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A Detector for Proton Computed Tomography

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PREFACE

- Radiation therapy is a widely recognized treatment for cancer. Energetic protons have distinct features that set them apart from photons and make them desirable for cancer therapy as well as medical imaging.
- The clinical interest in heavy ion therapy is due to the fact that ions deposit almost all of their energy in a sharp peak – the Bragg peak- at the very end of their path. Proton beams can be used to precisely localize a tumor and deliver an exact dose to the tumor with small doses to the surrounding tissue.
- Proton computed tomography (pCT) provides direct information on the location on the target tumor, and avoids position uncertainty caused by treatment planning based on imaging with X-ray CT.
- The pCT project goal is to measure and reconstruct the proton relative stopping power distribution directly in situ. To ensure the full advantage of cancer treatment with 200 MeV proton beams, pCT must be realized.

Introduction

- In our pCT project the general idea is to use an approximately 2,200 channel system in a low intensity beam to sample the trajectory of 200 MeV protons before and after passing through a "Herman head" phantom, to fully reconstruct the proton tracks, and register each proton's residual energy in the range calorimeter. A collection of such events is used to build a 3D-image of the density distribution inside the phantom.
- The primary project goal is to record about one billion proton tracks and reconstruct the image in about 10 minutes.
- Our pCT project has extensive software and hardware sub-projects. The tracker and range calorimeter information are collected by an ultra fast data acquisition system. The track and energy information are used by a sophisticated reconstruction program on a dedicated CPU-GPU farm to build a 3D-image of the tumor.
- This presentation will concentrate on the range calorimeter including the frame-modular design, construction, extensive testing and optimization in the laboratory using radioactive source, and the response to a 200 MeV proton beam.

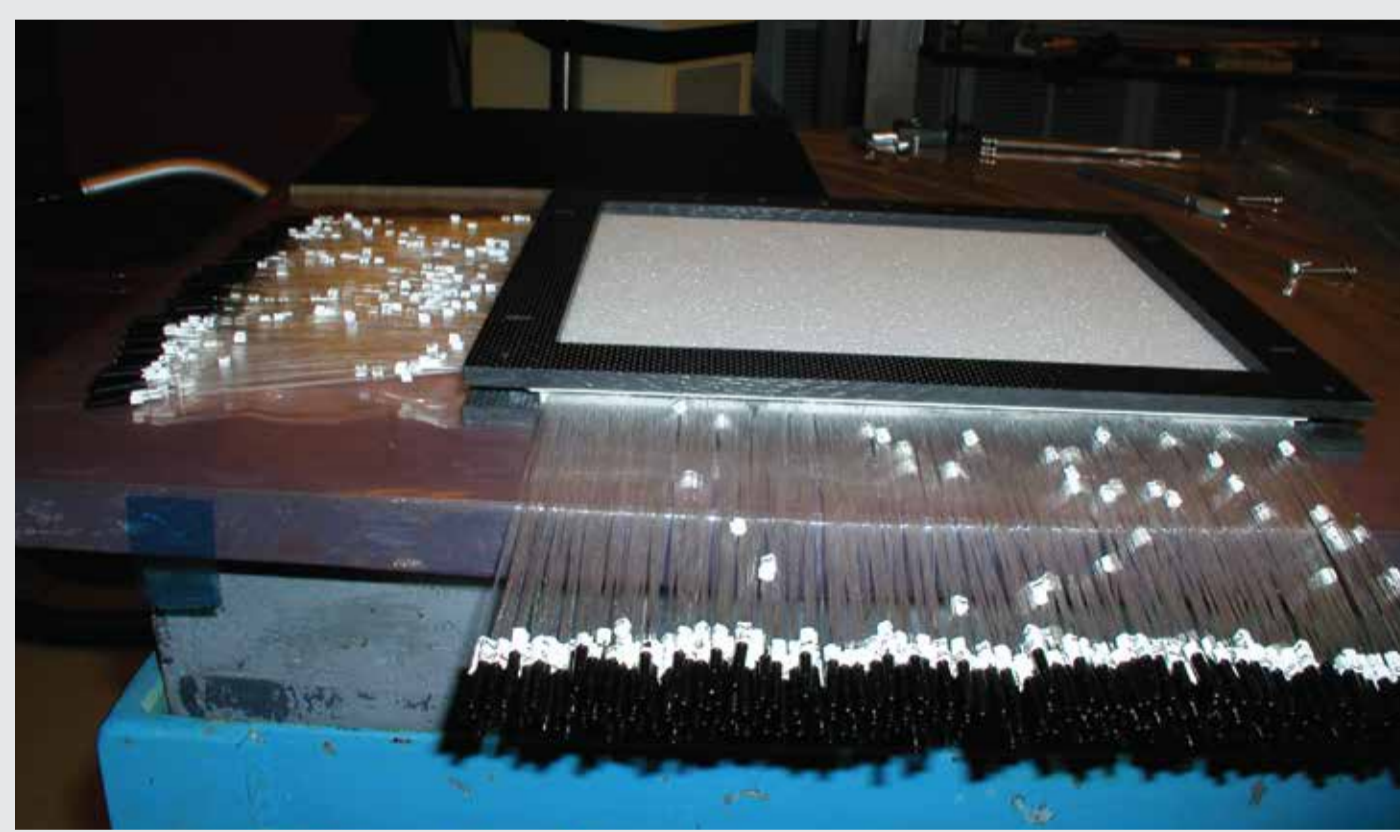
pCT Head Scanner Specifications

- Tracker area 20x24 cm² (upstream) and 24x30 cm² (downstream) with 15 cm separation between plains
- Calorimeter area 27x36 cm²
- Proton exposure time 7.4 min with a gantry rotation speed of 0.1 RPM (gantry is a structure to rotate the particle beam and guide it to the patient at chosen angles)
- 100 useful protons per ~10 million voxels (for a 1.25x1 mm² voxel area)
- DAQ rate needed ~3 MHz
- Detector resolution time ~100nsec; ~25nsec between two events

Tracker and Calorimeter

- The proton will be tracked before and after the phantom by the fiber tracker system. The tracker consists of four planes before the phantom and four planes after the phantom. Each fiber tracking plane is composed of a double layer of 0.5mm diameter Kuraray scintillating fibers SCSF-3HF(4500)M grouped into bundles of three nearest neighbors that are readout with a single silicon photomultiplier (SiPM).
- The purpose of the range detector is to determine the energy loss of a 200 MeV proton after passing through the phantom. Ninety-six scintillating tiles with dimensions of 27cm width, 36 cm height, and 3.2mm thickness made of EJ-200 (similar to BC-408 or Pilot F) were used in the range stack. Plastic scintillators were machined on one side to a thickness of 3.2mm with a tolerance within 0.05 mm. Each scintillator tile has four straight "key" shaped shallow grooves embedding a single Kuraray Y11 1.2mm diameter WLS fiber holding to the frame with collets for SiPM readout at both ends. There is no glue in the range detector.
- CPTA-151-30 SiPMs (Metal-Resistor-Semiconductor Geiger gain Avalanche Photo Diode) made in Russia are used for readout. The active area of the photo detector is about 1.28 mm in diameter. Each SiPM consists of 796 pixels. The SiPM quantum efficiency is about 40% at $\lambda=600\text{nm}$.

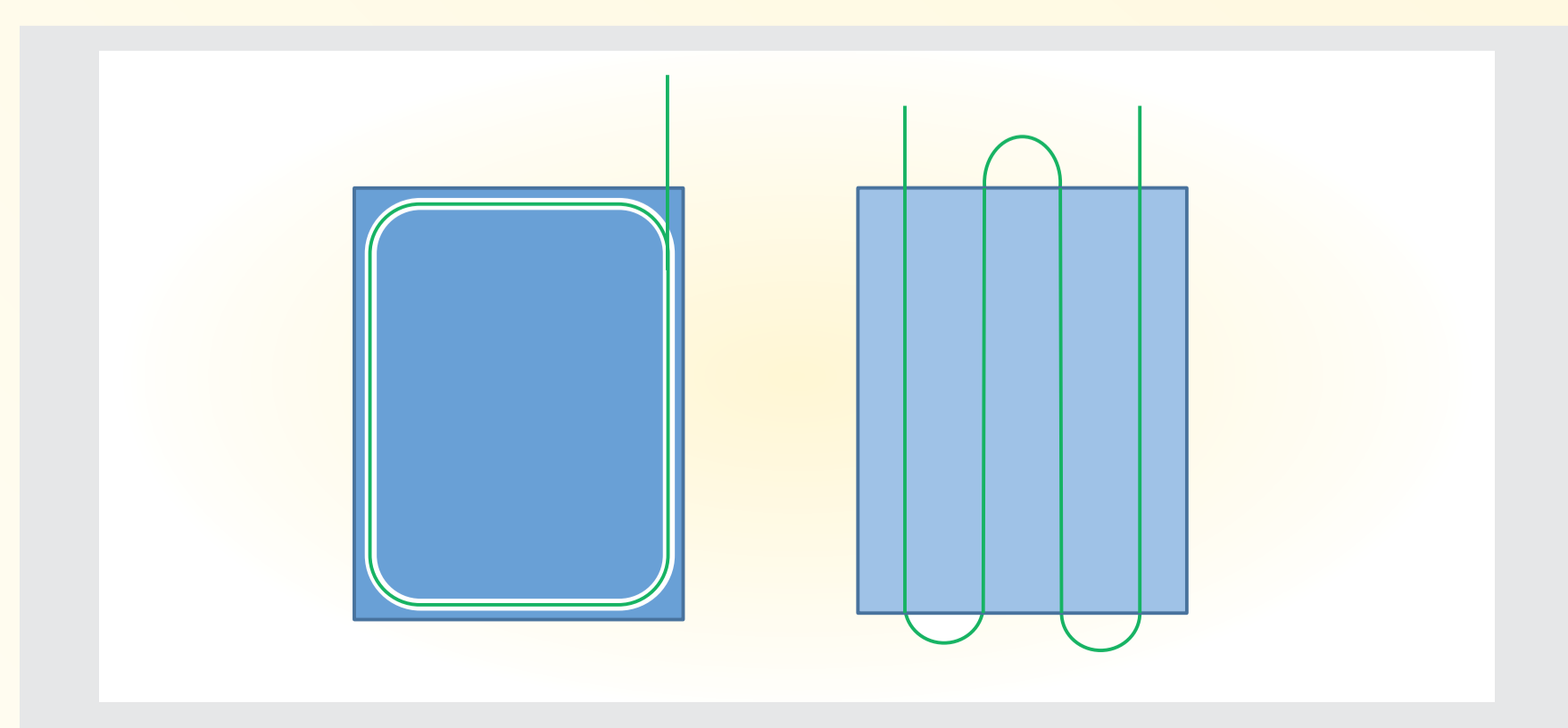
Tracker Assembly



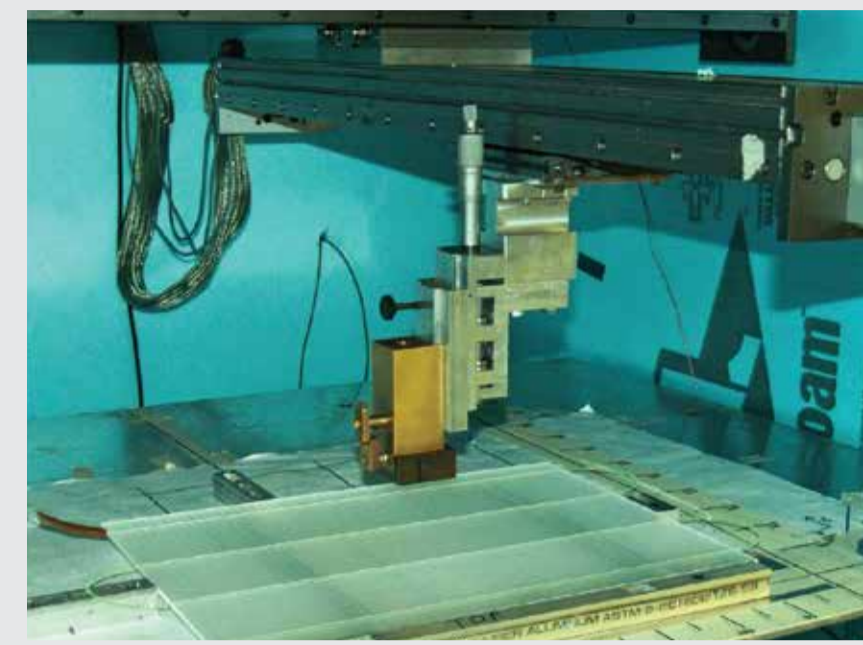
Laboratory Study

- The impacts of the groove shape, dimension, configuration, and position on light output and uniformity were extensively studied in the laboratory using precision two dimensional tables with a collimated Sr-90 radioactive source for scanning.
- The impact of reflective wrapping material on the light output and uniformity of response was studied to reduce the dead material between scintillators.
- A silicon photo detector connected to a Keithley 6487 picoammeter/ voltage source was used for current measurements.

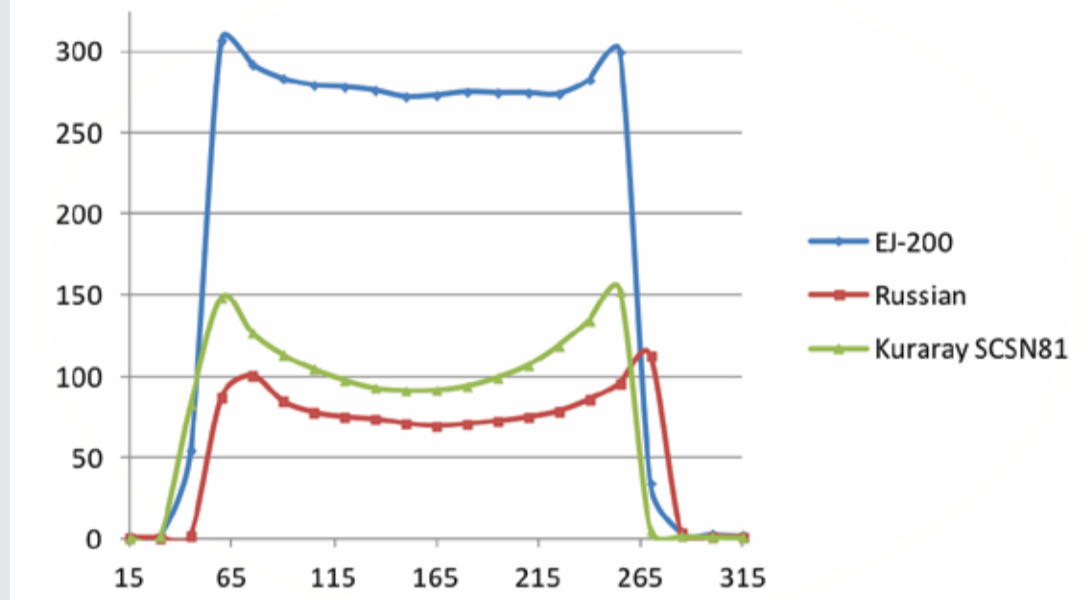
σ -grooved Tile (to the left) and with Four Straight Grooves (to the right)



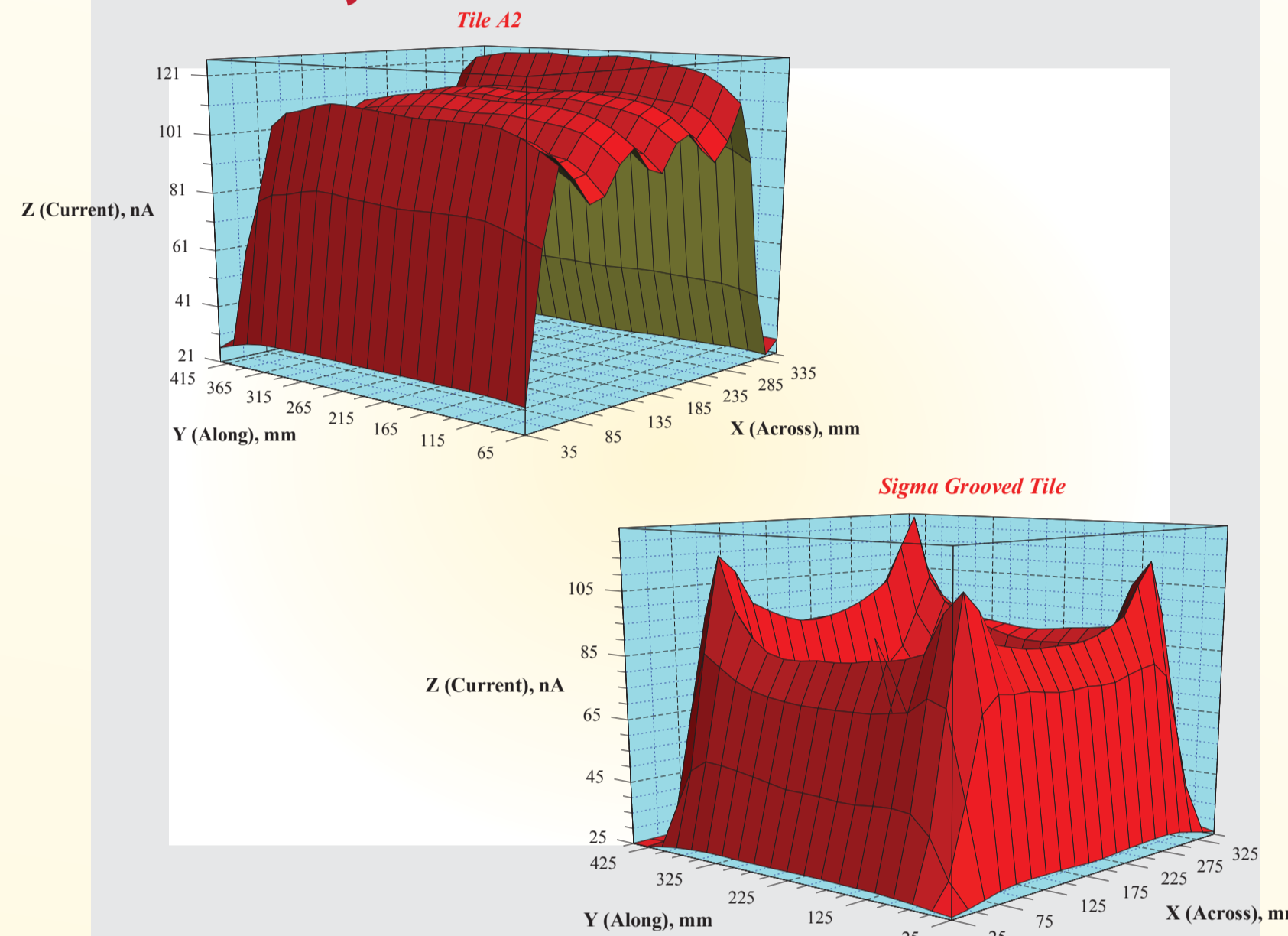
X-Y Precision Scanner with Sr-90, Tile, and WLS Fiber



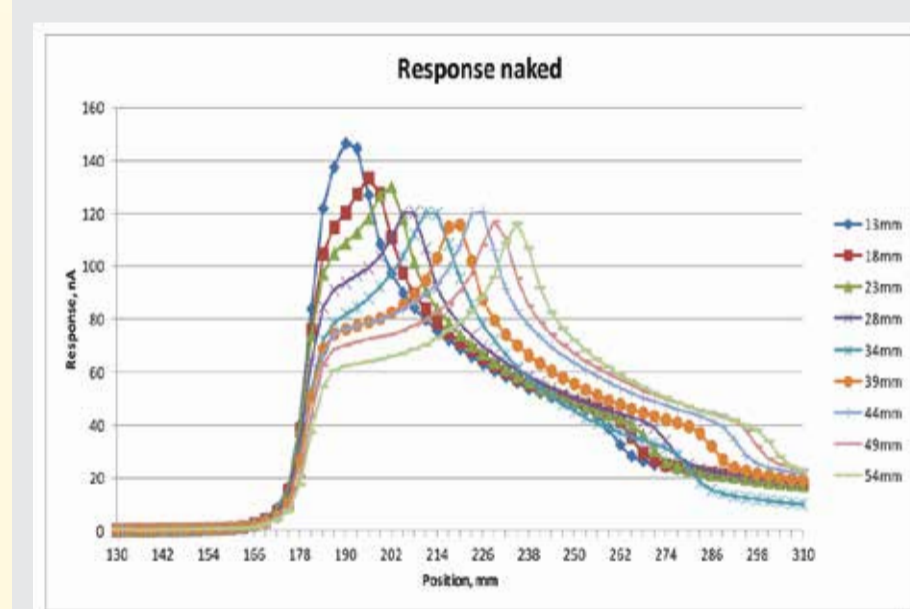
Scan Across the 18cm Wide σ -grooved Tiles with Scintillator from Different Vendors



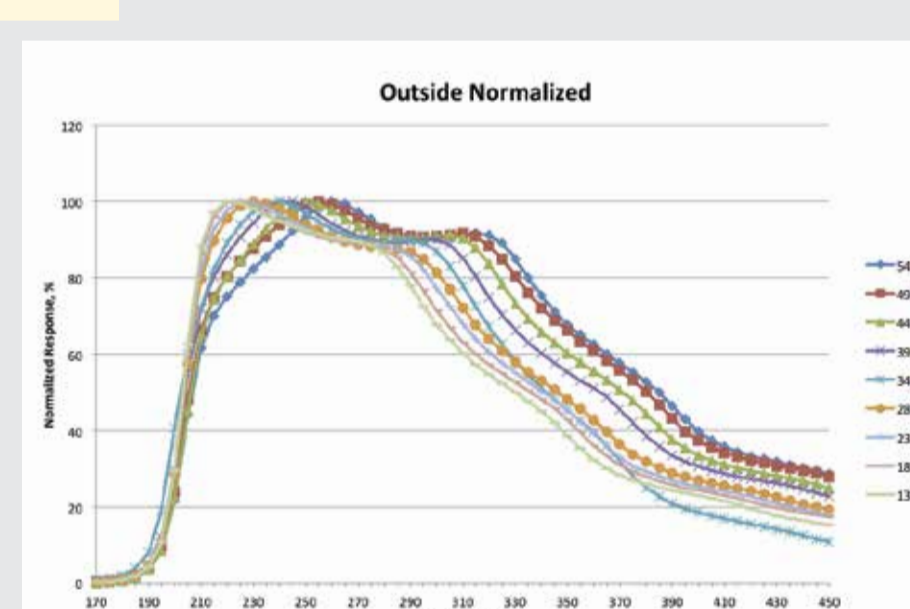
Tiles Uniformity



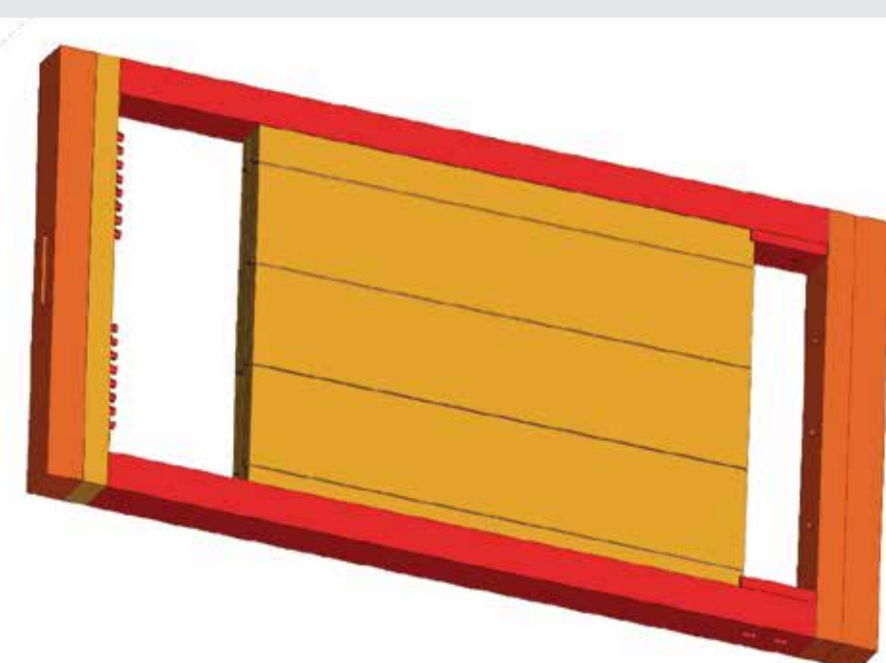
Scan Across the Tiles with Groove Displacement- Distance from the Edge of the Tile to the Groove



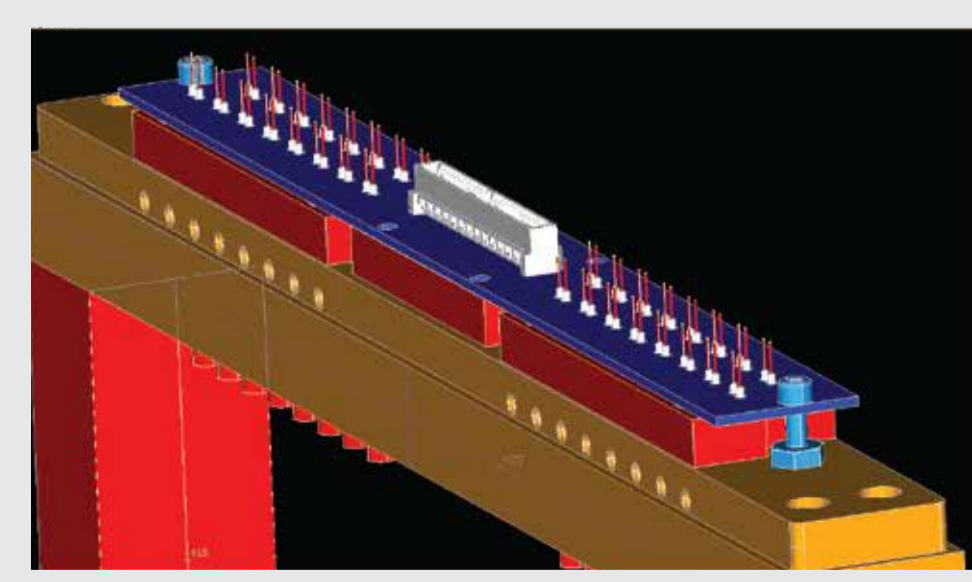
Normalized Response of Tiles with Groove Displacement (3.2mm Scintillator without Wrapping)



Frame Made from Noryl Holds 8 Tiles with 8 WLS Fibers and 16 SiPMs



pCT Frame Interface



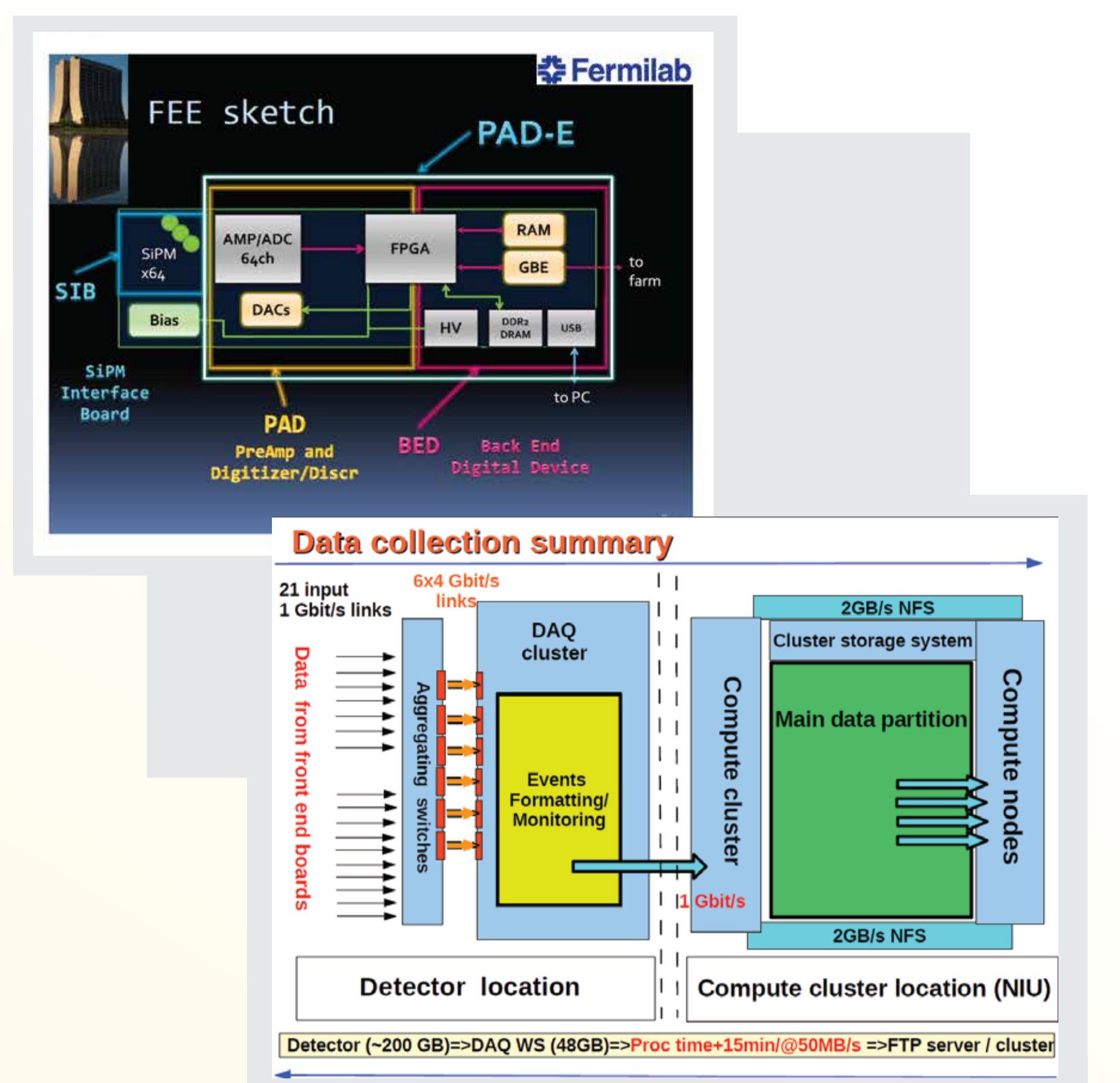
pCT Electronics and Event Size

- The pCT electronics consists of the SiPM Interface Board (SIB) and the amplifier digitizer board (PAD-E). There are two types of the detector interface boards; one for the fiber tracker that is connected to 64 photo detectors and one for the range stack that can be connected to 32 or 16 photo detectors.
- The digitizer board uses four AD9276 chips, for a total of 32 channels, to measure the amplitude vs. time as the signal develops. A single Xilinx XC6SLX16 "Spartan6" FPGA on the board receives data from the digitizer and transfers only data appropriate for reconstruction of the proton track.
- The board also includes a generator to adjust the individual bias voltage of each SiPM, a gigabit DDR2 DRAM working memory, gigabit Ethernet interface, and two high speed serial links for distribution of the clock signal and synchronization of data across the system.
- The fiber tracker data rate is 30MB/s and the Scintillator Stack rate is 720 MB/s total at 10 M protons/sec
- The data size for one event is about 800 bytes.

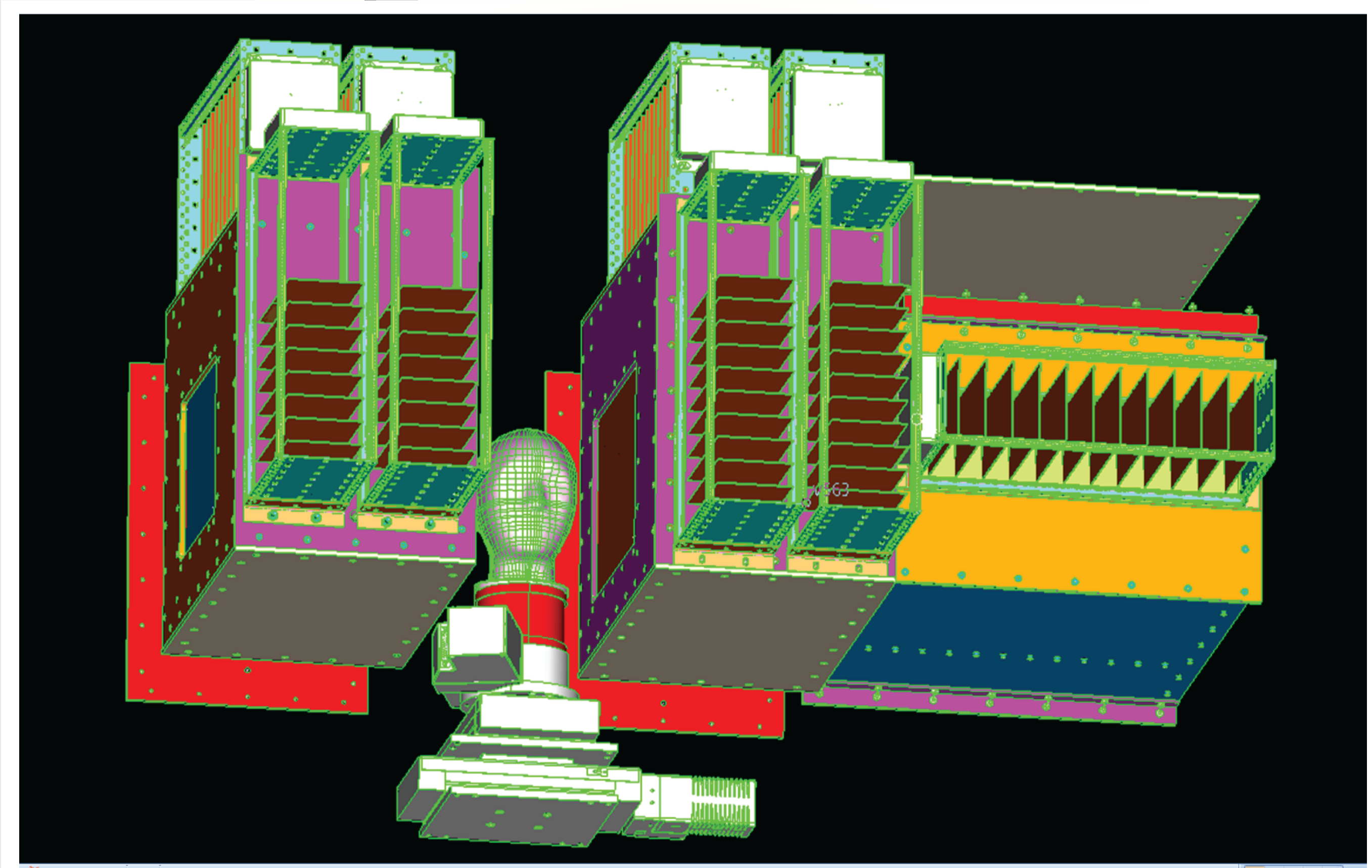
Back-End DAQ System

- We are developing the hardware and software framework for the Back-End Data Acquisition system. The high pCT data collection and processing rates require six data collection work stations connected with a 2Gbit/s internal network. Each workstation has four 1Gbit/s input channels; twelve 2.6GHz CPU cores; 64 GB RAM, and a solid state drive RAID array.
- The Back-End DAQ accumulates data from the input streams and runs the reconstruction software as well. Tests indicate that the system can collect data at about 50 MB/s with a data loss rate less than 0.06%.
- A full GEANT4 simulation of the pCT detector has been developed. The QGSP BERT model, based on the Bertini cascade model, is used. Two types of phantoms and two types of beam are available in the simulations.

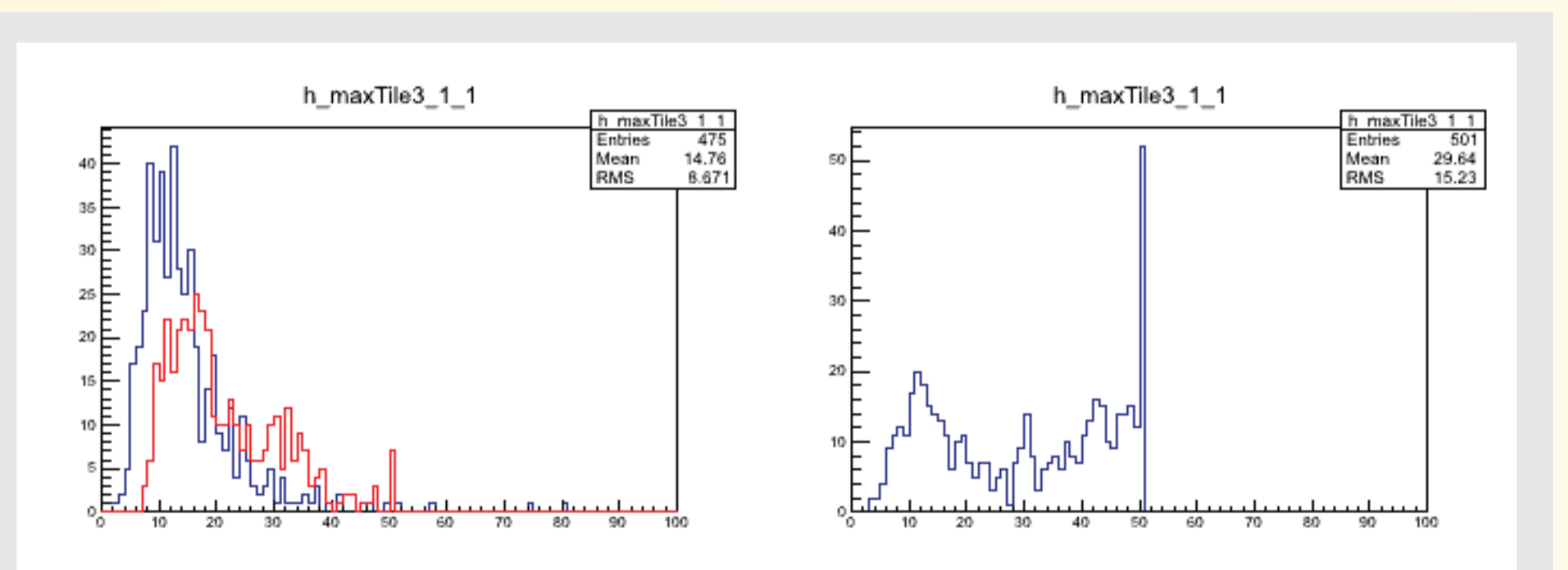
pCT Electronics and DAQ System



pCT Test Beam Setup



Tile Response to a 200MeV Proton Beam (left). Tile Response to Stopping Protons (right) (X axis in units of photo electrons)



Comments

- The final design prototypes of our range stack frames were tested at Loma Linda University Medical Center (California, USA) in a 200 MeV proton beam. The light output is adequate and demonstrates the possibility of designing the range stack without light shields, thereby reducing the dead material.
- Tests indicate that the Back-End DAQ system can collect data at about 50MB/s with a data loss rate less than 0.06%.
- A full GEANT4 simulation of the pCT detector has been developed.
- All parts of the detector are in the final production, assembly, or testing stage.
- A full hardware system will be ready for commissioning in April 2013.

Acknowledgements

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