Fermilab

U.S. DEPARTMENT OF ENERGY Office of Science

Mu2e Extinction System

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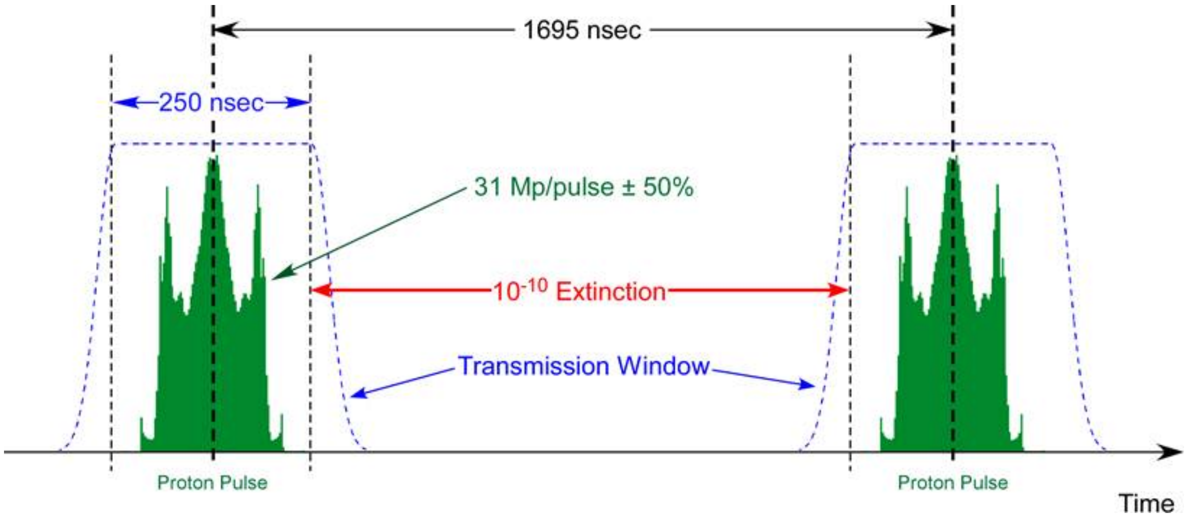
Extinction L3 Manager

7/8/2014

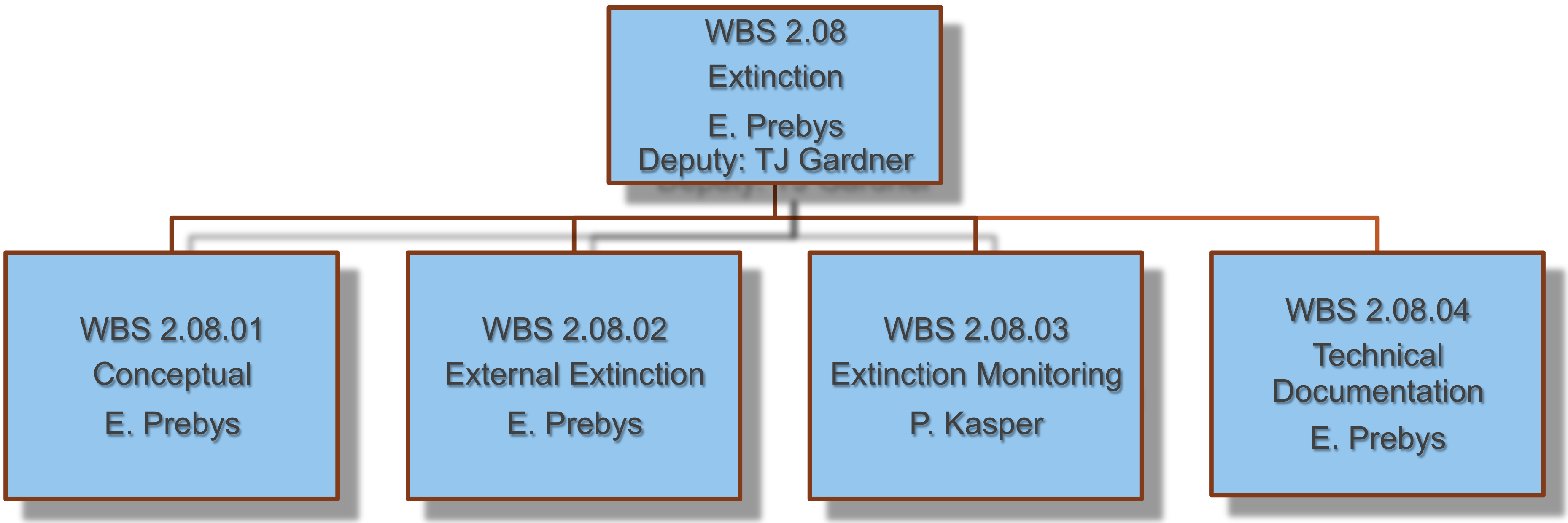
WBS 475.02.08 Extinction

- The Mu2e experiment has very stringent limits on the amount of beam that appears between pulses



- The extinction task is comprised of
  - Providing this level of extinction.
  - Monitoring to verify that we have achieved it.
- Will address “Extinction” and “Extinction Monitoring” separately

Organizational Breakdown



Extinction Requirements*

- The total extinction requirement is

< 1 every ~300 bunches

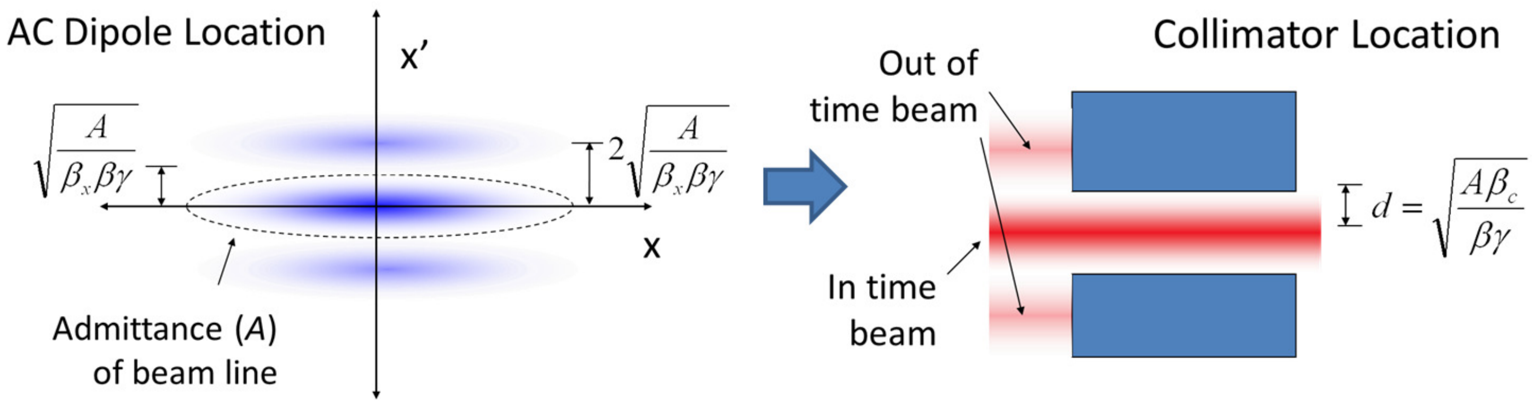
$$\frac{\text{(beam outside of transmission window)}}{\text{(beam in transmission window)}} < 10^{-10}$$

- This is primarily driven by the need to eliminate radiative pion capture, as described in detail in Mu2e-DOC-1175
- Extinction will be achieved in two steps
  - Our beam delivery technique will "naturally" provide an extinction of $\sim 10^{-5}$ or better.
    - The "Internal Extinction Collimation" discussed at CD-1 will not be needed (see discussion under "value engineering")
  - An "External Extinction System" will consist of a set of resonant dipoles and collimation system, such that only in time beam will be transmitted to the production target
    - Aiming for additional 10^{-7} extinction.

*extinction monitor requirements will be discussed shortly

Principle of Operation of AC Dipole System

- An angular deflection at the AC dipole cause a position displacement 90° later in phase advance



- Define normalized deflection angle

Admittance of collimator (set to 40 π-mm-mr

$$\delta \equiv \frac{\theta}{\theta_0}; \quad \text{where } \theta_0 \equiv \sqrt{\frac{A}{\beta_D \beta\gamma}}$$

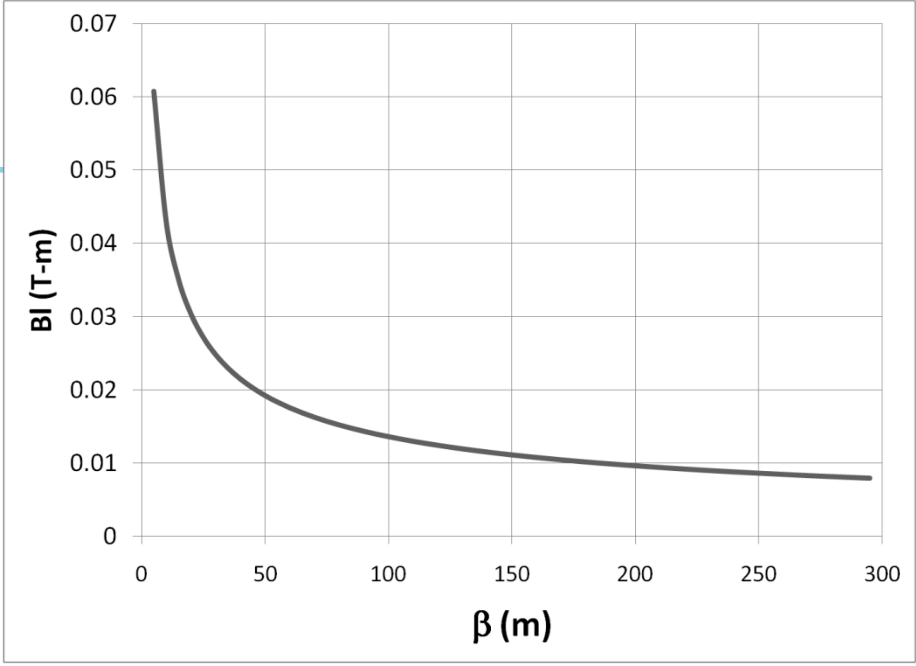
β at AC dipole (=250 m)

- In terms of this angle

$$\delta = 1 \rightarrow \text{ center of beam hits edge of collimator}$$

$$\delta = 2 \rightarrow \text{ all beam hits collimator} \equiv \text{"extinction angle"}$$

Design Considerations



Bend strength to extinguish:

$$(BL) = 2(B\rho)\sqrt{\frac{A}{\beta_x \beta\gamma}} \propto \beta_x^{-1/2}$$

Stored Energy:

$$U \propto B^2 Lwg = \frac{(BL)^2}{L} wg \propto \frac{1}{\sqrt{\beta_x L}}$$

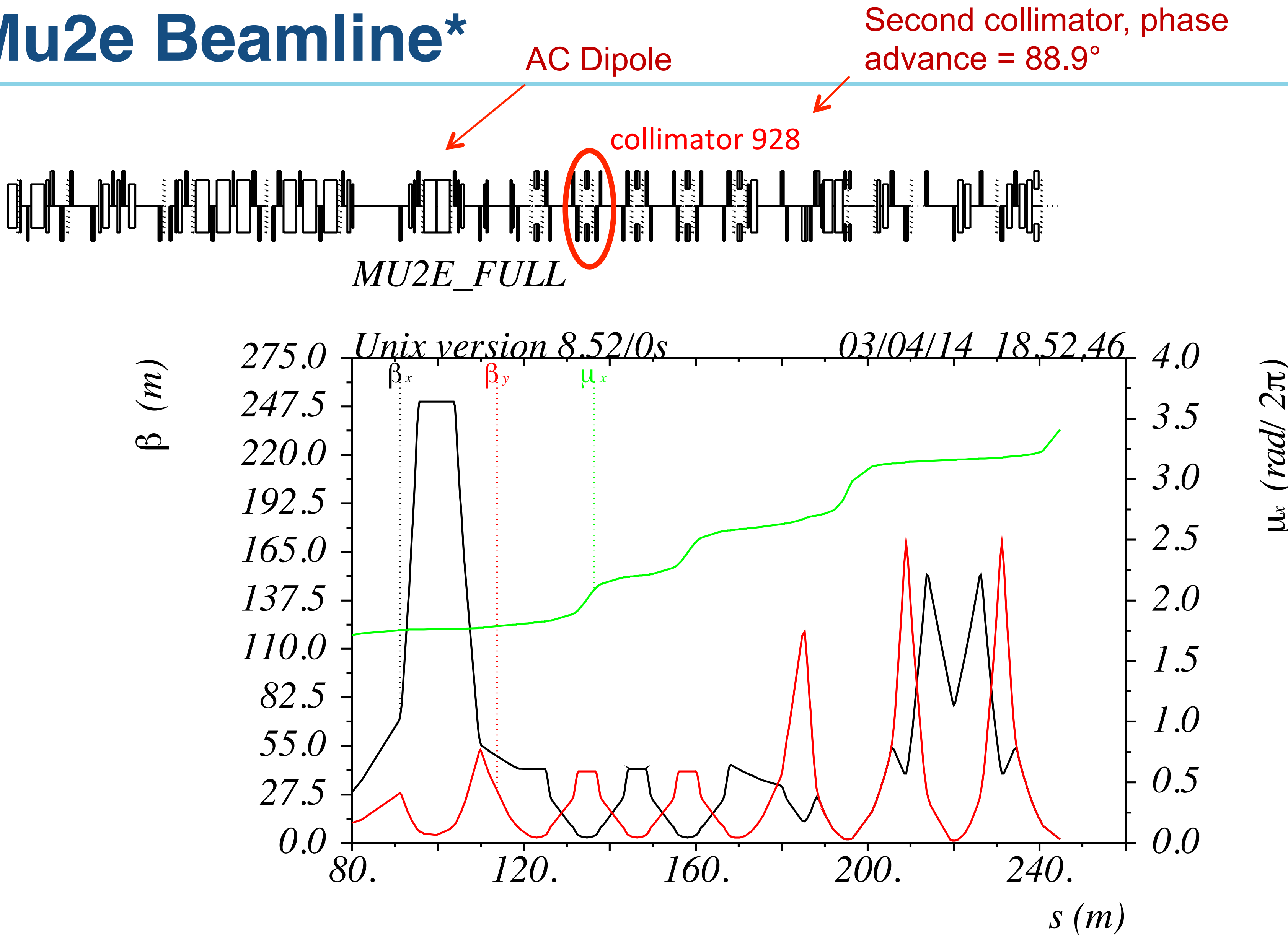
$$\propto \beta_x^{1/2} \qquad \propto L^{1/2}$$

➔Large β_x, long weak magnets

- Assume β_x=250m, L=6m
- Factor of 4 better than "typical" values of β_x=50m, L=2m

Driving consideration in beam line design!

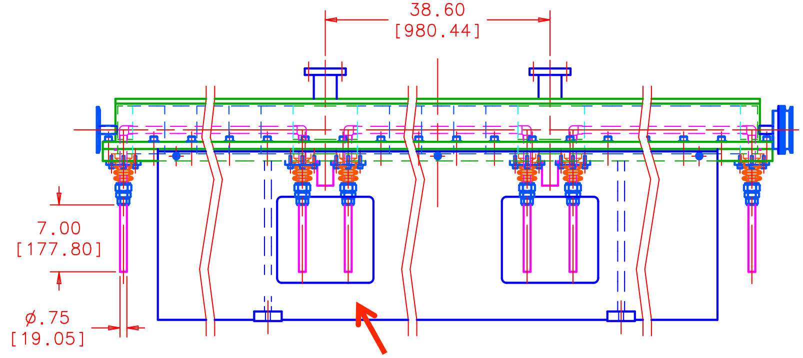
Mu2e Beamline*

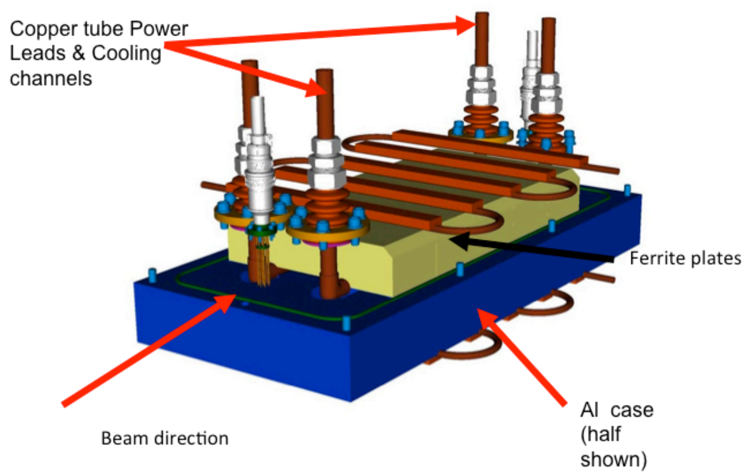


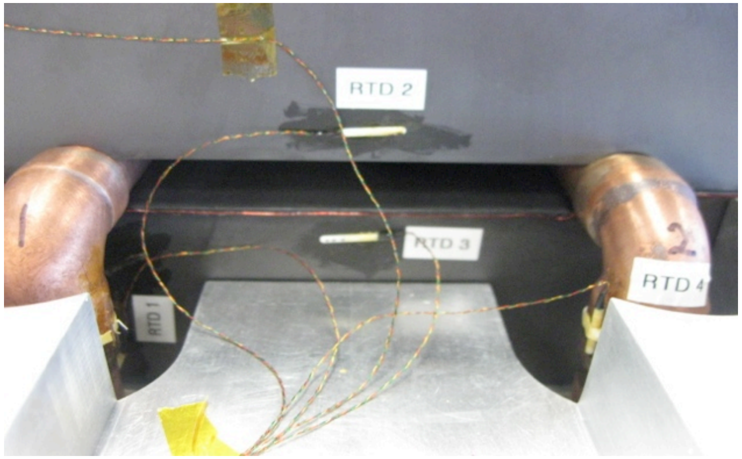
*C. Johnstone

AC Dipole Design and Prototype

- AC dipole system consists of 6 identical one meter elements, arranged in two 3-meter vacuum vessels.
- Extensive tests done with half-meter prototype
  - meets all specificiations

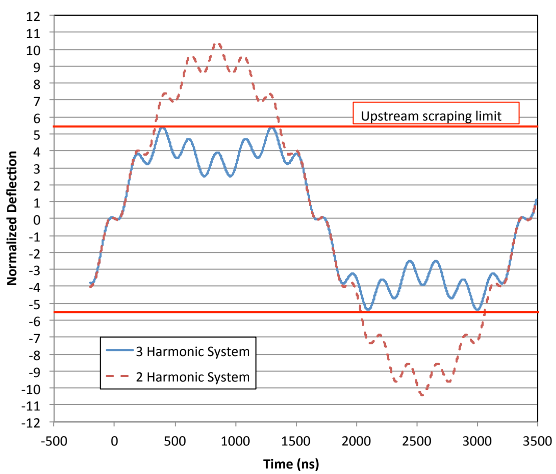


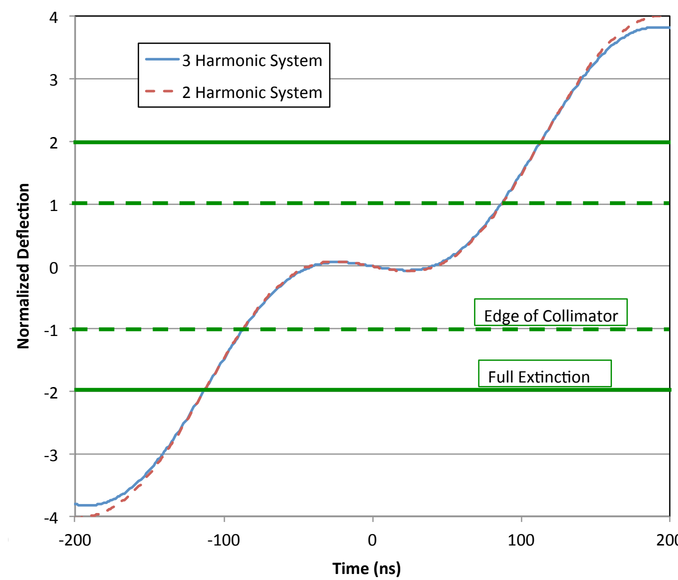




AC Dipole Harmonics

- The AC dipole elements will be driven by 3 harmonics
  - 2 elements @ 300 kHz (half bunch frequency), such that beam is transmitted at the nodes.
  - 3 elements @ 4.5 MHz to reduce slewing during transmission
    - Optimized to maximize transmission of in-time beam.
  - 1 elements @ 900 kHz, to reduce amplitude and prevent beam pipe scraping upstream of the collimator.



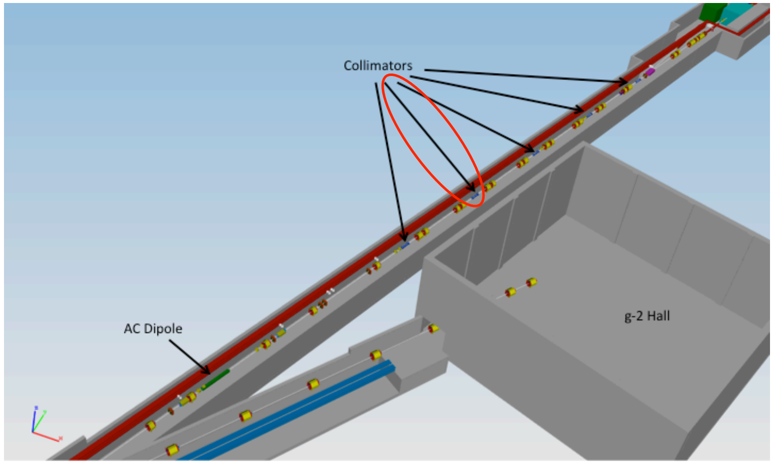


Configuration	Harmonic Amplitude [G-m] 300 kHz	900 kHz	4.5 MHz	Peak Amplitude (normalized)
Two Harmonic (baseline)	413.7	-	35.2	10.4
Three Harmonic (proposed)	206.7	73.2	35.2	5.4

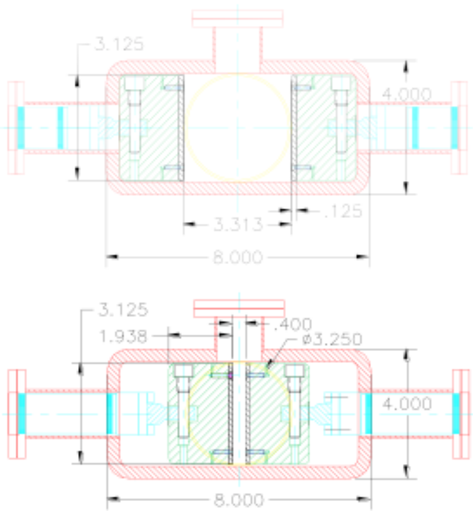
Collimator Design

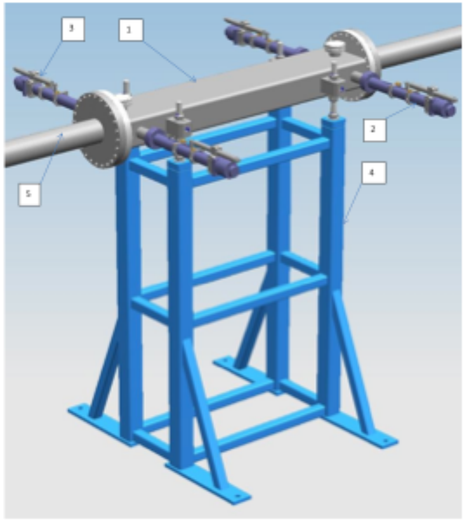
- Collimator based on standard two-jaw design
- Separate motion controllers/LVDTs at each end so position and angle can be precisely controlled

Location:

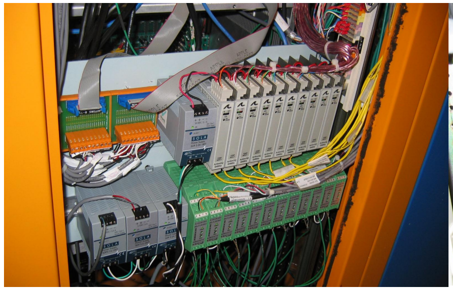


Collimator and stand:





Control and position measurement



Extinction Performance

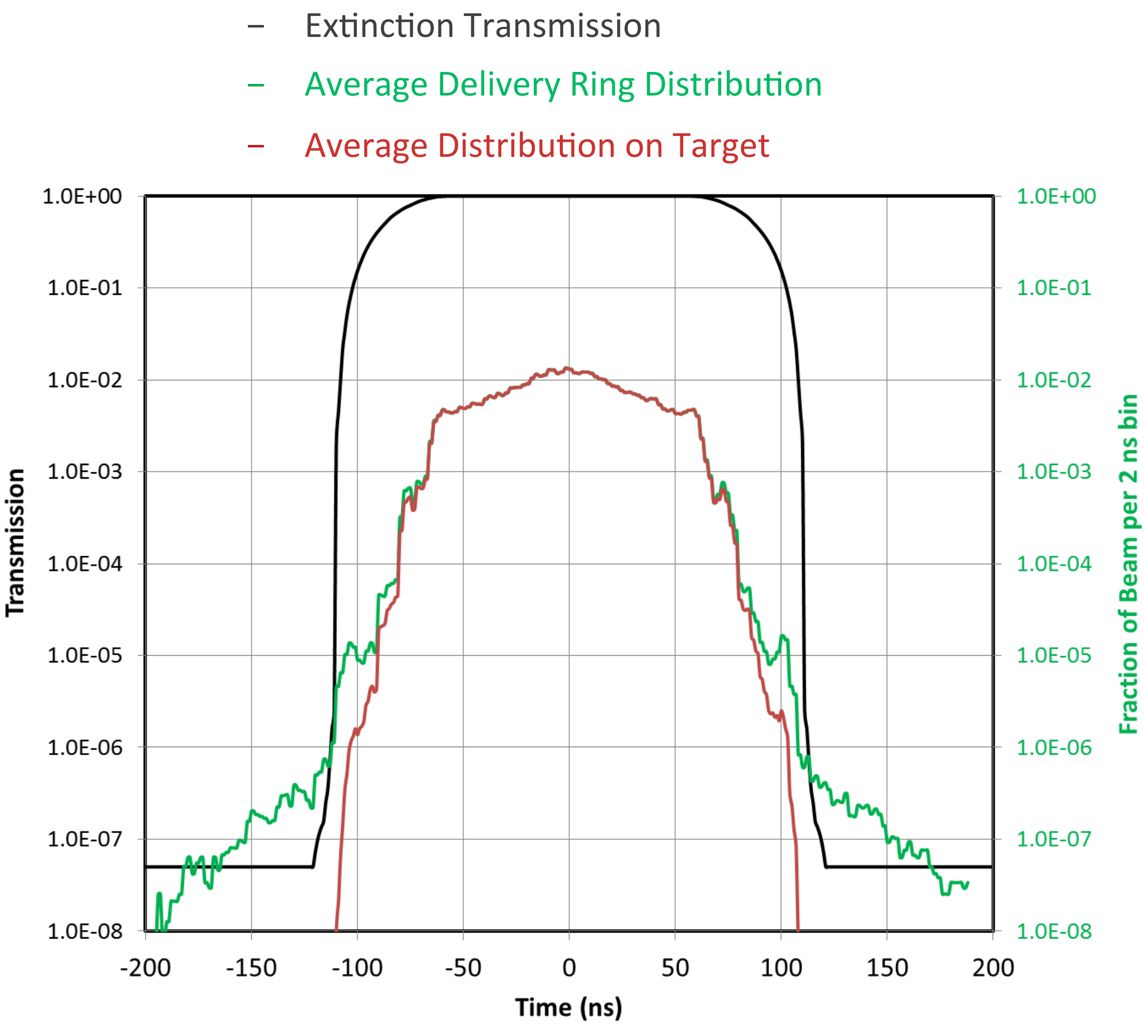
Two Models:

1. Beam distribution from ESME longitudinal tracking model in the Delivery Ring.
2. G4Beamline tracking model of extinction section of the M4 beamline. (Mu2e-DOC-5054)

Results:

Upstream extinction:	1.6×10^{-5}
In-time beam transmission:	99.7%
Downstream extinction:	8×10^{-13}†

† This number assumes that there is no contribution from long transverse tails.



Extinction Monitor Requirements

- The extinction monitoring is divided into two parts, to address two classes of issues
  - "Upstream" (or "Internal") Monitor will monitor the extinction of the beam coming out of the Delivery ring, before the AC dipole system. Because this might be affected by things on a short time scale (RF, slow extraction, etc), this system should provide a fairly fast reading, with a sensitivity on the order of 10^{-5}.
  - "External" (or "Target") Monitor will monitor the extinction of beam hitting the target; that is, the final extinction of interest to the analysis. If the upstream extinction is performing properly, then this depends on the performance of the AC dipole, which we do not expect to change quickly.

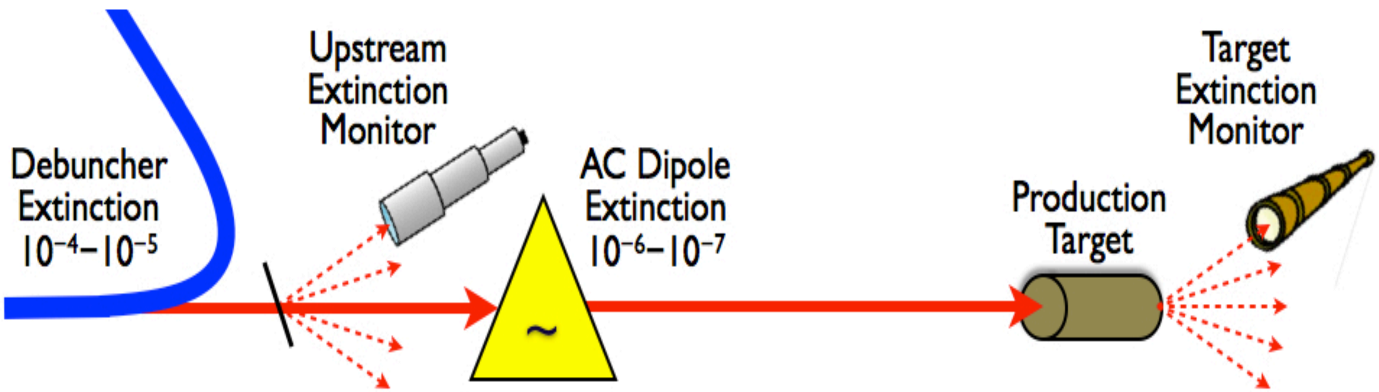
Extinction Monitor Requirements (cont'd)

- From Mu2e-DOC-894:

Specification	Upstream Monitor	Target Monitor
Extinction sensitivity over the specified integration time (90% CL)	10^{-5}	10^{-10}
Extinction accuracy	10%	10%
Integration time	$<2\times10^{14}$ POT (~10 s at 100% duty factor)	6×10^{16} POT (~1 hr at 100% duty factor)
Timing resolution (RMS)	<10 ns	<10 ns
Dead-time	<10 ns	<10 ns
Rate-dependent error over dynamic range	<10%	<10%
Increase in beam emittance	<10%	N/A
Initial readiness	When beam is deliverable to the Acc/Deb complex	When the production target is ready
Access time (assuming monthly access is needed)	4 hrs	4 hrs
Radiation hardness (minimum protons delivered before replacement is required)	4×10^{20} POT	4×10^{20} POT

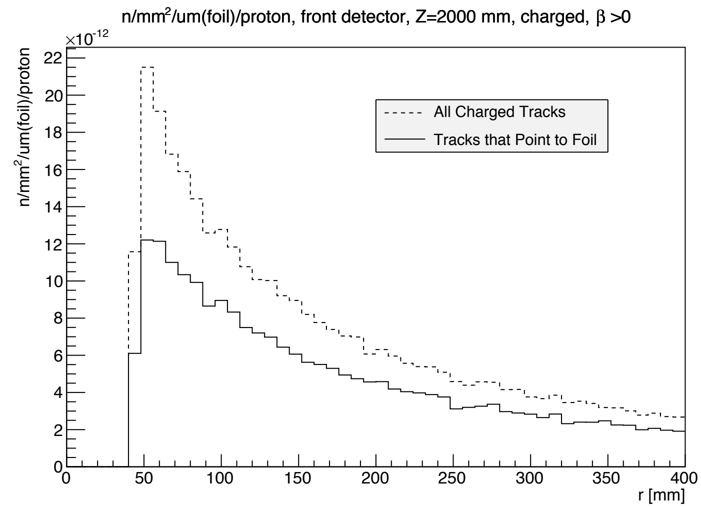
Principle of Operation

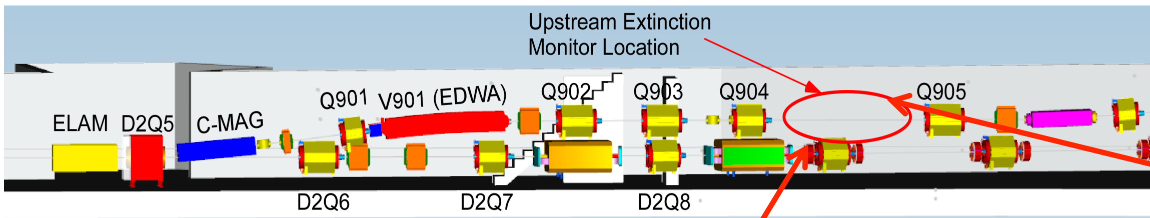
- Because of the large dynamic range required, we determined it was not feasible to measure individual out of time particles, so both extinction monitors are based on “statistical techniques”
  - A small fraction of incident particles are scattered into a detector.
  - An accurate statistical pictures of both in and out of times particles is built up over time.
  - Sensitivity limited by integration time and background fake rate.
  - The goal is *not* to veto individual out of time particles, but rather to establish that the background due to these particles is negligible.

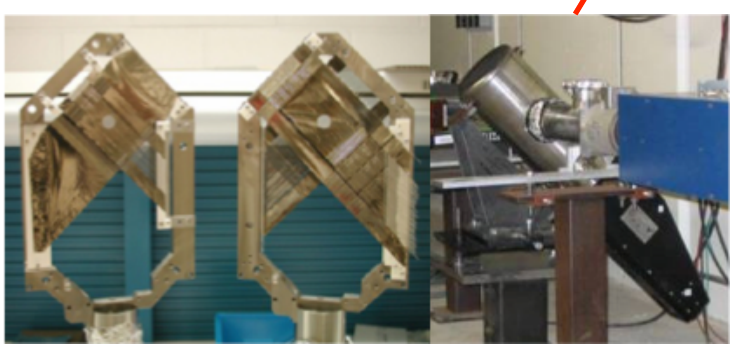


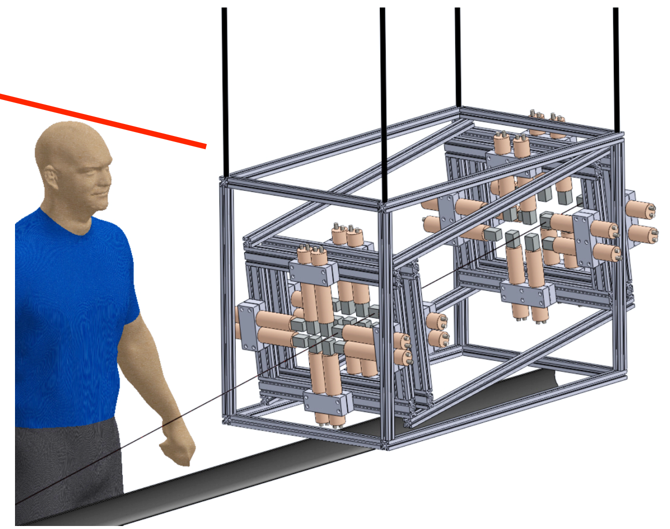
Upstream Extinction Monitor

- A thin foil placed upstream of the AC Dipole scatters a small fraction of the incident protons into a telescope based on Cerenkov radiators
  - A 5 μm foil would provide a few particles per bunch in a detector 2 meters downstream. This would give a 10^{-5} measurement in the requisite number of pulses*.





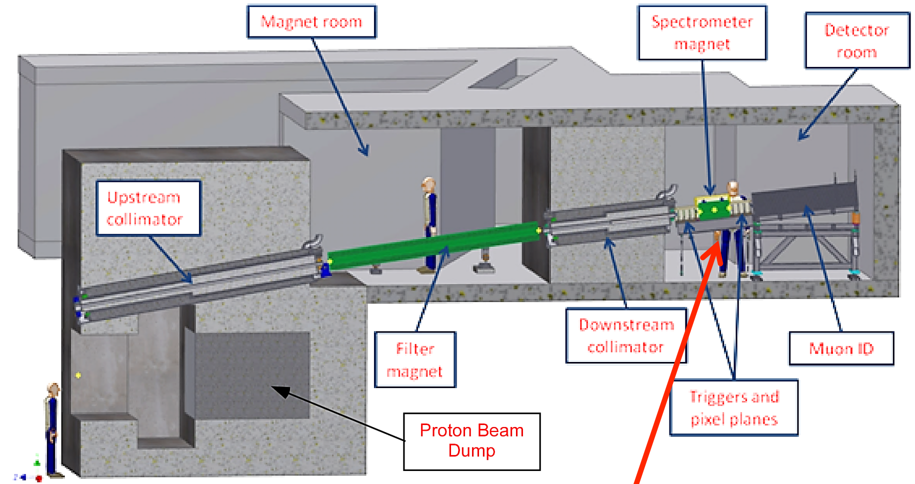


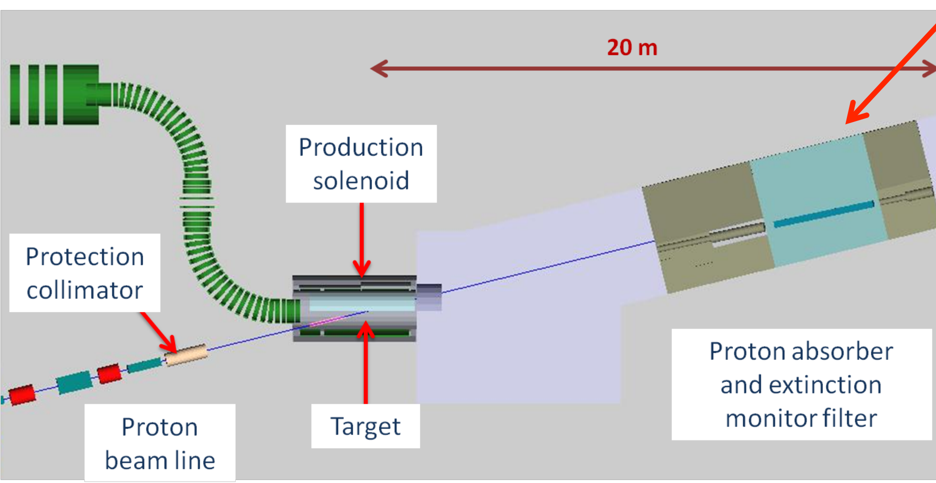


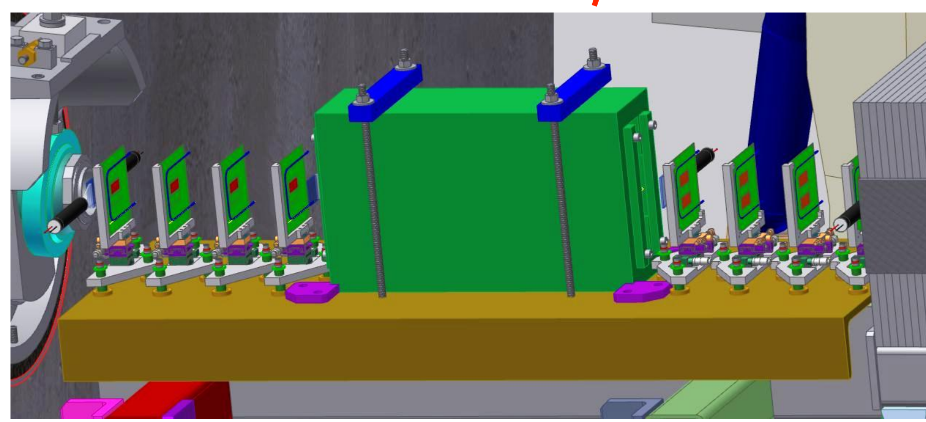
*Mu2e-DOC-3298

External (Target) Monitor

- Particles scattered from the production target pass through a "filter", consisting of collimators and permanent spectrometer magnet, and are reconstructed by planes of pixels developed for the ATLAS experiment
- Includes calorimeter to measure muon content in the event of unanticipated positives.

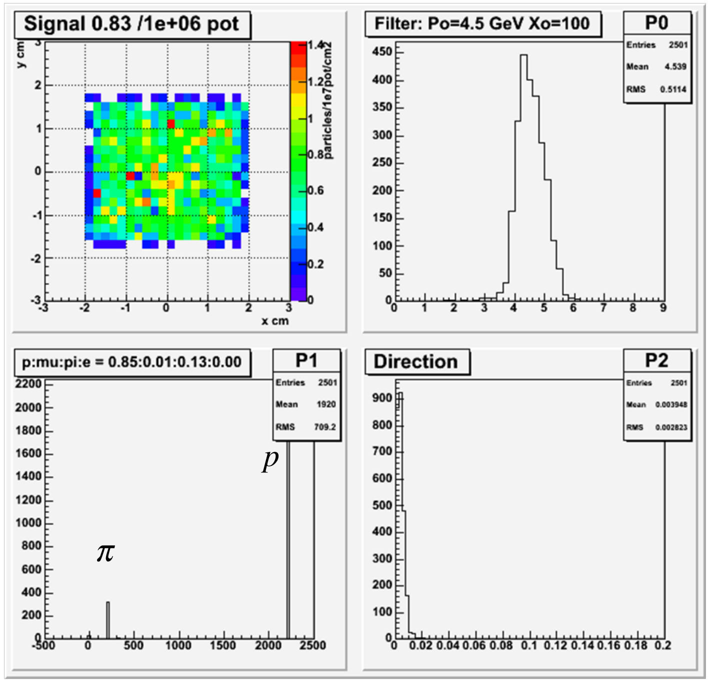




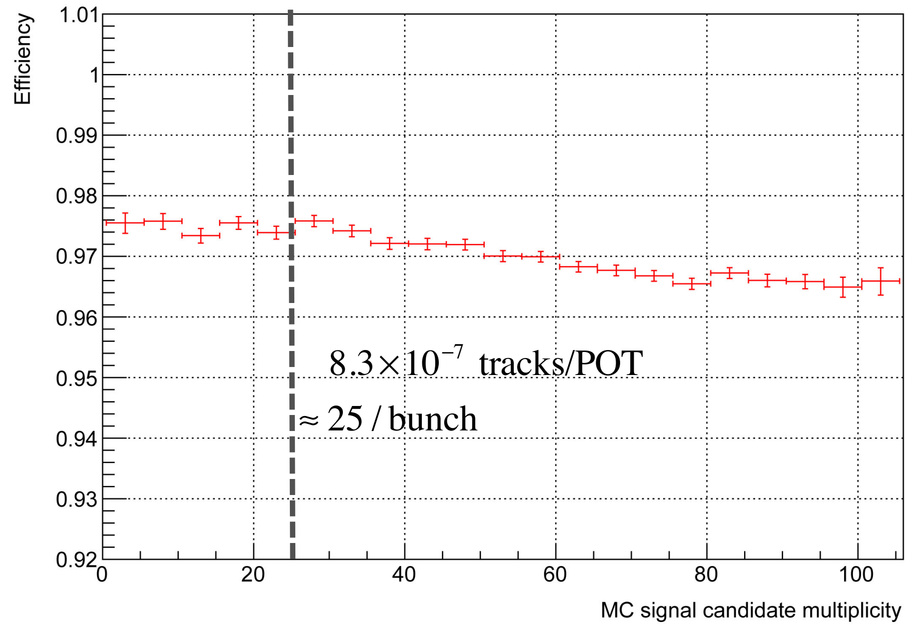


External Extinction Monitor Performance

Track distributions surviving filter



Track reconstruction efficiency:



- $1\text{x}10^{-10}$ extinction = 5 tracks for $6\text{x}10^{16}$ POT (meets specification)
- Background (cosmics, noise, etc) = .03 tracks/hour
  - ~ .1 track/($6\text{x}10^{16}$ POT)
  - ~ $2\text{x}10^{-12}$ extinction (note: this can be measured and subtracted!)

Changes since CD-1

- At CD-1, we were still considering the possibility that we might need collimation inside the Delivery Ring to reduce out of time beam.
  - Simulations showed this will not be necessary, so it was de-scoped.
- CD-1 design had 5 collimators downstream of the AC dipole. New design has 2 upstream and 1 downstream.
- The third harmonic has been added to the AC dipole system to prevent particles from scraping upstream of the collimator.
- “Muon catcher” calorimeter added to external monitor to measure muon content of out of time signal as a test for false positives.

Value Engineering since CD-1

- Elimination of internal extinction collimation (see previous slide).
- Reduction in number of external extinction collimators from 5 to 3 (see previous slide).
- Low frequency (300 kHz) power supply based on existing standard Fermilab (Krafczyk) design.

Downselects

- At the time of CD-1, we were considering two possible designs for the external ("target") monitor:
  - The pixel-tracking based design presented here.
  - A design proposed by UC Irvine, based on scintillators
- An independent review committee was appointed by the spokespersons
- The committee concluded that both designs could in principle satisfy the specification, but that the pixel-based design entailed lower risk.

Remaining work before CD-3

- The following designs are very mature
  - AC Dipole and power supply
  - Collimators
  - Upstream and downstream extinction monitors
- These require only finalized designs and more accurate cost estimates
- The only significant work before CD-3 is the finalization of the collimation upstream of the AC dipole to eliminate the large amplitude tails.
  - Working on this design in conjunction with the beam line design.

Quality Assurance

- AC Dipole magnets and Power supplies
  - Magnets will be constructed by Technical Division, which has standard procedures for QA for all devices they build, as overseen by the Quality and Materials Department
    - See http://www-td.fnal.gov/departments/quality_and_materials.html
  - After assembly, magnets will be powered using the final power supply, and fields verified using the same procedure as for the prototype.
- Collimators
  - Fabrication will follow best practices, as outlined in the "Fermilab Quality Assurance Plan".
  - Collimators will be assembled and fully exercised prior to installation in the tunnel

Quality Assurance (cont'd)

- Upstream Extinction Monitor
  - Charged track telescope and DAQ will be assembled and fully commissioned with cosmic rays well before installation in the beam line.
- Target Monitor
  - The most important issue in the construction is alignment, which will be monitored continuously during installation.
  - Fabrication will be largely subcontracted, and will adhere to the subcontractor requirements in the "Fermilab Quality Assurance Plan".
  - The pixels themselves will be qualified according to the standard ATLAS quality control procedure (See JINST Vol 8. C02048 (2012)).

Risks

- Both the extinction and extinction monitoring system are based on mature technology, so risks from CD1 have been retired

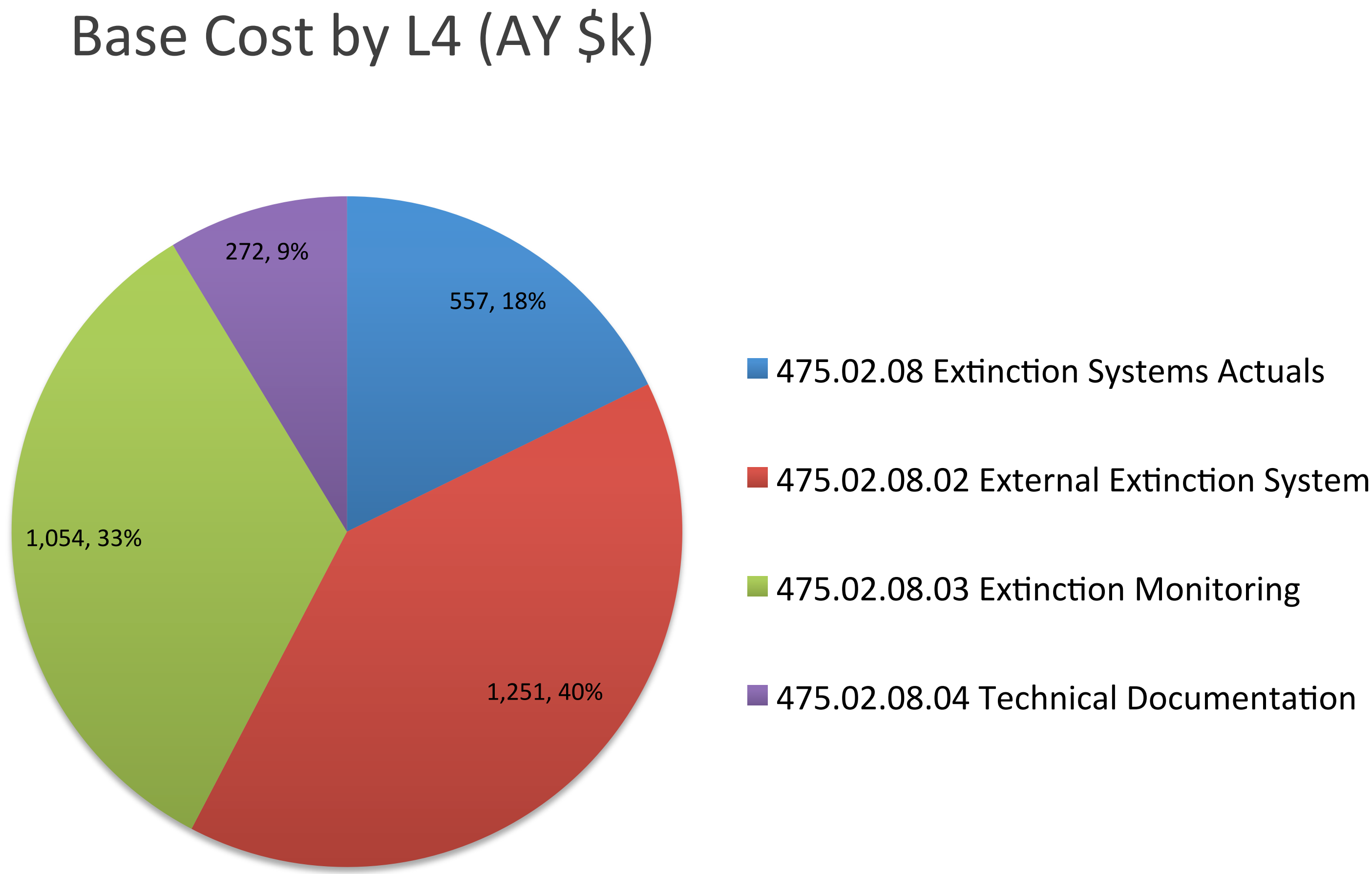
ACCEL-035	**3342**	Threat	Failure of extinction system to sufficiently eliminate out of time beam	retired
ACCEL-036	**3343**	Opportunity	No need in internal extinction collimation	realized!
ACCEL-037		Threat	Extinction monitor fails to perform to requirements.	retired

- We have budgeted for two collimators upstream of the AC dipole to remove high amplitude tails. It's possible that modeling will show these are not sufficient, and as many as two additional collimators might be required.
  - Potential cost impact: $xxxxx

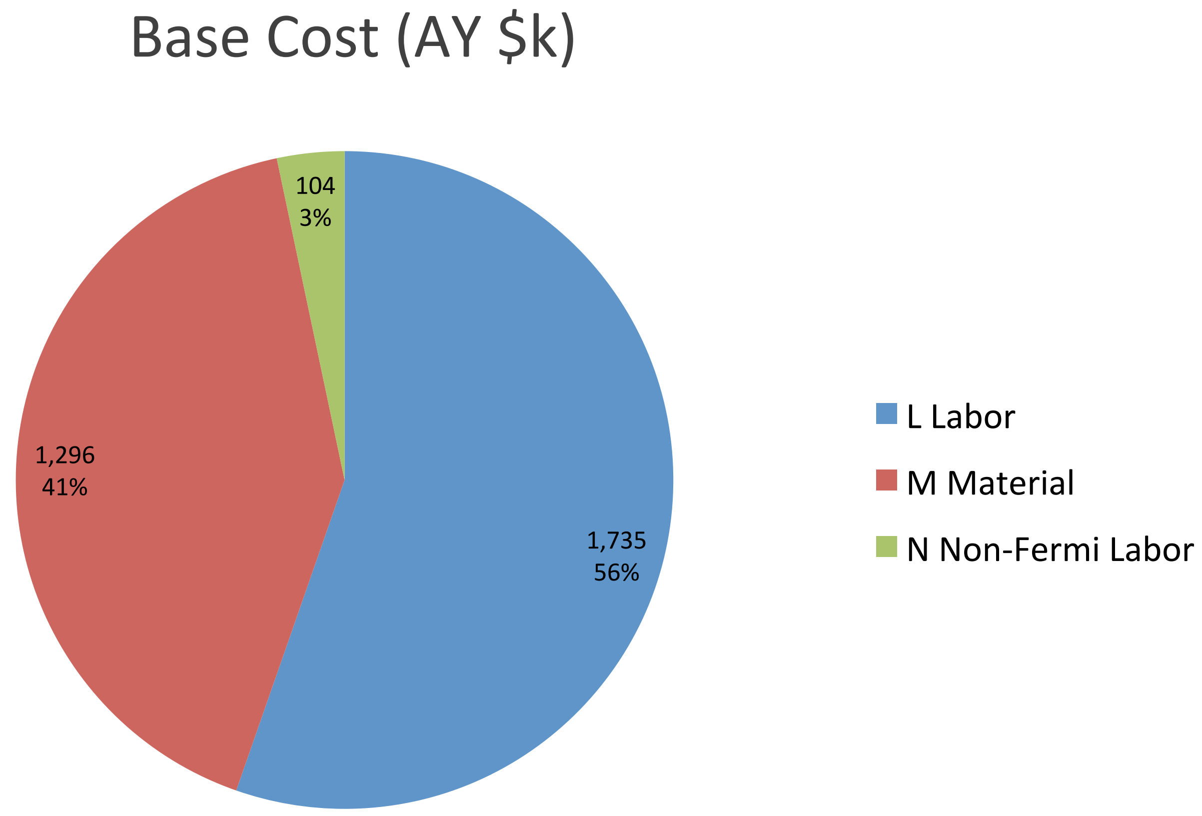
ES&H

- The AC Dipole, collimators, and internal extinction monitor will be in the beam line enclosure, and must follow established ES&H procedures all such elements.
- In addition, the AC dipole power supply will require a written LOTO procedure, which will be generated as part of it's documentation.
- The external monitor will not be accessible during operation, but simulations show there will not be any significant activation when beam is off.
- The upstream end of the filter channel will be in an extremely radioactive area, so it has been designed so it can be aligned from a safe location downstream.

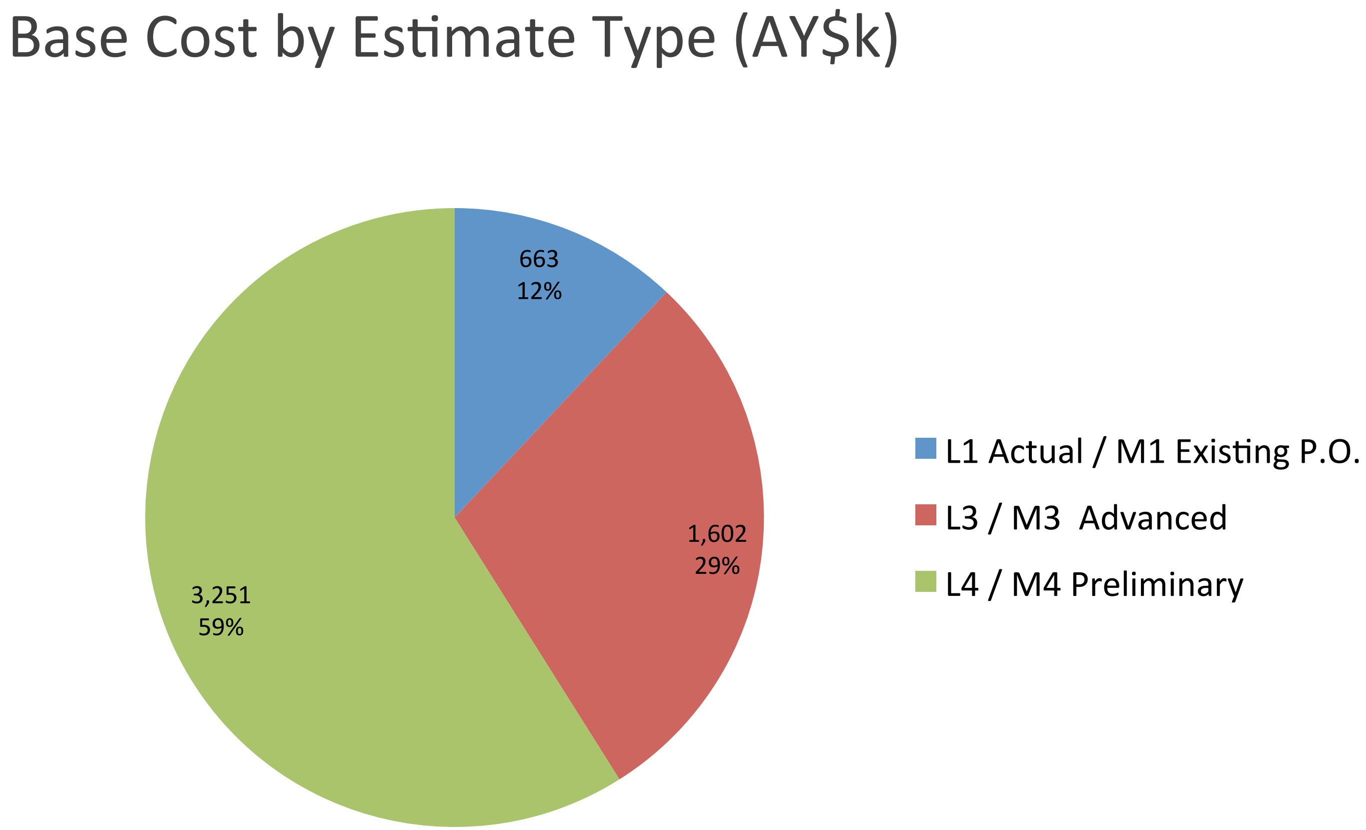
Cost Distribution by L4



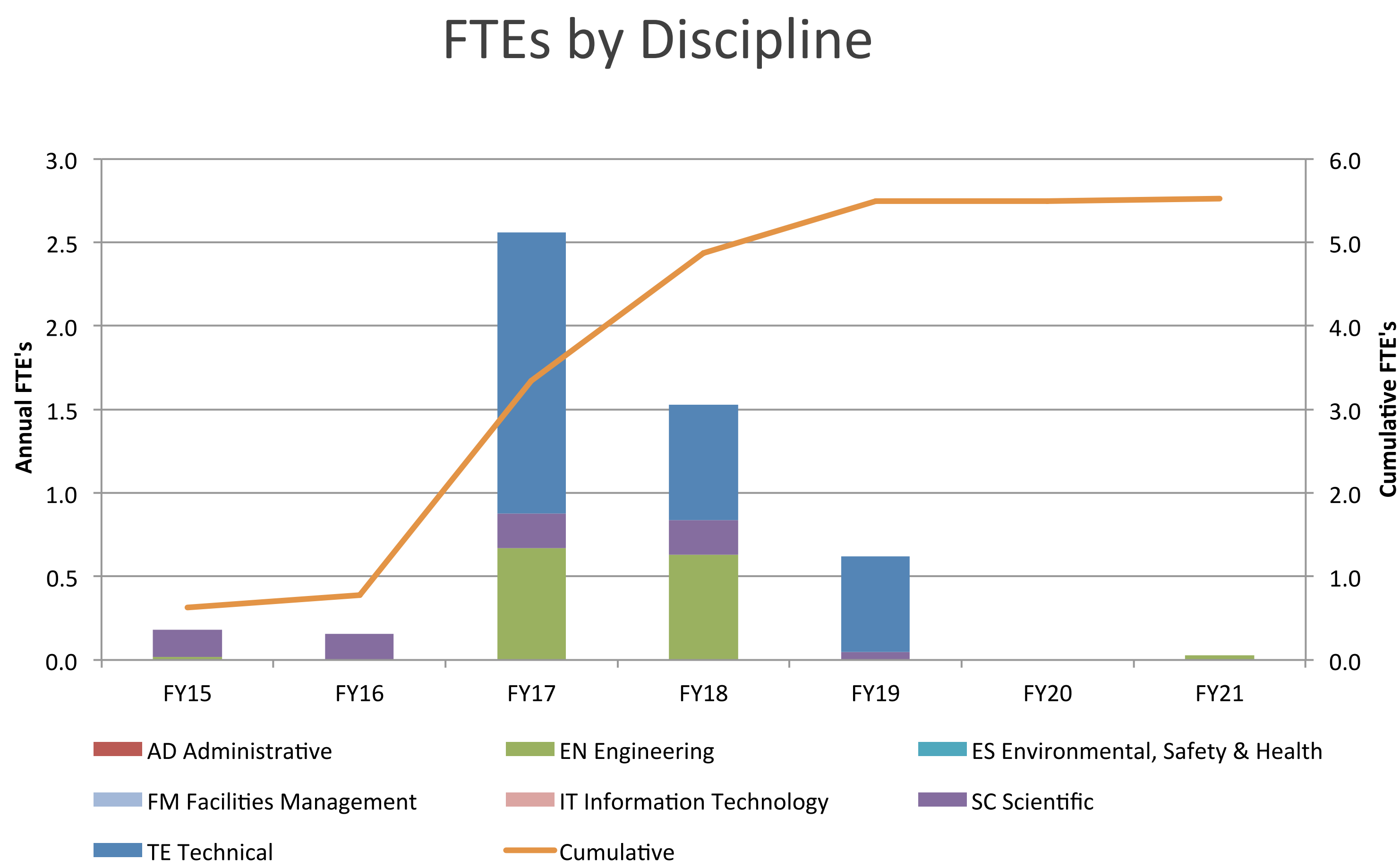
Cost Distribution by Resource Type



Quality of Estimate



Labor Resources



Cost Table

- Cost is roughly equally divided between the extinction and extinction monitoring

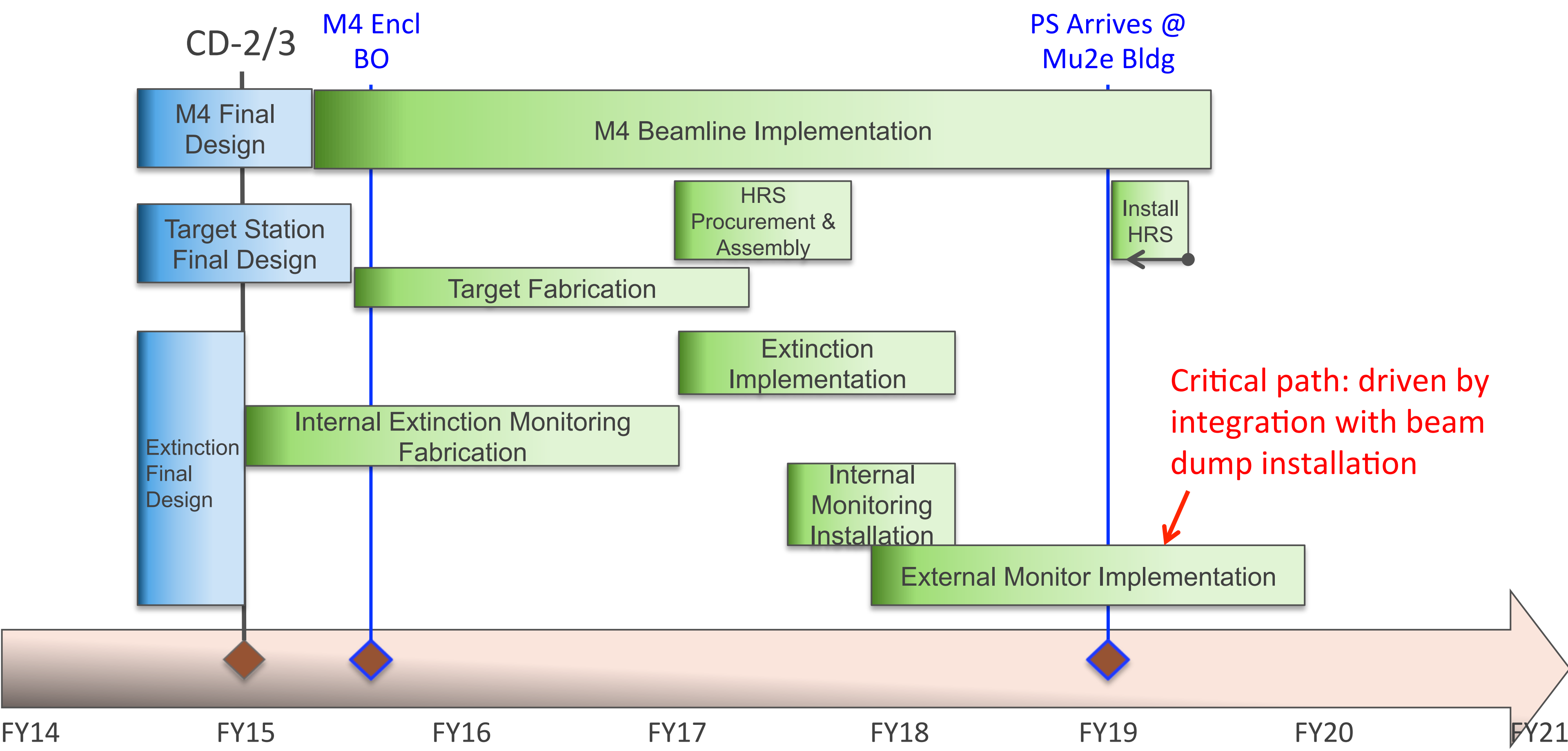
	M&S	Labor	BAC	Estimate Uncertainty	% contingency on ETC	Total
475.02.08 Actuals	66	490	557			557
475.02.08.02 External Extinction System	430	821	1,251	293	23%	1,544
475.02.08.03 Extinction Monitoring	538	516	1,054	354	34%	1,408
475.02.08.04 Technical Documentation		272	272	54	22%	327
Grand Total	1,035	2,100	3,134	701	27%	3,835

Major Milestones

Milestone Name	Milestone Description	Milestone Date	
Mu2e Extinction System Conceptual Design Complete	Completion of the conceptual design of the Mu2e extinction and extincion monitoring systems	June 28, 2012	✔
Mu2e Extinction System Preliminary Design Complete	Completion of the preliminary design of Extinction and Extinction Monitoring systems.	May 1, 2014	✔
Mu2e External Extinction System Final Design Complete	Completion of the final design of Extinction and Extinction Monitoring systems.	October 28, 2014	
Mu2e External Extinction Monitoring System Final Design Complete	Completion of the final design of the External Extinction Monitoring system.	November 6, 2014	
Mu2e Extinction System AC Dipole & Power Supply Installation and Close-out Complete	Fabrication and installation of all external extinction components complete.	September 18, 2017	
Mu2e External Extinction System Complete	Fabrication, procurement, and installation of the AC dipole extinction system and the internal extinction monitoring system components complete	December 12, 2017	
Mu2e Extinction System Installation and Close-out Complete	Fabrication, procurement, and installation of all extinction system and extinction monitoring system components complete	May 21, 2019	

Schedule

- Entirely resource driven



Schedule

- The extinction and extinction monitoring systems are entirely resource driven, and far from the critical path of the experiment.
- All beam line elements (AC Dipole, Collimation, Upstream Monitor) are scheduled to be complete by the first quarter of FY18
- The installation of the Target Monitor is intimately linked to construction of the building and beam dump, and therefore sets the critical path for the Extinction Task.

Summary

- We have designed an effective system to provide the extinction required by the Mu2e experiment and to verify that we have achieved that extinction.
- We are confident that we have met the requirements for CD-2 approval of this system.
  - Preliminary design complete
  - Project ready to baseline