DEVELOPMENT OF A PROTON CT (PCT) SCANNER

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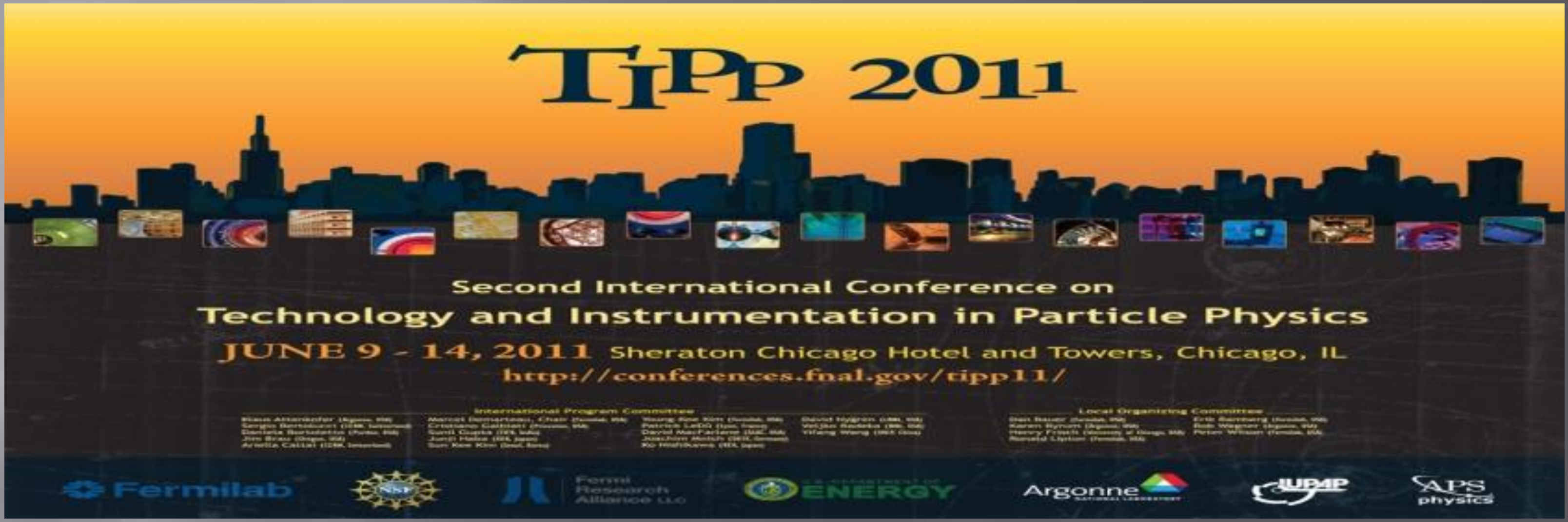

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NORTHERN ILLINOIS UNIVERSITY

University of Wollongong

Fermilab

SCIPP

pCT cast, 1st scanner, NIU – LLUMC – SCIPP

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pCT cast, 2nd scanner, NIU - FNAL

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Overview

- **History**
- **pCT Premises**
- **Constituents of pCT**
- **Current status of the pCT detector**
- **Premises for pCT of next generation**
- **New pCT R&D results**
- **Summary**

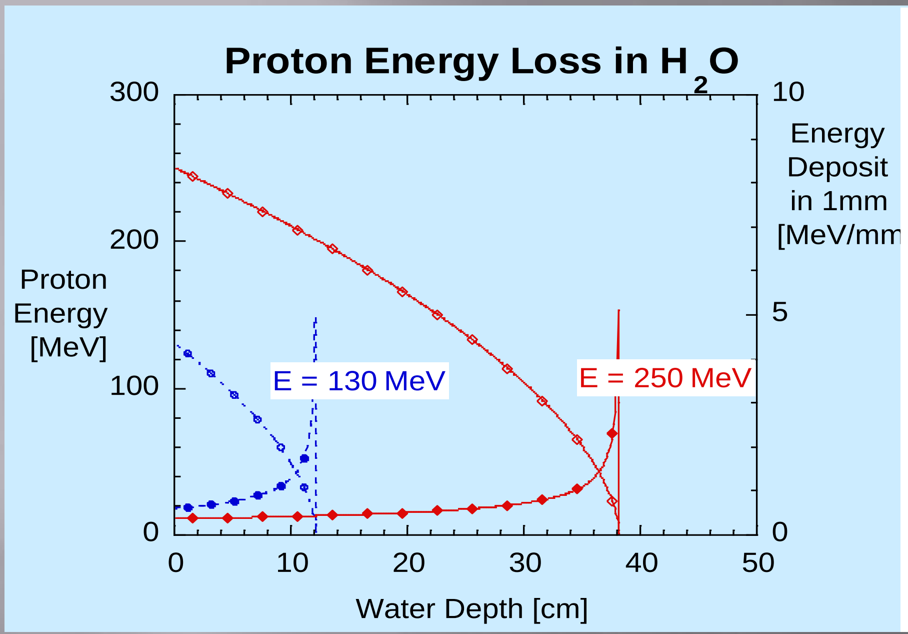
pCT History

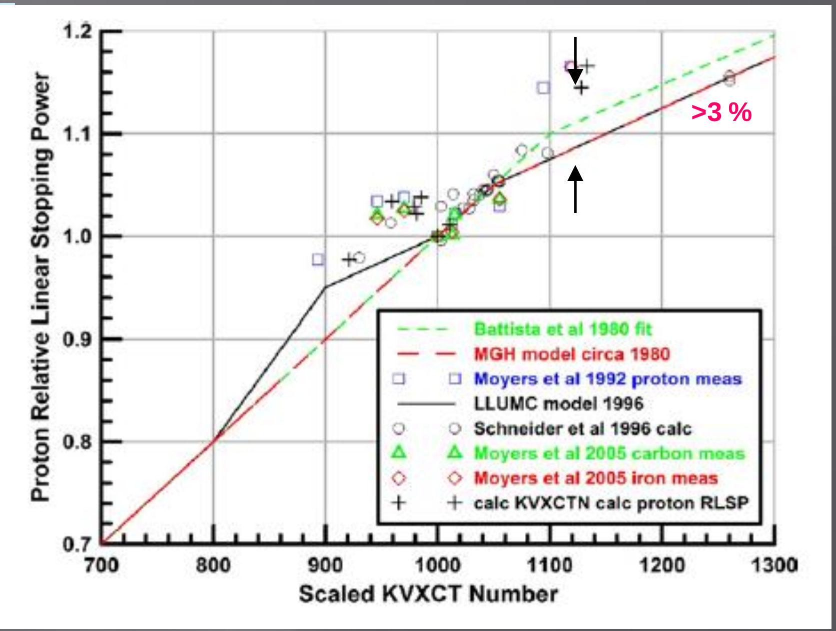
- **1963 – Allan Cormack mentions pCT in his landmark CT paper (J. Appl. Phys. 34, 2722-2727)**
- **1968 – First proton radiography experiments at HCL, LBL (Koehler, Cormack, Lyman, Goitein)**
- **1979 – Cormack shares CT nobel prize with Hounsfield**
- **1979-1981 – First pCT experiments at Los Alamos NL (K. Hanson)**
- **1990s – Talks on pCT at PTCOG meetings** (Particle Therapy Co-Operative Group)
- **1994 – Proton radiography at PSI (Schneider, Pedroni)**
- **1999-2000 – pCT with mod-wheel/CCD (Zygmanski, Gall)**
- **2003 – Formation of the pCT collaboration (SCIPP, BNL, SUNYSB, LLUMC)**
- **2004 – MLP concept (D.C. Williams)** (Most Likely Path)

Implementation phase

- **2008-2010– NIU-SCIPP-LLUMC pCT prototype scanner project, Si tracker and CsI calorimeter (Done)**
- **2010 – current , NIU-FNAL scintillator based pCT scanner project, SFT tracker and Sc. Pl. Range Detector, SiPM readout(preproduction R&D)**

Premises



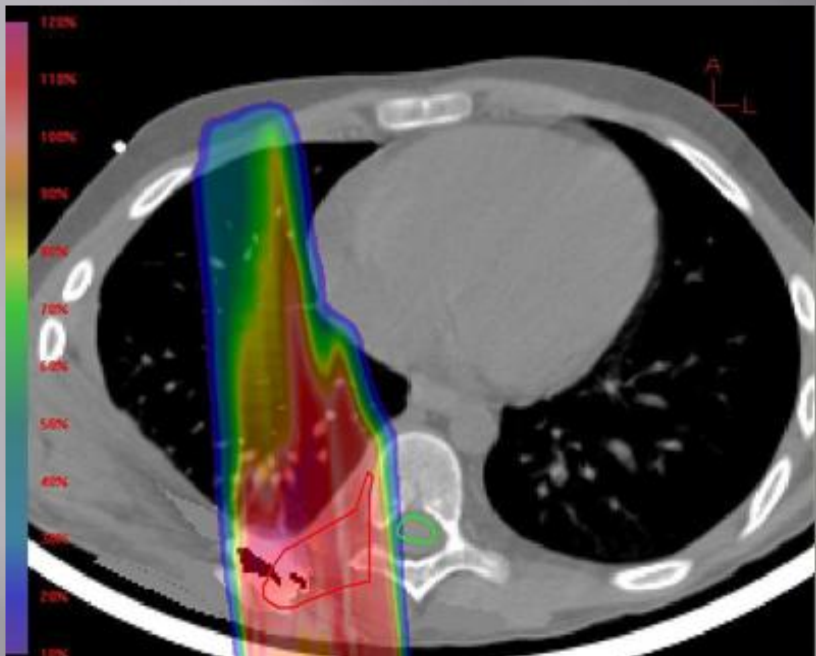


- **Maximum at depth (Bragg peak)**
- **Differences in the interaction of x-rays and protons with matter make proton range calculations uncertain**

Uncertainty in RLSP from XCT data can exceed 3% (Moyers, 2010)

Overshoot due to standard 3 mm range uncertainty

The same plan, with 1 mm range uncertainty. (pCT goal)

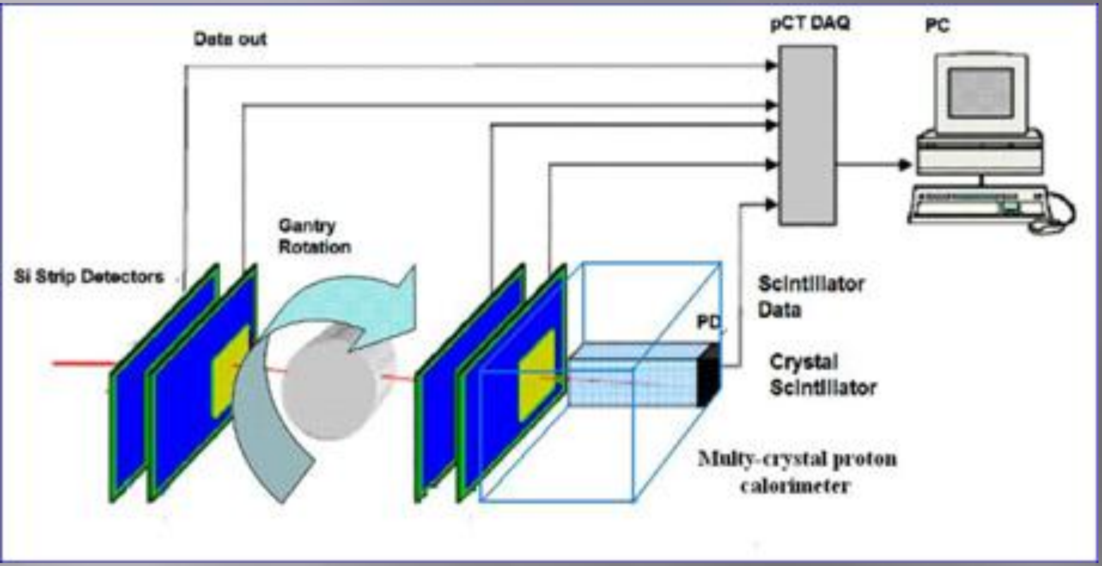


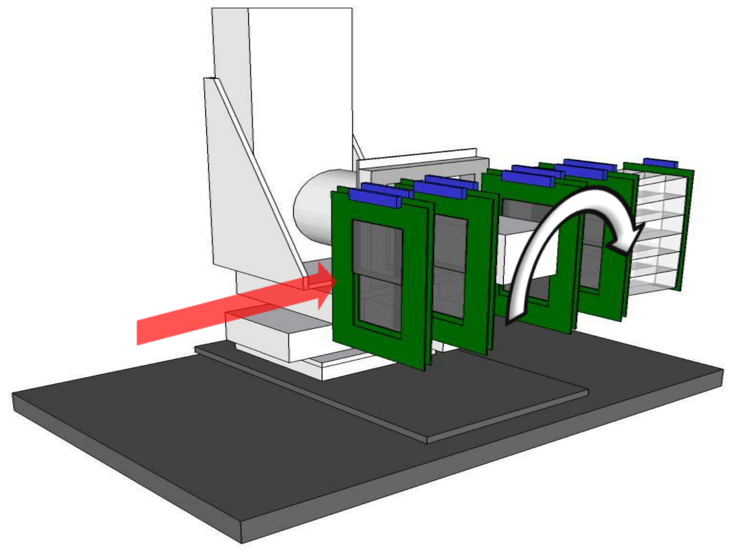
¤ The distribution of stopping power (relative to water) is presently determined from X-ray CT

¤ Uncertainty in calibration curve leads to range uncertainties of about 3.5% of proton range

WE NEED PROTONS FOR IMAGING !

Modern pCT design

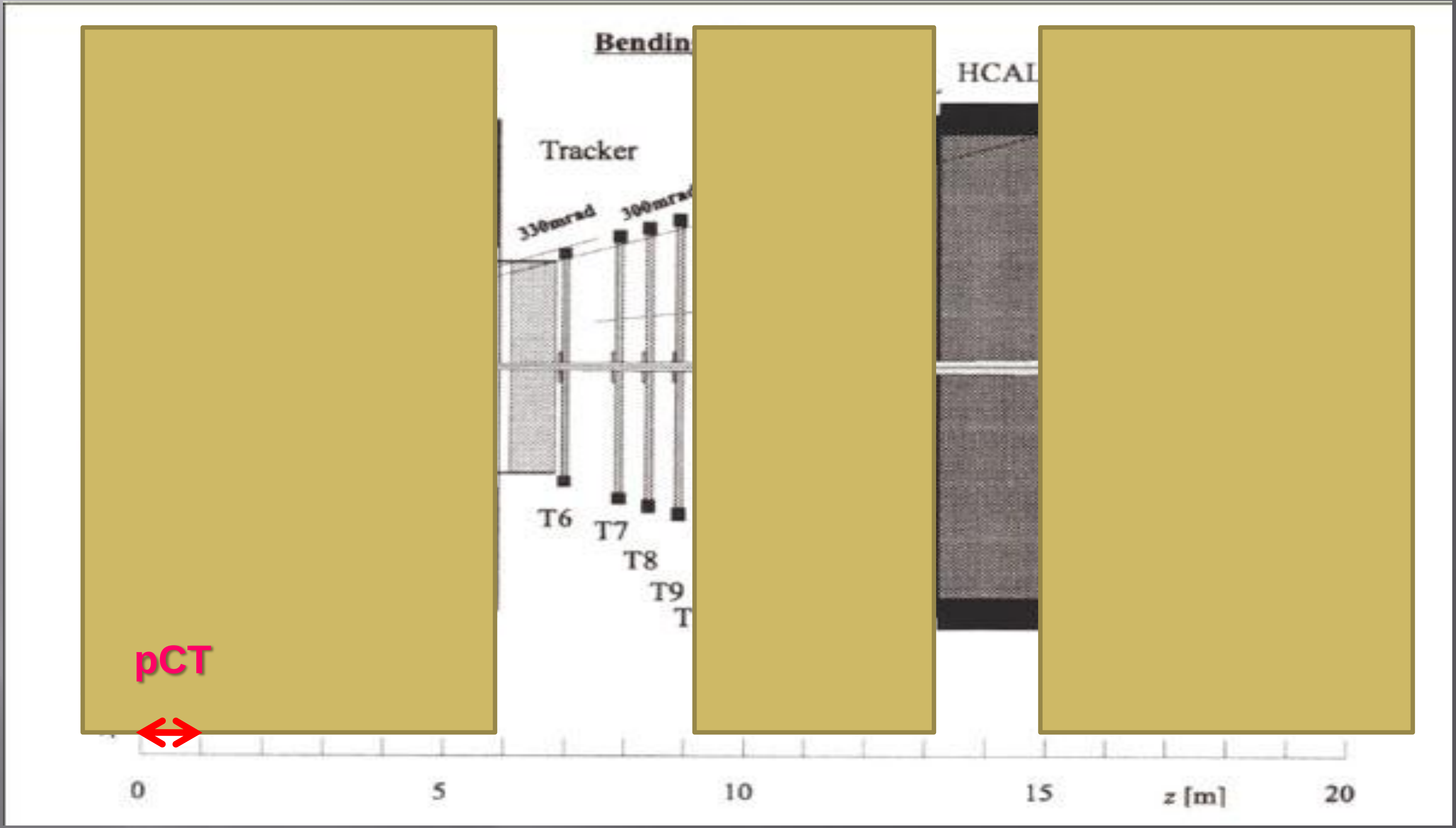




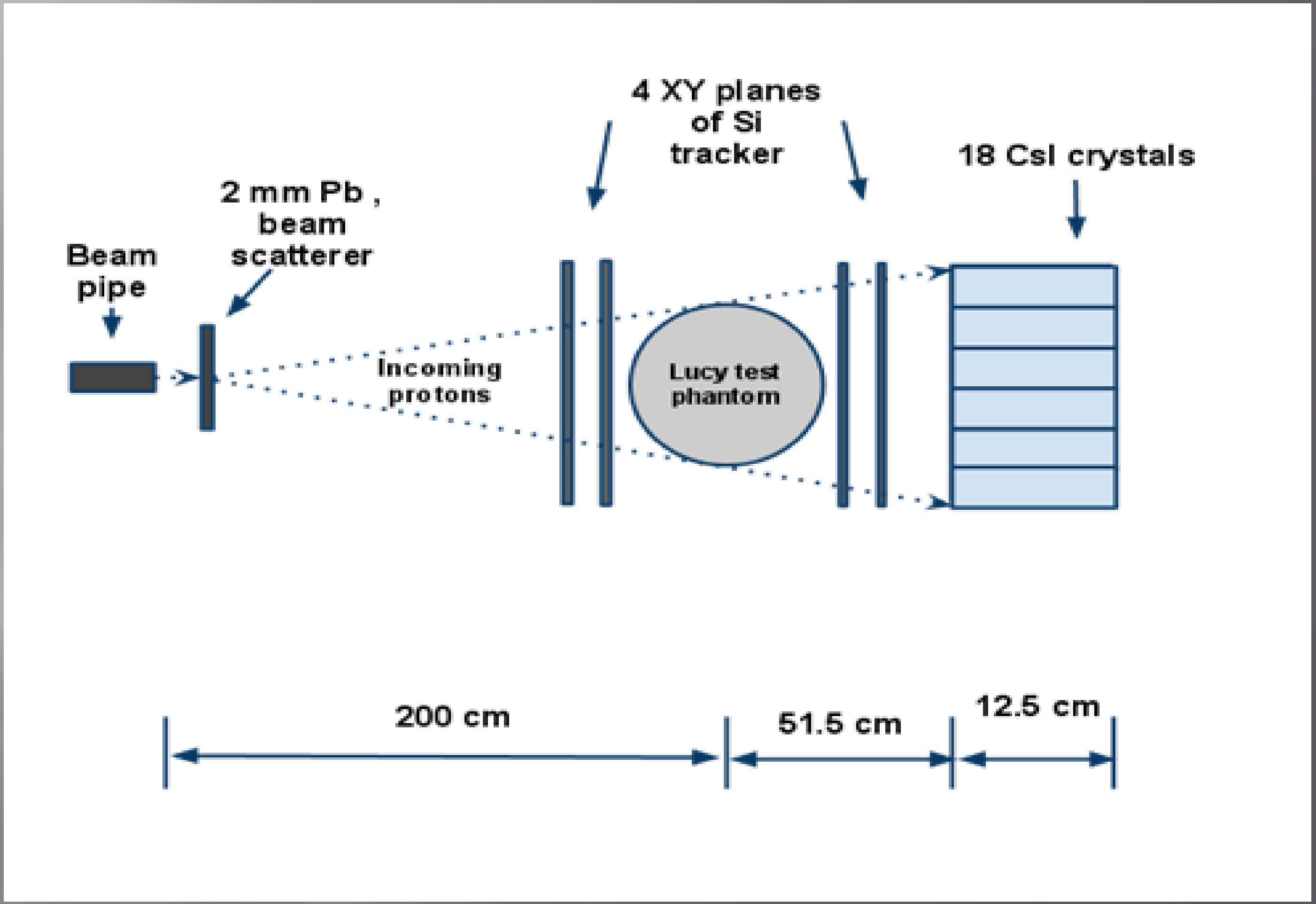
Basic idea behind pCT: Track each proton (Si tracker), measure residual energy (CsI calorimeter) for each proton, subtract residual energy of each proton (+ΔE_{Si}) from incoming energy = Lost energy inside object . Lost energy inside object ~ Most Likely Path inside object, apply reconstruction algorithm, reconstruct image! (much, much more complicated in real life).

We anticipate that approximately one billion protons must be recorded and distributed through all gantry angles and in a time less than 10 minutes when the detector is fully developed. Since we wish to determine proton range to within +/- 1 mm for head, neck and brain tumors, the voxel size for spatial resolution should be of order 1 mm for the image reconstruction, similar to X-ray CT images. We estimate that a proton beam of 200 MeV entering the patient will be adequate for complete penetration for a human head.

pCT is IMAGE RECONSTRUCTION + fixed target experiment – particle identification !



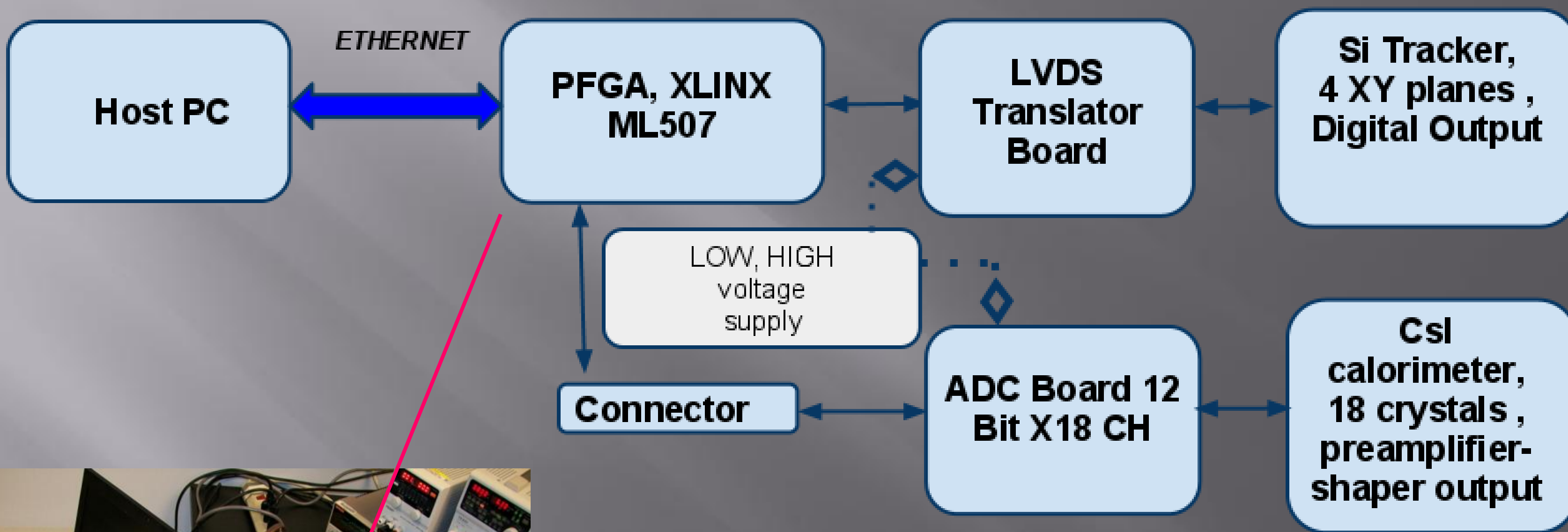
pCT geometry



! Trigger is formed by either coincidence of all 4 Si tracker planes or sum of 18 crystal signals !

pCT includes : Si tracker, Calorimeter, DAQ

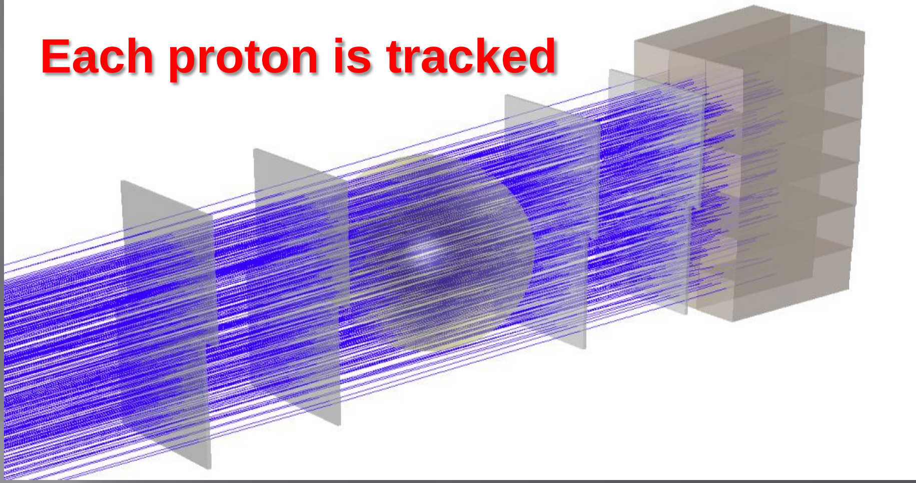
DAQ

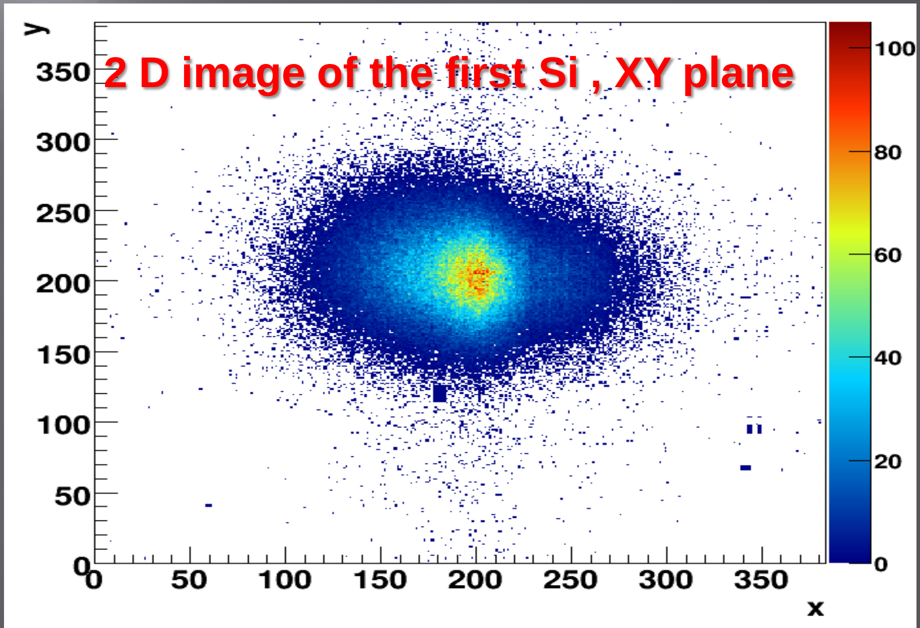


Host PC
ETHERNET
PFGA, XLINX ML507
LVDS Translator Board
Si Tracker, 4 XY planes , Digital Output
LOW, HIGH voltage supply
Connector
ADC Board 12 Bit X18 CH
CsI calorimeter, 18 crystals , preamplifier-shaper output

04/03/2010

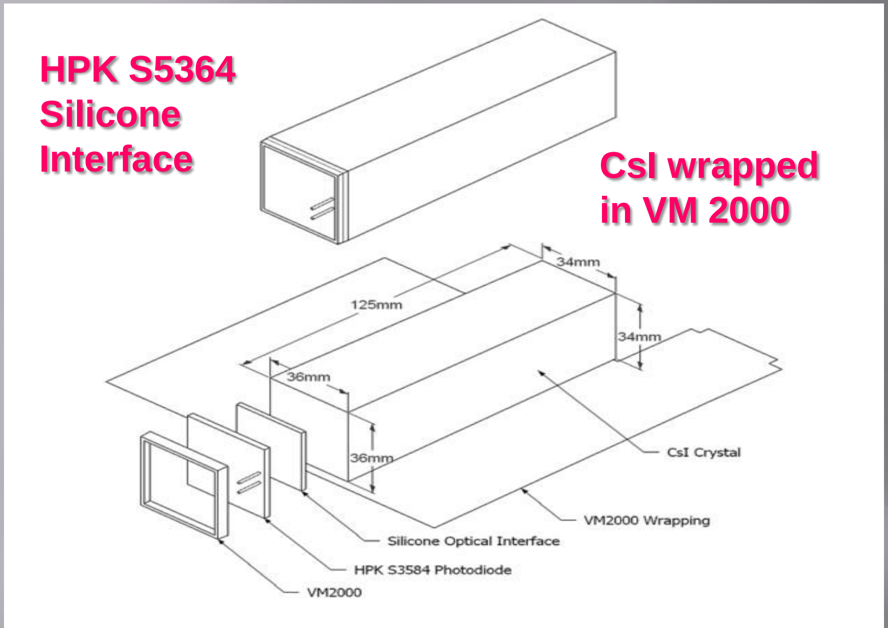
pCT, each proton is tracked

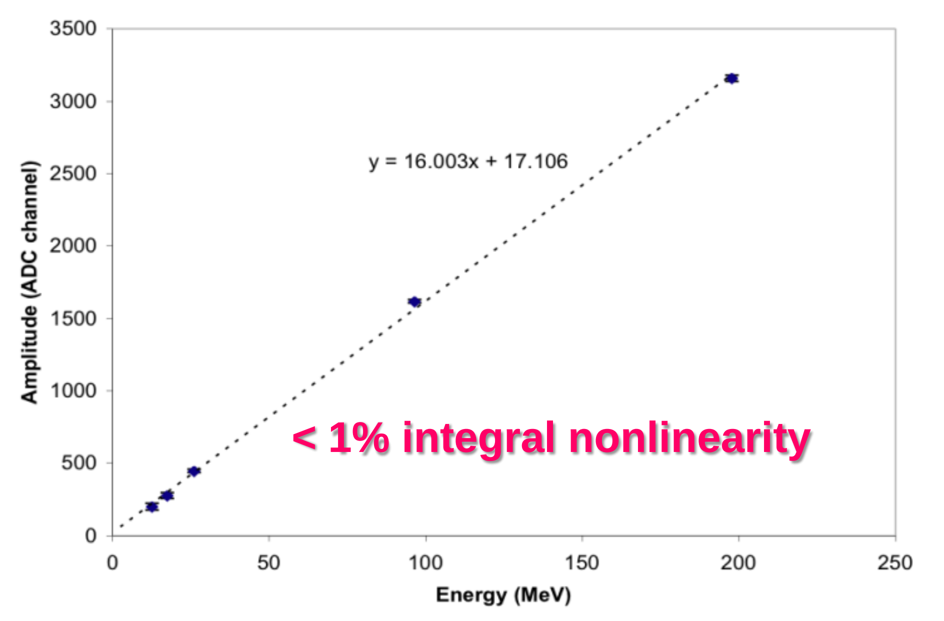


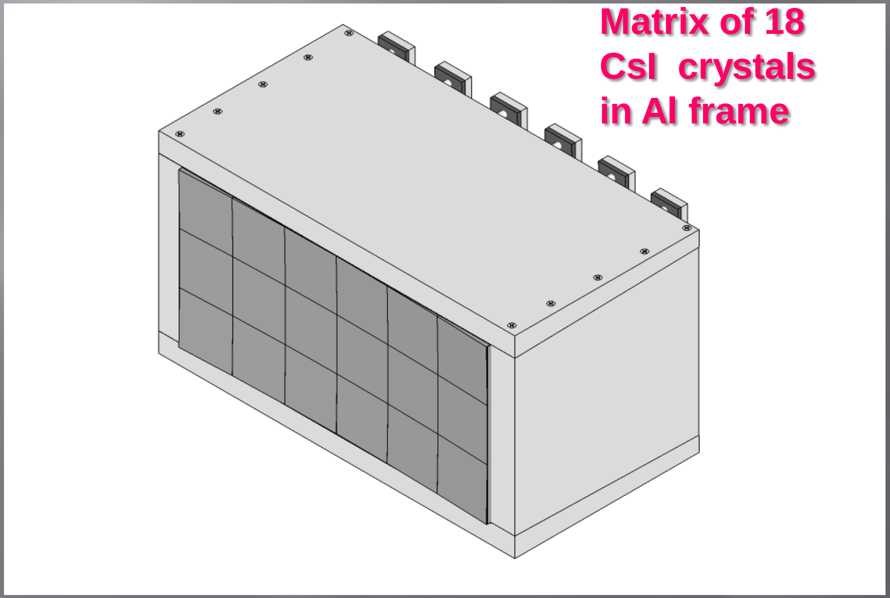


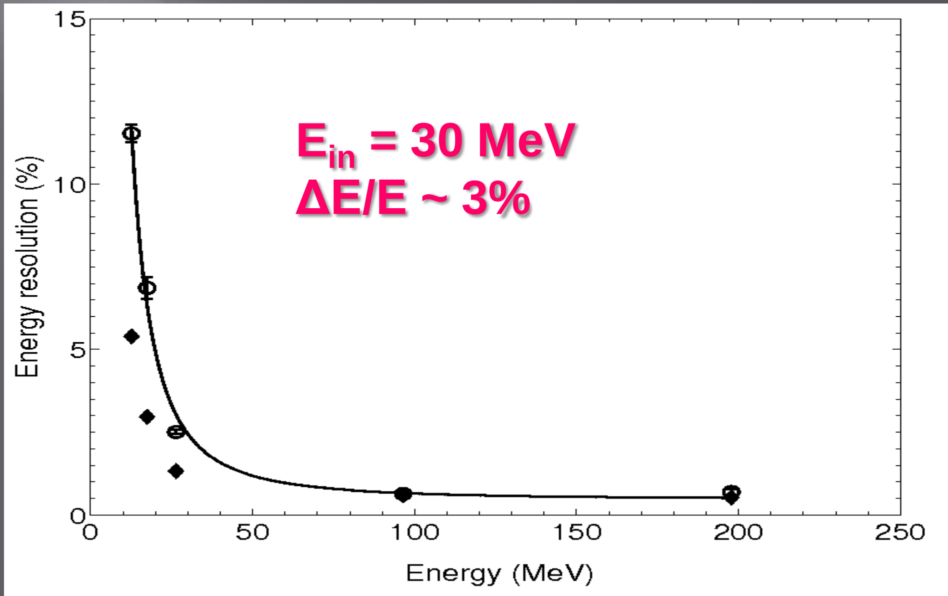
∗ The silicon detector - two layers of silicon strip detectors.
∗ The sensors are 89.5 x 89.5 mm2 with strip pitch of 238 um and 400 um thickness.
∗The strips of each layer are individually connected to 6 ASICs*64 strips.
∗The sensors are shingled to create 9 X 18 cm^2 aperture !

CsI calorimeter



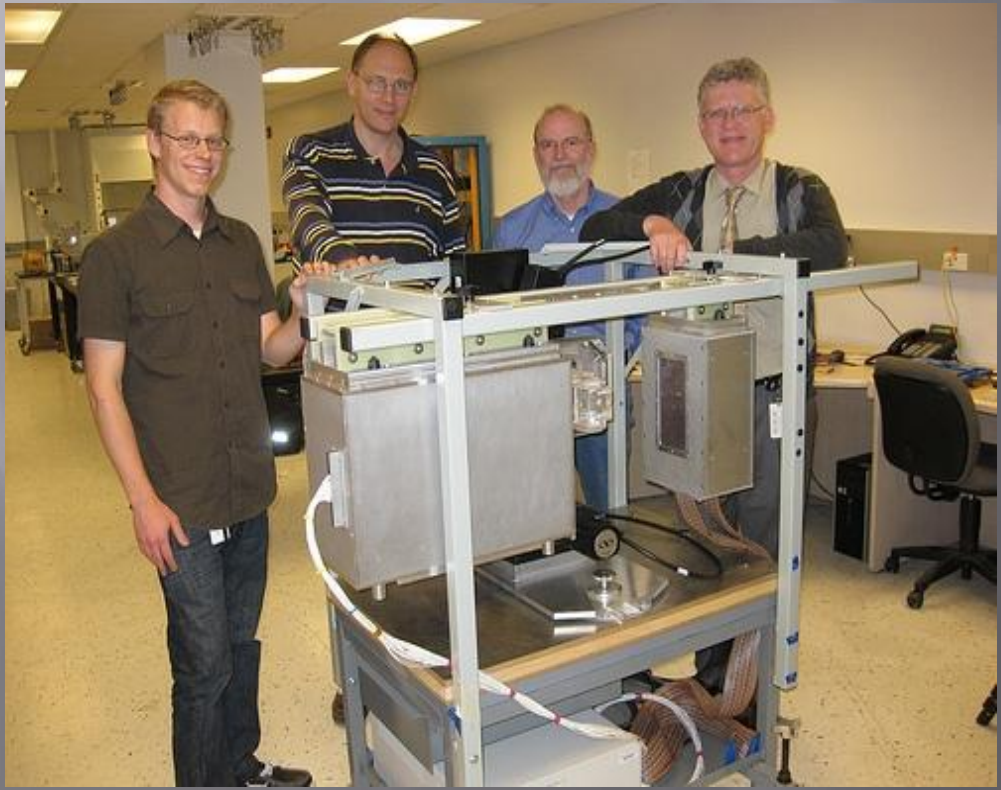


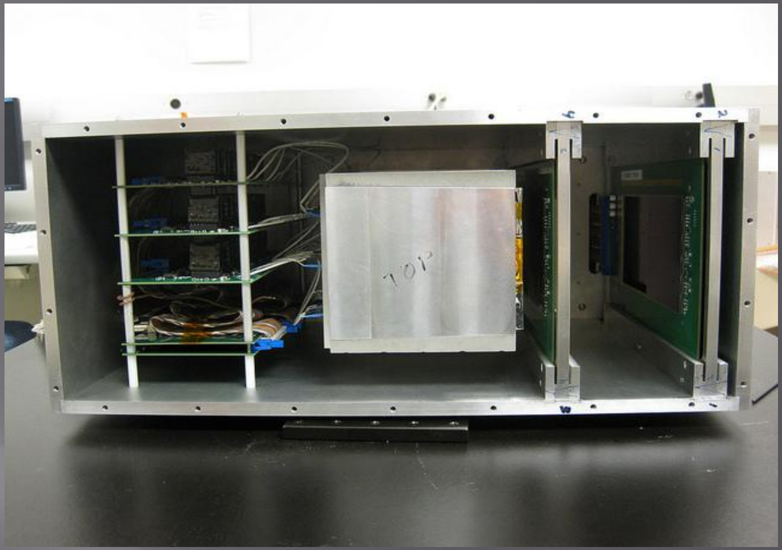


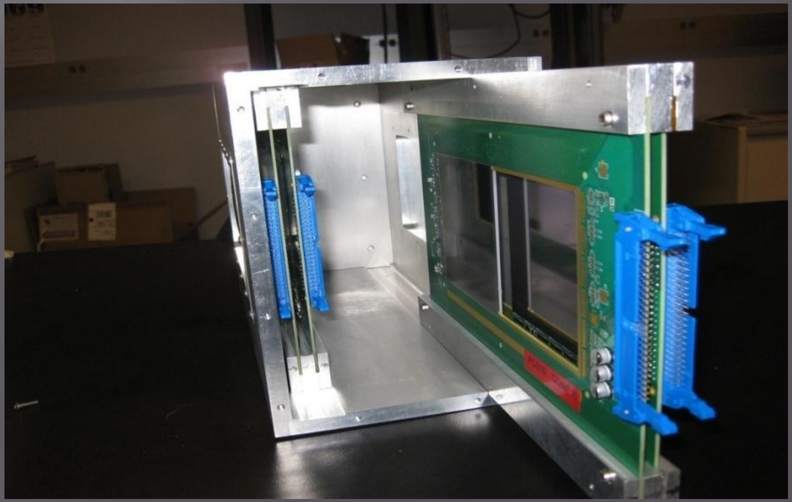


Bringing all parts together

- Upstream detector includes 2 Si X-Y planes + electronics(front enclosure)
- Downstream detector includes 2 Si X-Y planes + 18 CsI crystals + electronics (rear enclosure)
- Rotational stage with a phantom
- DAQ
- Mech. Support







pCT
Hardware tree + reconstruction related part

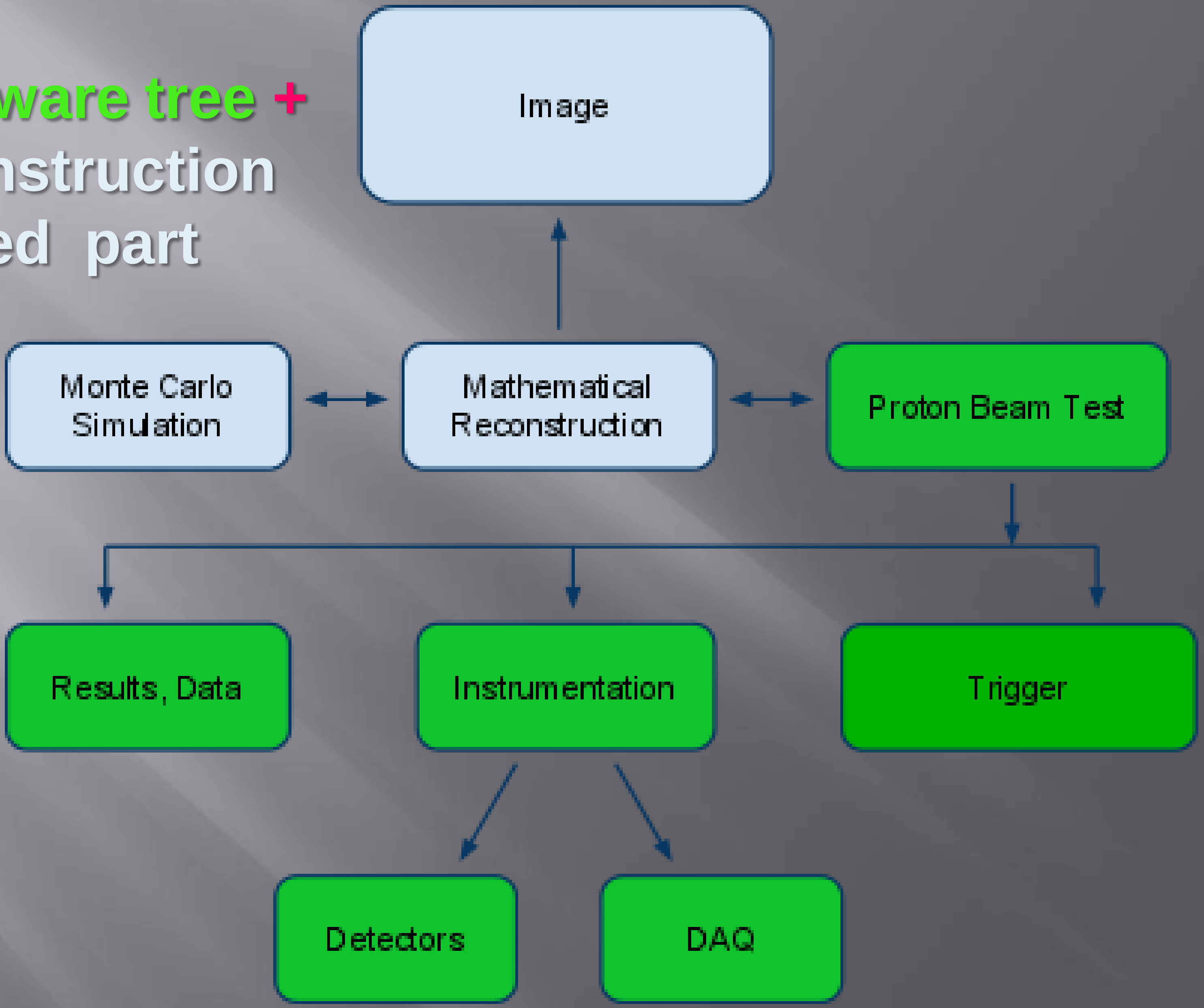
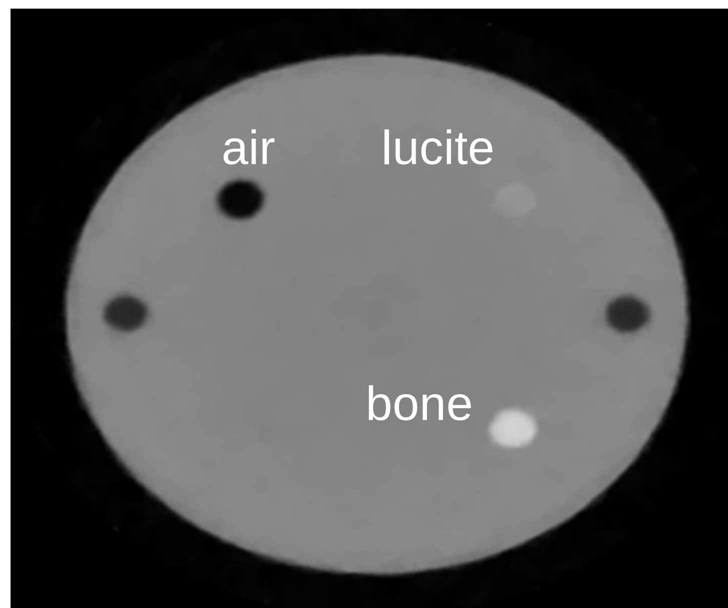


Image reconstruction

1. WEPL calibration and cut
2. Correction for overlapping of Si tracker
3. Correction matrix with Calorimeter response
4. Angular and spatial binning
5. Filtered Back Projection and Iterative Algebraic reconstruction
6. MLP formalism for final reconstruction

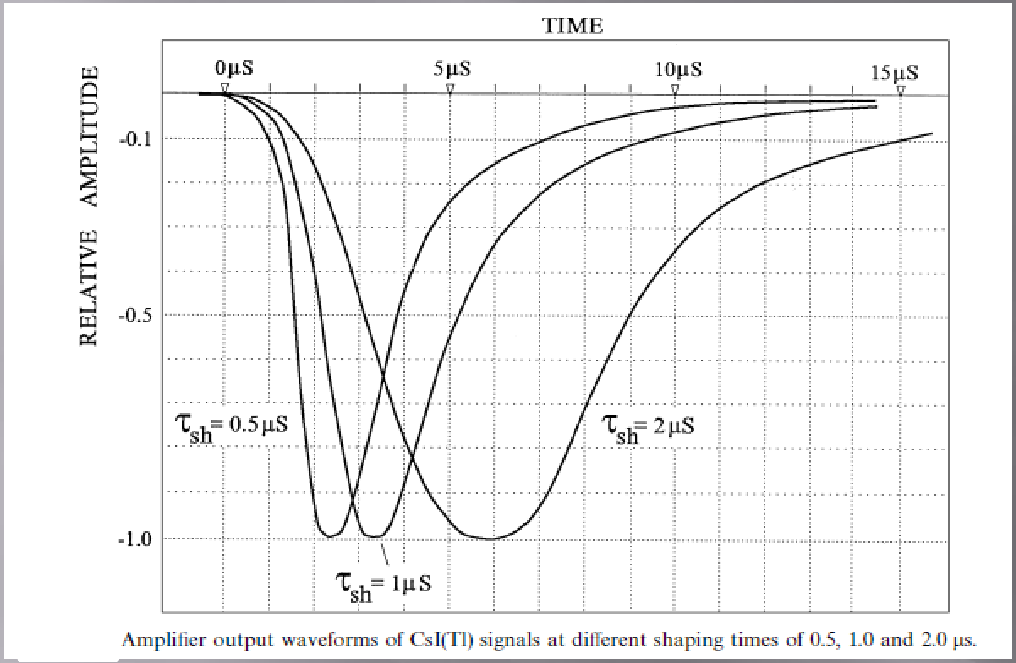
Material	True RSP	Reconstructed from measurements RSP
Polystyrene	1.037	1.065
Bone	1.70	1.68
Lucite	1.2	1.19
Air	0.004	0.05



2.5 mm slice
0.65 mm voxel

We accumulated data for the followed by image reconstruction during 4 hours ! It is not acceptable for clinical applications ! Goal – Faster pCT scanner

Upgrade issues:



Amplifier output waveforms of CsI(Tl) signals at different shaping times of 0.5, 1.0 and 2.0 µs.

Why ?

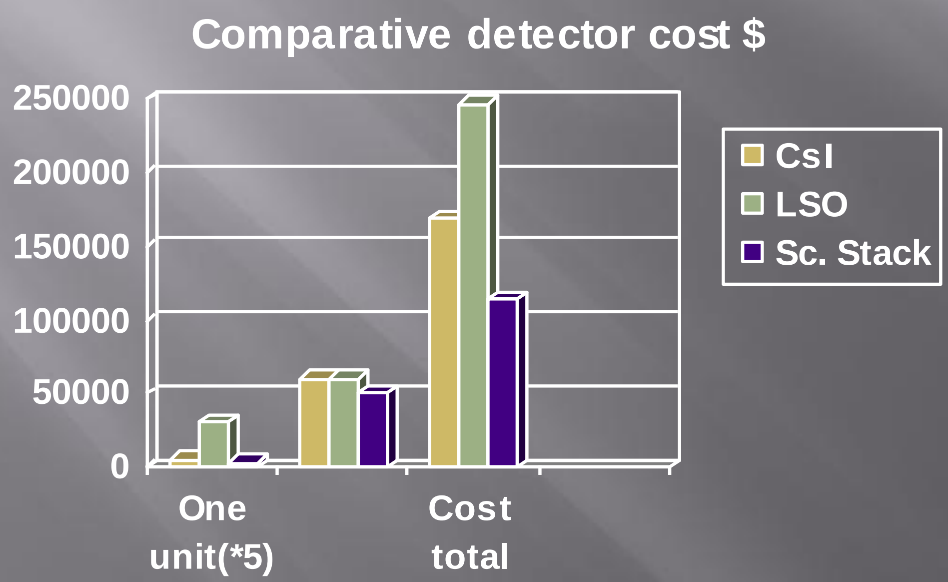
→ ~ 100 KHz current limit

10^8 protons / head volume (360°)

2 min

→ ~ 2 MHz /spill

(2 sec duty cycle)



To use fine segmentation CsI (expensive)

LSO crystal gives 50 nS decay time (expensive)

Summary of premises for a new pCT

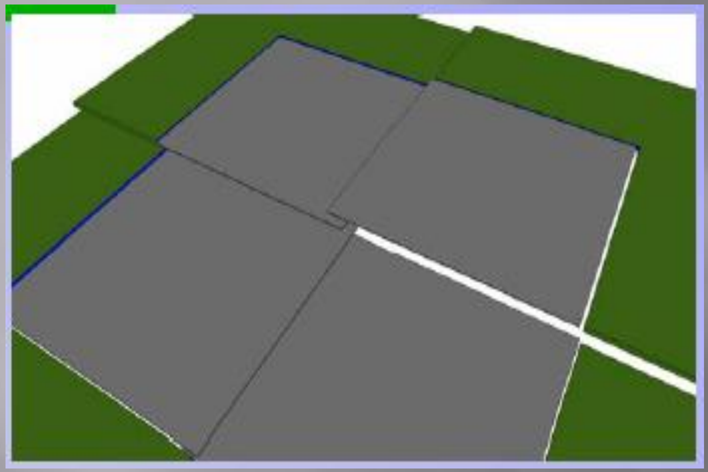
- **Si tracker + CsI calorimeter**
- GTRC limits DAQ rate at 100 KHz
- CsI (Tl) , **3.3μs decay time**
- **Area 18 X 36 cm^2 , overlap or edgeless Si, total number of channels : Tracker ~ 4512, Calorimeter = 72**

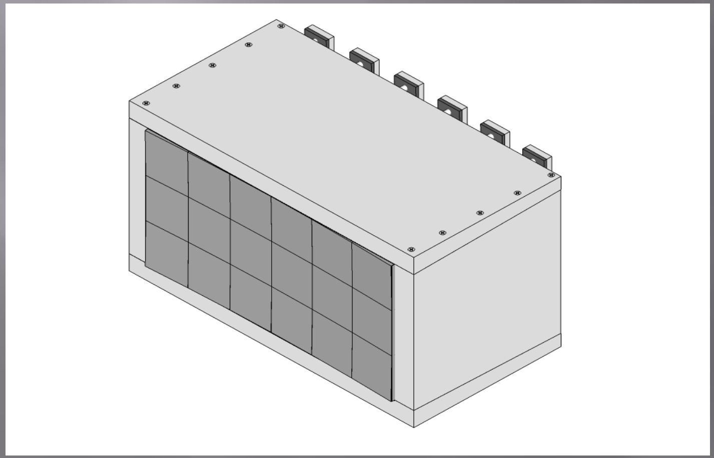
- **Fiber tracker + Range detector**
- FPGA based DAQ, 20 MHz acquisition rate, 100 MHz clock
- SiPM for both subsystem, 100 ns pulse separation (10 MHz seems possible), impressive vendor list
- Area 18 X 36 cm^2, no overlap, total number of channels: Tracker ~ 2160, Range Detector ~ 100

Ratio of multiple scattering $\theta_{Si} / \theta_{Sc}$ ~ 1.1 ! **Si = 800 μm, SFT = 3.2 mm**

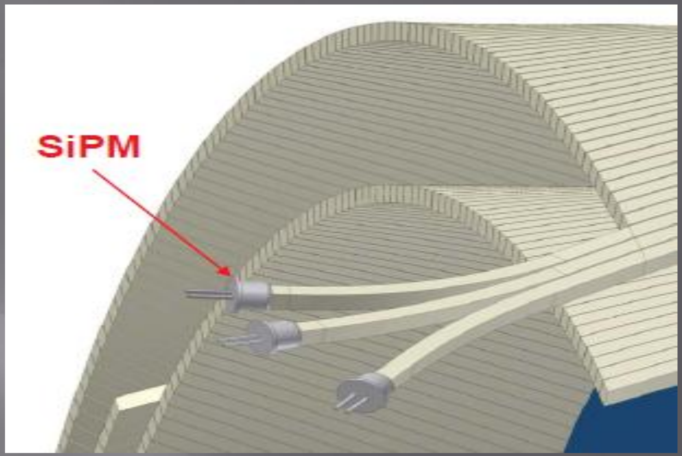
1 st scanner vs 2 nd

SI TRACKER + CSI CALORIMETER





SFT TRACKER + SC RANGE DETECTOR



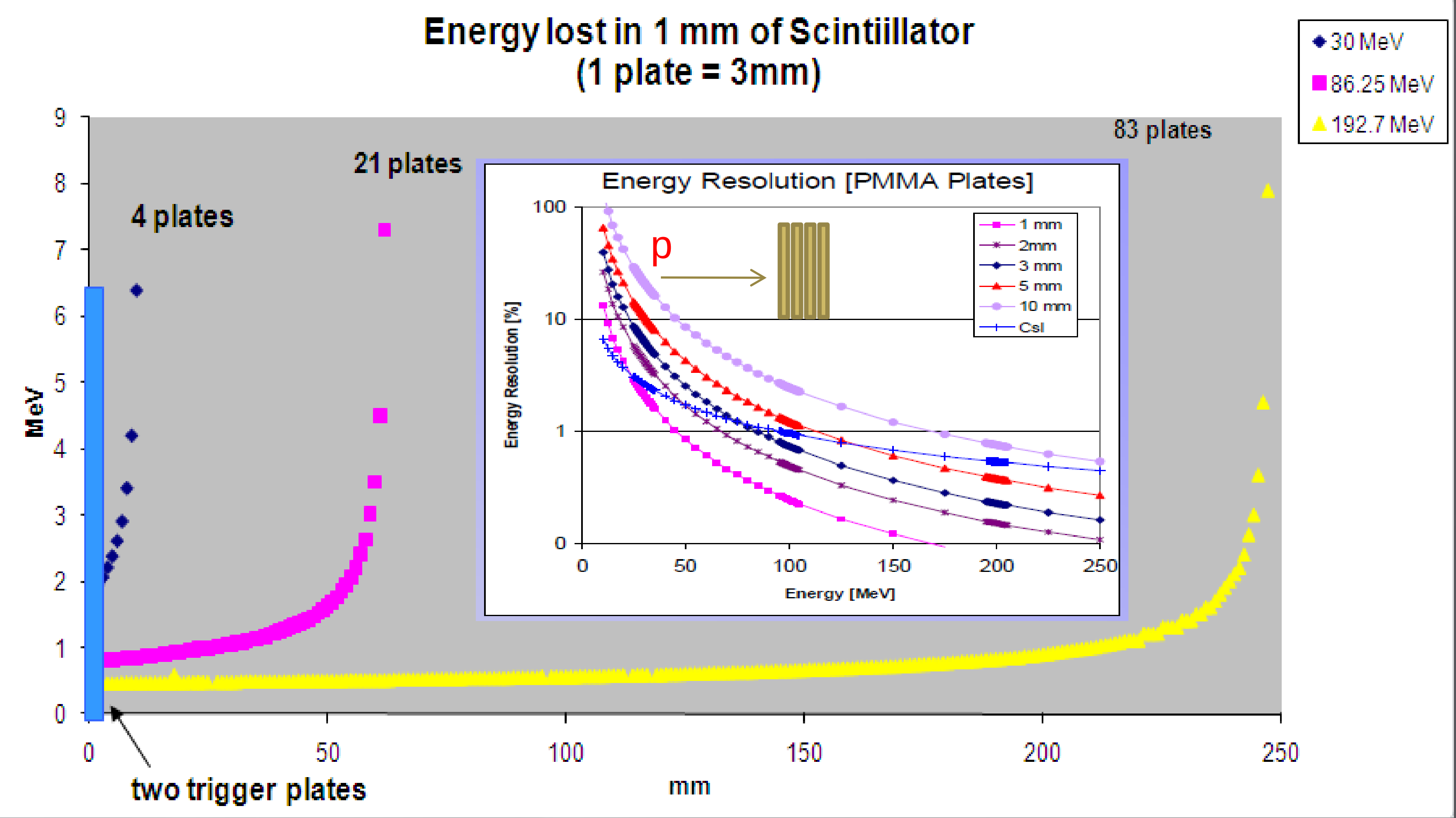
100 plates, 3 mm, Polystyrene Sc. ~ 1% resolution

Specs for a new (2 nd) scanner

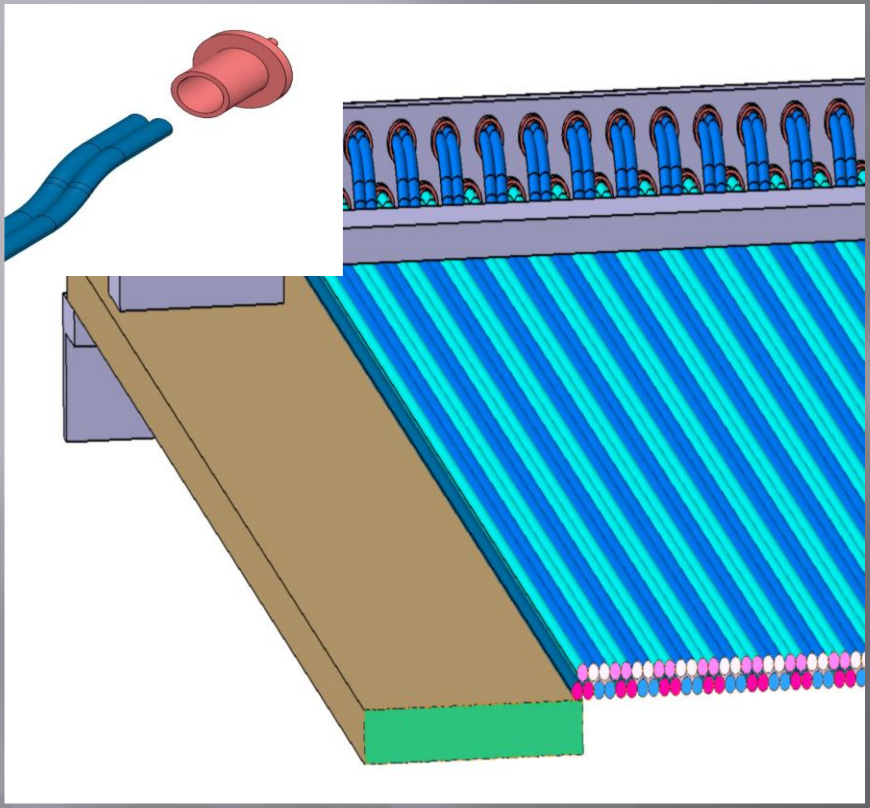
Parameter	Baseline	Preferred	Comments
Upstream Tracker Size Downstream Tracker Size Calorimeter Size	18 x 36 cm 18 x 36 cm 18 x 36 cm	17 x 36 cm 23 x 32 cm 27 x 36 cm	Assume Scan beam geometry and +/- 2.5 cm "flashover"
Number of projection angles	Continuous	Continuous	One continuous gantry speed from 0^o to 360^o
Total scan time	7.6 minutes	5.7 Minutes	Calculated from no. of protons required, resolving time, and assumed pile-up percentage.
Useful protons per voxel Voxel Size	100 1.25 mm	100 1.0 mm	No. of voxels approx. = 8.3 x 10E6 (preferred)
Total number good proton tracks needed through human head	4.15 x 10E8	8.3 x 10E8	For 1% electron density resolution
Nuclear interactions(loss) Protons lost to carving Protons lost from Pile-up	25% 25% 25%	25% 25% 25%	Pre-selected for rate calc.
Total protons recorded	1 x 10E9	2 x 10E9	
DAQ rate	10 MHz	20 MHz	

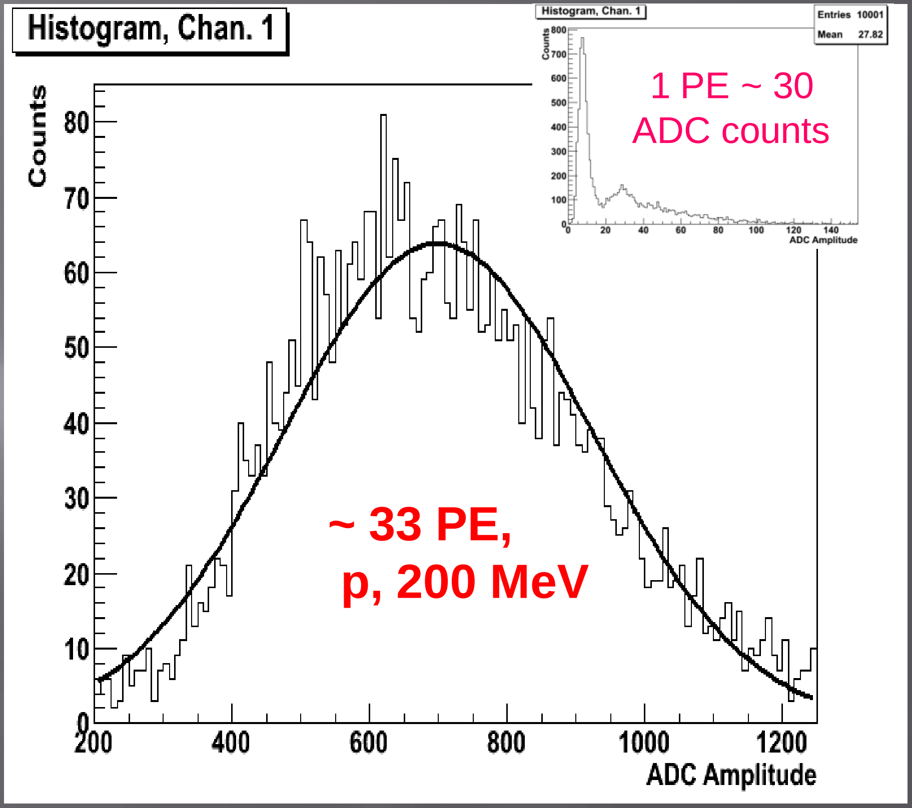
Transition from current pCT scanner to the new one

Scintillating Plate Range Detector will replace CsI calorimeter calorimeter !



Scintillating fiber tracker with SiPM readout will replace Si Tracker



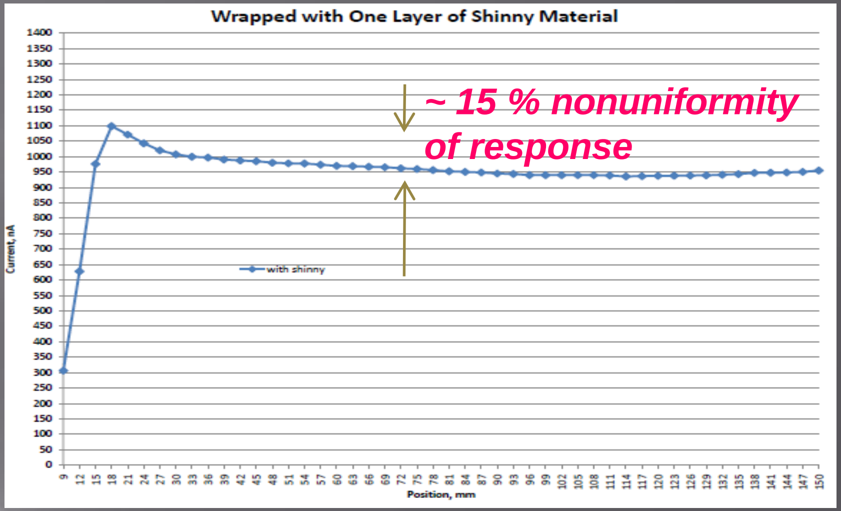


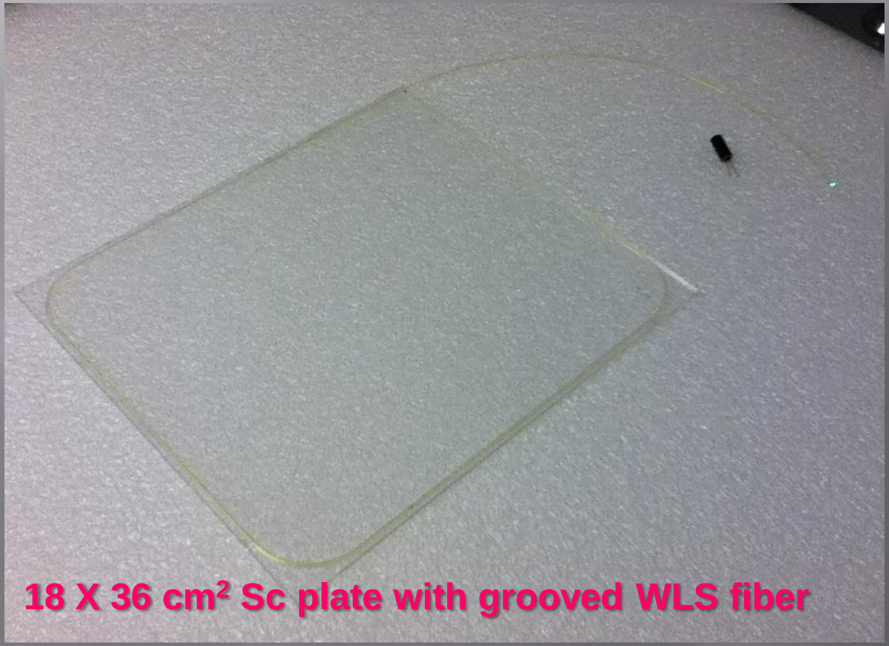
SF, Green, Polystyrene, KURARAY, 0.75 - 1 mm, 2 clad., 3HF, Al spattering .

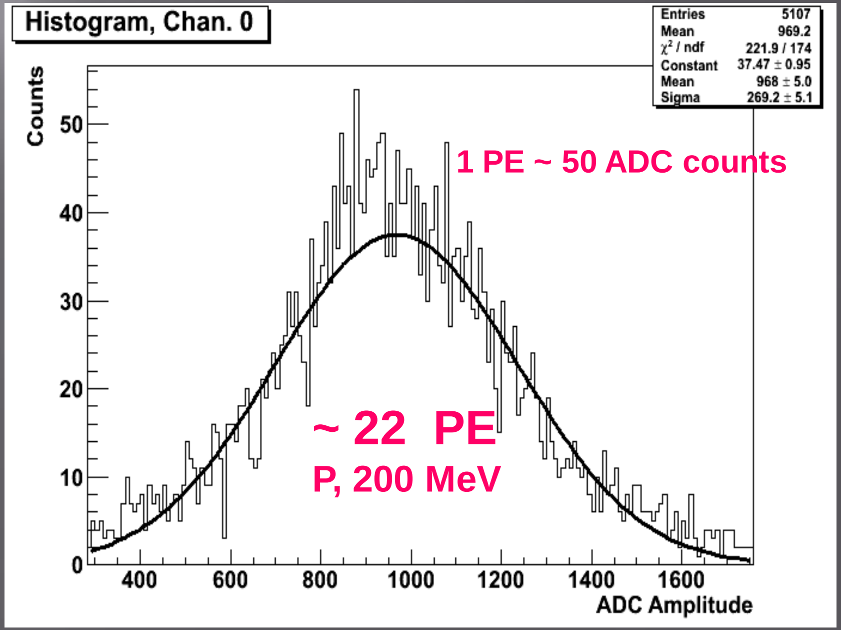
~ 33 PE, 36 cm Scint. Fiber , trigger fiber covers 5 cm from the far end.

Range detector with 3 mm scintillating plates, SiPM readout.

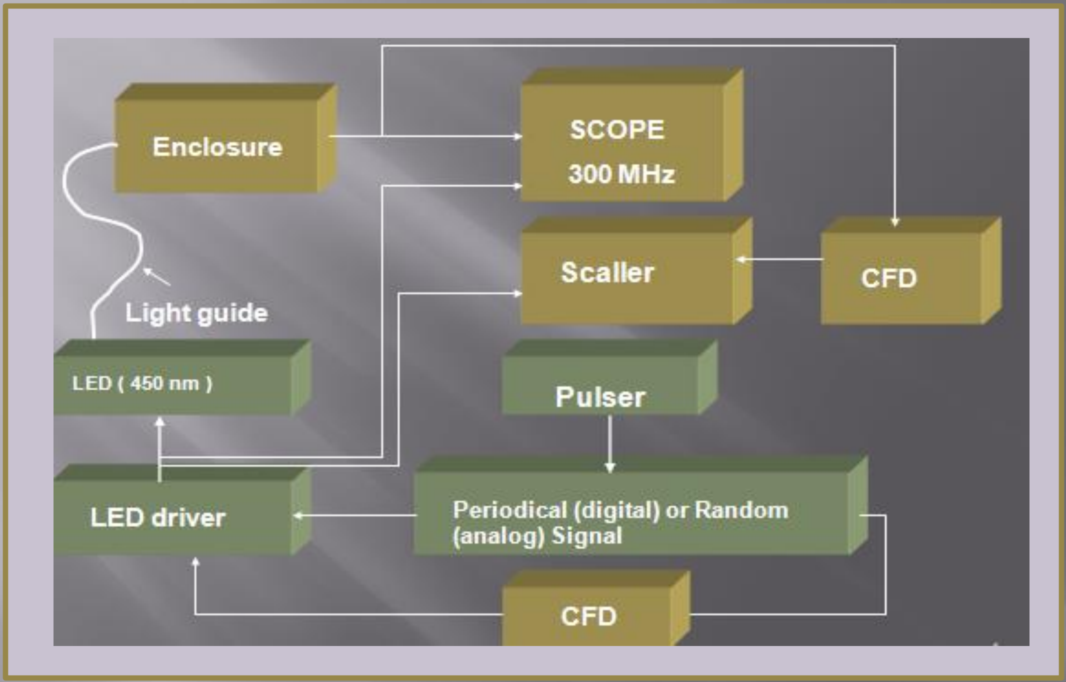
Total number of channels ~ 120
One plate dimensions
18 X 36 X 0.3 cm^3
Digital or analog readout ?
SiPM readout through 1.2 mm WLS fiber
SiPM is of 1.3 mm diam.

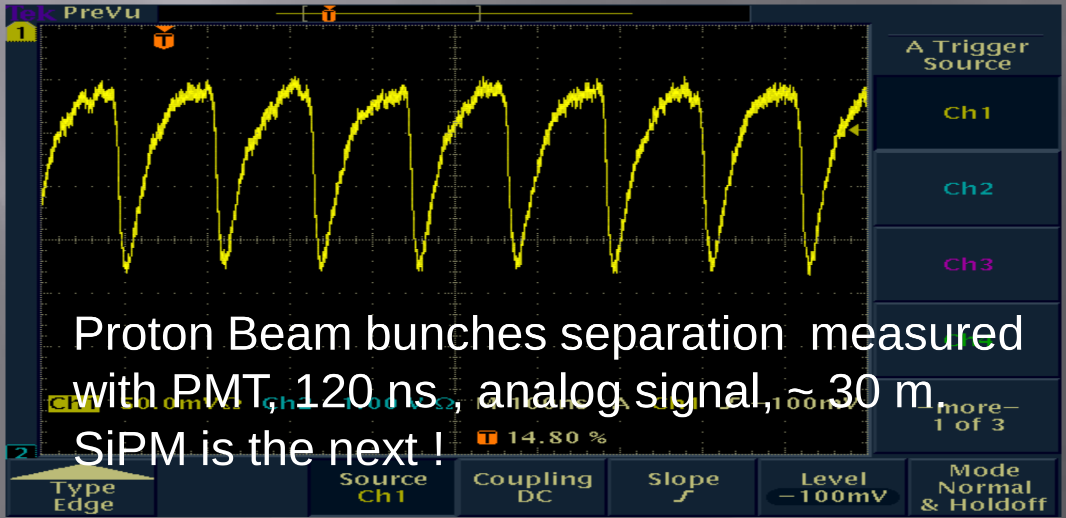






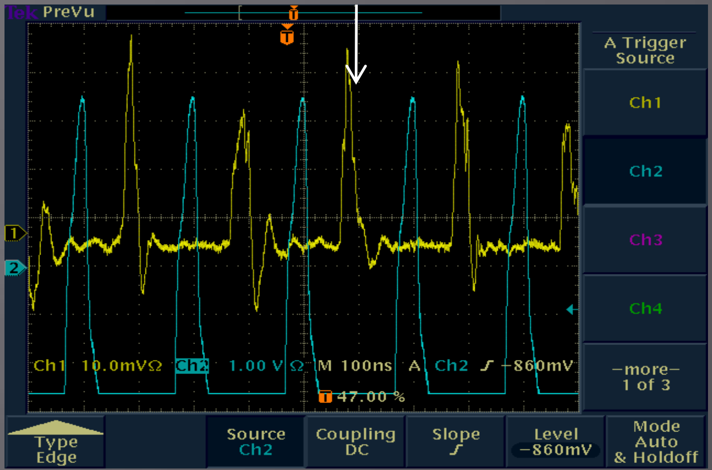
Rate studies



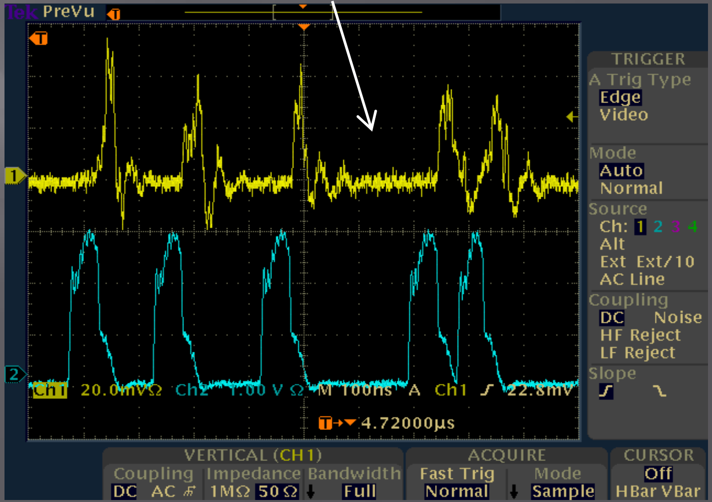


Proton Beam bunches separation measured with PMT, 120 ns , analog signal, ~ 30 m.
SiPM is the next !

Periodical signal

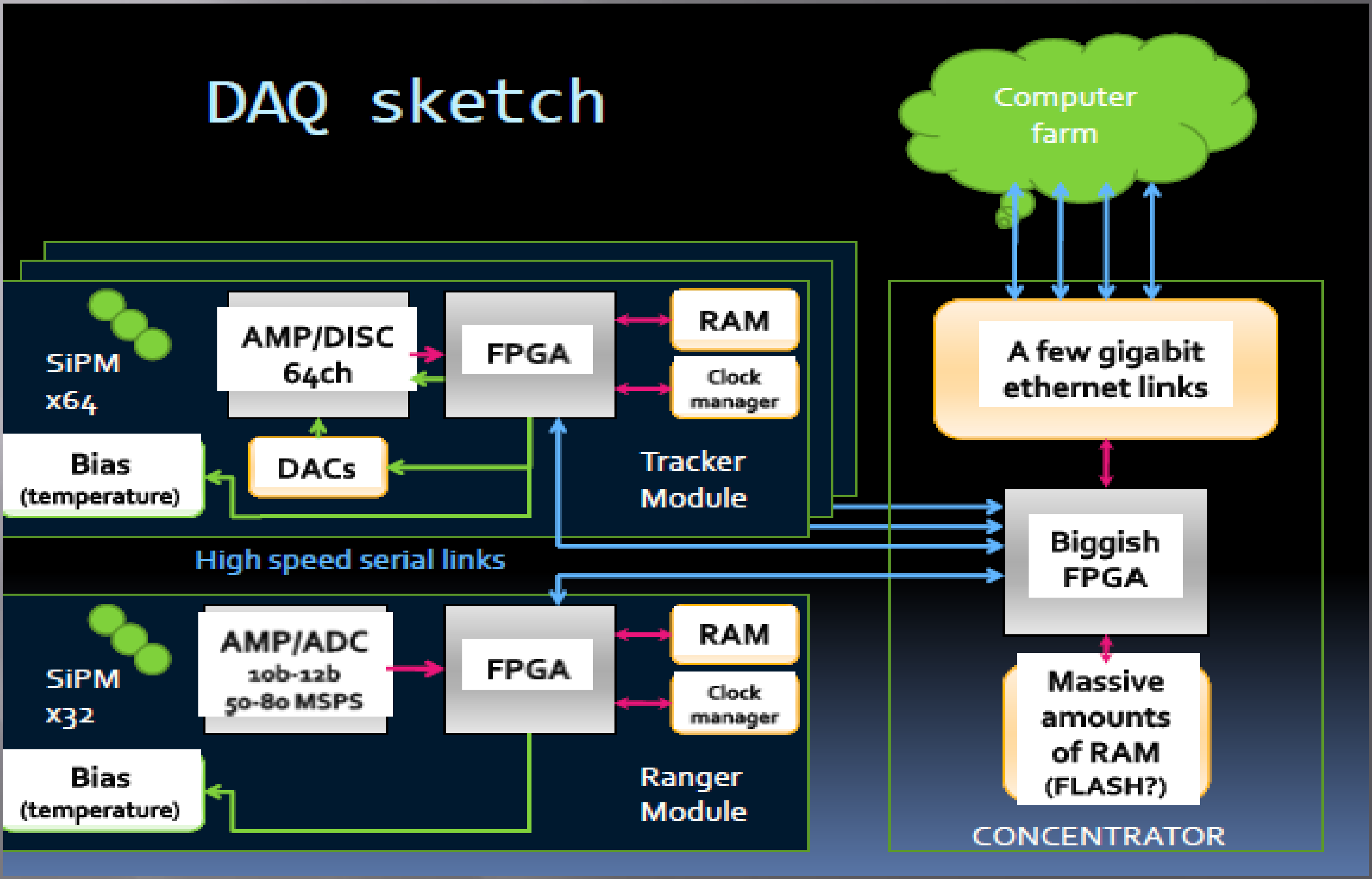


Random signal



SiPM , Comfortable at 5 MHz rate !!! LED measurements

10 MHz DAQ



DAQ sketch
Computer farm
SiPM x64
AMP/DISC 64ch
FPGA
RAM
Clock manager
Bias (temperature)
DACs
Tracker Module
High speed serial links
SiPM x32
AMP/ADC 10b-12b 50-80 MSPS
FPGA
RAM
Clock manager
Bias (temperature)
Ranger Module
A few gigabit ethernet links
Biggish FPGA
Massive amounts of RAM (FLASH?)
CONCENTRATOR

pCT production plan tree

R&D with I SF , SP,
January 10 of 2011 as R&D starting point

Results evaluation

FPGA based DAQ, 64 channel FT prototype, + a few plates range detector

We are here, June 10, 2011

Results evaluation

GEANT 4 simulations

Range Detector, Fiber Tracker construction

PCT integration, mech. assembly, testing,

Anticipated Completion: September 2012 , (~ 3 month behind)

Summary

! pCT scanner composed of Si strip detectors and CsI calorimeter is up and running

! Slow Data Acquisition Rate (100 KHz) !

! R&D on new generation of pCT scanner is on its way

! Signal (fiber ~ 33 PE, SP ~ 22 PE) is well above of single electron noise level, threshold 4-5 PE without efficiency lost , 5 MHz rate is obviously reachable for SiPM tested !

! More results to come

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