Mu2e Extinction Systems

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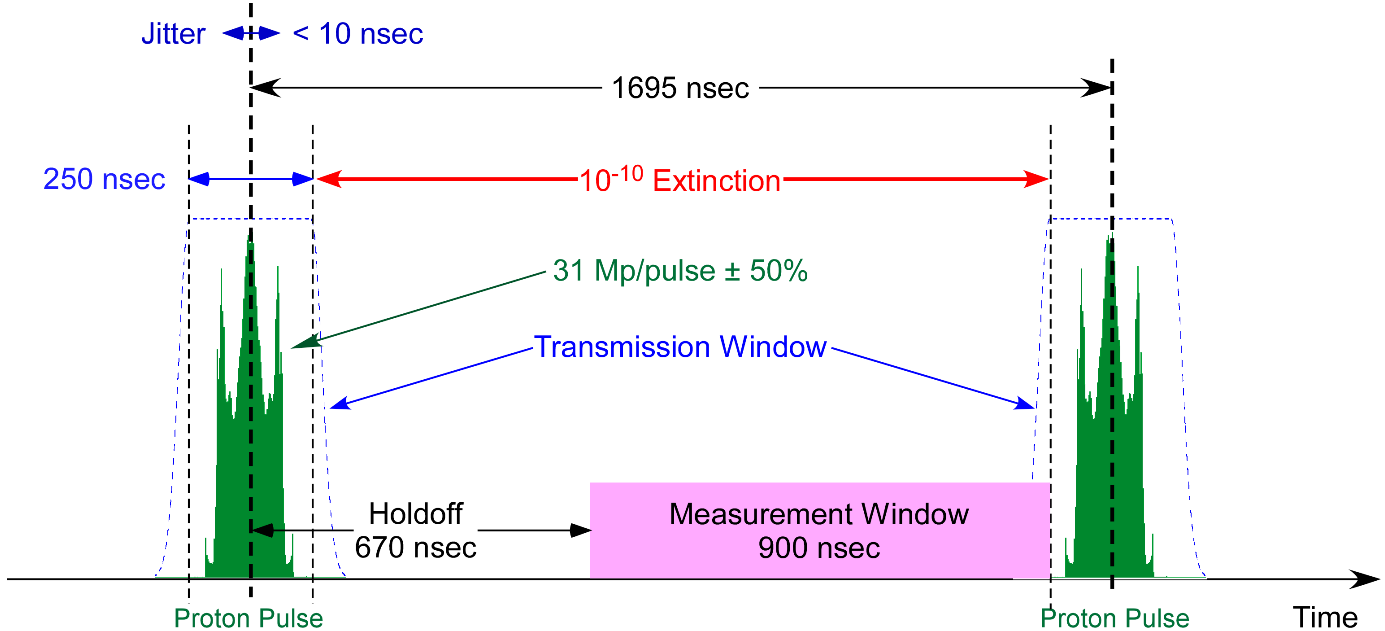
Mu2e CD-2/3b Review

October 21-24, 2014

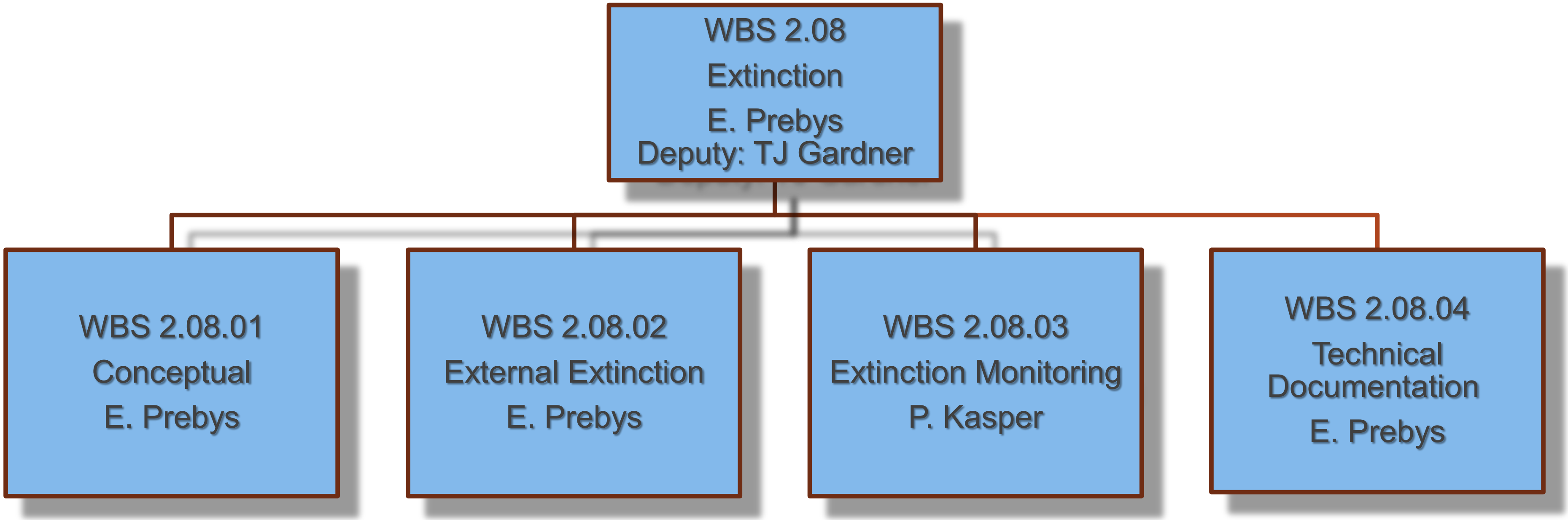
WBS 475.02.08 Extinction

- 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.
- We will address "Extinction" and "Extinction Monitoring" in separate talks

Organizational Breakdown



Organization of Talks

- My talk:
  - Extinction System:
    - Requirements
    - Technical design
    - Projected performance
    - Value engineering, risks, etc…
  - Cost and schedule for *both* Extinction and Extinction Monitoring
- P. Kasper's talk:
  - Extinction Monitor
    - Requirements
    - Technical design
    - Projected performance
    - Value engineering, risks, etc

Extinction Requirements*

- The total extinction requirement is

< 1 every ~300 bunches

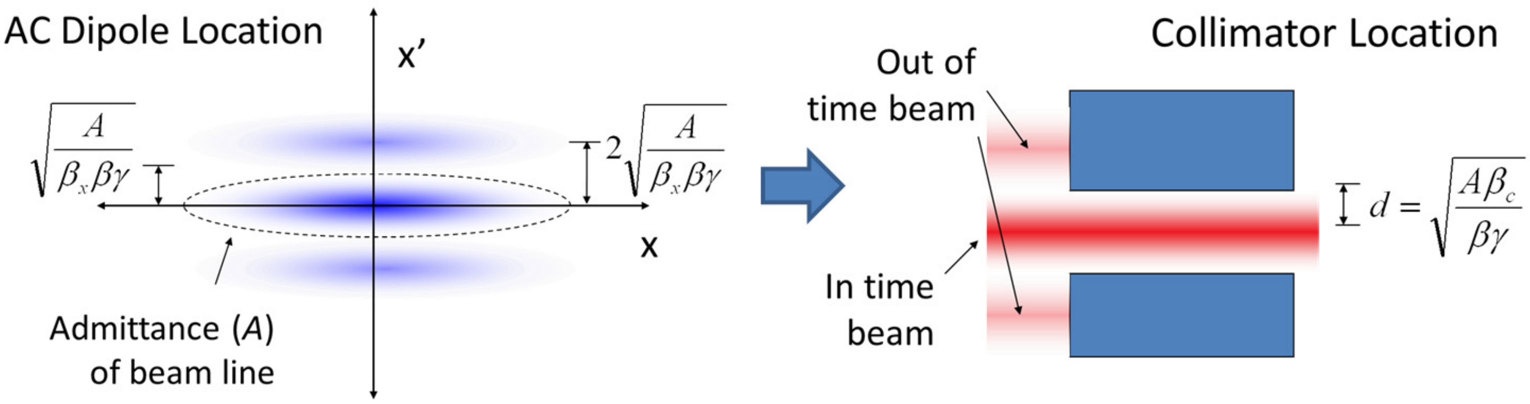
$$\frac{\text{(beam on target outside of transmission window)}}{\text{(total beam on target)}} < 10^{-10}$$

- 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 ~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

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

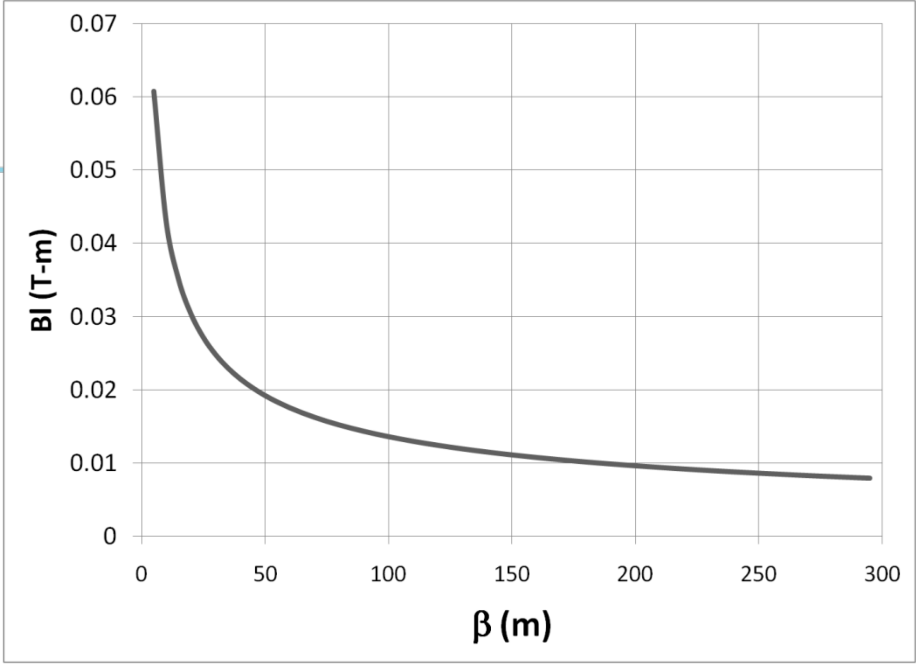
β at AC dipole (=250 m)

- 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:

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

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

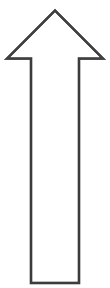
➔Large β_x, long weak magnets

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

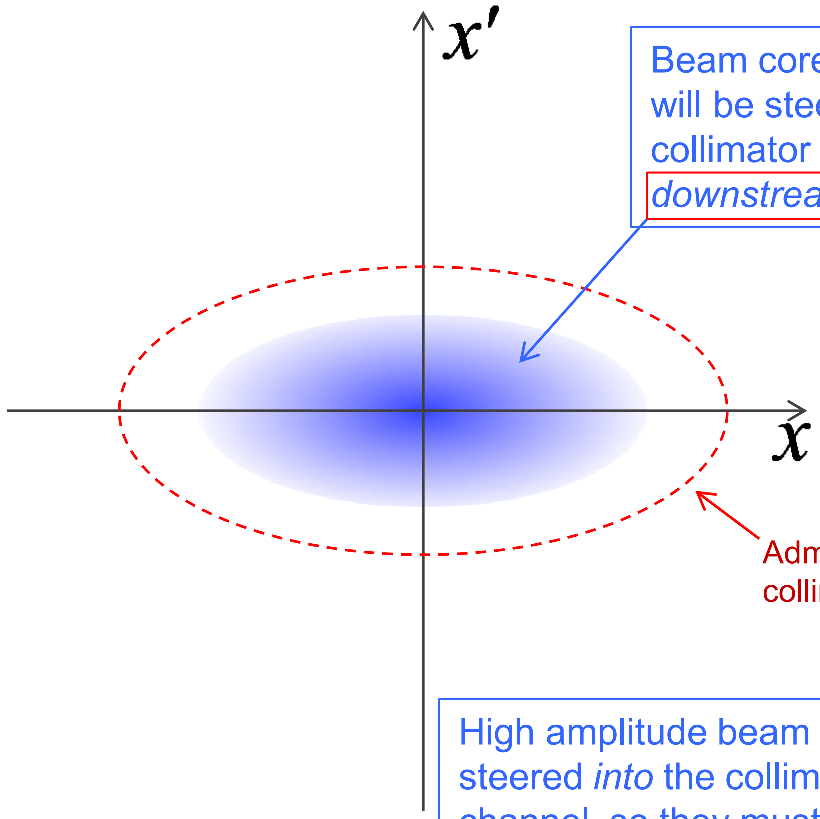
Driving consideration in beam line design!

Two Separate Collimation Issues

Phase space distribution of out of time beam at location of AC dipole



AC dipole shifts distribution along x' axis in phase space

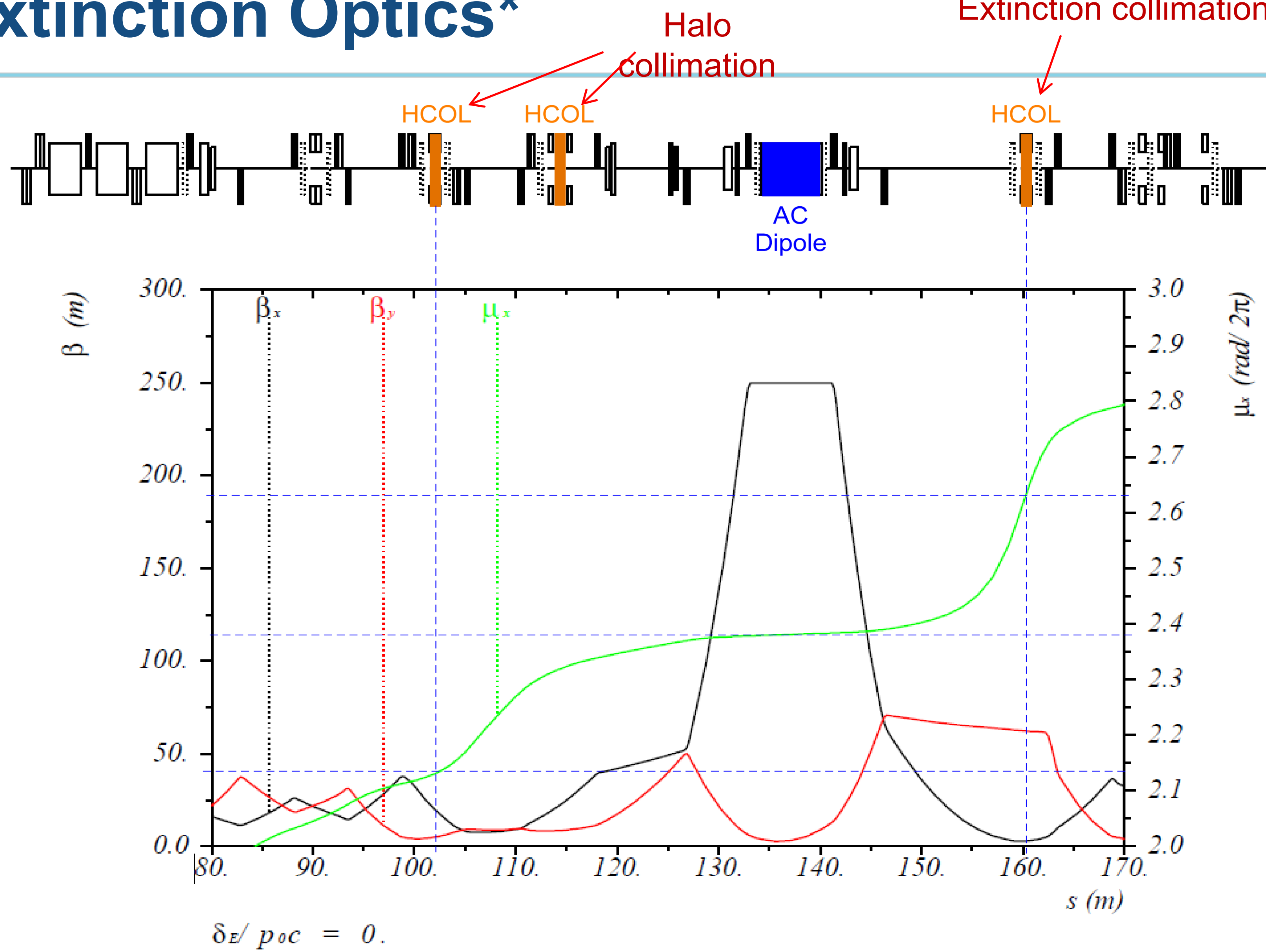


Beam core: out of time beam will be steered into the collimator or collimators *downstream* of the AC dipole

Admittance of downstream collimation system

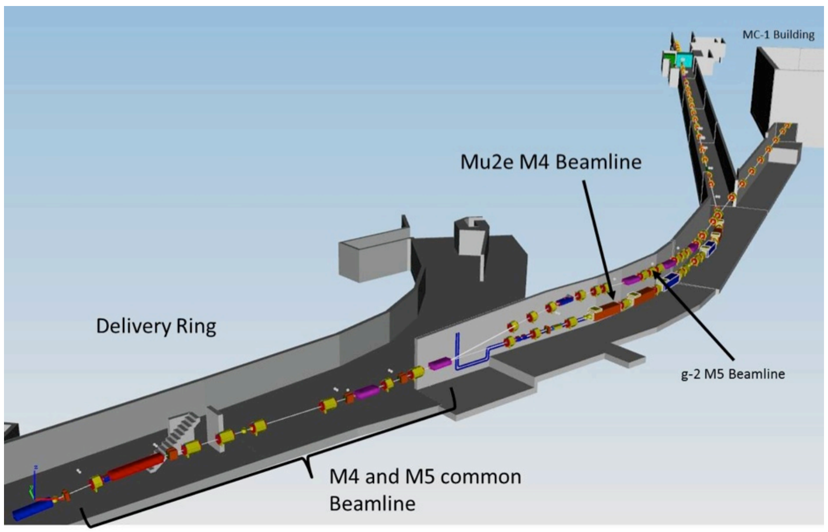
High amplitude beam tails will be steered *into* the collimation channel, so they must be cleaned up *upstream* of the AC dipole

Extinction Optics*



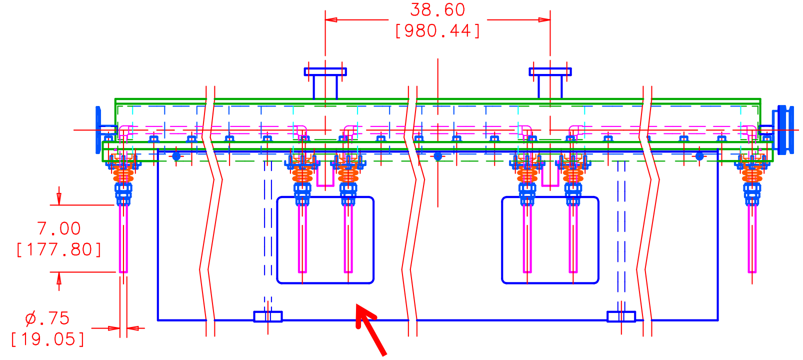
*E. Gianfelice

Mu2e Beam Line

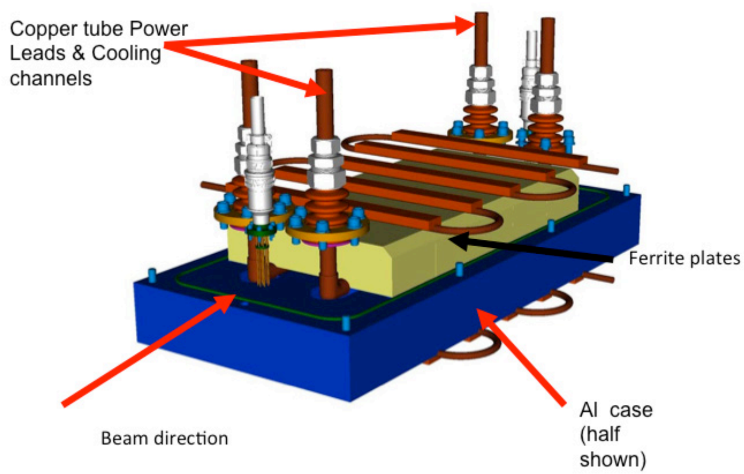


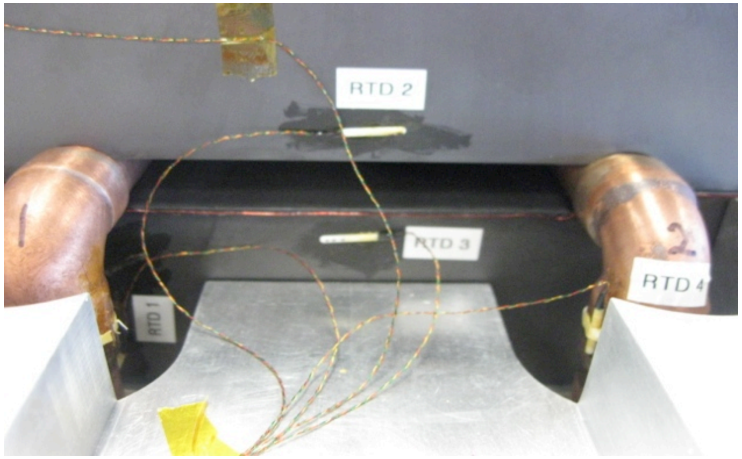
AC Dipole Design and Prototype

- 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 specifications



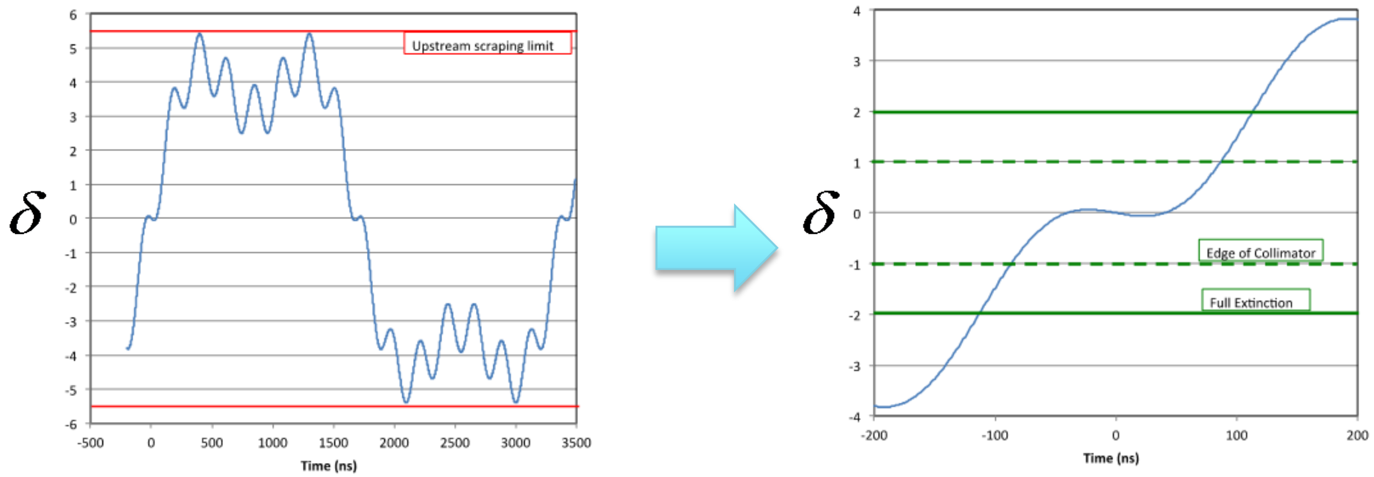
Elements individually powered





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 element @ 900 kHz, to reduce amplitude and prevent beam pipe scraping upstream of the collimator.

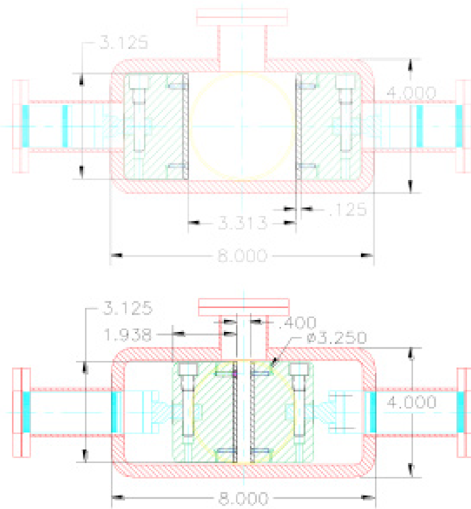


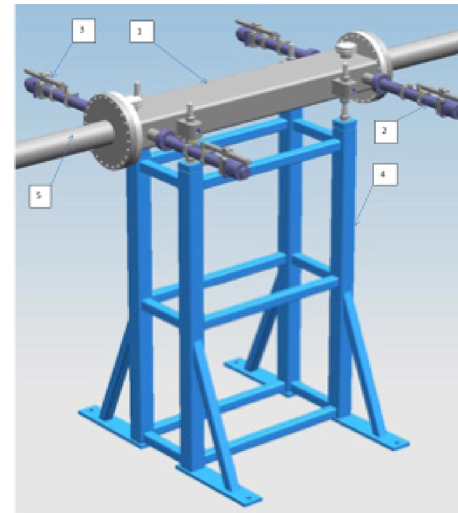
Magnet	Frequency (kHz)	Length (cm)	Aperture		Peak B Field (Gauss)
			bend plane (cm)	non-bend (cm)	
A	300	200	7.8	1.2	207.0
B	900	100	7.8	1.2	73.2
C	4500	300	7.8	1.2	35.2

Collimator Design

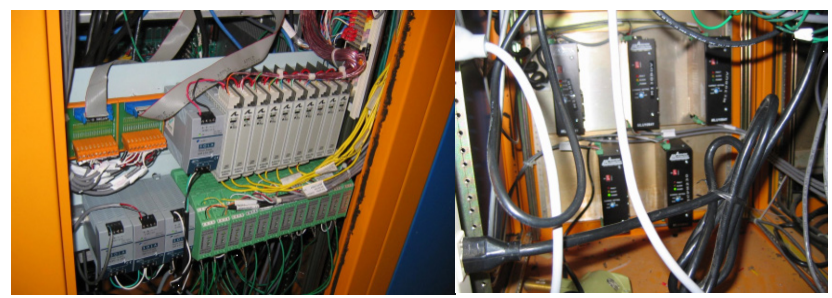
- Collimator based on designs previously used in Main Injector and Tevatron
- Separate motion controllers/LVDTs at each end so position and angle can be precisely controlled

Collimator and stand:





Control and position measurement



Extinction Performance

Two Models:

1. Beam distribution from ESME longitudinal tracking model in the Delivery Ring. (Mu2e-DOC-4105)
2. G4Beamline tracking model of extinction section of the M4 beamline. (Mu2e-DOC-5054)

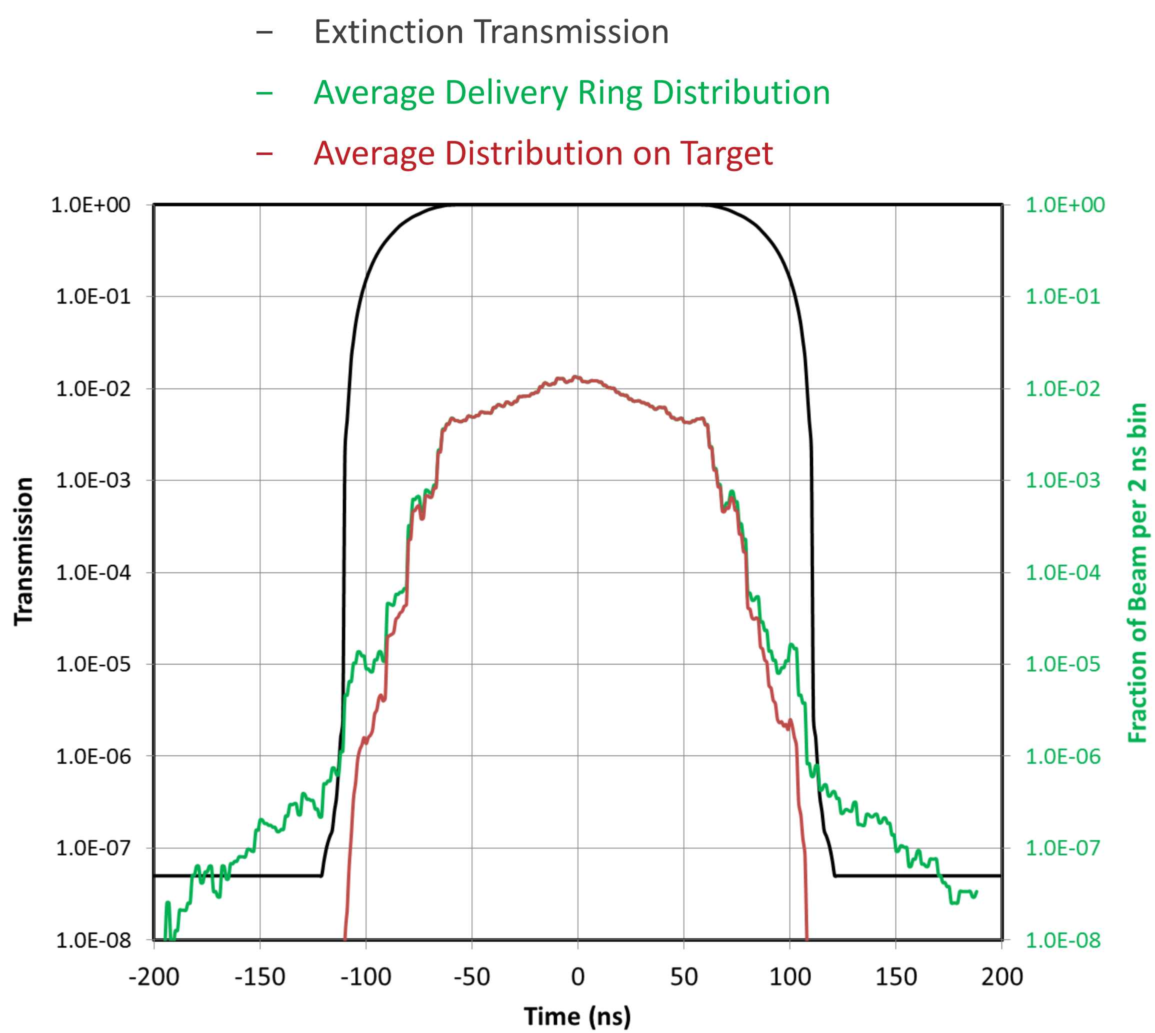
Results:

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.



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.

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.

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

Risks

- Both the extinction and extinction monitoring system are based on mature technology, so some risks from CD1 have been transferred to operations

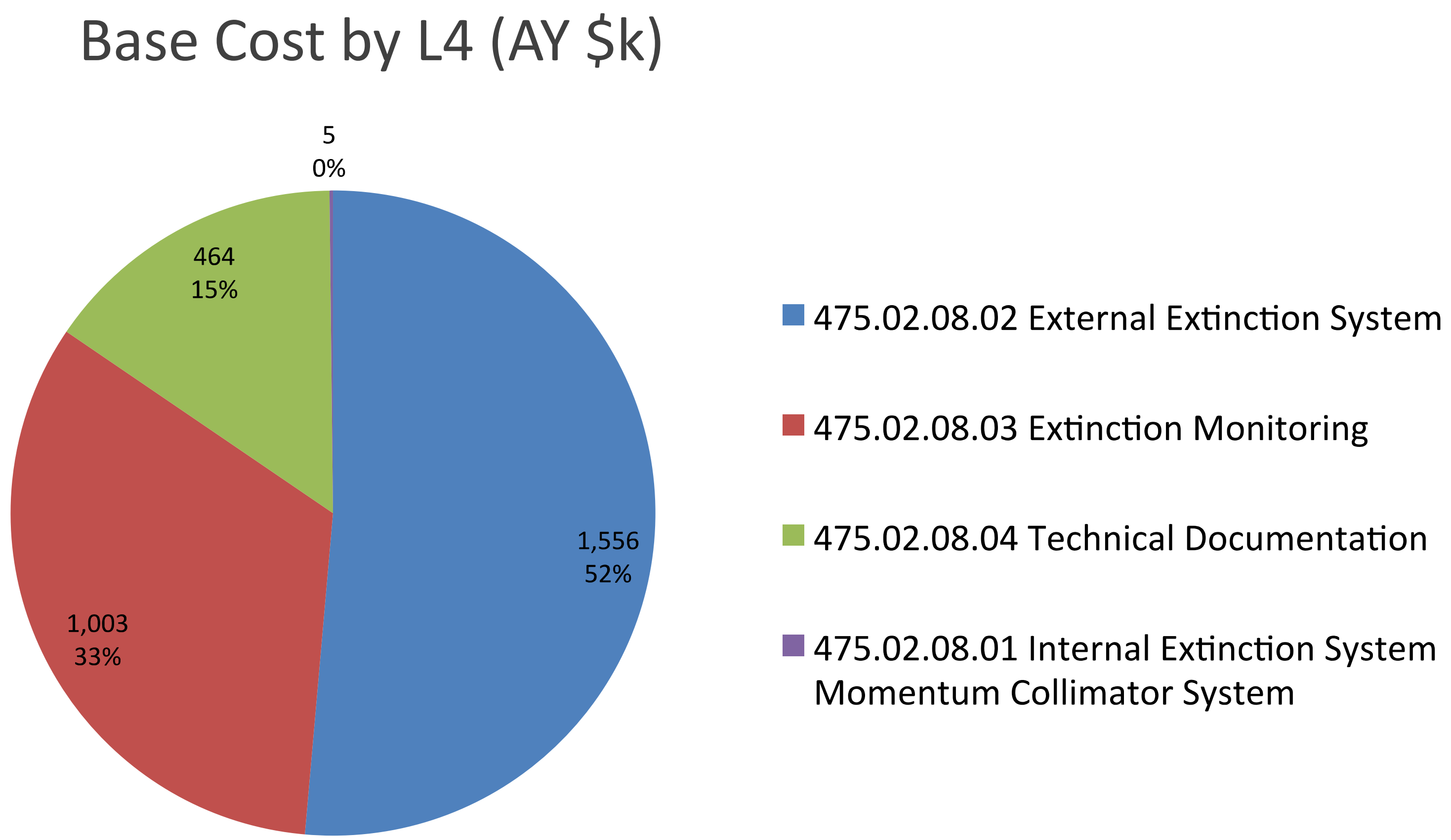
ACCEL-035	Threat	Failure of extinction system to sufficiently eliminate out of time beam	transferred to operations
ACCEL-036	Opportunity	No need in internal extinction collimation	realized!
ACCEL-037	Threat	Extinction monitor fails to perform to requirements.	transferred to operations

- Remaining risk: ACEL-204
  - 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: $160k
    - Probability: Low

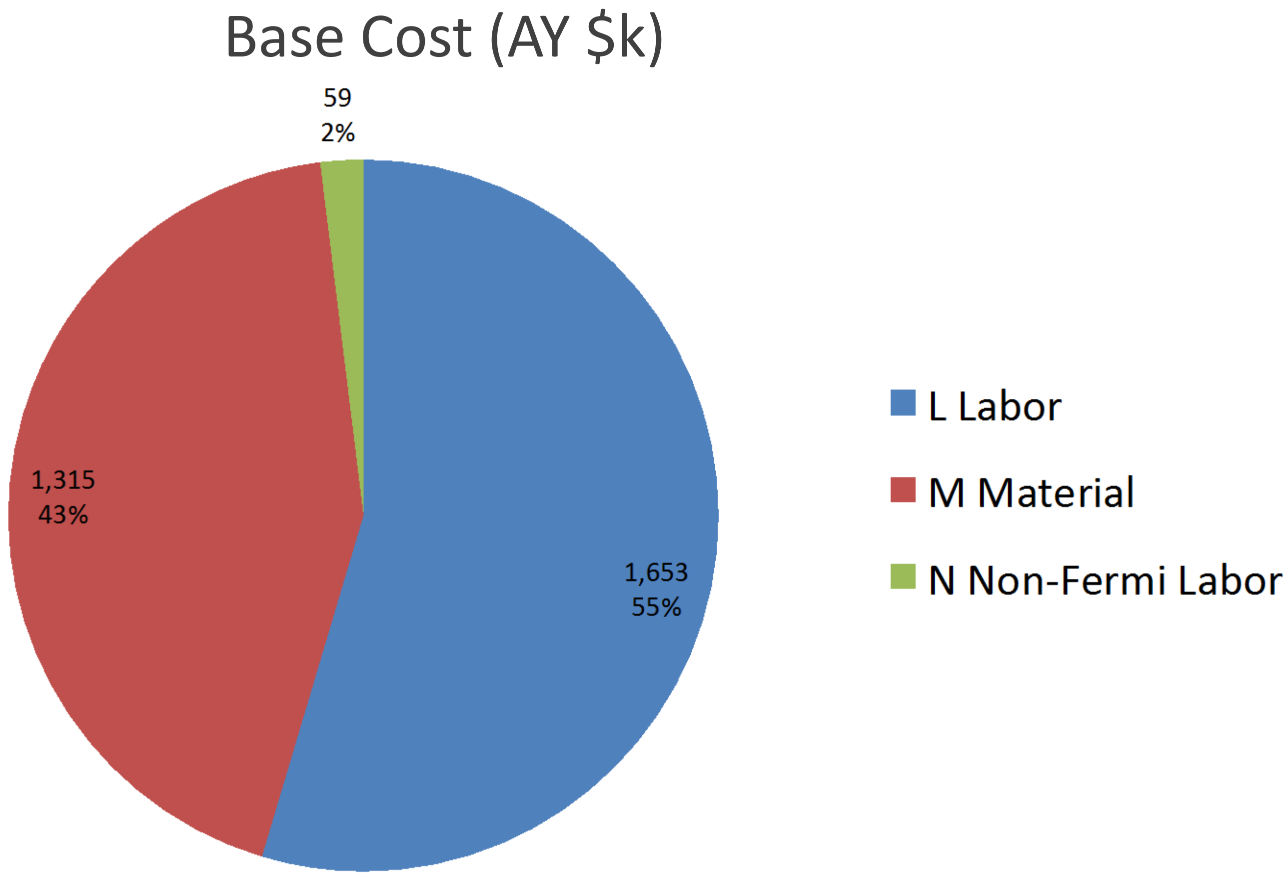
ES&H

- 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

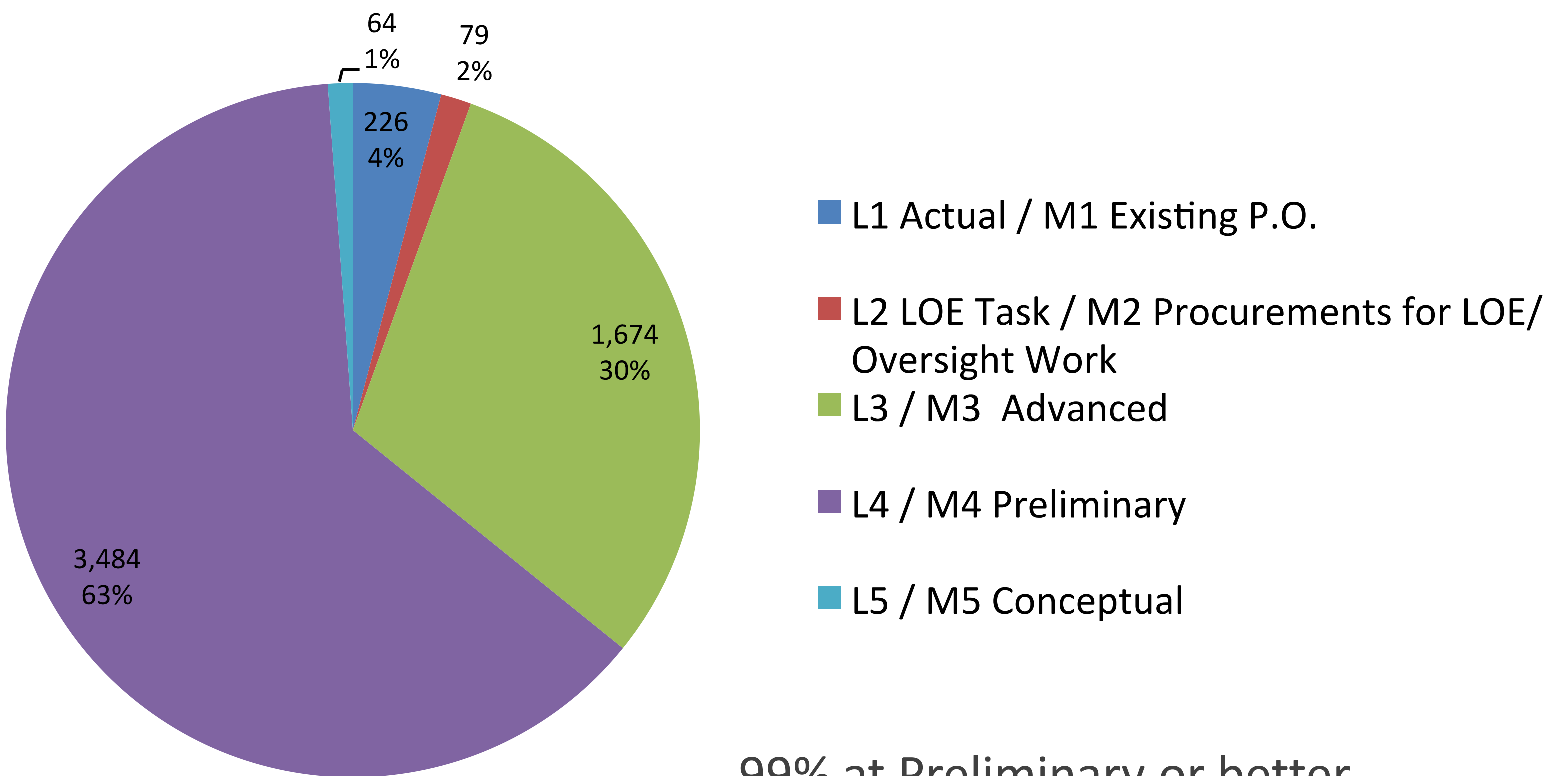


Cost Distribution by Resource Type



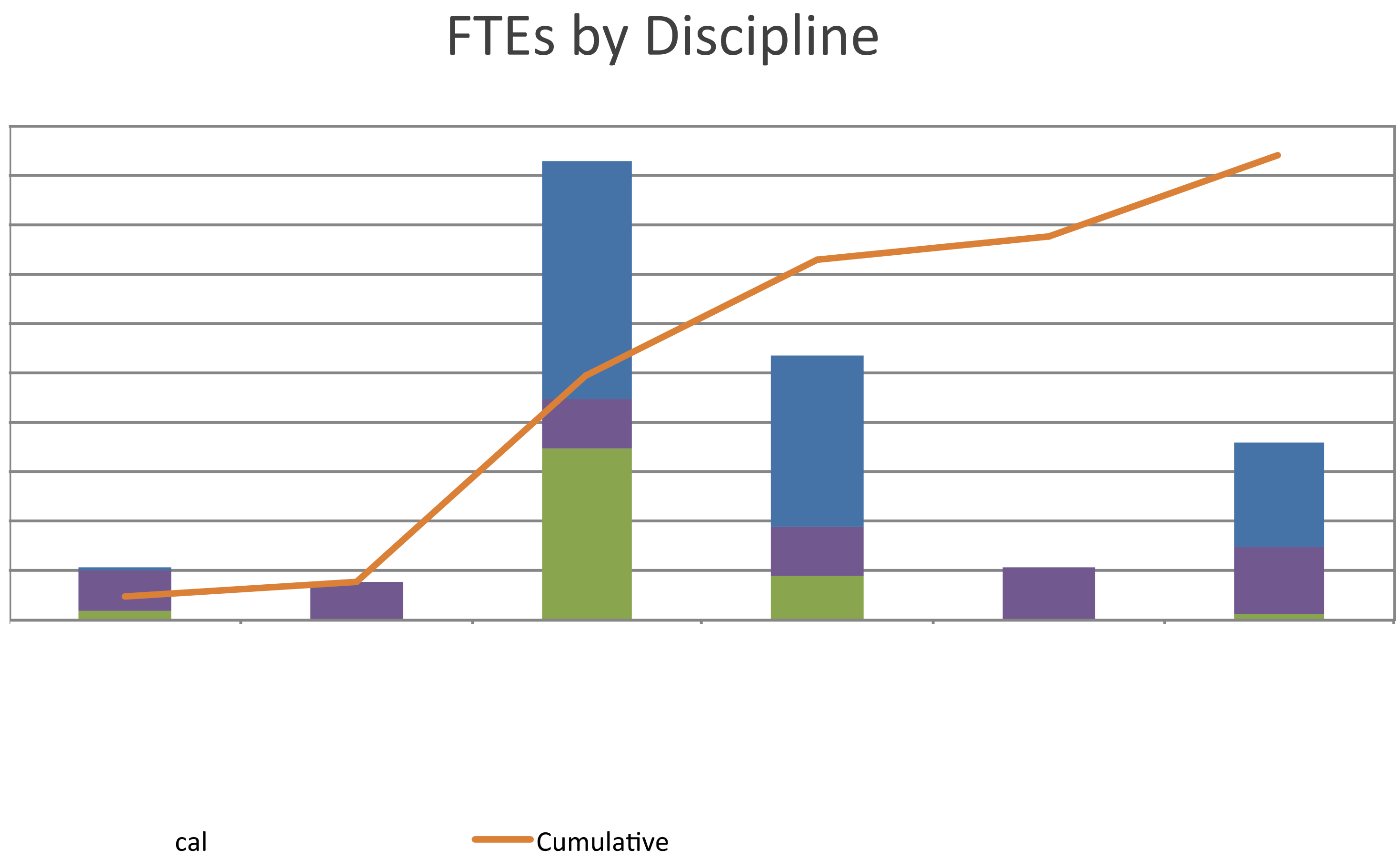
Quality of Estimate

Base Cost by Estimate Type (AY$k)

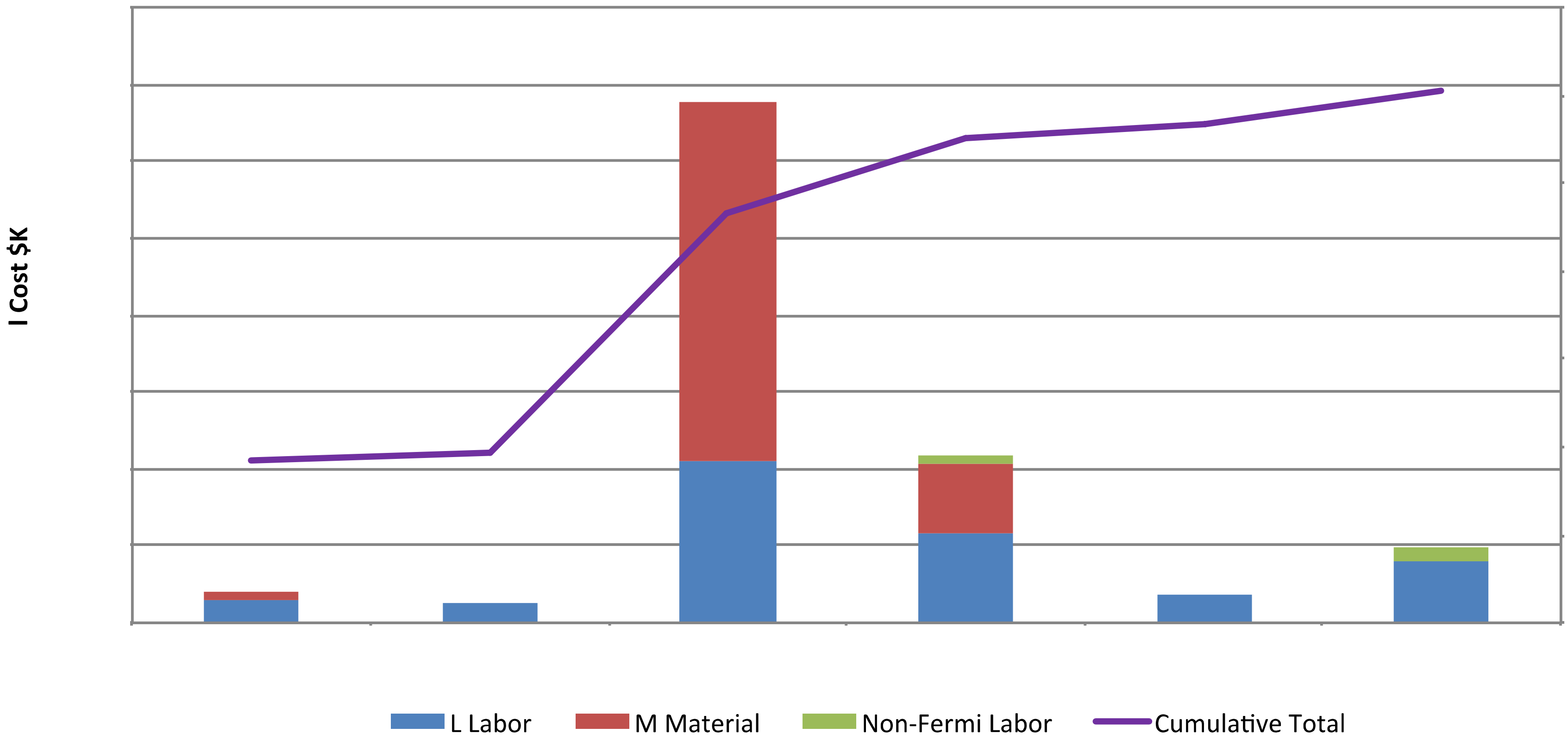


99% at Preliminary or better

Labor Resources by FY



Labor and M&S by FY



Cost Table

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

	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency on (on remaining budget)	Total Cost
475.02.08.01 Internal Extinction System Momentum Collimator System	5		5		n/a	5
475.02.08.02 External Extinction System	661	894	1,556	352	32%	1,908
475.02.08.03 Extinction Monitoring	707	296	1,003	306	37%	1,309
475.02.08.04 Technical Documentation		464	464	81	24%	545
Grand Total	1,374	1,653	3,027	740	33%	3,767

Major Milestones

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 middle 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