# Mu2e CD-2/3b Review
# 8.5 CRV Photodetectors

Julie Whitmore
Mu2e CRV Deputy L2 & Photodetectors L3
10/21/2014

# CRV Photodetector Team

- Julie Whitmore – CAM and L3 Manager
  - Fermilab scientist for over 20 years.
  - L2 Manager: CMS HCAL Maintenance & Operations
  - L3 Manager: CMS HCAL FE Elec, CMS HCAL Upgrade FE Elec
  - Technical: KTeV CsI Calo and CMS HCAL FE Electronics
- Paul Rubinov
  - Fermilab Eng Phys for over 15yrs.  Mu2e CRV since 2009.
  - Technical: over 13yrs photodetector experience, D0 fiber tracker, Minerva FE Elec, SiPM experience from Proton Computed Tomography (PCT), SiPM readout for Fermilab test beam
- Vishnu Zutshi
  - Assoc Prof NIU.
  - Technical: SiPMs for PCT and LC Hadron Shower Imager.
- Yuri Oksuzian (see CRV Fiber L3 talk)

# Outline

- Organizational Breakdown
- Scope & Deliverables
- Requirements
- Design
- Improvements Since CD-1
- Value Engineering Since CD-1
- Performance
- Remaining Work Before CD-3
- Quality Assurance
- ES&H Issues
- Interfaces
- Risks & Opportunities
- Costs
- Schedule
- Milestones
- Summary

# Organization

**WBS 475.8 Cosmic Ray Veto**
Craig Dukes / Virginia
Julie Whitmore / Fermilab (Deputy)

**475.8.1 Project Management**
Craig Dukes / Virginia
CAM: Dukes

**475.8.2 Mechanical Design**
Craig Dukes / Virginia
CAM: Dukes

**475.8.3 Scintillator Extrusions**
Anna Pla-Dalmau / Fermilab
CAM: Pla-Dalmau

**475.8.4 Fibers**
Yuri Oksuzian / Virginia
CAM: Dukes

**475.8.5 Photodetectors**
Julie Whitmore / Fermilab
CAM: Whitmore

**475.8.6 Electronics**
Sten Hansen / Fermilab
CAM: Dukes → Whitmore

**475.8.7 Module Fabrication**
Craig Group / Fermilab & Virginia
CAM: Group

**475.8.8 Detector Assembly & Installation**
Jim Fagan / Fermilab
CAM: Dukes

# Scope

**WBS 8.5 Photodetectors**
Julie Whitmore / Fermilab

**8.5.1 Photodetector Procurement**
This task covers all aspects of the selection and evaluation of prototype photodetectors, and the procurement and testing of the production photodetectors.

**8.5.2 Photodetector Quality Assurance Design & Fabrication**
This task covers: (1) specifying the requirements for the photodetectors, including those required of the manufacturer, (2) determining the parameters to be tested upon receiving the photodetectors, (3) designing the test stand for photodetector testing, and (4) fabricating the test stand.

**8.5.1**

- Identify SiPM device(s) that meets requirements (Rad & Longevity testing)
- Procure Devices
- Characterization/Testing
- Value engineering

**8.5.2**

- Fabricate QA tester for large scale testing
- Test critical parameters to validate vendor batches
- Value engineering

# Scope & Deliverables

**A. Technical Objective**

This task covers the selection, evaluation, procurement, and testing of the photodetectors for the cosmic ray veto scintillation counters.

**B. Scope of Work Statement**

The scope of work includes:

1. The selection and evaluation of prototype photodetectors, and the procurement and testing of the production photodetectors.
2. Quality assurance design and fabrication, including: (1) specifying the requirements for the photodetector parameters, including those required of the manufacturer, (2) determining the parameters to be tested upon receiving the photodetectors, (3) designing the test stand for photodetector testing, and (4) fabricating the test stand.

**C. Deliverables**

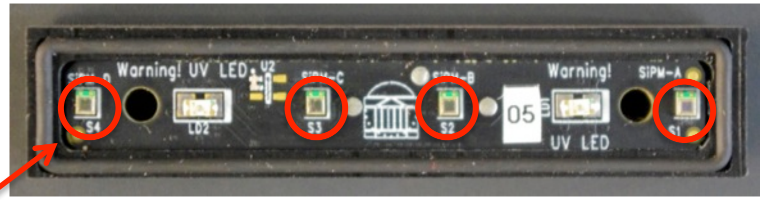
Deliverables include:

1. A photodetector test stand.
2. Photodetectors for prototype counters and modules.
3. Photodetectors for production modules.

# SiPM Requirements

1. The photodetector must operate in a magnetic field of 0.1T.
2. Nominal photosensitive size must be greater than the 1.4mm diameter fiber size with a minimum additional 0.25mm to allow for easy alignment to the fiber.
3. Device must have a PDE at least as high as 100μm device (Hamamatsu S10362-11-100P) used in test beam (>30%).
4. SiPM must have a gain of $>10^5$.
5. The number of pixels must be sufficient to cover a dynamic range up to 200 PE with a well understood response.
6. The device must operate after exposure to $1\times10^{10}$ n/cm$^2$ @1 MeV neq. S/N for single photoelectron must be distinguishable in order to maintain the in-situ calibration of the devices. Any degradation after 3yrs of operation must not compromise the efficiency requirement of the CRV.
7. SiPM must produce an intrinsic dark current hit rate <50kHz (3PE threshold). Any after-pulsing must not cause excessive detector deadtime.
8. The device must be packaged in a small form factor/low profile package that allows tight direct coupling of the SiPM to the fiber.

# SiPMs in the CRV




Counter Mother Board (surface)

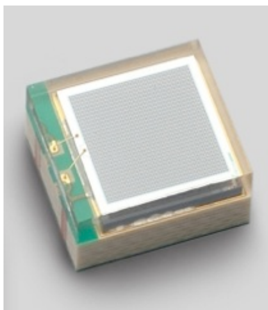
SiPM

**Counter Motherboard**

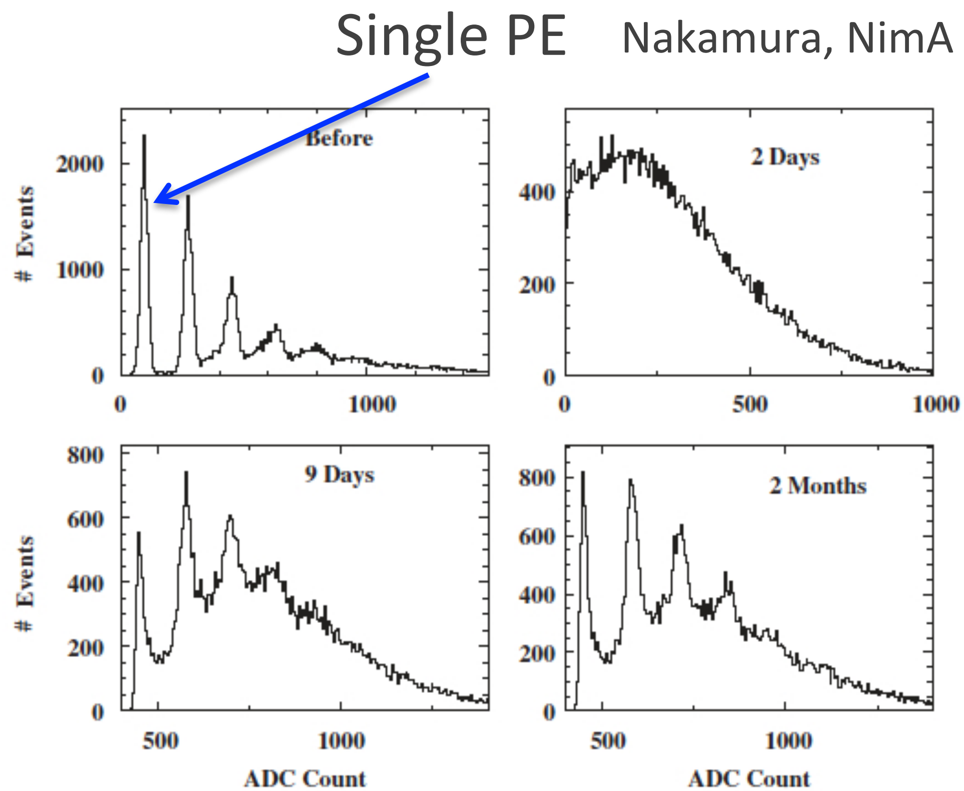
- 5,152 counters, each with 2 fibers
- Each counter read out on both ends (with exception of those in the TS region)
- 18,944 photodetectors: SiPMs (read out both ends, except CRV-U and CRV-T, CRV-cryo)
- Surface mount SiPMs large enough to mate to 1.4mm diameter fiber.
- 1 Counter motherboard per di-counter.
- SiPMs must couple tightly to the 4 fibers on the di-counter without mechanical damage to the SiPMs.
- Alignment of the SiPMs must be maintained during reflow soldering
    - "Oversized" SiPMs that self-register during reflow or by using template
- Gasket hood over motherboard to maintain light-tightness

# Radiation Damage

Sufficient Shielding is needed to mitigate radiation damage to CRV electronics.



Integrated flux to SiPMs is required to be kept below $1 \times 10^{10}$ n/cm$^2$. (1 MeV neutron equivalent)




Nakamura, NimA 610 (2009), 110-113

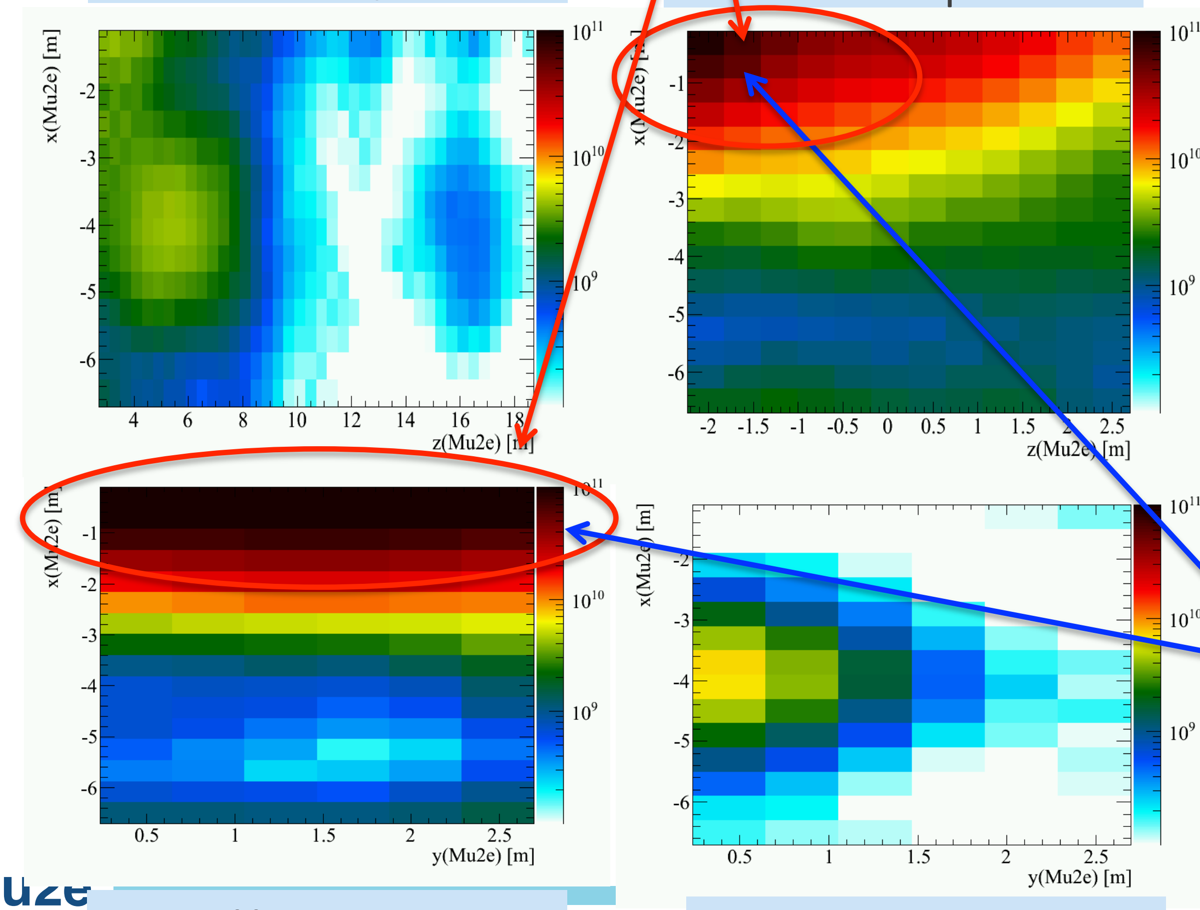
SiPM – Irradiated with $2 \times 10^{10}$ n/cm$^2$. Dark count before and after irradiation, And after 2 days, 9 days, and 2 months of annealing.

# Simulations:  Neutron Radiation Damage

- Fold rates and spectrum into 1 MeV equivalent damage curve
- Note:  No timing cut used!   No devices used in these regions

DS Top

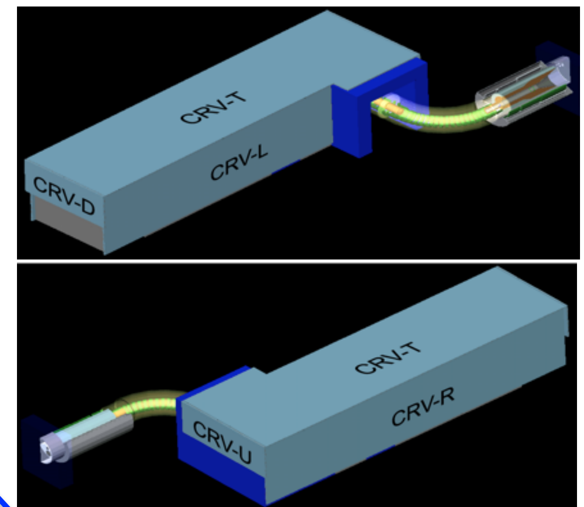
TS Top




Upstream

Downstream

SiPM damage must stay below limit $10^{10}$ n/cm2




Upstream region a problem
Red = $10^{10}$ n/cm2
Black = $10^{11}$ n/cm2

# SiPM Operation Plan

- Operational model similar to T2K (T2K has ~60,000 devices operating for 3 years).
  - No temperature stabilization for SiPMs in T2K
    - No special temperature control for SiPM beyond standard building HVAC.
  - Monitor single PE peak to track gain. Periodically adjust operating voltage (period to be determined) to align single PE across CRV.
    - Correct bias voltage for temperature changes and changes due to radiation.
  - Monitor dark count rate. PE spectrum, temperature, SiPM response (via LED flasher system).
  - Ability to measure I-V curve in-situ (not during operation).
  - Ability to monitor cosmic ray spectrum in modules.

# Improvements since CD-1

- No significant changes to Mu2e photodetector requirements
  - Better understanding of our backgrounds and required light yield
- Significant improvements in SiPMs since CD-1 review
  - More vendors are developing lower noise, higher PDE devices that are intrinsically more radiation hard
- Device decisions
  - Surface mount devices, 2mm x 2mm COTS SiPM, quality assurance sampling (10% testing of production devices)

# Value Engineering since CD-1 (1)

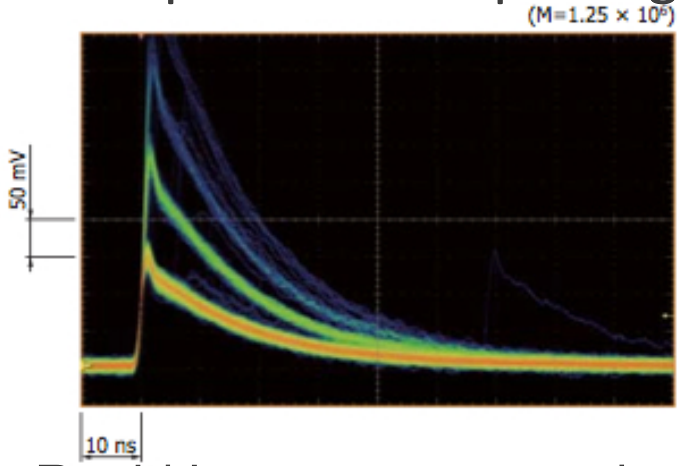
- Benefited from US CMS SiPM R&D with vendors
  - Multiple vendors fabricating radiation hard SiPMs
    - Improved performance (PDE and noise), wider dynamic range, lower cost
    - Quite likely current commercially available SiPMs will meet our requirements
- Benefited from T2K Experience
  - T2K has operated 60,000 devices for several years.
    - Extensively characterized SiPMs
      - Key parameters to measure are understood.
        - Mu2e only needs to test a subsample of devices.
      - Operational experience applicable to Mu2e (with one exception…)
    - T2K SiPMs are not in a radiation zone → device characteristics are stable over time.
      - Mu2e will need to carefully monitor device characteristics during running to ensure stability of CRV efficiency

# Value Engineering since CD-1 (2)

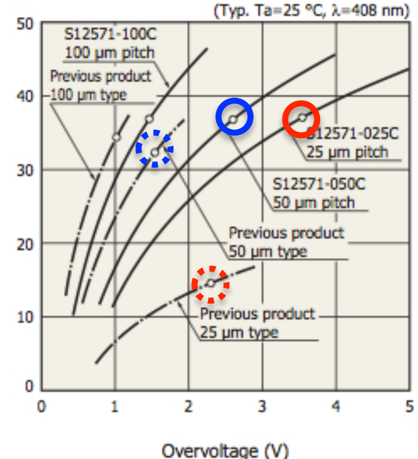
- Benefited from NIU/FNAL/Delhi Proton Computed Tomography (pCT) Scanner Project
  - Developed test procedures and infrastructure for pCT project (3000 SiPMs)
  - Mu2e NIU and FNAL experimenters involved in pCT project
    - SiPM expertise: FNAL Eng Phys (Paul Rubinov), NIU physicists and students
    - Experienced in handling large number of devices
    - Mu2e will leverage pCT software and hardware development

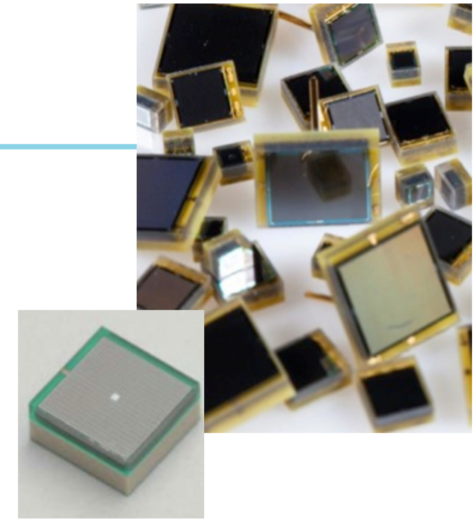
# SiPM Procurement

Improved Afterpulsing




PDE: New vs Old



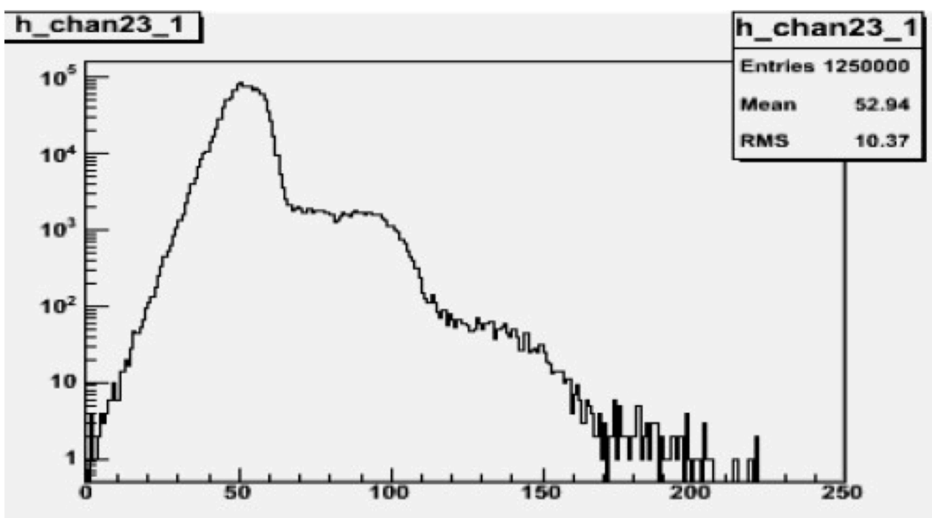



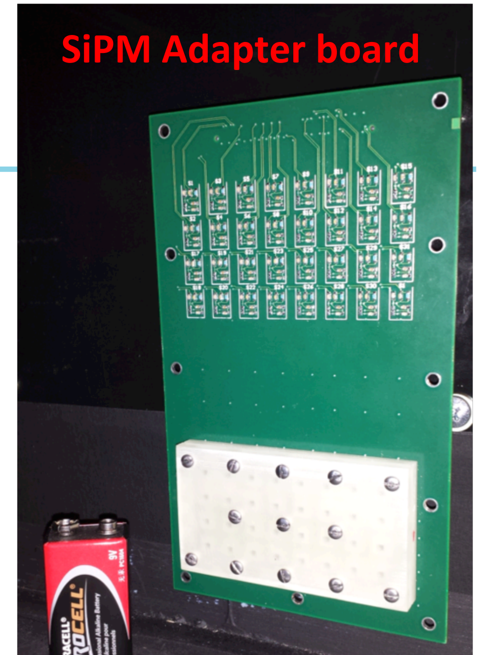
TSV-Thinner epoxy coating than SMD (100 μm vs 300 μm)

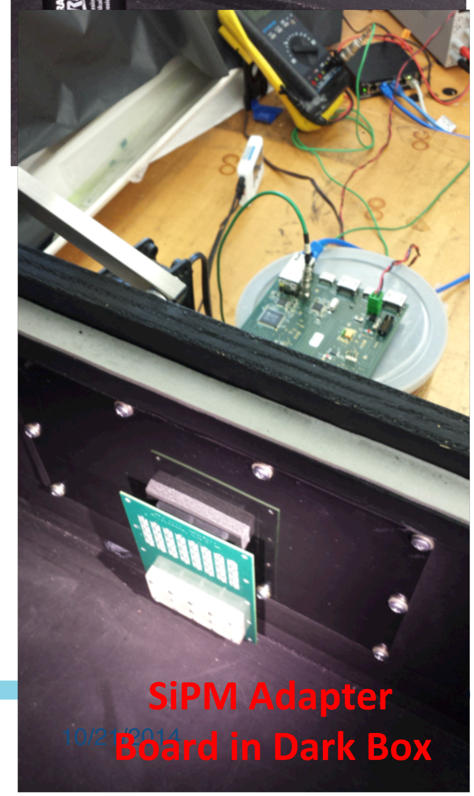
- Rapid improvements to device processes
  - Higher PDE
  - Better process allows for higher over-voltage operation
  - Lower x-talk and after-pulsing
  - Better temperature coefficient
- Many vendors with new candidate devices
  - Hamamatsu and KETEK have 2mm x 2mm COTS SiPMs
    - Hamamatsu has Through Silicon Via (TSV) and surface mount packaging. KETEK will have TSV by end of 2014.
  - FBK/AdvanSiD has new SiPM with trenching (custom size available)
  - SENSL will have TSV late 2014 (custom size available)

# SiPM Characterization

- SiPM characterization before/after irradiation/longevity testing (@NIU)
  - Measure device parameters:
    - I-V curve, waveform
  - Derived parameters:
    - $V_{BR}$, Vbias, Dark current/count rate, gain, xtalk, etc.

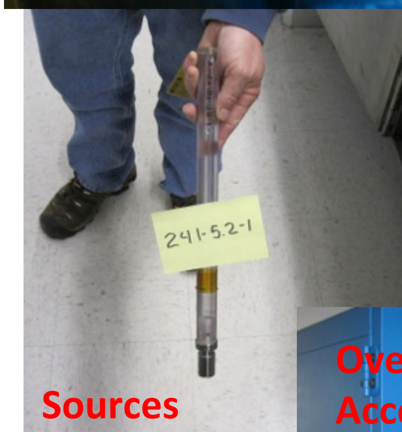


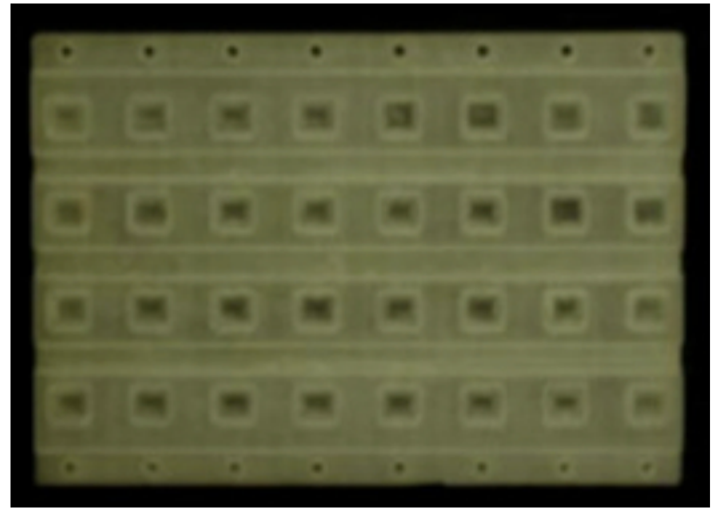



# SiPM Radiation & Longevity Testing

- Radiation Qualification
  - Reactor neutrons
    - UC Davis reactor (Energy 1-10 MeV)
    - U of Florida reactor (thermal neutrons)
    - Sources (Fermilab)
      - AmBe
        - Energy - 2-10 MeV
        - 2.1E5 n/s
      - Cf-252
        - Energy - 2 MeV
        - 2.7E4 n/s
- Accelerated Aging Test
  - Arrhenius equation
    - Counter Motherboard temperature: ~25 °C
    - Mu2e running (3 yrs) + commissioning (1yr)
  - Device oven test:
    - 70 °C for 64.5 days

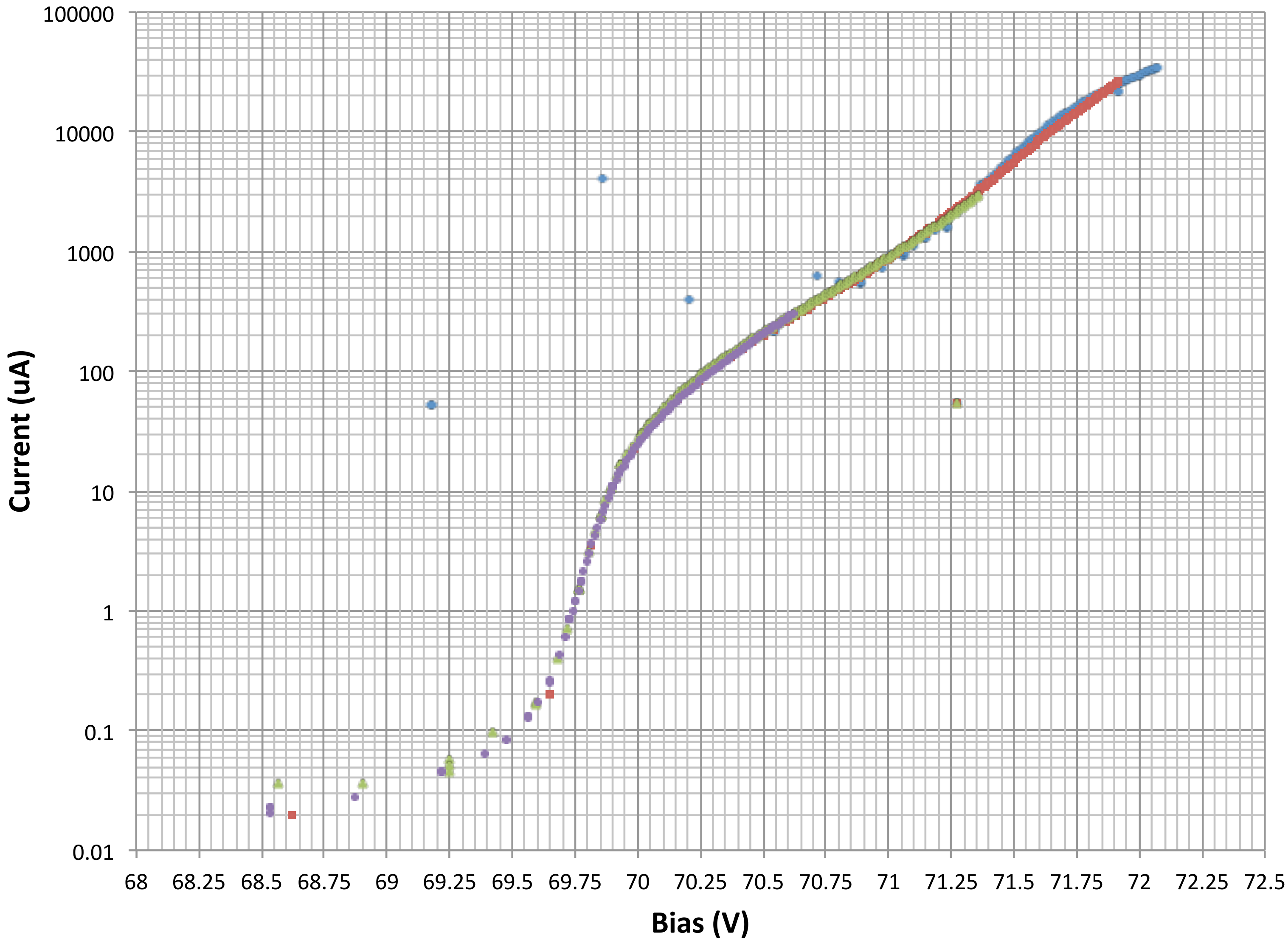




# SiPM QA Tester



- QA Testing
  - Need to test many devices in parallel
    - Testing design for I-V tester with a simple scheme for providing bias
  - Need to do both I-V and pulse mode testing on a small number of devices
    - Longevity/Radiation testing for batch validation

# I-V Curve from QA Tester



# Remaining work before CD-3

- Device selection
  - Identify candidate SiPMs and validate they meet requirements
    - SiPM characterization (dark count rate, $V_{BR}$, gain, temp dependence, etc.)
    - Radiation and Longevity Testing
    - Determine whether COTS SiPM will work. If not, custom size device will be needed.
    - We don't expect any surprises since these devices will be relatively mature (1-2yrs old) by the time of production purchase
- Finish prototype QA Tester
  - 3d printed device holder must be designed/fabricated to match the specific SiPM being tested.

# Quality Assurance

- Mu2e needs to validate quality of the SiPMs
  - Learn from T2K experience (T2K INGRID – 18,000 devices)
    - T2K extensively tested all devices at various temps
      - Found only a few key parameters were needed for operation (dark count, $V_{BR}$, temp dependence of gain)
        - Need to track properties in-situ (monitor single PE, dark count, gain)
      - Temperature dependence is specific to the process
        - Need to test a few to fully characterize
  - Plans for QA testing of SiPMs
    - Test a small subset (10%) of SiPMs to validate the vendor batches
    - Destructive Radiation and Longevity tests on a smaller subset of devices (.5%)

# ES&H

- SiPM operation
  - SiPM operating voltages vary by vendor (KETEK ~ 30V, Hamamatsu ~ 80V, etc.)
  - Operation of SiPMs will follow Fermilab ES&H Manual (FESHM) standards for electrical equipment operation.
- QA SiPM testing jig
  - Hazards are minimum (Soldering, epoxy, etc.)

# Interfaces & Integration

- Internal
  - CRV photodetector interfaces to the fibers and FE Electronics
    - SiPM size must match fiber with sufficient tolerance for alignment
    - FE electronics: Bias voltages & dynamic range are understood and documented. Counter motherboard design documented.
- External
  - SiPM interfaces with muon beamline shielding: Radiation must be <1E10 n/cm$^2$.
  - Photodetector dark count rate impacts DAQ
  - Building temperature variations affect photodetector response
- Interfaces
  - DocDB # 1551
  - Participation in the weekly CRV meetings.
  - Participation in DAQ & Integration meetings

# Risks

| Risk ID | Docdb # | Type | Title | Date | Probability | Point Estimate (cost k$) | Point Estimate (prob) | Expectation Value (cost k$) |
|---|---|---|---|---|---|---|---|---|
| VETO-158 | 4257 | Threat | Custom SiPM size is needed | FY15 | Low | $50 | 20% | $10 |

- Dark count rate in COTS 2mm x 2mm SiPM too high → Smaller SiPM required (e.g. 1.6mm diameter active area)
  - Strategy: measure performance on prototype counters
  - Low cost risk ($50k). No serious schedule impact. No technical risk.

# Cost Table

## Cosmic Ray Veto 475.08

Cost in AY k$

| | Base Cost (AY K$) | | | | | |
|---|---|---|---|---|---|---|
| | M&S | Labor | Total | Uncertainty (on remaining budget) | % Contingency (on remaining budget) | Total Cost |
| 475.8.1 Project Management | 267 | 178 | 445 | 75 | 21% | 520 |
| 475.8.2 Mechanical Design | 135 | 3 | 138 | 24 | 38% | 162 |
| 475.8.3 Scintillator extrusions | 567 | 462 | 1,029 | 209 | 25% | 1,238 |
| 475.8.4 Fibers | 462 | | 462 | 106 | 24% | 568 |
| 475.8.5 Photodetectors (SiPMs) | 464 | 305 | 769 | 190 | 41% | 959 |
| 475.8.6 Electronics | 1,314 | 407 | 1,720 | 511 | 33% | 2,231 |
| 475.8.7 Module Fabrication | 1,482 | 8 | 1,490 | 466 | 35% | 1,956 |
| 475.8.8 Detector assembly and installation | 127 | 81 | 208 | 64 | 35% | 273 |
| 475.8.9 Conceptual Design/R&D | 258 | 252 | 511 | | 0% | 511 |
| 475.8.99 Risk Based Contingency | | | | 318 | - | 318 |
| Grand Total | 5,077 | 1,696 | 6,773 | 1,963 | 38% | 8,735 |

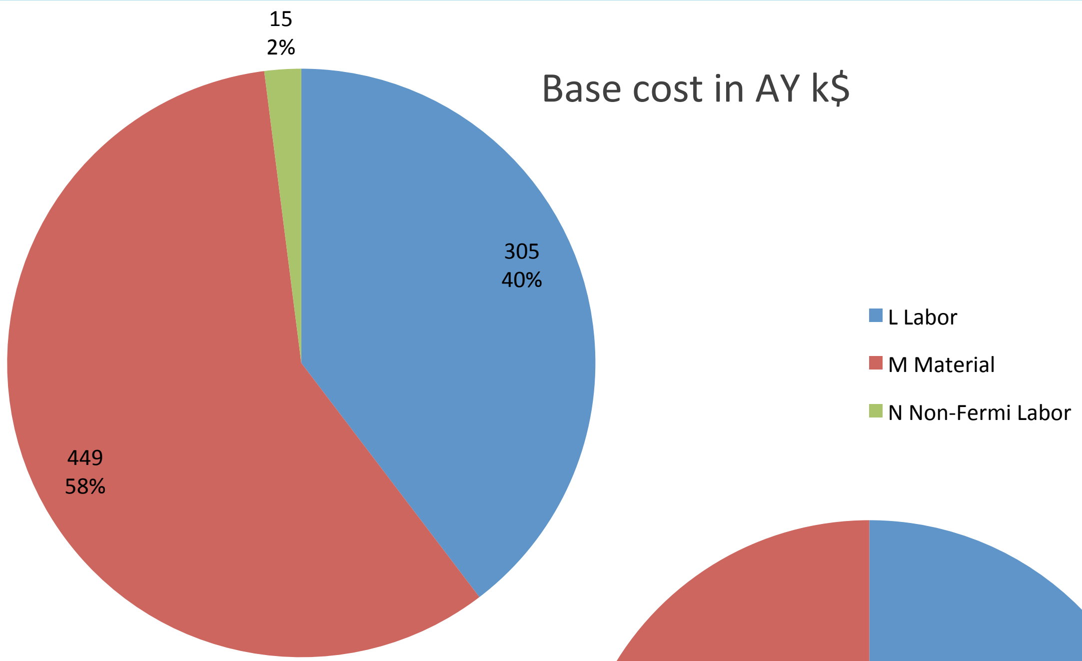
# Cost Table

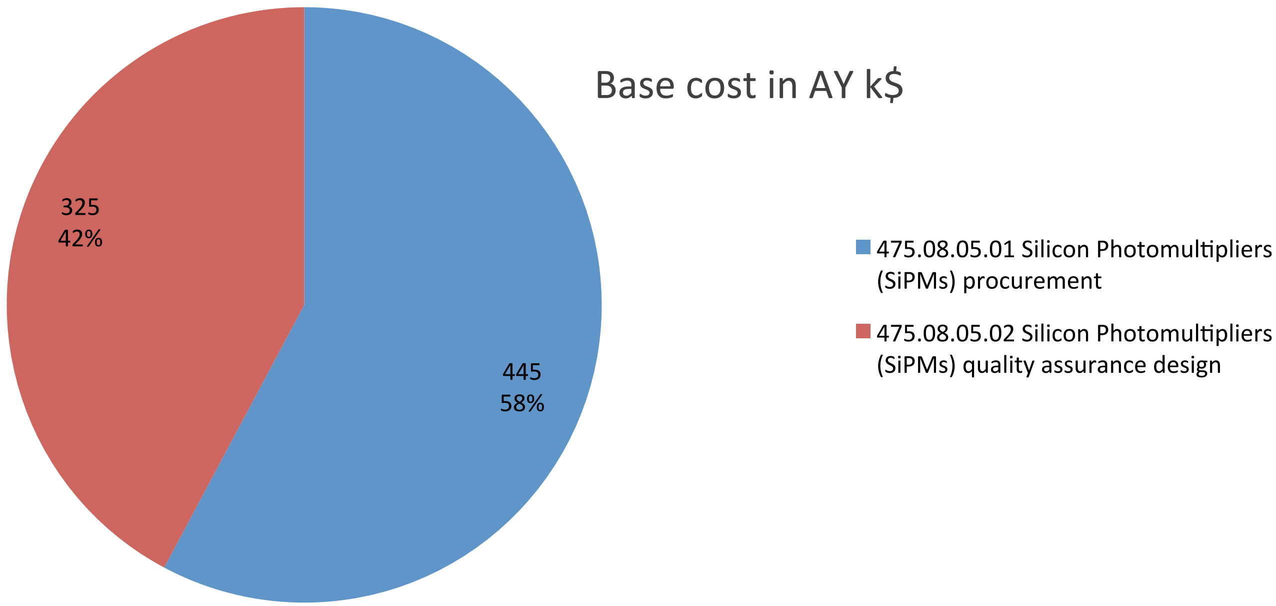
## Silicon Photomultiplier (SiPM) 475.08.05

| | Base Cost (AY K$) | | | | | |
|---|---|---|---|---|---|---|
| | M&S | Labor | Total | Uncertainty (on remaining budget) | % Contingency (on remaining budget) | Total Cost |
| 8.05.01 Photodetectors (SiPMs) procurement | 409 | 36 | 445 | 148 | 36% | 593 |
| 8.05.02 Photodetectors (SiPMs) quality assurance design | 56 | 269 | 325 | 42 | 80% | 367 |
| Grand Total | 464 | 305 | 769 | 190 | 41% | 959 |

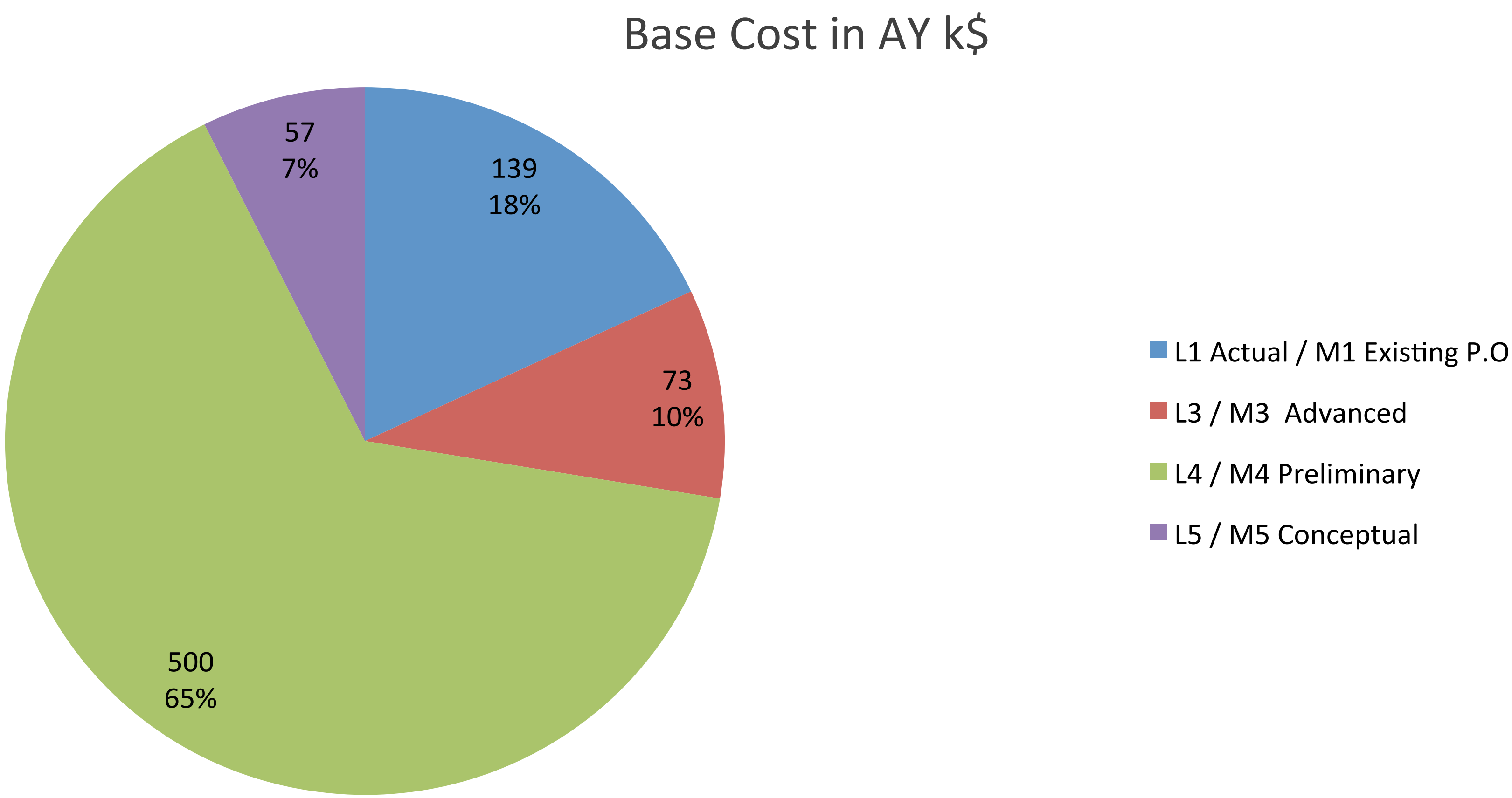
Labor in table is Fermilab Labor only

# Cost Breakdown



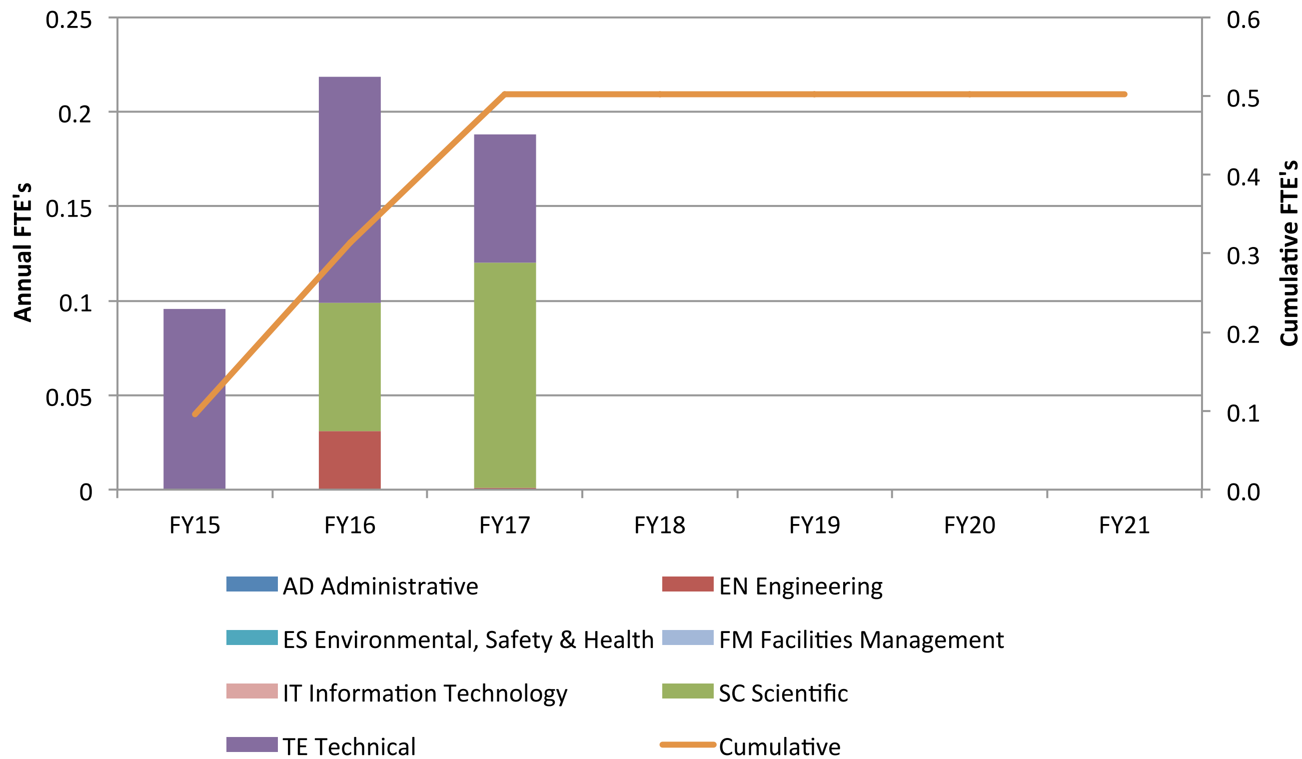



# Quality of Estimate



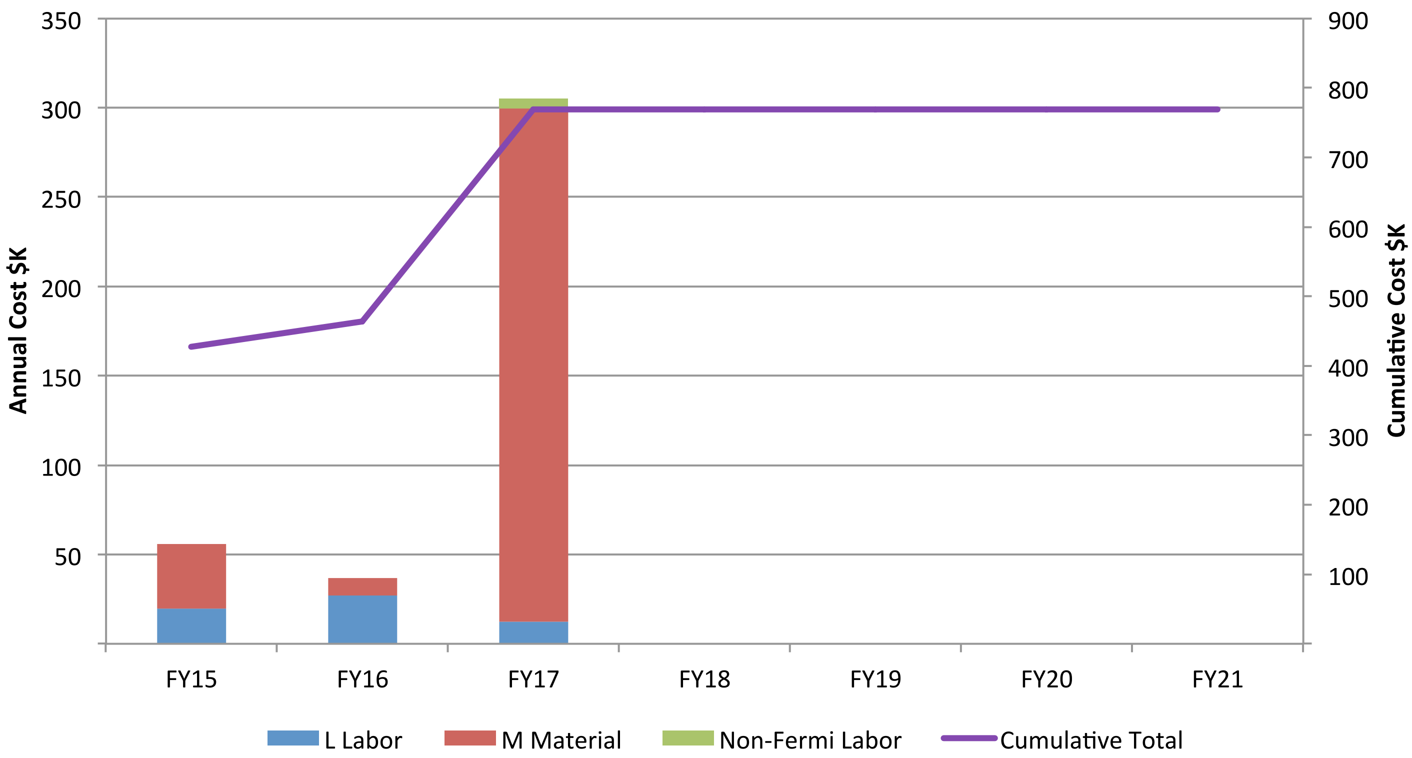
# Labor Resources by FY

## 475.08.05 Silicon Photomultipliers (SiPMs)

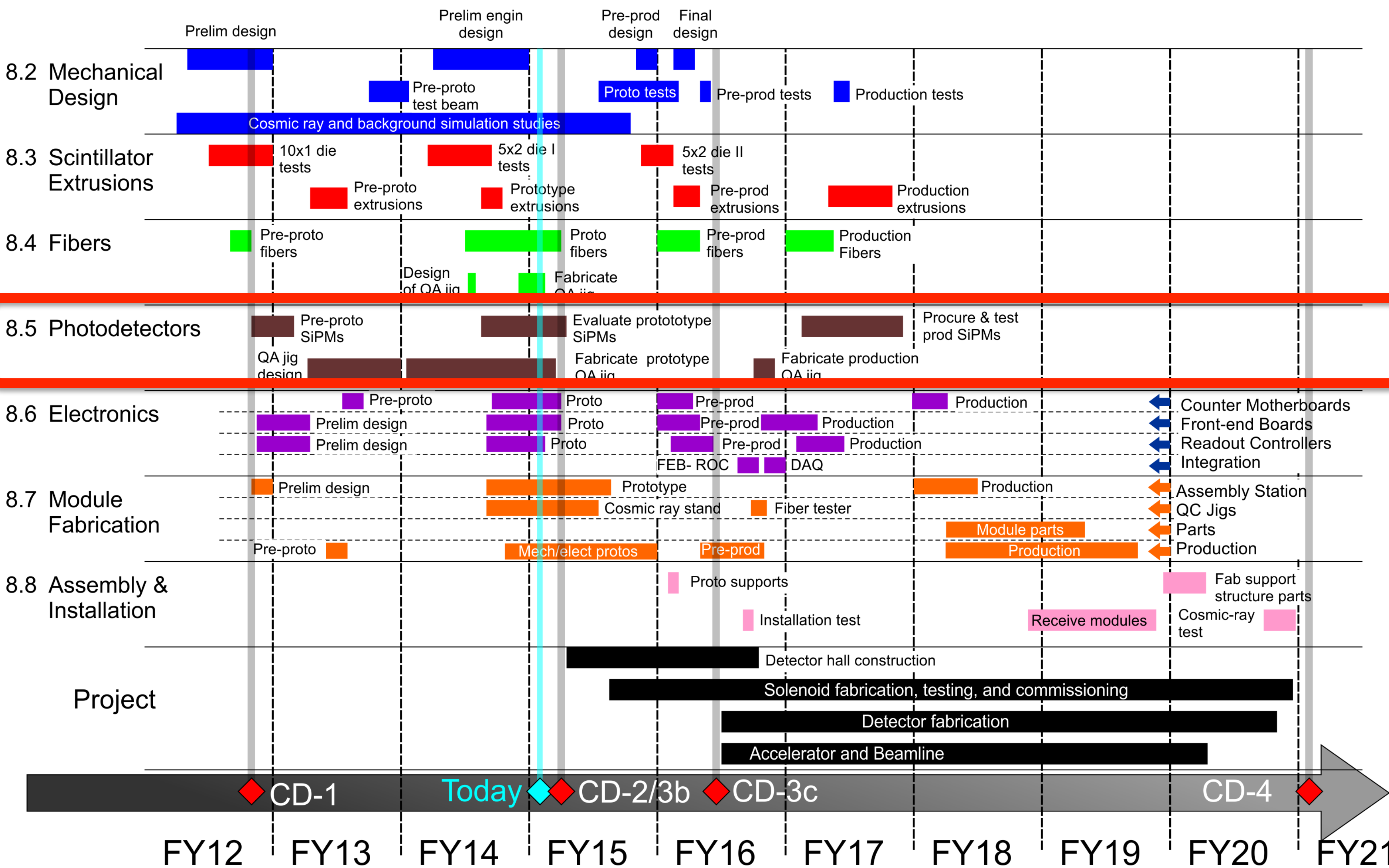


# Labor & Material Resources by FY

475.08.05 Silicon Photomultipliers (SiPMs)

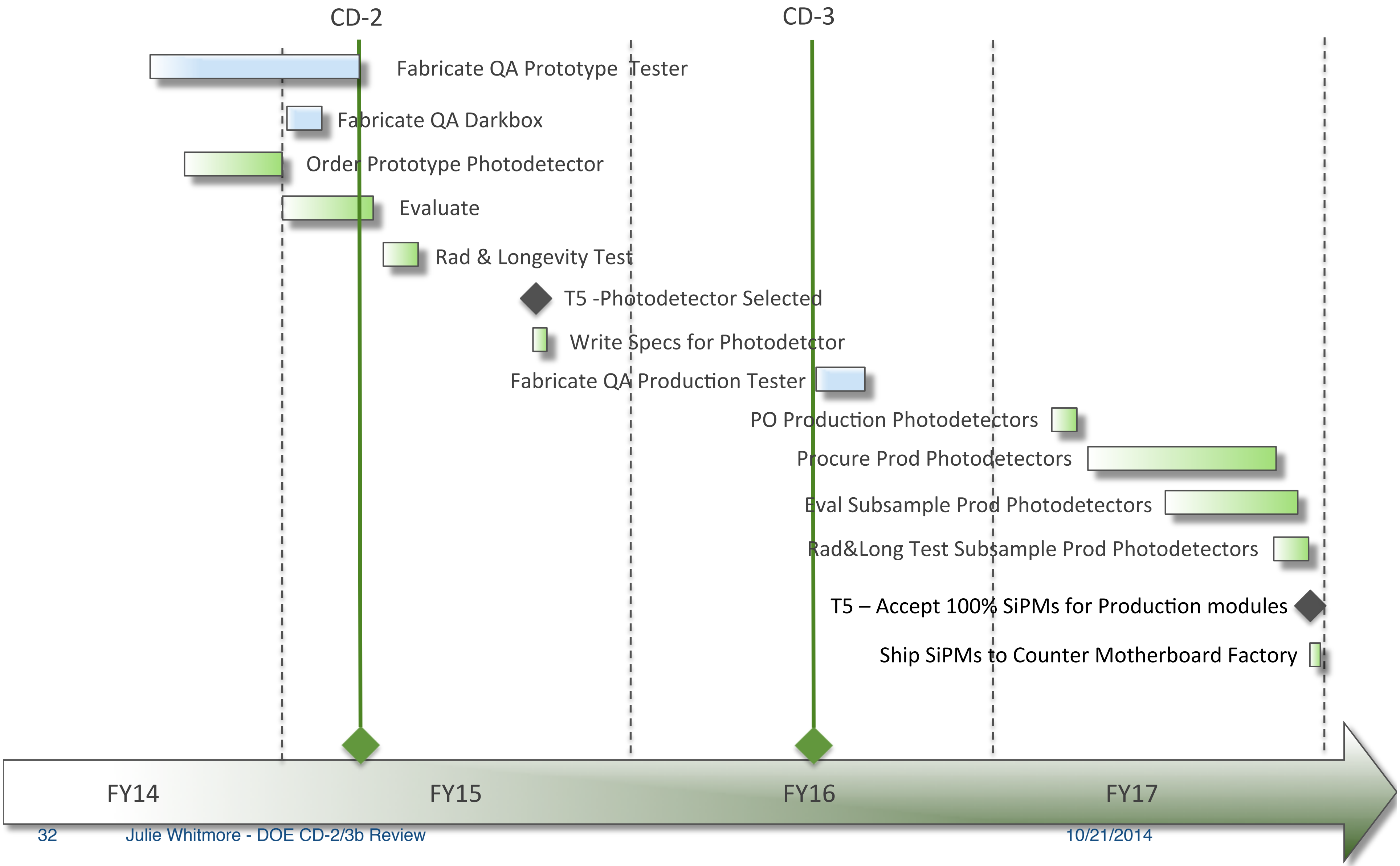


# CRV Schedule



# Schedule

## Silicon Photomultiplier (SiPM) 475.08.05



# Milestones

## Photodetectors 475.08.05

| | | | |
|---|---|---|---|
| 47508.5.2.001063 | T5 - QA Prototype Tester for photodetectors complete | 12/19/2014 | Prototypes have been evaluated, the design has been modified based on their performance, and work can begin on pre-production prototypes. |
| 47508.5.1.001082 | T5 - Prototype and pre-production photodetector testing complete | 1/28/2015 | Prototypes have been evaluated, the design has been modified based on their performance, and work can begin on pre-production prototypes. |
| 47508.5.1.001085 | T5 -Photodetectors Selected | 5/26/2015 | Photodetectors are selected for the Cosmic Ray Veto. |
| 47508.5.2.001086 | T5 - QA Production Tester for photodetectors complete | 5/16/2016 | Prototypes have been evaluated, the design has been modified based on their performance, and work can begin on pre-production prototypes. |
| 47508.5.1.001240 | T5 - Production Photodetectors 100% accepted | 8/31/2017 | 100% of production SiPMs have been procured and tested. |

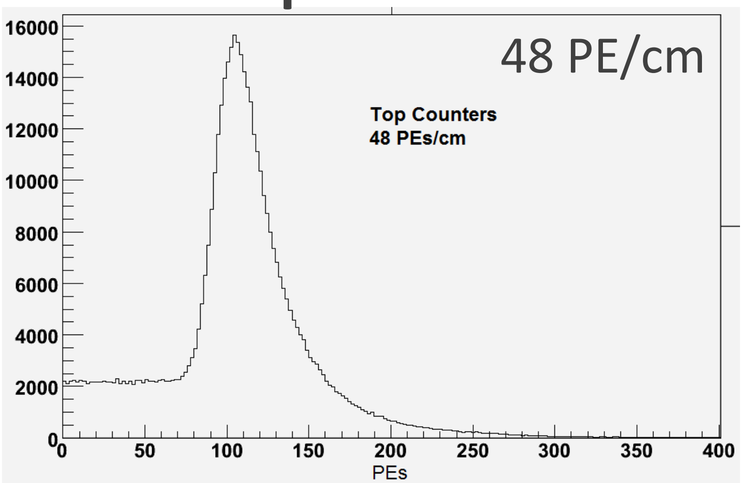
# Summary

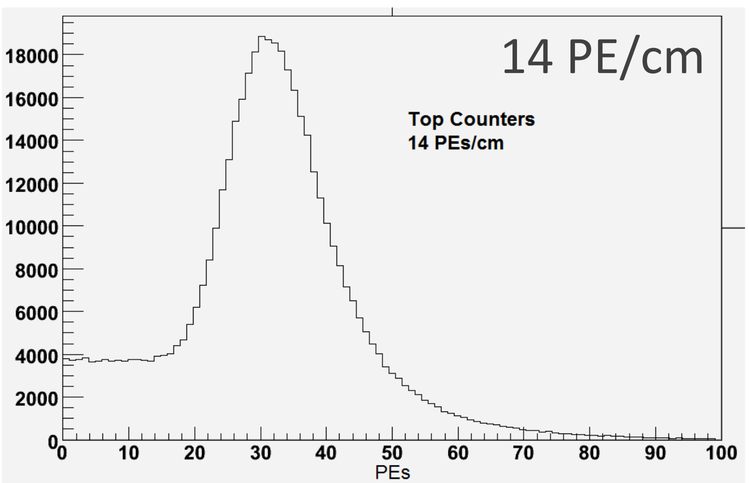
- Overall requirements are well understood
- SiPM requirements can be achieved with commercially available devices
  - May need custom mask to reduce active area and assoc. dark count noise, but SiPM process will be from standard catalog
  - Prototype devices have been ordered (some are in hand)
    - Radiation and Longevity qualification testing to begin in Fall 2014
    - Prototype counters should be available for study in Winter 2014
  - QA prototype tester fabrication is complete
    - Hardware is fabricated and testing software is being developed.
- SiPM cost and schedule are well understood.
  - SiPM development is not on the critical path.

# Backup Slides

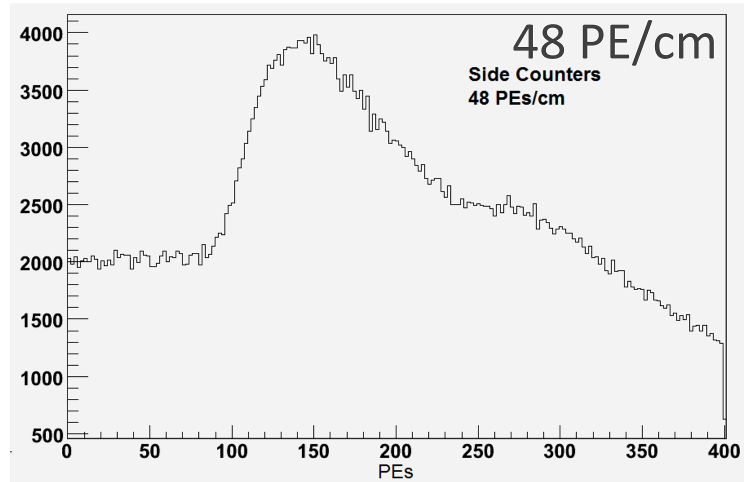
# Monitoring SiPM Calibration

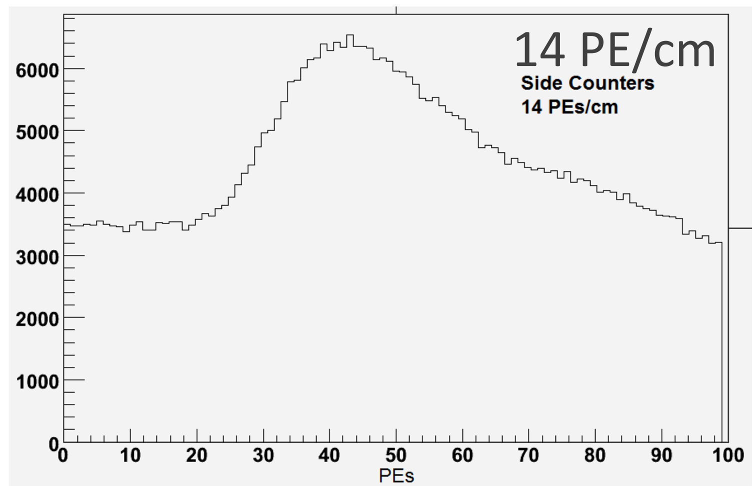
## Top Counters




## Side Counters



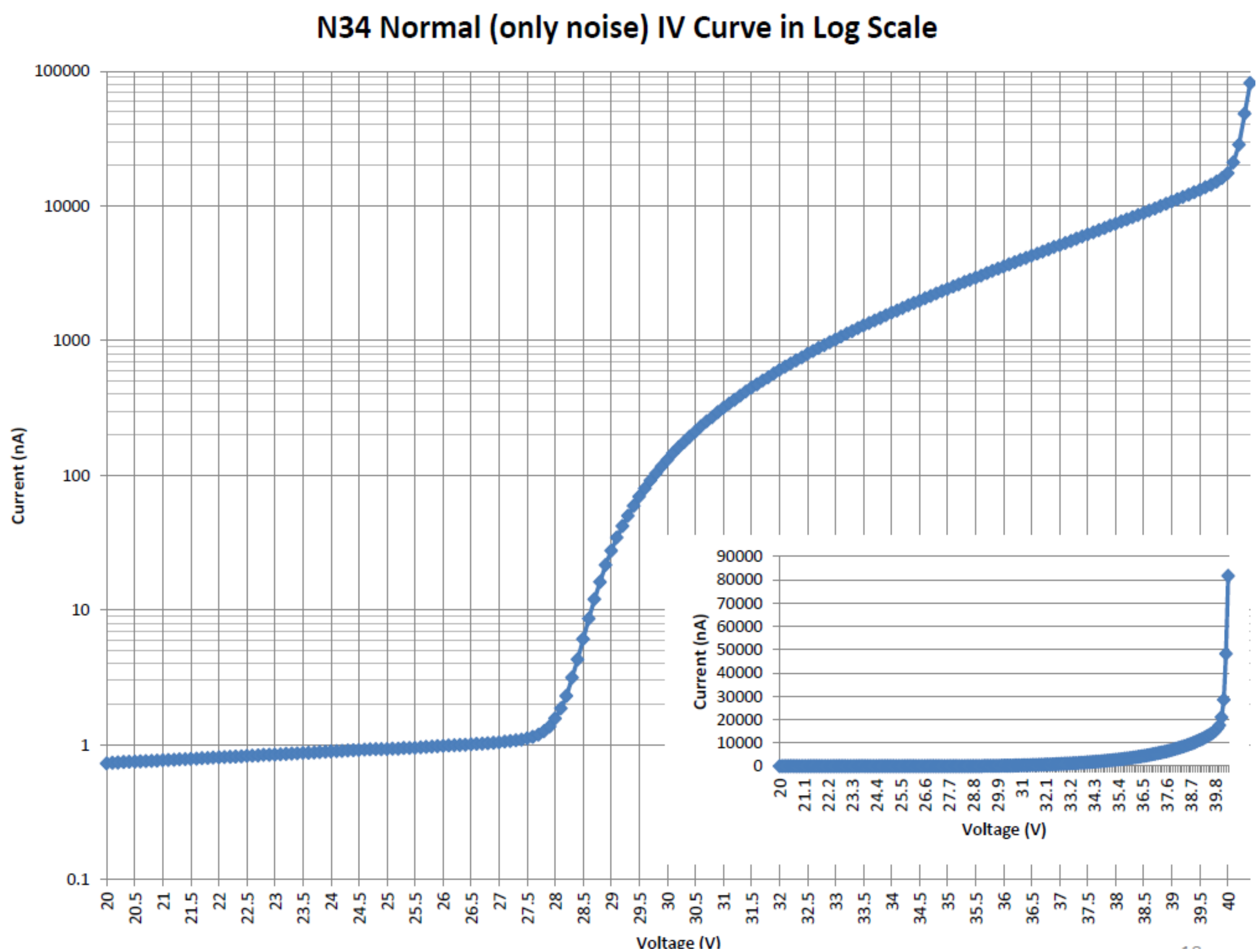




Monitor SiPMs via muon distributions.

Device dynamic range: up to 200 PE

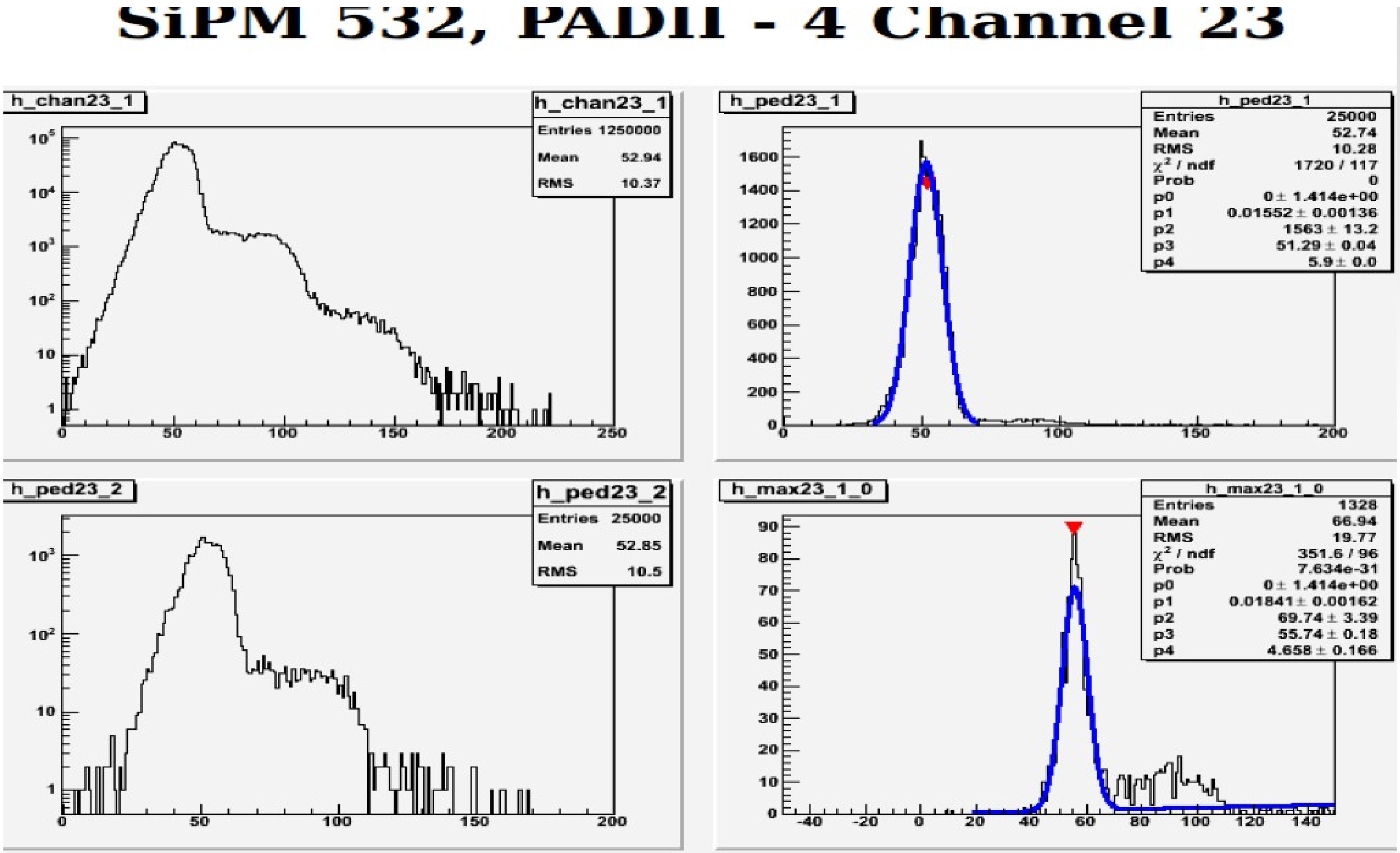
# SiPM IV Curve

From NIU Test Stand – SiPM IV Curve



# SiPM Spectrum

From NIU Test Stand - SiPM Spectrum



# SiPM Characterization DB

From NIU Test Stand - SiPM Characterization DB

| SiPM#, color | PAD/SIB | Channel | Manufacturer $V_{op}$ | 1PE $V_{op}$ | Temp | Pedestal | $\sigma_{ped}$ | ADC/PE | $\sigma_{pe}$ |
|---|---|---|---|---|---|---|---|---|---|
| 518, RED | II-4/2 | 0 | 25.3 | 25.9 | 19.1 | 52.4515 | 5.43197 | 51.6219 | 5.88819 |
| 522, RED | II-4/2 | 1 | 25.3 | 25.9 | 19.1 | 69.0442 | 6.12989 | 50.7803 | 7.38995 |
| 519, RED | II-4/2 | 2 | 25.3 | 25.9 | 19.1 | 66.2889 | 5.52662 | 48.9158 | 7.27518 |
| 523, RED | II-4/2 | 3 | 25.3 | 25.9 | 19.1 | 64.912 | 5.91942 | 48.5432 | 6.64108 |
| 524, RED | II-4/2 | 4 | 25.3 | 25.9 | 19.1 | 63.6442 | 3.92661 | 47.7755 | 5.25292 |
| 520, RED | II-4/2 | 5 | 25.3 | 25.9 | 19.1 | 63.934 | 6.30455 | 52.9114 | 7.12688 |
| 521, RED | II-4/2 | 13 | 25.3 | 25.9 | 19.1 | 58.0117 | 6.75008 | 9.14155 | 0.922428 |
| 525, RED | II-4/2 | 14 | 25.3 | 25.9 | 19.1 | 60.8009 | 5.03709 | 53.1796 | 5.46644 |
| 526, RED | II-4/2 | 20 | 25.3 | 25.9 | 19.1 | 59.1828 | 4.29849 | 49.6961 | 5.78099 |
| 531, RED | II-4/2 | 21 | 25.3 | 25.9 | 19.1 | 62.661 | 5.35824 | 51.4587 | 5.72444 |
| 527, RED | II-4/2 | 22 | 25.3 | 25.9 | 19.1 | 55.6841 | 4.81777 | 54.5687 | 7.77767 |
| 532, RED | II-4/2 | 23 | 25.3 | 25.9 | 19.1 | 51.2943 | 5.89964 | 50.0822 | 5.19438 |
| 528, RED | II-4/2 | 27 | 25.3 | 25.9 | 19.1 | 50.9599 | 6.89733 | 53.157 | 5.56358 |
| 529, RED | II-4/2 | 28 | 25.3 | 25.9 | 19.1 | 56.8352 | 3.74752 | 53.6804 | 6.82988 |
| 533, RED | II-4/2 | 29 | 25.3 | 25.9 | 19.1 | 55.8558 | 3.34772 | 49.0546 | 5.11184 |
| 530, RED | II-4/2 | 30 | 25.3 | 25.9 | 19.1 | 59.6764 | 3.90095 | 53.6732 | 5.52982 |
| 534, RED | II-4/2 | 31 | 25.3 | 25.9 | 19.1 | 53.275 | 3.5067 | 51.5266 | 4.66009 |