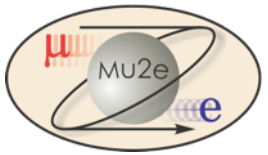
Fermilab

U.S. DEPARTMENT OF ENERGY Office of Science

Mu2e CD-2 Review
8.5 CRV Photodetectors

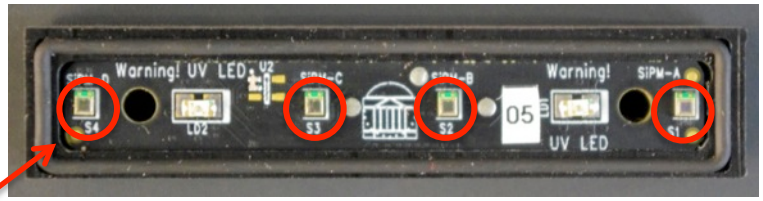


Julie Whitmore
Mu2e CRV Deputy L2 & SiPMs L3
7/8/2014

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 1×10^{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)

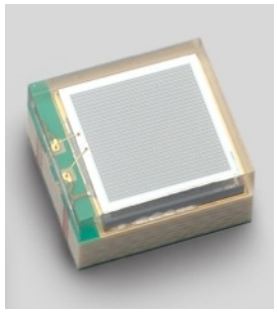
SiPM

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

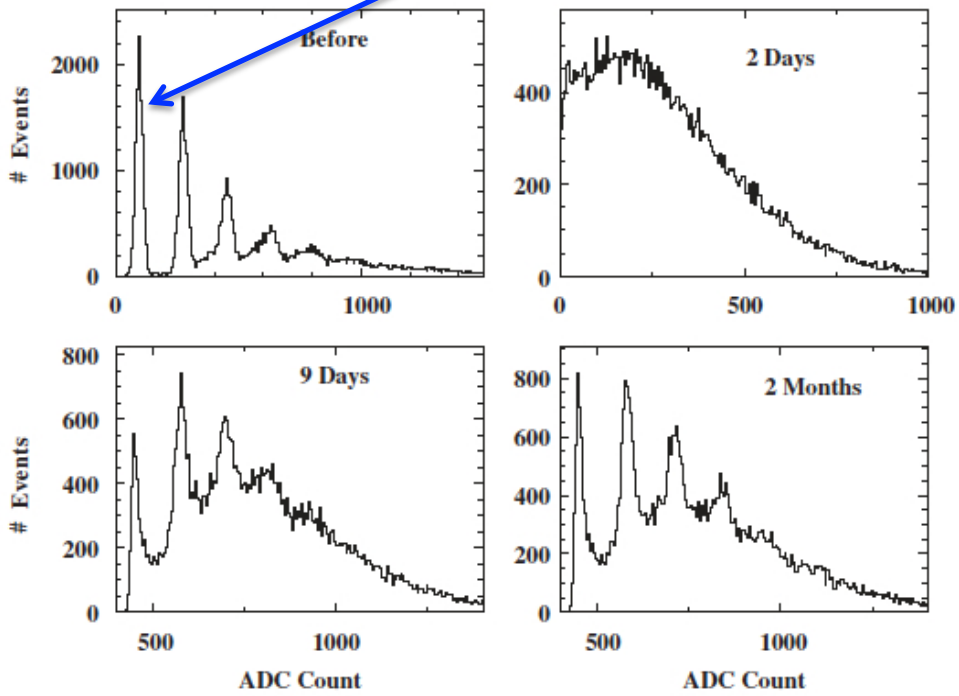
Radiation Damage

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



Integrated flux to SiPMs is required to be kept below $1x10^{10}$ n/cm^2 . (1 MeV neutron equivalent)

Single PE Nakamura, NimA 610 (2009), 110-113



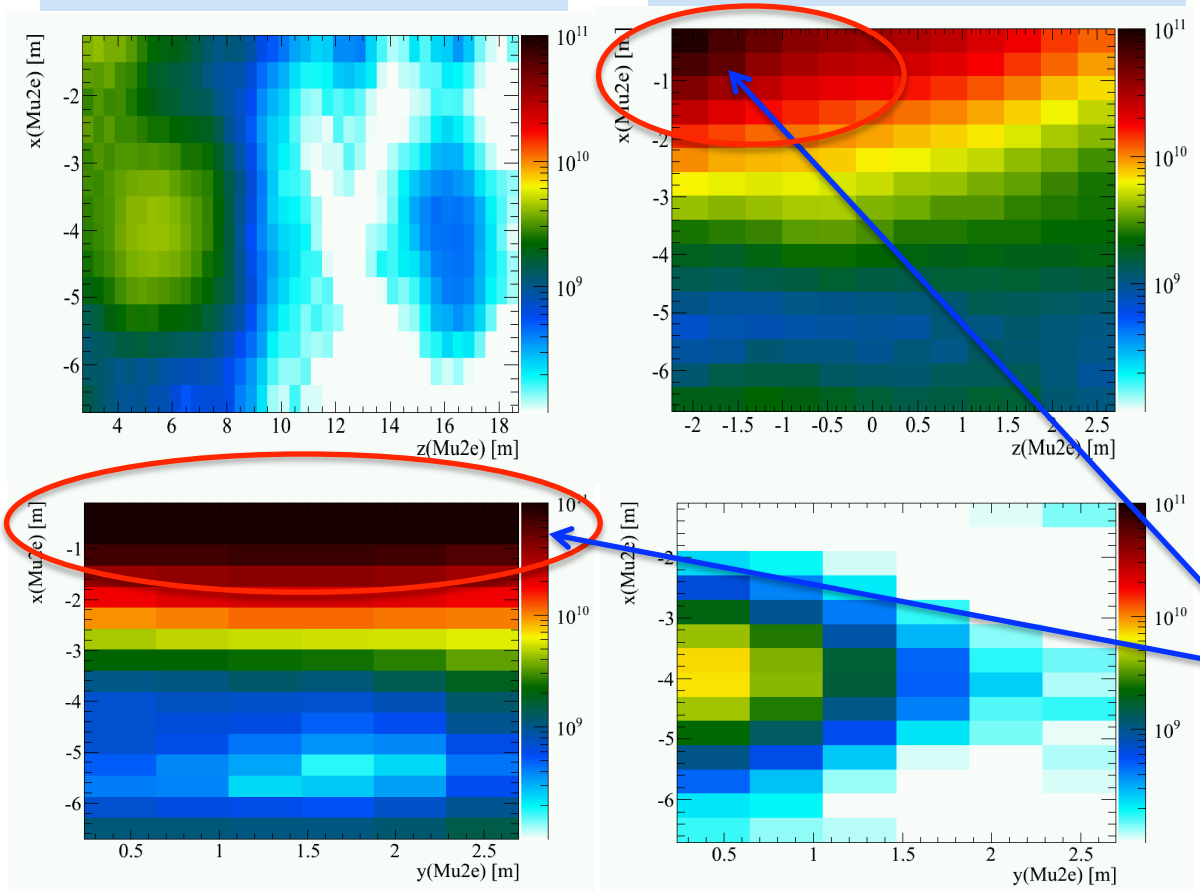
SiPM – Irradiated with $2x10^{10}$ n/cm^2. Dark count before and after irradiation, And after 2 days, 9 days, and 2 months of annealing.

Simulations: Neutron Radiation Damage

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

DS Top

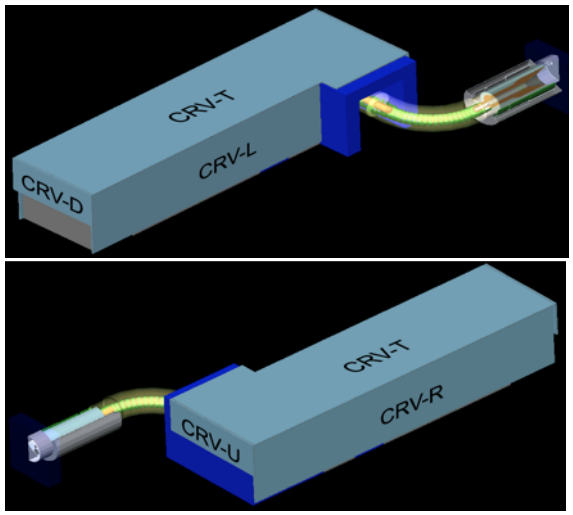
TS Top



Upstream

Downstream

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



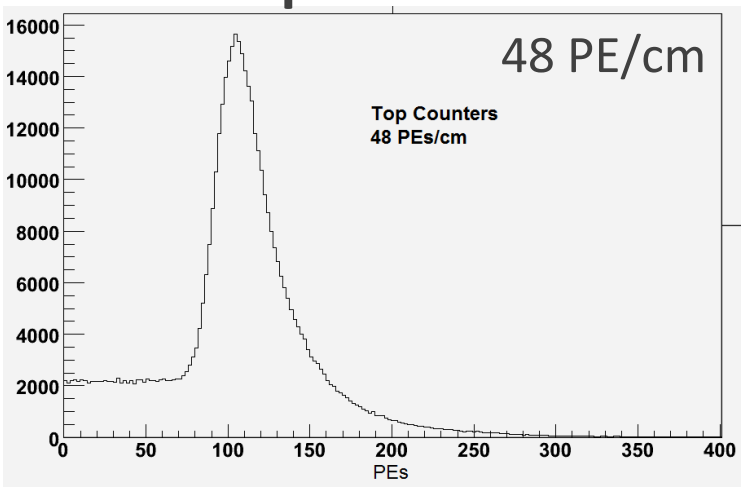
Upstream region a problem
Red = 10^{10} n/cm2
Black = 10^{11} n/cm2

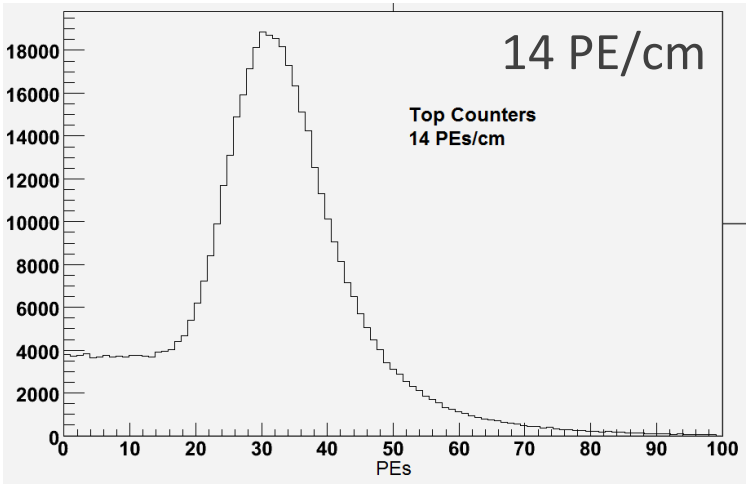
SiPM Operation Plan

- 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.
  - 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.

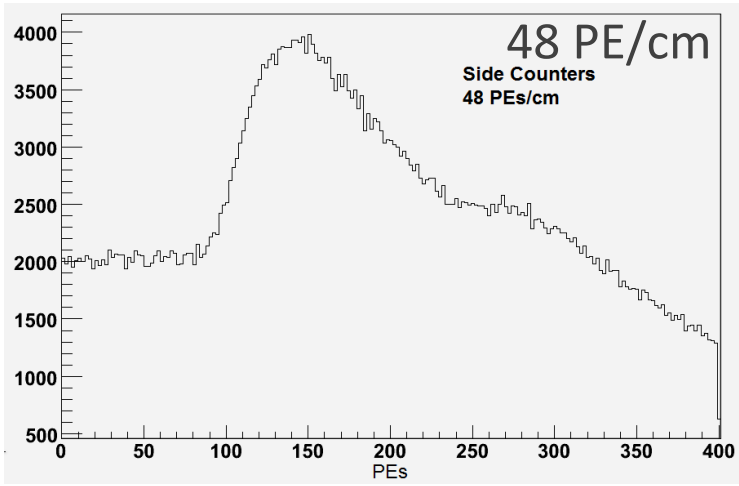
Monitoring SiPM Calibration

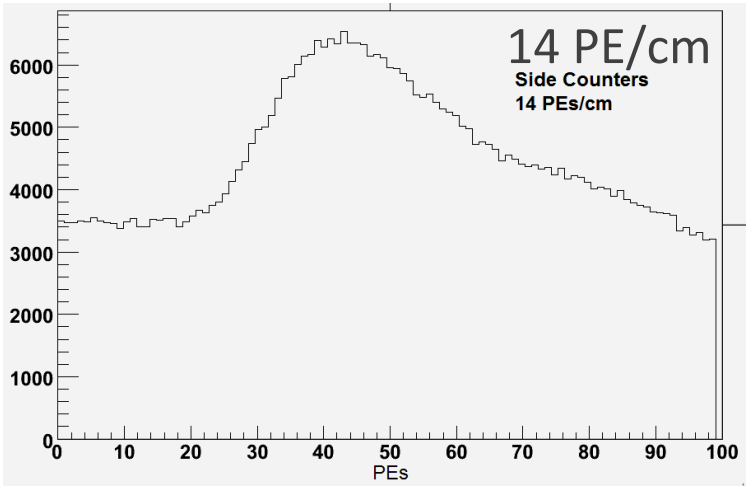
Top Counters





Side Counters





Monitor SiPMs via muon distributions.

Device dynamic range: up to 200 PE

Changes since CD-1

- No significant changes to Mu2e photodetector requirements
  - Better understanding of our backgrounds and required light yield

- Major changes since CD-1 are significant improvements in SiPMs
  - More vendors are developing lower noise, higher PDE devices that are intrinsically more radiation hard

Value Engineering since CD-1 (1)

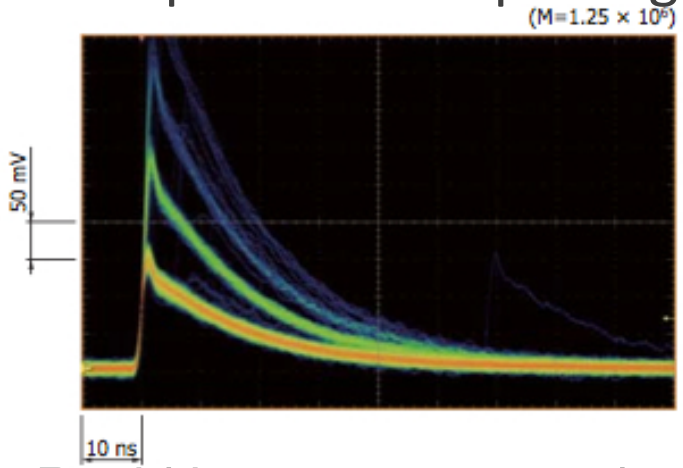
- Benefited from US CMS SiPM R&D with vendors
  - Multiple vendors fabricating radiation hard SiPMs
    - Improved performance (PDE and noise), wider dynamic range, lower cost
    - Quite likely current commercially available SiPMs will meet our requirements
- Benefited from T2K Experience
  - T2K has 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)

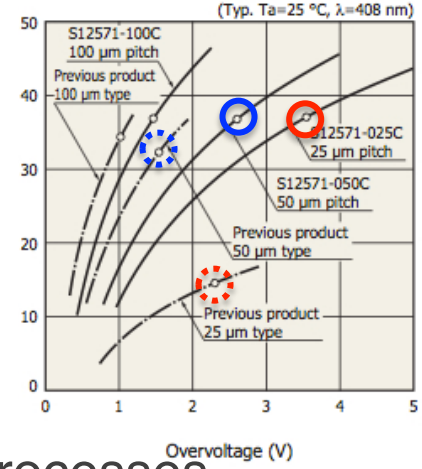
- Benefited from NIU/FNAL/Delhi Proton Computed Tomography (pCT) Scanner Project
  - Developed test procedures and infrastructure for pCT project (3000 SiPMs)
  - Mu2e NIU and FNAL experimenters involved in pCT project
    - SiPM expertise: FNAL Eng Phys (Paul Rubinov), NIU physicists and students
 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

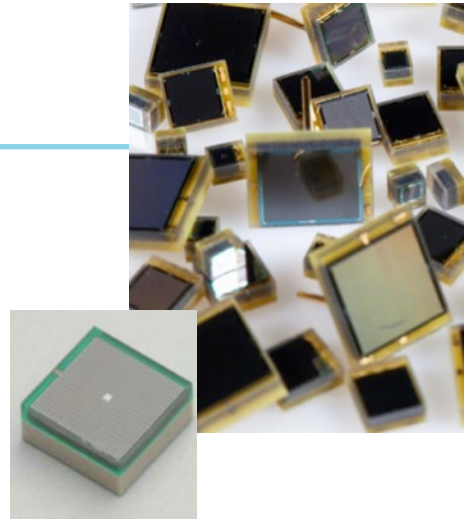
SiPM Procurement

Improved Afterpulsing



PDE: New vs Old





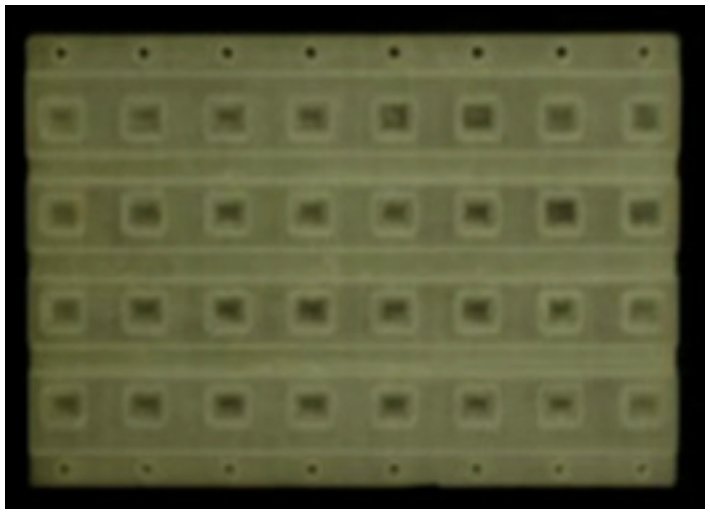
TSV-Thinner epoxy coating than SMD (100 µm vs 300 µm)

- 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 has 1mm x 1mm or 3mm x 3mm (no custom size)

SiPM Testing

- Radiation Qualification
  - Reactor neutrons
    - UC Davis reactor (Energy 1-10 MeV)
    - 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 ^{o}C
    - Mu2e running (3 yrs)
  - Device oven test:
    - 70 ^{o}C for 48.4 days

SiPM QA Tester

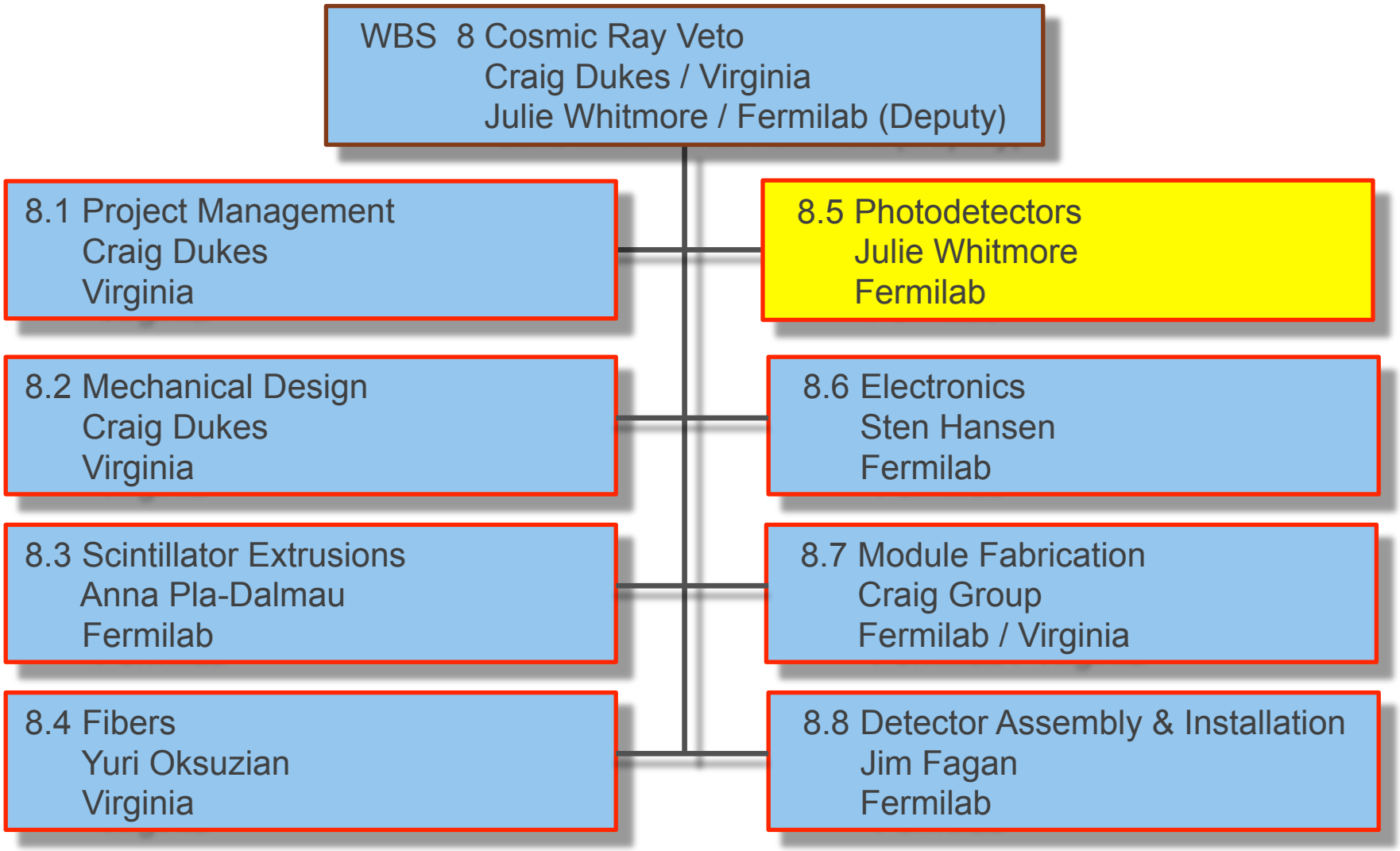


- QA Testing
  - Need to test many devices in parallel
    - Testing design for I-V tester with a simple scheme for providing bias
  - Need to do both I-V and pulse mode testing on a small number of devices
    - Longevity/Radiation testing for batch validation

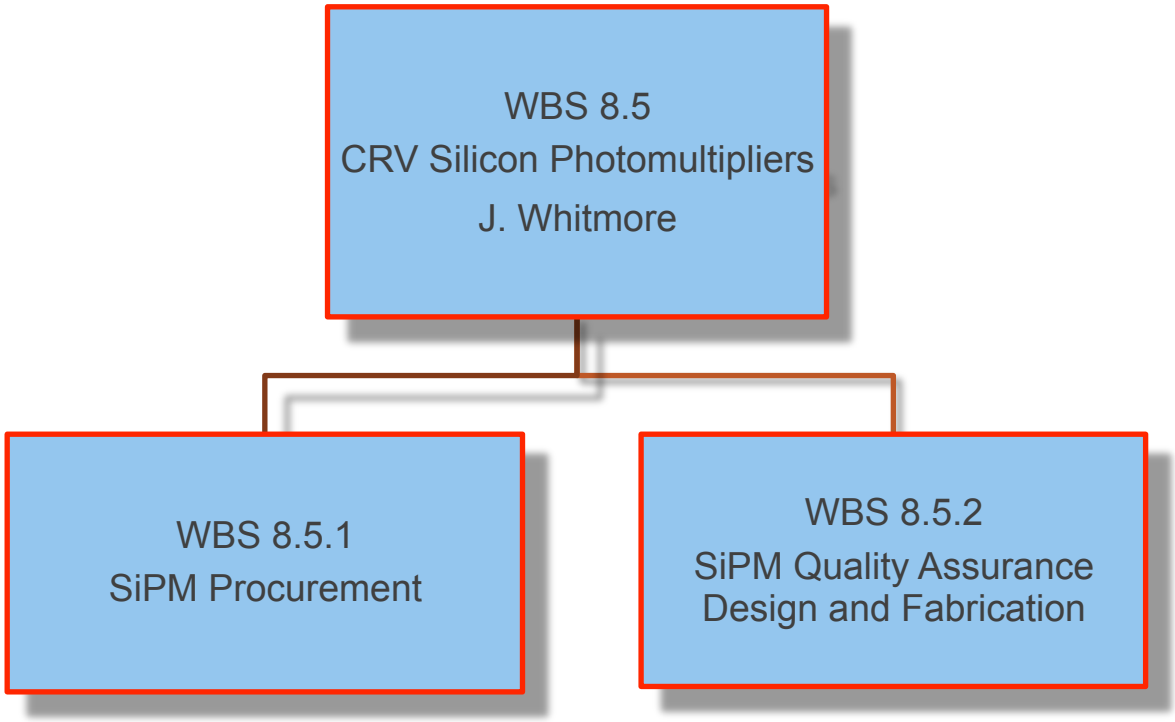
Remaining work before CD-3

- 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.

Organizational Breakdown



Organizational Breakdown



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

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

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%)

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	10%	$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
  - Cost is ~$50k. No serious schedule impact.

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.)

Cost Table

Cosmic Ray Veto 475.08

Cost in AY k$

	M&S	Labor	Base Cost	Estimate Uncertainty	% Contingency on ETC	Total
475.08.01 Project Management	273	178	452	75	20%	526
475.08.02 Mechanical Design	136	3	139	24	29%	163
475.08.03 Scintillator extrusions	559	457	1,015	206	22%	1,221
475.08.04 Fibers	455		455	105	24%	559
475.08.05 Silicon Photomultipliers (SiPMs)	460	306	766	188	36%	954
475.08.06 Electronics	1,312	406	1,718	509	32%	2,227
475.08.07 Module Fabrication	1,460	16	1,476	462	34%	1,938
475.08.08 Detector assembly and installation	124	80	204	63	35%	267
475.08.09 Cosmic Ray Veto Conceptual Design/R&D	258	252	511	0	0%	511
Risk Based Contingency				323		323
Total	5,036	1,698	6,735	1,955	36%	8,690

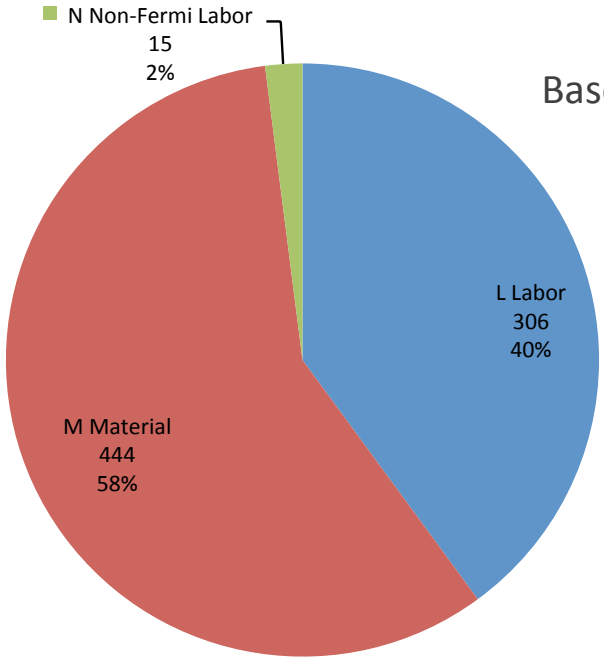
Cost Table

Silicon Photomultiplier (SiPM) 475.08.05

	Base Cost (AY k$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining costs)	% Contingency on ETC	Total Cost
475.08 Cosmic Ray Veto						
475.08.05 Silicon Photomultipliers (SiPMs)						
475.08.05 SiPMs Actuals	31	213	243			243
475.08.05.01 SiPMs procurement	375	33	408	147	36%	555
475.08.05.02 SiPMs quality assurance design	54	60	114	42	37%	156
Grand Total	460	306	766	188	36%	954

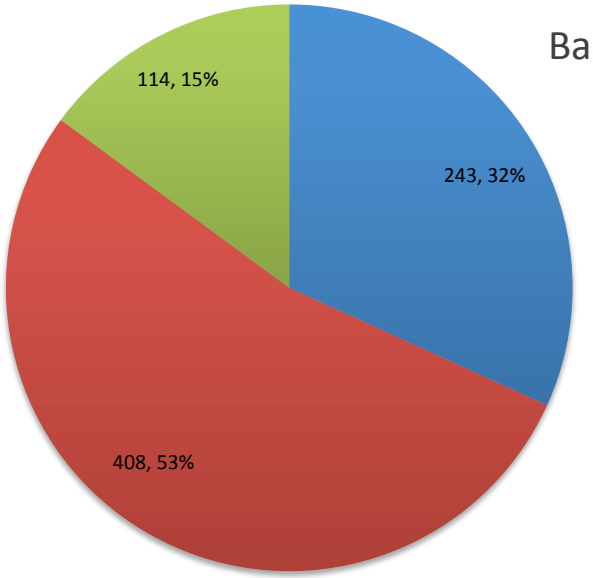
Labor in table is Fermilab Labor only

Cost Breakdown



Base cost in AY k$

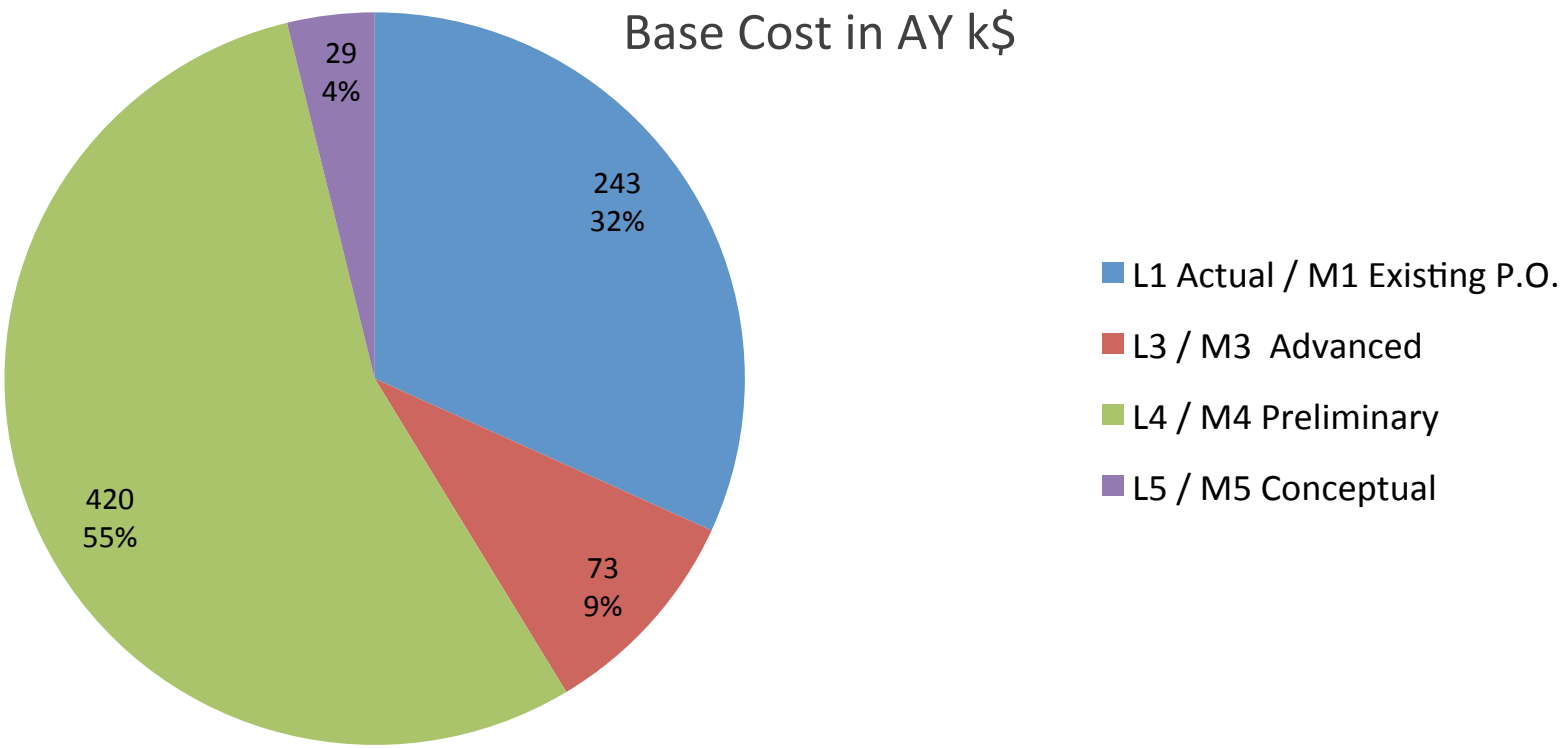
L Labor
M Material
N Non-Fermi Labor



Base cost in AY k$

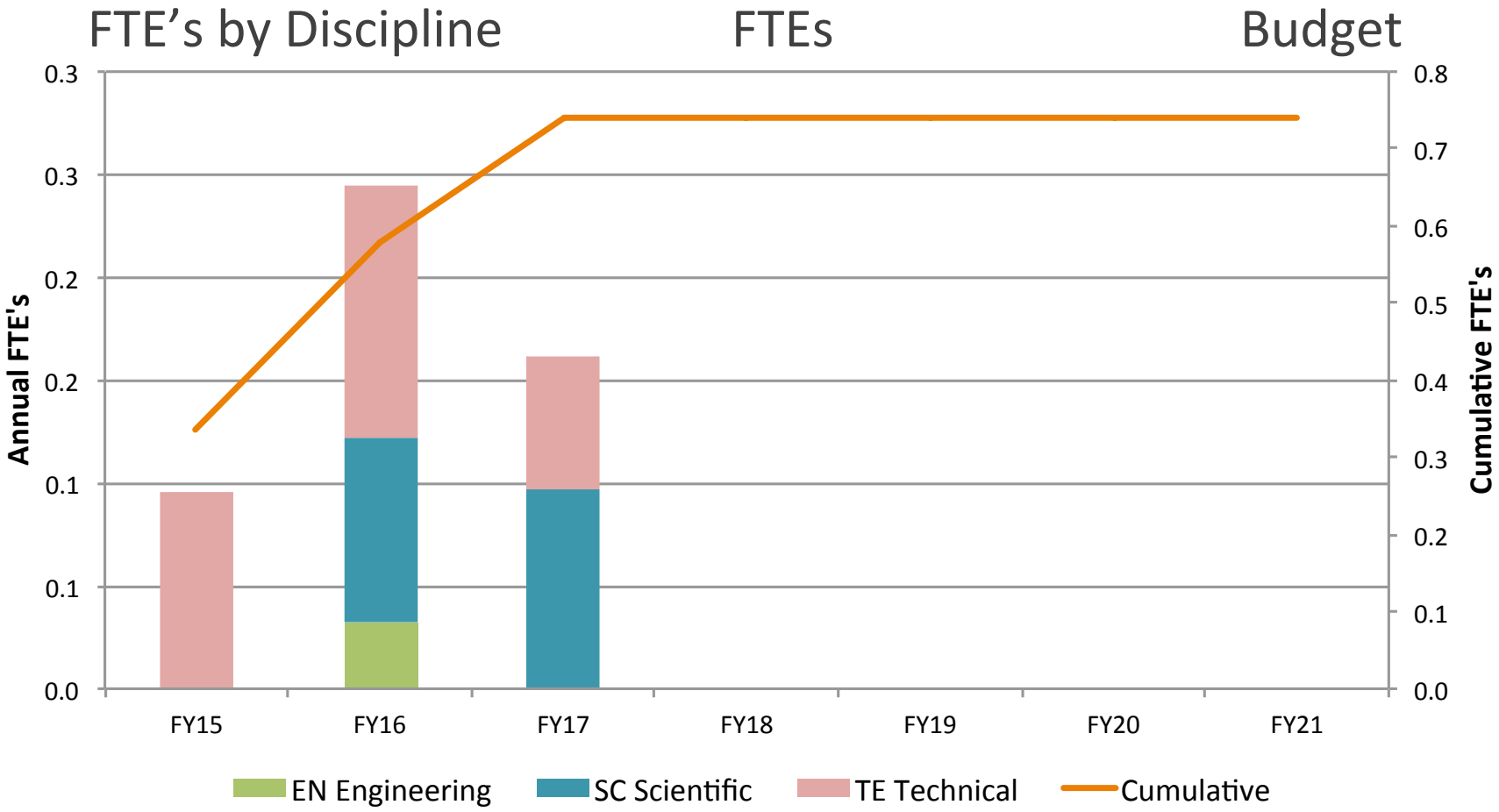
475.08.05 Silicon Photomultipliers (SiPMs) Actuals
475.08.05.01 Silicon Photomultipliers (SiPMs) procurement
475.08.05.02 Silicon Photomultipliers (SiPMs) quality assurance design

Quality of Estimate



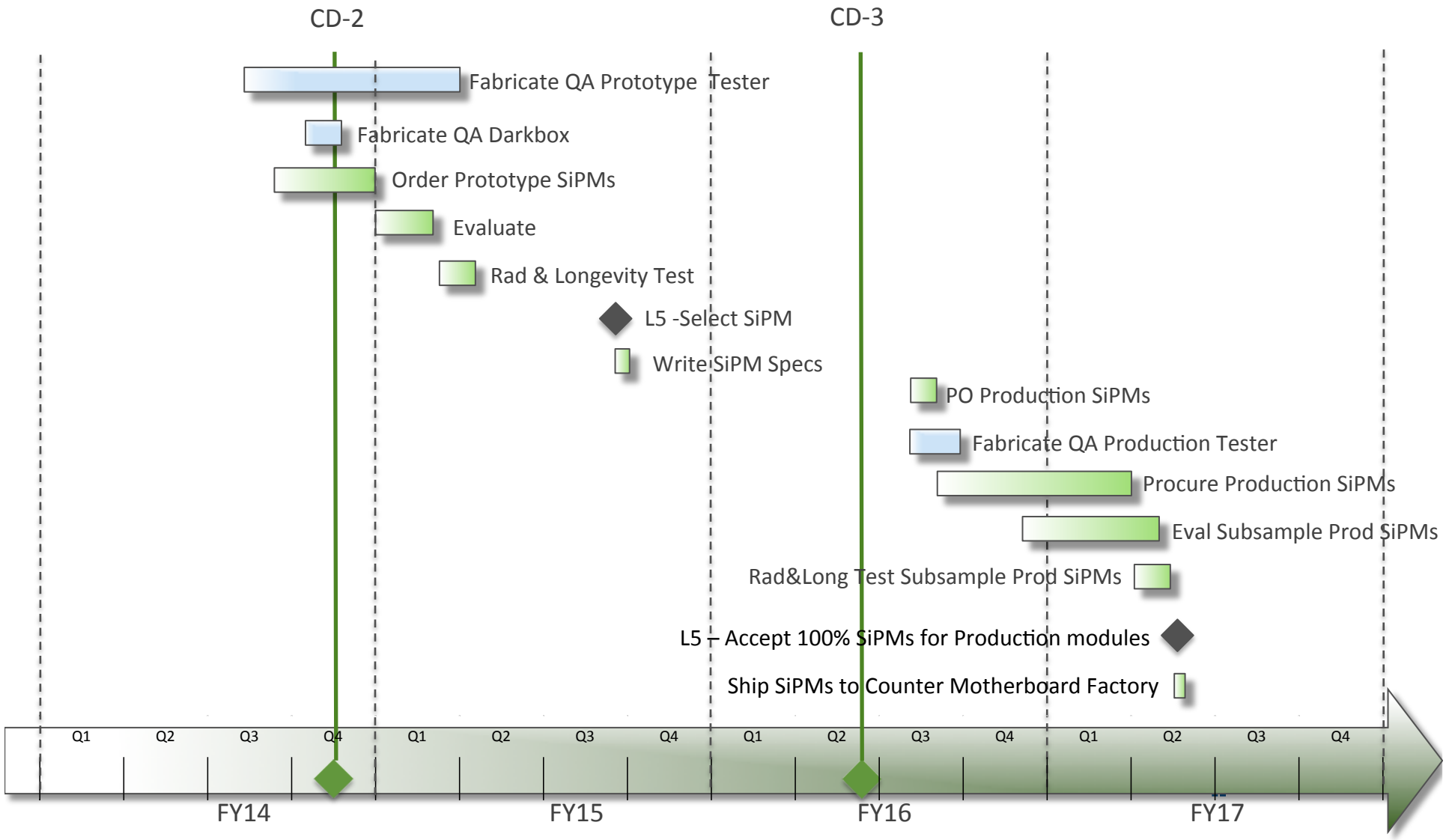
Labor Resources by FY

475.08.05 Silicon Photomultipliers (SiPMs)



Schedule

Silicon Photomultiplier (SiPM) 475.08.05



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
    - Radiation and Longevity testing to begin in late summer 2014
    - Prototype counters should be available for study in Fall 2014
  - QA prototype tester fabrication is underway
    - Hardware is being fabricated and software is being developed.
- SiPM cost and schedule are well understood.
  - SiPM development is not on the critical path.