A Novel Scintillator Detector for the Mu2e Experiment and a Muon Tomography Search for Hidden Chambers in the Great Pyramid

CPAD Instrumentation Frontier Workshop
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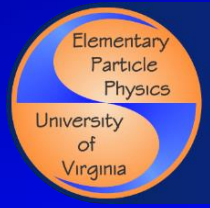
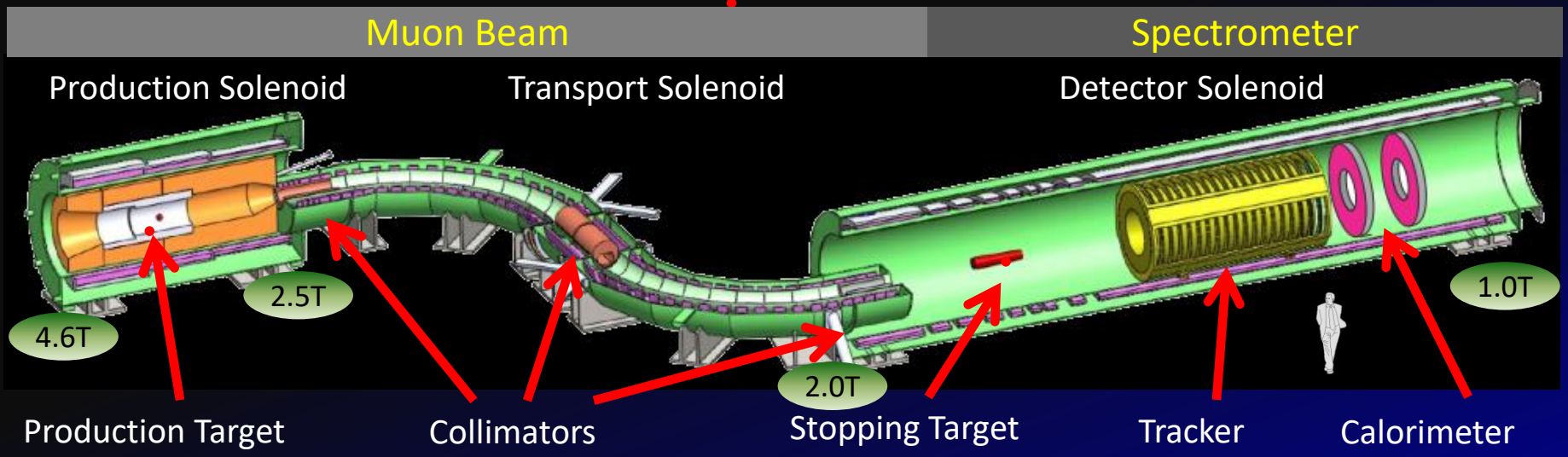


Frontier Physics Group
University of Virginia

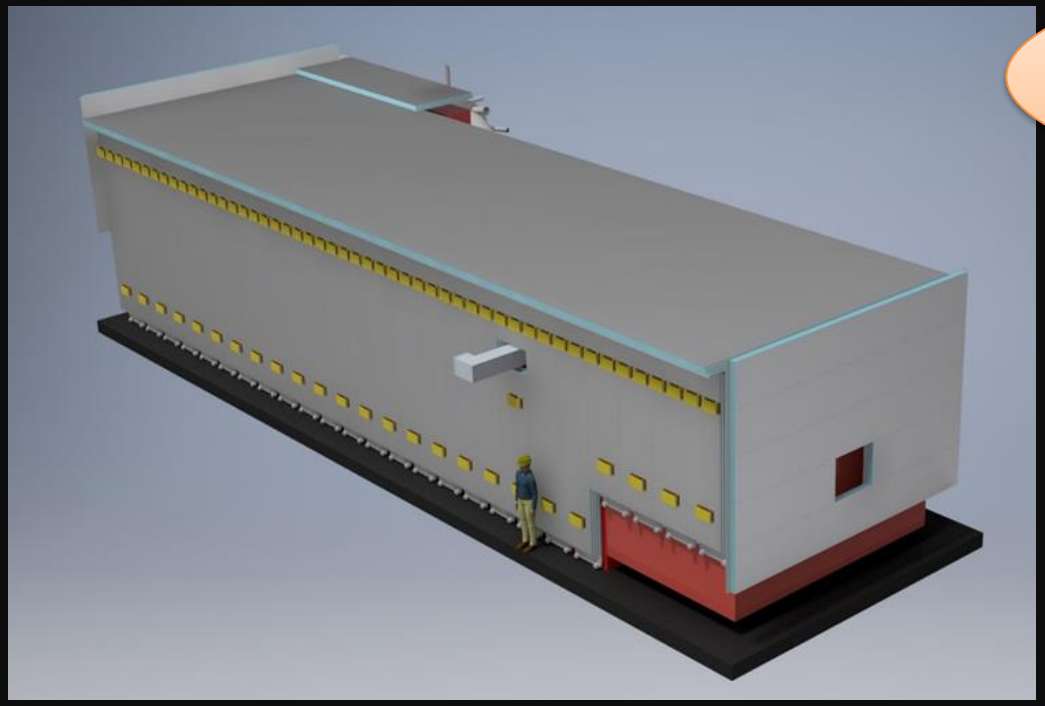
Mu2e Experiment: Muon to Electron Conversion

$$\mu^- N \rightarrow e^- N'$$

Probing new physics through lepton flavor violation through muon-to-electron conversion using a novel detecter design



Mu2e Experiment: Cosmic Ray Veto



1 conversion-like electron per day is produced by cosmic-ray muons

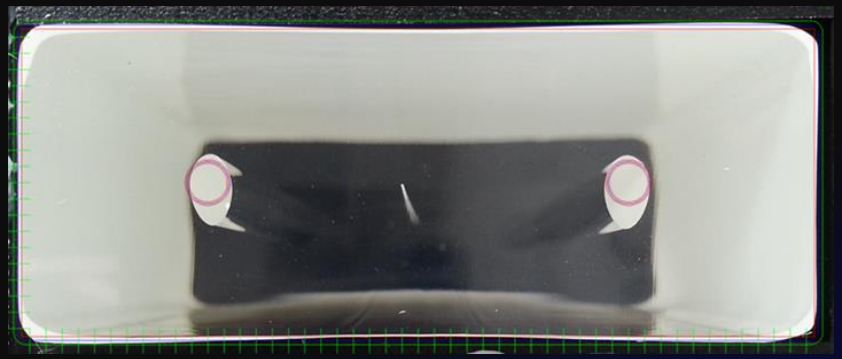
Details:

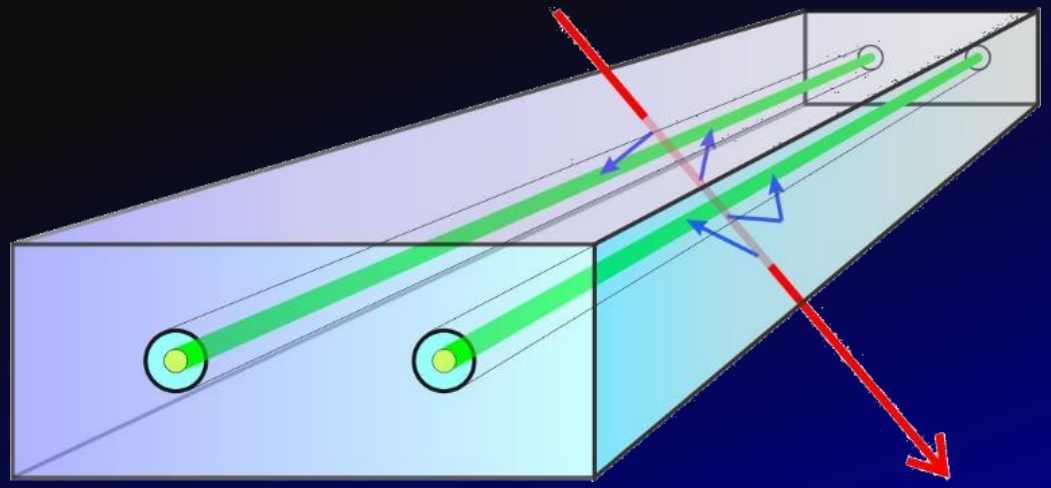
- Area: 335 m^2
- 83 modules 10 types
- 5,376 counters
- 10,752 fibers
- 19,456 SiPMs
- 4,864 Counter Motherboards
- 316 Front-end Boards
- 16 Readout Controllers

- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high neutron and gamma rates, access to electronics, and constrained space.
- Technology: Four layers of extruded polystyrene scintillator counters with embedded wavelength shifting fibers, read out with SiPM photodetectors.
- Track stub in 3/4 layers, localized in time/space produces a veto in offline analysis.
- **Overall efficiency of 99.99% is needed to keep the background to less than 1 evt**

Mechanical Design: Counter

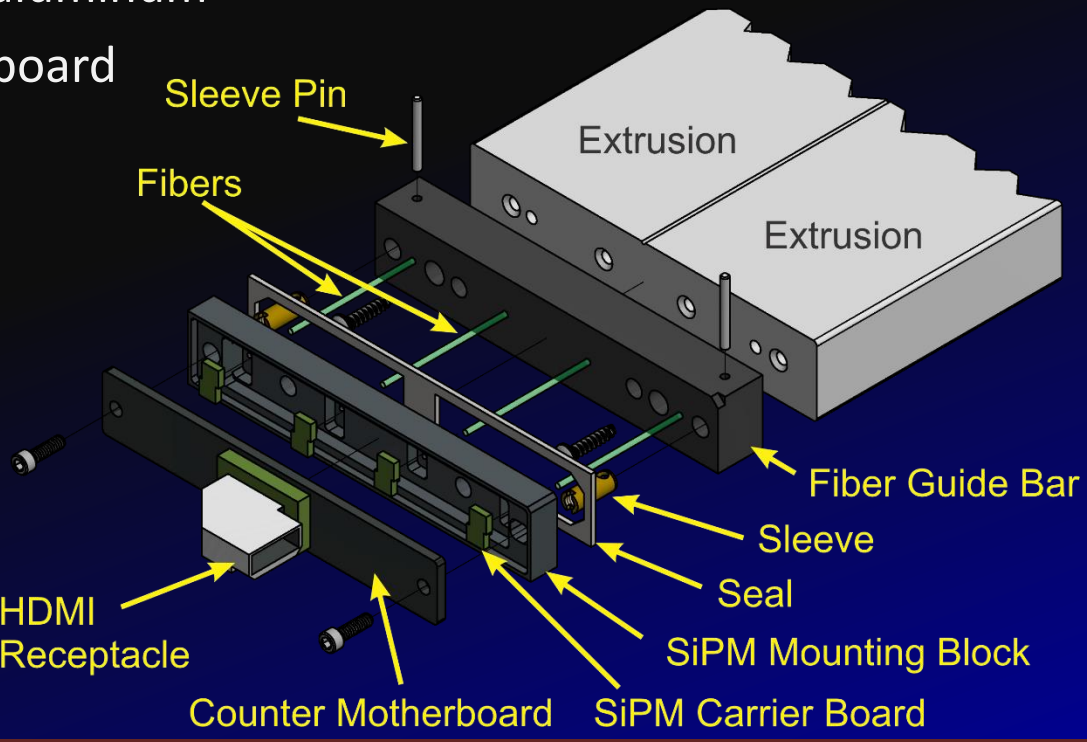
- Fundamental element of the CRV (5,376 total)
- Counters are extruded at the Fermilab NICADD facility
- Each counter has two 1.4/1.8 mm wavelength-shifting fibers placed in channels in extruded PS doped with 1% PPO + 0.05% POPOP and coated with with TiO_2
- All counters, except a handful where the radiation doses are too high, or if they are too short, are read out on both ends by silicon photomultipliers (SiPMs)
- Counters range from 1045 mm to 6900 mm long
- Counter profile: 51.3 x 19.8 mm^2



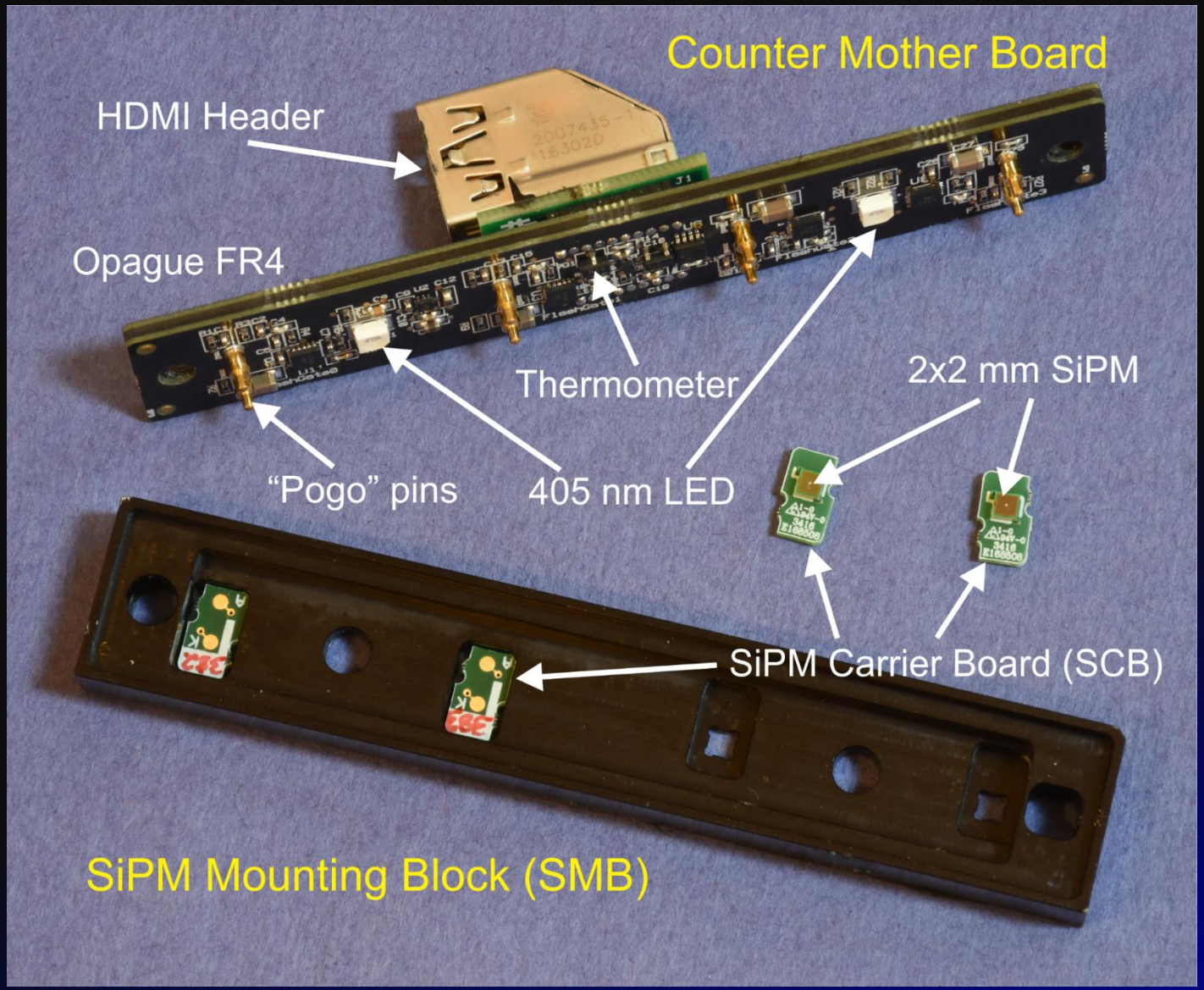


Mechanical Design: Di-counter Manifold

- Counters grouped in pairs to form a di-counter
- Each di-counter end served by a single counter motherboard with 4 2x2 mm^2 SiPMs, 2 flasher LEDs, 1 thermometer
- Designed to minimize pressure damage to SiPMs, eliminate light leaks, facilitate SiPM-fiber registration, provide easy removal/installation, and have a low profile
- Opaque counter motherboard forms manifold top; SiPM mounting block of anodized aluminum
- Pogopins connect counter motherboard and SiPM carrier boards
- SiPM temp not controlled, but bias adjusted based on temperature
- HDMI header can have vertical and horizontal orientation



Mechanical Design: Di-counter Manifold



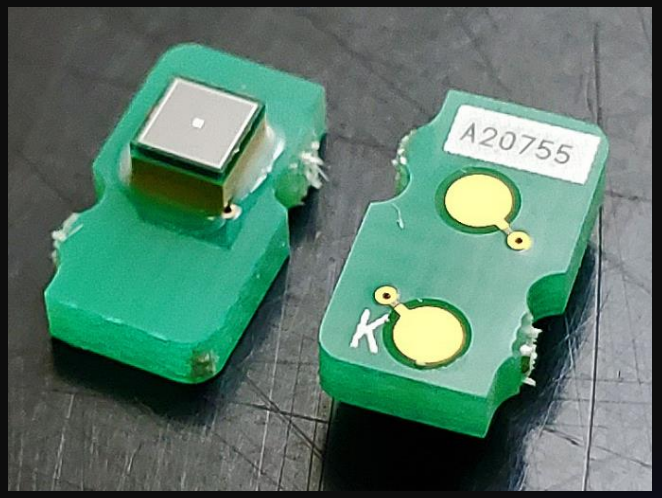
Mechanical Design: Modules

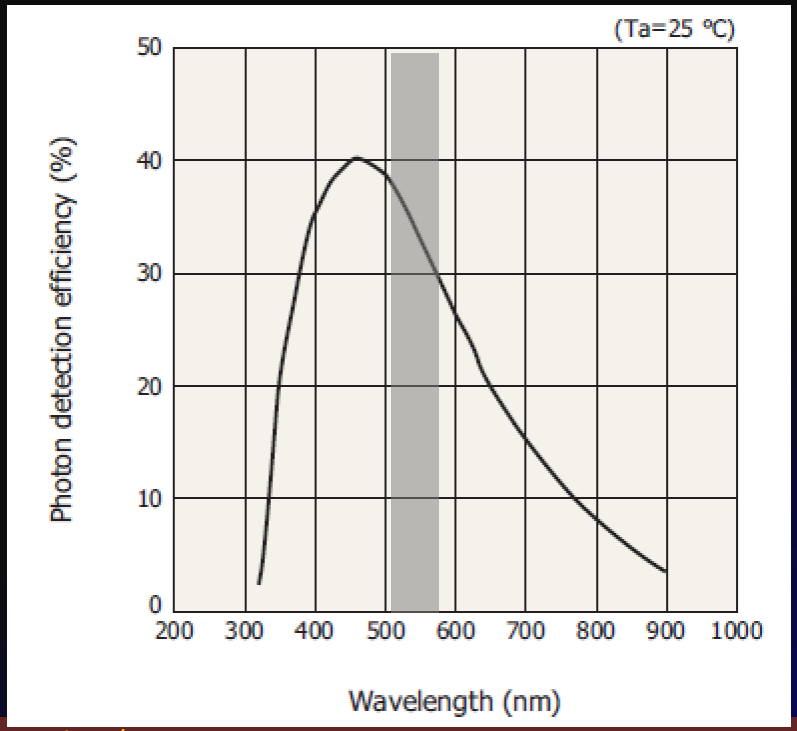
- Fundamental mechanical element of the CRV
- 4 layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters (8 di-counters) /layer
- Layers are offset to avoid projective gaps between counters
- Total: 83; of 10 different types
- Mechanical tolerances very tight and critical
- Weight: 179 kg - 1165 kg.
- Lengths ramge from
  1.0 m – 6.9 m

Silicon Photomultipliers (SiPMs)

We chose this photodetector type because:

- Good effective quantum efficiency
- Ability to measure absolute light yield
- Small size: facilitates on detector mounting
- Works in high magnetic fields
- Low cost: $9.56/ch mounted on carrier board





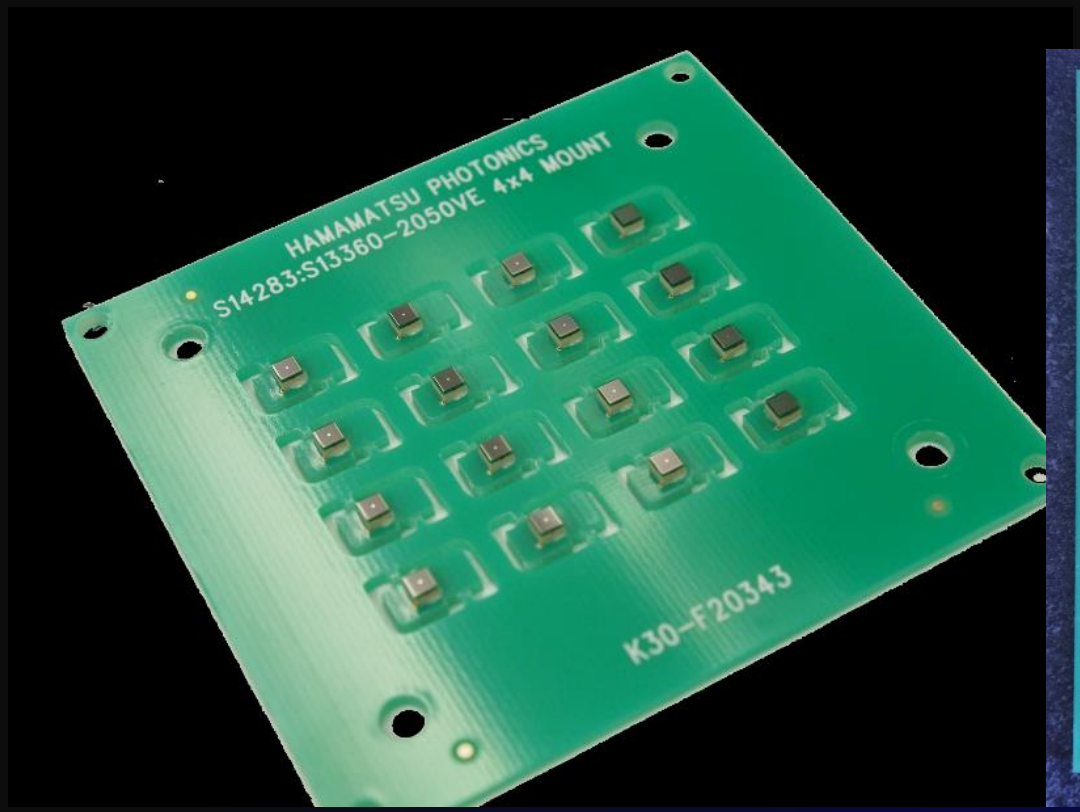
Hamamatsu MPPC S13360-2050VE

All values at 25° C at overvoltage of 2.5V:

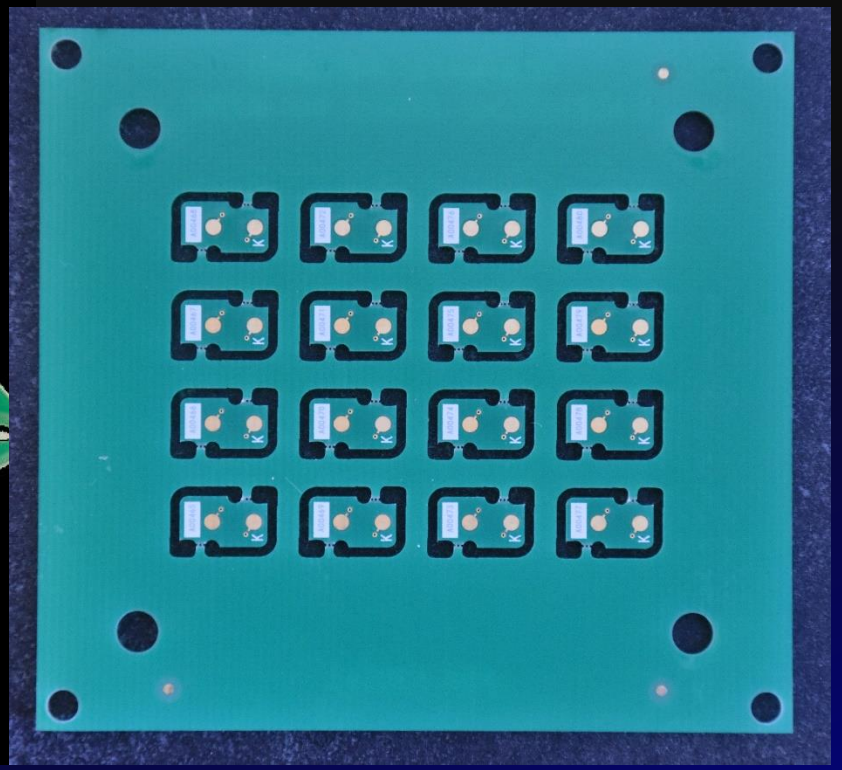
1) 2mm x 2mm, 50 µm pixel
2) Surface-mount, TSV packaging
3) PDE > 35% (530 nm)
4) Gain ≥ 1.0×10^6
5) Pulse rise time < 5 nsec
6) Dark rate < 250 kHz @ 0.5 PE threshold
7) X-talk (inter-pixel) < 2%
8) Bias spread: ±0.5V (within batch); ±1.5V (all)
9) Temperature dependence ≤ 50 mV/°C

SiPM Delivery and Testing

SiPMs are mounted on small 8.4 x 4.9 mm^2 “SIPM carrier boards” (SCBs)
They are delivered and tested on “waffle” pack boards, each with 4 x 4 = 16 SCBs
Punched out of the waffle pack when needed



SiPM side of “waffle pack”



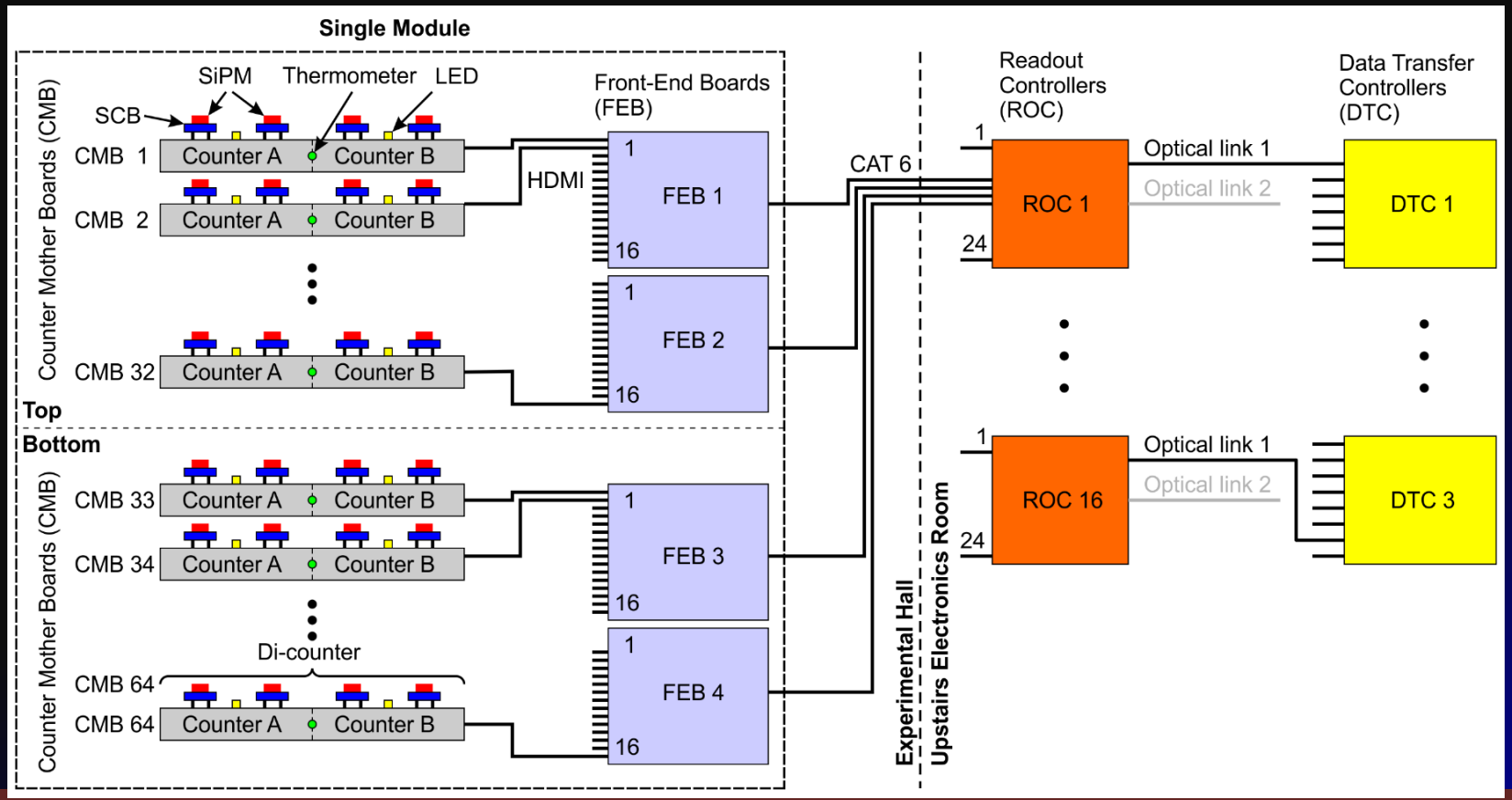
Pogopin pad side of “waffle pack”

Electronics: Block Diagram

Four components: (1) Mounted SiPMs (SCB w SiPM: 19,456, $9.56 ea), (2) Counter Motherboards (CMB: 4864, $32.71 ea), (3) Front-end Boards (FEB: 316, $1750 ea), (4) Readout Controllers (ROC: 16, $2000 ea)

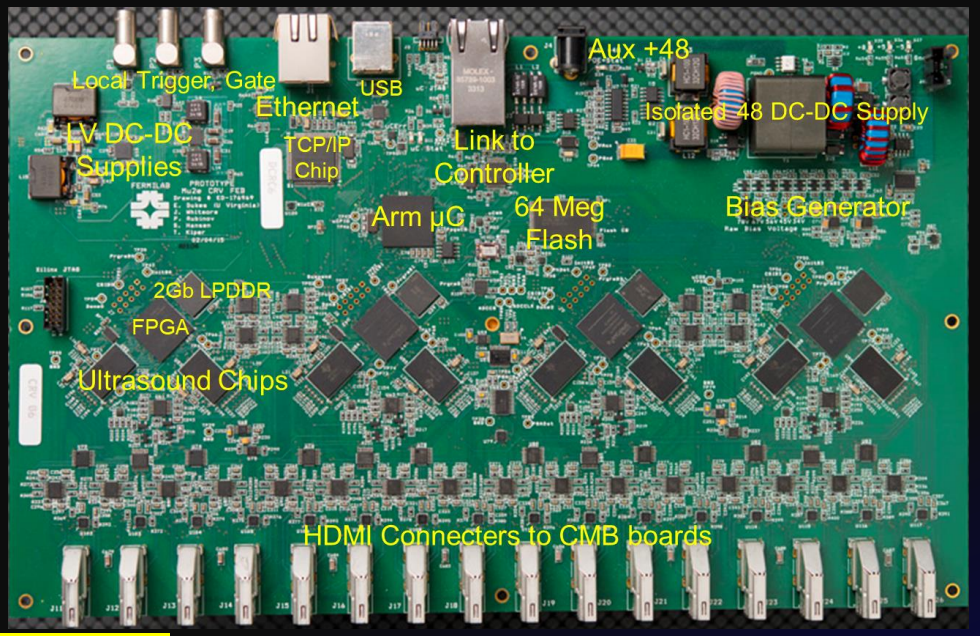
All commercial-off-the-shelf parts (80 MHz ultrasound octal amp/ADC)

Dynamic range:	2000
Max rate/SiPM:	1 MHz
Max rate FEB-ROC:	5 MB/s
Max rate ROC-DTC:	300 MB/s
Time resolution:	~ 2 ns
Magnetic field:	~ 0.1 T
Max dose:	10^{10} n/cm^2

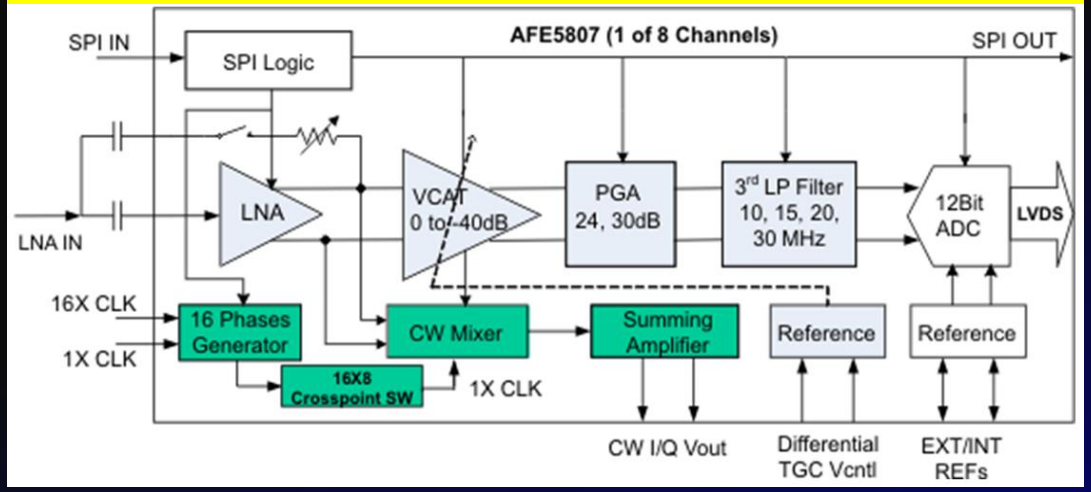


Front End Board: Amplifier, Digitizer, Shaper

- Serves 64 SiPMs
- Takes SiPM signals from 16 CMBs over HDMI cables
- Individual bias for all 64 SiPMs
- Amplifies, shapes, digitizes in amplitude and time, zero-suppresses, and buffers signals
- Power provided by Ethernet
- Can be read out (& powered) locally or through a readout controller



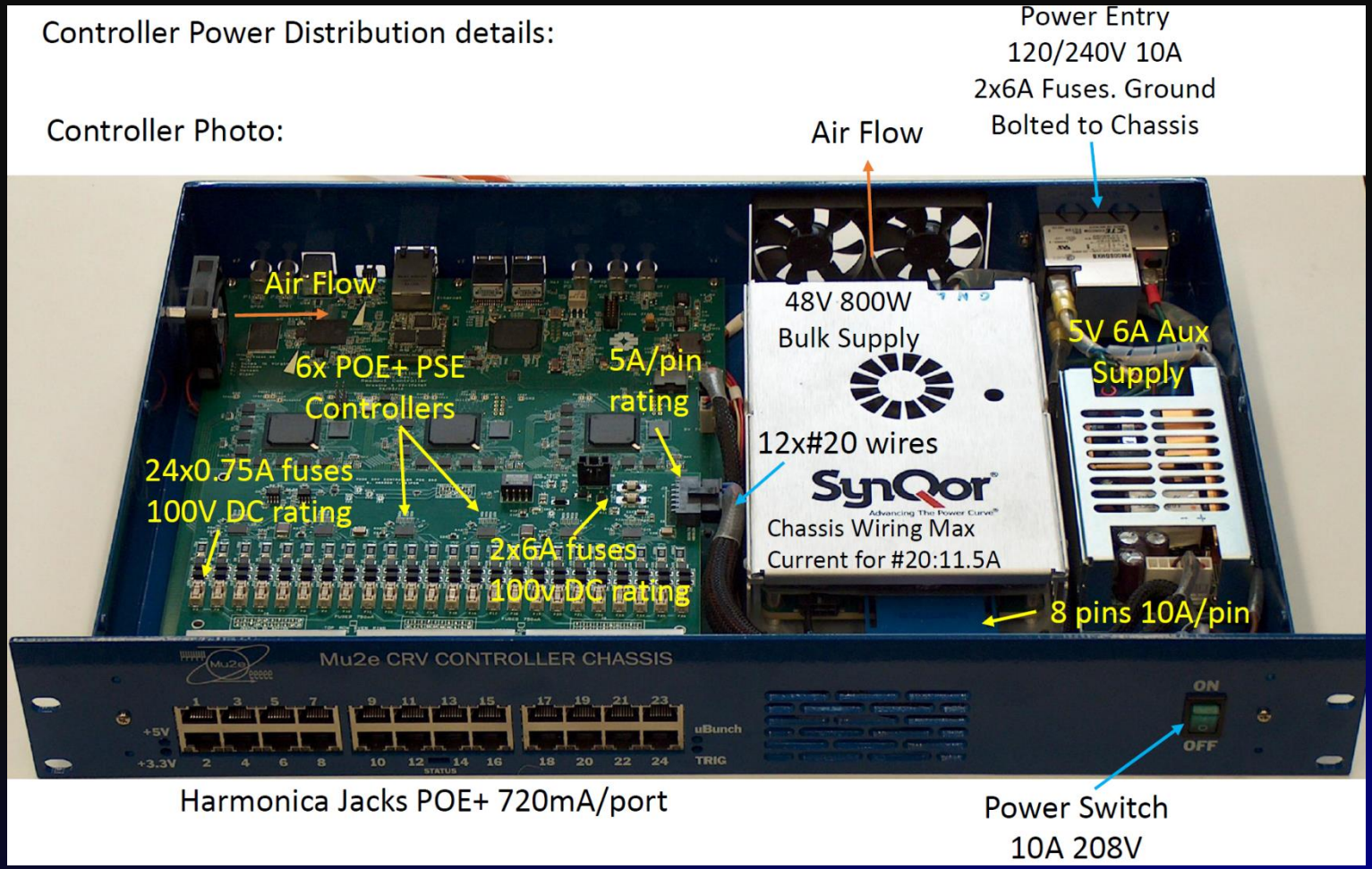
The core of the readout is a commercial ultrasound chip



TI AFE5807: Eight channels of low noise preamp, variable gain amp, programmable gain amp, programmable low pass filter, 80msps 12 bit ADC. $7 per channel, 120mW per channel. Adjust gain such that 1p.e. = 10 ADC counts.

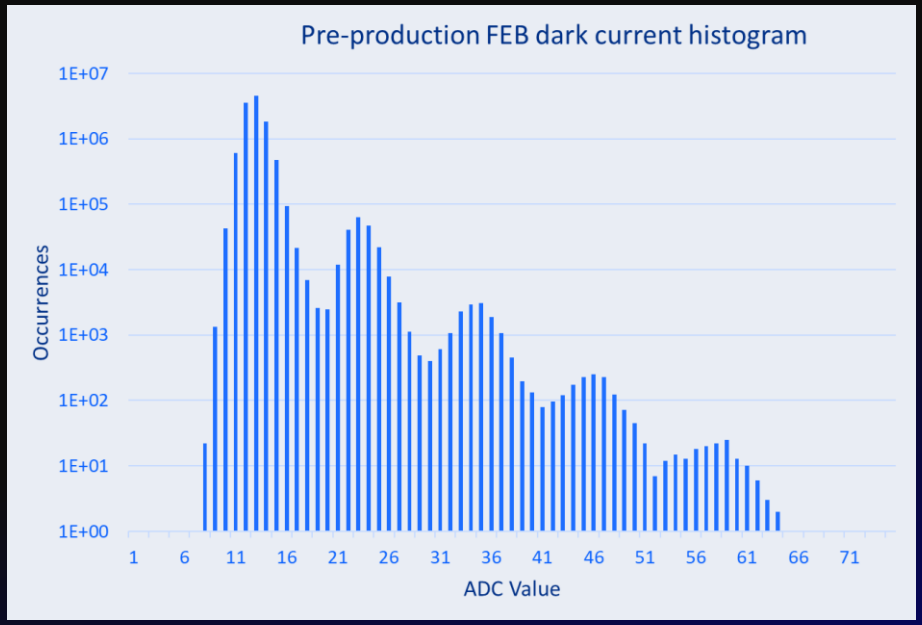
Readout Controller

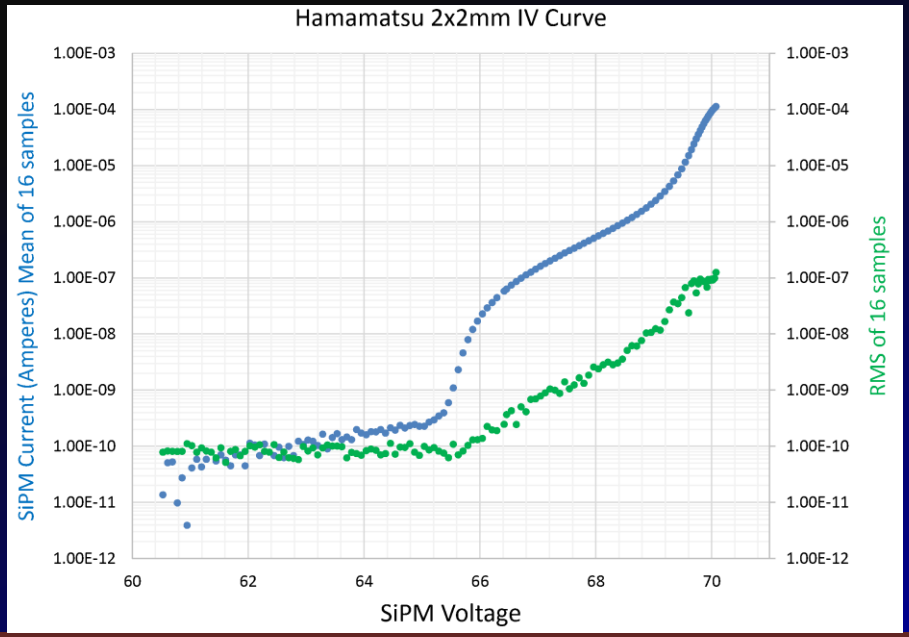
- Powers entire system
- Serves up to 24 FEBs (PoE)
- Interface to the DAQ computer



Electronics: Features

- All COTs parts: system can be reproduced inexpensively by others
- PoE from ROC to FEB eliminates need for any power supplies (other than 110V wall power)
- Histogramming firmware in FPGA allows fast dark-noise spectra to be obtained within seconds to calibrate the PE spectrum
- In-situ IV curves can be taken (100 pA precision, 1 mA max) that rivals commercial test equipment

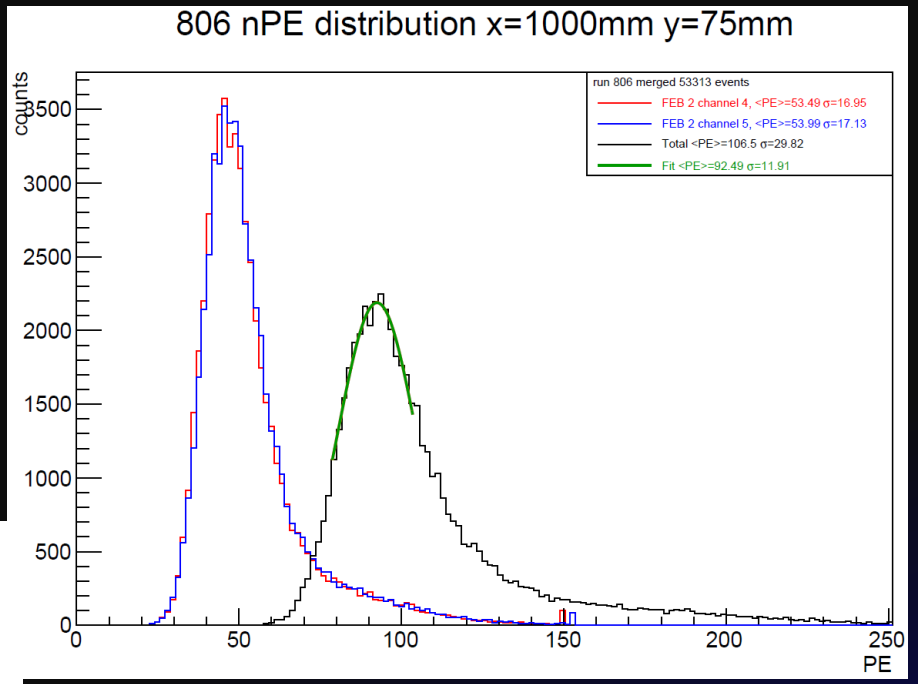


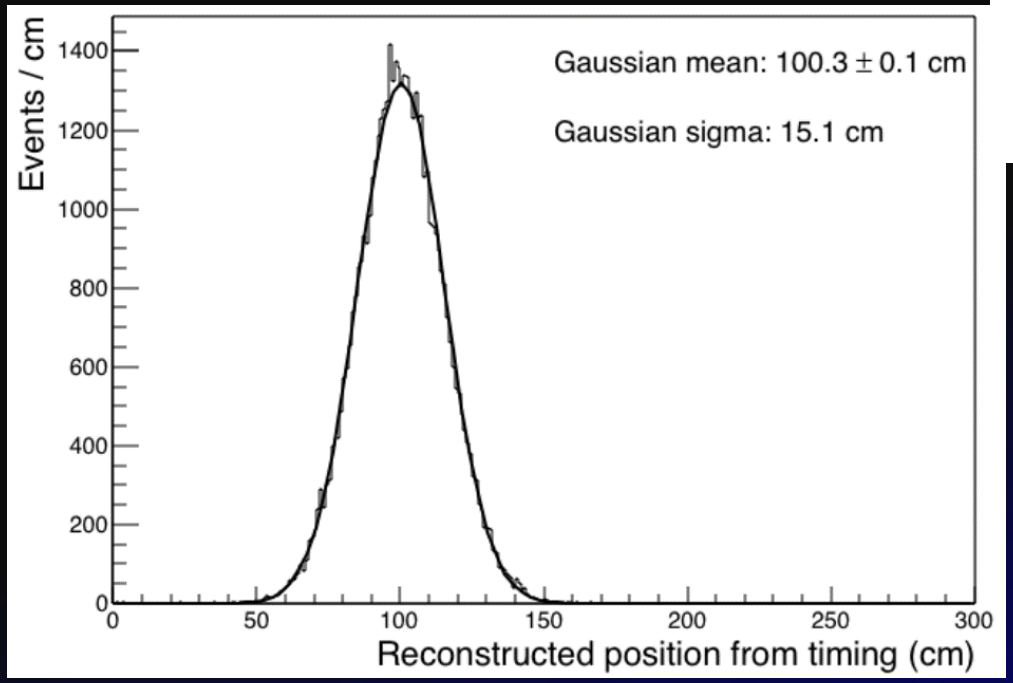


Performance

Light yield from 120 GeV protons normally incident 1 m from readout end

- ~53 PE/SiPM
- 1.4 mm fibers





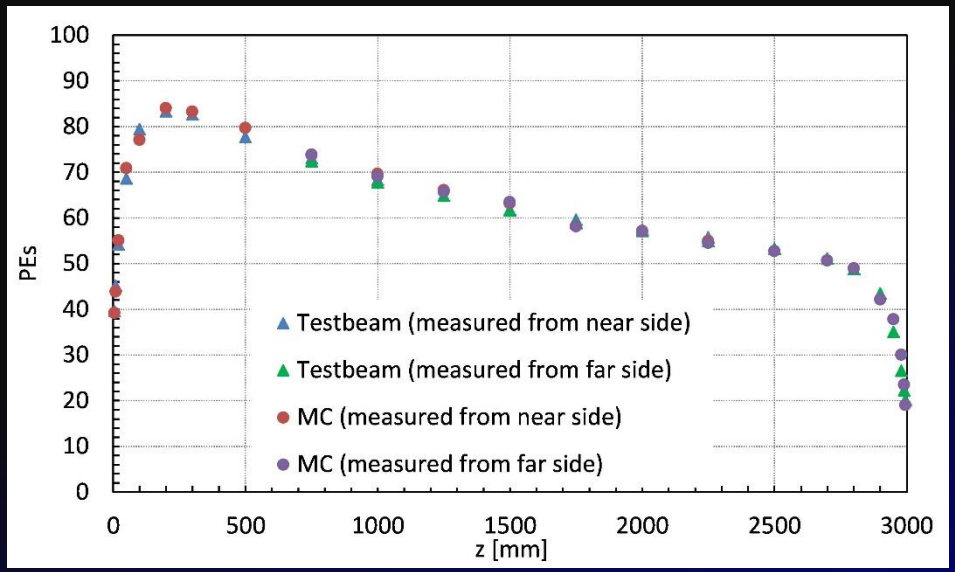
Reconstructed position using TOF from readout on both ends of a counter

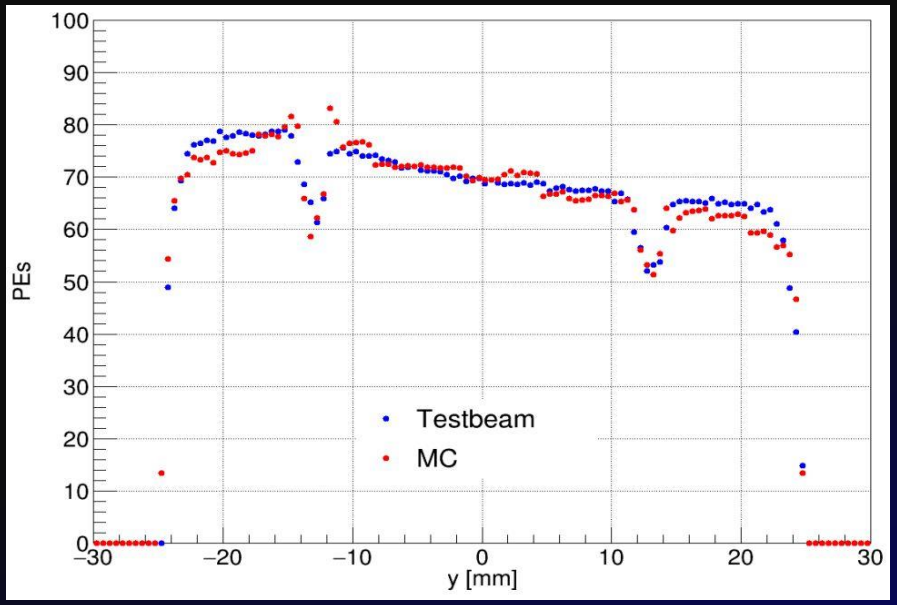
- σ = 15 cm
- 1.4 mm fibers

Simulation Code

- A huge effort has gone into developing a detailed, fast, soup-to-nuts MC with a complete simulation of the counter response to incident particles.
- MC includes timing jitter, SiPM crosstalk, and afterpulsing, Front-end Board digitization, etc.
- MC has been extensively tuned to agree with test-beam data.

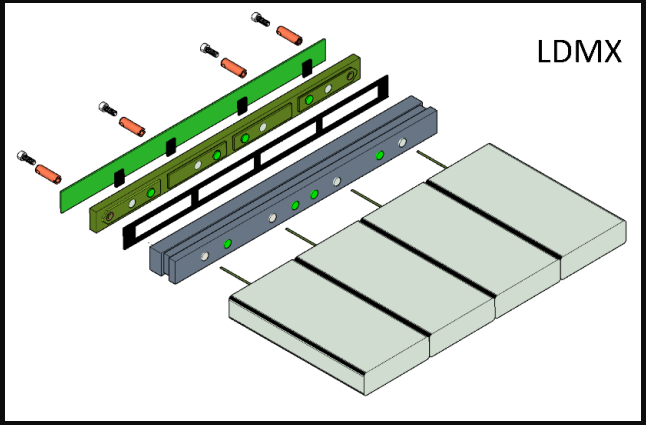
Response to 120 GeV protons along a 3-m long counter





Transverse response to 120 GeV protons for a 3-mm wide counter. Only data from left fiber used.

Other Experiments with Similar Systems

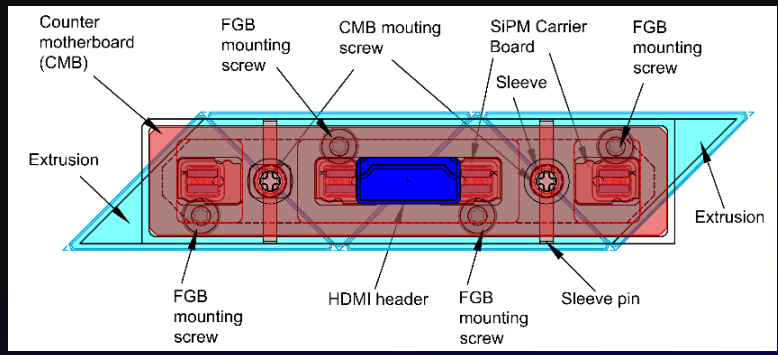


Light Dark Matter eXperiment (LDMX) hadronic calorimeter

- quadcounter with 1 fiber/50-mm wide extrusion rather than di-counter

Exploring the Great Pyramid Experiment (EGP)

- Quadcounter with 1 fiber/extrusion rather than di-counter
- Better resolution needed: triangular counter: 40 x 20 mm^2 (base x height) gives ~1 mm



Exploring the Temple of Kukulcan at Chichen Itza

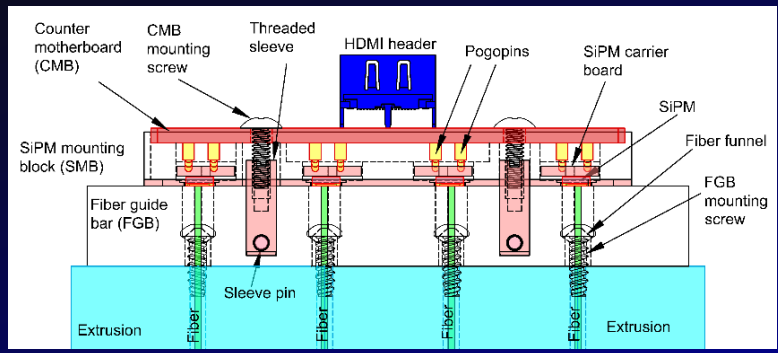
- Same design as EGP

Mu2e-II

- Exploring using same design as EGP

DUNE

- Exploring similar design for Near Detector



Summary

- We have developed a complete detector system based on scintillator counters with embedded wavelength-shifting fibers read out by SiPMs
- The detector is simple to fabricate using modest resources and is inexpensive
- A fast, inexpensive readout system using all COTS parts and that needs only wall power has been designed: it can be reproduced with ease
- The design is flexible and is being used or considered for multiple experiments

Many thanks to my colleagues on Mu2e, EGP, and LDMX