Fabrication of a High Efficiency Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab

MATHUSLA Seminar

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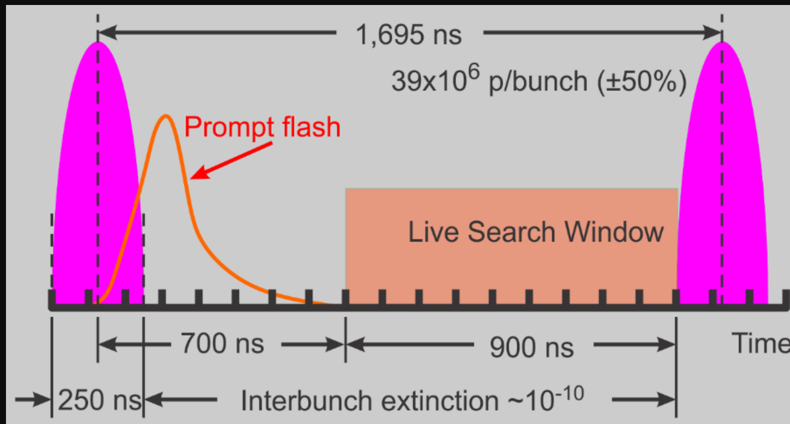
Elementary Particle Physics University of Virginia

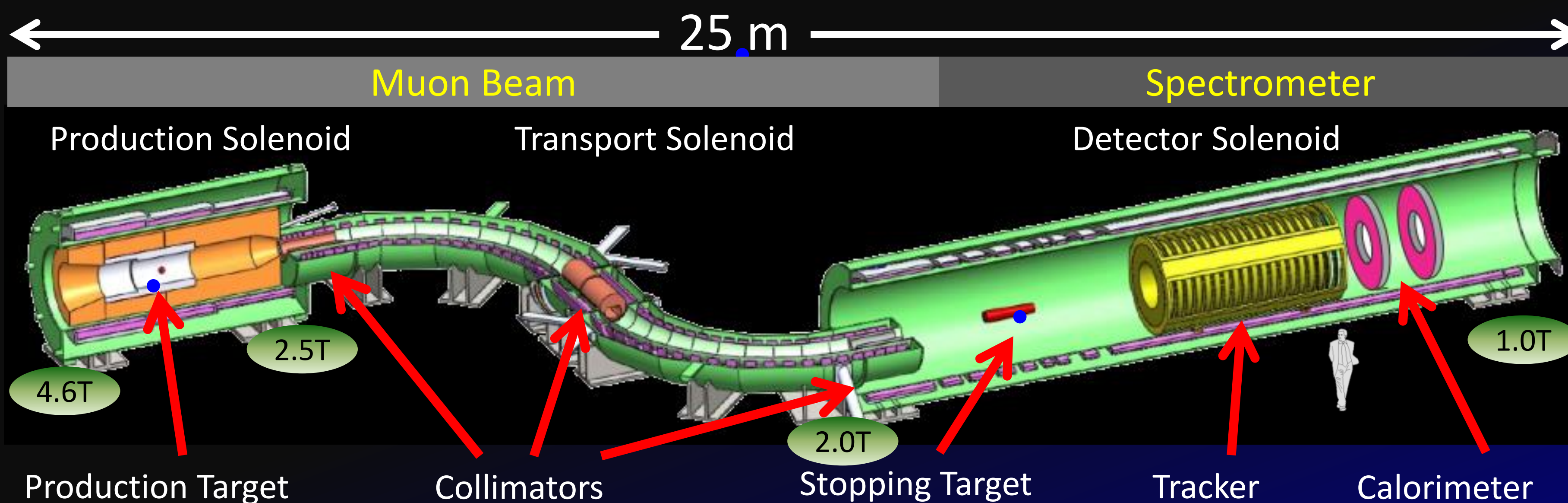
Frontier Physics Group
University of Virginia

How Mu2e Works



Searching for a "forbidden decay" of a stopped muon

Signature single delayed (τ = 864 ns in Al) isolated electron

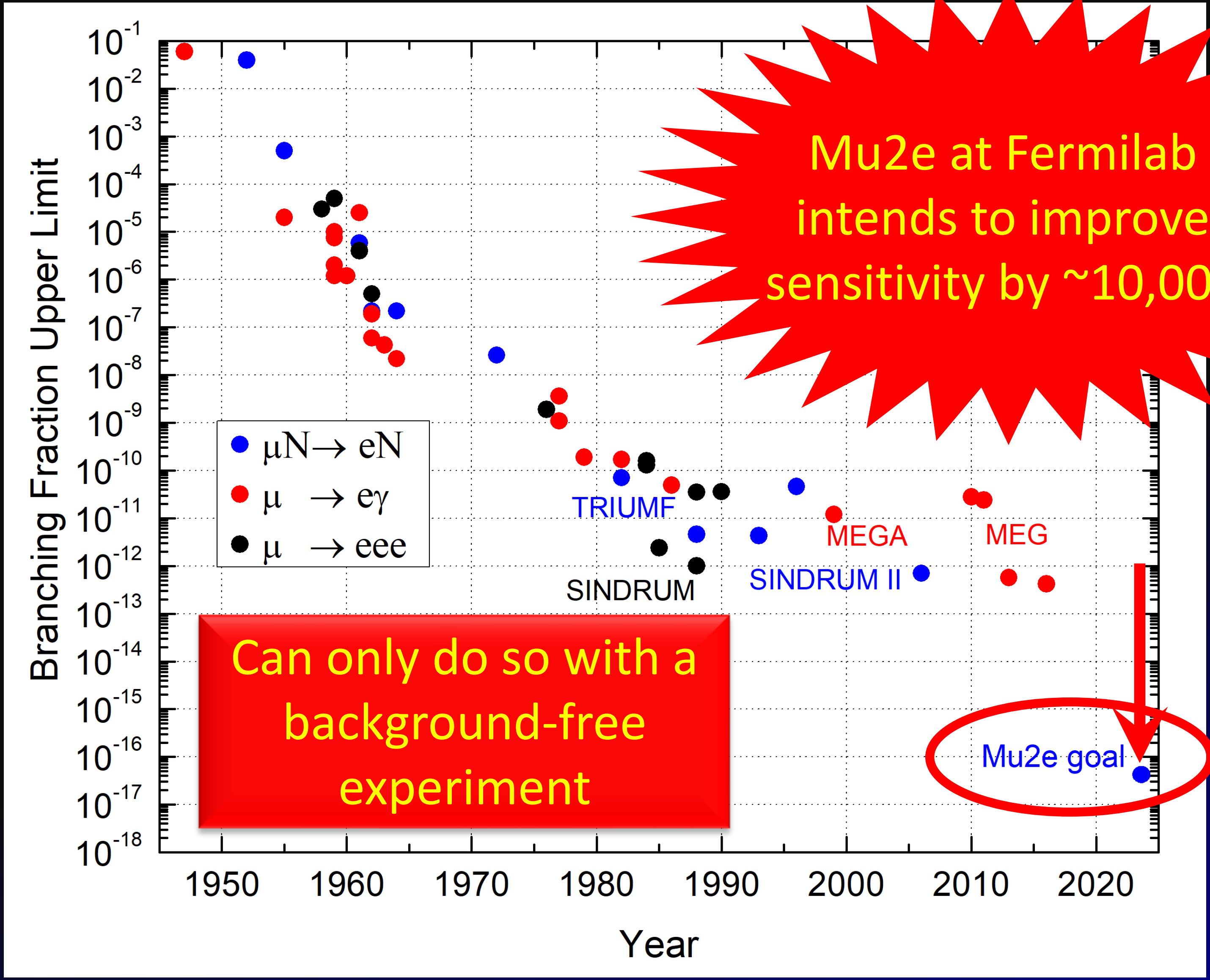


$$p + tgt \rightarrow \pi's + X$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

73,500 μ^- stop every 1.7 μs

43 billion μ^- stops/spill-second

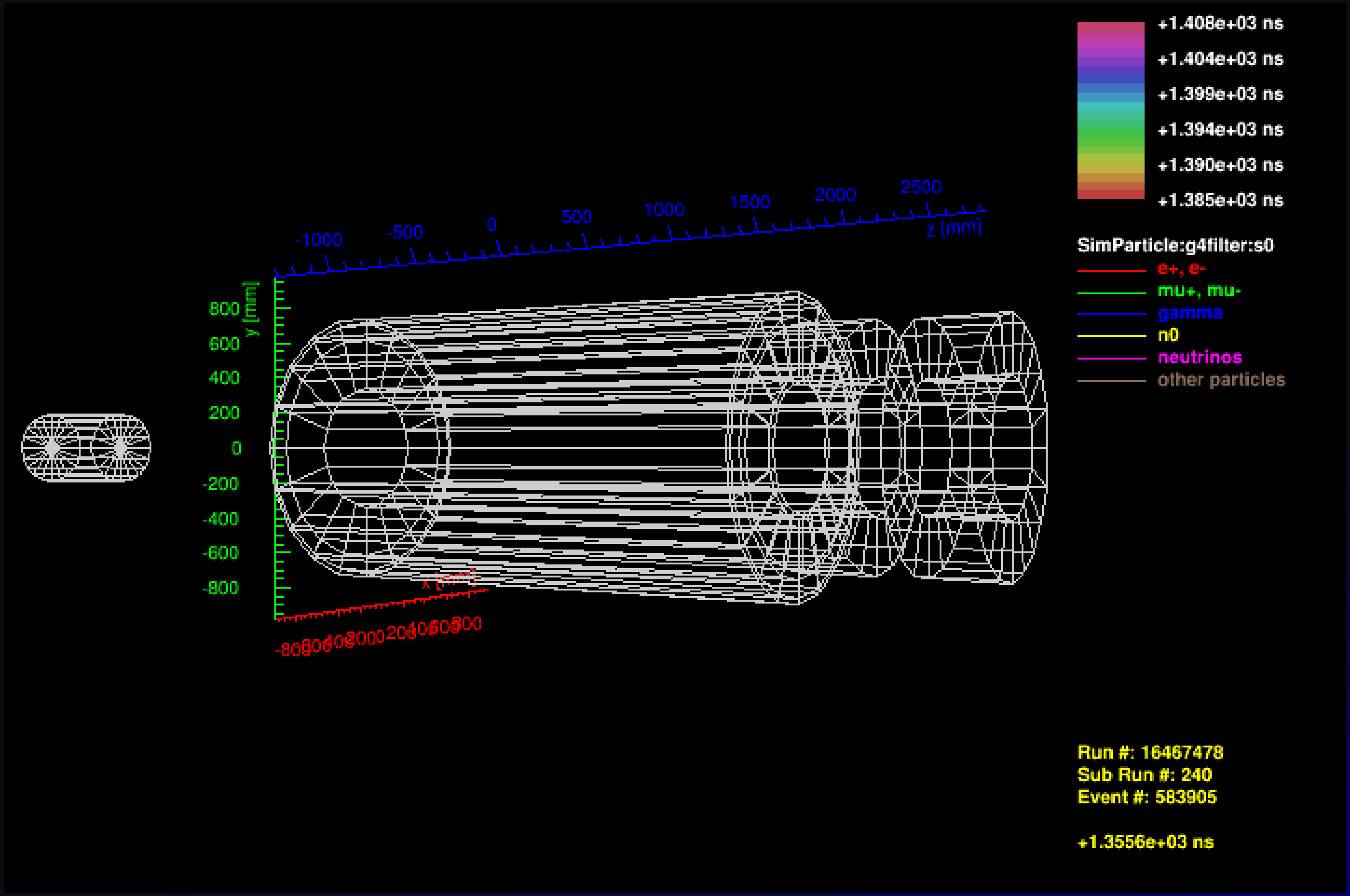
Mu2e Goal: Senstive Search for New Physics through Lepton Flavor Violation – $\mu^- N \rightarrow e^- N$



Mu2e at Fermilab intends to improve sensitivity by ~10,000

Can only do so with a background-free experiment

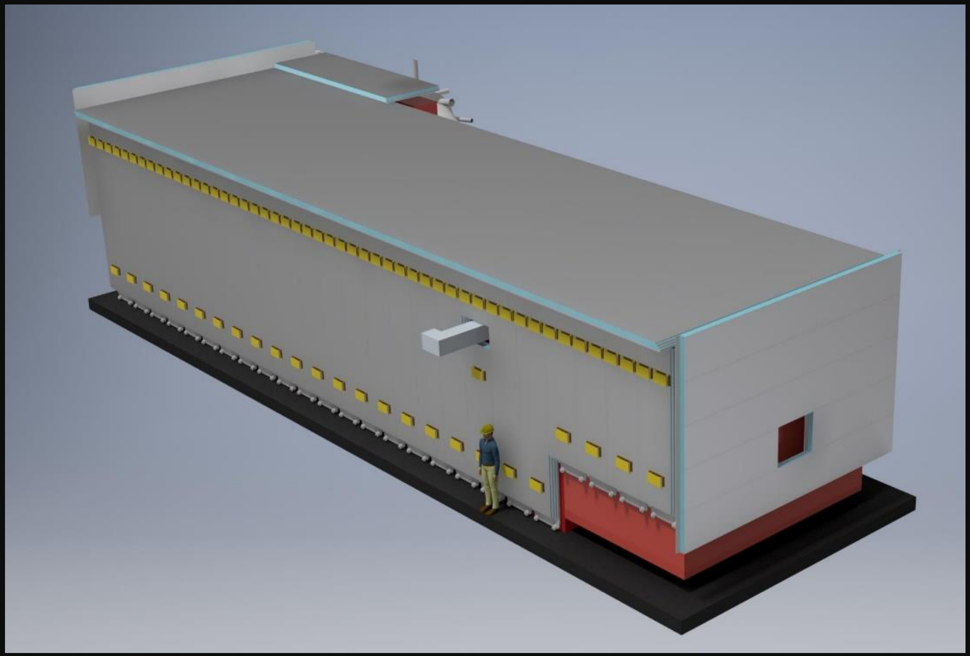
Cosmic Rays Can Produce Background Electrons!



We will get one such event every day!

These have to be identified and vetoed.

The Cosmic Ray Veto in a Nutshell



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

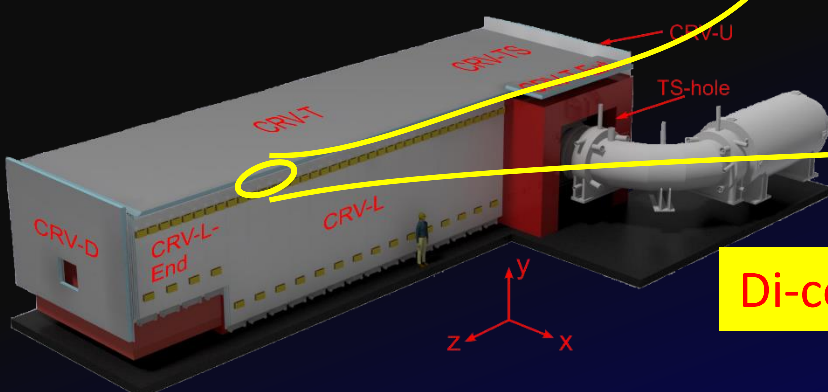
Details:
- Area: 335 m^2
- 83 modules; 10 types
- 5,344 counters
- 10,688 fibers
- 19,392 SiPMs
- 4,848 Counter motherboards
- 339 Front-end Boards
- 17 Readout Controllers

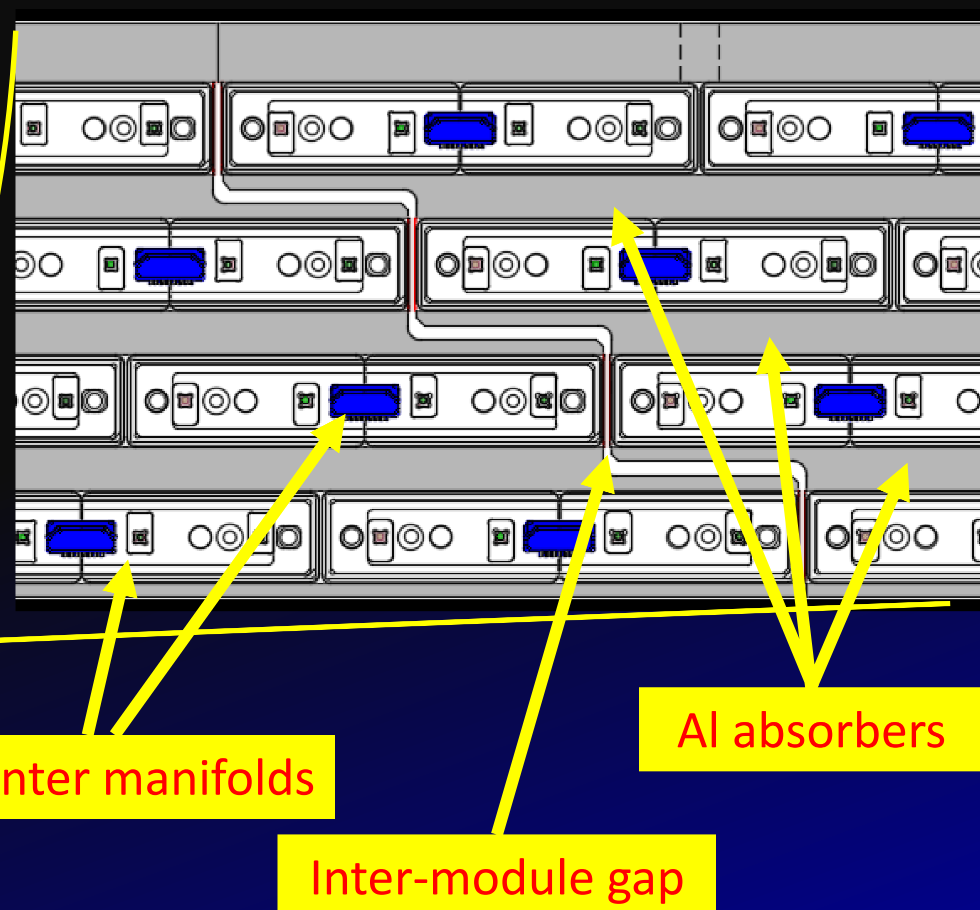
- CRV identifies cosmic ray muons that can produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, access to electronics, constrained space, and subject to high neutron and gamma rates.
- Technology: Four layers of extruded polystyrene scintillator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

Mechanical Design

Design Requirements

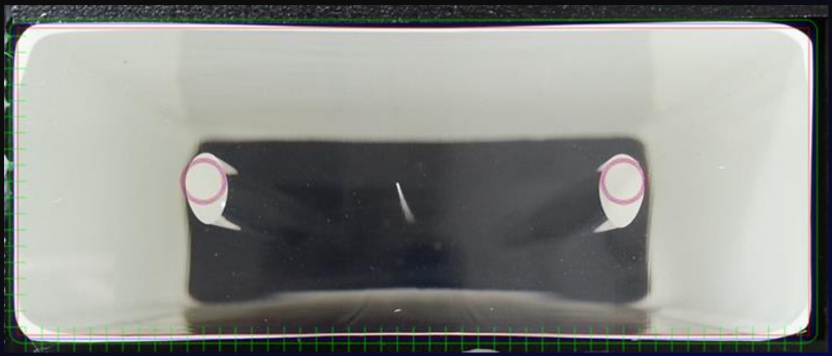
- Need a very good efficiency to get a 10,000X rejection
- Gaps are bad and are must be minimized: some are unavoidable
- Want muons to produce more light than γ/neutron backgrounds → thick counters
- Need at least 4 layers of scintillator to reduce rate of fake coincidences with a ¾ requirement
- Al absorbers between layers reduce electron punch through
- Layers offset to mitigate effect of projective gaps
- Electronics needs to work in a high ambient magnetic field

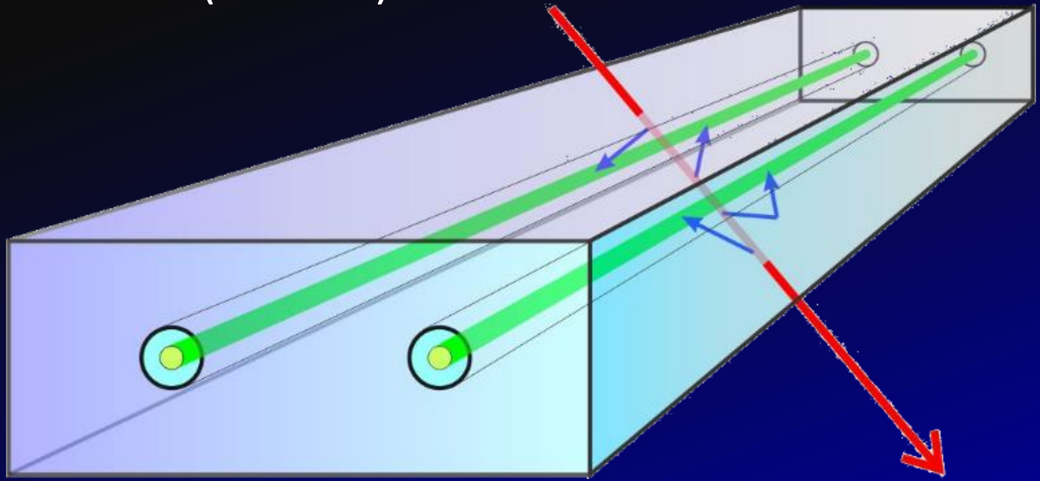




Mechanical Design: Counter

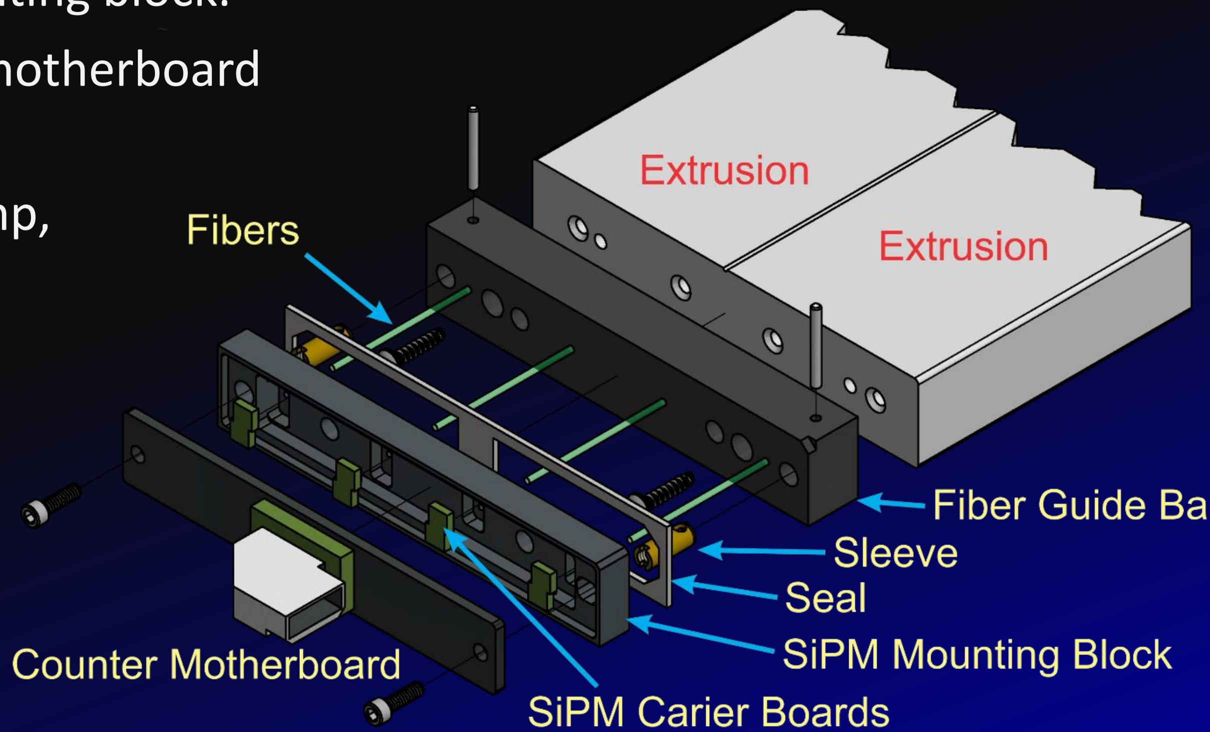
- Fundamental element of the CRV (5,344 total).
- Each counter has two 1.4 (1.8) mm wavelength-shifting fibers placed in channels in extruded PS doped with 1% PPO + 0.05% POPOP and coated with with TiO_2.
- About 90% of the counters are read out on both ends by silicon photomultipliers (SiPMs). Exceptions are a few short counters and a few with one end in a high radiation or inaccessible area. Reflective fiber ends are used instead.
- Counters range from 1050 mm to 6900 mm long.
- Profile: 51.3 x 19.8 mm^2. This is a compromise between need to minimize rates (smaller), maximize efficiency (larger), and extrusion production limitations (smaller).



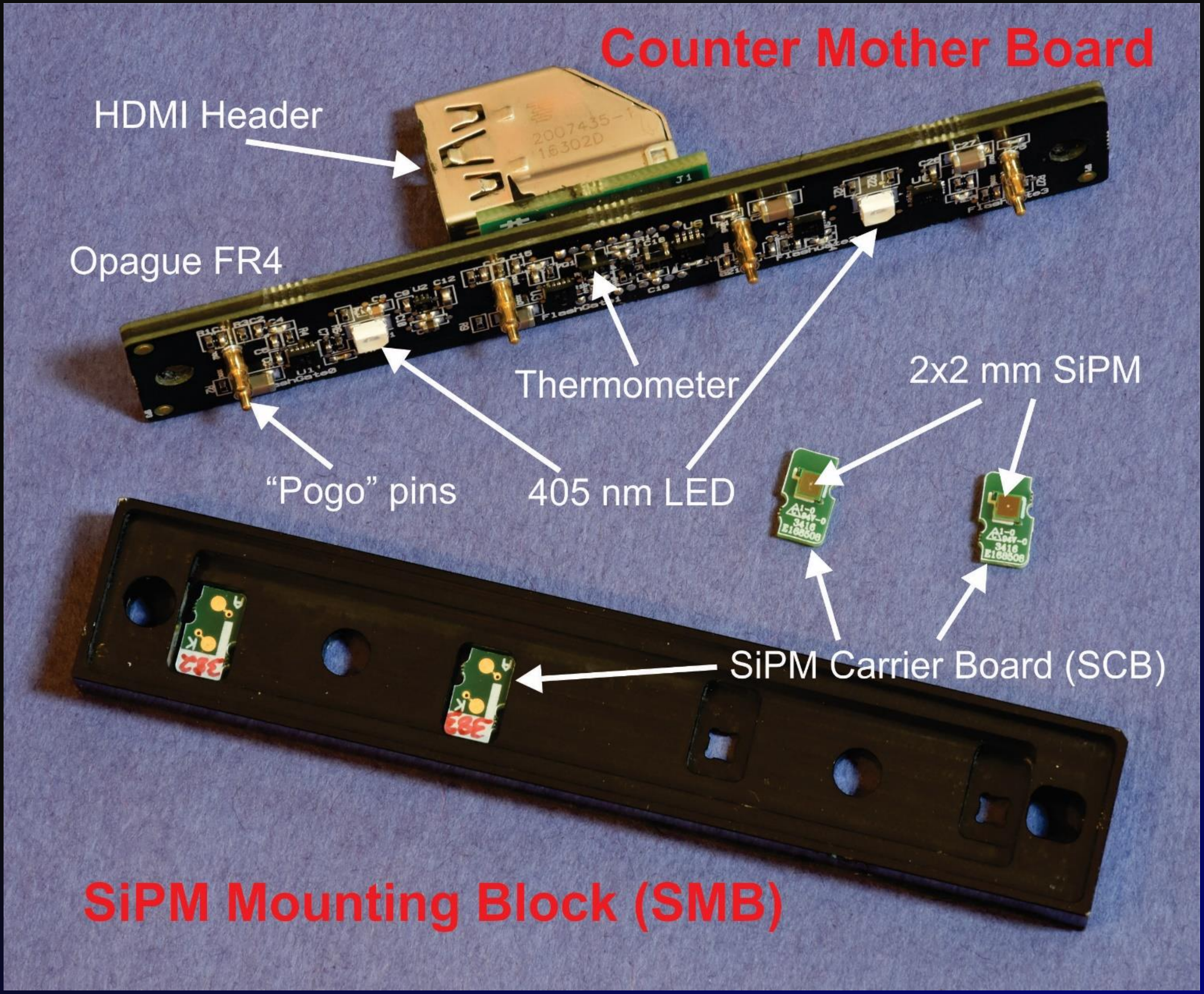


Mechanical Design: Di-counter Manifold

- Two extrusions glued together 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; sits on top of Al SiPM mounting block.
- Pogopins connect counter motherboard and SiPM carrier boards.
- We do not control SiPM temp, but adjust bias based on temperature.



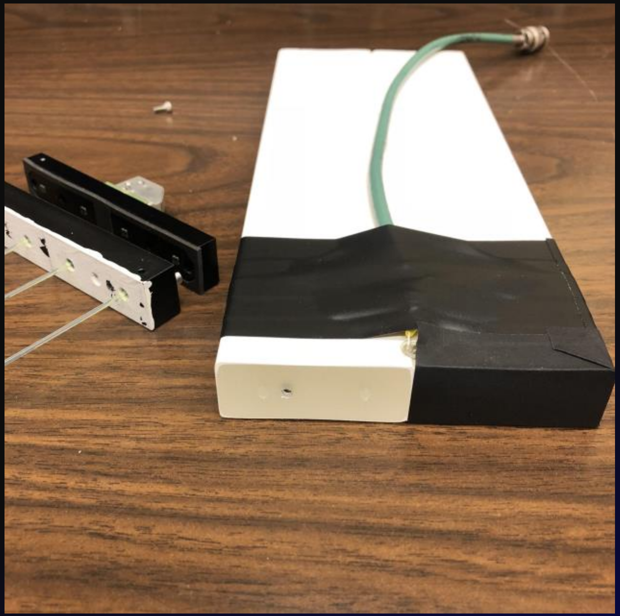
Mechanical Design: Di-counter Manifold



Improving Light Yield Near Counter Ends

- Drilled a hole in between di-counters, 10 mm away from readout end
- Glued a blue LED inside the hole
- One counter used as reference
- Second counter had different refelectors/coatings

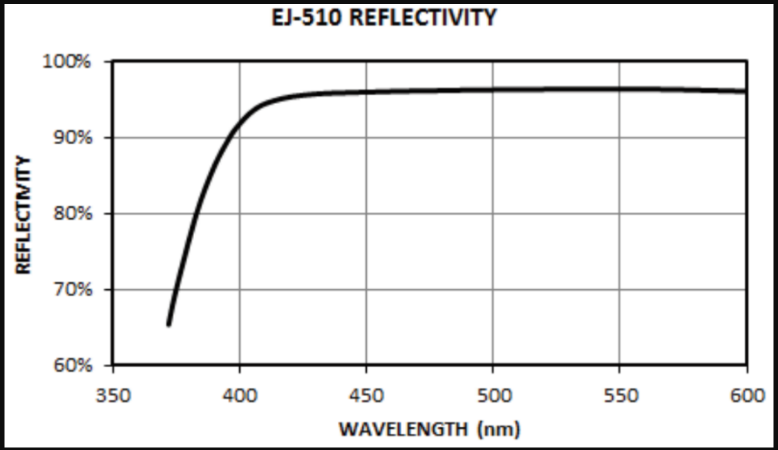
Configuration	$\bar{\Delta}_{\mathrm{LightYield}}$
BC-620 on FGB	1.7
BC-620 on Extrusion	1.7
VM2000	1.9
Tyvek	1.7

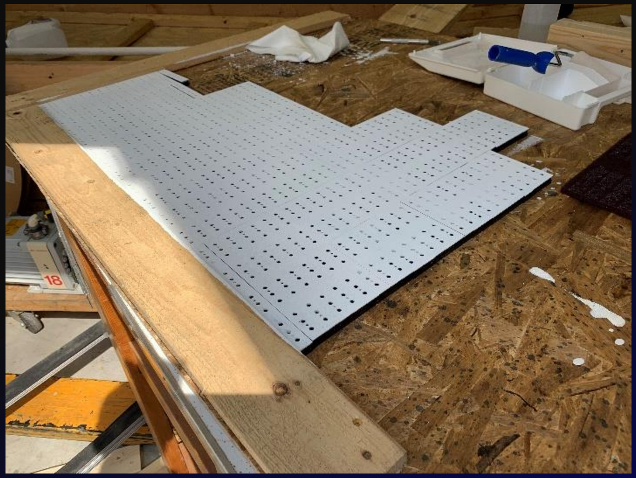


Chose BC-620 (EJ-510) on FGB due to ease of application

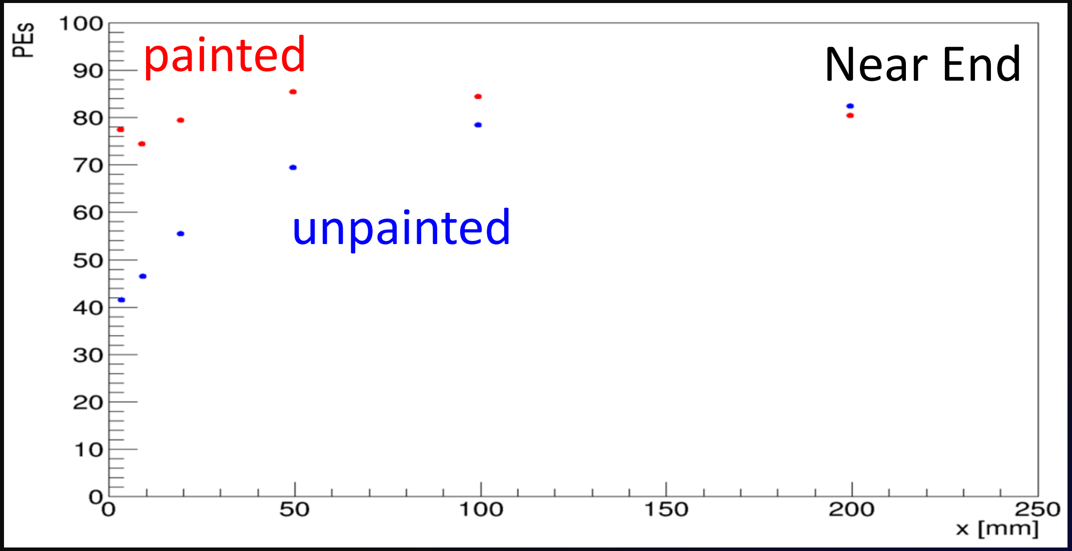
Improving Light Yield Near Counter Ends

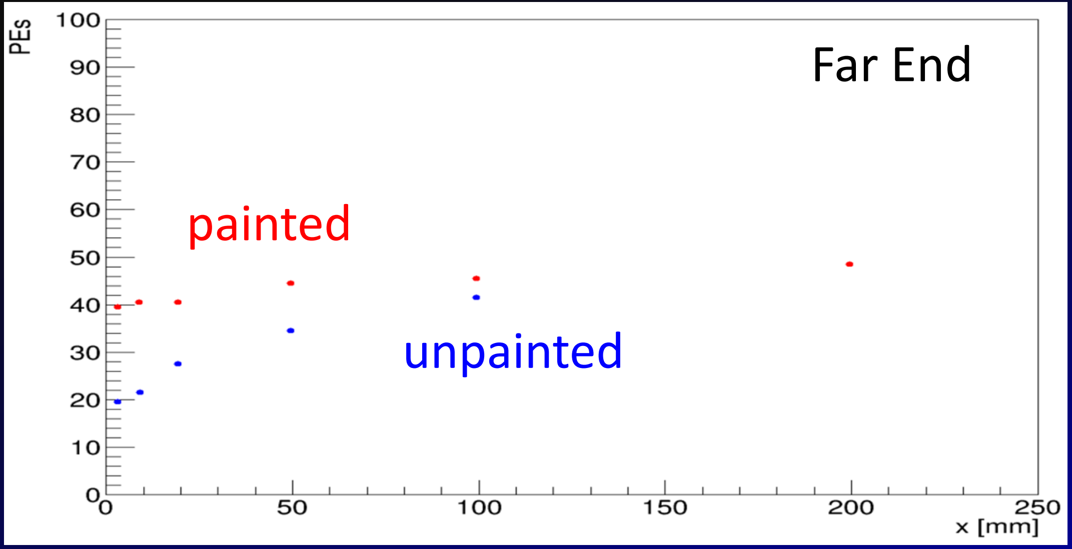
Fiber Guide Bars are painted with Eljen EJ-510 TiO_2 paint; one layer





Test beam: 3-m long counter



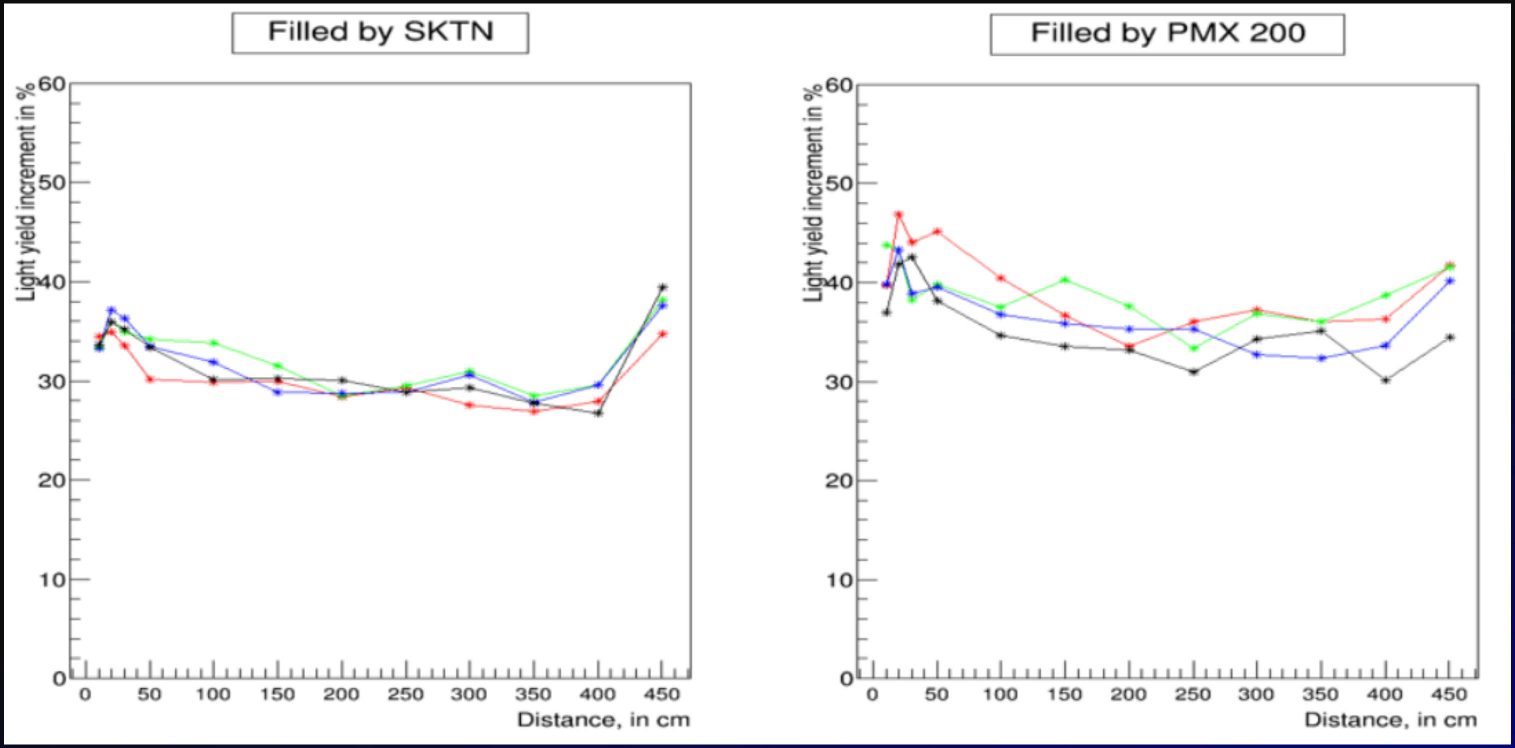


Improving Light Yield: Potting Fiber Channels

- Light yield can be increased significantly by potting fibers in silicone or epoxy
- We chose not to do so because of: (1) potential for leaks damaging CMB electronics; and (2) increase labor costs
- Rather, we tuned the light yield to the desired level by adjusting fiber diameter
- However, studies were made in potting fibers and a potting jig was designed

Improving Light Yield: Potting Fiber Channels

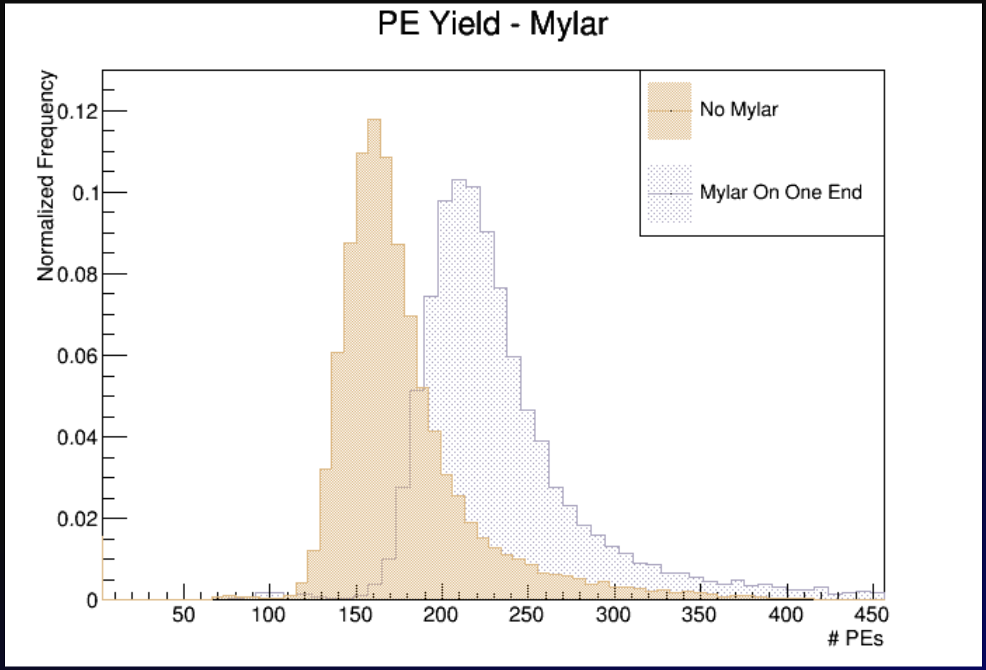
- Holes were drilled in each end of the extrusions into the fiber channels
- pneumatic filler apparatus filled the channel
- Hole then sealed with DP-100 epoxy
- Light yield increase 30-40% as measured with Cs-137 source

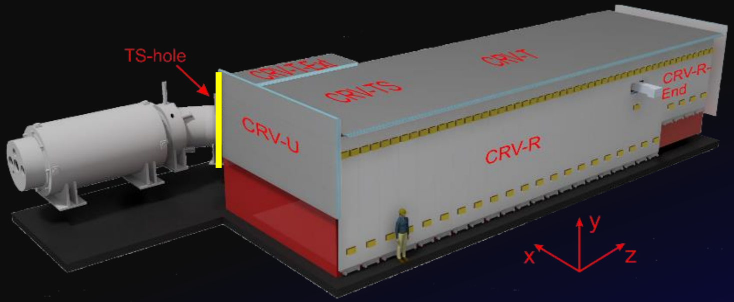


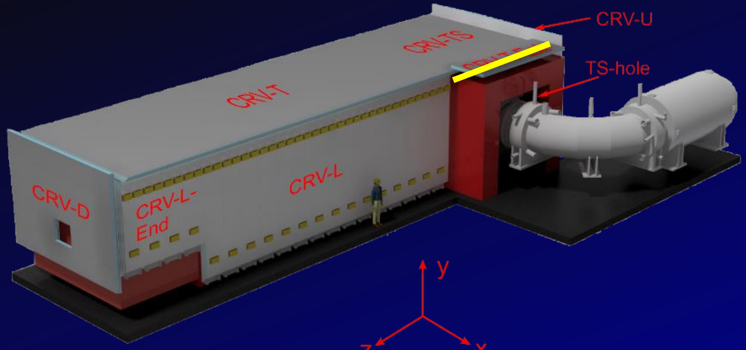
Light yield increase for two 4.5-m long di-counters filled with silicone fluid

Mechanical Design: Di-counter Reflector

- Not every counter is read out at both ends.
- Single-ended readout for extra-long counters in high radiation areas. (CRV-TS, U, D, Cryo)
- Studies done at UVA show that a simple Mylar coated Al reflector works well
- Average reflectivity is 84%
- Gives 30% more light

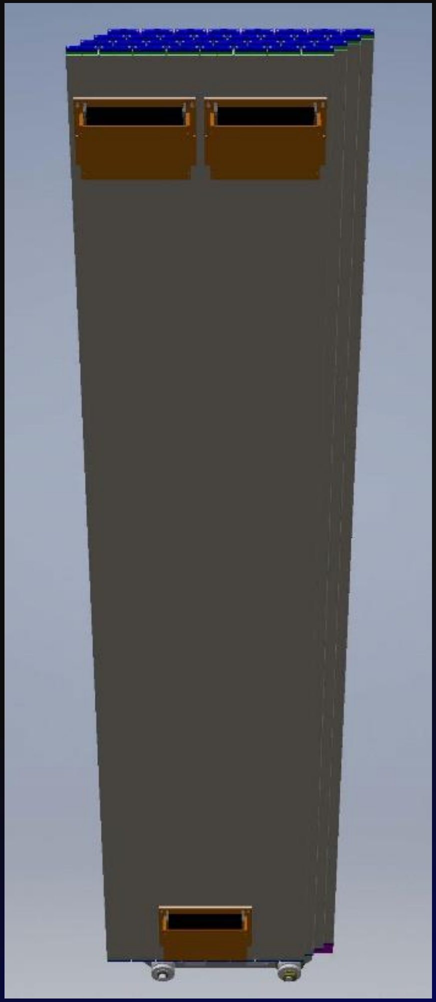




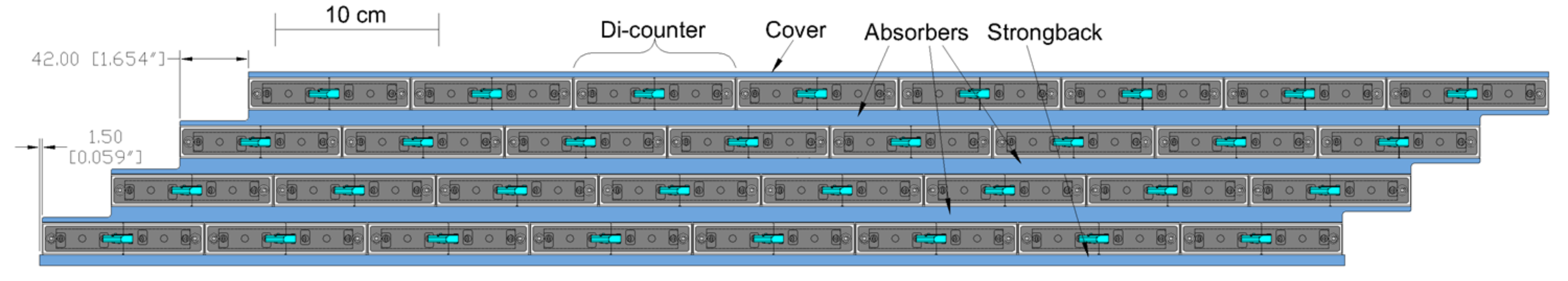


Design: Modules

- Fundamental mechanical element of the CRV
- 4 layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters/layer.
- Entire assembly glued together.
- Layers are offset to avoid projective gaps between counters.
- Mechanical tolerances very tight and critical
- Weight: 182 kg -- 1165 kg.
- Total: 83; lengths from 1.165 m -- 7.1 m; widths are 951 (826) mm for offset (non-offset) modules; thickness is 123.65 mm

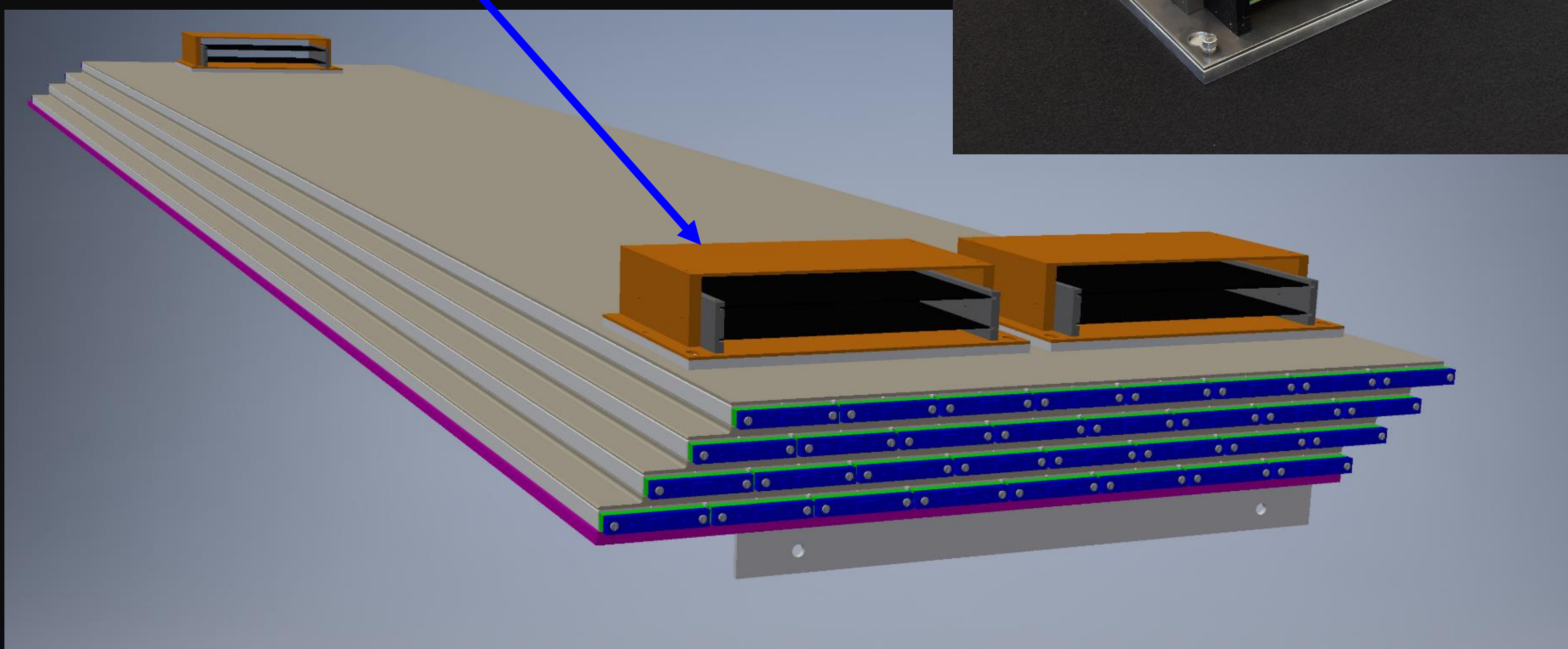


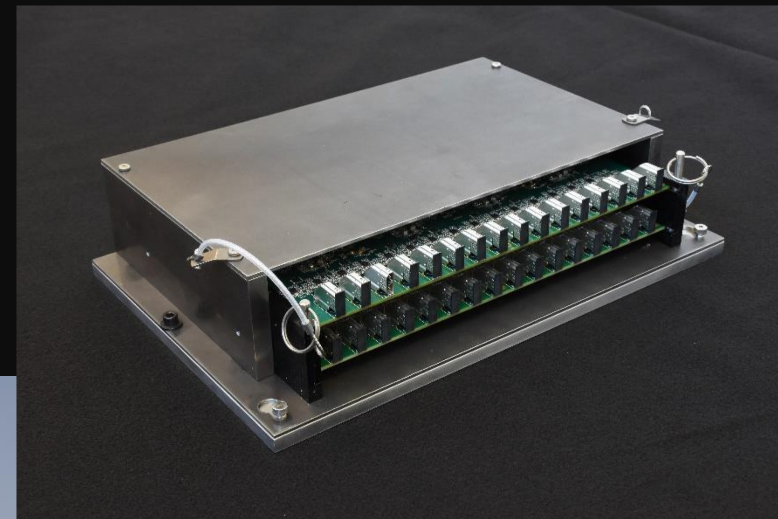
End view of module showing layer offsets



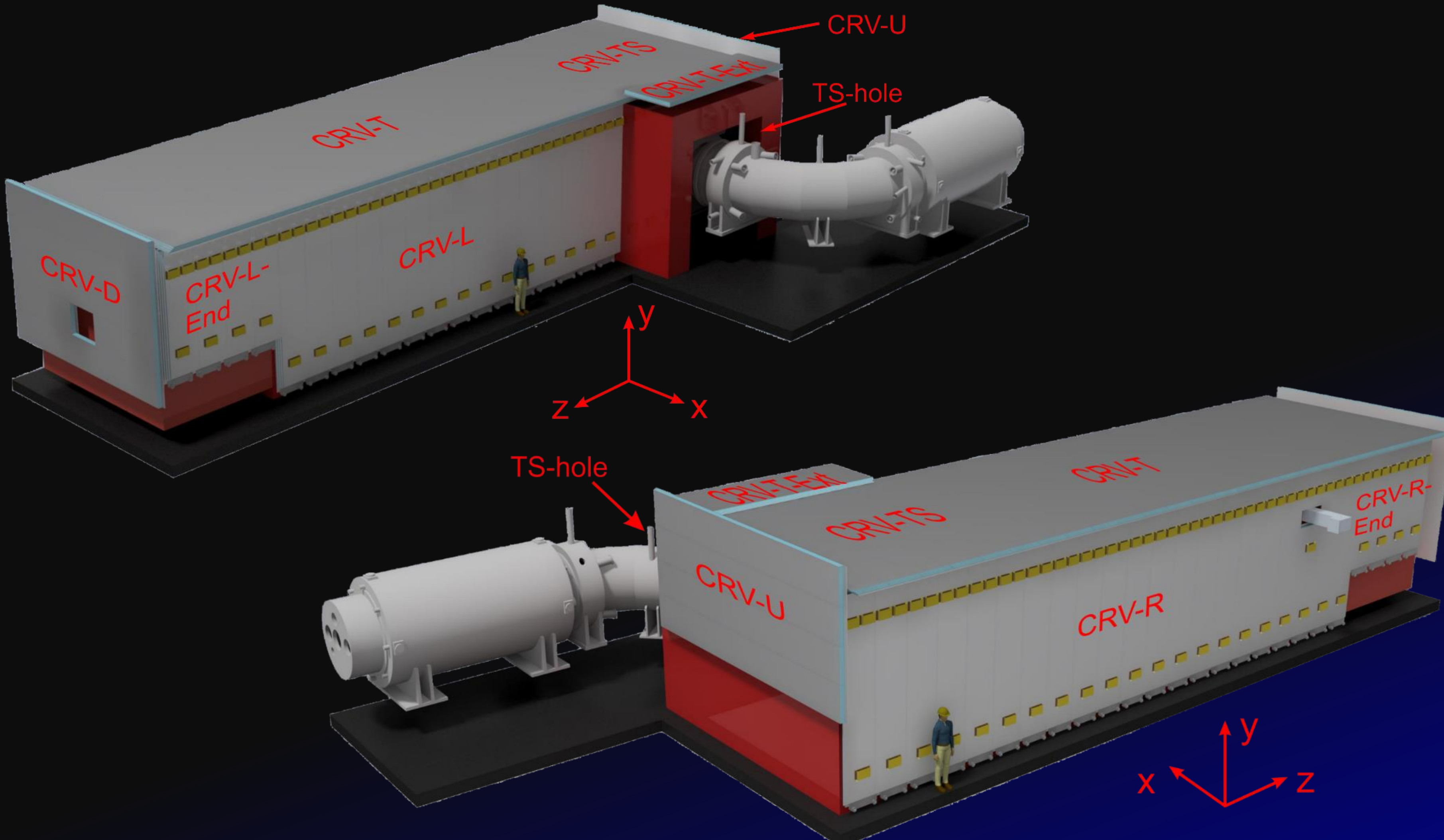
Design: Side Module Top

Magnetically shielded electronics boxes house 2 Front-end Electronics Boards each.





Design: Layout of the CRV

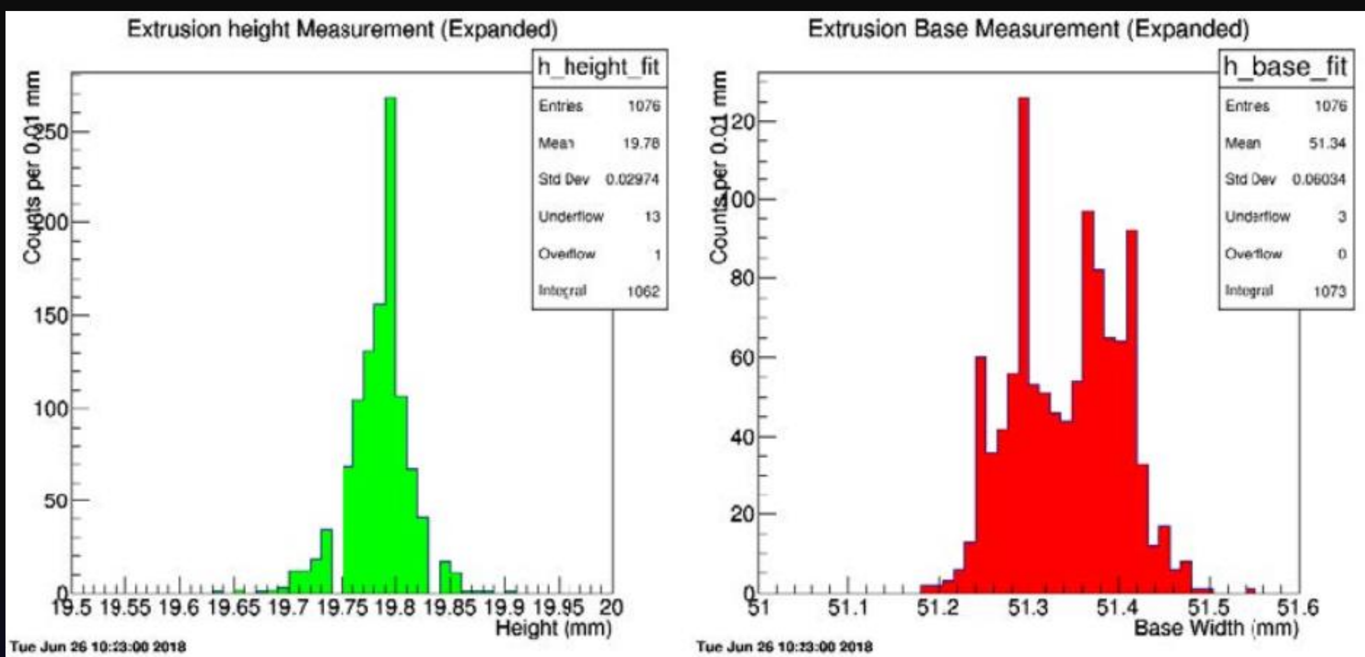


Positioned over the Detector Solenoid, over ~ 1m of concrete shielding used to mitigate the rates of neutrons and gammas coming out of the Detector Solenoid.

Extrusions

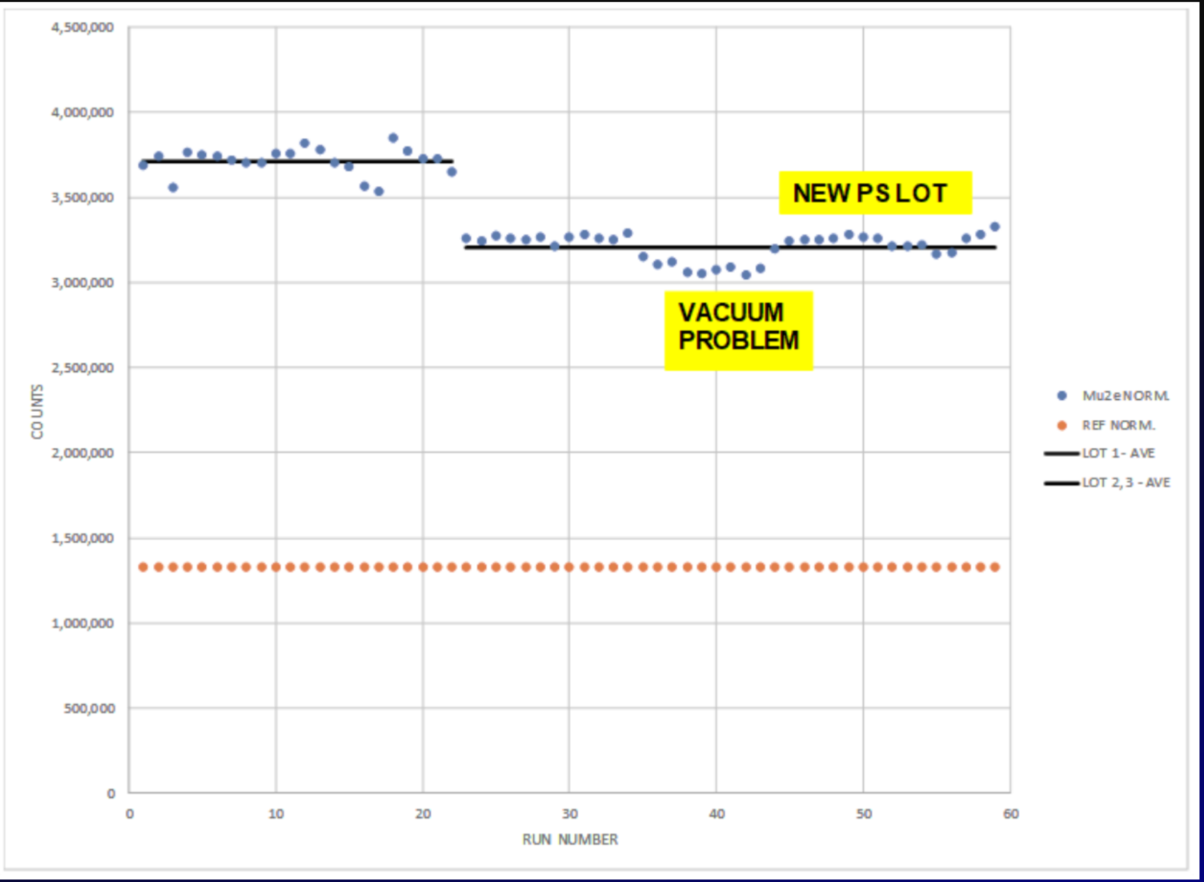
Extrusions

- 31.3 km of scintillator extruded at Fermilab-NICADD over a period of 5 months
- Co-extruded with PS-TiO_2 coating (30% TiO_2)
- Variations in width and height had to kept to a minimum in order to insure they would fit within the module mechanical specifications



Extrusions: Light Yield

The light yield measured with a PMT from a Cs-137 source for each scintillator sample as a function of extrusion number (blue dots). The orange dots are the response of a reference sample to the Cs-137 source to which all the measurements have been normalized. After a new PS batch was used, the light yield decreased by roughly 13%. An issue with the vacuum used in production also lowered the light yield.



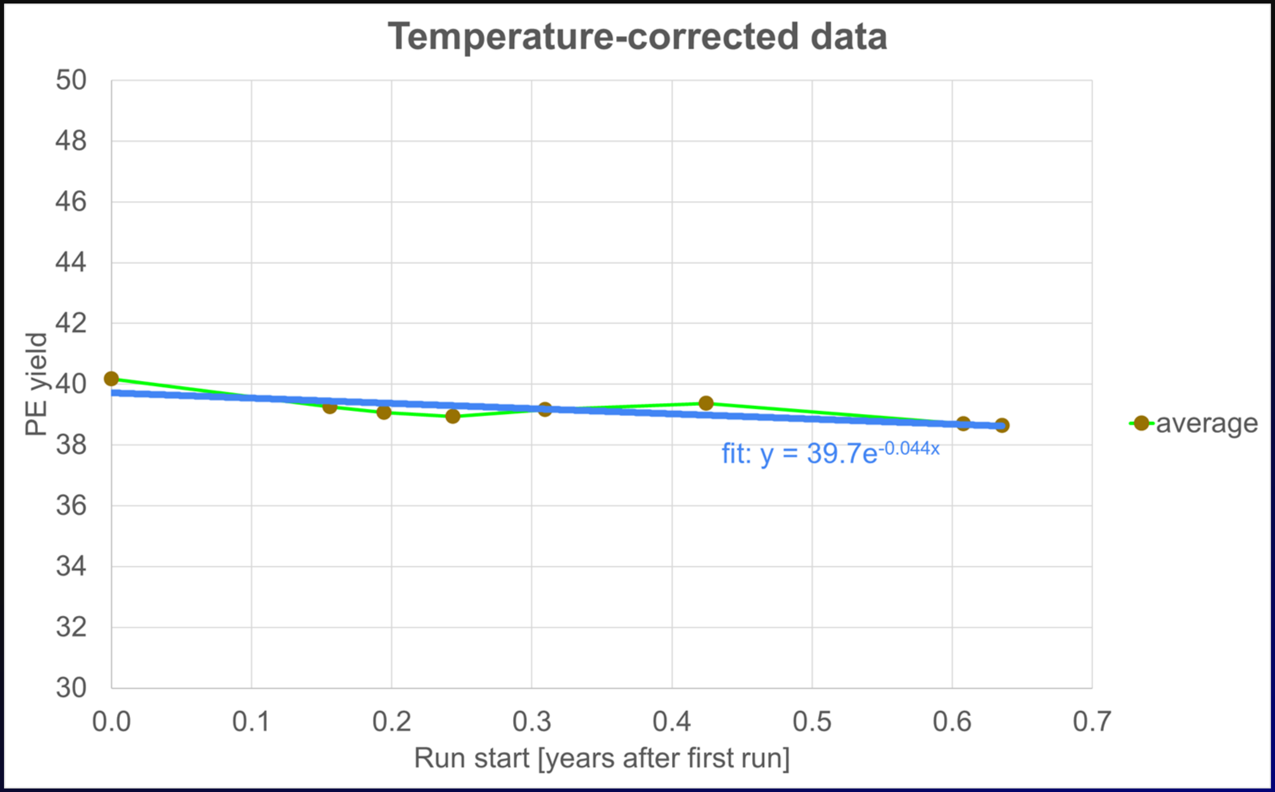
Extrusions: Aging

- The CRV was designed assuming a 3%/year light yield decline from measurements made by MINOS
- Preliminary measurements made by CRV were consistent with this
- In 2019 measurements at UVA and with Fermilab test-beam data (over several years) showed a much larger aging rate: ~9%/year
- Larger diameter fiber (1.8 mm) was purchased to increase light yield in critical sectors

Response of a counters to a Cs-137 source as a function of time since extrusion.

Extrusions: Aging Measurements at Wideband

- Recent measurements with modules shipped out to Wideband indicate that the aging rate has ameliorated to 4.4%/year
- The aging is in the scintillator (or TiO_2 coating) itself
- The cause of the aging is unknown and under active investigation

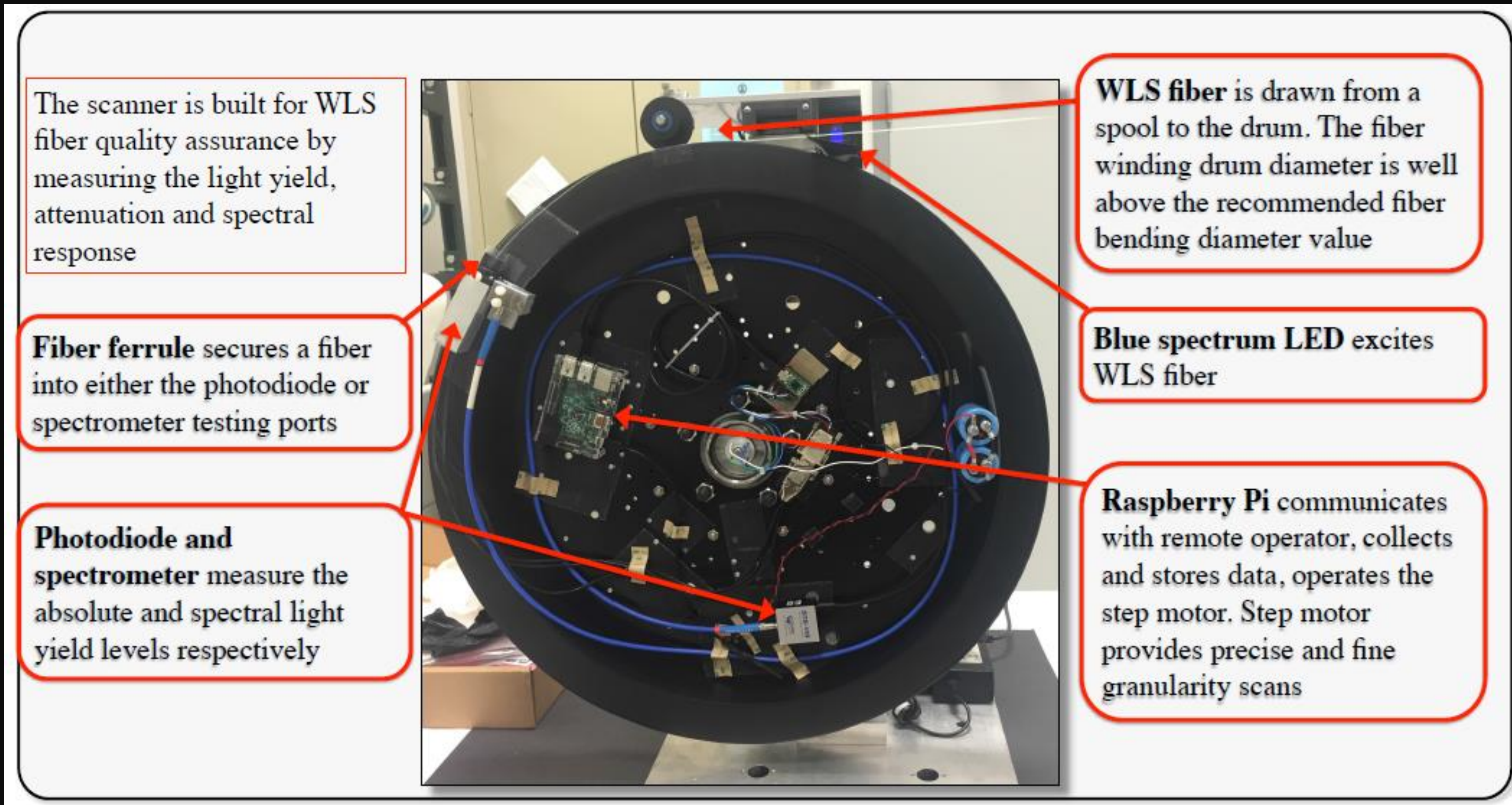


Fibers

Wavelength Shifting Fibers

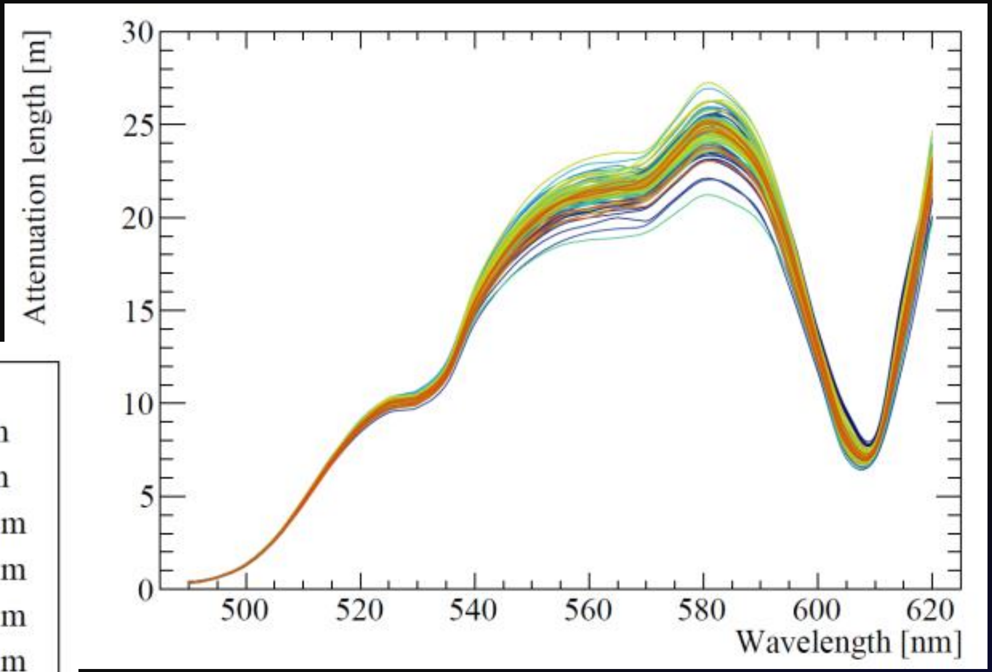
- We need 60,000 m of fiber (< 1% of what NOvA used)
- Two options on the market:
  - Bicron BCF-91A
  - Kuraray Y11
- We chose Kuraray Y11
  - Previous experience
  - Better performance and quality control
- Fiber type:
  - 1.4 mm (1.8 mm), non-S type, 175 ppm Y-11, double cladding

Fiber Quality Assurance

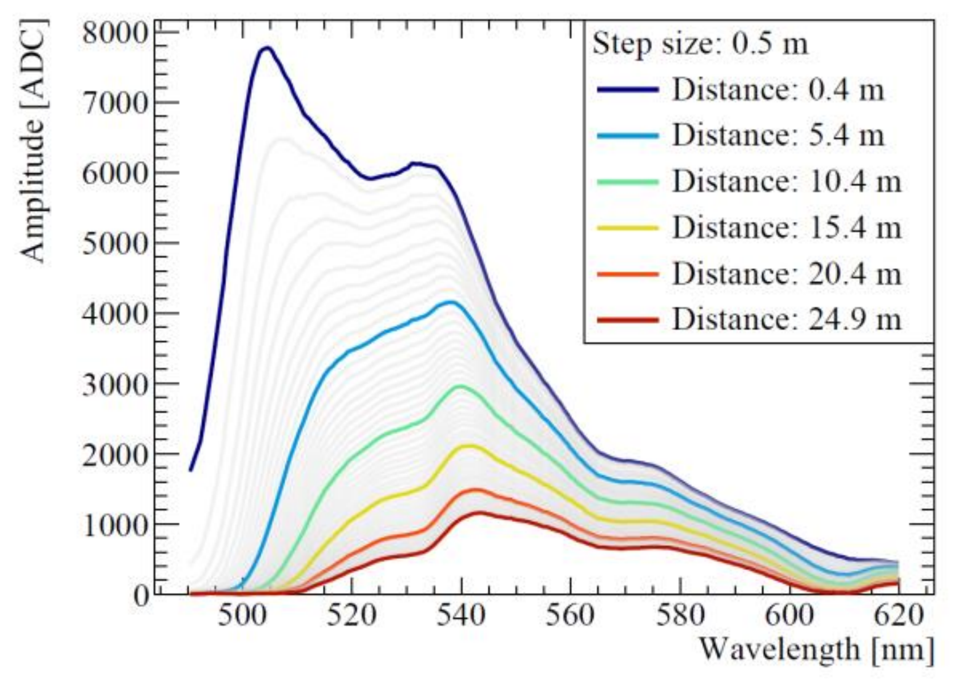


Fiber scanner designed to test first 25 m of fibers on each spool

Fiber: Quality Control

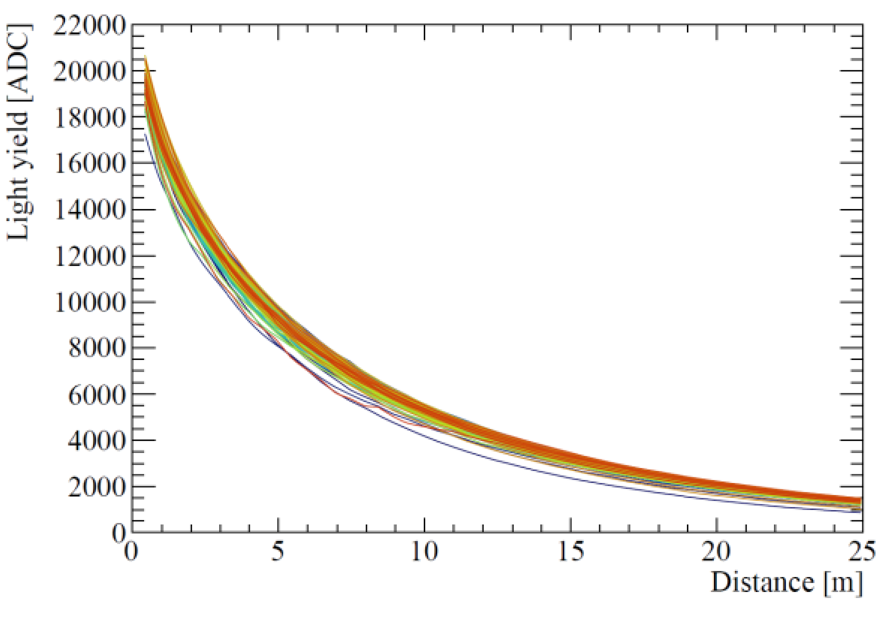


The attenuation length as a function of wavelength for all fiber spools

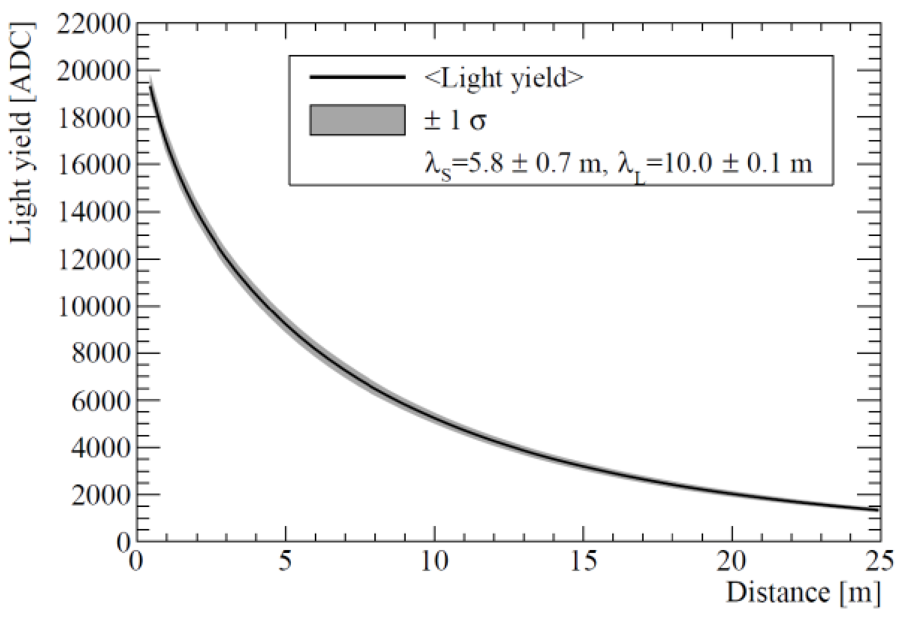


Measured intensity at the end of a fiber spool as a function of wavelength at various distances from the excitation point.

Fiber: Quality Control

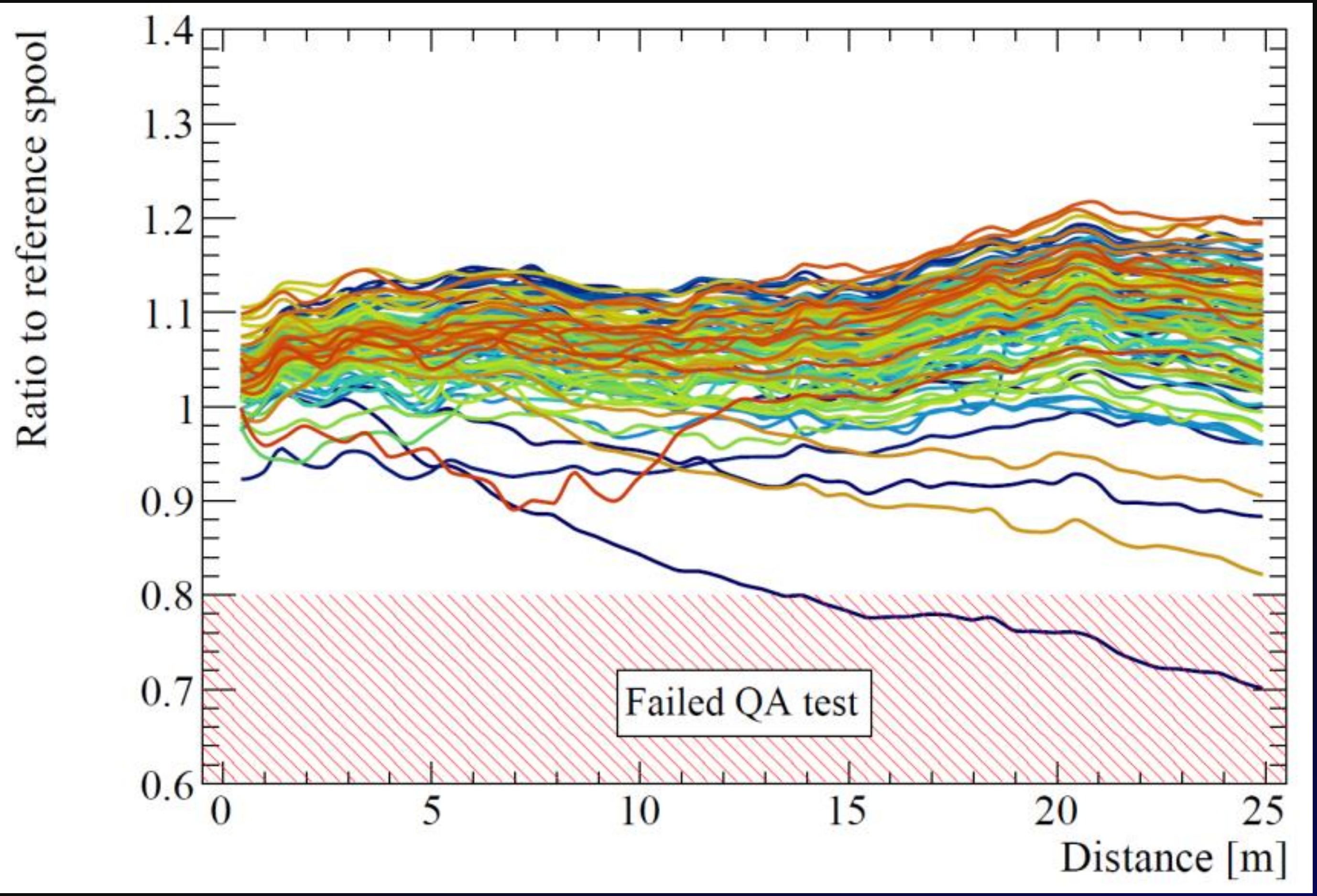


Light yield as a function of distance for all 104 production spools.



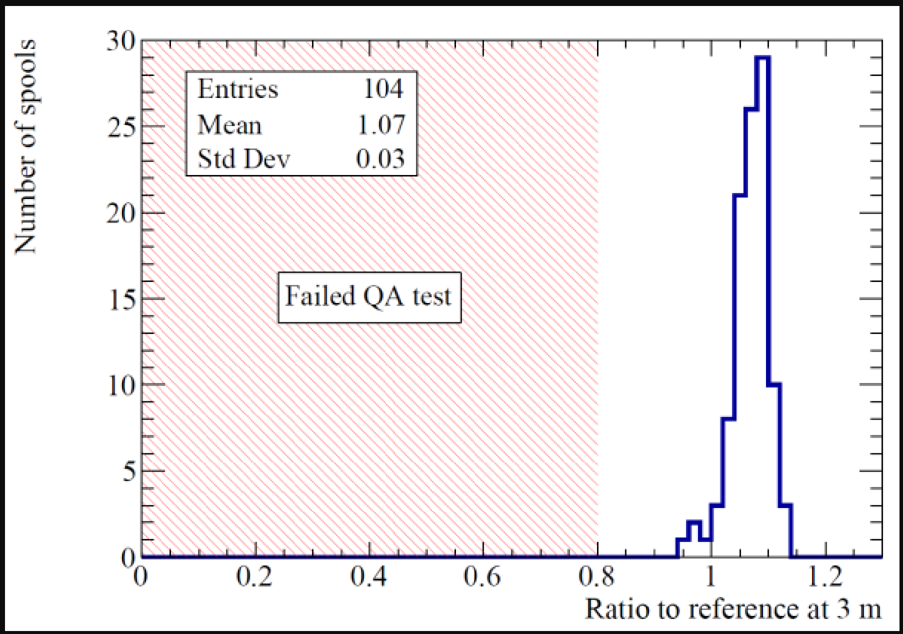
Average light yield as function of distance.

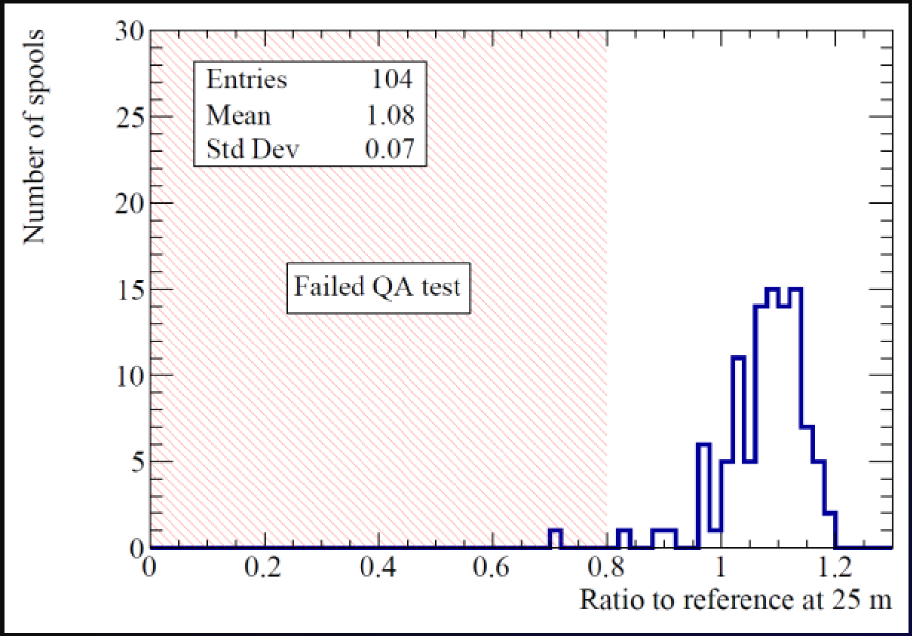
Fiber Quality Assurance



Light yield as a function of distance from the excitation point for all 104 production spools of fiber, normalzied to the reference fiber. It was required that all spools perform at least 80 % or better than the reference fiber. One spool failed and was replaced.

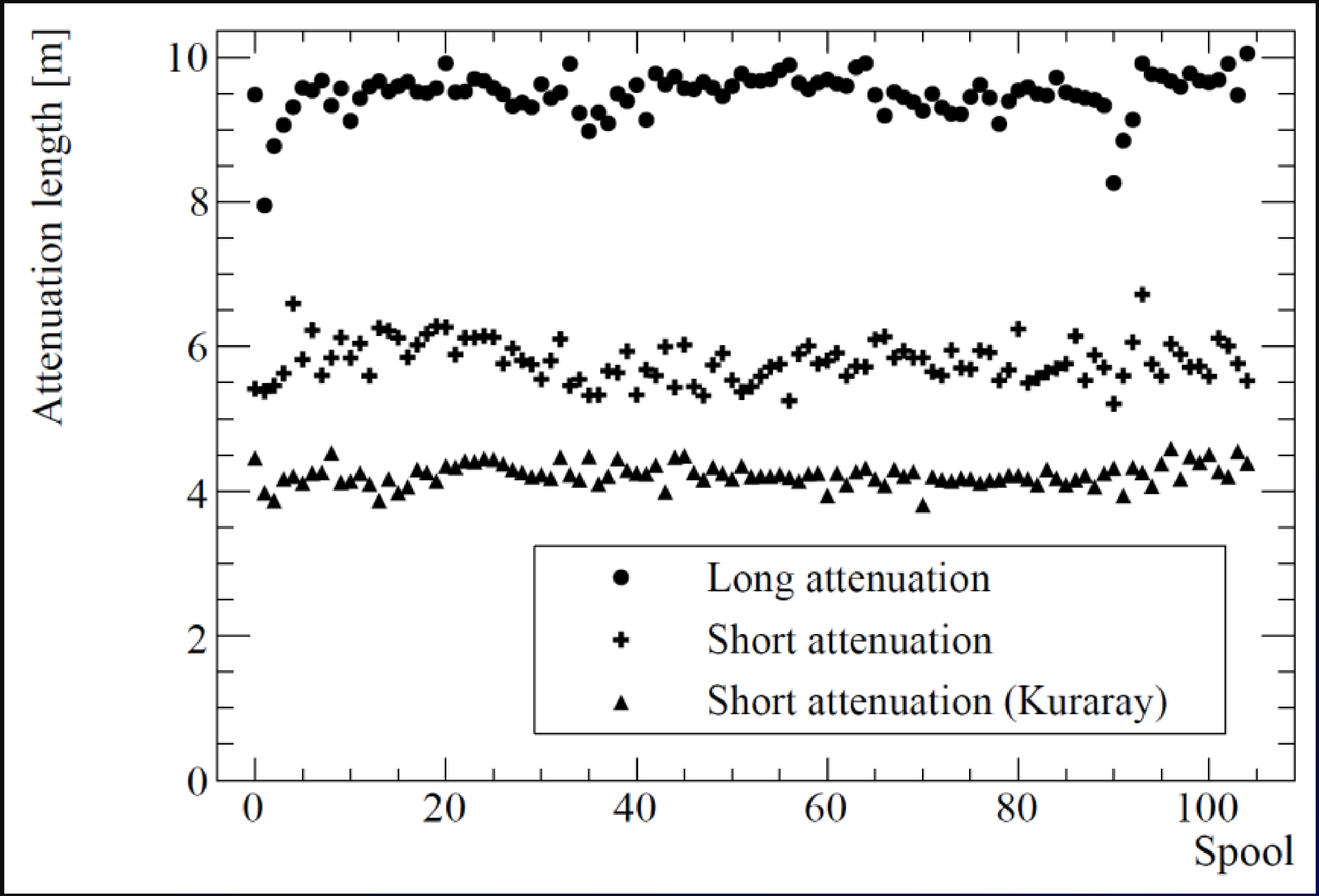
Fiber Quality Assurance





The relative light yield of all spools at 3 m (left) and 25 m (right)

Fiber Quality Assurance



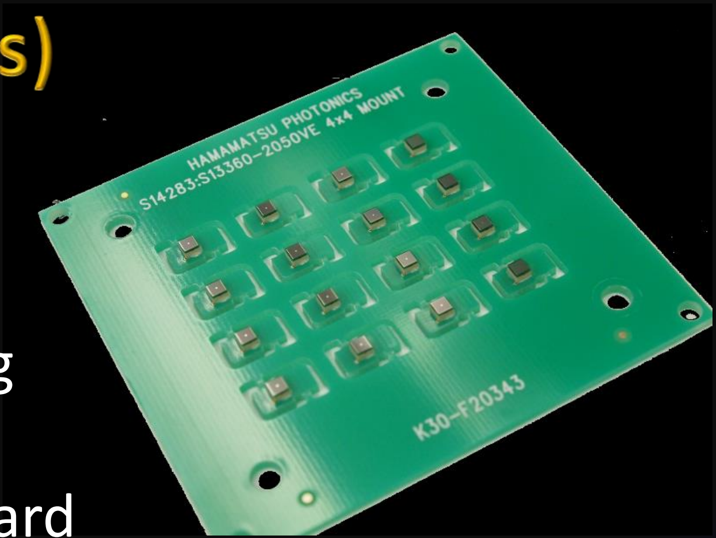
Short (0:5 m to 3 m) and long (3 m to 25 m) attenuation length for each spool. Included is the short attenuation length as measured by the vendor, Kuraray, the region of 1 m to 3 m. The reference fiber is included, which is the first point in the plot.

Photodetectors

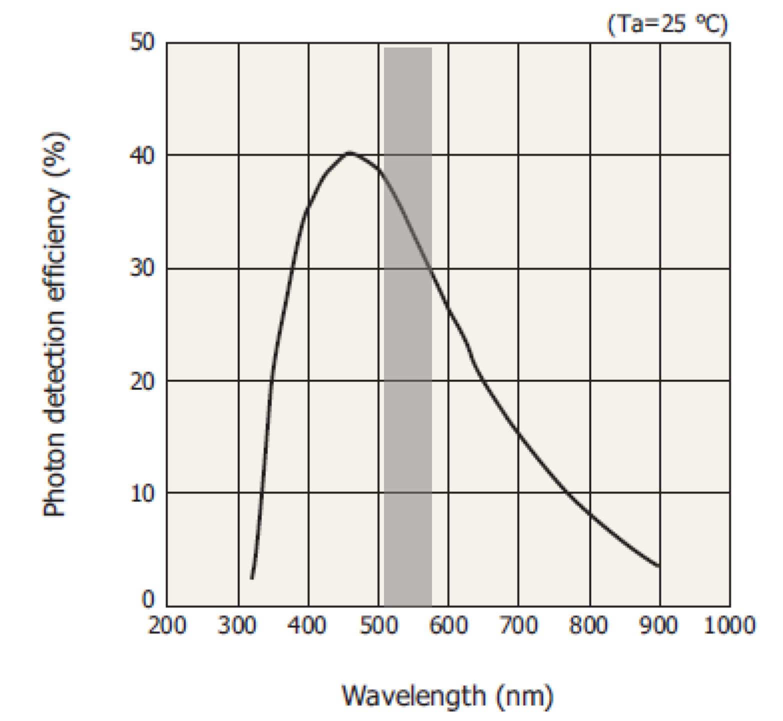
Silicon Photomultipliers (SiPMs)

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



SiPMs on 4x4 carrier board "waffle pack"



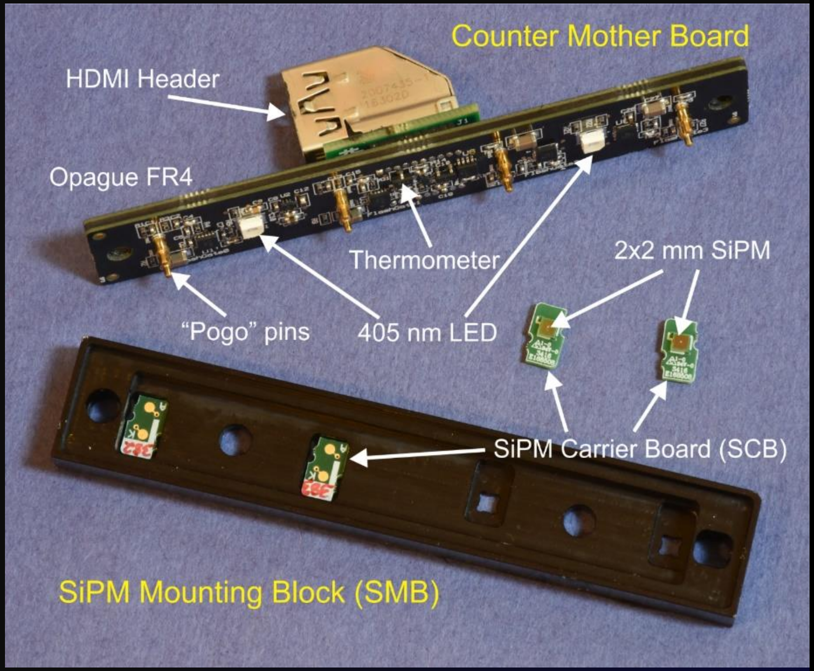
Hamamatsu MPPC S13360-2050VE

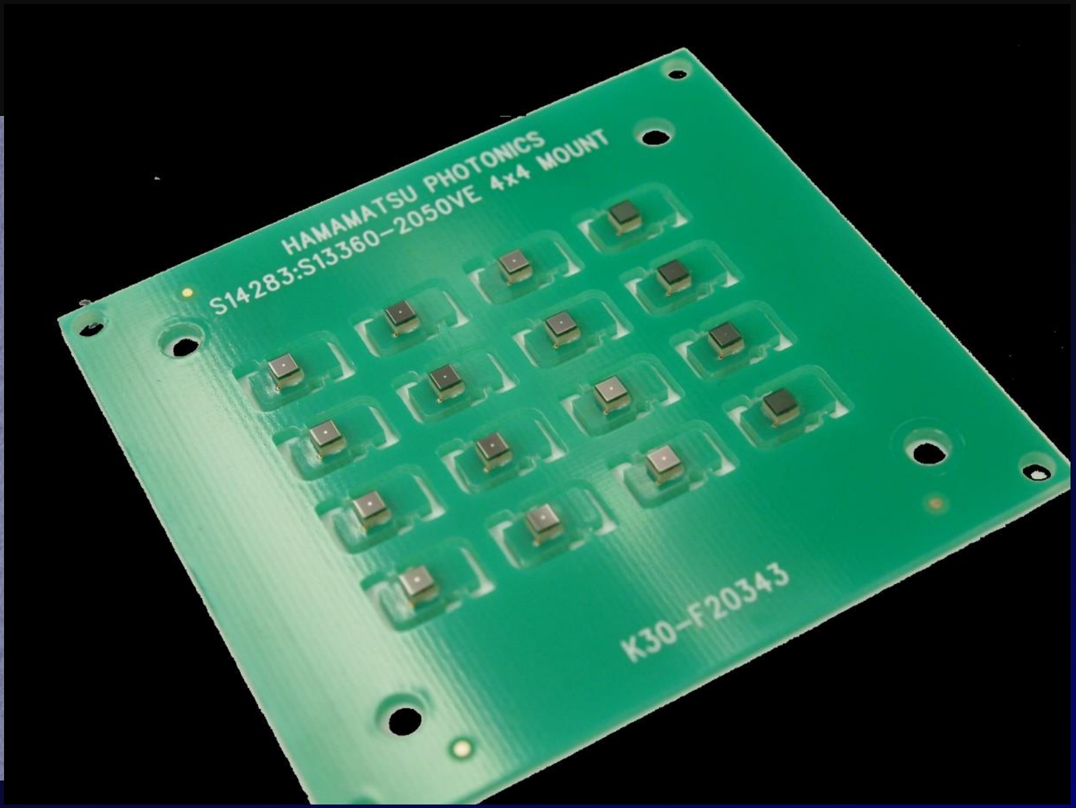
All values at 25° C at overvoltage of 2.5V:

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

Design

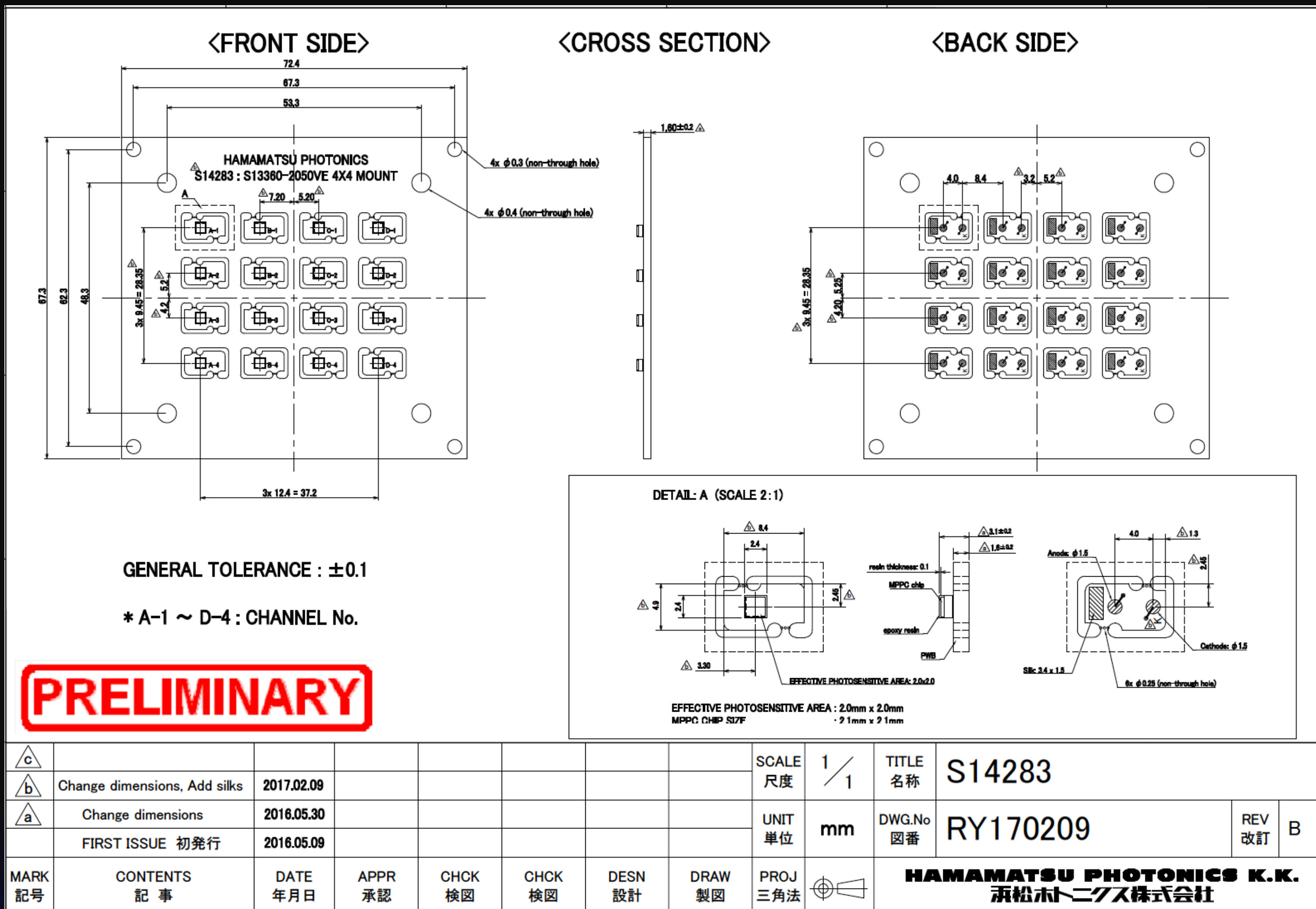
- Devices are mounted on substrates (SiPM Carrier Boards – SCBs) by Hamamatsu
- They are delivered (and tested) on a 4 x 4 "waffle pack"



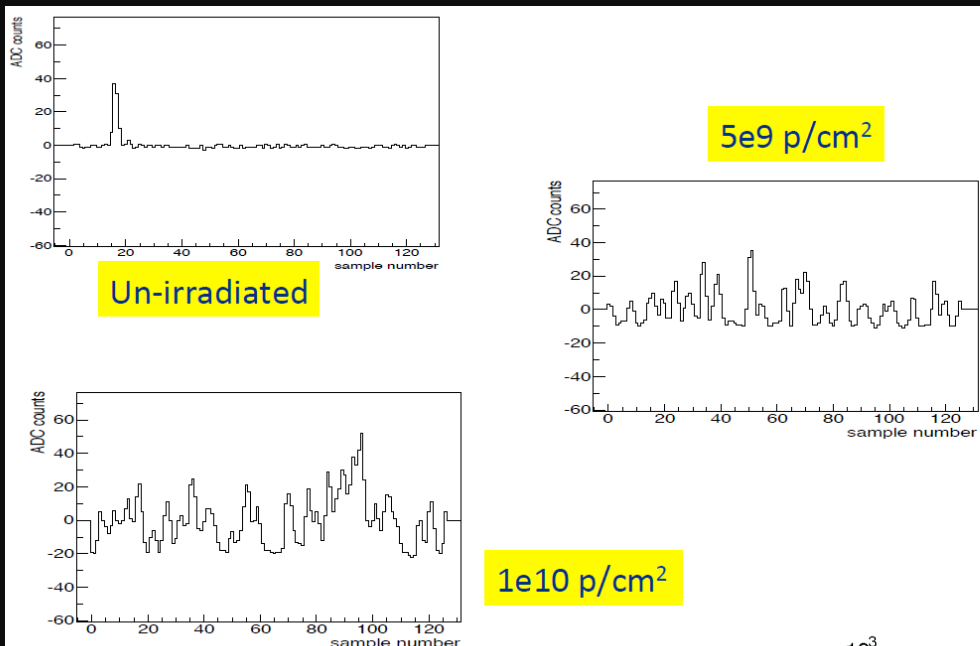


Design

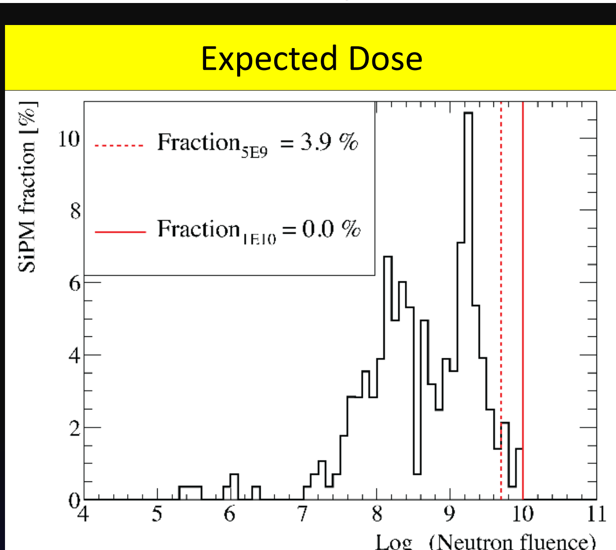
Devices are delivered and tested on boards with 16 SCBs each

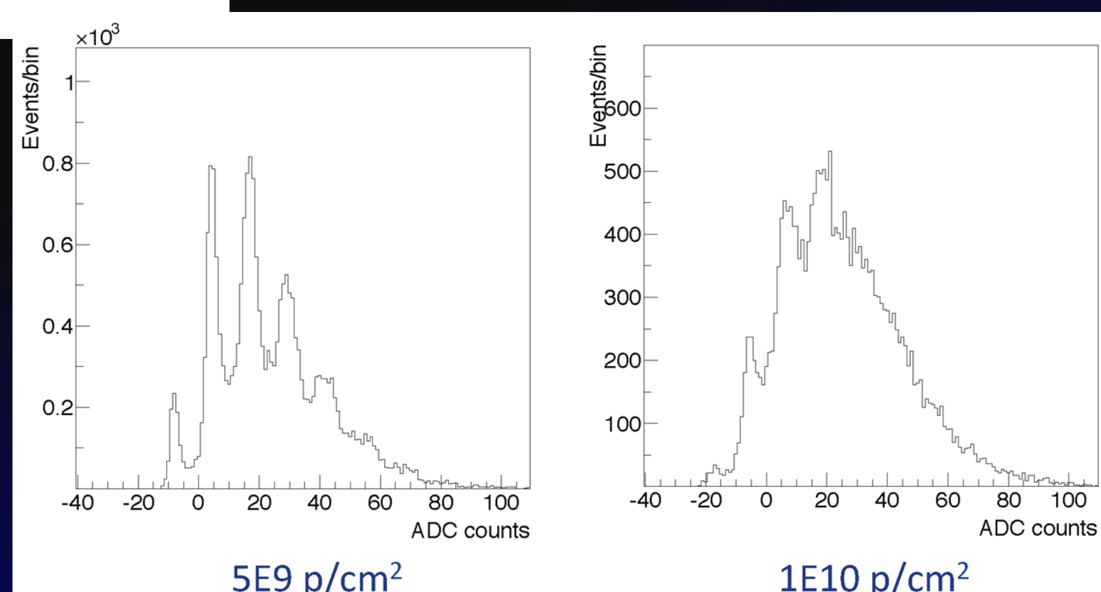


Effect of Non-ionizing Radiation on SiPMs



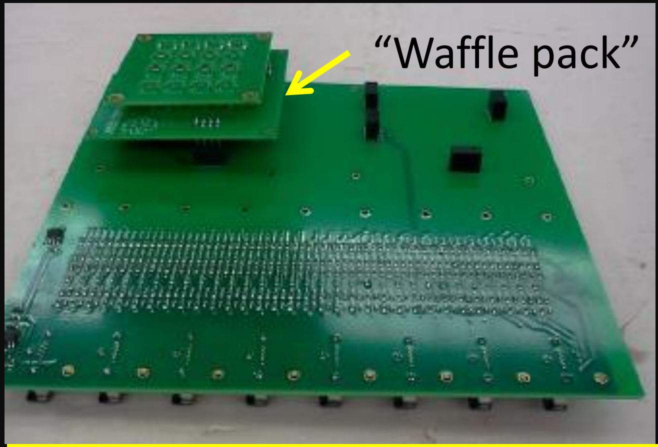
- Mu2e has an intense beam: SiPMs live in a harsh radiation environment
- A requirement is to be able to see the photoelectron peaks
- OK up to 1×10^{10} n/cm^2



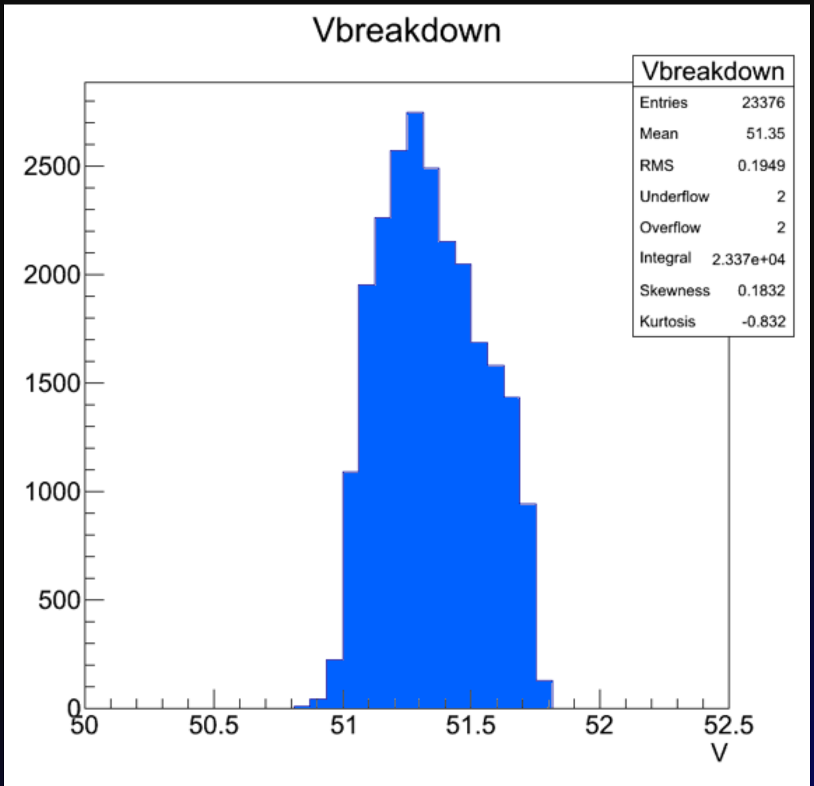


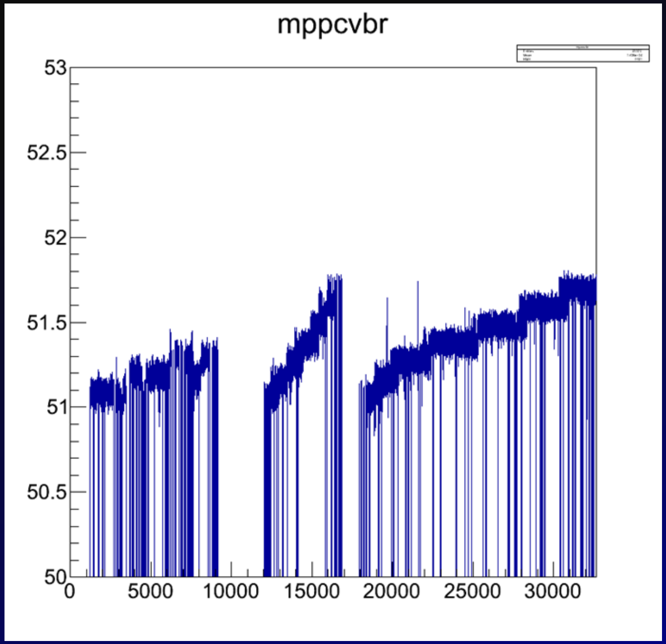
SiPM Testing Performance: Breakdown Voltage

- Specifications require the spread to be < +/- 0.75
- Vbr changes over the course of production
- Not an issue since ‘neighbors’ have similar Vbr’s and are likely to be place in same CMB



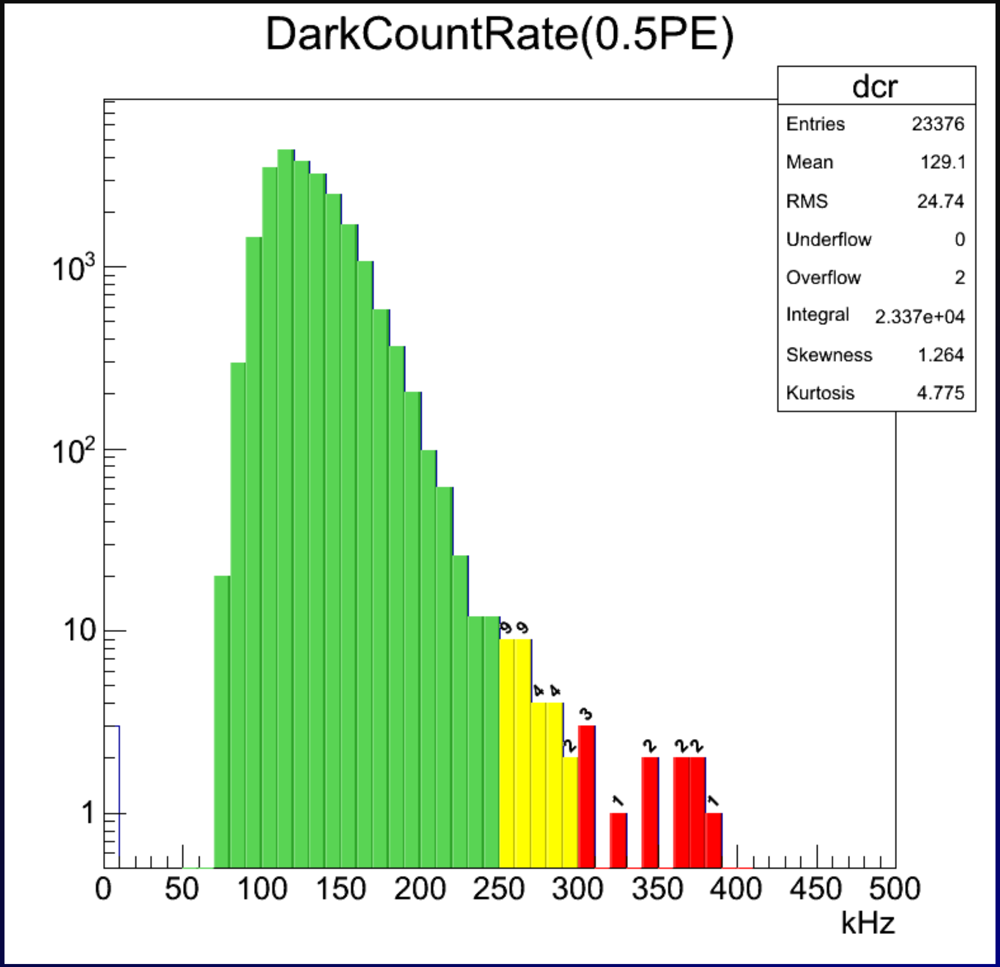
SiPMs test setup at NIU





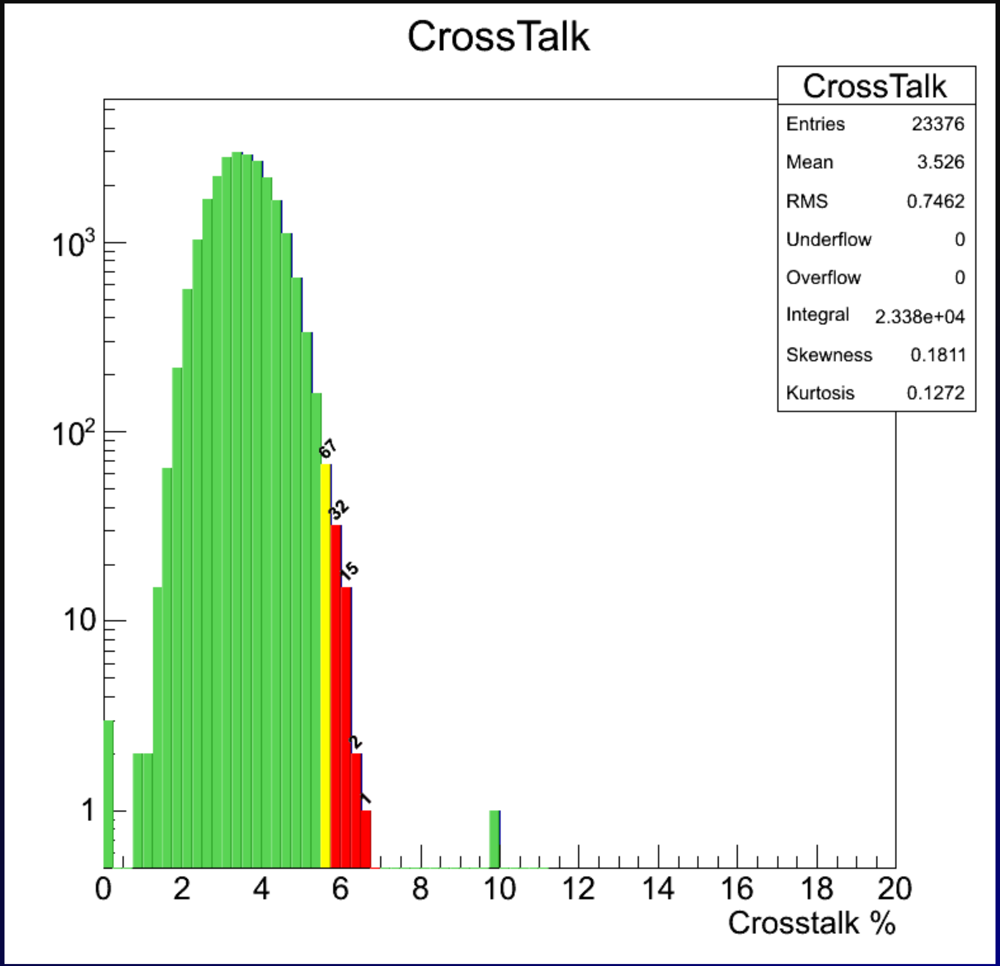
SiPM Testing Performance: Dark Count Rate

- Dark count rate is taken from gain runs outside of the expected LED pulse window
- The threshold is 0.5 P.E.
- Specifications require DCR < 300kHz
- 0.05% are rejected because of high DCR



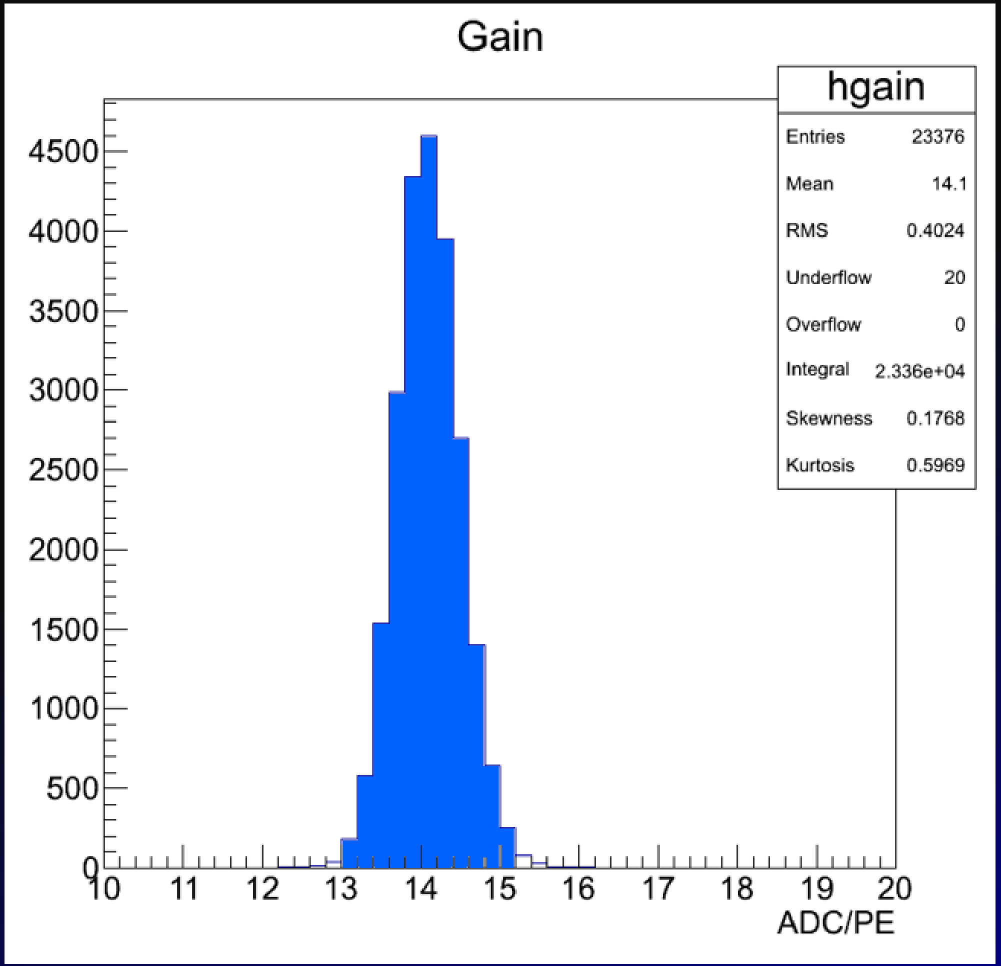
SiPM Testing Performance: Crosstalk

- Crosstalk is calculated from the Dark count rate at the 1.5 P.E. threshold / DCR at 0.5 P.E. threshold
- Our calculated crosstalk is systematically higher by 2.35% than that measured by Hamamatsu
- Because of the systematic bias, we increased the threshold to 5.85%
- 0.22% are rejected because of high xtalk



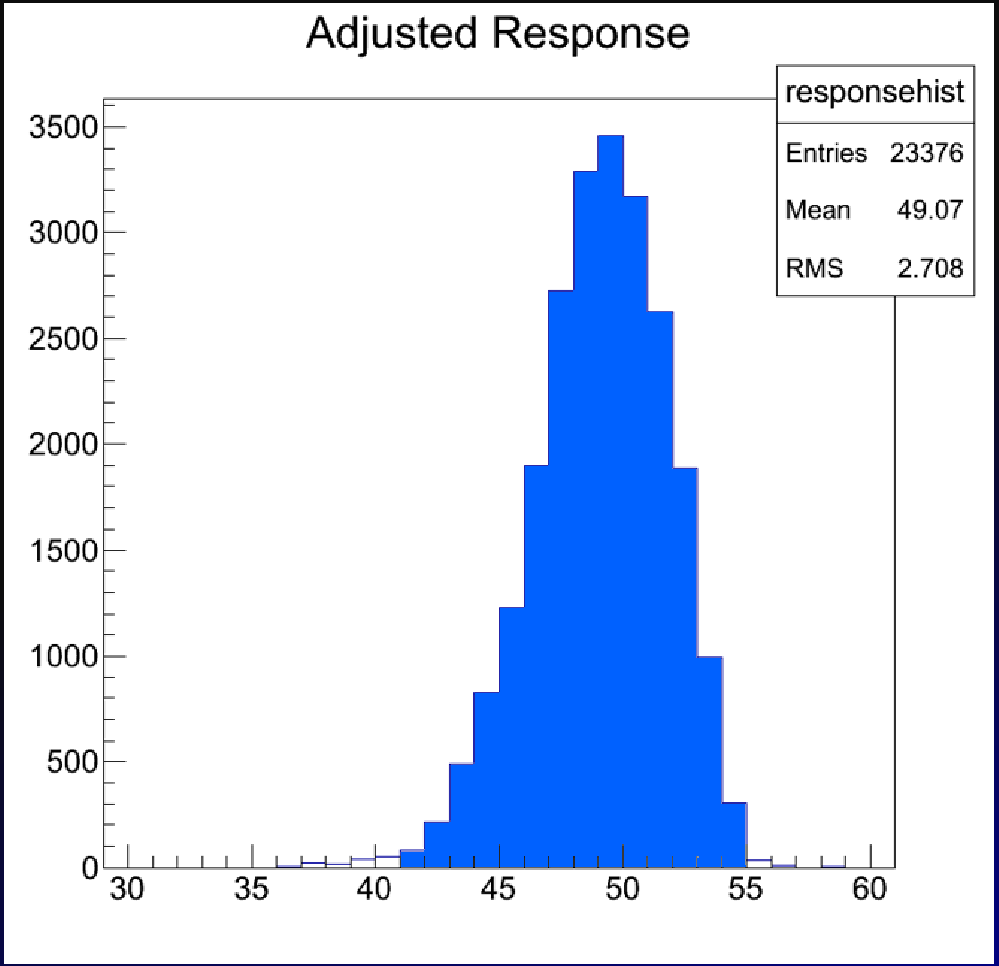
SiPM Testing Performance: Gain

- This is from a fit of the first P.E. peak at Vover=2.5V
- Specifications require >=1.25 x106 which is ~11ADC/PE



SiPM Testing Performance: Response

- The response is the number of PE generated by the SIPM to a fixed high level LED flash
- The output is monitored by a reference panel always mounted in the light tight box next to the panel/waffle pack under test
- No values or limits in the response have been specified before testing had started. I have selected acceptable range to be the Response mean +/- 3.5 RMS
- This gives a low response threshold of 39.5 PE
- 0.15% have been rejected due to low response



SiPM Status

24,576 SiPMs ordered
1536 Waffle Packs of 16 SiPMs each

- 0.01% rejected due to poor fit of Vbreakdown
- 0.05% are rejected because of High Dark Count Rate
- 0.22% are rejected because of High Crosstalk
- None rejected due to low gain
- 0.15% are rejected because of Response
- Total number rejected = 100

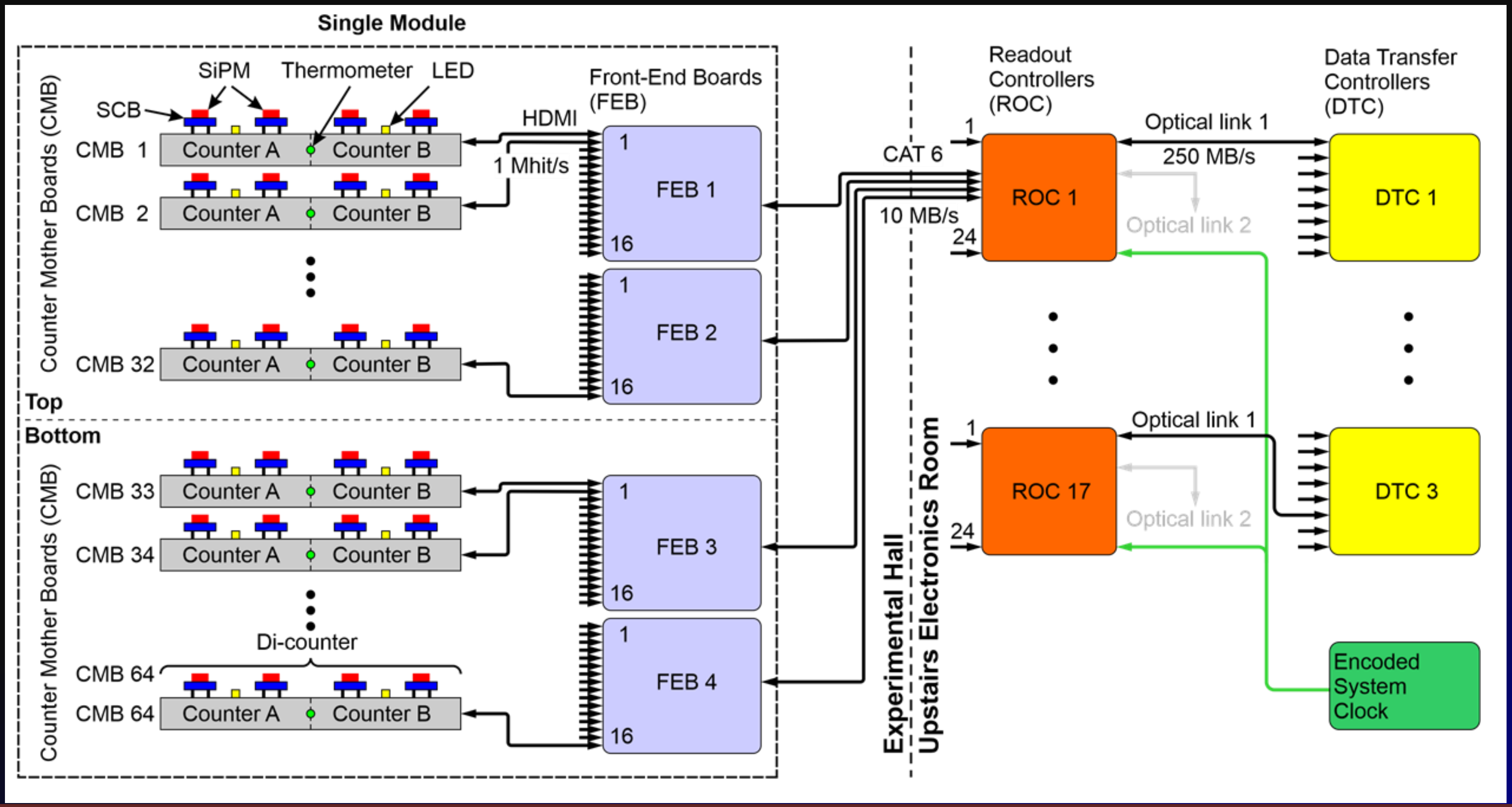
Electronics

Electronics: Block Diagram

- Four components: (1) Mounted SiPMs (SCB w SiPM), (2) Counter Motherboards (CMB), (3) Front-end Boards (FEB), (4) Readout Controllers (ROC)
- All commercial-off-the-shelf parts (80 MHz ultrasound octal amp/ADC)
- FEB digitizes SiPM signals and time and amplitude

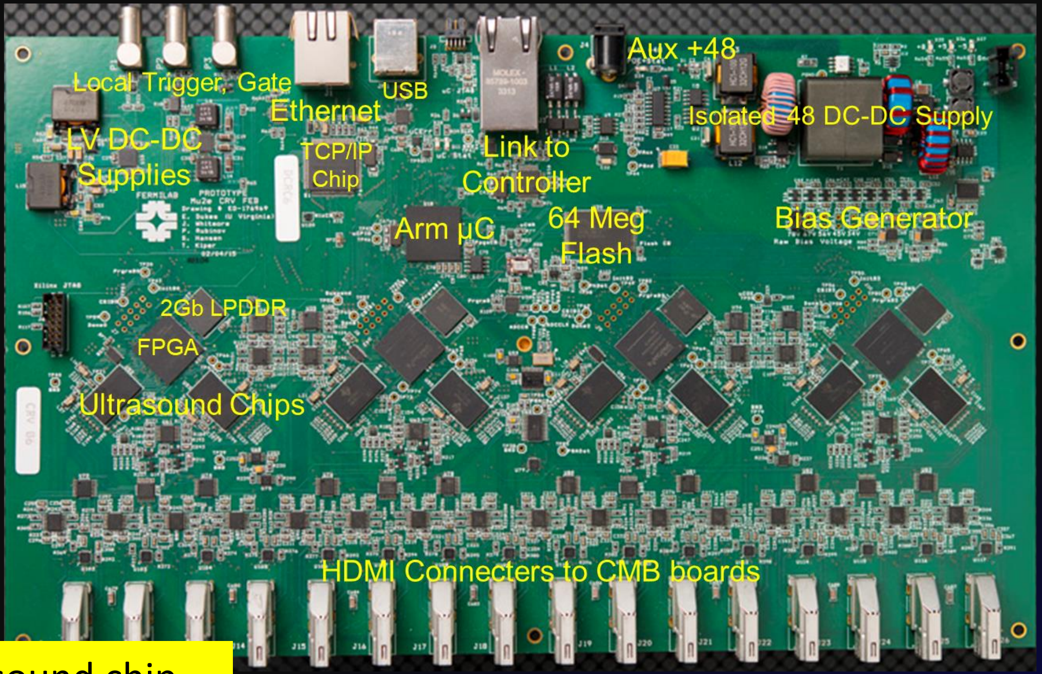
Dynamic range:	2000
Max rate/SiPM:	1 MHz
Max rate FEB-ROC:	10 MB/s
Max rate ROC-DTC:	250 MB/s
Time resolution:	~ 2 ns
Magnetic field:	~ 0.1 T
Max dose:	10^{10} n/cm^2

Designed at FNAL

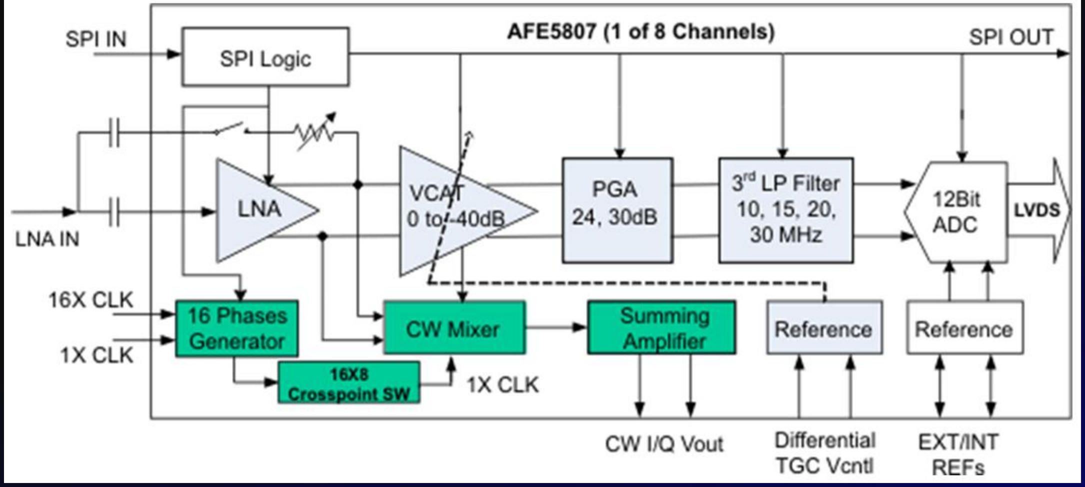


Front End Board: Amplifier, Digitizer, Shaper

- Serves 64 SiPMs
- Takes SiPM signals from 16 CMBs over HDMI cables
- Biases SiPMs
- Amplifies, shapes, digitizes in amplitude and time, zero-suppresses, and buffers signals
- Power provided by Ethernet



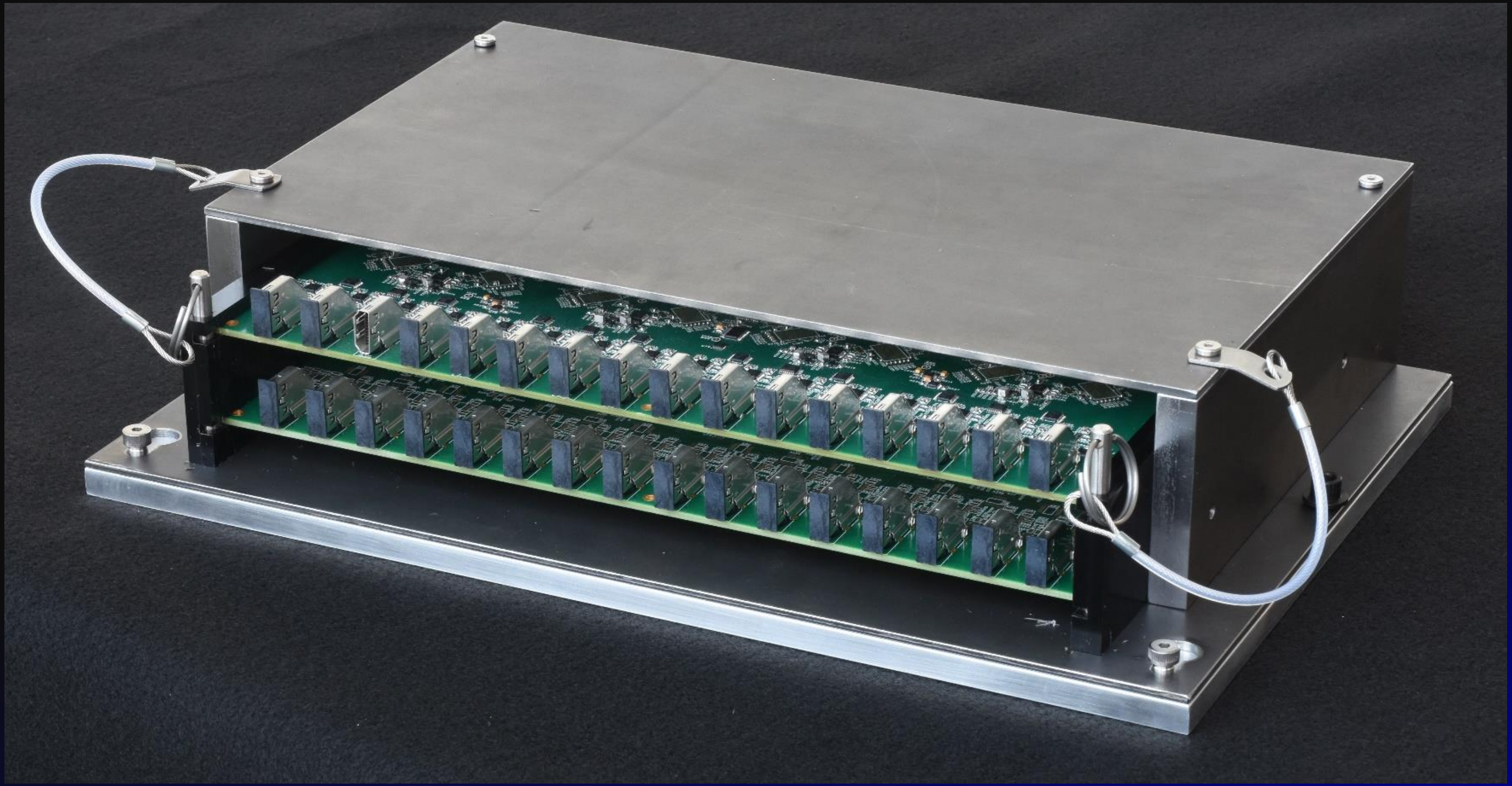
The core of the readout is a commercial ultrasound chip



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.

Magnetic Shield

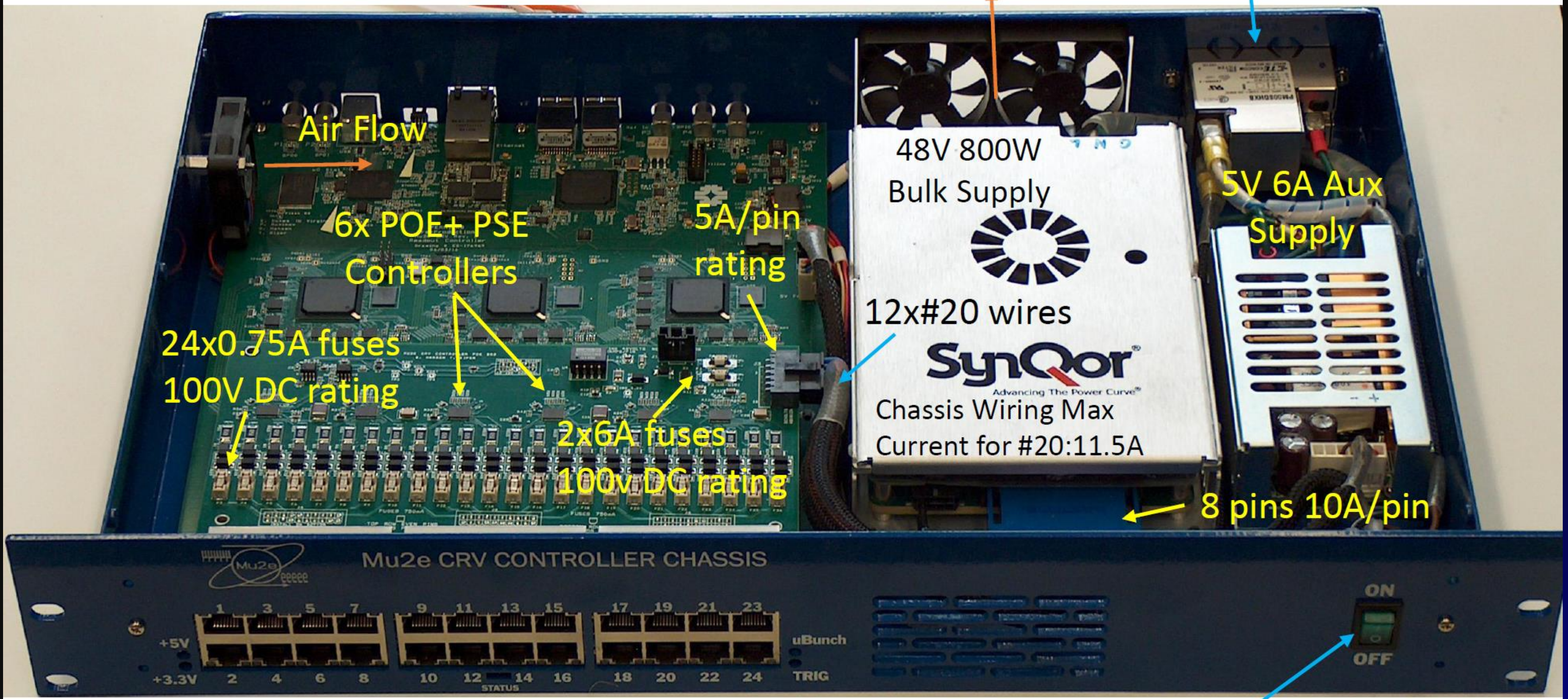
- FEB boards will experience large solenoid fringe field (400G max)
- FEBs mounting vertically with internal Rails to allow board removal without shield disassembly
- No cooling fans



Readout Controller

Controller Power Distribution details:

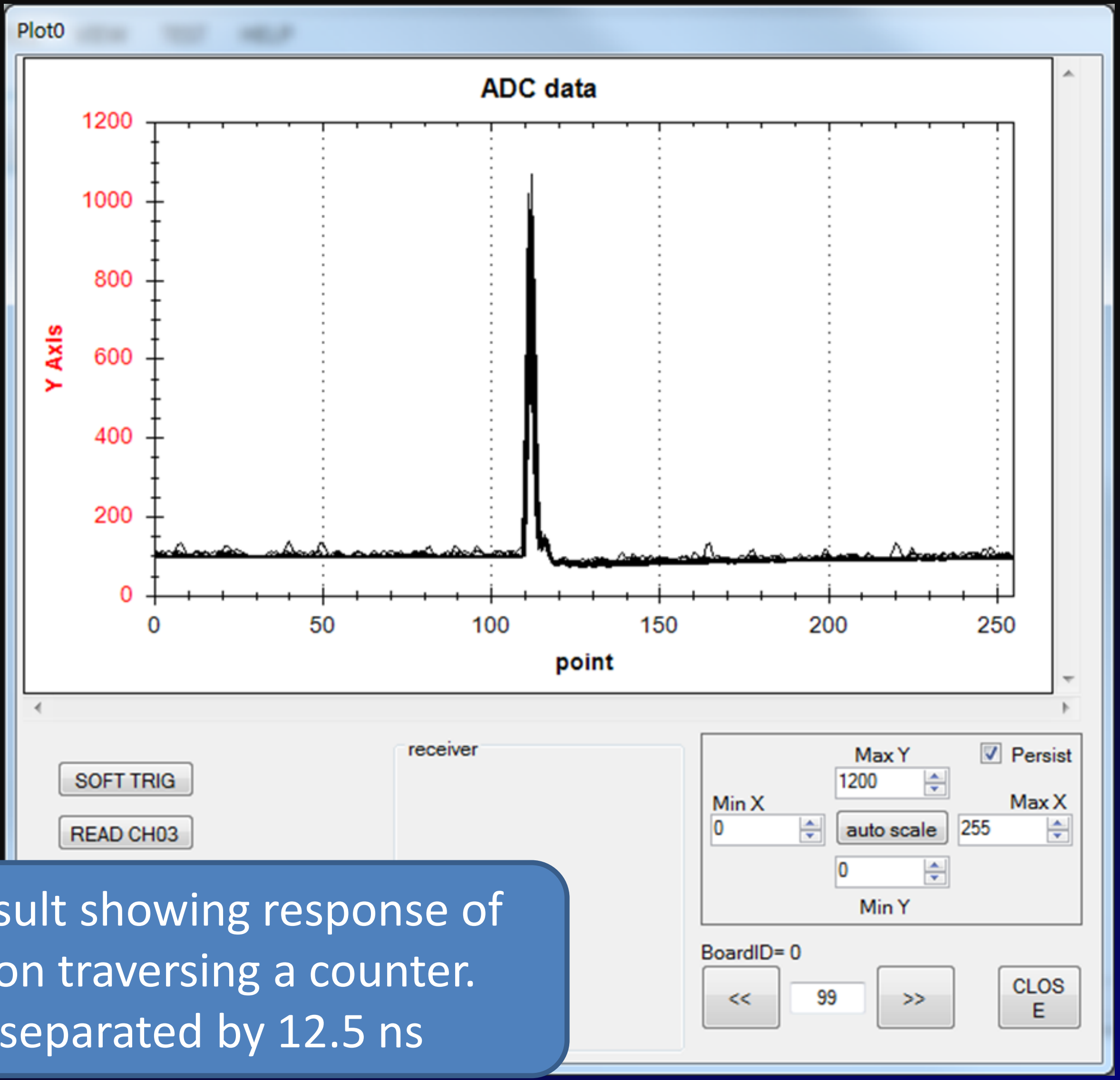
Controller Photo:



Harmonica Jacks POE+ 720mA/port

Power Switch
10A 208V

Electronics Performance: What MIP Looks Like

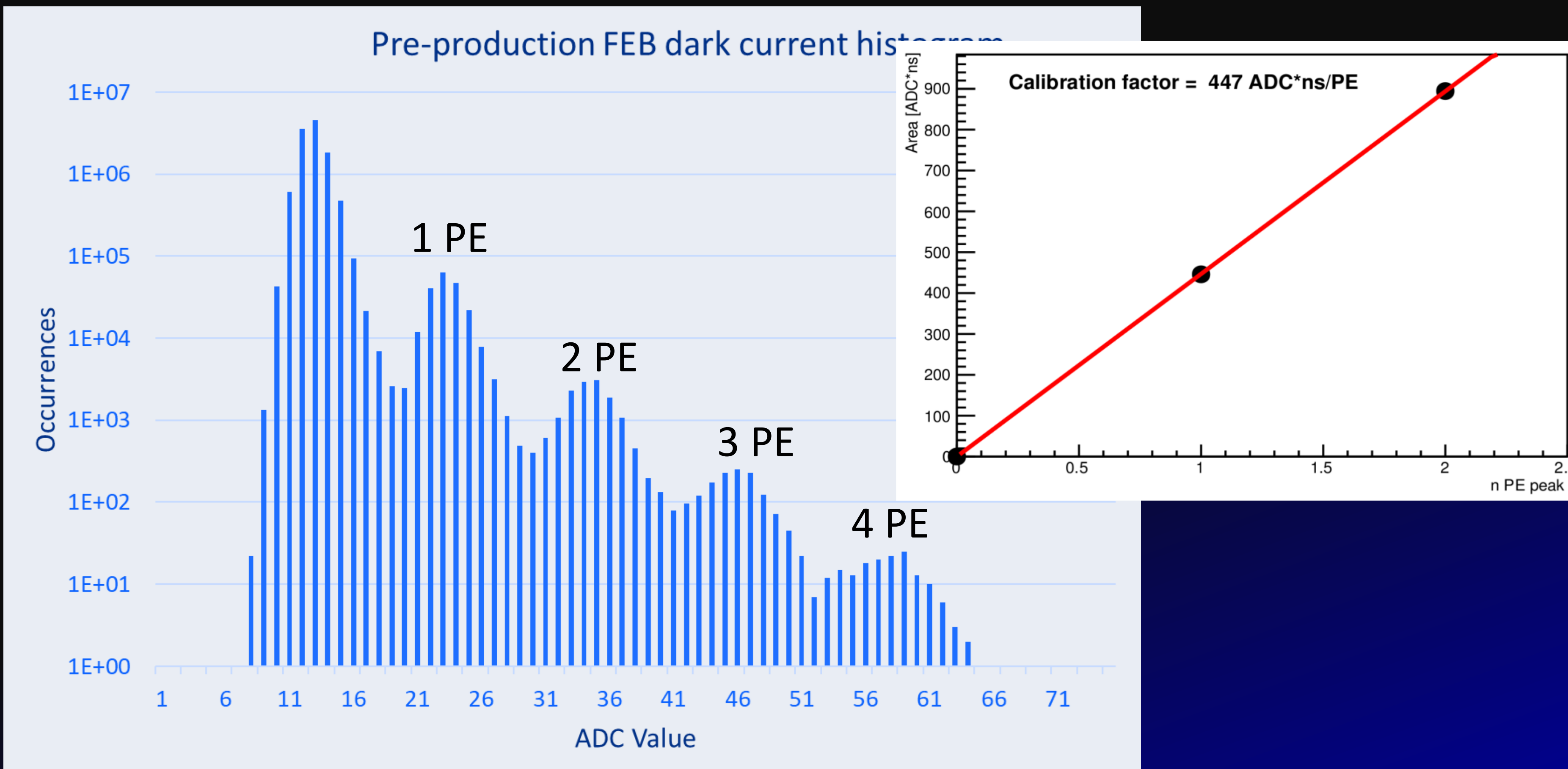


Test beam result showing response of FEB to a proton traversing a counter. Each point is separated by 12.5 ns

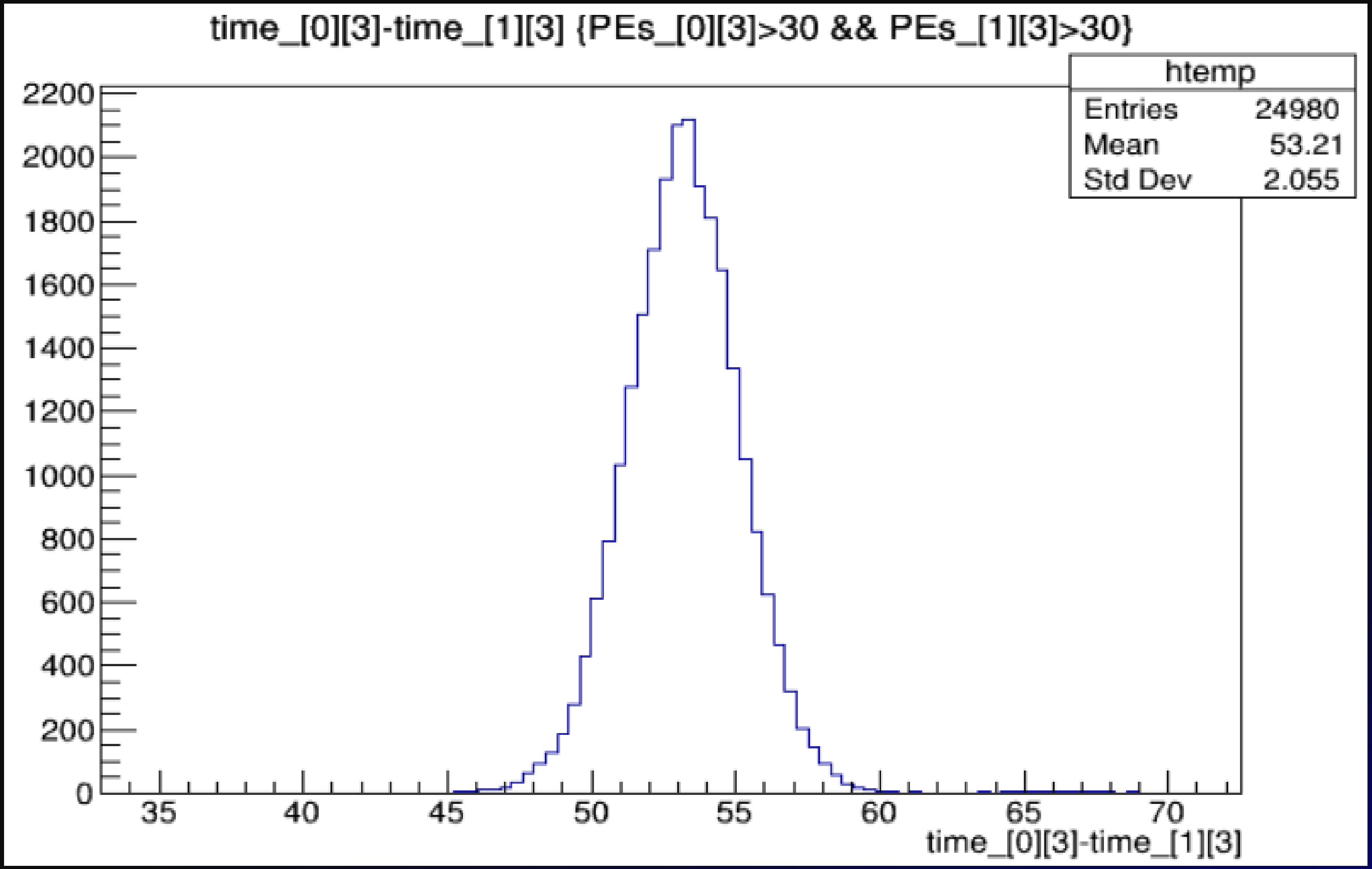
Electronics Performance: PE Spectrum

- One of our requirements is that we see the PE spectrum in order to calibrate the PE yield
- Front-end Board FPGA allows this to be done in seconds

Pedestal

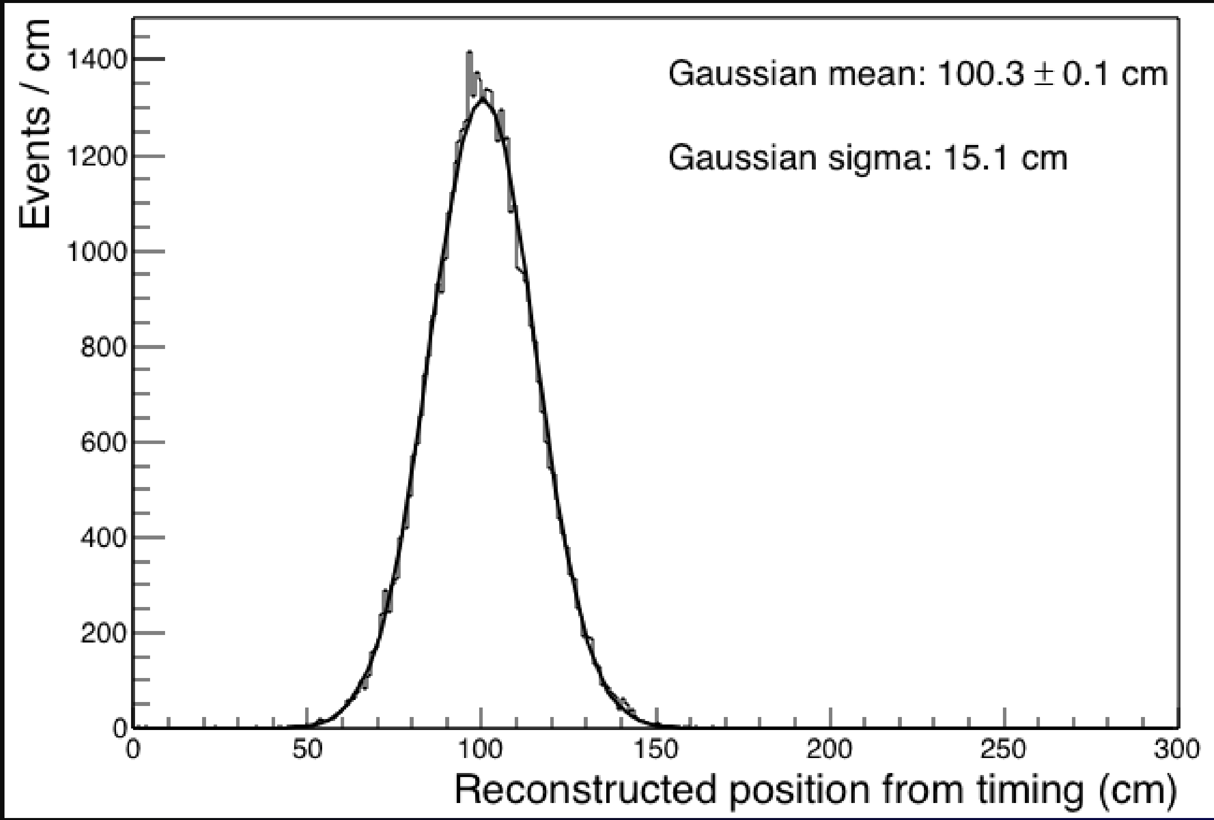


Electronics Performance: Timing



Plot of arrival time difference (ns) between opposites counter ends
Test Beam data 06/17. 120 GeV protons 2cm beam diameter

Electronics Performance: Timing



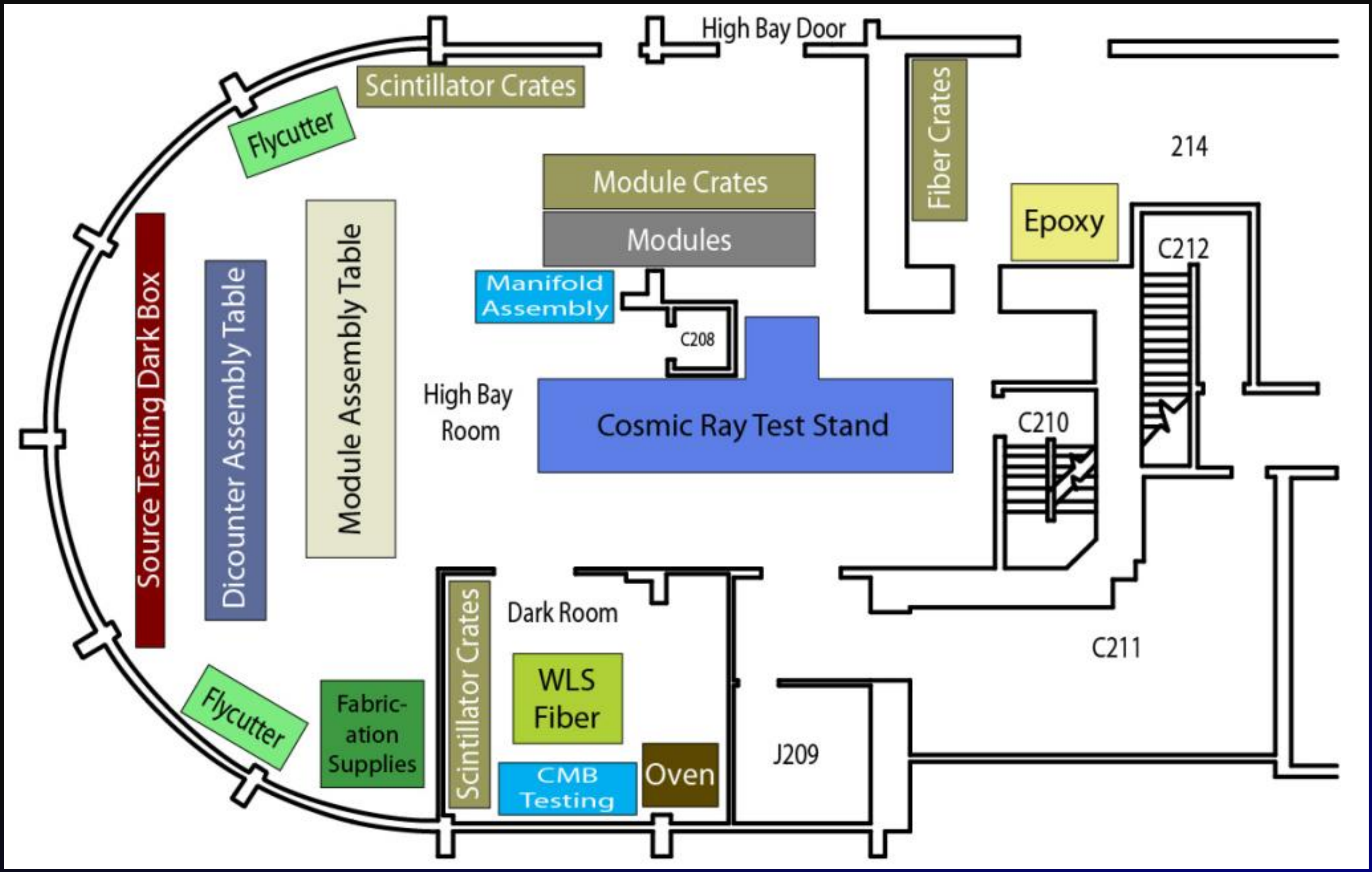
- Arrival time difference between opposites counter ends allows us to determine the longitudinal position along a counter
- Get ~20 cm resolution from timing

Module Fabrication

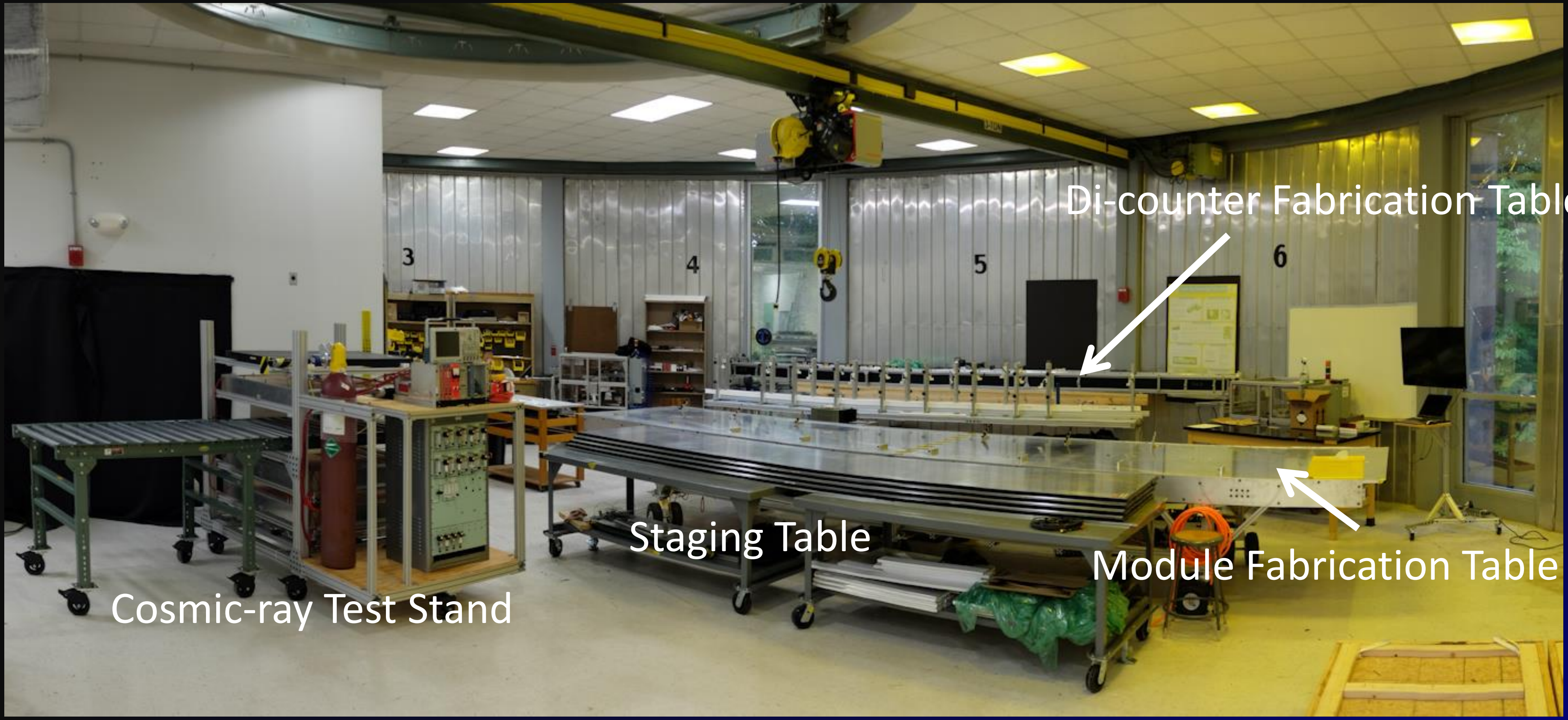
Module Fabrication at University of Virginia

- Module factory has been set up in UVA High Energy Physics Laboratory
- 62/83 modules have been fabricated: all shipped to Fermilab
- Di-counters assembled, fibers inserted, then flycut. QC tests performed.
- Modules assembled from di-counters and aluminum sheets using expoxy. Manifolds/SiPMs installed and module QC tests performed.
- Manufacturing tolerances very demanding and critical.
- Production started in February 2019 with 5 pilot modules; can produce modules at a rate of one per week with a crew of 2 technicians and 3 part time students/postdocs.

Module Factory at Virginia



Module & Di-Counter Assembly Factory



Module & Di-Counter Assembly Factory

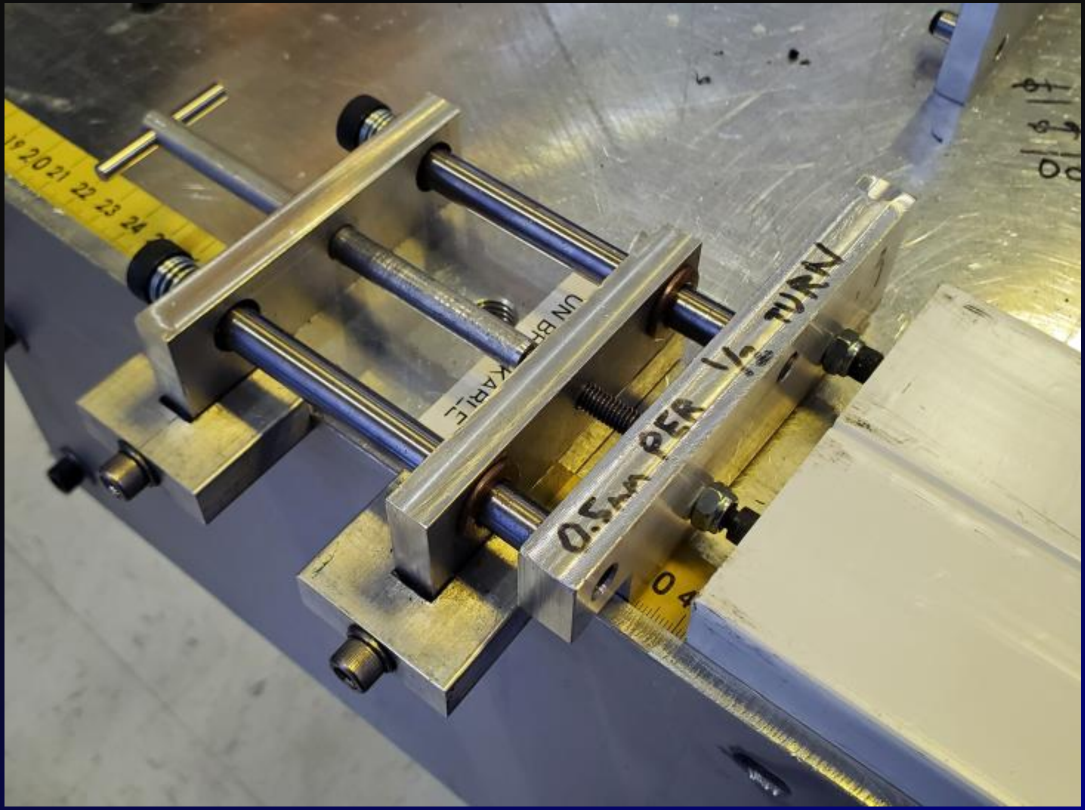
Loading Dock Cosmic-ray Test Stand

Di-counter Dark Test Box Di-counter Fabrication Stand Module Fabrication Table

Di-Counter Fabrication: Cutting Extrusions

A custom-made chop saw fixture used for cutting scintillator extrusions to the proper length.

An adjustable stop is used to fine tune the length of the counters, with separate adjustments for squareness, so all extrusions lengths are within ±0:5 mm

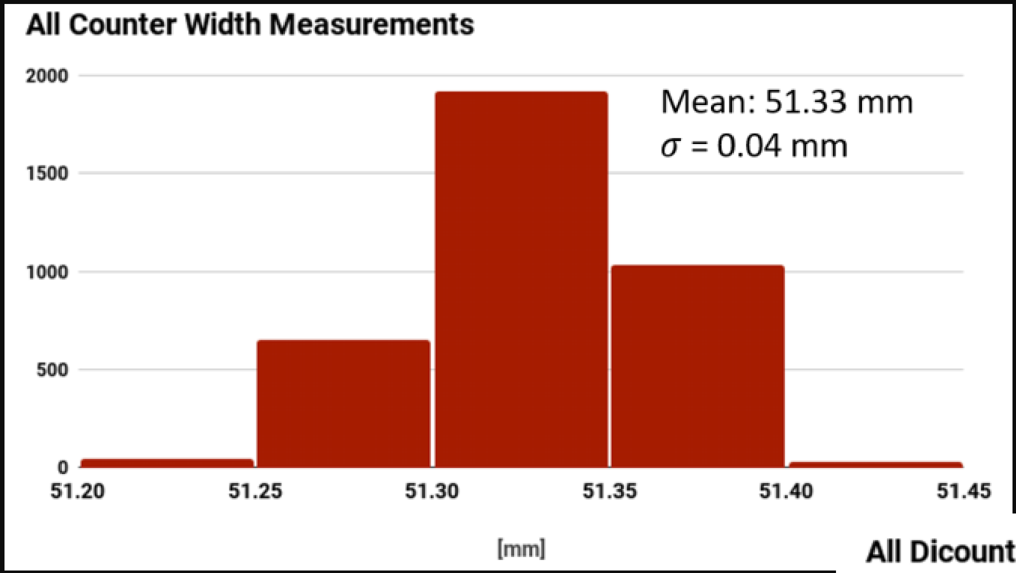


Di-Counter Fabrication: Vertical Assembly Jig

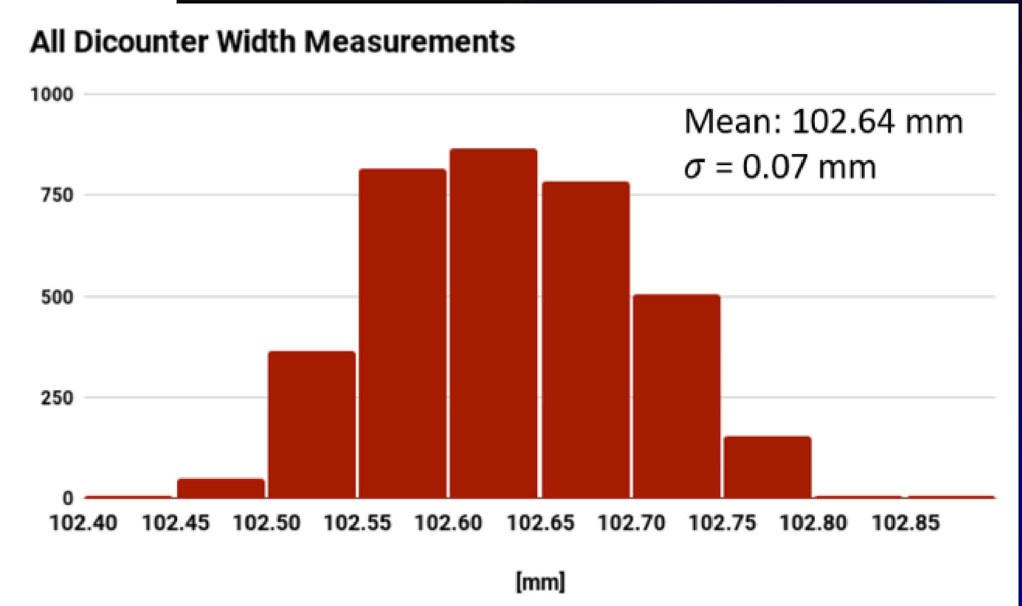
- Two extrusions glued together to form a di-counter in vertical assembly table
- The edges to be epoxied are scored with Scotch-Brite
- The fixture applies spring pressure to the stack of scintillator to ensure an adequate bond is made between extrusions.
- Four pairs of di-counters can be fabricated simultaneously

Di-Counter Fabrication: Di-Counter Widths

- Extrusion and di-counter widths are measured at the module factory



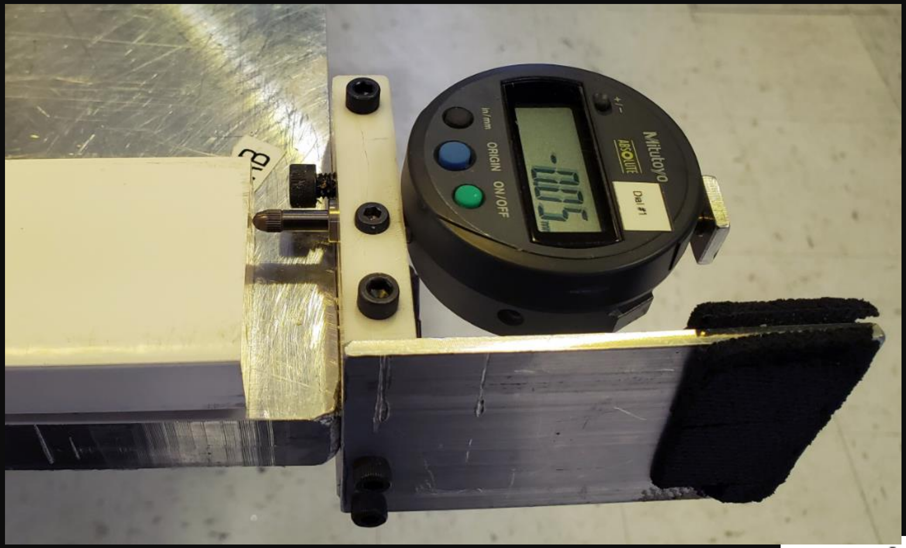
1530 counter (single extrusion) widths; the designed counter width is 51.3 mm



1250 dicounter widths; nominal dicounter widths are expected to be 102.6 mm

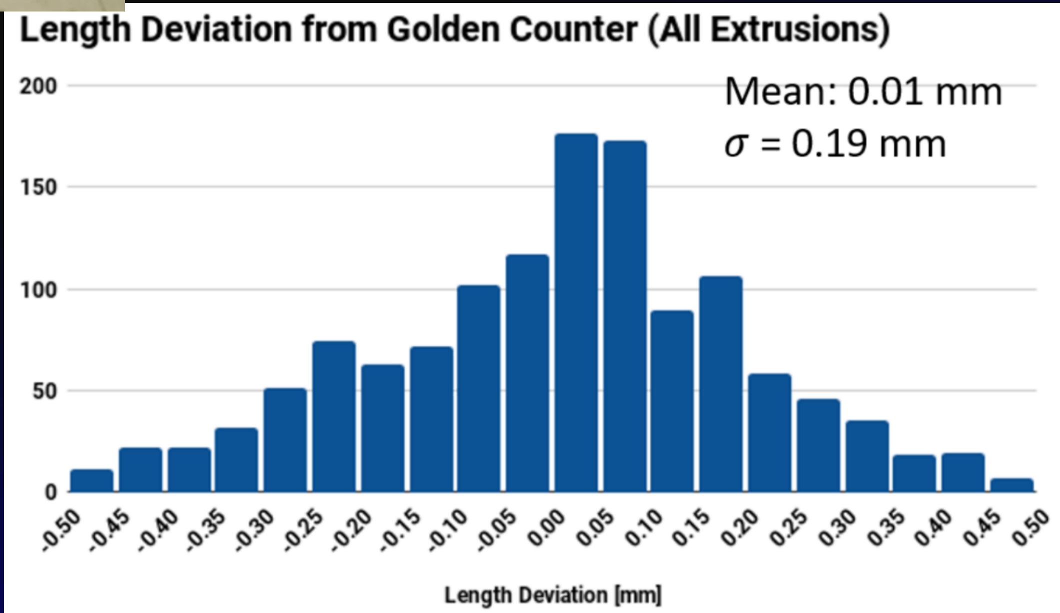
Di-Counter Fabrication: Di-Counter Lengths

- Di-counter lengths are measured at the module factory



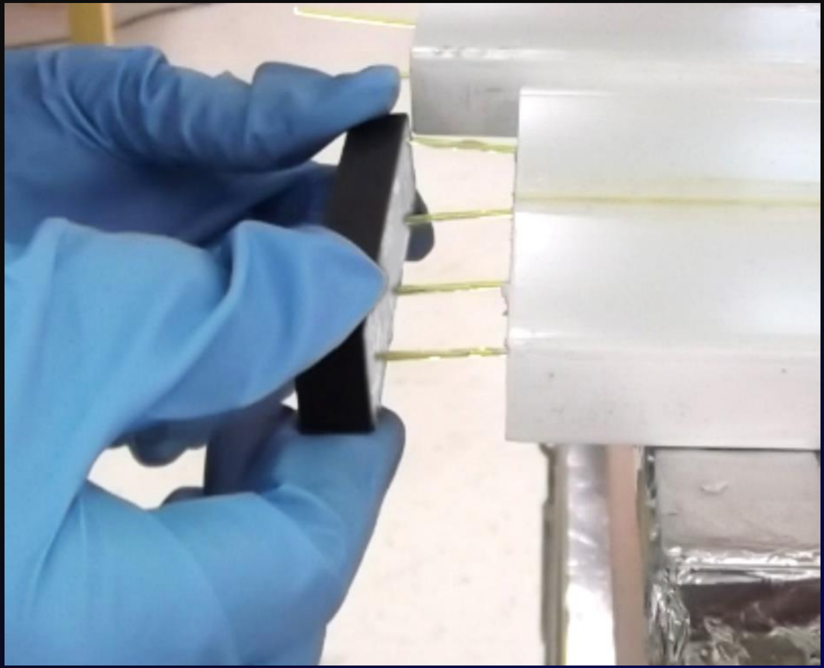
Placing the extrusions against a stop, a dial indicator measures the length relative to the target length.

The counter lengths are measured relative to a reference (golden) counter of the target length. No counter outside of ±0.5 mm is accepted. Outliers are cut shorter or recycled into shorter counters.



Di-Counter Fabrication: Fiber Threading

- While the di-counters are bonding on the vertical assembly jig, four WLS fibers inserted into di-counter channels, exending out 50-100 mm
- A Fiber Guide Bar is bonded to each end using fast-curing 3M DP100 epoxy and held in place with #4-20 3/8” Plastite screws (which have no measurable effect on the light yield)
- The WLS fibers are glued into the Fiber Guide Bars with DP100 epoxy
- After the epoxy has cured excess fiber is cut off using a hot knife

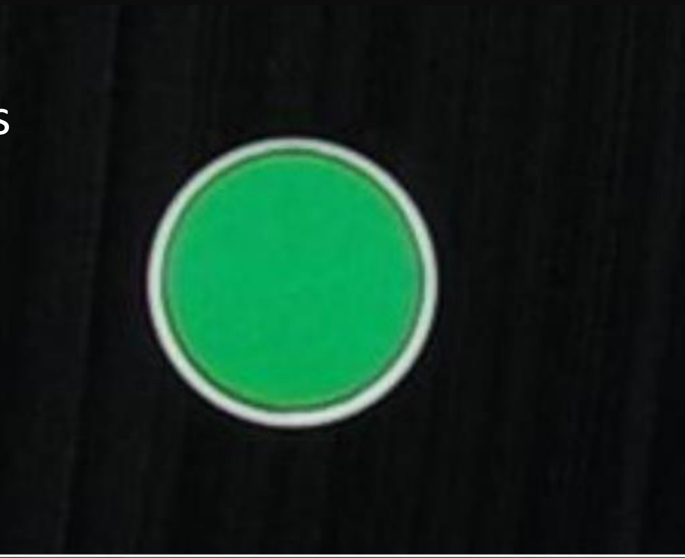


Di-Counter Fabrication: Fiber Polishing

- Two repurposed NOvA flycutters are used to polish the fibers after they have been potted in the Fiber Guide Bars
- Diamond-tipped flycutters employ at SICK IVC-3D smart camera and several motion tables to adjust the cut properly
- Two rough cuts of 0.5 each are followed by a polish 0.1 mm deep @ 3500 RPM.

Di-Counter Fabrication: Quality Control

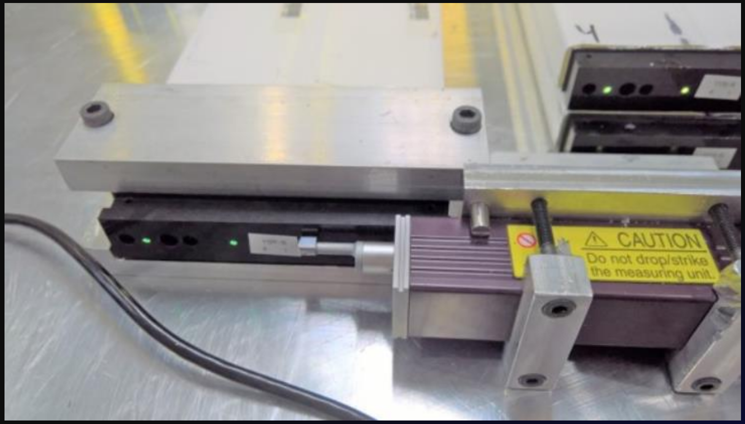
- A Pentax K-1 36.2 MP DSLR with a 110 mm f/28 macro lens performs visual inspections of the fibers
- A Python program automatically crops, displays for the operation, and saves the image of each of the four fiber faces
- Abnormal fibers are re-flycut. If this does not produce desired results the di-counter is discarded

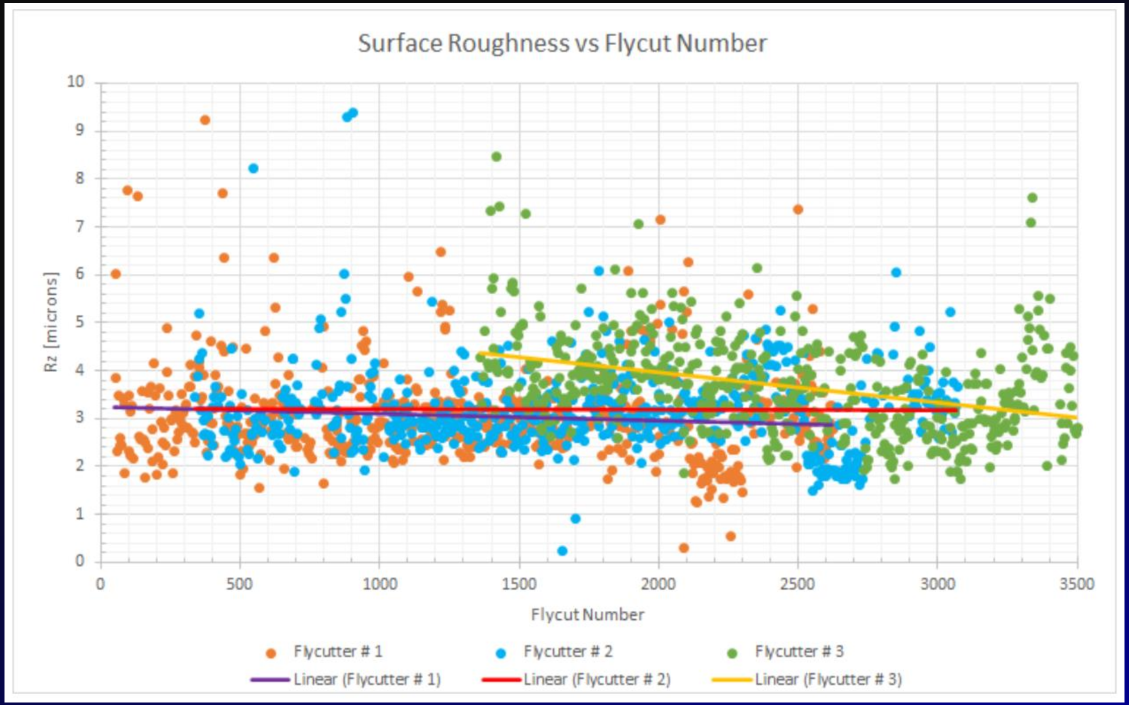


A good (top) and damage (bot) fiber

Di-Counter Quality Control: Roughness

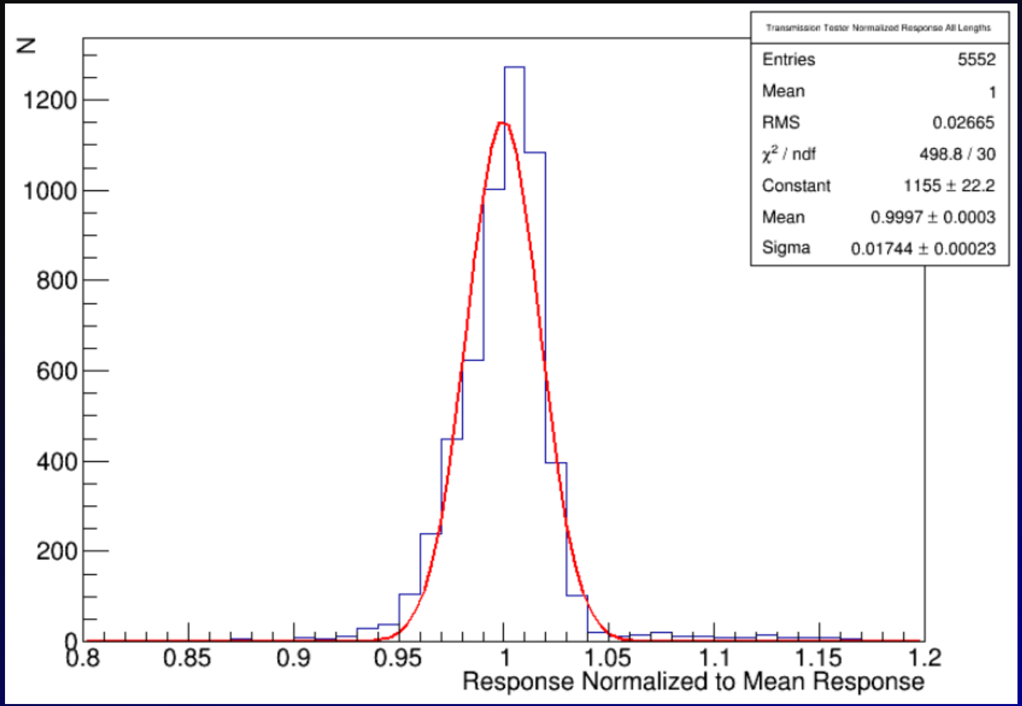
- A Mitutoyo Surftest SJ-210 series surface roughness tester is used to provide a quantifiable measurement as to the quality of the flycut.
- Surface roughness, Rz, is defined as the average vertical distance between the highest peak and lowest troughs over several sampling lengths. The sampling length used is 0:1 mm and three samples are obtained. The surface roughness of the FGBs for a sample of 1250 dicounters was found to be 3:23 ± 1:01 µm. There is no appreciable degradation in flycut quality over time (Fig. 5.22)





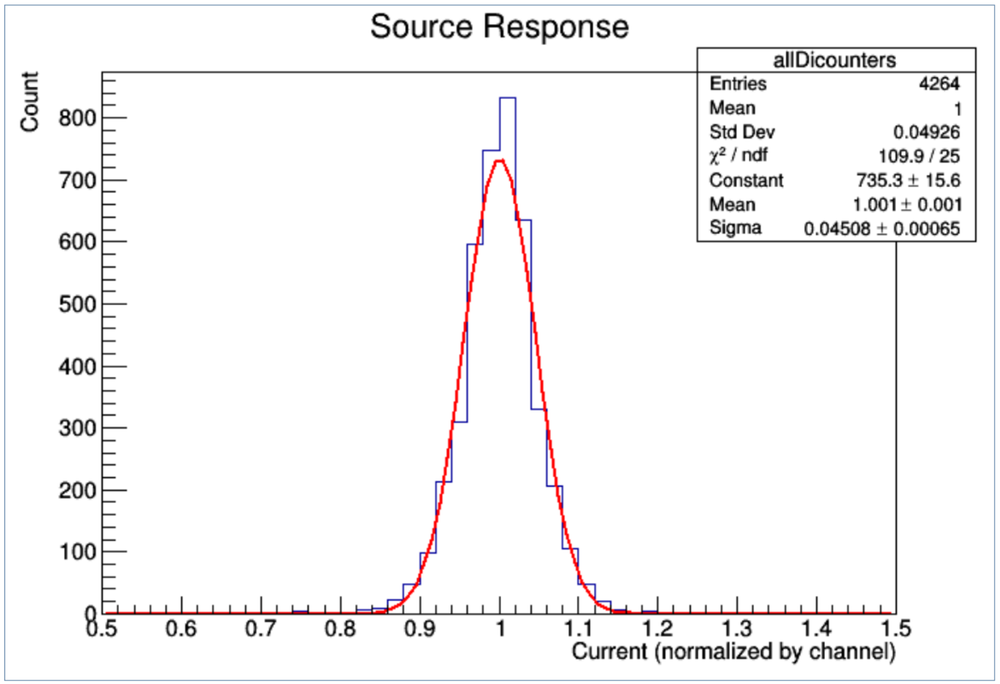
Di-Counter Quality Control: Light Transmission

- The fibers are then evaluated for light transmission; a test designed to determine the presence of damage to the fiber that was not visible using the camera.
- A custom device that has two testing heads that attach to opposite ends of the dicounter, uses an LED and a PIN-diode to measure light transmission through each fiber.
- A comparison for each fiber is made to the mean response of all tested fibers: those with a transmission of less than 90 % are flagged as defective.



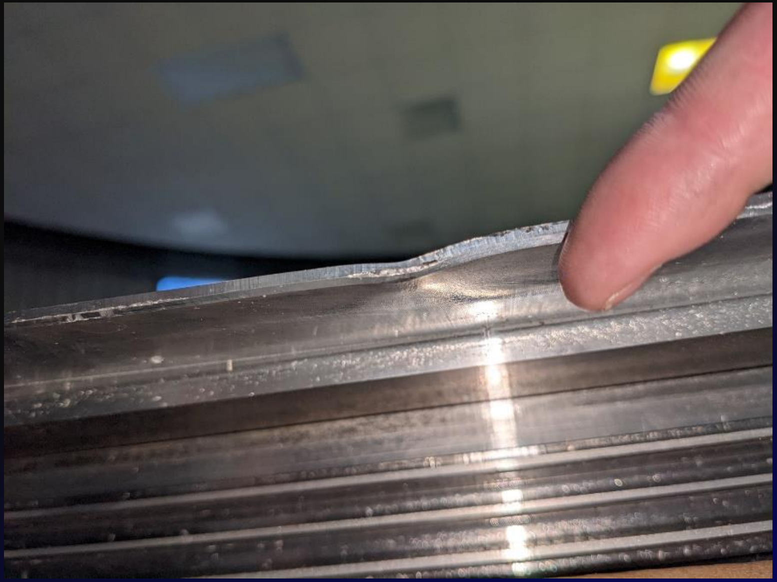
Di-Counter Quality Control: Source Test

- The light yield of each counter is measured using a radioactive source.
- The dicounter is placed into a 7 m long dark box . Measurements are made 1 m from each readout end (separately) with a 1.0 mCi Cs-137 source.
- The same manifolds/SiPMs are used for each dicounter. The current is measured for each of the eight SiPMs, with and without the source. It is compared to a 2.3 m reference dicounter, measured at the same time in the same manner.
- Counters with less than 80% of yield are not used



Aluminum: Quality Control

- Although the aluminum vendor, Pierce Aluminum, makes a series of dimensional measurements we specified, the aluminum sheets, upon arrival, are checked by Module Factory personnel for conformity to specifications through a number of measurements.
- Features, such as the terraced edges, are checked for proper dimensions using calipers and thickness using a Dakota PVX ultrasonic thickness gauge.
- Modules must be very flat (~2-3 mm) in order to fit together: rolled Al (much less expensive than cast Al) has very large tolerances on flatness. However, we have found that warped Al gets flattened out during module fabrication

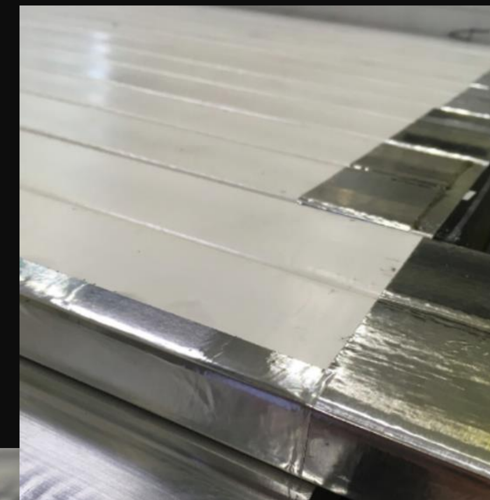


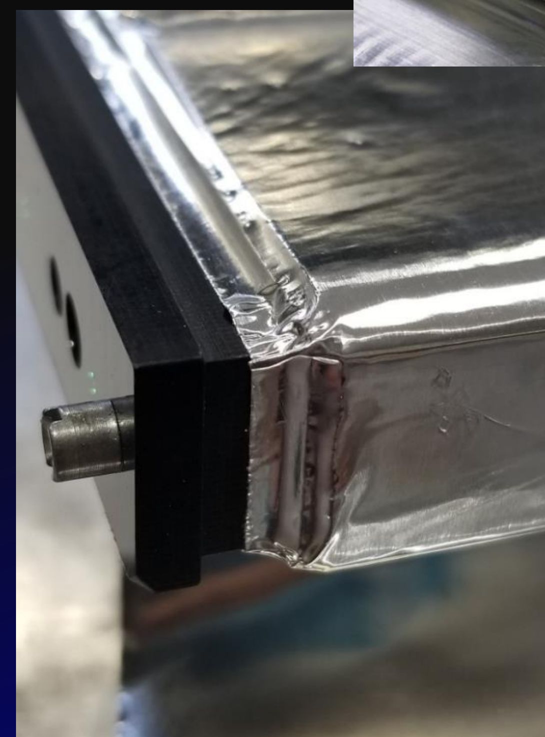
Module Fabrication: Assembly Table

- Great pains were taken to make the module assembly table as flat as possible (1.5 mm)
- Cleats are used to get the proper layer offset
- A dry stack is done first
- Shims are used to space di-counters equally
- Di-counters are scored with Scotch-Brite
- Di-counters & Al cleaned with isopropanol

Module Fabrication: Preparation of Di-counters

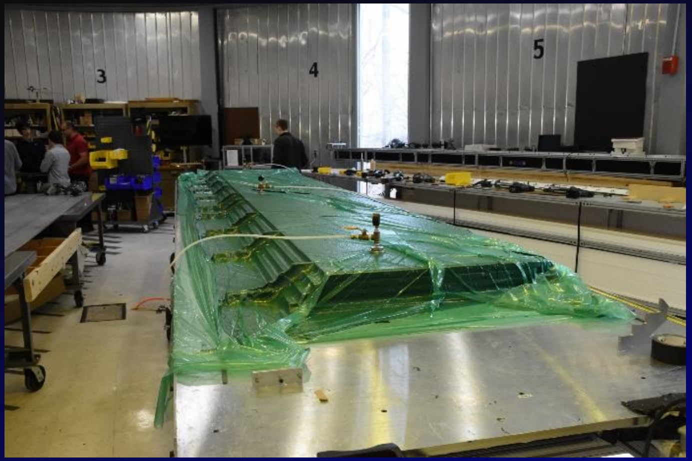
Dicounters are prepared for module assembly by the application of aluminum tape around the FGB-scintillator interface, as well as the sides of the outermost dicounters in each layer, to prevent light leaks





Module Fabrication

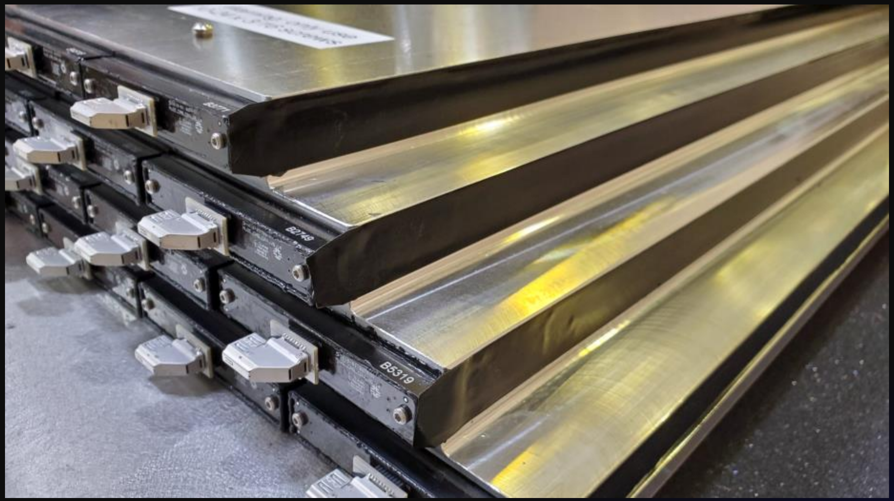
- Aluminum strongback laid down on module fabrication table
- Devcon HP-250 adhesive applied to strongback using electrical dispensing guns
- A bead of black Geocel-3300 RTV is applied to dicounter edges that are on the outer perimeter of the module, and between di-counters at each end, to eliminate light leaks
- Di-counters placed on strongback, constrained to proper position by cleats
- Adhesive applied to di-counters
- Aluminum absorber placed on di-counters
- Process repeated until cover placed: 2 hr total time
- Module vacuum bagged for 24 hours
- Module placed in cosmic-ray test stand to measure its response

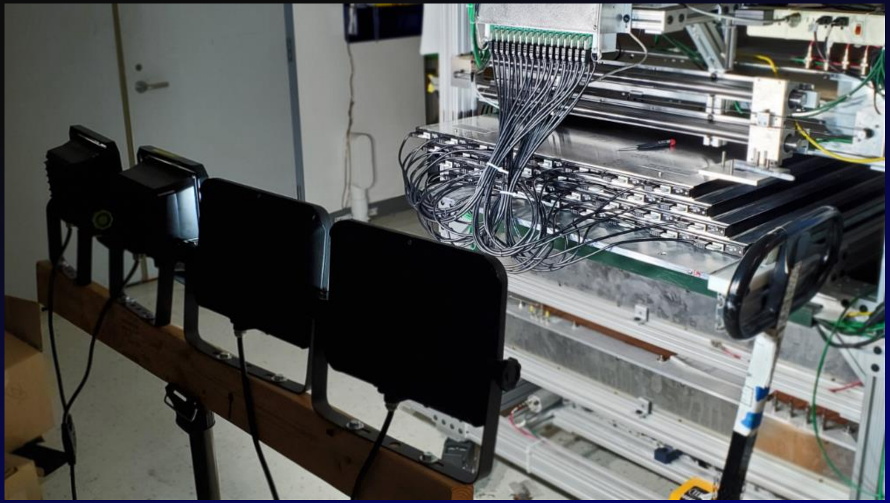


Module Fabrication: All are Recorded

Module Fabrication

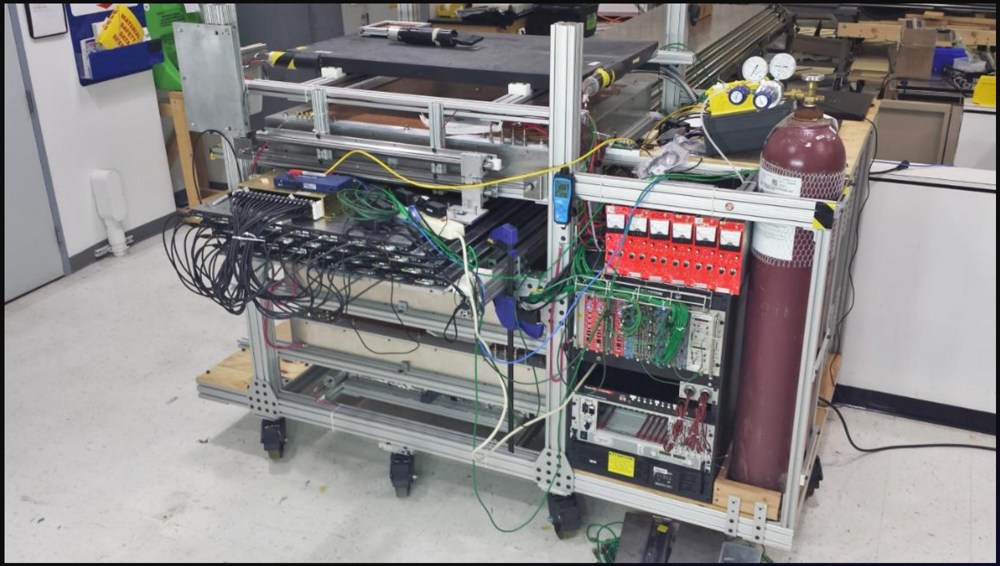
- After the epoxy is cured, the module is measured for flatness and epoxy and the RTV press-out is removed.
- Low-friction fiberglass Teflon PTFE coated tape is applied to the long edges for protection.
- The modules are outfitted with manifolds and undergo light-leak testing using flood lights. Light leaks are found by measuring the current of the SiPMs in the absence of ambient light (dark current) and with flood lights. An increase of 10 % or more is classified as a leak. Areas that allow light into the module are sealed with RTV.
- Once the module is light-tight, it undergoes extensive testing in the Cosmic Ray Test Stand.

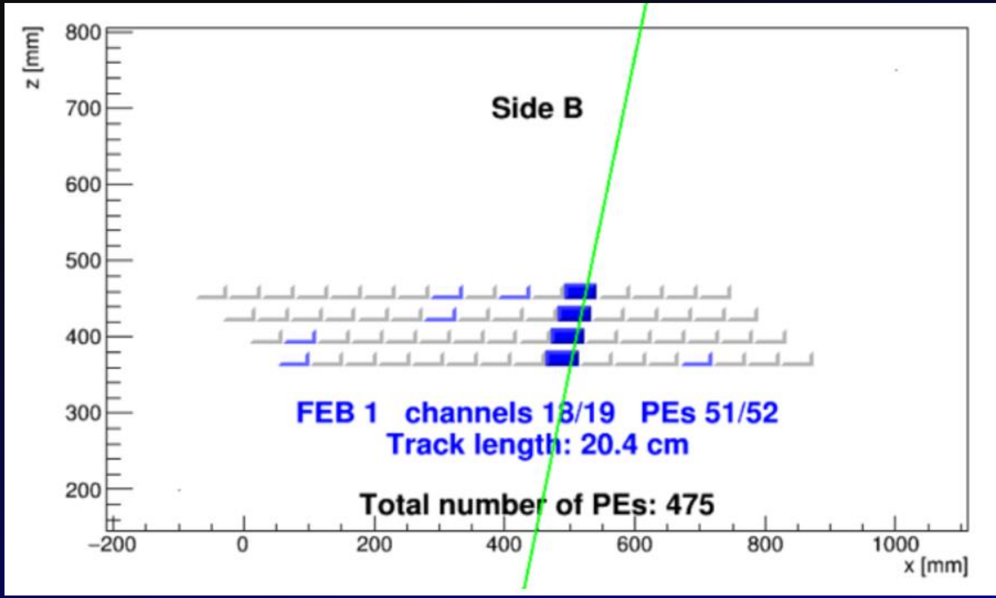




Module QC: Cosmic Ray Test Stand

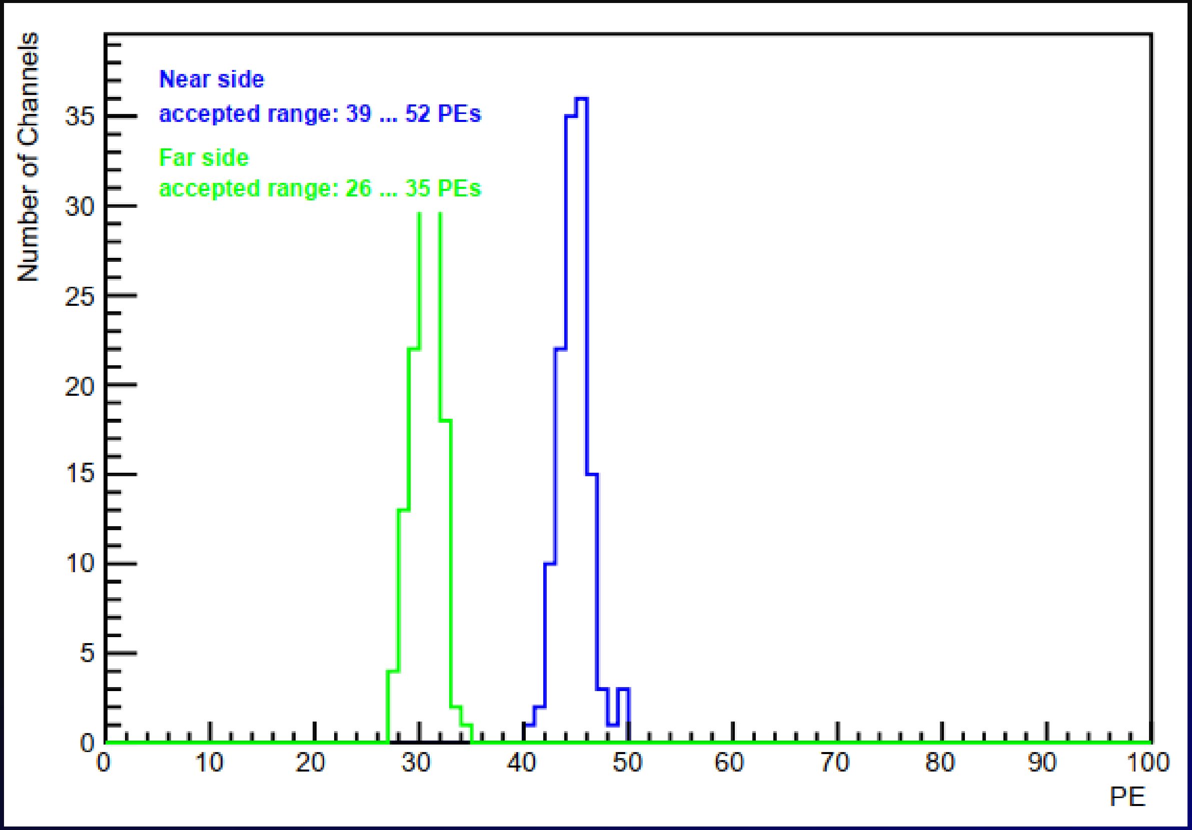
- Modules are evaluated for light yield and per-layer detection efficiency in the Cosmic Ray Test Stand: a scintillator-triggered test stand that uses cathode strip chambers to provide tracking information for use in module quality control.
- Mobile stand with rollers that allow the modules to be wheeled in and out
- Electronics for the CSCs performed poorly and is no longer used





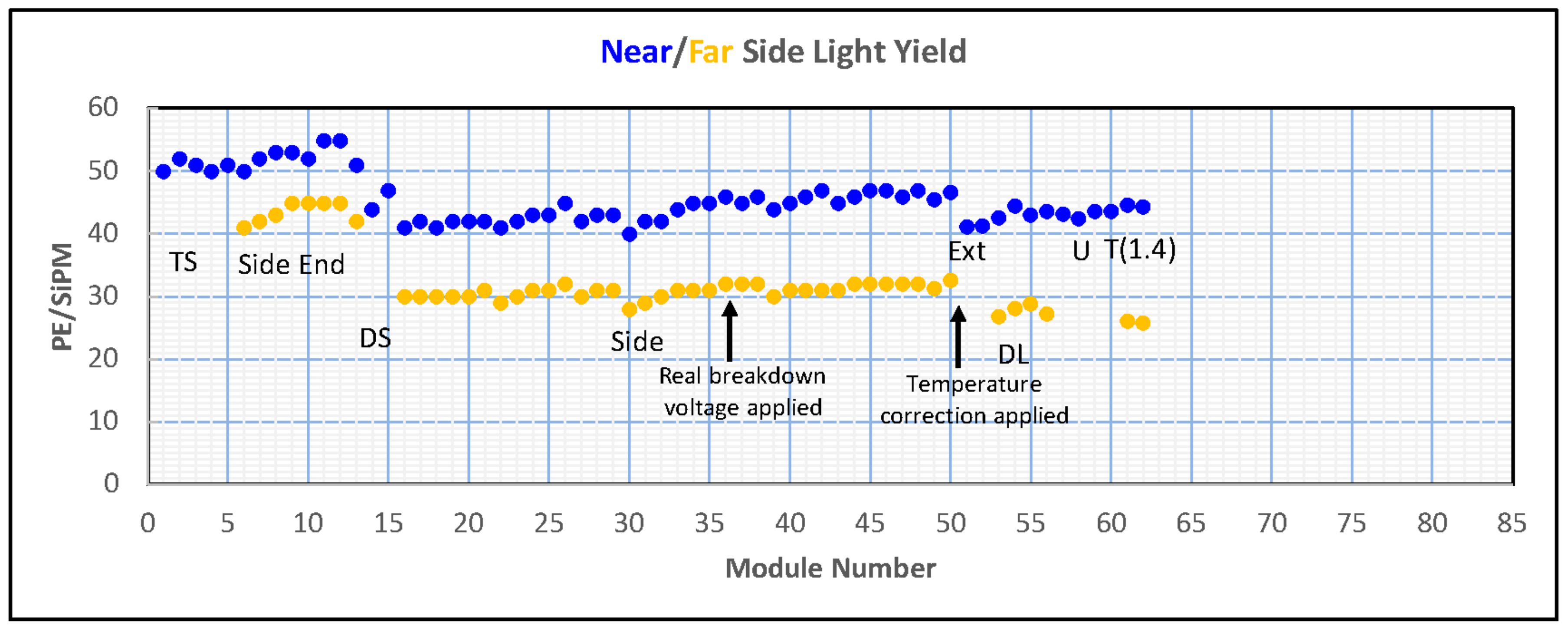
Module QC: Cosmic Ray Test Stand

- PE yield for module 34 with SiPMs at a bias voltage of 2.5 V over breakdown
- The data is taken 1.0 m from the readout end of this 4.55 m long module



Module QC: Cosmic Ray Test Stand

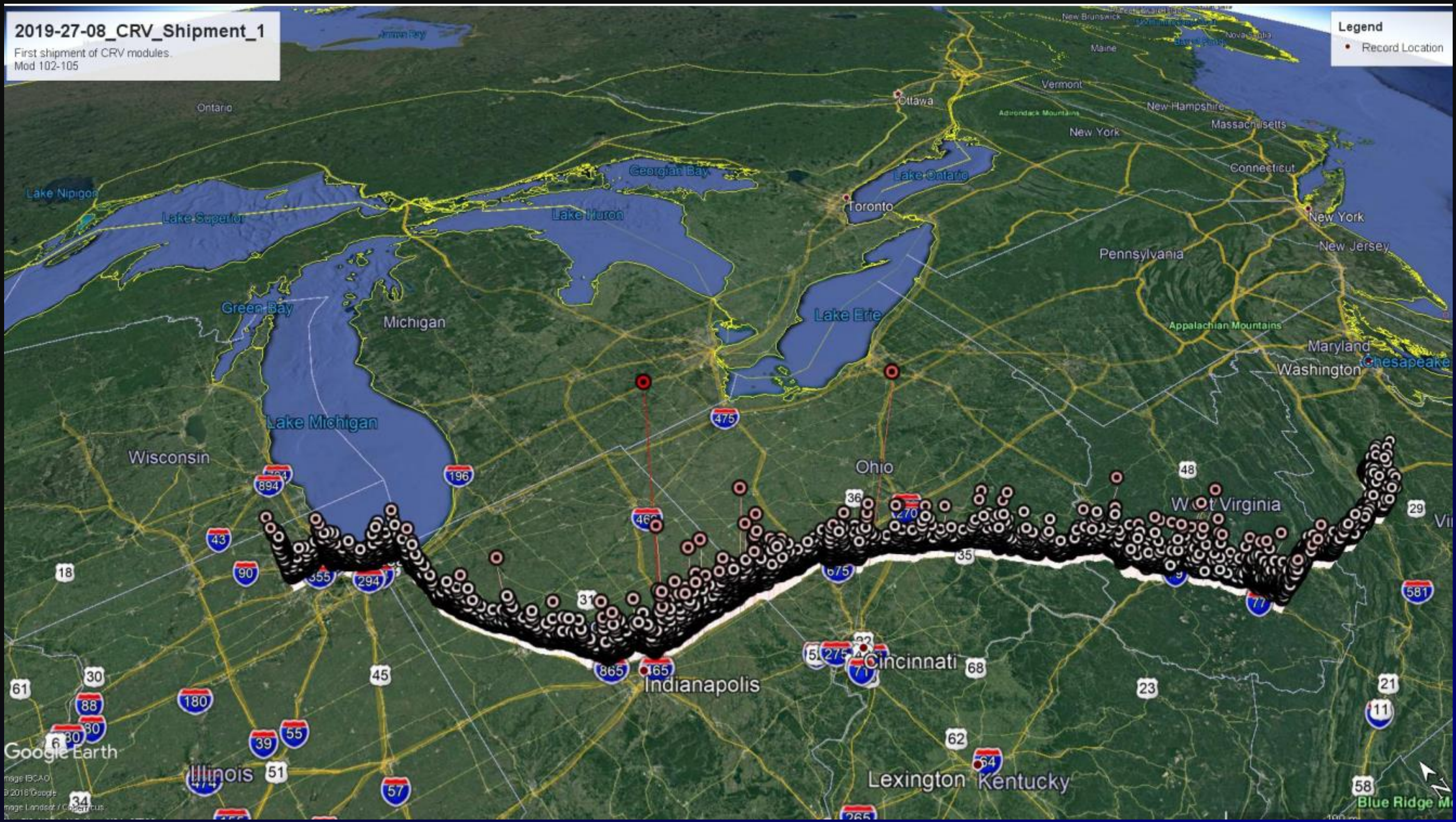
Near and far side light yields for all modules fabricated to date



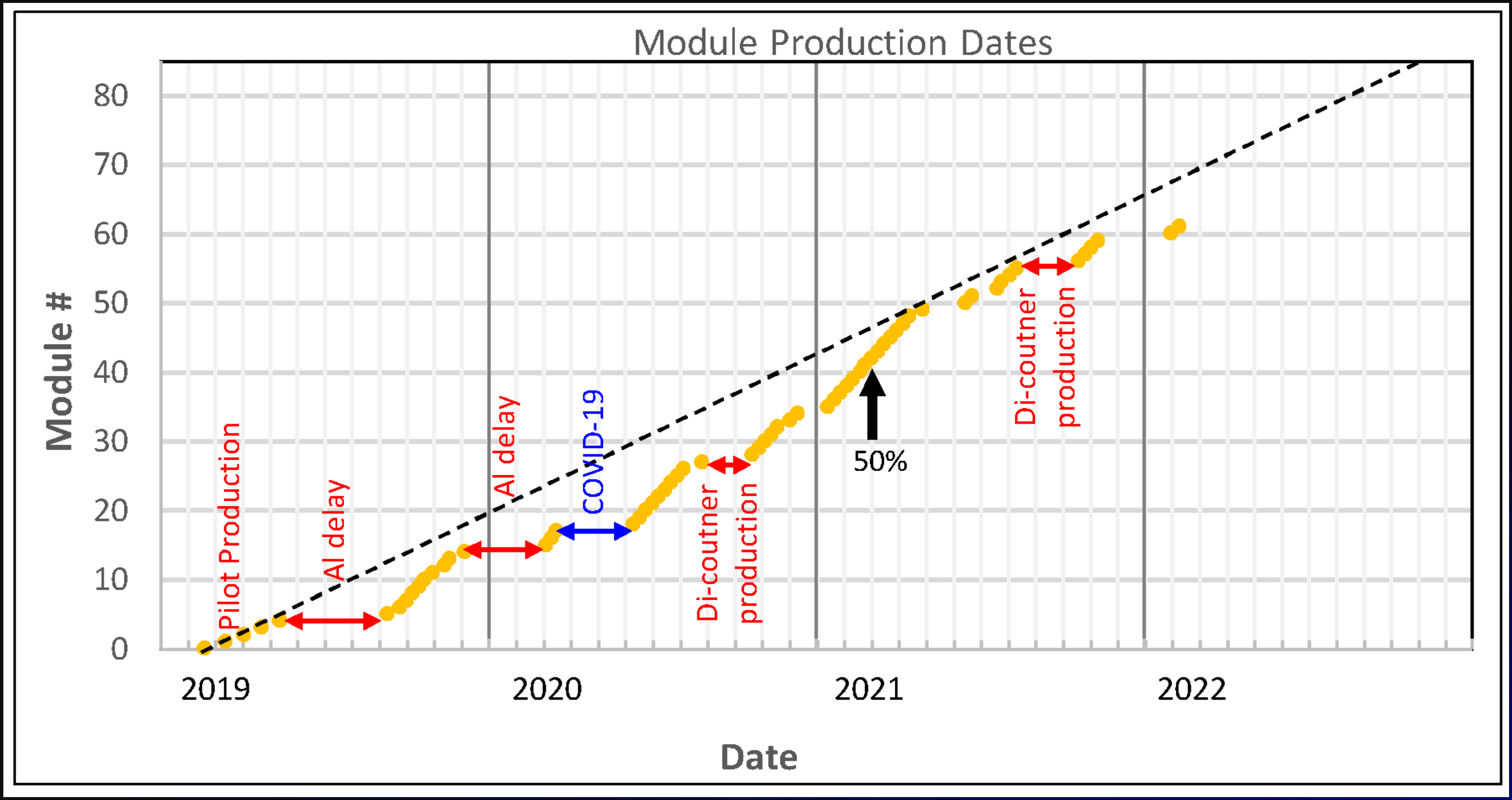
Module Factory: Packing a Module for Shipping

Module Factory: Packing a Module for Shipping

A custom logging unit, assembled using off the shelf components from Adafruit, records location, temperature, humidity, and acceleration experienced during transit. The collected data is visualized using Google Earth.



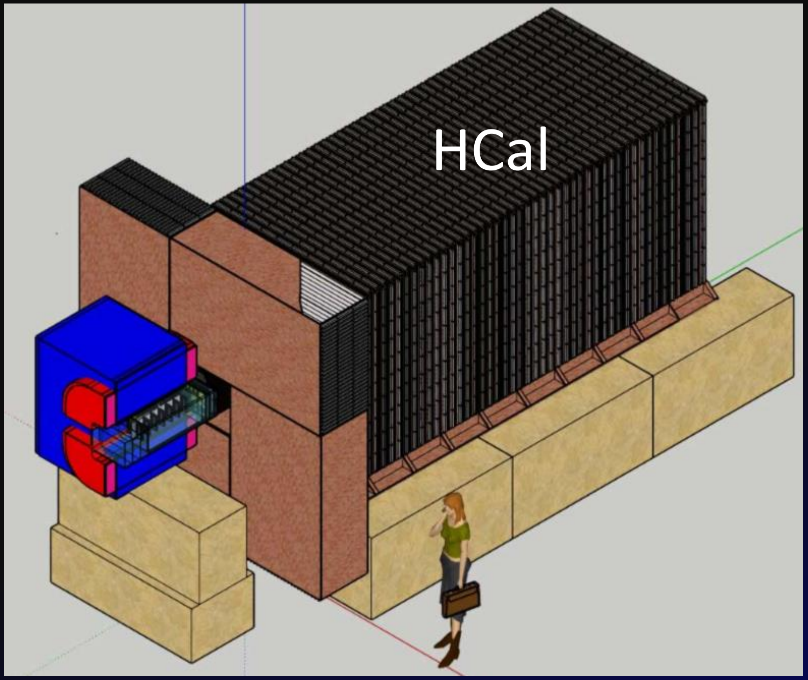
Module Production Status

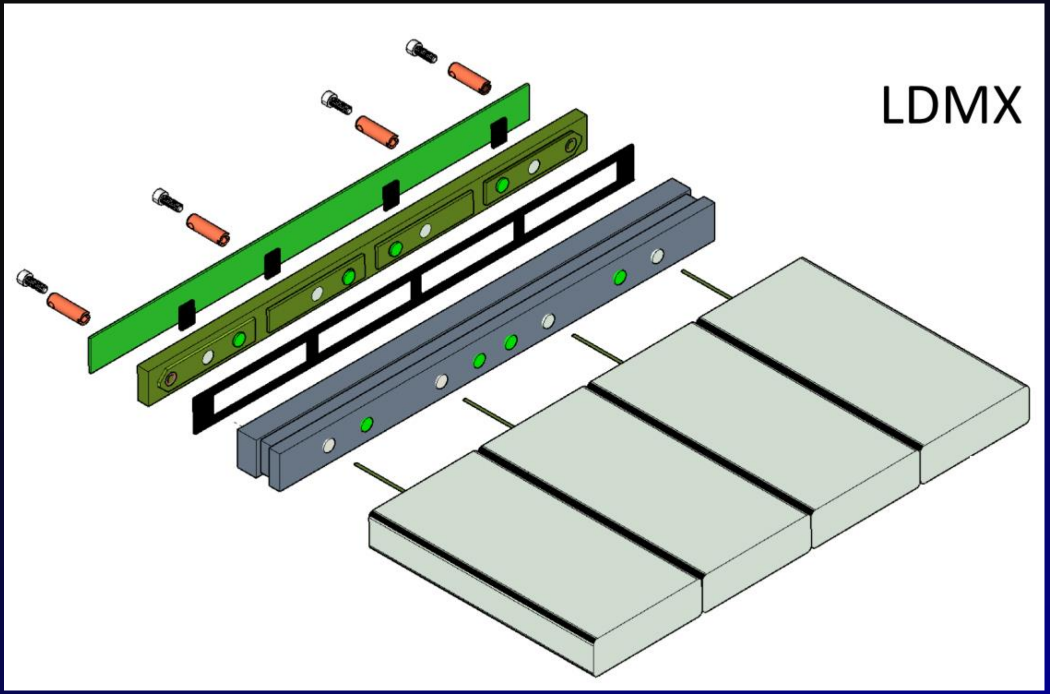


Backup Slides: Other Applications

Other Applications of Design: LDMX

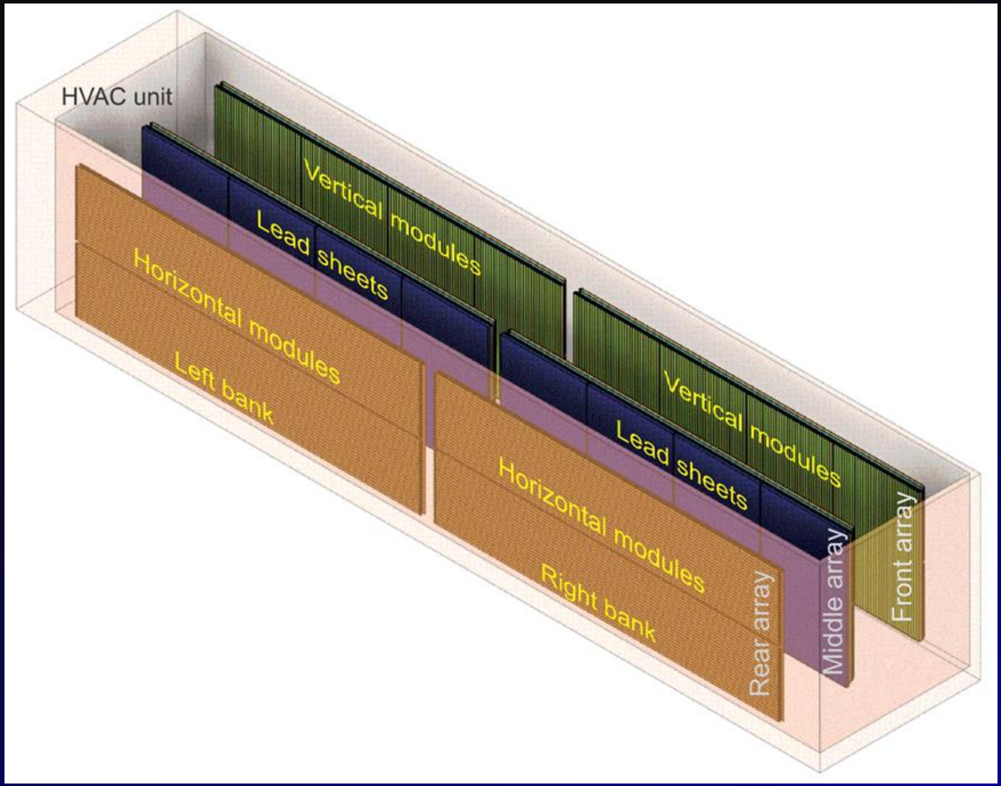
- Similar design concept as Mu2e CRV
- Counters identical size but with only 1 fiber
- Quad-counter inside of di-counter
- Used for the hadronic calorimeter
- Counters to be fabricated at UVA and shipped to Caltech for module assembly





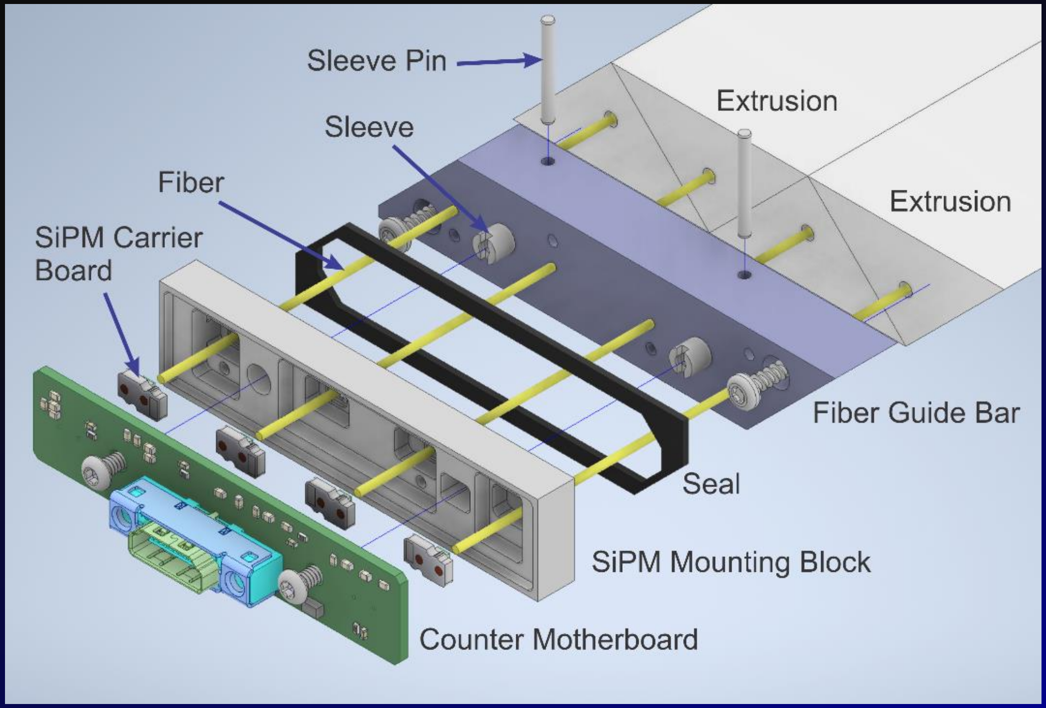
Other Applications of Design: EGP

- EGP: exploring the Great Pyramid of Khufu at Giza
- Use the Mu2e Cosmic Ray Veto design to fabricate an inexpensive detector to detect cosmic-ray muons coming through the pyramid
- Detectors placed in shipping containers around the pyramid
- Much larger area should allow us to see voids of roughly 2 m size



Other Applications of Design: El Castillo

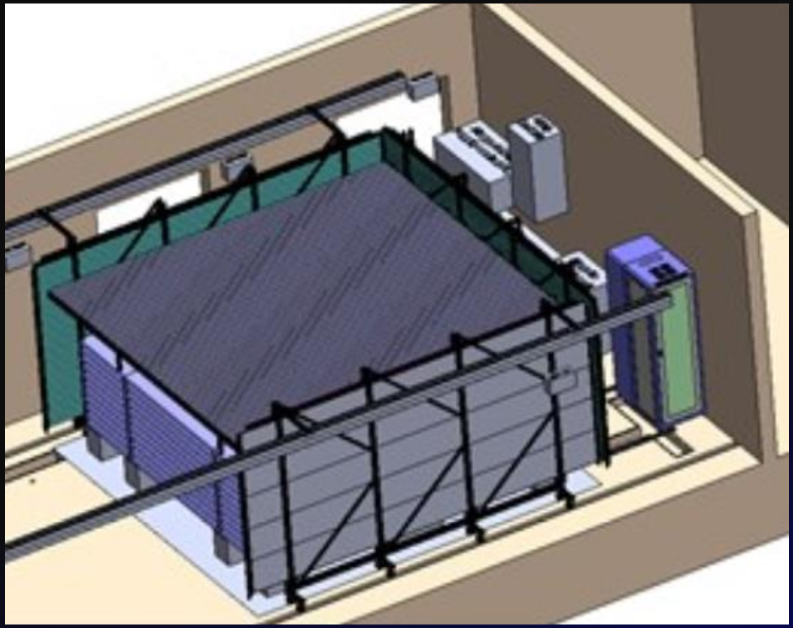
- NSF funded experiment to explore interior of El Castillo (Temple of Kukulcán) at Chichen Itza
- Much smaller detector needed
- Detectors placed inside in base tunnel
- Triangular extrusions used to improve position resolution



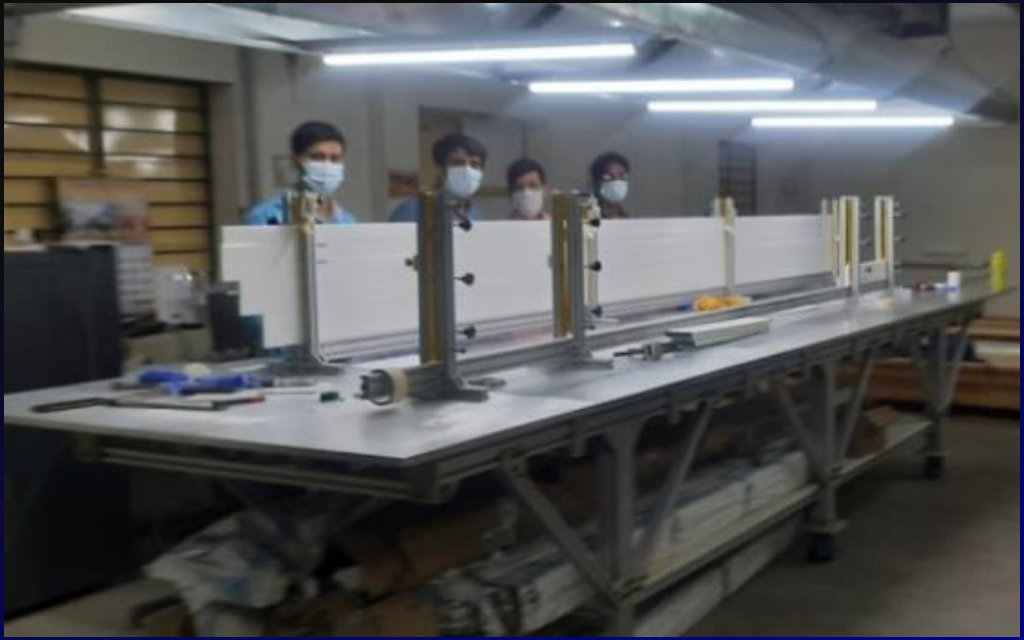
Other Applications of Design: mini-ICAL

- A 51-kiloton magnetised Iron Calorimeter detector, using RPCs as active detector elements to study atmospheric neutrinos
- To be built at in the Pottipuram Research Centre in India
- Cosmic-ray veto design based on Mu2e CRV

Layout of Cosmic-ray veto



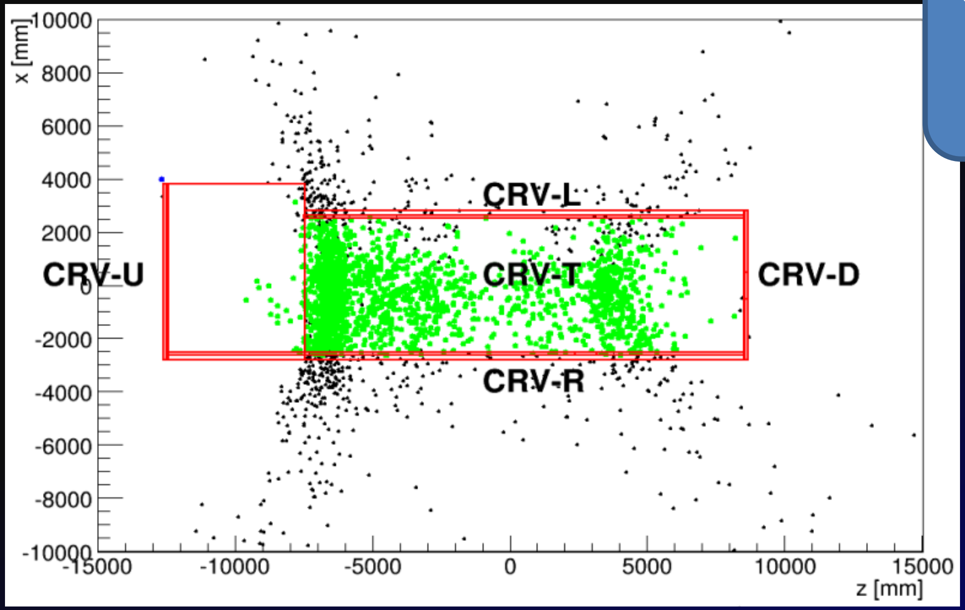
Cosmic-ray veto under fabrication



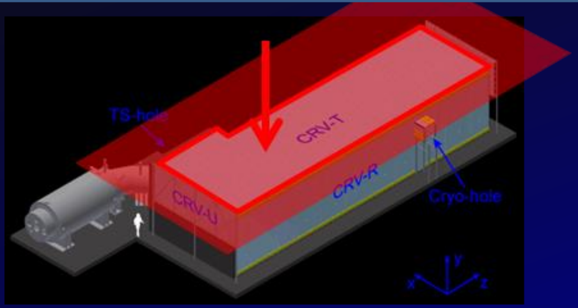
Simulation Effort

Determining Required Veto Coverage & Efficiency

- Probability that a cosmic-ray muon produces a conversion-like event is small: $< 1 \times 10^{-9}$ → need to generate a huge number of events
- Simulation campaign: **3.8 x 10^{12} total cosmic ray muons** generated
- Two types of simulations done:
  - **Global simulation:** covering an area much larger than the CRV with 4X the total live time
  - **Targeted simulations:** covering areas with gaps in coverage with over 250X the total live time



Global simulation shows all background-creating cosmic muons hit the cosmic ray veto and hence can be vetoed



black dots: muons intersecting CRV-T plane
green dots: muons creating hits only in the CRV-T
blue dots: muons creating no hits in any CRV sector

Simulation History

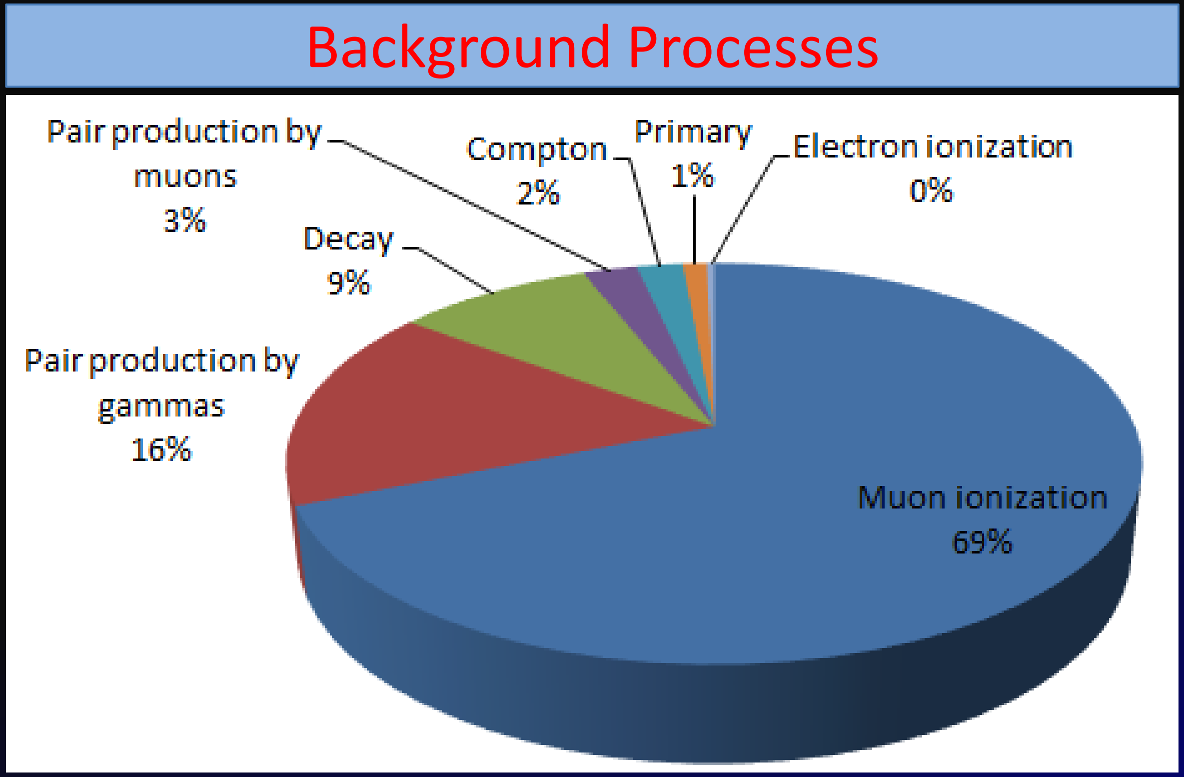
Global Simulation				
	CD-1 (CDR)	CD-2 (TDR)	CD-3	Post-CD-3
MC Muons	1.1×10^9	27.9×10^9	500×10^9	-
Effective Live Time	0.05X	0.19X	4X	-
Background Events	14 ± 4	159 ± 13	3170 ± 56	-

Targeted Region Simulation					
Region	Fraction of Total Live TIme				Events
	CD-1 (CDR)	CD-2 (TDR)	CD-3	Post-CD-3	
TS entrance	0	7X	260X	-	1000×10^9
CRV-U	0	8X	260X	-	1000×10^9
CRV-D	0	8X	260X	-	1000×10^9
Cryo	0	0	360X	-	200×10^9
Gap-left	0	0	0	22X	25×10^9
Gap-right	[illegible]	[illegible]	0	17X	25×10^9

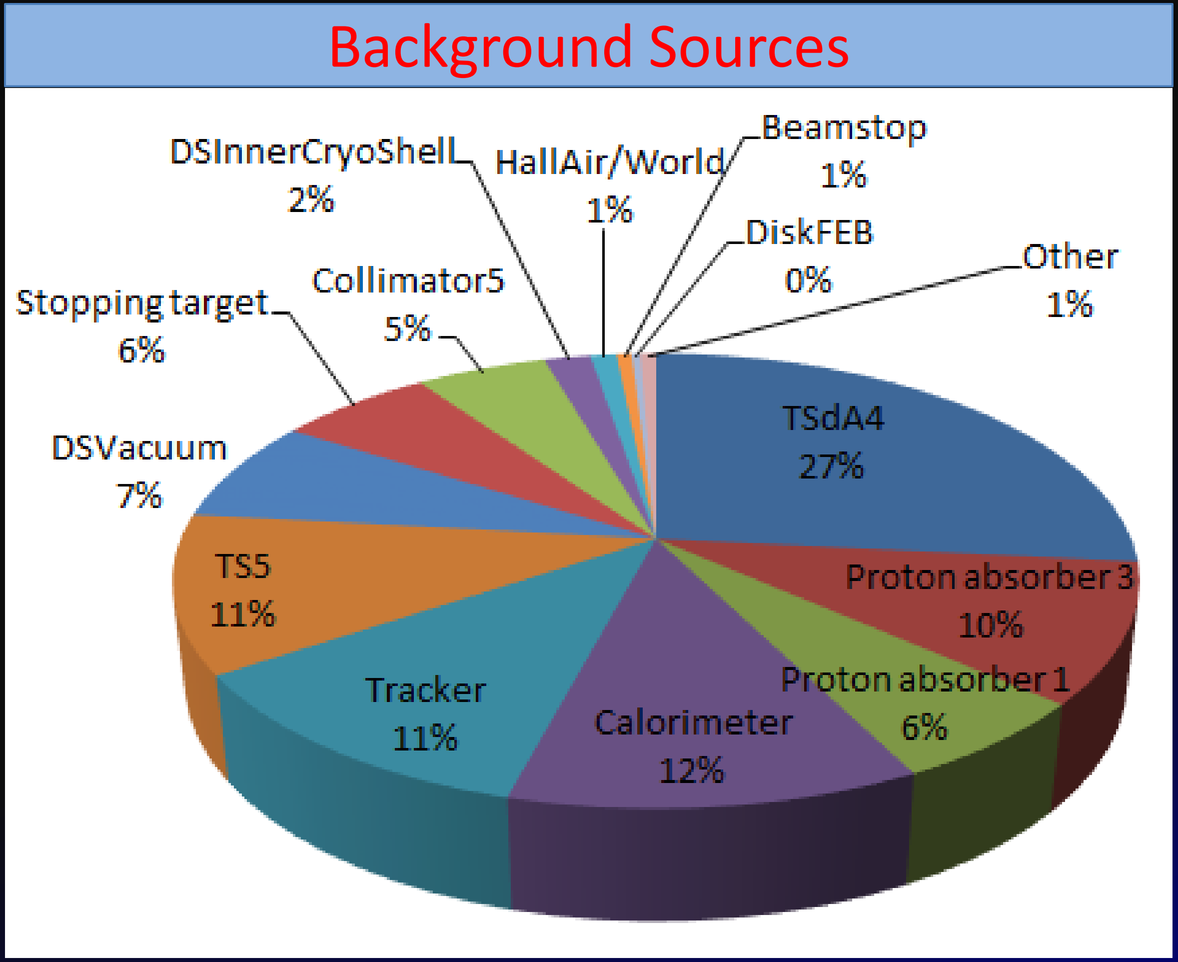
3.8×10^{12} total cosmic ray muons generated

Conversion-like Electron Background Processes

Largest process is delta-ray production

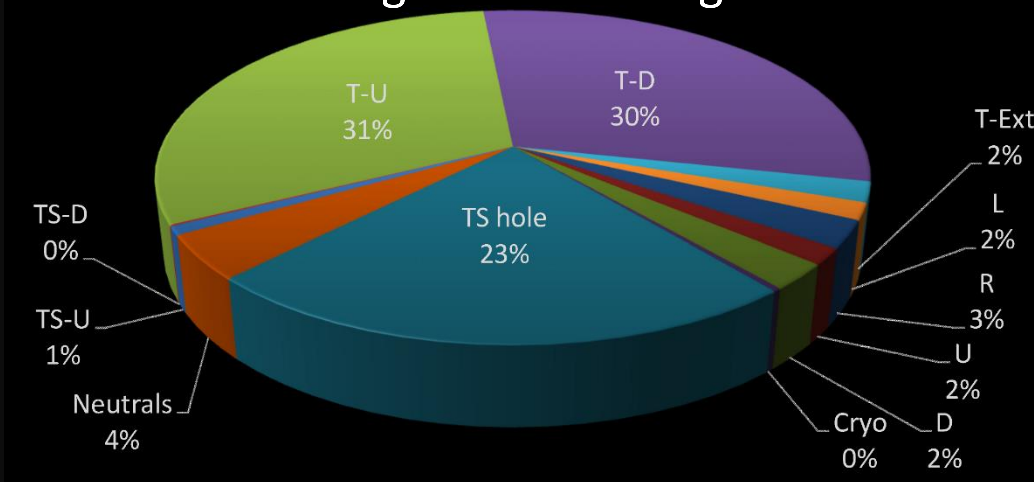


Background Sources

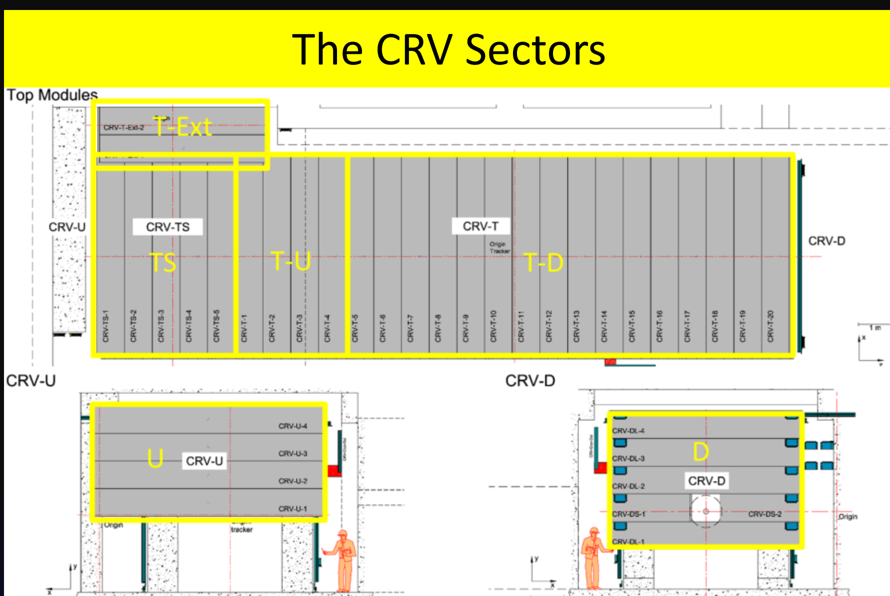


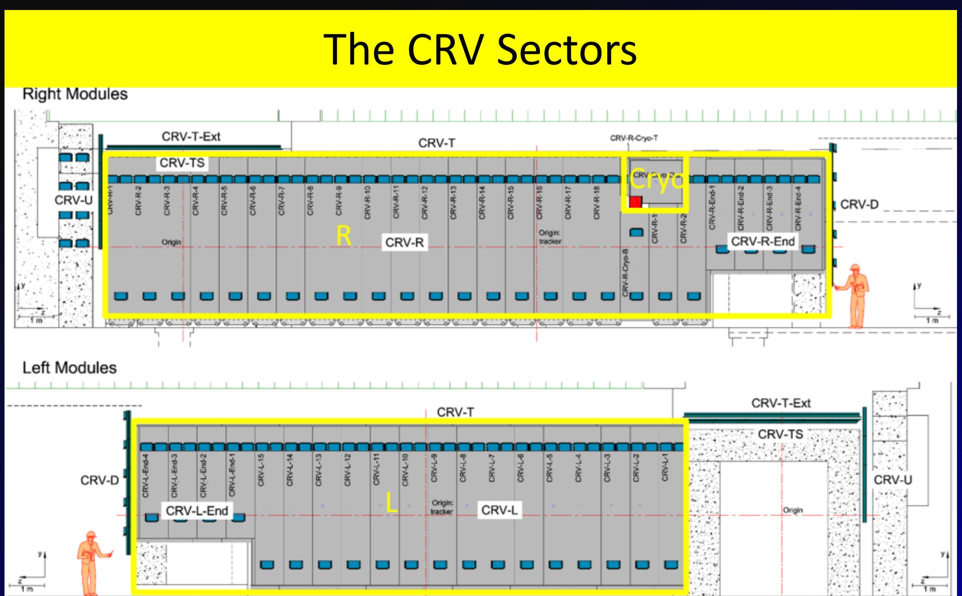
Where the Backgrounds Come From

Where the background creating muons hit



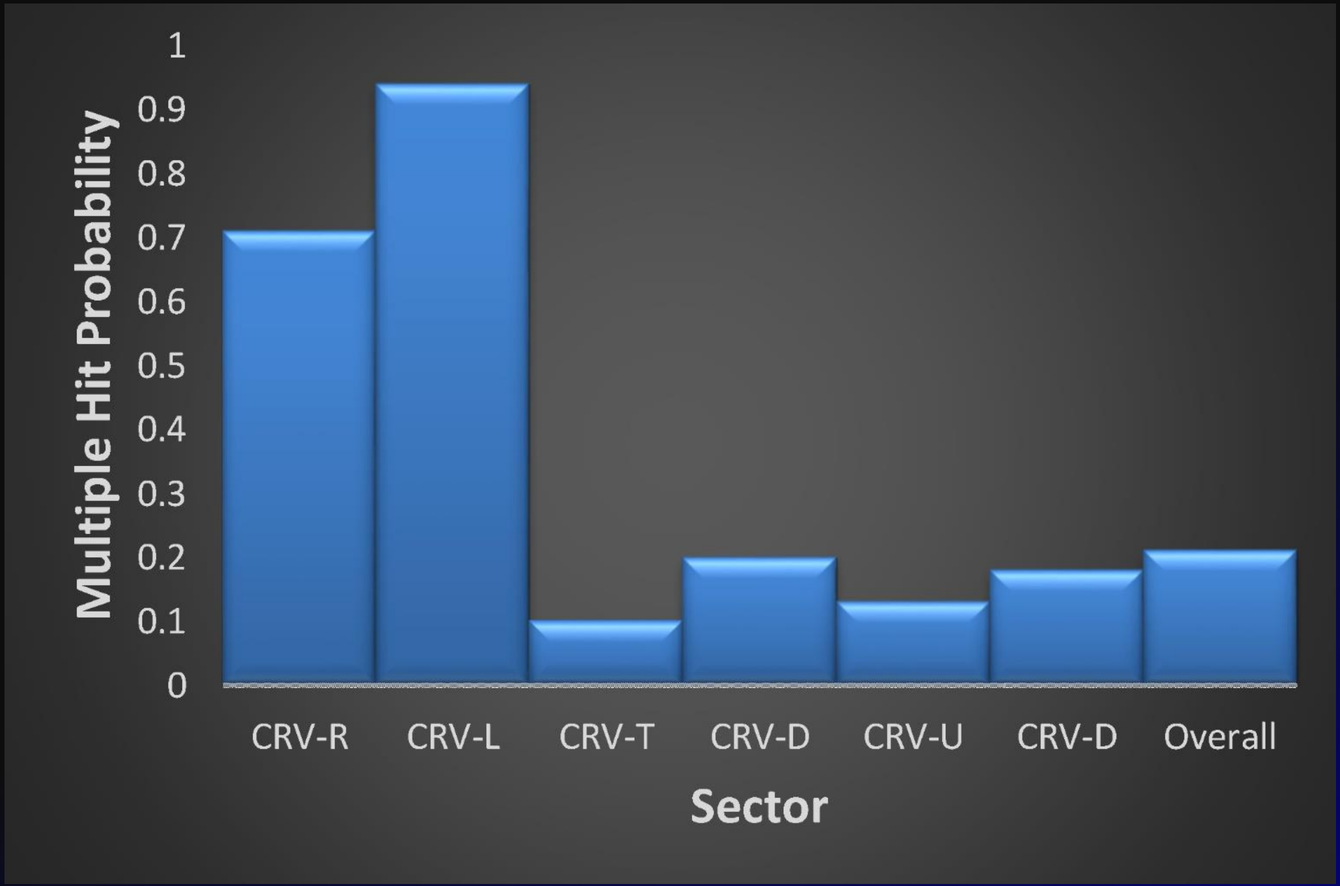
- Break up CRV into sectors
- Most of the background-creating muons hit the top sectors
- Inefficiencies in those sectors have to be 1 x 10^{-4} or better
- TS hole has a large background because those muons cannot be vetoed





Multiple Sector Hits by Electron Producing Muons

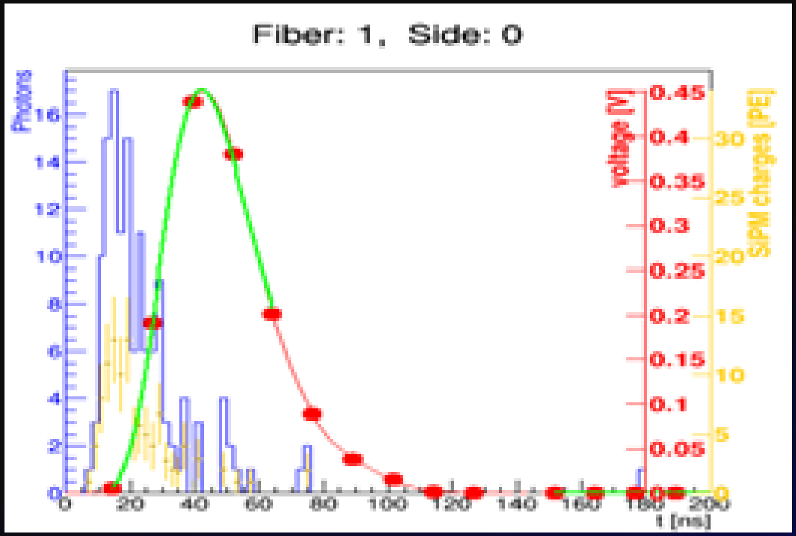
We have not added the fact that some muons have a chance of being vetoed twice by going through two sectors of the CRV

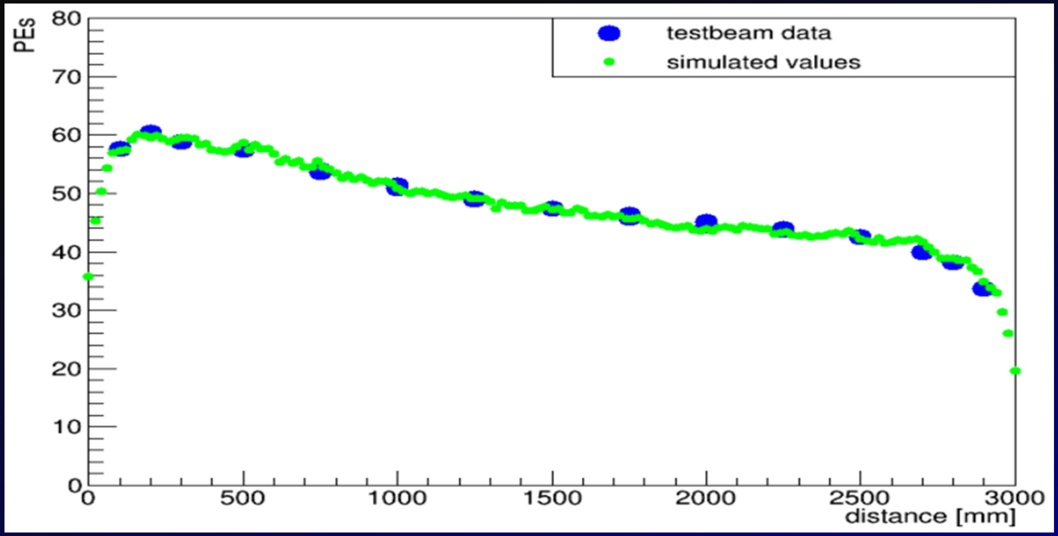


Modeling Counter Performance

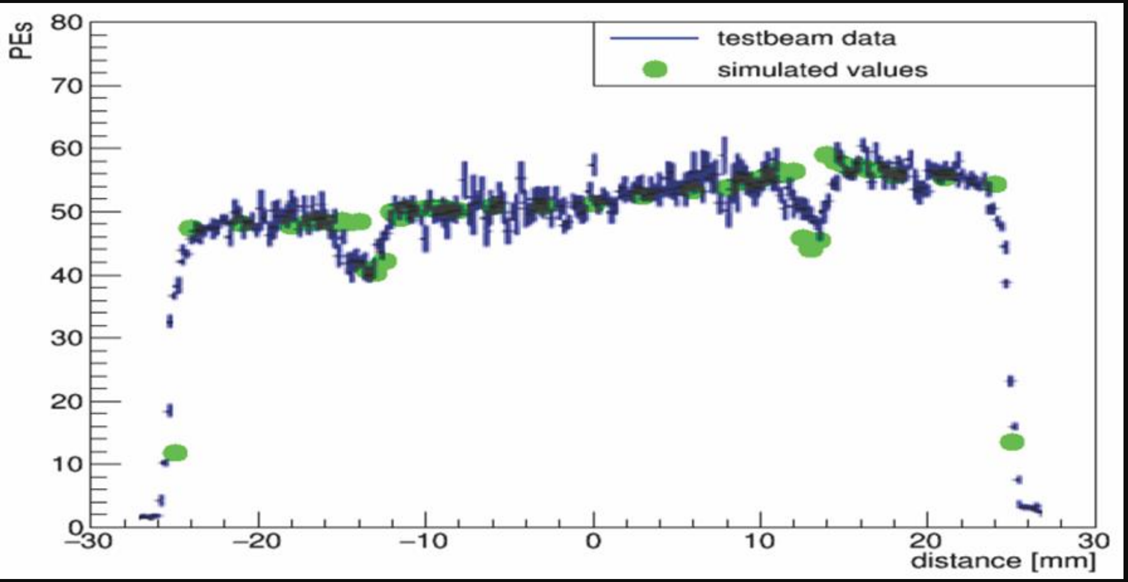
Modeling Counter Response and Readout

- A detailed soup-to-nuts MC has been developed that uses the framework software environment with a complete simulation of the CRV response to incident particles.
- MC includes 2% dead SiPMs, timing jitter, overlayed backgrounds, SiPM crosstalk and afterpulsing, etc.
- MC is tuned to agree with test-beam data.
- Using our track-stub finder code this is used to determine the PE yield for given gaps between counters, di-counters and modules, as well as offsets between layers.





Modeling Counter Response and Readout



Right fiber only readout

Both fibers read out