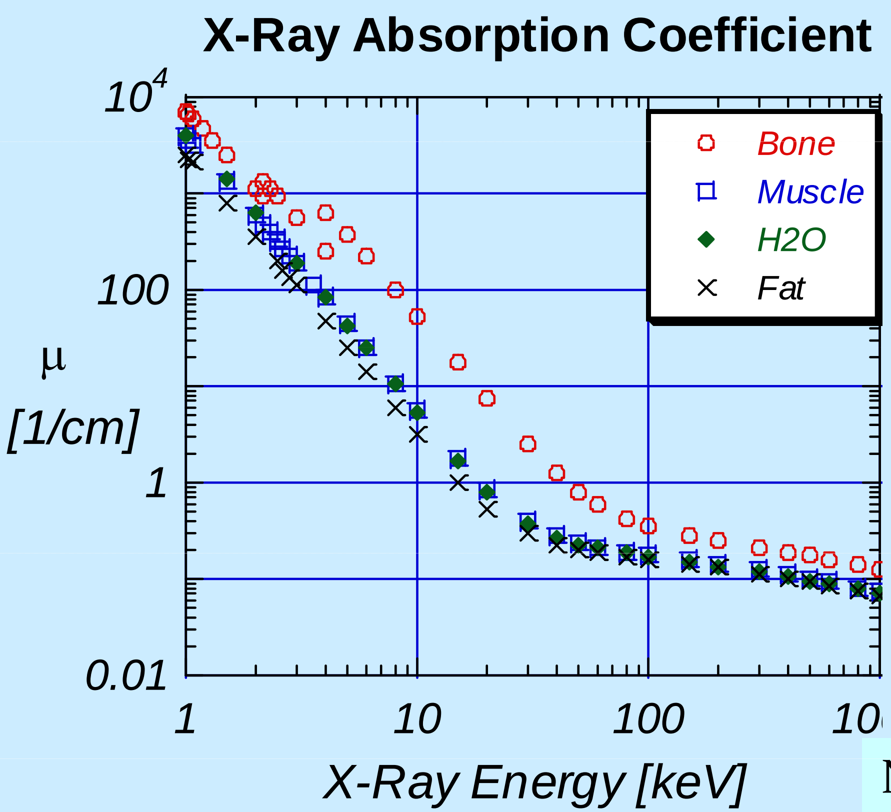
Radiography: X-rays vs Protons

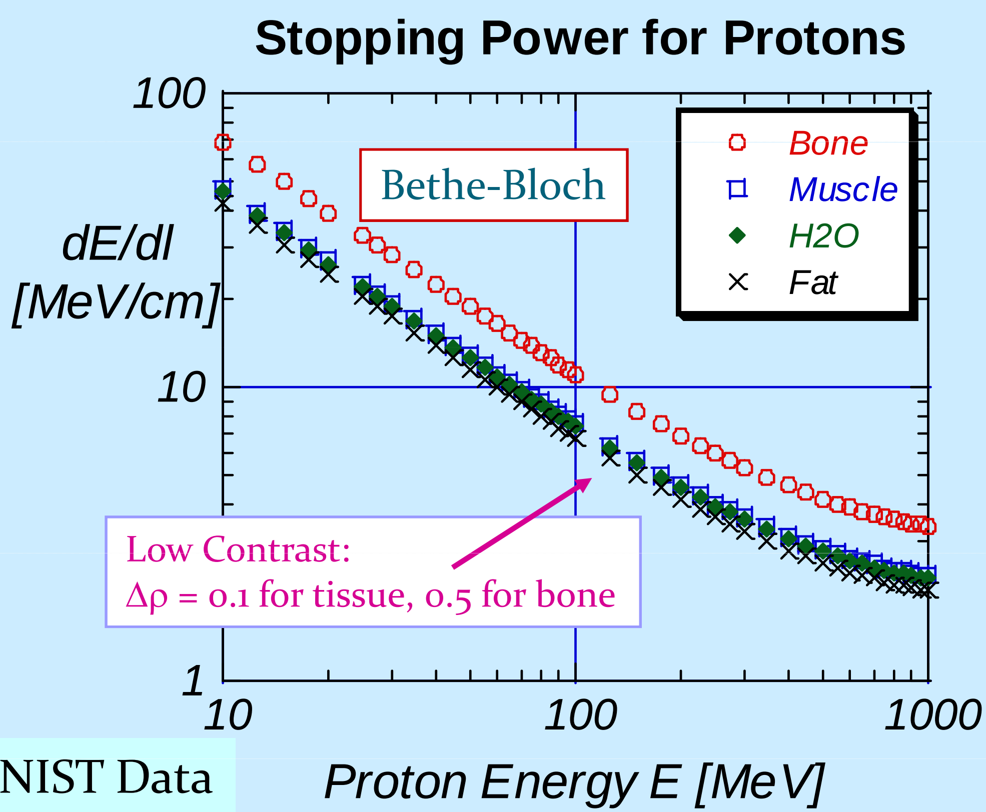
Attenuation of Photons, Z

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

Energy Loss of Protons, ρ

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





NIST Data

Measure statistical process of X-ray removal

Measure energy loss of individual protons

Proton Beam Computed Tomography

- Proton CT for diagnosis
  - First suggested by Alan Cormack (1963), who shared the Nobel prize for his work on X-ray CT image reconstruction.
  - First studied during the 1970s with experimental results published in the early 1980s.
  - A dose advantage over x rays was observed.
  - But it was not further developed after the advent of X-ray Computed Tomography
- Proton CT for treatment planning and delivery
  - Renewed interest during the 1990s (2 Ph.D. theses)
  - Preliminary results are promising
  - But further R&D is needed

Why proton CT for treatment planning?

- Image in the same facility where the treatment will take place, immediately prior to treatment.
  - Alleviate issues with ensuring the same patient positioning between the X-ray CT scan and the proton treatment.
- Possibly a lower radiation dose than X-ray CT.
- Most important: in principle, proton CT images measure much more directly (than X-ray) the quantities relevant to tuning the accelerator to create a proton beam that stops in the tumor.

From our proposal: "One unsolved problem in proton therapy is the current inability to predict the exact range of protons in tissue due to inaccuracy of converting CT Hounsfield Units (*HU*) to proton stopping power and the lack of a low-dose imaging modality in the treatment room predicting the range of protons on a day-to-day basis."

$$HU \equiv \frac{\mu_X - \mu_{\text{water}}}{\mu_{\text{water}} - \mu_{\text{air}}} \cdot 1000$$

μ is the X-ray attenuation coefficient:

$$I = I_0 e^{-\mu x}$$

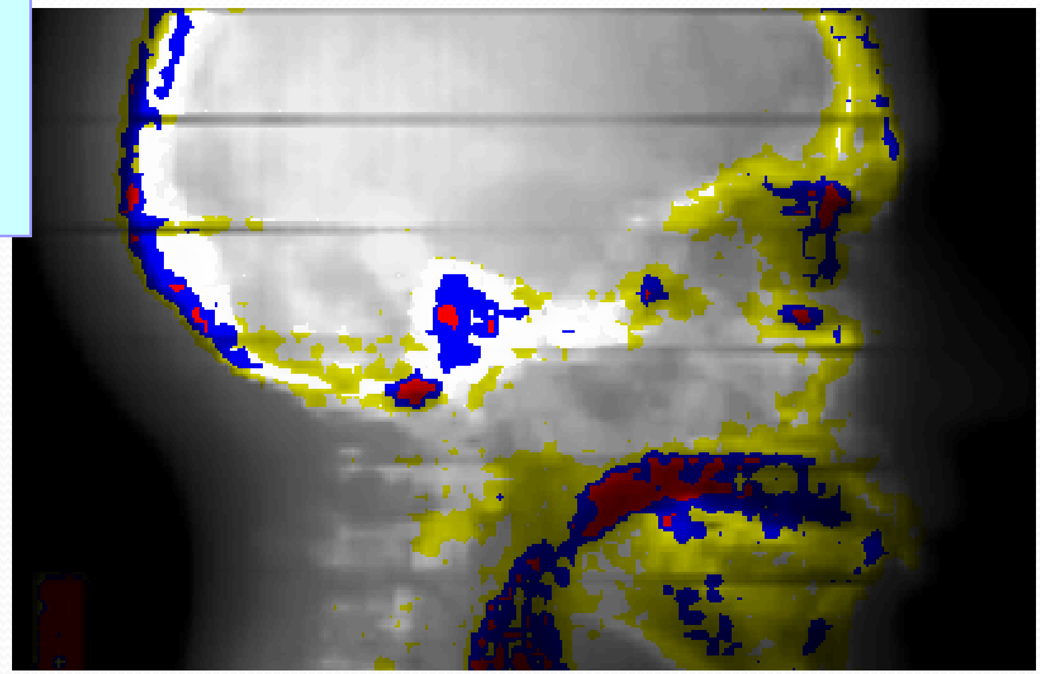
pCT for Proton Therapy Treatment Planning

X-ray CT use in proton cancer therapy can lead to large uncertainties in range determination, which limits its use in the case of some tumors located close to critical healthy tissue.

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 can measure directly the density distribution needed for range calculation and is less affected by intervening dense structures.

Proton-CT Project Goals and Plans

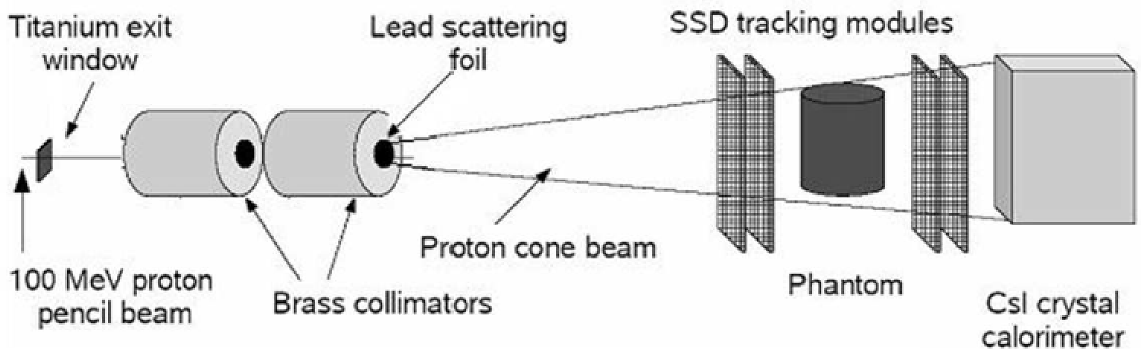
Goals:

1. Overcome challenges of pCT by performing systematic studies based on Monte Carlo simulations with Geant4.
2. Build pCT prototypes of increasing sophistication.
3. Prove the advantages of pCT compared to x-ray CT;
4. Build a clinical head scanner pCT system for applications in proton therapy.

The pCT project phases:

- **Phase 0 (2003-2007):** *Conceptual phase, development of design concepts and testing various methods of pCT reconstruction.* First experiments with a small laboratory prototype.
- **Phase I: (2008-2012):** *Design and manufacture of a first preclinical pCT prototype (head scanner), utilizing concepts developed during Phase 0.* Evaluation of the prototype and documentation of the advantages of pCT in comparison with x-ray CT.
- **Phase II (2012-2014):** *Design and manufacture of a clinical pCT head scanner including fast data acquisition and image reconstruction.*
- **Phase III (2014-2016):** *Development of conceptual and detailed designs as well as business models to transfer pCT technology into the clinical environment.*
- **Phase IV (2016 and beyond):** *Clinical implementation, including integration of a pCT system into a proton treatment room, preclinical testing on small animals, approval of clinical protocols for pilot studies.*

A Proton CT Prototype Concept

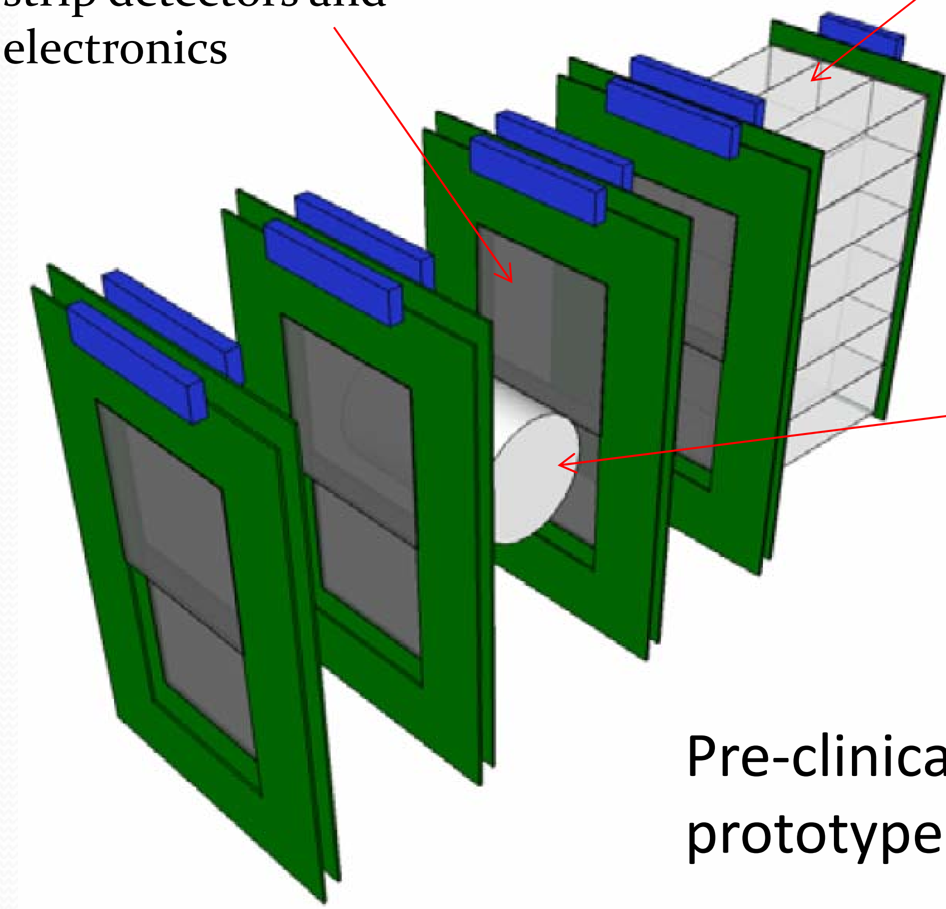


- A diffuse, weak (1 at a time) proton beam is extracted from the accelerator.
- Silicon-strip tracking planes before and after the subject measure where each individual proton passed through.
  - Complicated by multiple scattering (X-rays don't have this problem).
  - What we get is an accurate prediction of the "most likely path".
- A calorimeter measures the proton energy after passing through the subject.
  - The energy lost while passing through the subject is the crucial quantity needed to measure the tissue density along the path. The energy is lost by ionization—*exactly the same process that slows down and stops therapeutic protons during treatment*.
  - Note the difference: X-ray CT measures the fraction of X-rays that get stopped in the subject.
- Rotate about the subject to obtain 3-D data for computed tomography

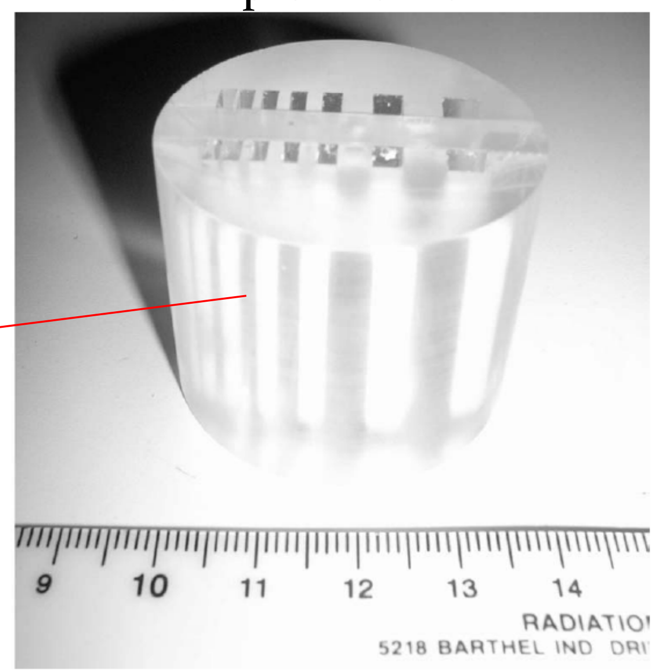
Prototype pCT Scanner (UCSC + LLUMC + NIU)

Surplus Fermi-LAT silicon-strip detectors and electronics

CsI calorimeter



Simple Phantom



Pre-clinical prototype

Prototype pCT Scanner (UCSC + LLUMC + NIU)

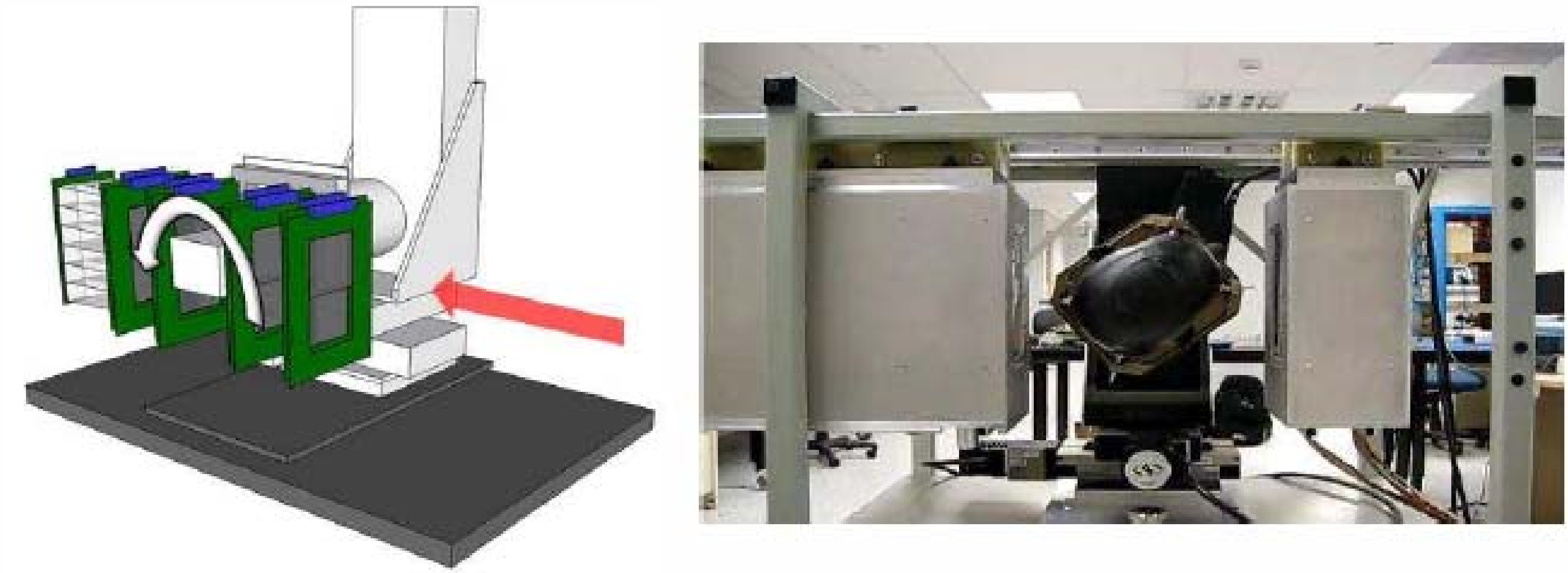
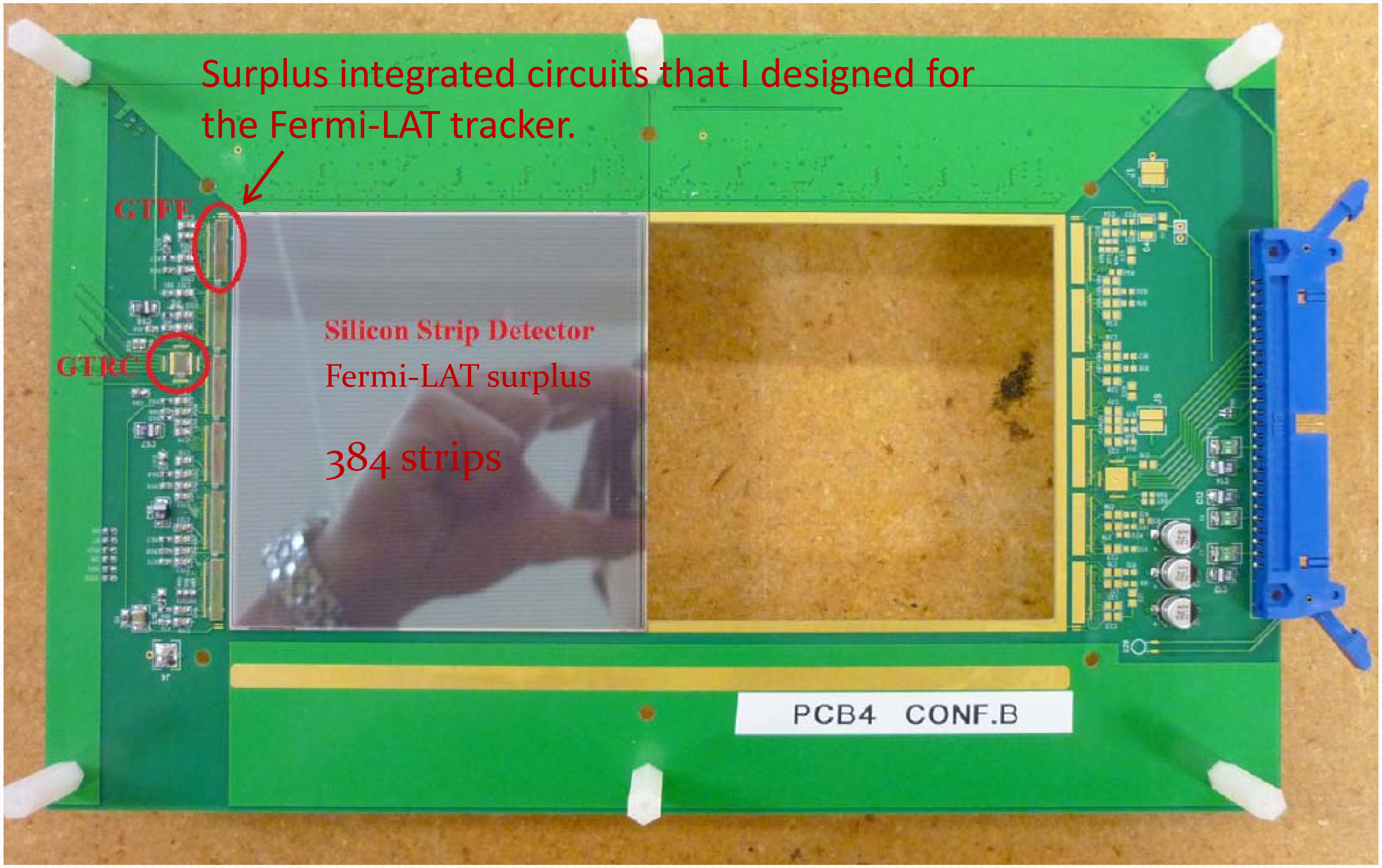


Fig. 5. Schematic sketch (left) and view (right) of the Phase I pCT scanner completed in 2010. The system consists of a front and rear module with a total of 4 silicon tracker planes and a crystal-calorimeter with an array of 18 CsI(Tl) crystals. The object (here a Rando head phantom) is rotating between the front- and rear-module on a rotational stage.

Prototype Pre-Clinical pCT Scanner SSDs



Toward a pCT Scanner for Clinical Use

- A larger size is needed: 9 cm by 36 cm, to cover the entire head height while rotating around the head.
- A much higher rate is needed: about a million protons per second sustained rate
  - The Fermi-LAT based tracking system is limited by a design never intended to exceed 10 kHz—low power was one of the most critical parameters for the space-based application! For pCT it has been operated in a modified mode up to 200 kHz, but for the new system I had to design a completely new ASIC (Application Specific Integrated Circuit)
  - A CsI calorimeter cannot operate at MHz rates—the scintillation signal from the thallium doping takes several microseconds to develop.

The LLUMC beam has a structure with 110 ns separation between bunches. We need to localize our tracks in time to better than 100 ns in order to distinguish between protons in separate bunches.

We have an NIH grant to support work on the advanced pCT scanner

Loma-Linda University Medical Center

U.C. Santa Cruz

California State University San Bernardino

SCIPP researchers apply particle physics expertise to cancer therapy

NIH grant supports work on proton computed tomography to guide proton therapy for cancer treatment

May 12, 2011

By Tim Stephens

http://news.ucsc.edu/2011/05/proton-ct.html

Physicists at the University of California, Santa Cruz, are working with medical researchers at Loma Linda University Medical Center to develop a new imaging technology to guide proton therapy for cancer treatment.

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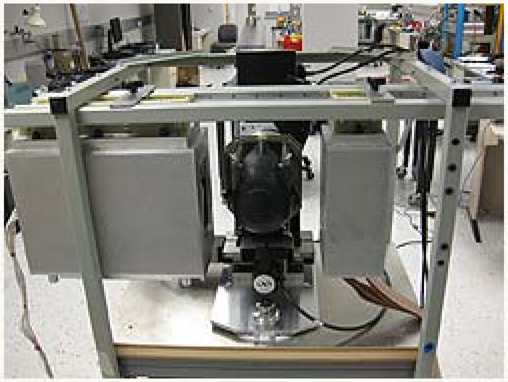
Proton therapy is a type of radiation therapy that allows powerful doses of radiation to be delivered directly to a tumor with little damage to the surrounding healthy tissues. Currently, images and data for planning and guidance of proton therapy are obtained from x-ray computed tomography (commonly known as a CT scan or CAT scan). But using information from x-rays to guide proton beams results in uncertainties that limit the accuracy with which the tumor can be targeted.



This prototype proton CT scanner was developed in the SCIPP laboratories by a team of physicists led by Hartmut Sadrozinski (below).

To overcome these limitations, researchers at the Santa Cruz Institute for Particle Physics (SCIPP) at UC Santa Cruz and their collaborators have been working since 2003

UCSC pCT Group

- Faculty:
  - Robert Johnson
  - Hartmut Sadrozinski
- Postdoc: Andriy Zatserklyaniy
- Graduate Student: Tia Plautz
- Undergraduates: many are involved, and numerous senior theses have been done on this subject over the past decade.

Layout of the New pCT Scanner

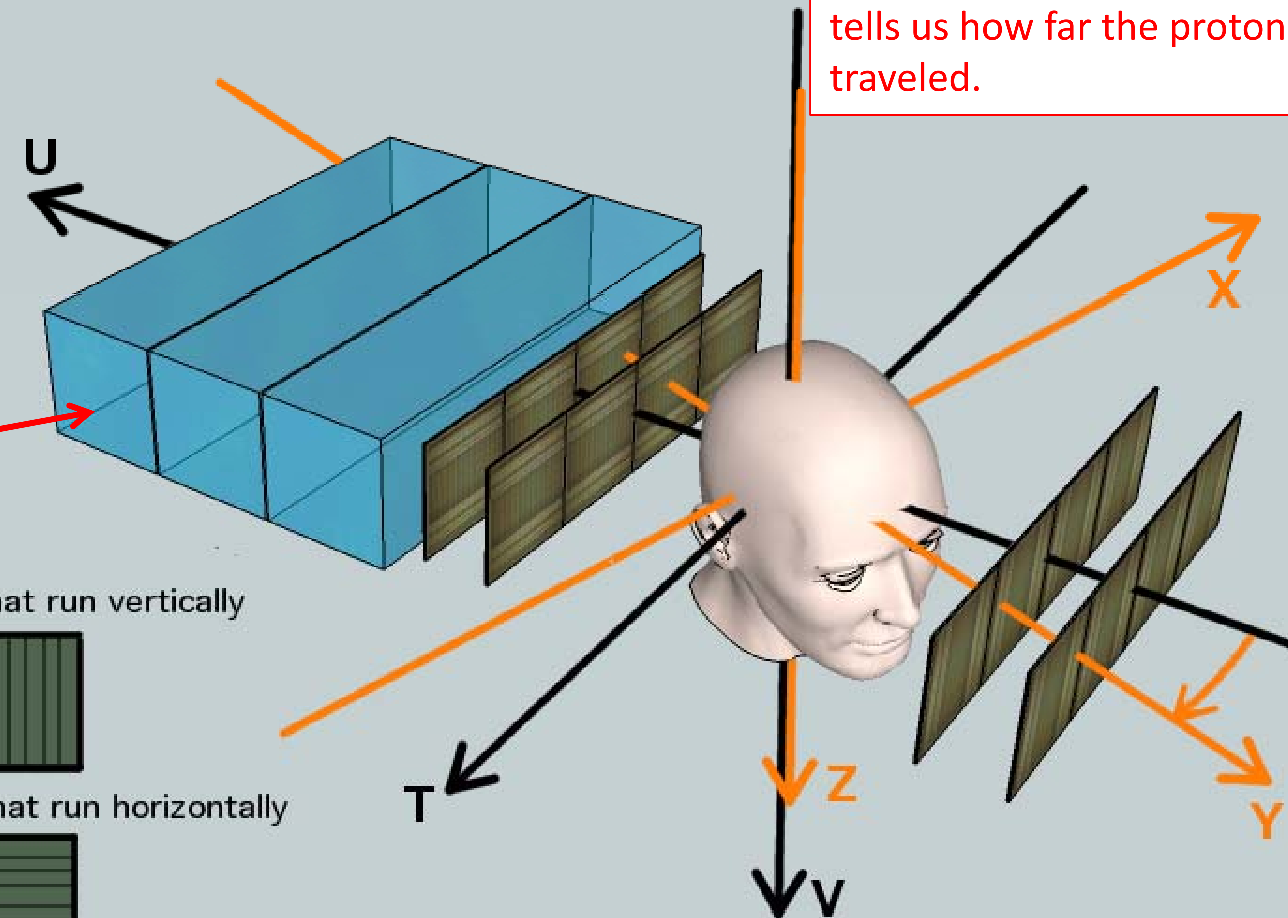
X, Y, Z coordinates are measured with respect to the phantom.
The xyz system rotates around the v-axis following the right-hand-rule. (pictured)
T, U, V coordinates are measured with respect to the detector.
The tuv system rotates around the z-axis following the left-hand-rule.
U points along the beam.

The protons stop in the plastic scintillator. The pulse height from the last scintillator with a signal tells us how far the proton traveled.

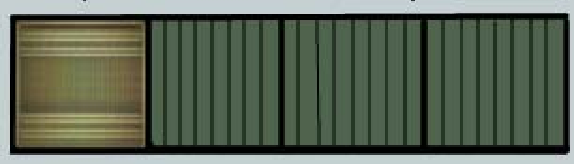
Strip detectors are double sided and oriented such that T-detectors are on the side closest to the phantom.

V|T, V|T, phantom, T|V, T|V

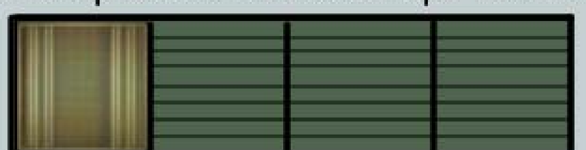
There will be 5 of these plastic scintillators, each read out by a photomultiplier tube.



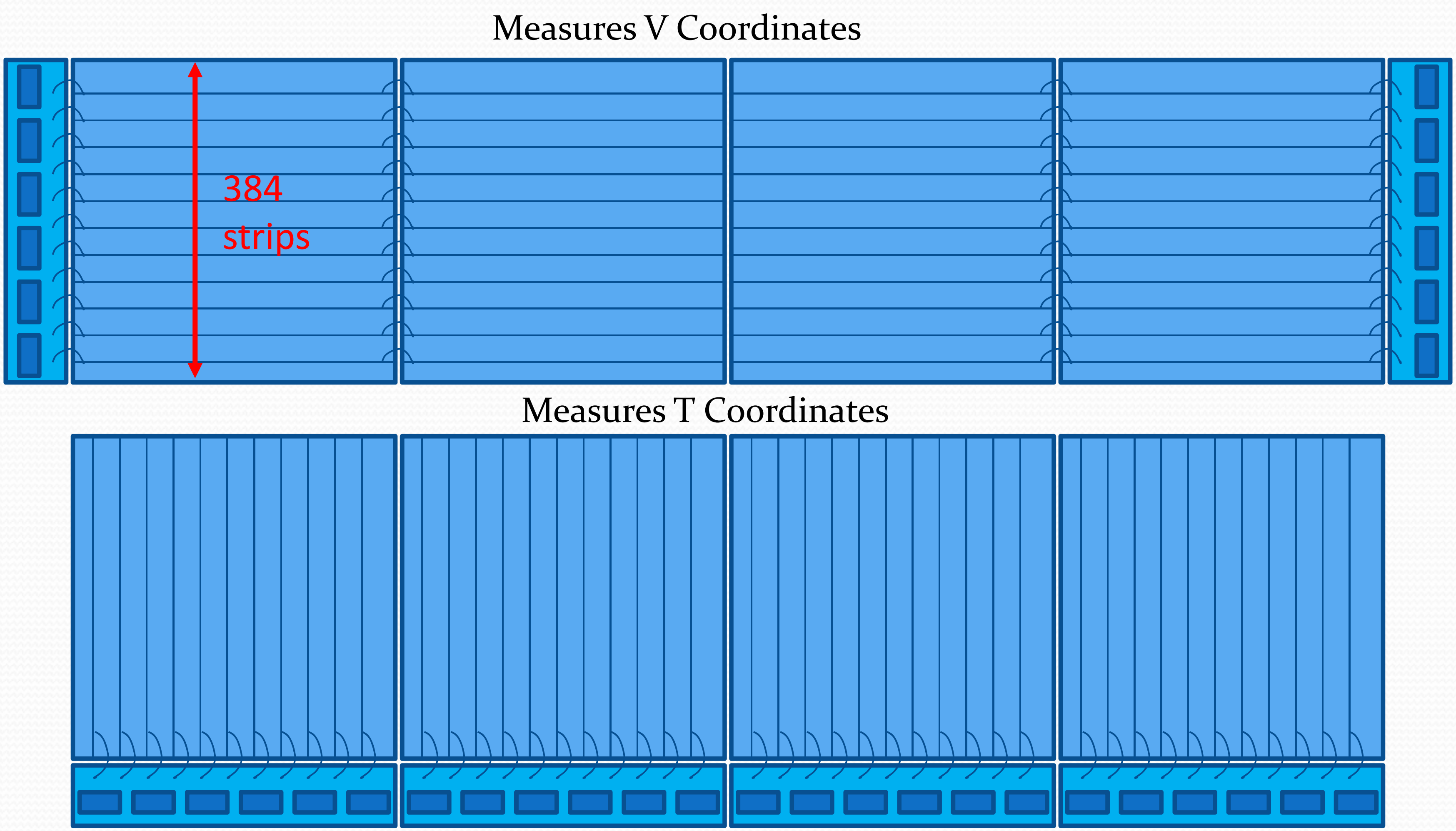
T- strip detectors have strips that run vertically



V- strip detectors have strips that run horizontally



pCT Tracker Plane Layouts



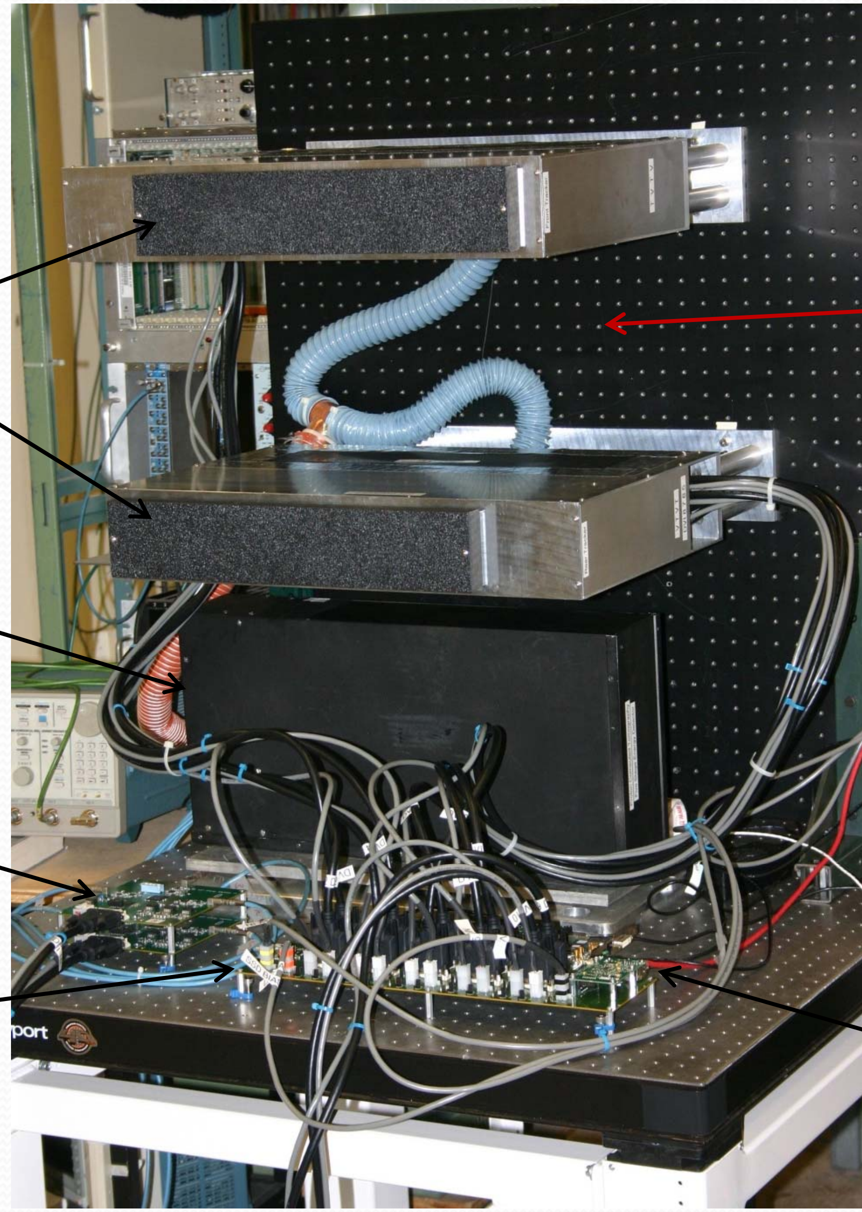
The new pCT scanner set up in the SCIPP lab and oriented to record cosmic rays.

Trackers, each with 4 silicon-strip layers.

Energy detector, with 5 scintillator layers and PMTs.

Two energy detector digitizer boards.

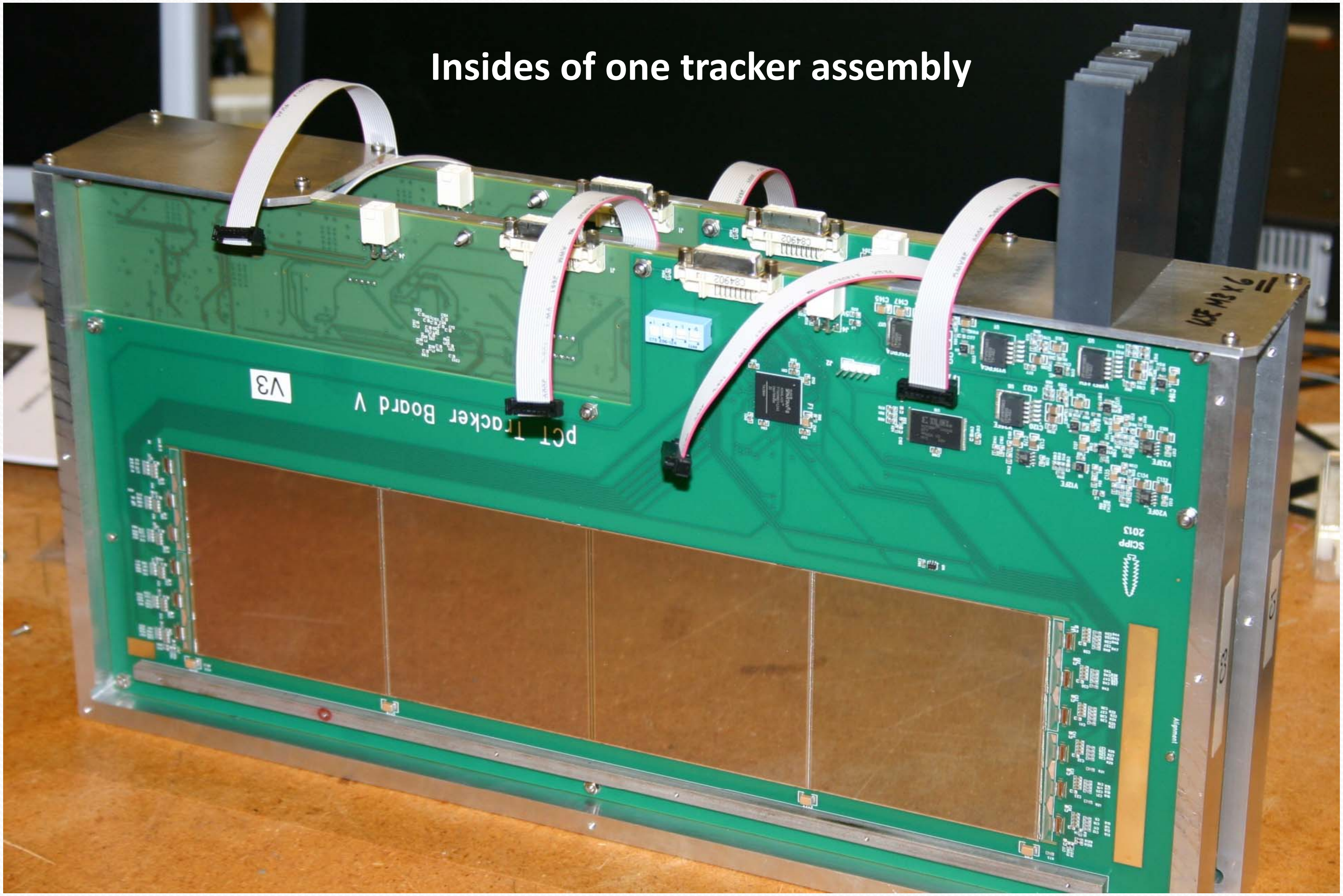
Event builder



Rotating stage will go in between the trackers

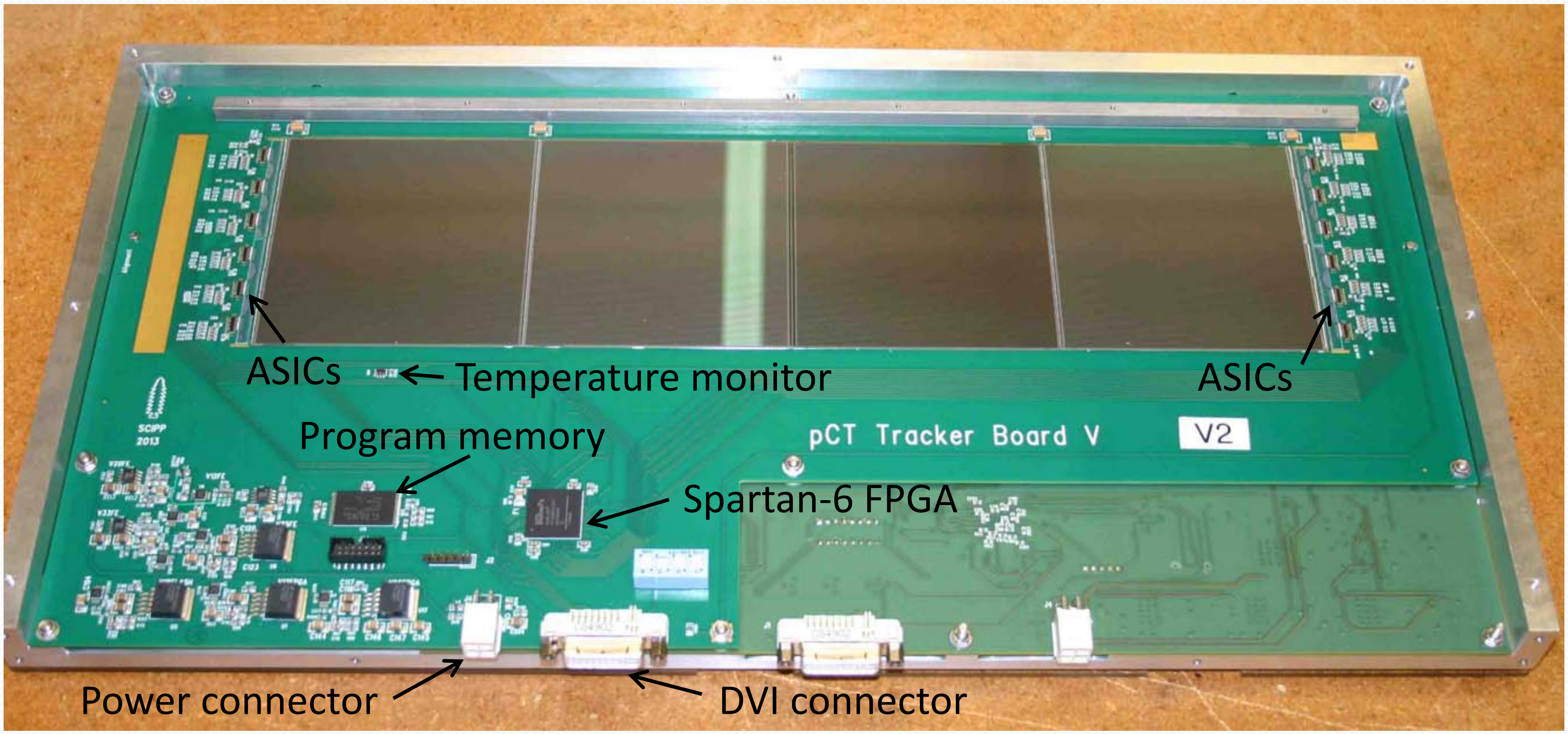
Ethernet interface

Insides of one tracker assembly

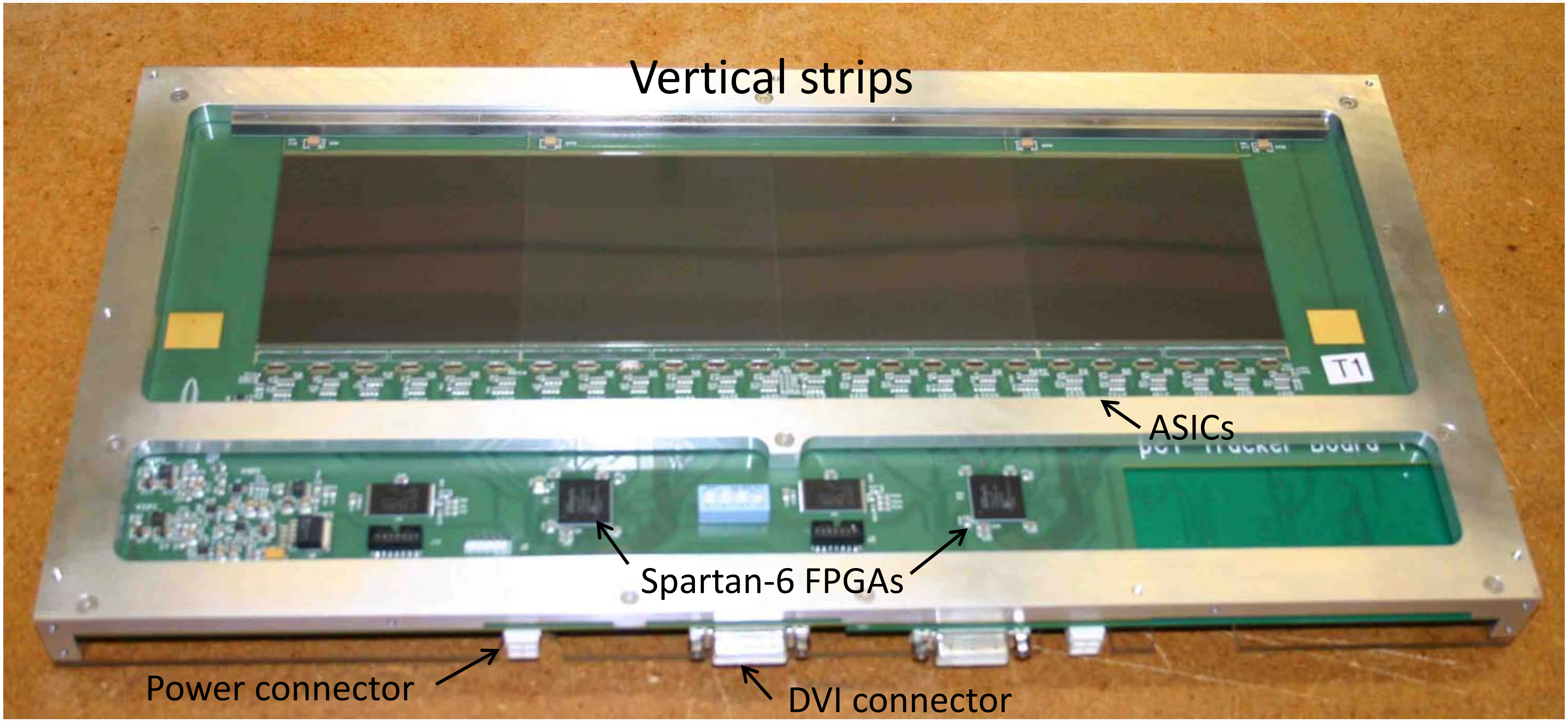


One tracker "cassette", V side.

←horizontal strips→

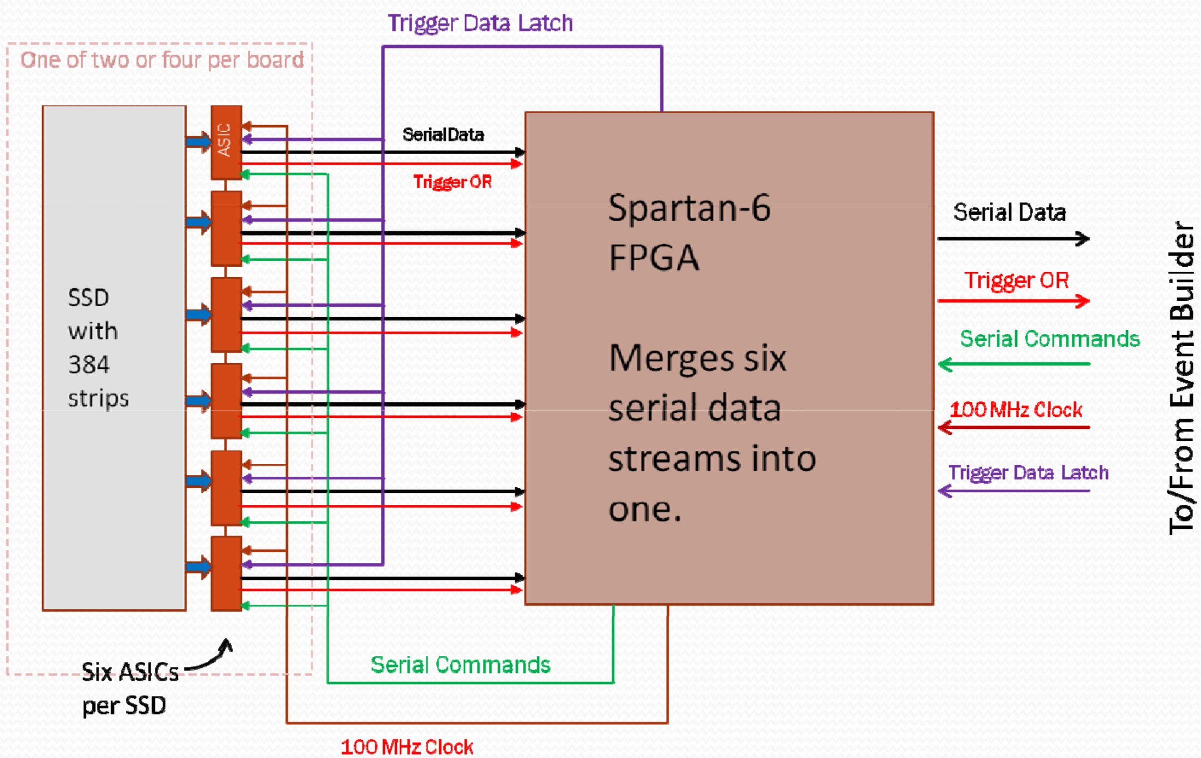


One tracker “cassette”, T side.



The T side has twice and many amplifier channels as the V side, and two FPGAs, each with a dedicated data line to the event builder.

pCT Tracker Front-End Readout Concept

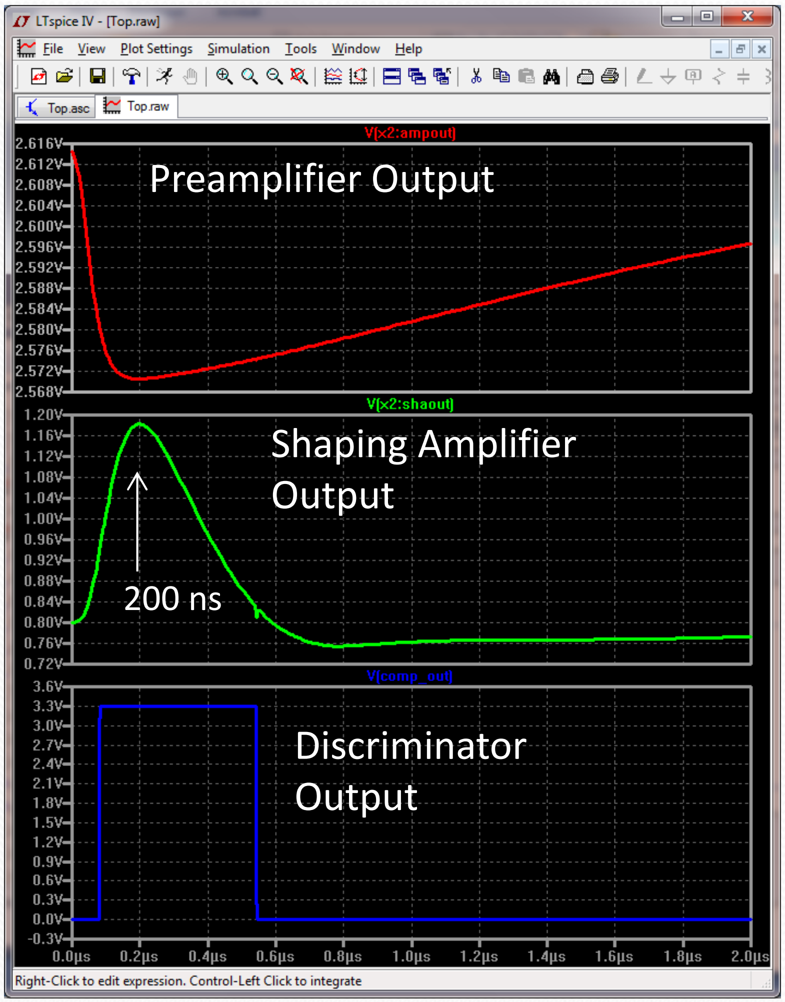


Six 64-channel amplifier chips per SSD.

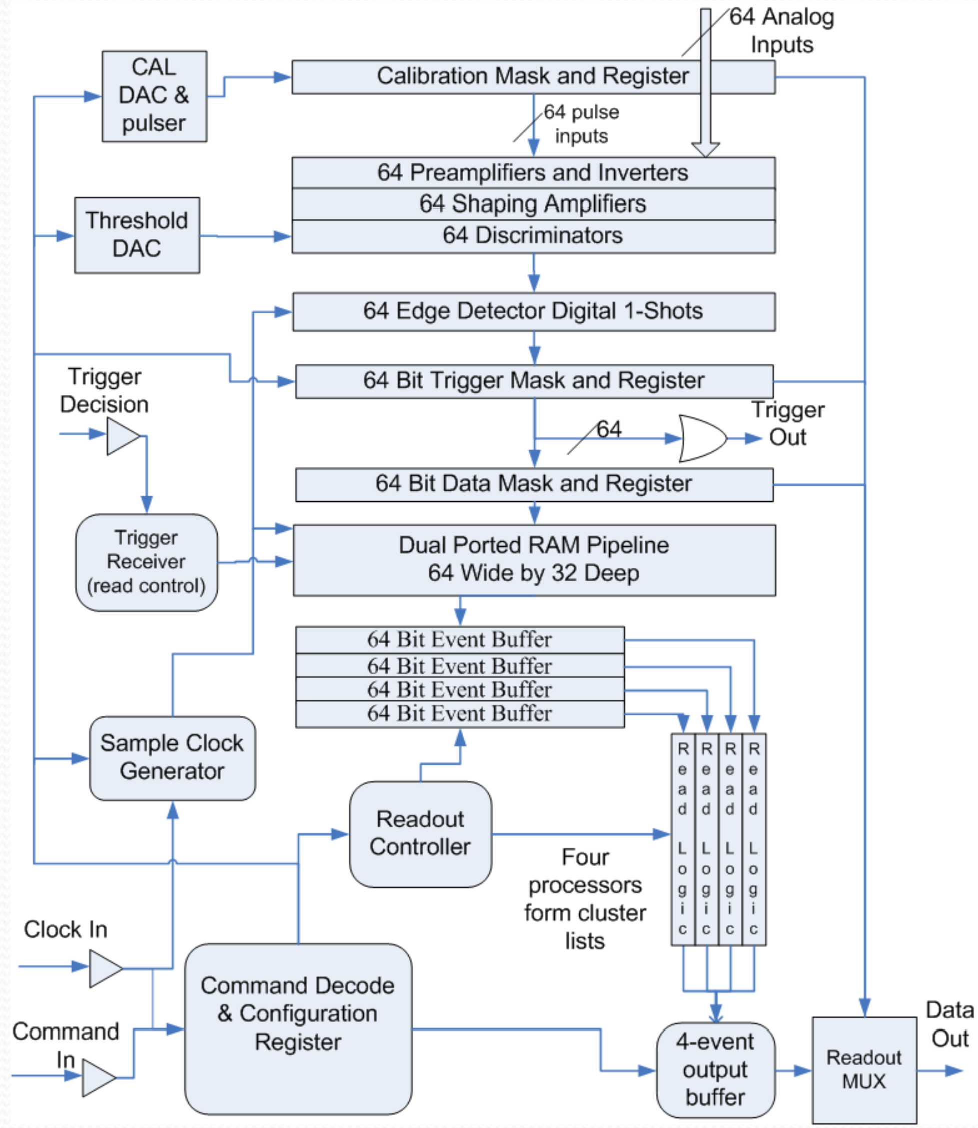
Readout trigger is based on a coincidence of multiple layers, each layer contributing a logical-OR of all of its strips.

The data stream is purely digital, indicating only which SSD strips had signals above threshold.

ASIC Design



LTspice IV - [Top.raw]
File View Plot Settings Simulation Tools Window Help
Top.asc Top.raw
V[x2:ampout]
Preamplifier Output
V[x2:shaout]
Shaping Amplifier Output
200 ns
V[comp_out]
Discriminator Output
0.0µs 0.2µs 0.4µs 0.6µs 0.8µs 1.0µs 1.2µs 1.4µs 1.6µs 1.8µs 2.0µs
Right-Click to edit expression. Control-Left Click to integrate



64 Analog Inputs
CAL DAC & pulser
Calibration Mask and Register
64 pulse inputs
64 Preamplifiers and Inverters
64 Shaping Amplifiers
64 Discriminators
Threshold DAC
64 Edge Detector Digital 1-Shots
Trigger Decision
64 Bit Trigger Mask and Register
64
Trigger Out
64 Bit Data Mask and Register
Trigger Receiver (read control)
Dual Ported RAM Pipeline 64 Wide by 32 Deep
64 Bit Event Buffer
64 Bit Event Buffer
64 Bit Event Buffer
64 Bit Event Buffer
Sample Clock Generator
Read Logic
Readout Controller
Four processors form cluster lists
Clock In
Command In
Command Decode & Configuration Register
4-event output buffer
Readout MUX
Data Out

ASIC Layout

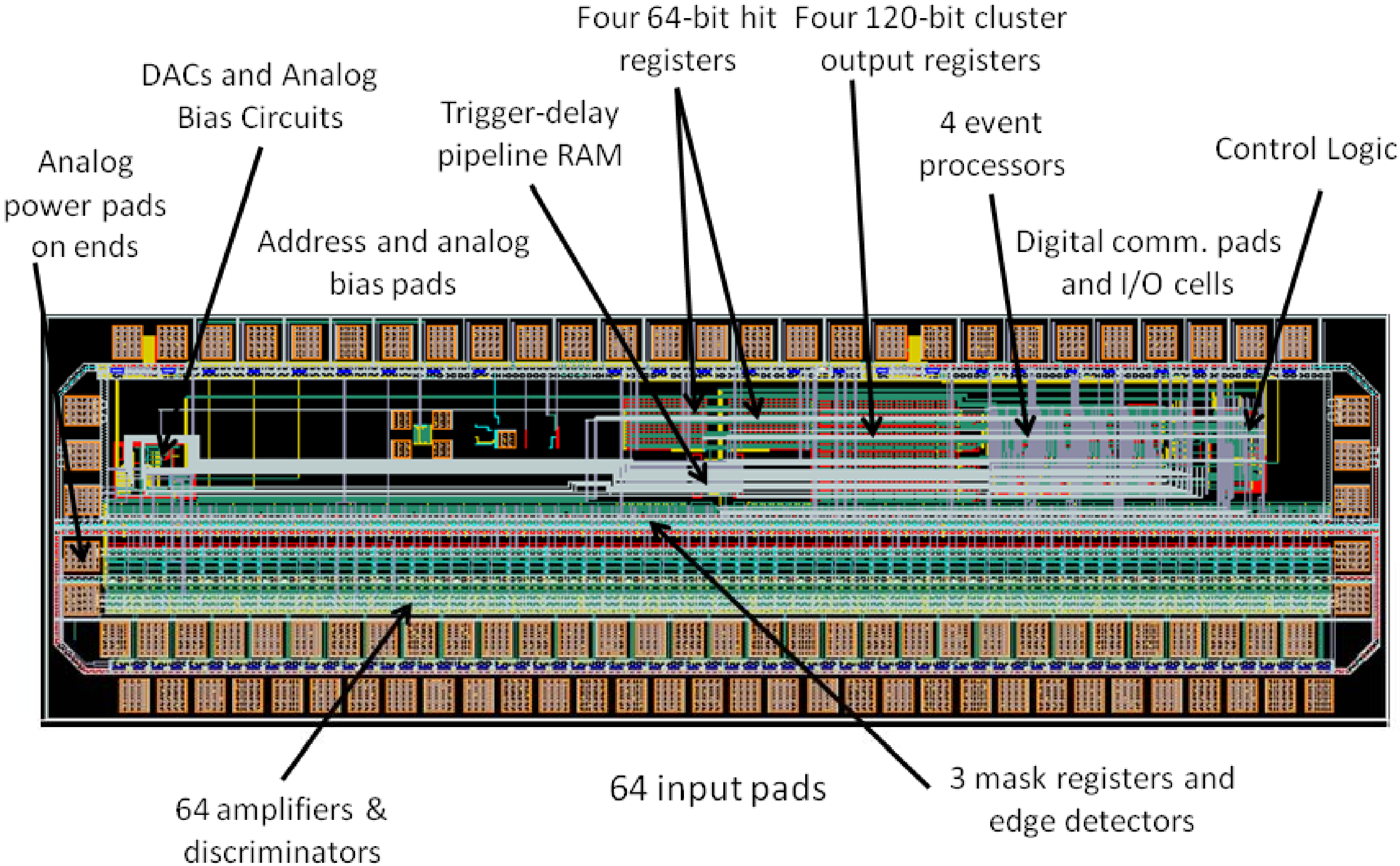
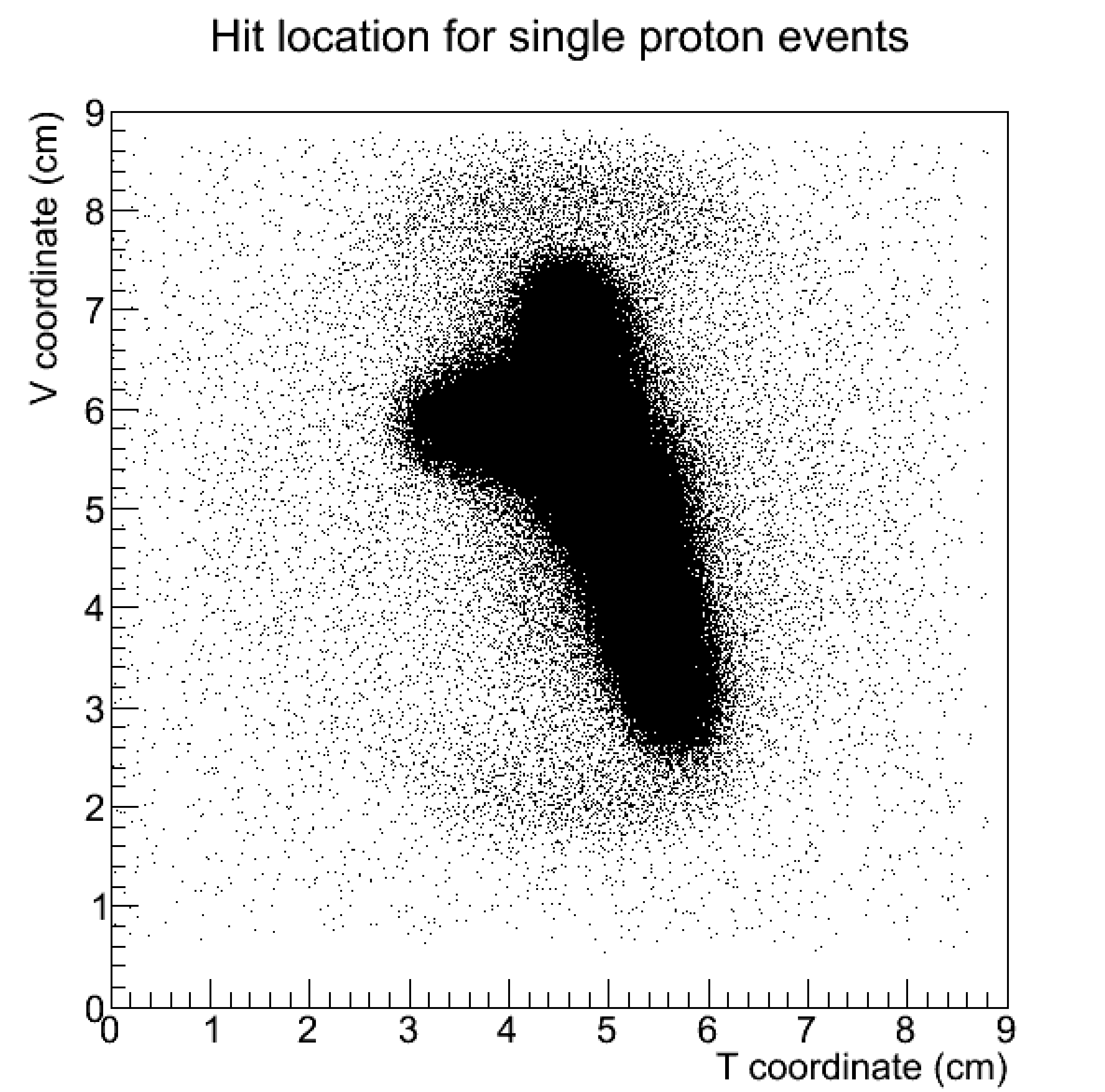
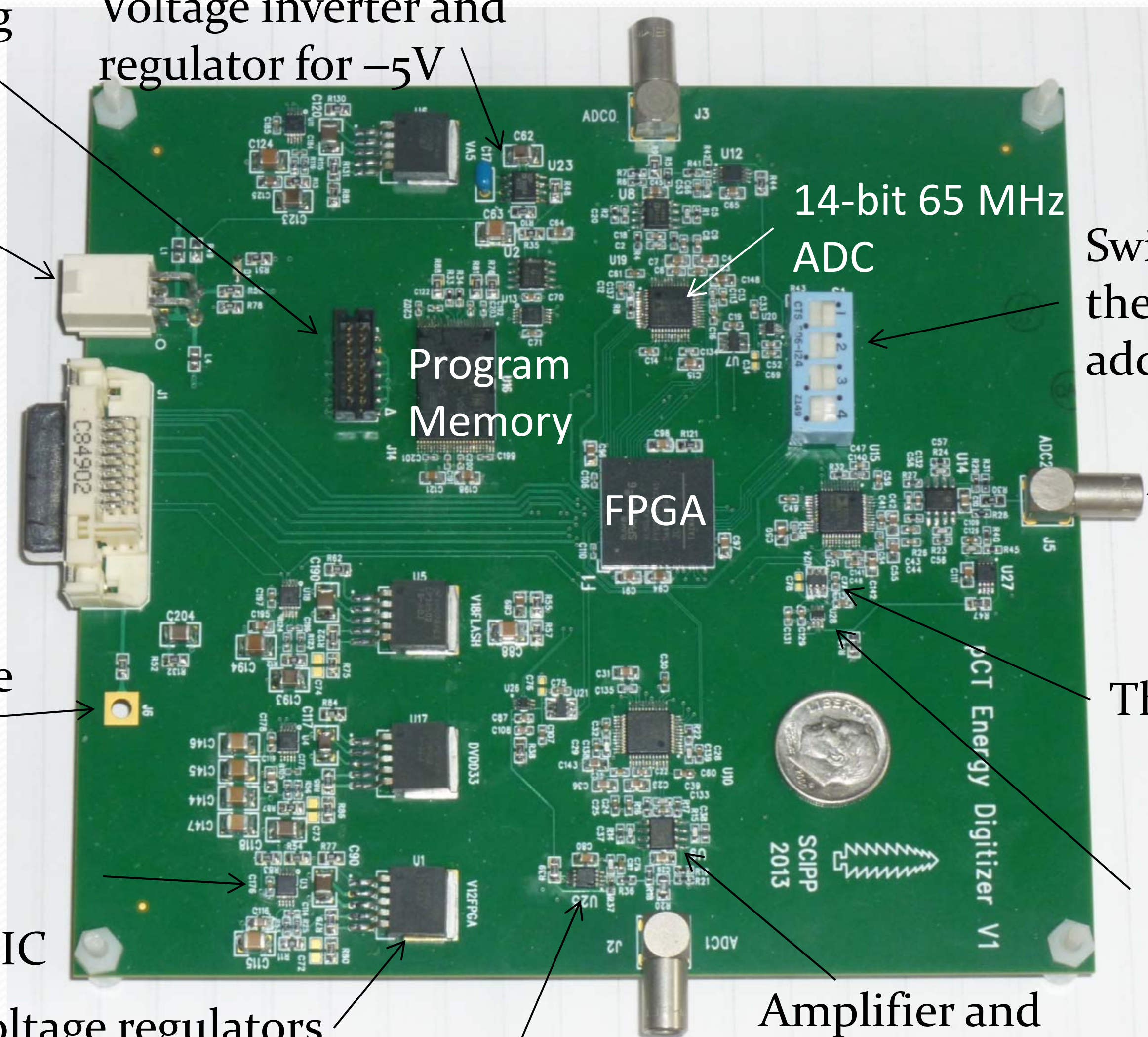

Four 64-bit hit registers
Four 120-bit cluster output registers
DACs and Analog Bias Circuits
Trigger-delay pipeline RAM
4 event processors
Control Logic
Analog power pads on ends
Address and analog bias pads
Digital comm. pads and I/O cells
64 amplifiers & discriminators
64 input pads
3 mask registers and edge detectors

Image of the Loma Linda accelerator beam spot, from a test of the tracking system last autumn.



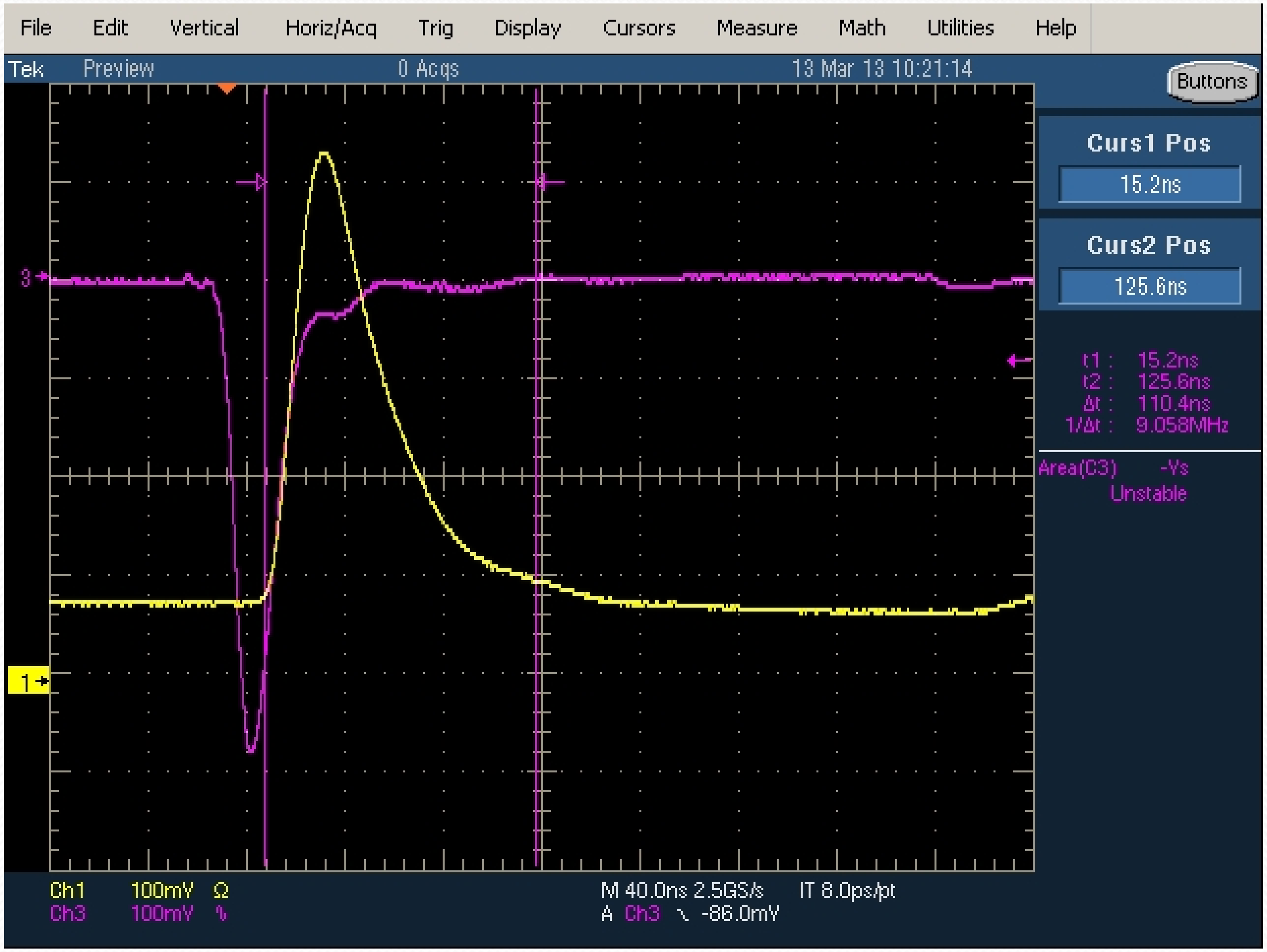
Energy Detector Digitizer Board



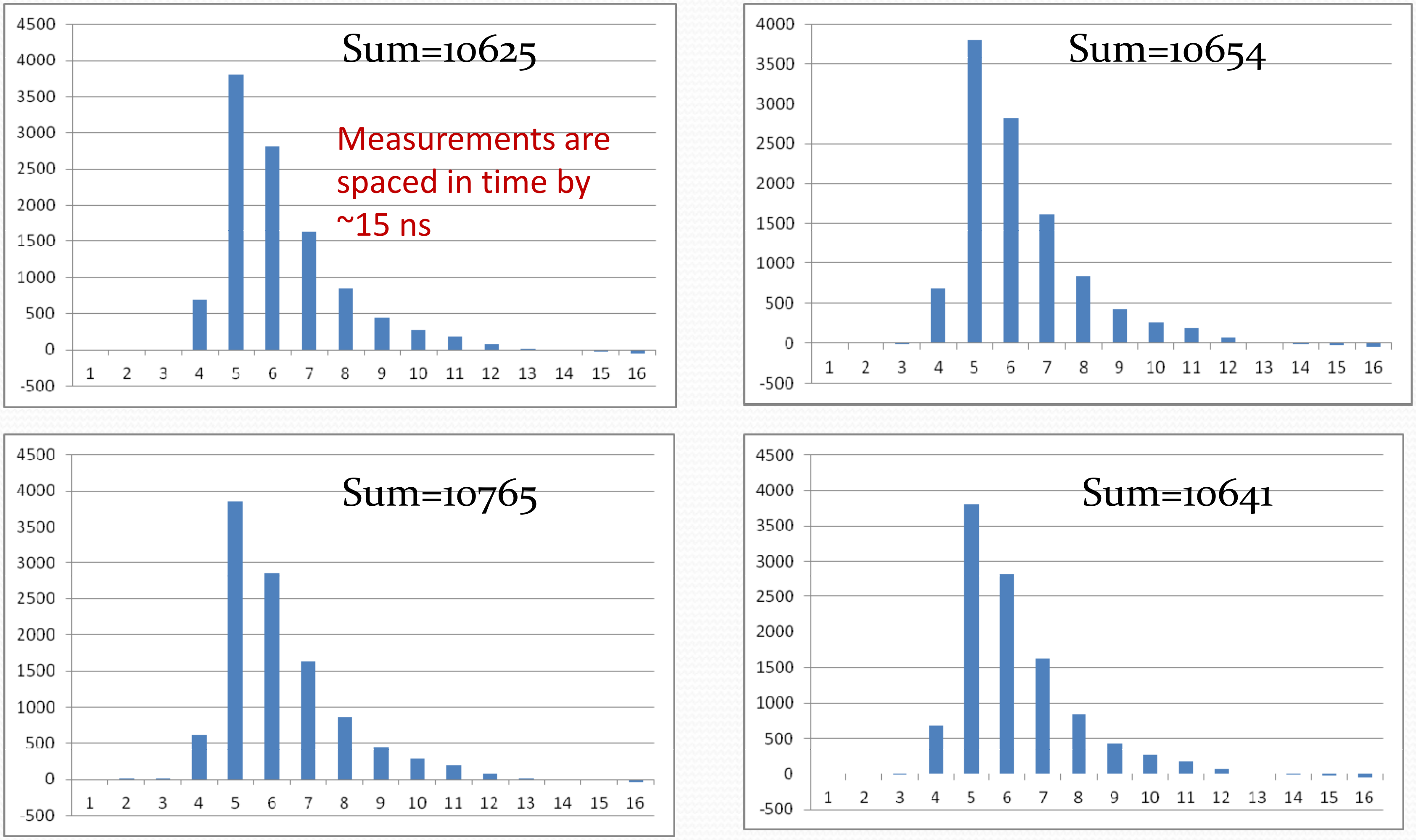
Energy Detector Signals

Simulated PMT pulse

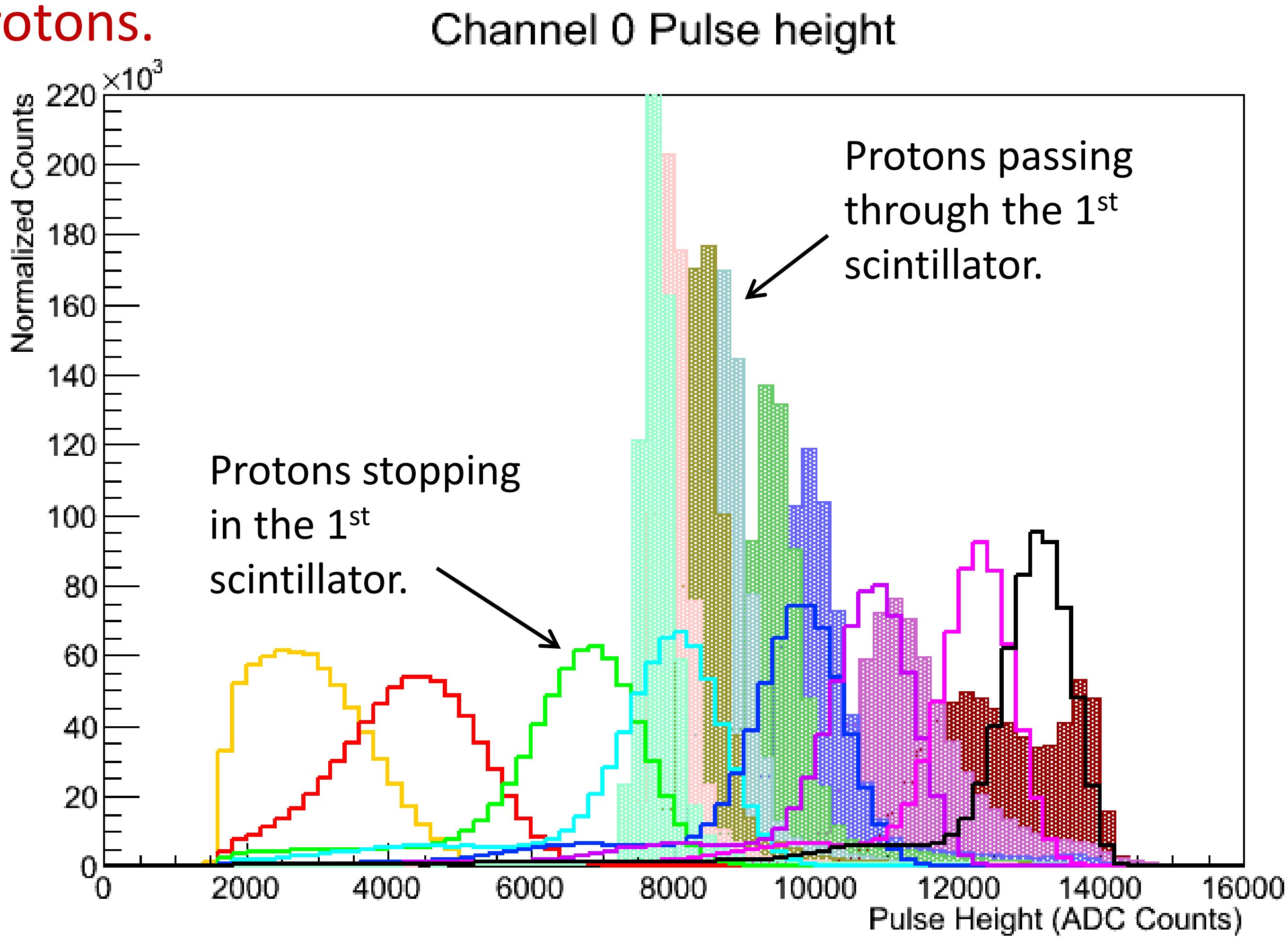
Output of the ADC drive amplifier



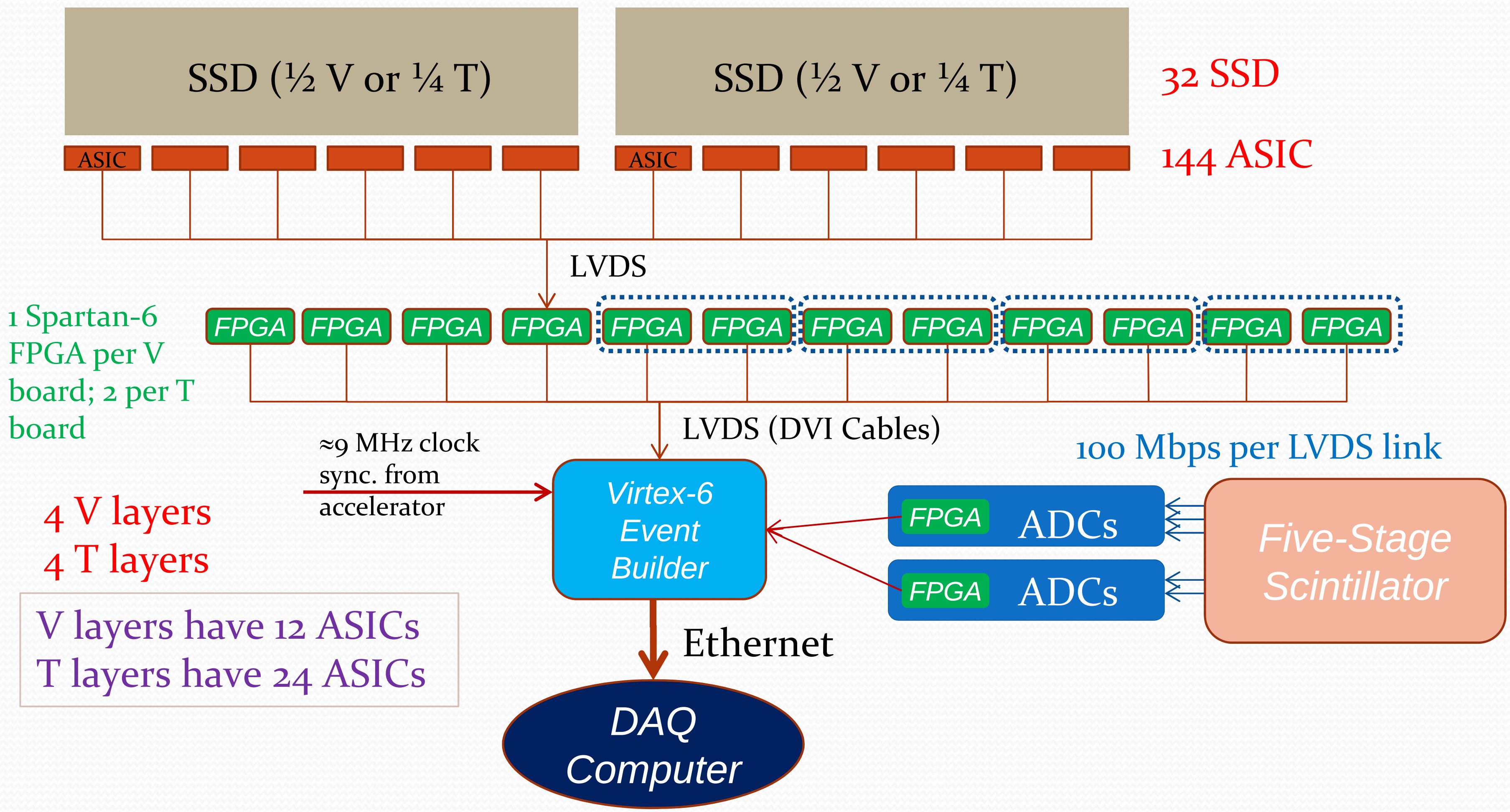
Pulses digitized by the 14-bit ADC



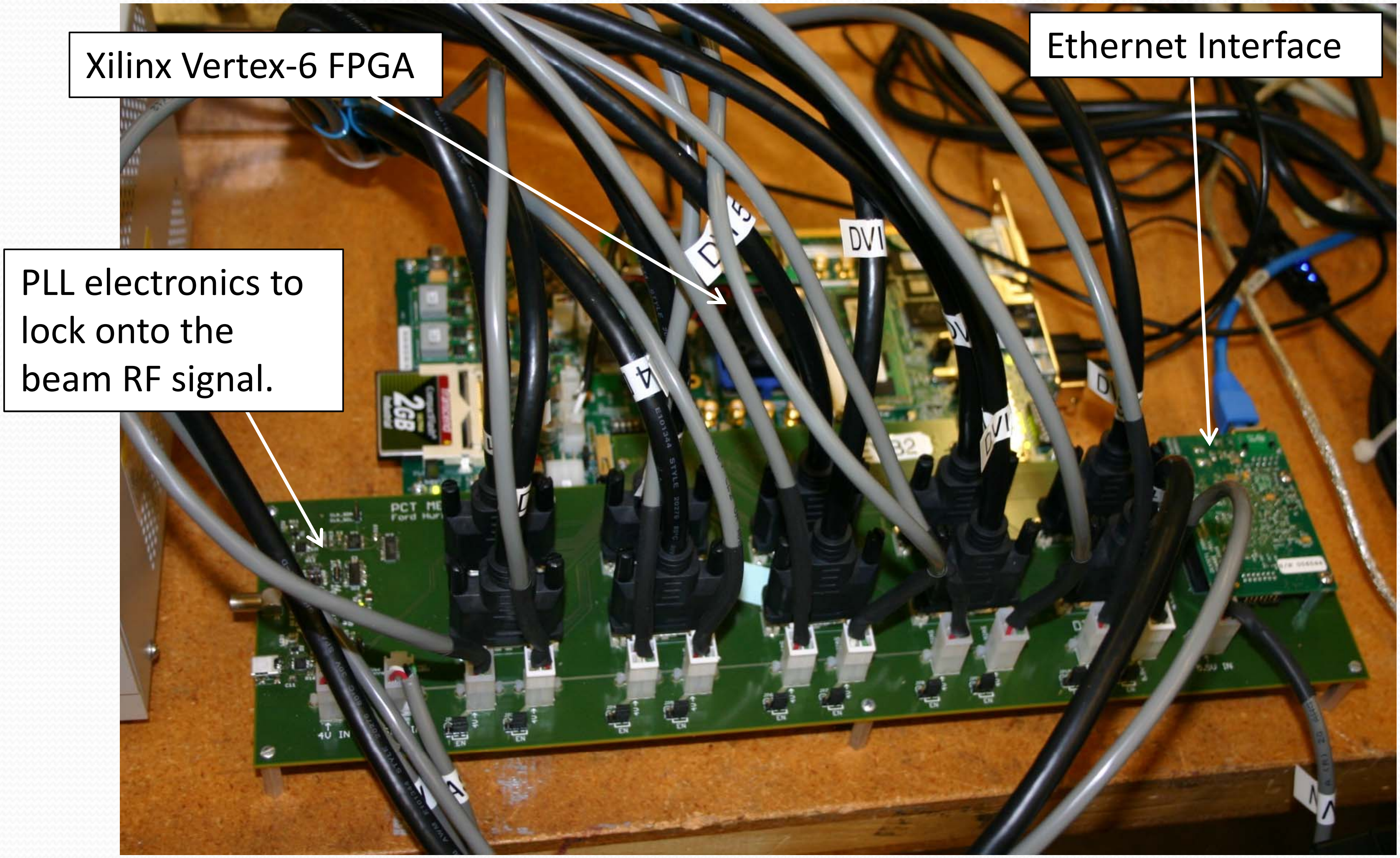
Some example energy detector measurements from a beam test last autumn. Each histogram represents a different absorber thickness used to slow down the protons.



Data Acquisition



Event Builder



Conclusions

- The existing pCT system, using Fermi-LAT detectors and electronics, has already told us a lot about the performance of pCT. Images of head "phantoms" have been acquired and reconstructed.
- Fabrication of the hardware of the new system is nearly complete, and it will tested in the proton beam at Loma Linda next month to produce some first trial images.
- Work is also in progress to improve the image reconstruction algorithms, and also to make them run faster, using an array of GPUs.
- Hopefully this effort eventually will improve the effectiveness of proton therapy!