Fermilab

Mu2e Cosmic Ray Veto

E. Craig Dukes (University of Virginia)
Cosmic Ray Veto (CRV) Project Manager

J. Whitmore (Fermilab)
Cosmic Ray Veto (CRV) Deputy Project Manager

10/21/2014

Cosmic Ray Veto Team

- **E. Craig Dukes** – L2 Manager
  - 30 years working at Fermilab
  - Co-spokesperson: HyperCP
  - L3 Manager: NOvA Power Distribution System
- **Julie Whitmore** – Deputy L2 Manager
  - Fermilab scientist for 20 years
  - L2 Manager: CMS HCAL Maintenance & Operations
  - L3 Manager: CMS HCAL Upgrade

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

Requirements: Fundamental

The requirements for the Cosmic Ray Veto are described in Mu2e-doc-944.

Fundamental (detector independent) requirements:

1. To reduce the conversion-like electron background from cosmic rays to less than 0.1 events over the course of the run
2. To provide a cosmic-ray trigger primitive to the DAQ
3. Not to produce more than 10% dead time
4. Not to use more than 20% of the DAQ bandwidth

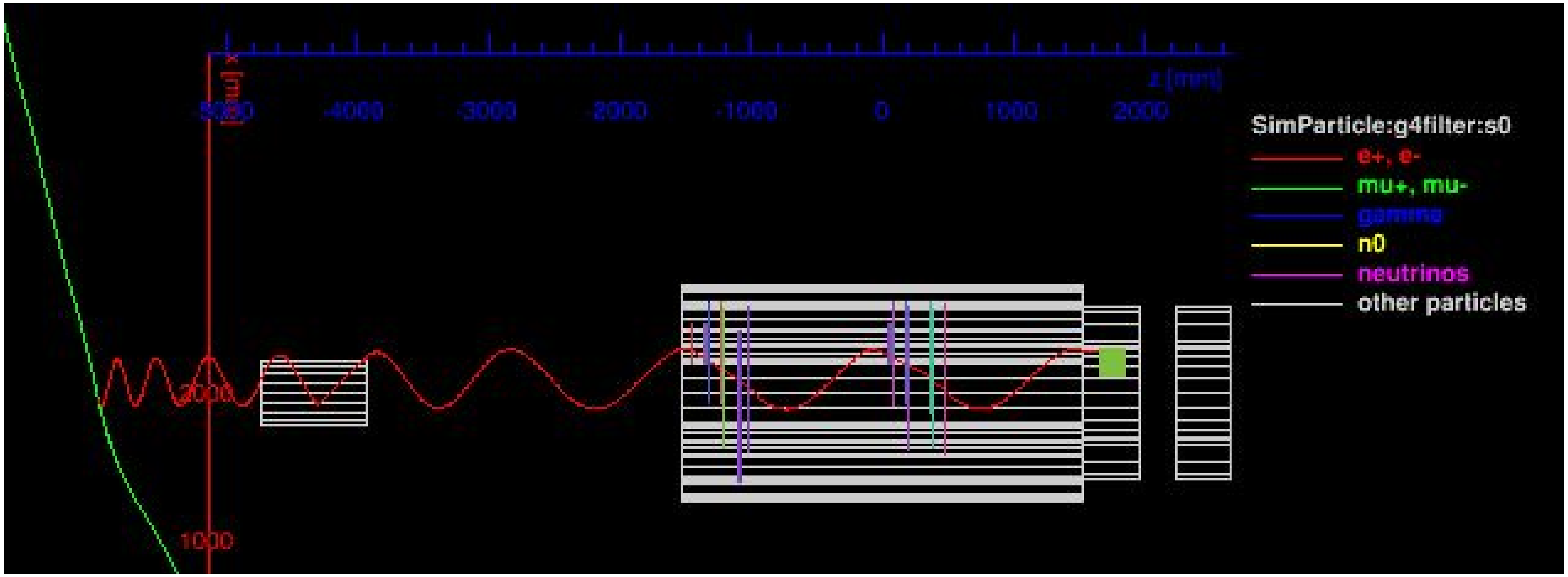
Note: about 1 conversion-like electron per day is produced by cosmic-ray muons

Requirements: Derived

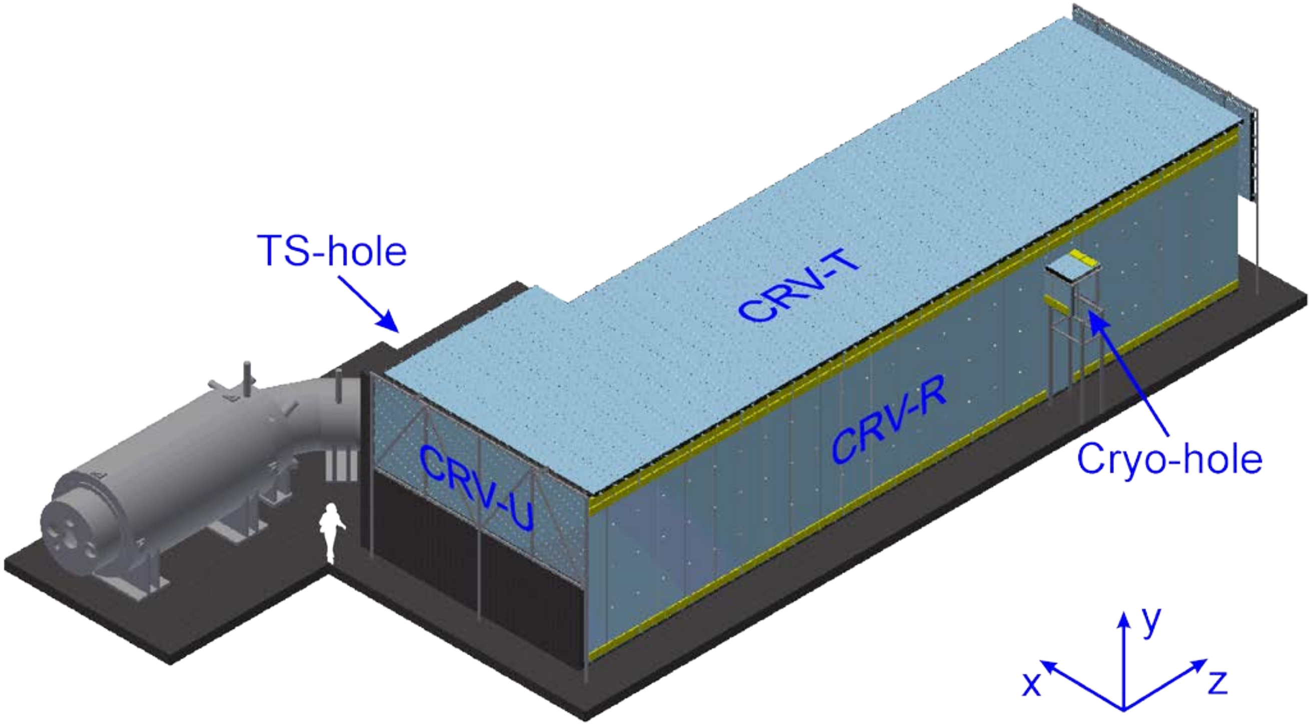
1. The overall inefficiency for identifying cosmic-ray muons must be no worse than $1x10^{-4}$.
2. The photoelectron yield of the cosmic-ray scintillation counters must be at least 14 PE/cm.
3. The time resolution of the cosmic ray veto should be on the order of 5 ns in order to reduce the accidental coincidence rate from counter "noise".
4. The hit rate per photodetector (SiPM) should be no more than 1 MHz.
5. The total neutron dose to the photodetectors and front-end electronics must be less than 1×10^{10} n/cm^2, and the electronics must survive this dose with no untoward effects.
6. The DAQ should trigger on no more than 1/100 microbunches.
7. The detectors and DAQ should run during the interspill period.

Requirement: Background Rejection

- Simulations of 28 billion cosmic ray muons show that an inefficiency of no worse than10^{-4} is required.
- These simulations have vetted the CRV coverage described in the CDR.
- A targeted simulation of ~100% of the total live time show that no electron conversion-like background events come through the TS “hole”; however there are muons that mimic conversion-electron events that need to be removed by the calorimeter and tracker.



Design: Layout



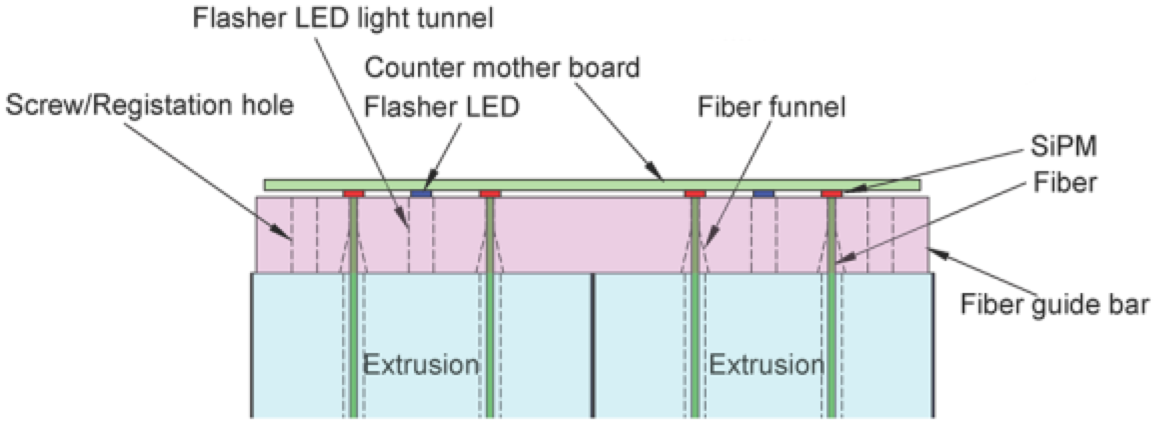
Design vetted in outside CRV-Review (June 3, 2014)

Details:
- Area: 323 m^2
- 82 modules 7 sizes
- 5,152 counters
- 10,254 fibers
- 18,944 SiPMs

- CRV identifies cosmic ray muons that produce conversion-like backgrounds.
- Design driven by need for excellent efficiency, large area, small gaps, high 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.
- A track stub in 3/4 layers, localized in time and space produces a veto.

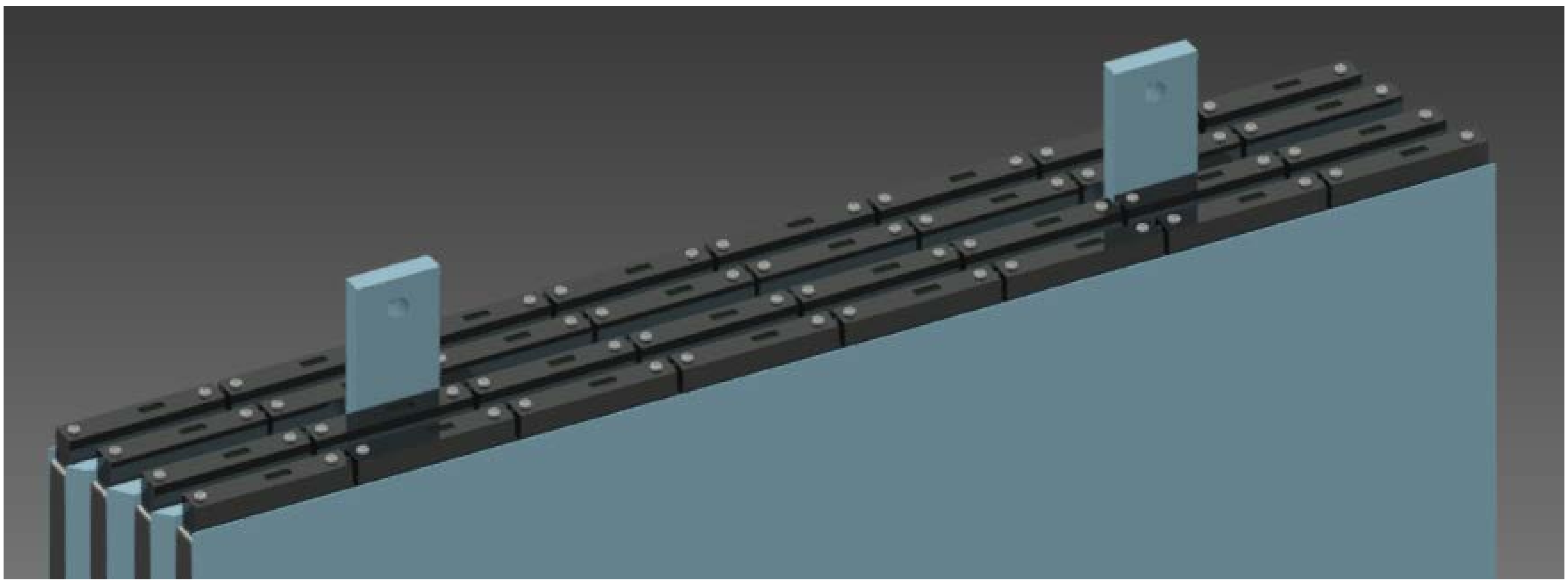
Design: Counter

- Fundamental element of the CRV
- 50 x 20 x 900-6600 mm^3
- Extruded at the FNAL-NICADD facility
- Two 1.4-mm diameter wavelength shifting fibers
- Readout: 2 x 2 mm^2 SiPMs on each fiber end
- Flasher LED on each end for calibration and monitoring
- Glue two extrusions together to form di-counters that are served by one counter motherboard



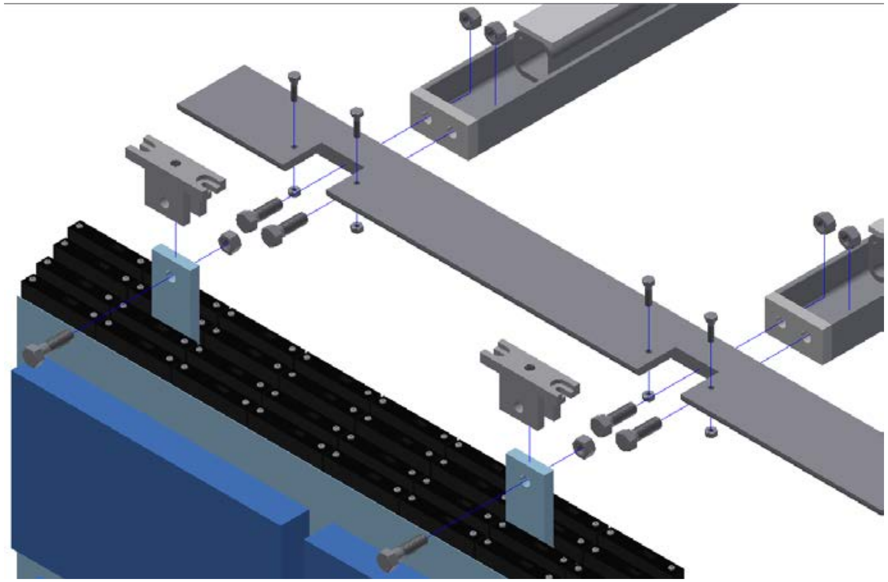
Design: Modules

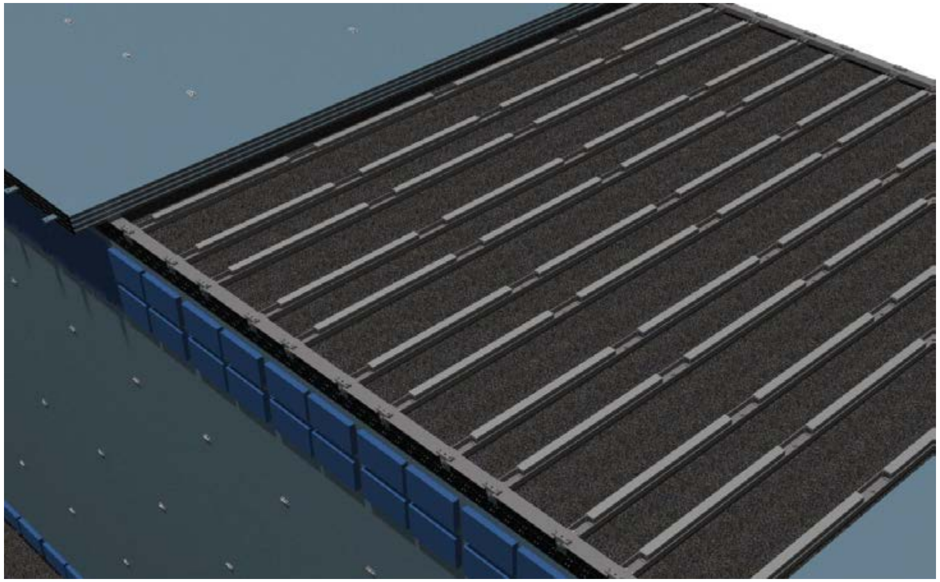
- Fundamental mechanical element of the CRV
- 4 layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters/layer (narrow module: 8)
- Layers are offset to avoid projective gaps between counters
- Total: 82; with two different widths; five different lengths



Design: Support Structure

- Simple design that sits on top of the concrete shielding blocks.
- Designed to minimized gaps between modules, to allow modules to be installed and removed without undue difficulty, and to allow access to electronics.
- Design vetted by FEA.

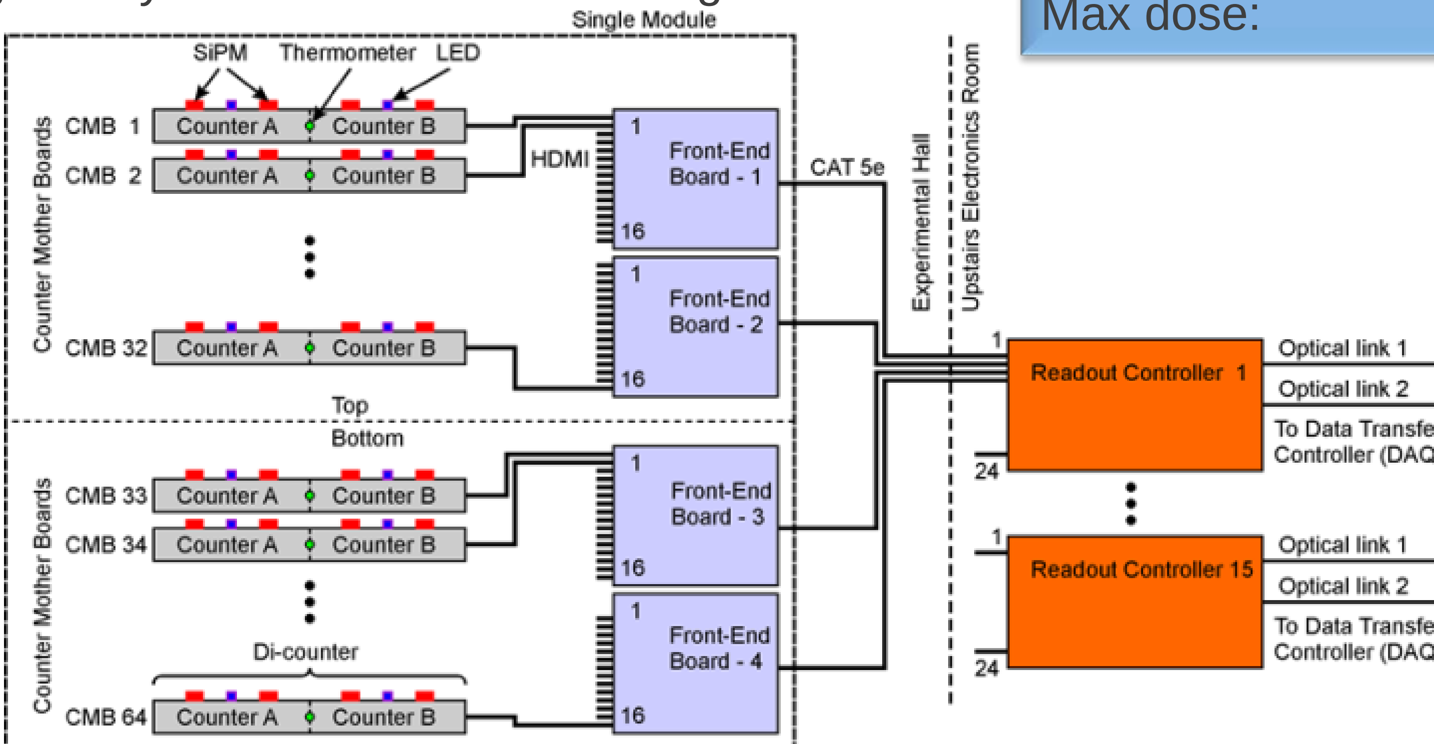




Design: Electronics

- Three components: (1) Counter Motherboards (CMB: 4736), (2) Front-end Boards (FEB: 296), (3) Readout Controllers (ROC: 15)
- Design based on MTB wire chamber readout
- All COTS parts (80 MHz ultrasound octal amp/ADC)
- Triggered system with ~1 s of buffering

Dynamic range:	2000
Max rate/SiPM:	1 MHz
Rate to DAQ:	76 MB/s
Data per run:	1.1 PB
Time resolution:	~ 1ns
Magnetic field:	~ 0.1 T
Max dose:	10^{10} n/cm^2



Integration and Interfaces

- Internal and external interfaces are described in docdb-1551.
- External interfaces to: (1) Conventional construction, (2) the Muon Beamline, and (3) the DAQ.
- We participate in the bi-weekly: electronics, muon beamline, DAQ, and integration meetings.
- Formal sign-off between owners of all external interfaces as part of final design requirements.
- Interfaces understood and under control.

Changes since CD-1

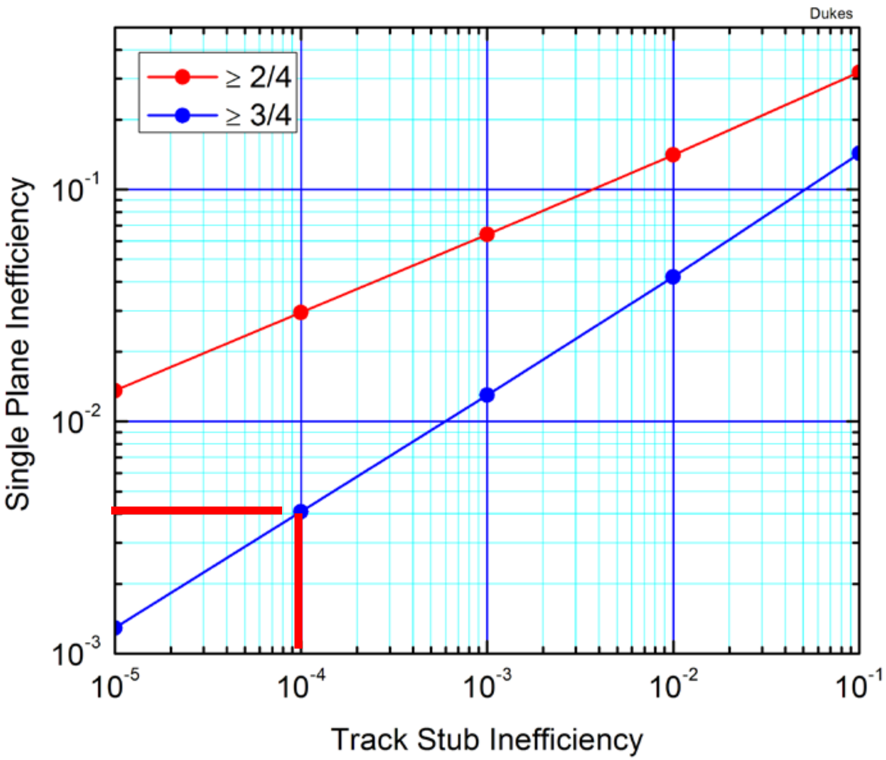
- Extensive simulation work by the Neutron Working Group has shown that the rates from neutrons and gammas are higher than CD-1 estimates that were extrapolated from MECO studies.
- To mitigate the higher rates we have:
  - added shielding to the CD-1 design (see Muon Beamline WBS 475.5)
  - added an extra layer of counters (2/3 → 3/4)
  - made the Al absorber layers thicker (to kill thru-going electrons)
  - moved to a triggered readout
- Moved to a 50 x 20 mm^2 extrusion profile to increase the light yield (energy deposit) from muons traversing each layer.
- The standard module width has been reduced by ~30% to ease fabrication and handling.
- Whitmore added as CRV subsystem deputy and L3: *Photodetectors*, Fagan L3: *Detector Assembly & Installation*

Value Engineering since CD-1

- We incorporate value engineering at every stage of design.
- Based on studies of other projects using large numbers of SiPMs, we cut back our testing from 100% to 10%.
- We are investigating using wider (60-70 mm vs 50 mm) extrusions, which will lower the counter/fiber/SiPM/electronics channel count and save costs. This is listed in the Risk Register as an opportunity.

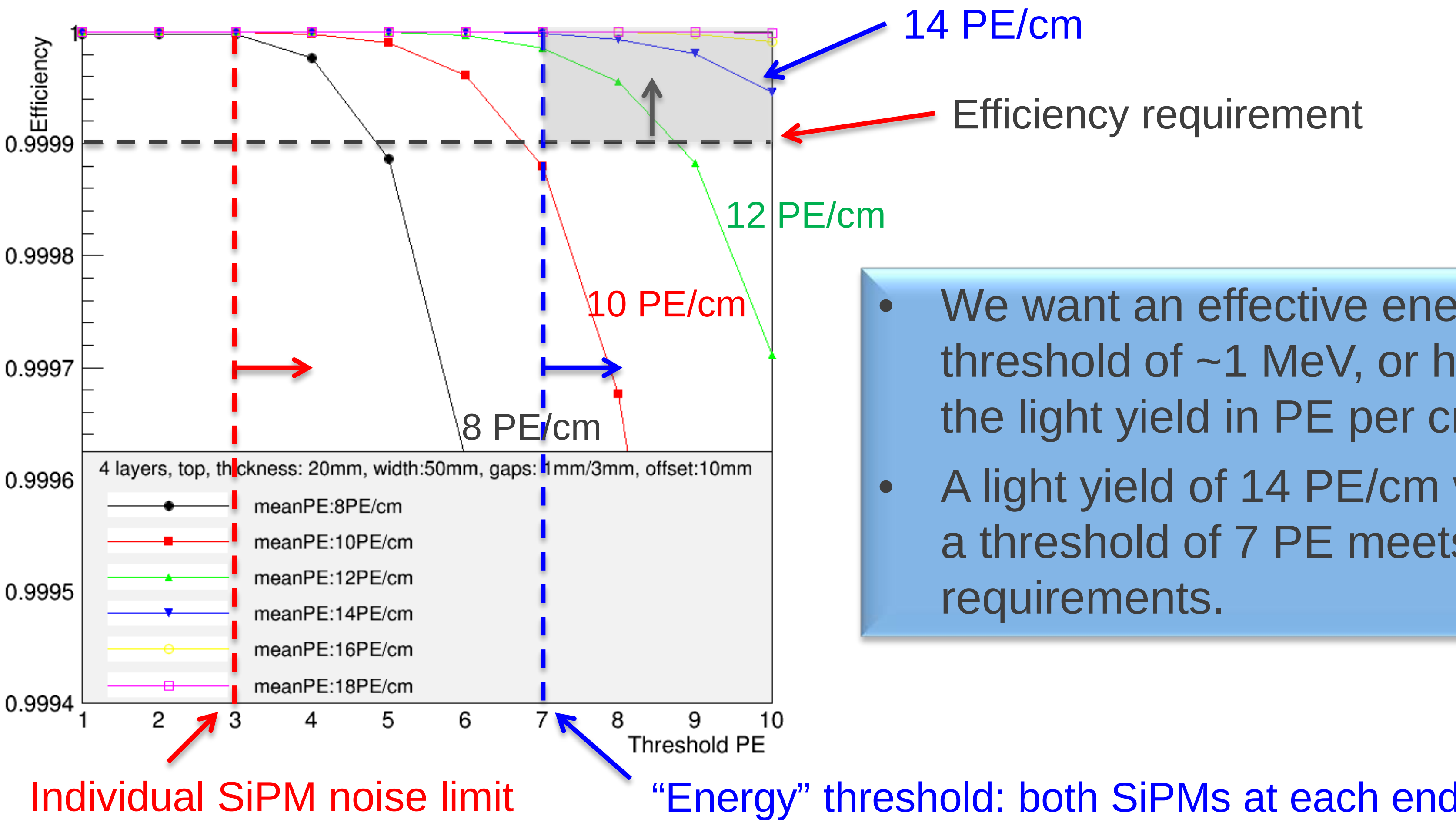
Performance: Efficiency Requirement

- An inefficiency of 10^{-4} in finding muon track stubs with a 3/4 hit plane requirement demands a 99.6% single-plane efficiency.
- The efficiency of a particular plane depends on the angles the muons make and the size of the gaps between counters.



Performance: Efficiency Requirement

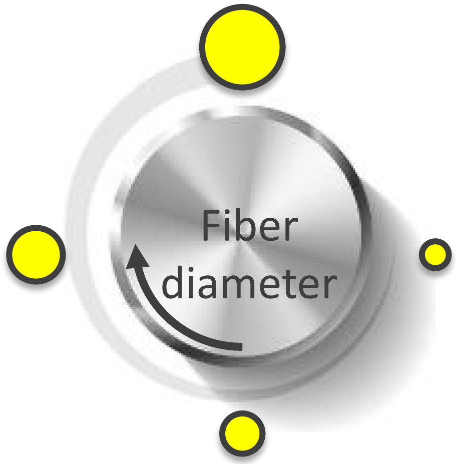
The single-plane efficiency requirement of 99.6% can be best couched in terms of a counter photoelectron yield requirement.



- We want an effective energy threshold of ~1 MeV, or half the light yield in PE per cm
- A light yield of 14 PE/cm with a threshold of 7 PE meets requirements.

Performance: Efficiency Requirement

- Important: the key parameter in meeting the efficiency requirement is the photoelectron yield.
- The means by which we meet the required PE yield is through the wavelength shifting fiber diameter.
- Extrapolations from test-beam data of a pre-prototype counter, and from NOvA measurements of the PE yield vs fiber diameter show that 14 PE/cm at the far end of a long counter can be achieved with a 1.4 mm diameter fiber. We will test modules with 1.4 mm and 1.8 mm fibers next spring in the Fermilab Meson Test Beam Facility and use the results to determine the appropriate diameter.



Simulations: Integrated Rates & Deadtime

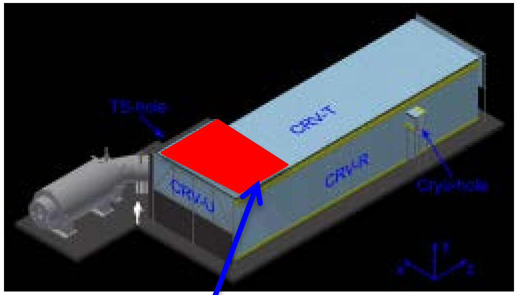
- Simulations of the rates due to neutrons and gammas have been done using a G4beamline model of the beam, shielding, and apparatus
- Rates have been checked with MARS
- Factorized simulation: beam → secondary transport to CRV → rates using CRV efficiencies determined from G4beamline, GEANT4, and MCNP
- A full non-factorized simulation in the Mu2e framework is underway
- **The PE (energy) cut will be applied offline, not in real time**
- **The veto will be applied offline, not in real time**

Threshold [MeV]	Max Instant Rate [kHz]	Average Rate [kHz]	Fractional dead time [%]
0.5	260	48	4.5
1.0	160	30	1.1

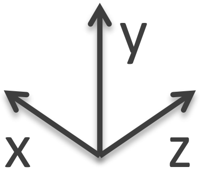
Offline SiPM threshold ← (1.0 MeV row)

Simulations: Radiation Damage

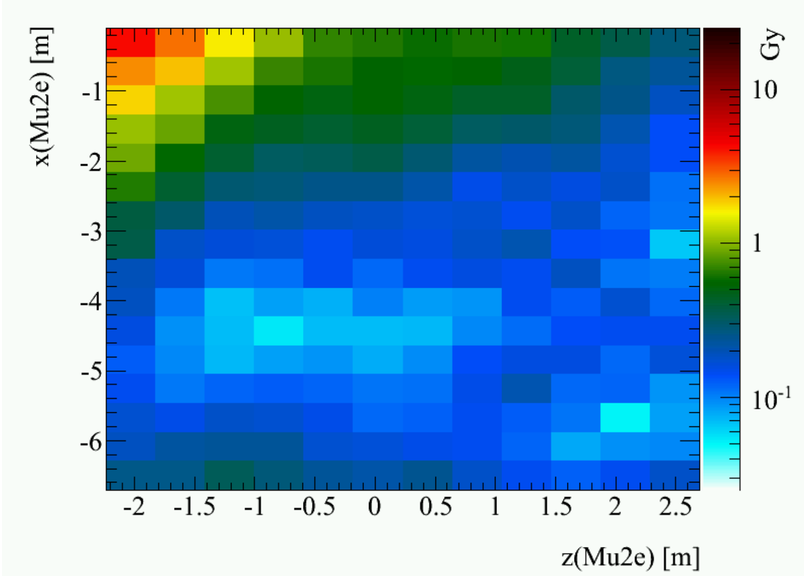
- Ionizing dose: no effect on detector or electronics – max. value ~10 Gy
- Non-ionizing dose: max. rate < 10^{10} (1 MeV eq) n/cm^2 is on the edge of needing testing
- Will irradiate and test SiPMs and Front-end Boards at 10^{10} n/cm^2



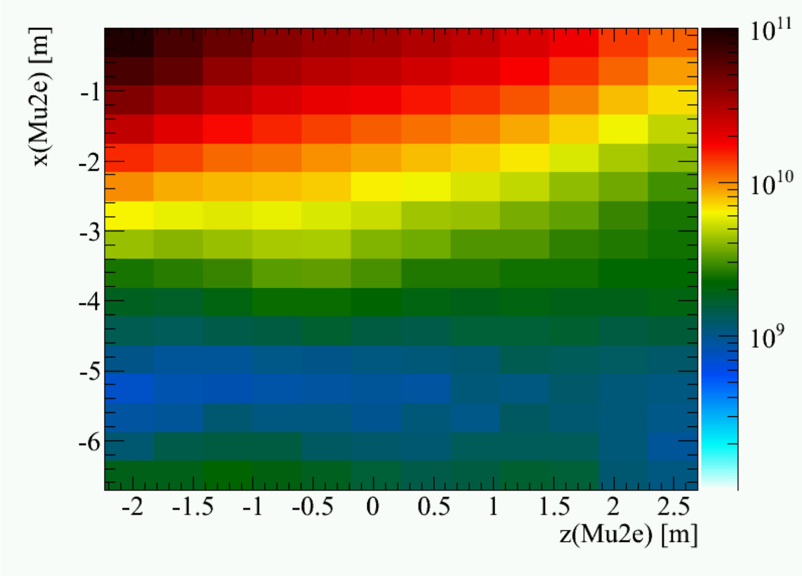
Readout at this end only



Ionizing Radiation Dose



Neutron (1 MeV) fluence (cm^{-2})



Quality Assurance

- We are following guidelines outlined in the project Quality Management Plan (Mu2e-doc-677).
- QA/QC procedures are integrated into each component of the Cosmic Ray Veto, and in fact consume a large fraction of the resources devoted to each task.
- See Level-3 breakout talks for details on QA/QC.
- Example: Module Factory
  - Details given in “Quality Assurance and Safety Program for Cosmic Ray Veto Module Factory” (Mu2e-doc-4150).
  - Each module will have their photoelectron yield measured over their entire area to insure they meet the photoelectron yield requirement, and after shipping to Fermilab they will be tested for damage.

ES&H Issues

- CRV has standard detector-related issues that are common at Fermilab
  - **Electrical hazards:** low-voltage power, modest high-voltage power
  - **Mechanical hazards:**
    - CRV modules are heavy: procedures for the safe handling of them are being developed for the module factory and for installation at Fermilab.
    - Compressed gas cylinders at the module factory.
  - **Toxic materials:**
    - Polystyrene is classified according to DIN4102 as a "B3" product, meaning highly flammable or easily ignited. The storage of the extrusions and fibers will take these properties into account.
    - Adhesives will be used in potting the fibers and for module assembly. Appropriate measures will be taken to reduce the fumes to safe levels.
- These hazards are all discussed in the Mu2e Hazard Analysis document (Mu2e-doc-675) and in the Quality Assurance and Safety Program for the Cosmic Ray Veto Module Factory (Mu2e-doc-4150)

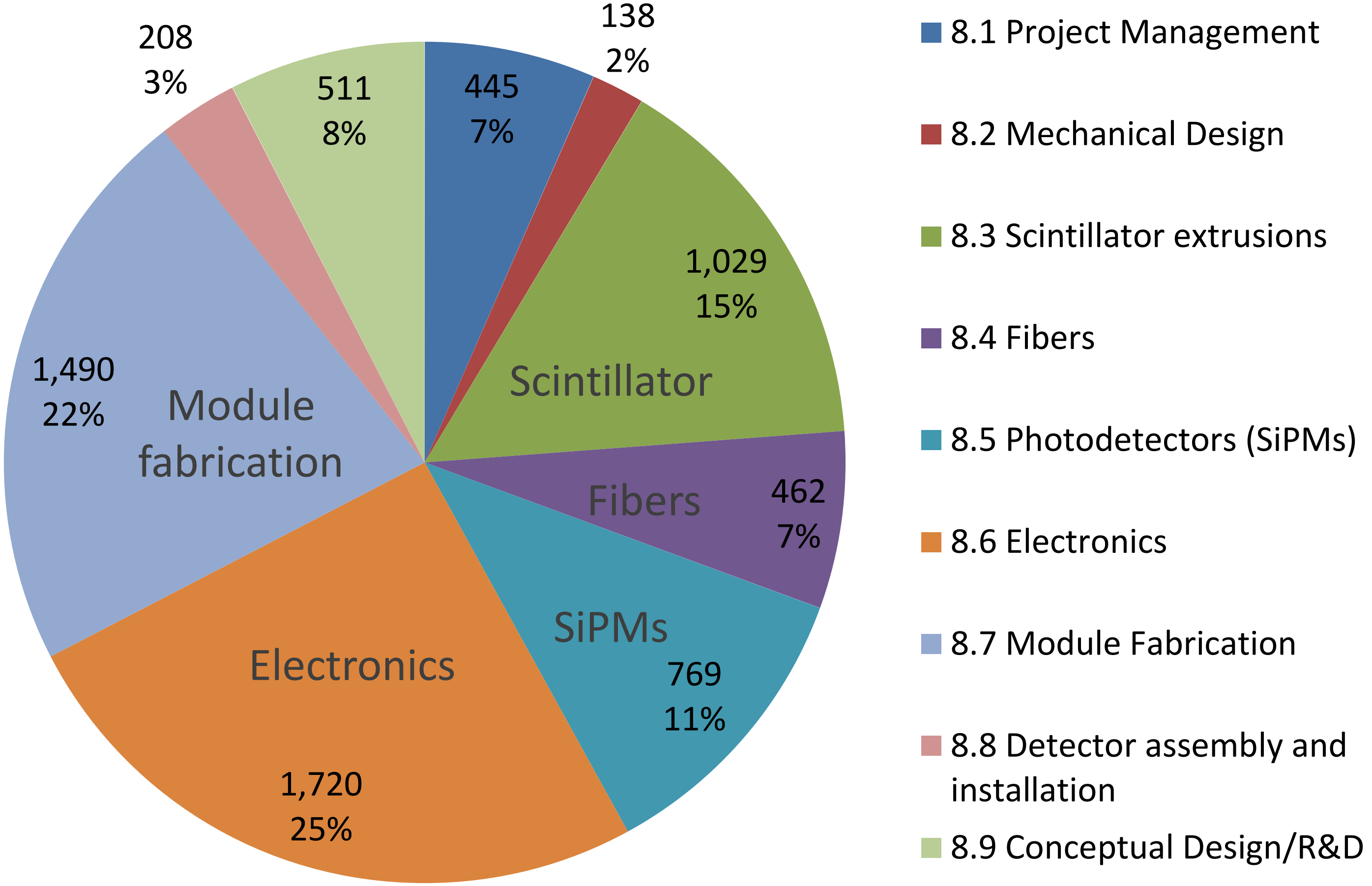
Risks & Opportunities

There are no major cost or schedule risks

- 7 Cosmic Ray Veto risks in the registry
  - Threats: 6
    - 5 low
    - 1 high
  - Opportunities: 3
  - Retired: 5
- Detailed mitigation plans for all risks, documented in risk forms on docdb and linked from Risk Register (docdb-4320)
- All risks understood and under control.
- Details in breakout session.

Cost Breakdown by L3

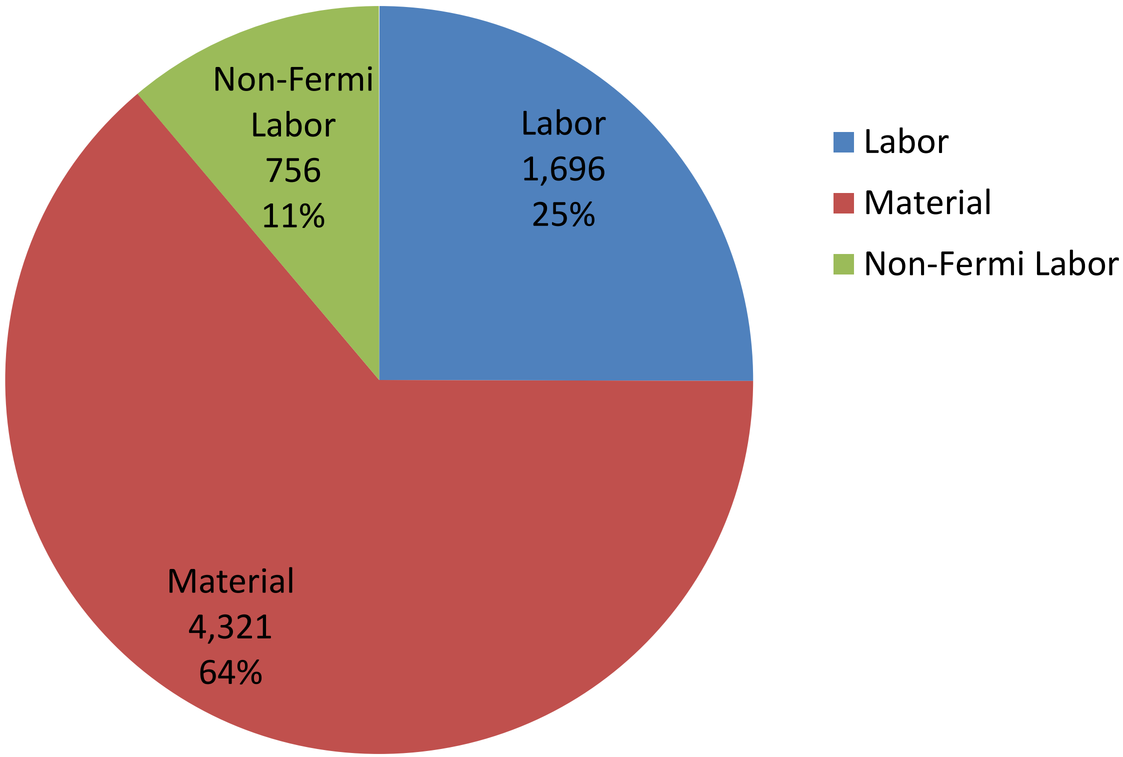
Base Cost by L3 (AY $K)



Cost Breakdown: Resource Type

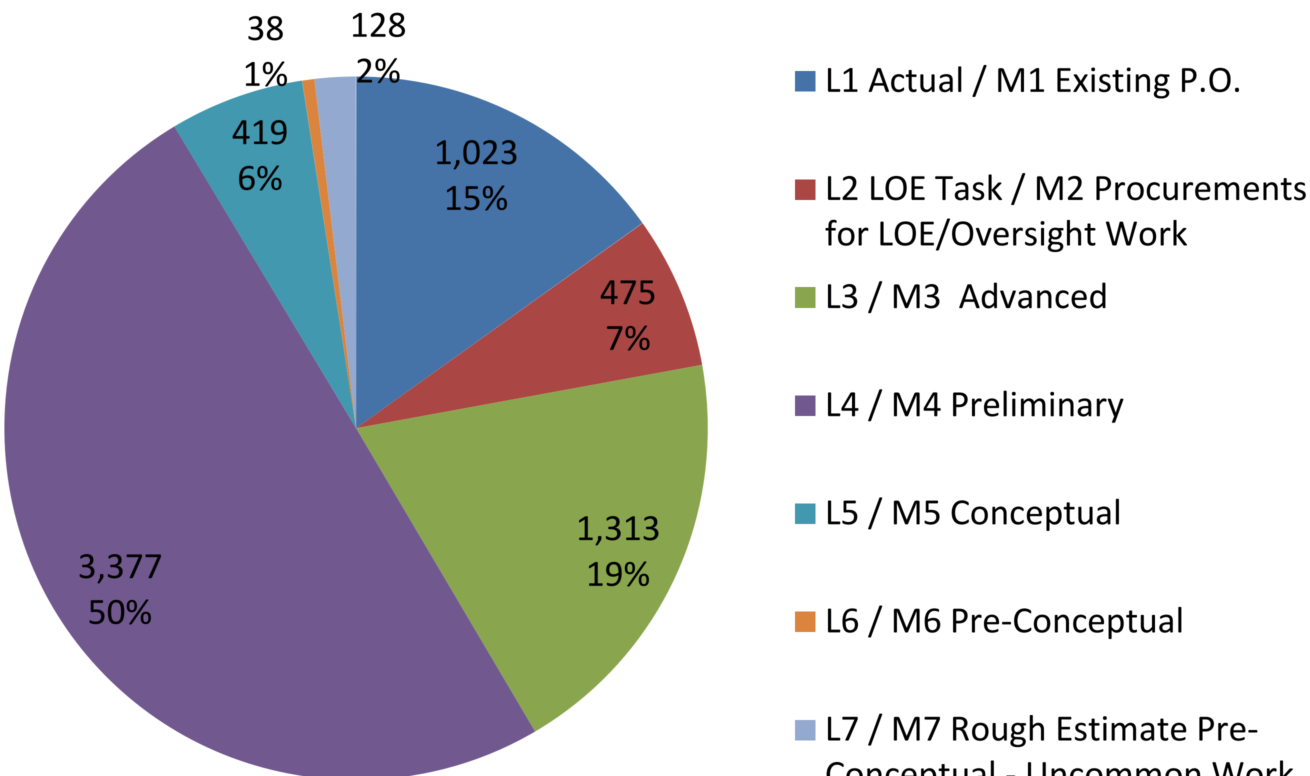
Base Cost by L3 (AY $k)

Note: non-Fermi labor hours > Fermi

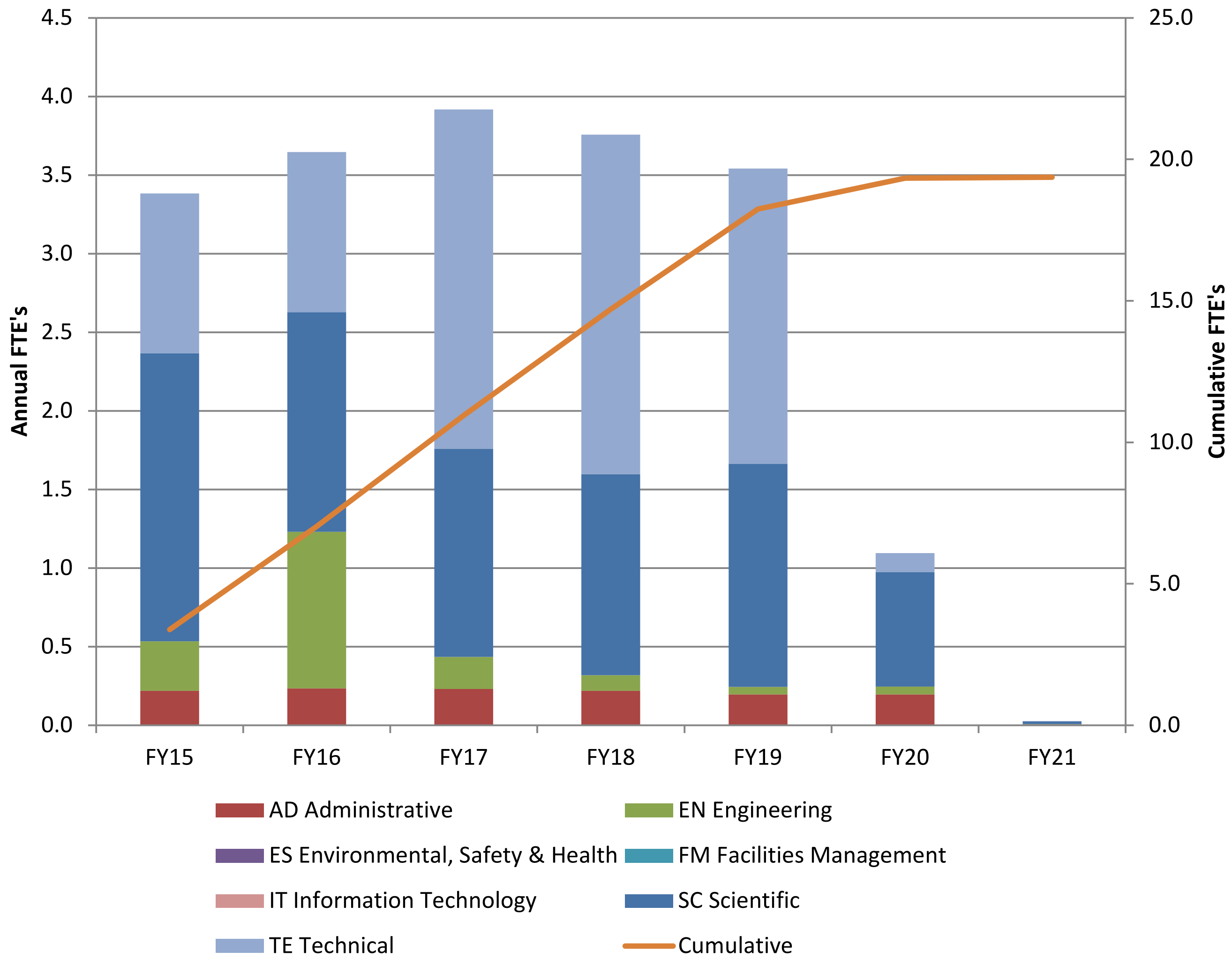


Quality of Estimate

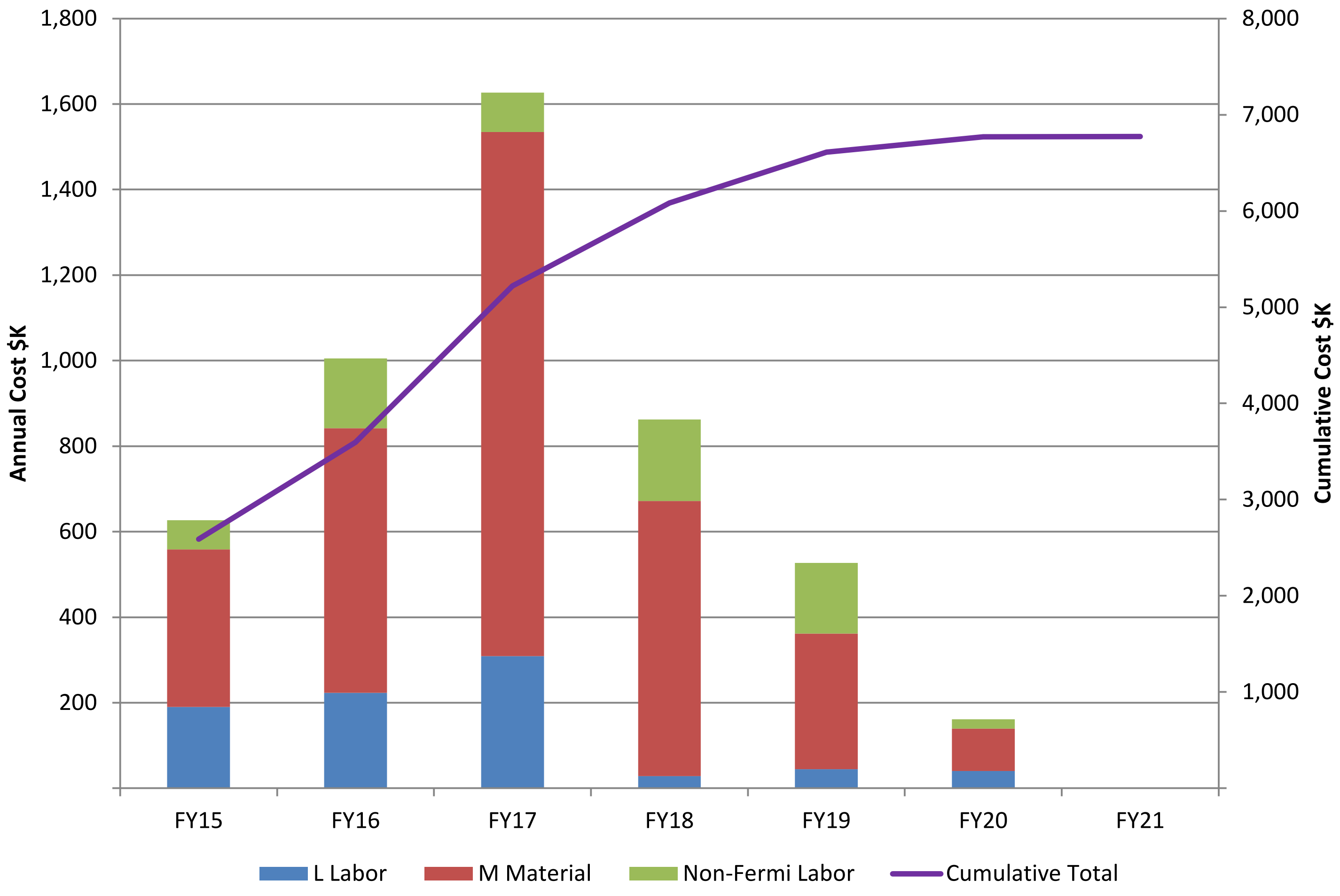
91% of cost understood at the Preliminary Design level or higher



Labor Resources by FY



Labor and M&S by FY



Cost Table

Costs are fully burdened in AY $K
Includes actuals

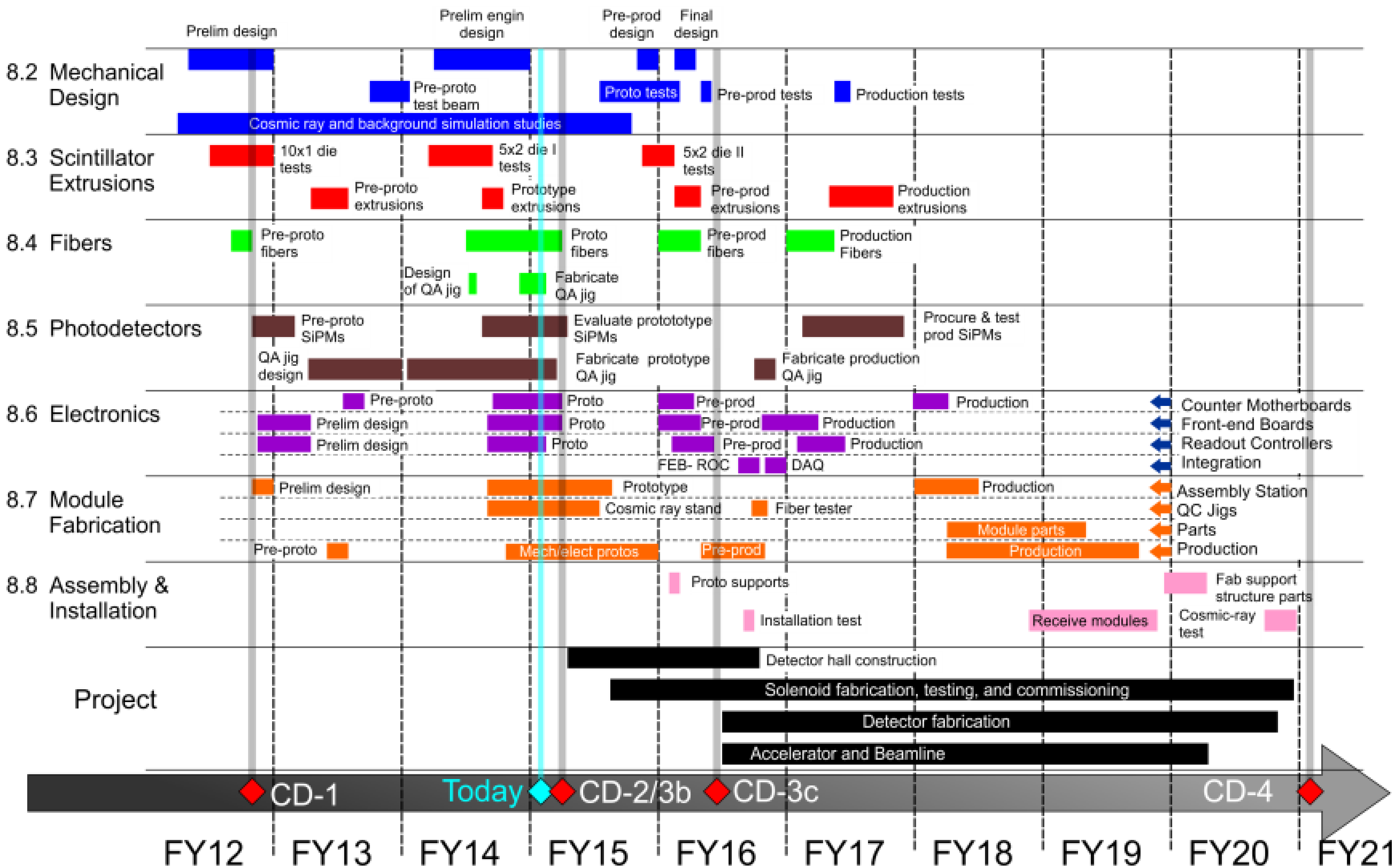
Note: Labor Fermilab only;
Univ. labor captured in M&S.

	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

Major Milestones

- Jun 2015: Select SiPM
- Sep 2015: Final engineering design complete
- Mar 2017: Wavelength shifting fiber tested and ready
- Feb 2017: SiPMs tested and accepted
- May 2017: Production of extrusions complete
- Dec 2017: Electronics fabricated and tested
- Jan 2018: Module production begins
- Sep 2019: Modules received at Fermilab

Schedule



Prelim design
Prelim engin design
Pre-prod design
Final design
8.2 Mechanical Design
Pre-proto test beam
Proto tests
Pre-prod tests
Production tests
Cosmic ray and background simulation studies
8.3 Scintillator Extrusions
10x1 die tests
5x2 die I tests
5x2 die II tests
Pre-proto extrusions
Prototype extrusions
Pre-prod extrusions
Production extrusions
8.4 Fibers
Pre-proto fibers
Proto fibers
Pre-prod fibers
Production Fibers
Design of QA jig
Fabricate QA jig
8.5 Photodetectors
Pre-proto SiPMs
Evaluate protoprototype SiPMs
Procure & test prod SiPMs
QA jig design
Fabricate prototype QA jig
Fabricate production QA jig
8.6 Electronics
Pre-proto
Proto
Pre-prod
Production
Prelim design
Proto
Pre-prod
Production
Prelim design
Proto
Pre-prod
Production
FEB- ROC
DAQ
Counter Motherboards
Front-end Boards
Readout Controllers
Integration
8.7 Module Fabrication
Prelim design
Prototype
Production
Cosmic ray stand
Fiber tester
Module parts
Pre-proto
Mech/elect protos
Pre-prod
Production
Assembly Station
QC Jigs
Parts
Production
8.8 Assembly & Installation
Proto supports
Fab support structure parts
Installation test
Receive modules
Cosmic-ray test
Project
Detector hall construction
Solenoid fabrication, testing, and commissioning
Detector fabrication
Accelerator and Beamline
CD-1
Today
CD-2/3b
CD-3c
CD-4
FY12
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- We have a design that meets requirements, can be built, and is costed.
- The design is simple and relies on technologies that have been proven in several recent Fermilab experiments.
- Estimates for the Cosmic Ray Veto are complete
  - 91% of cost understood at the Preliminary Design level or higher
  - Most estimates based on very similar systems, with the same personnel, that have recently been built at Fermilab.
- Risks are minor and understood, mitigated where possible.
- All interfaces have been identified and defined.
- ES&H is embedded into all aspects of the project.
- We understand exactly what has to be done to get to CD-3, and have a well-developed plan on how to get there.
- The Cosmic Ray Veto sub-project is ready for approval of its performance baseline.