Mu2e Accelerator Systems

Steve Werkema
Mu2e Accelerator Level 2 Manager
10/21/2014

Accelerator L2 Management Team

- **Steve Werkema** – L2 Manager
  - Projects Involvement:
    - Mu2e L2 manager since Fall of 2010; prior to that was in charge of Antiproton Source upgrades for Mu2e
    - Collider Run II Accelerator upgrades L2 manager for Antiproton Source aperture improvements
  - Deputy Head of Muon Department since its formation. Before that was Deputy Head of the Antiproton Source Department
- **Vladimir Nagaslaev** – Deputy L2 Manager
  - Accelerator physicist in AD/Muon Department
  - Involved in Mu2e project since 2009
  - Also Level 3 manager for Resonant extraction
- **Mike Campbell** – Accelerator Project Engineer
  - Senior Mechanical Engineer in AD/Mech. Suppt. Department
  - Engineer in charge of proton target remote handling

OVERVIEW

Scope Overview

475.02.08.03 Extinction Monitor

475.02.09 Target Station

475.02.07 External (M4) Beamline

475.02.08.02 Extinction

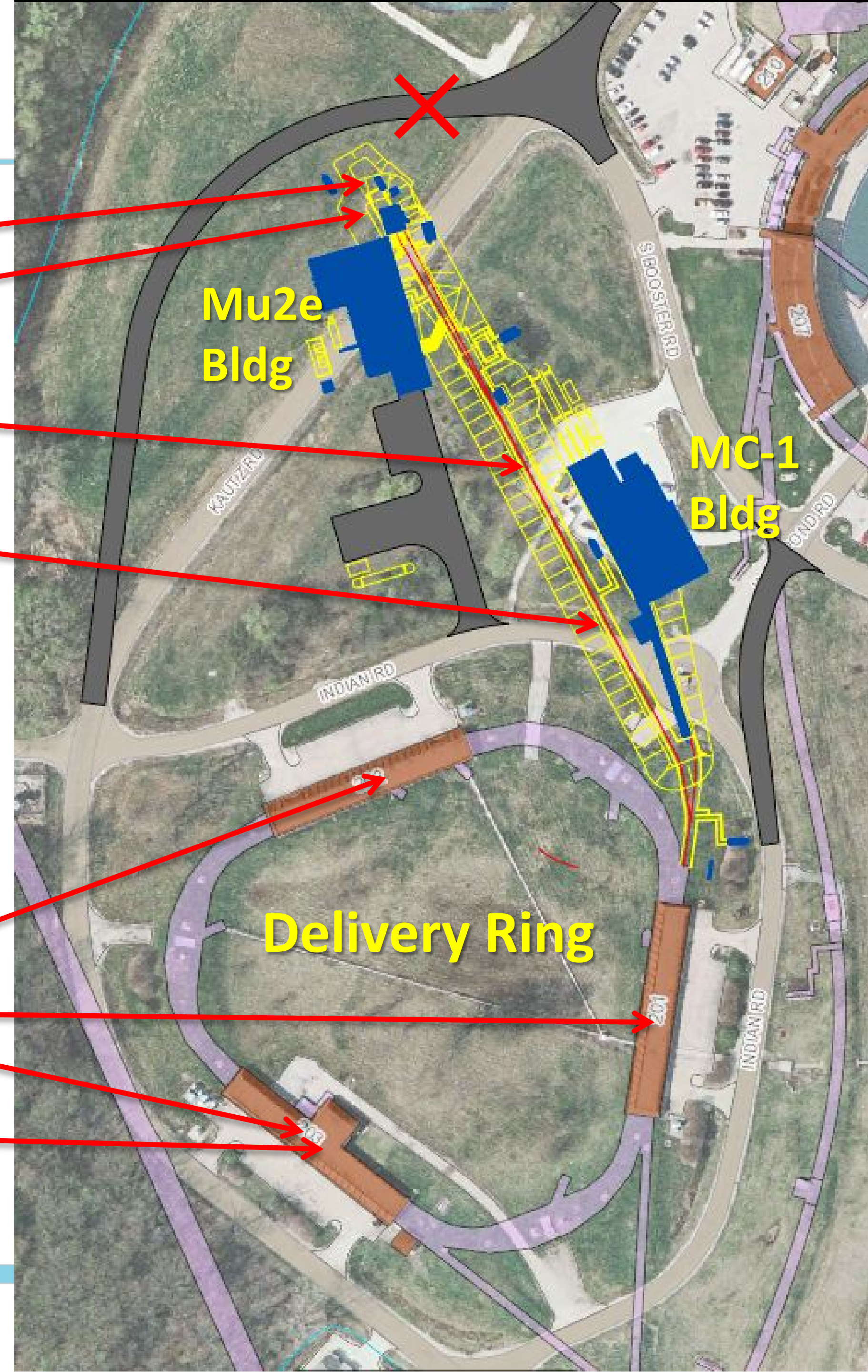
475.02.03 Instrumentation & Controls

475.02.04 Radiation Safety

Everywhere

475.02.05 Resonant Extraction

475.02.06 Delivery Ring RF



Mu2e Accelerator Systems Organization

- **475.2 Accelerator Systems** – S. Werkema (FNAL)
  - 475.2.1 Project Management
    L3 – S. Werkema
    CAM - S. Werkema
  - 475.2.3 Instrumentation & Controls
    L3 – B. Drendel
    CAM - B. Drendel
  - 475.2.4 Radiation Safety
    L3 – T. Leveling
    CAM - T. Leveling
  - 475.2.5 Resonant Extraction
    L3 – V. Nagaslaev
    CAM – V. Nagaslaev
  - 475.2.6 Delivery Ring RF
    L3 – J. Dey
    CAM – J. Dey
  - 475.2.7 External Beamline
    L3 – D. Still
    CAM – D. Still
  - 475.2.8 Extinction
    L3 – E. Prebys
    CAM – E. Prebys
  - 475.2.9 Target Station
    L3 – R. Coleman
    CAM – R. Coleman

REQUIREMENTS – DESIGN – PERFORMANCE

Requirements Overview

The Mu2e Accelerator Upgrades are governed by eight requirements documents

• Science Driven Requirements	Mu2e-doc-4381
• Proton Beam Requirements	Mu2e-doc-1105
• Beam Extinction Requirements	Mu2e-doc-1175
• Extinction Monitor Requirements	Mu2e-doc-894
• Production Target Requirements	Mu2e-doc-887
• Heat and Radiation Shield (HRS) Requirements	Mu2e-doc-1092
• Proton Absorber Requirements	Mu2e-doc-948
• Protection Collimator Requirements	Mu2e-doc-2897

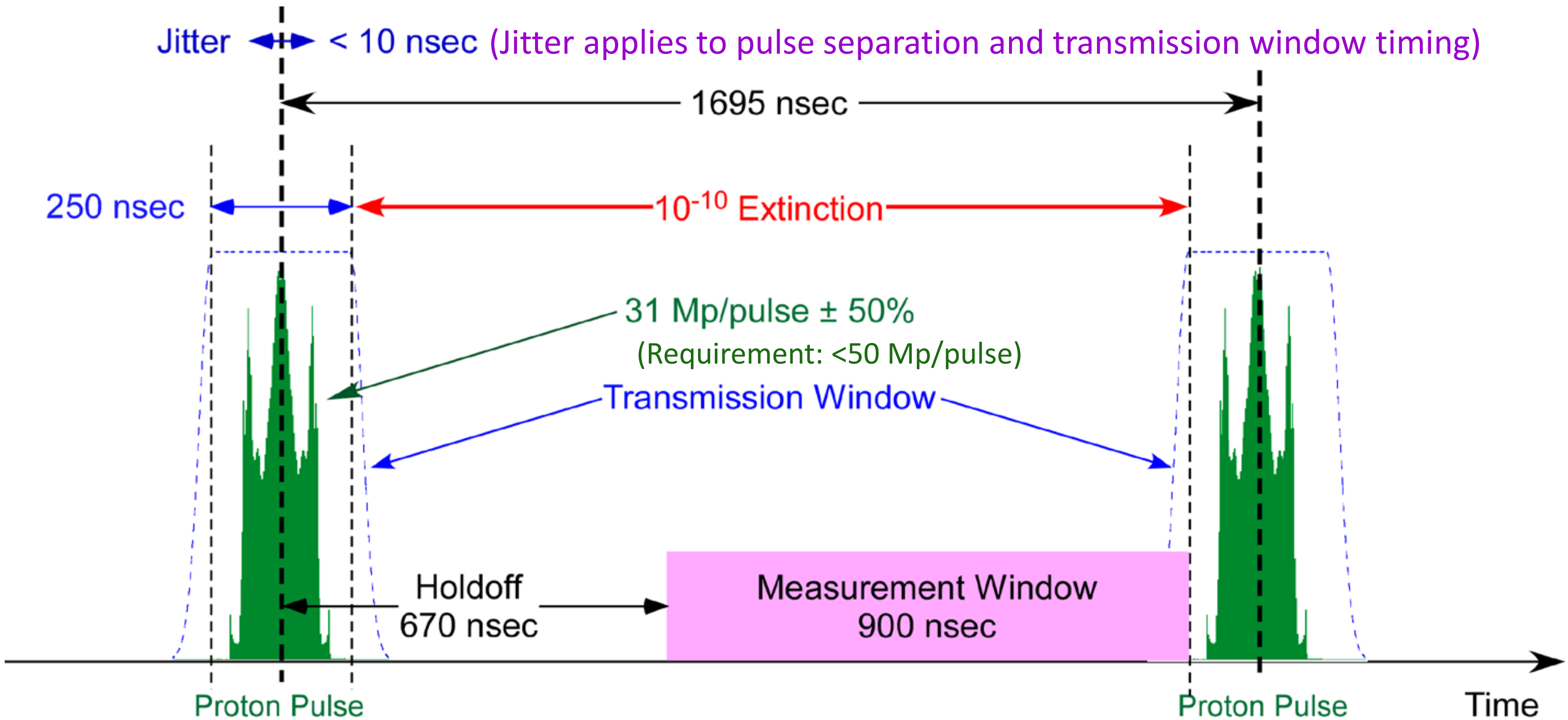
All of these documents are available on the review web site.

Proton Beam Requirements

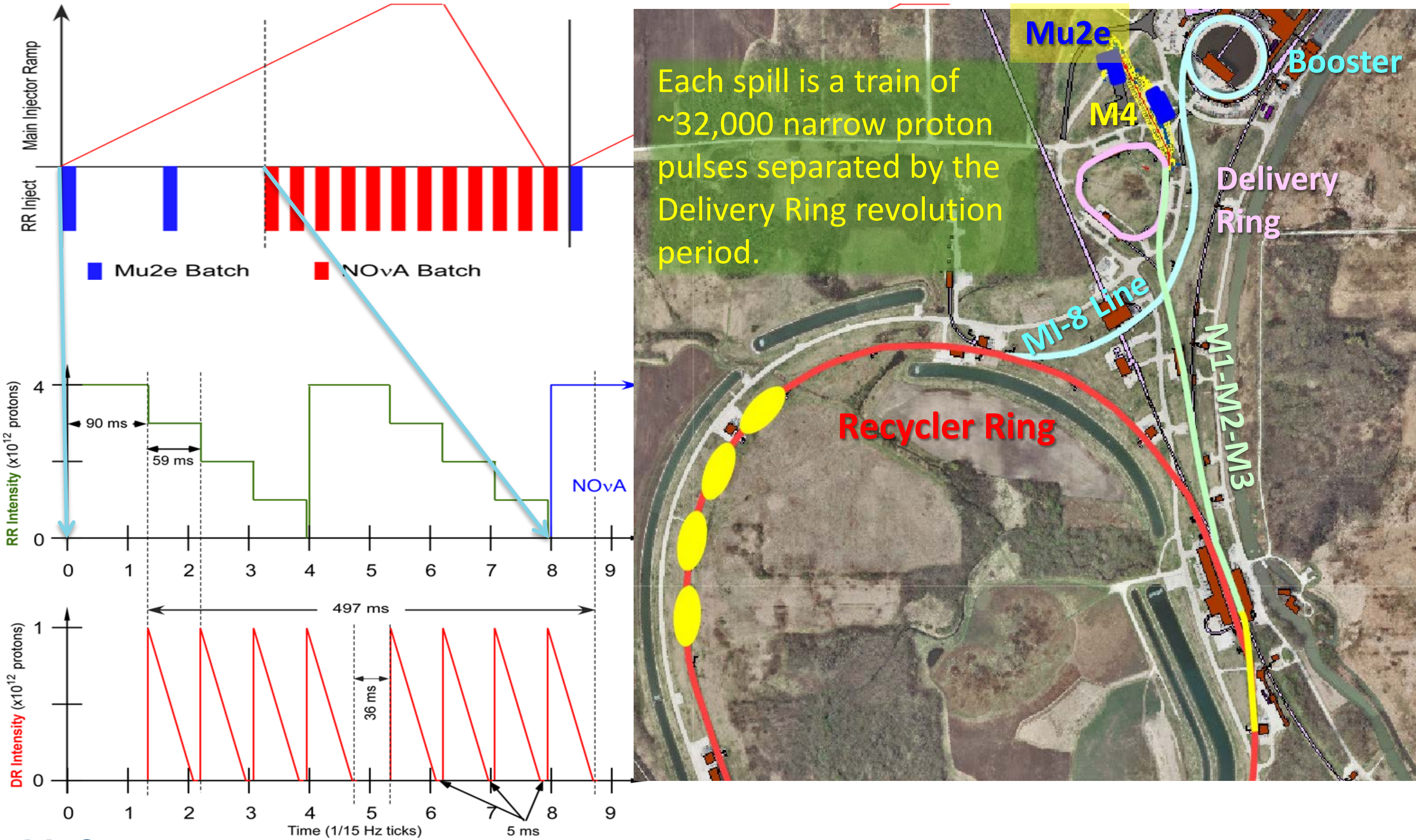
	Parameter	Design Value	Requirement	Unit
	Total protons on target	3.6×10^{20}	3.6×10^{20}	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
	Maximum variation in pulse separation	< 1	10	nsec
	Spill duration	54	> 20	msec
	Beamline Transmission Window	230	250	nsec
	Transmission Window Jitter (rms)	5	<10	nsec
	Out-of-time extinction factor	10^{-10}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.1×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
	Target rms beam divergence	0.5	< 4.0	mrad

Proton Beam & Extinction Requirements

Two successive proton pulses on the Mu2e target (out of 32,000 per spill)

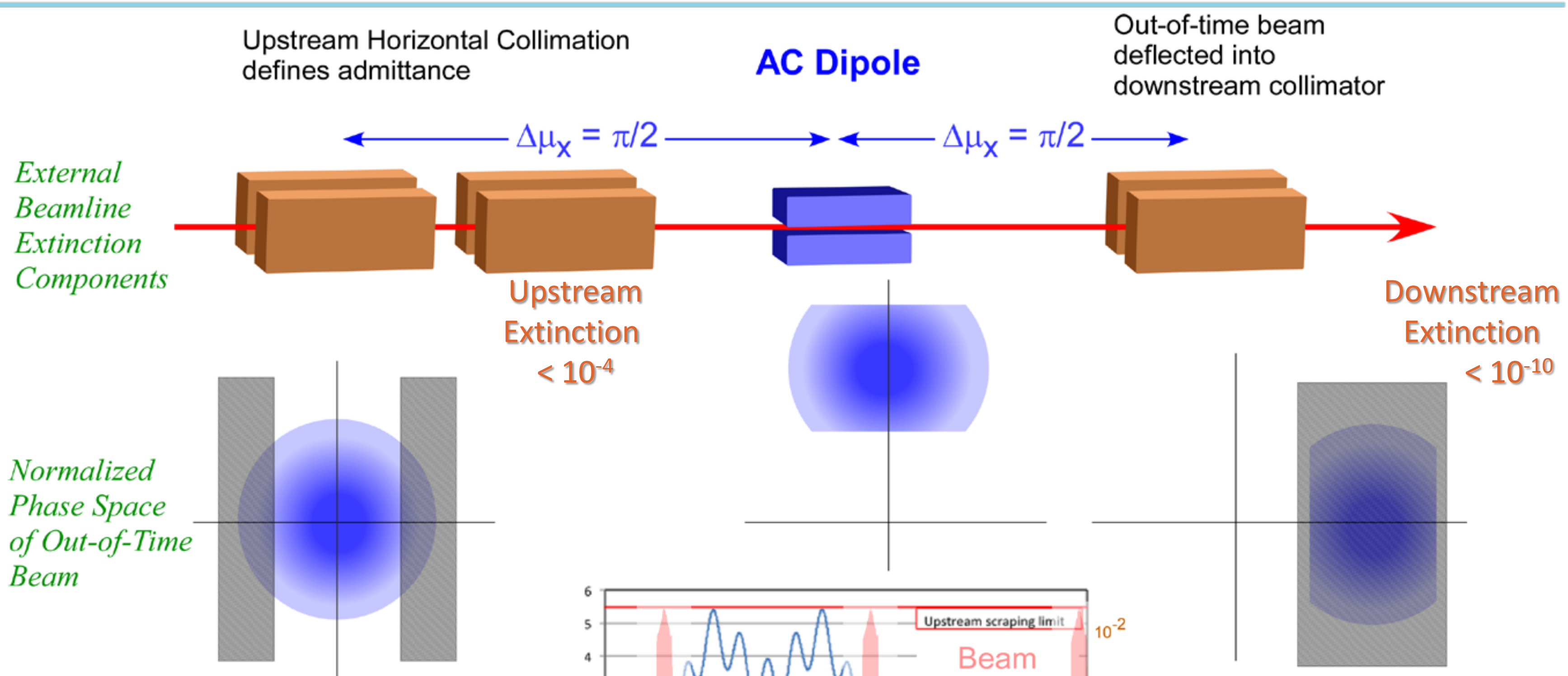


Design – Proton Beam Delivery to Mu2e

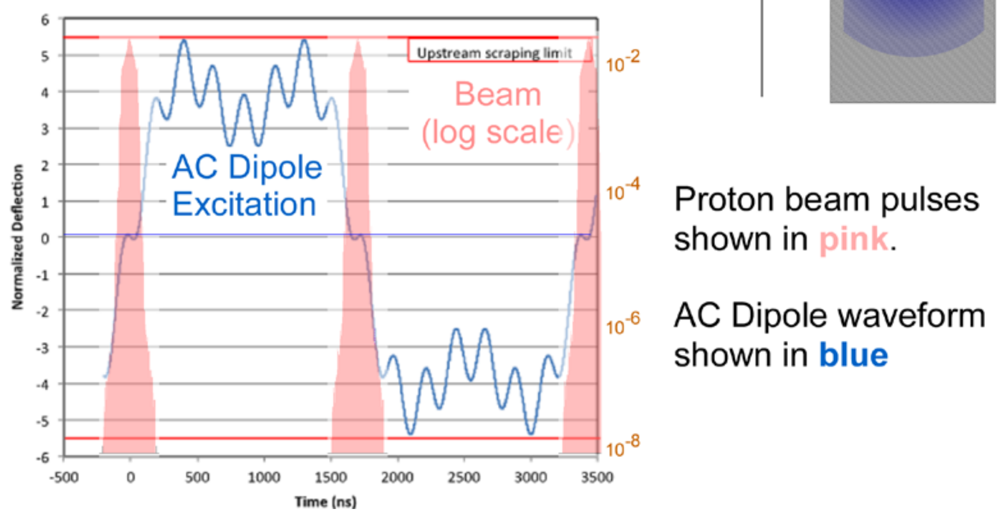


Each spill is a train of ~32,000 narrow proton pulses separated by the Delivery Ring revolution period.

Design – Extinction



AC Dipole Excitation



The AC Dipole excitation is a superposition of three harmonics: 300 kHz, 900 kHz, and 4.5 MHz.

Extinction Performance

Two Models:

1. Beam time distribution from ESME longitudinal tracking model in the Delivery Ring.
2. G4Beamline tracking model of extinction section of the M4 beamline.

Results:

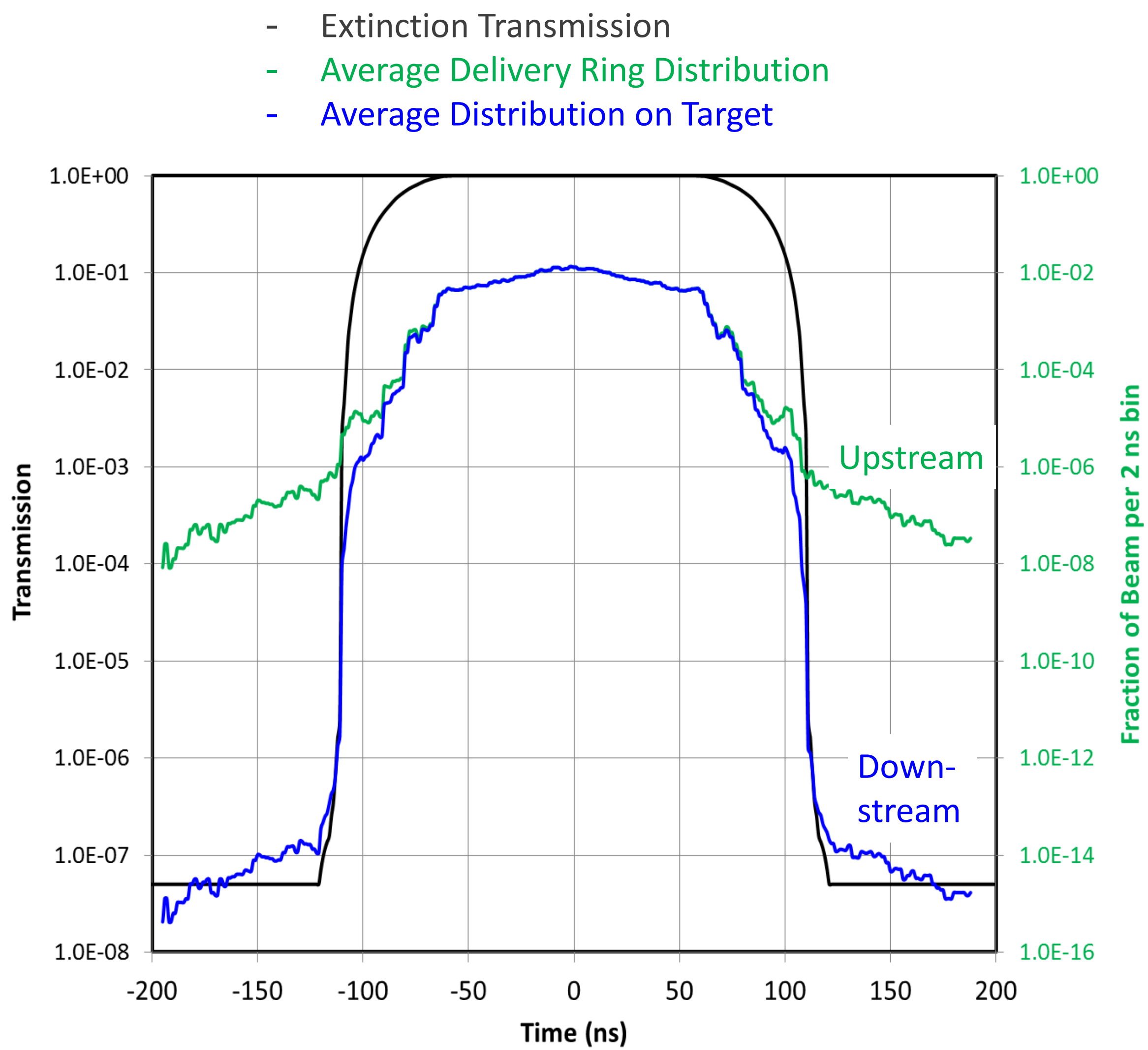
Upstream extinction: 1.6×10^{-5}

In-time beam transmission: 99.7%

Downstream extinction: 8×10^{-13}†

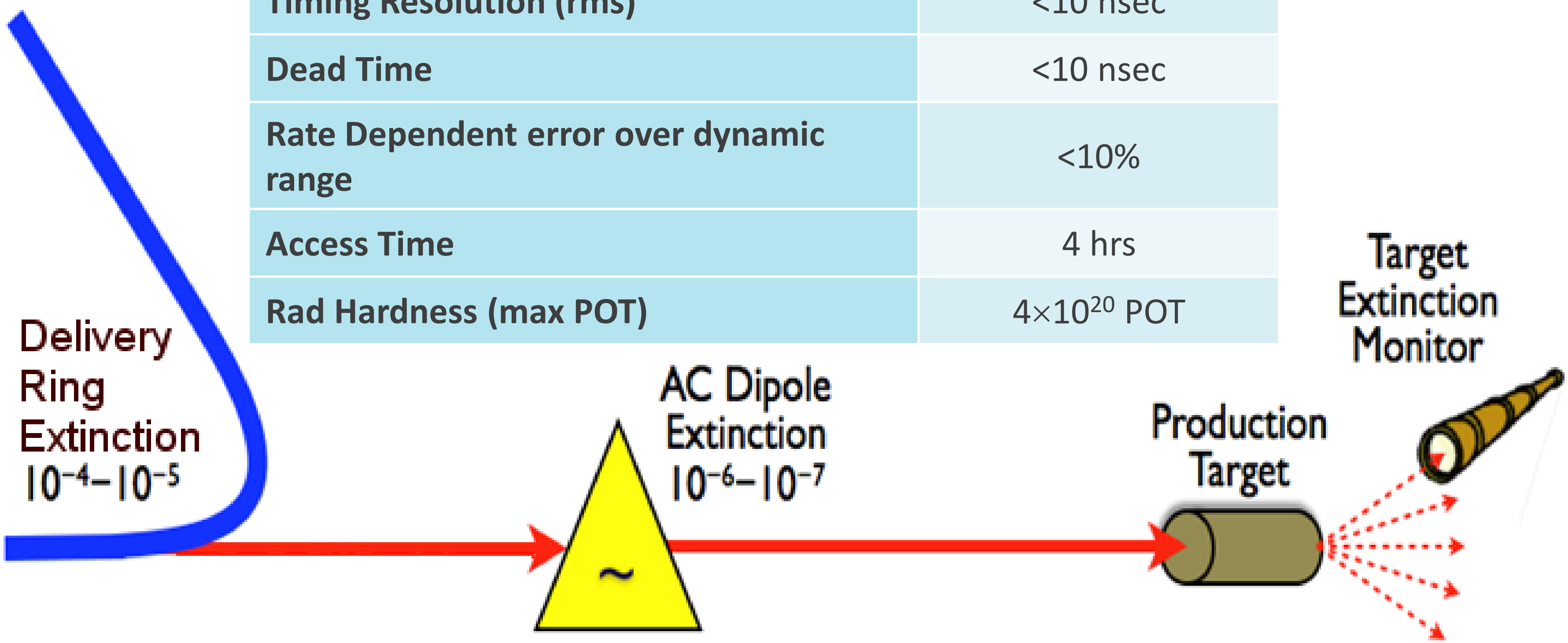
Extinction Requirement: 1×10^{-10}

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

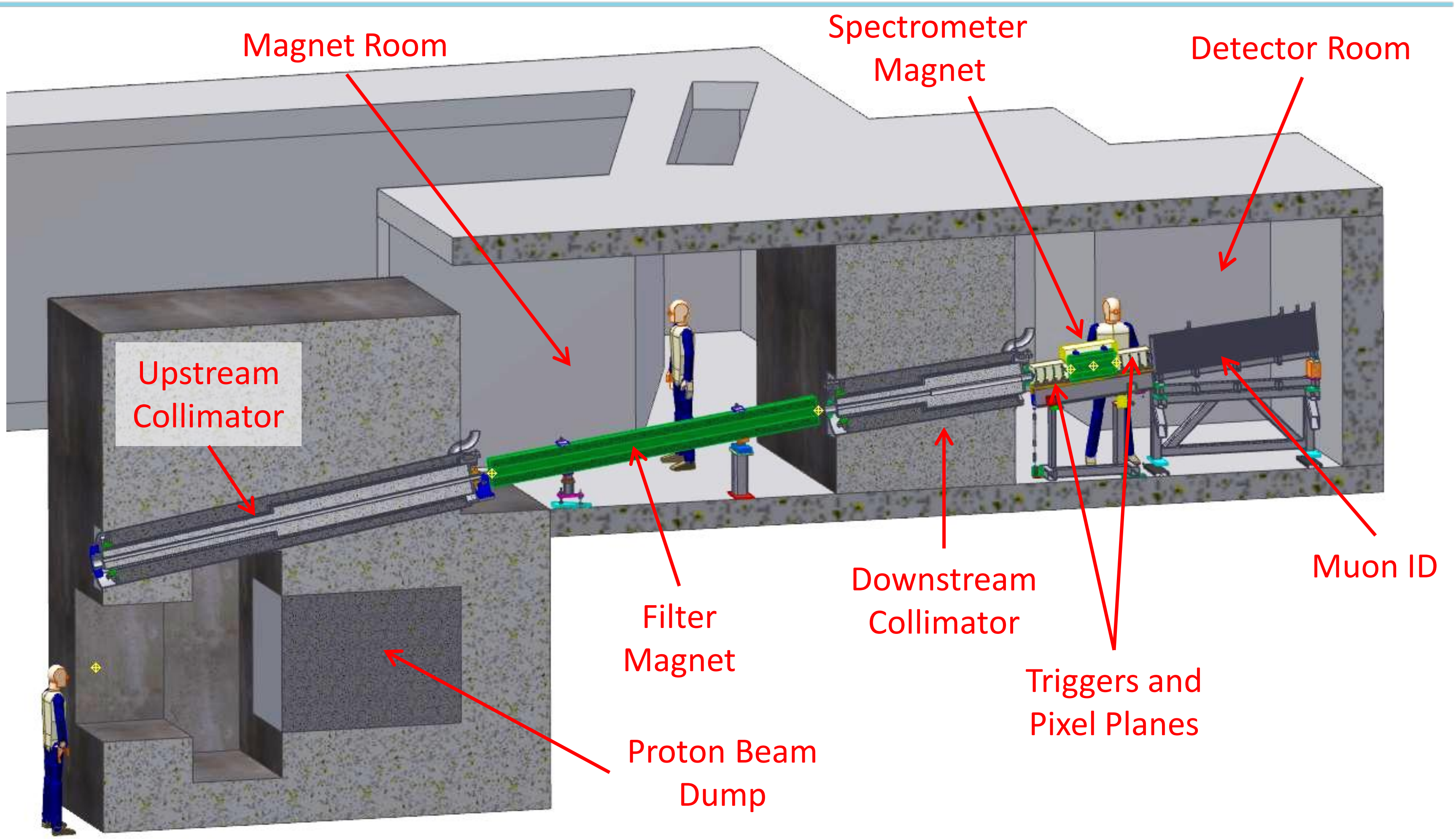


Extinction Monitor Requirements

Specification	Value
Extinction sensitivity (90% CL)	10^{-10}
Integration time	~3 hr (6×10^{16} POT)
Timing Resolution (rms)	<10 nsec
Dead Time	<10 nsec
Rate Dependent error over dynamic range	<10%
Access Time	4 hrs
Rad Hardness (max POT)	4×10^{20} POT



Mu2e Extinction Monitor



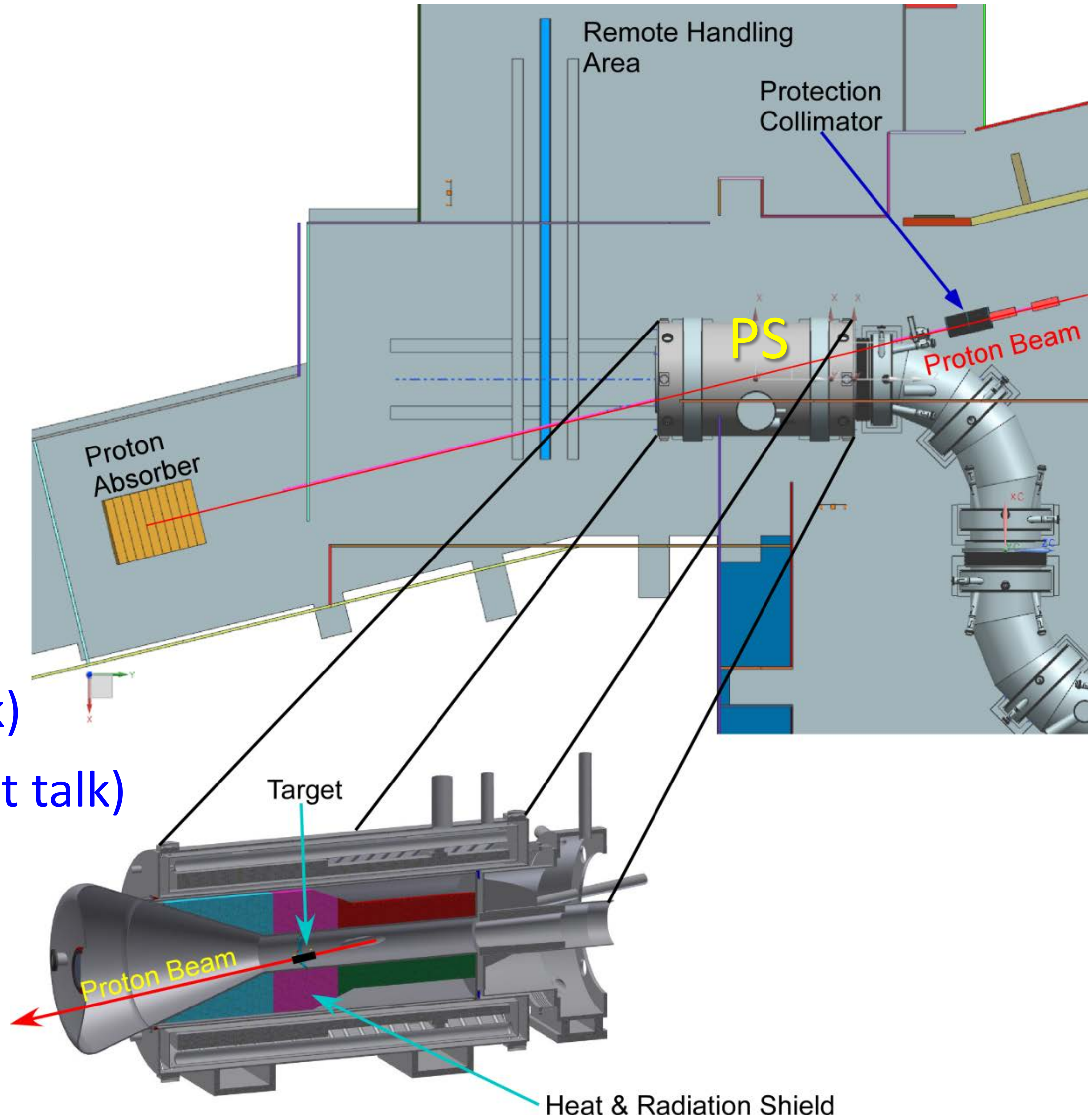
The target extinction monitor design is a momentum-selecting filter consisting of collimators and a permanent dipole magnet, a magnetic spectrometer, and a range stack.

Target Station Requirements

Target Station Layout

There are four requirements documents governing target station components.

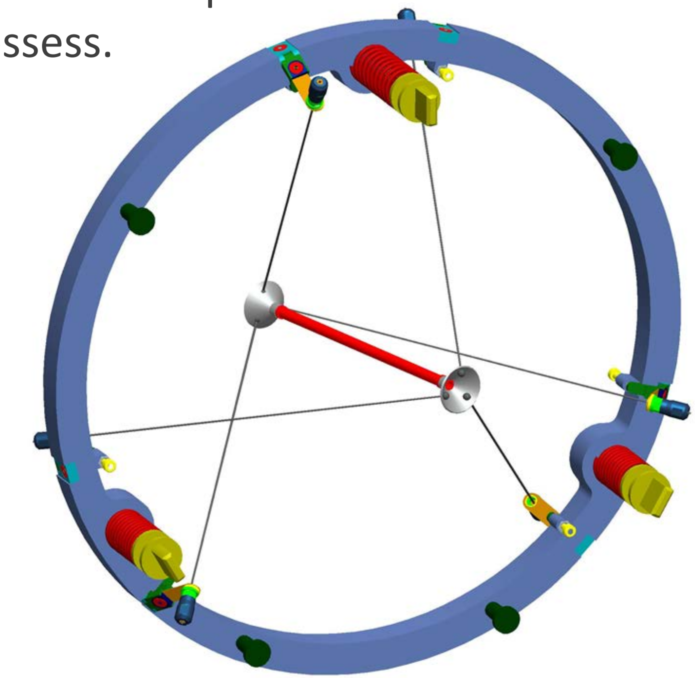
- Target
- Heat & Radiation Shield (HRS)
- Proton Absorber (breakout talk)
- Protection Collimator (breakout talk)



Production Target General Requirements

The target requirements document gives qualitative and quantitative specifications. Here are the general properties that the Mu2e proton target must possess.

- Maximize pion yield
  - High Z, high density
  - Compact geometry to minimize reabsorption
  - Mechanically stable, low mass target support structure
- lifetime > 1 year in high radiation, high temperature environment
  - High melting point
  - Corrosion resistant
  - High emissivity (lower operating temp.)
  - Robust support structure
- Replaceability
  - Remote target handling system
  - Target support structure/target handling system must allow removal of spent target and precise positioning of replacement target

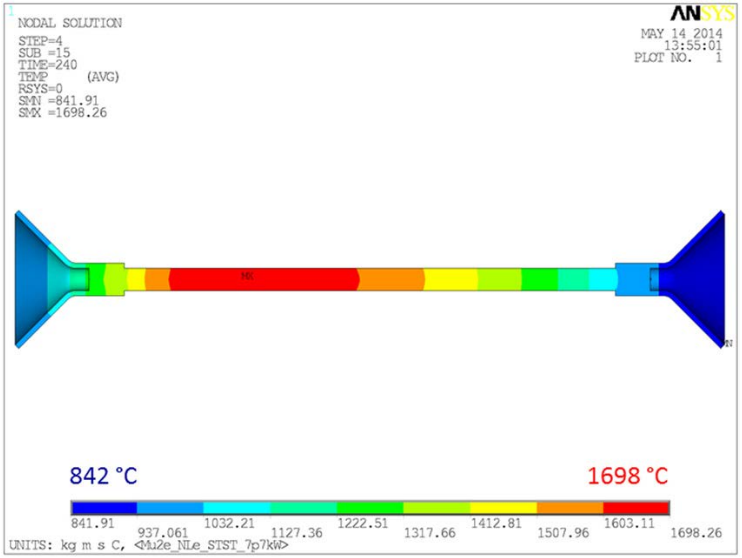


Mu2e proton target design

- *Tungsten Rod: 16 cm (long) × 6 mm (diameter)*
- *Radiatively cooled*
- *Peak Operating temp.: ~1700℃*
- *Resides in PS vacuum ~10^{-5} torr*

Target Performance

Target performance is assessed by modeling and by materials testing



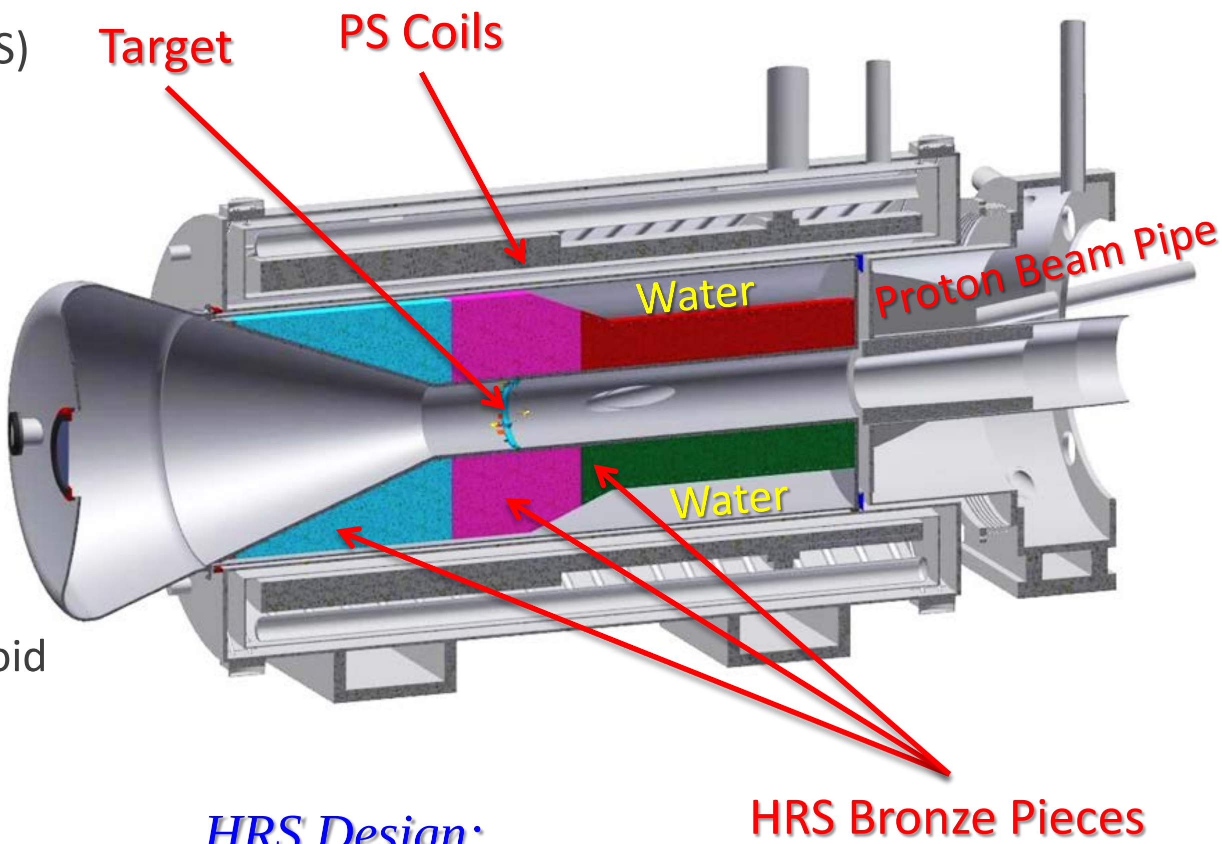
Steady-state target temperature distribution

Vacuum test chamber at RAL

- STFC RAL completed numerous ANSYS and Fluka simulations for thermal and mechanical stress and mechanical stability
- Completed 4 years equivalent design pulsing on vacuum test stand at RAL to assess mechanical durability (stress and fatigue)
- Ready to begin tests of corrosion effects as a function of vacuum
- STFC RAL Reports are posted on the review web site

HRS Requirements Overview

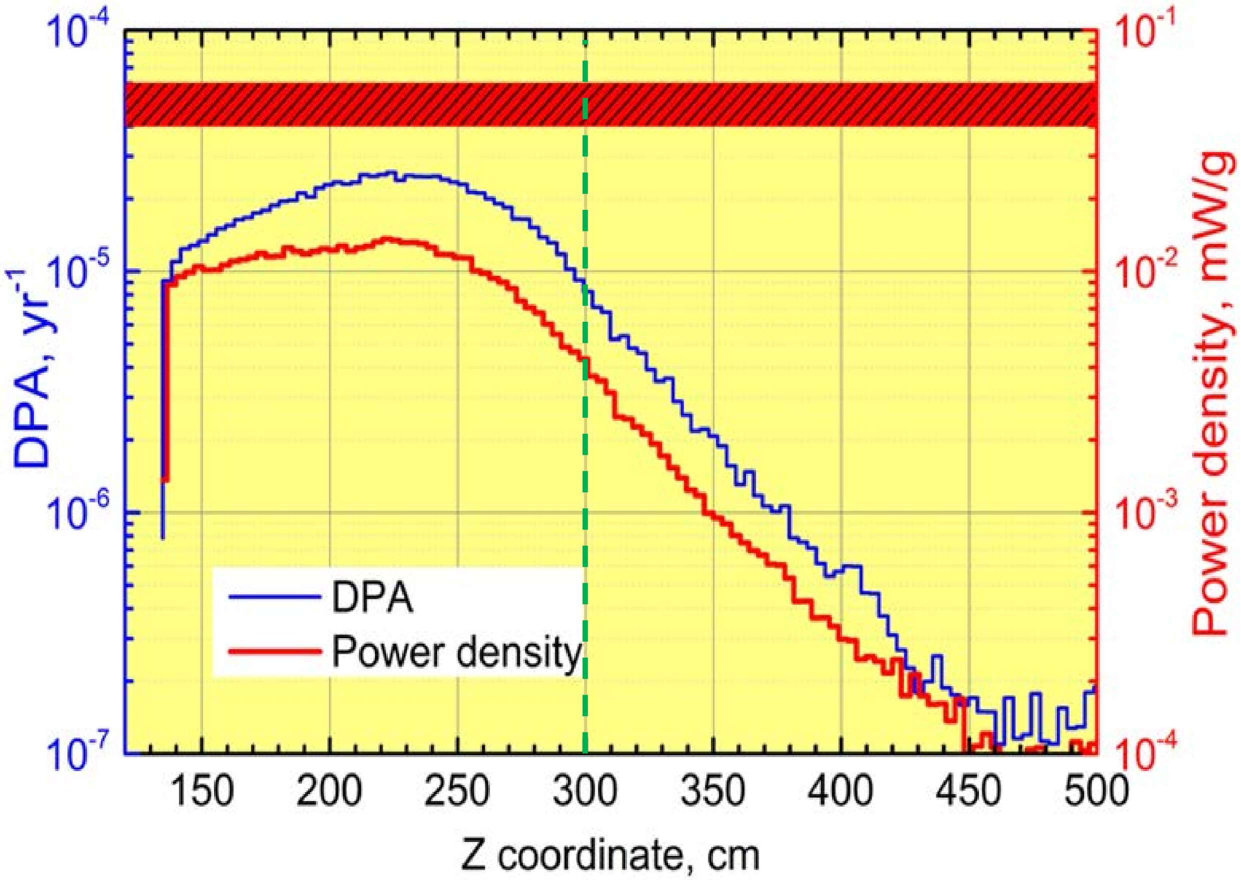
- Limit Production Solenoid (PS) thermal exposure from heat radiated from target to acceptable levels
- Limit radiation dose and radiation damage to the Production Solenoid superconducting coils to acceptable levels
- Limit heat and radiation exposure of Transport Solenoid (TS) to acceptable levels
- Constraints on HRS design:
  - PS field quality
  - Quench induced eddy currents
  - Muon yield



HRS Design:

- *Lines the inside of the PS cryostat*
- *Isolated from muon beamline vacuum*
- *~37 tons of bronze, stainless steel, and water*

HRS Performance



DPA Requirement:
< 4-6×10^{-5} DPA/yr

Power Density Requirement:
< 30 μW/g

MARS Simulation:

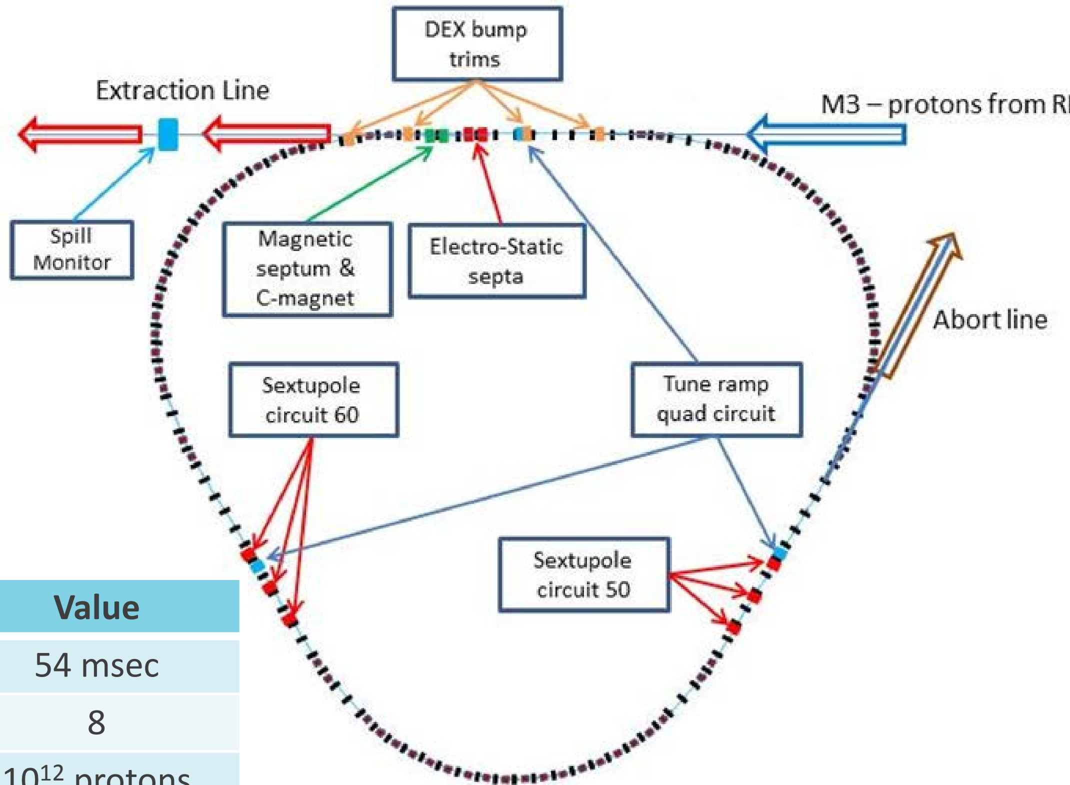
Peak DPA and Power Density in the PS coils as a function of position along PS axis.

Target is at z = 300 cm.

Resonant Extraction Design and Performance

The Mu2e project will install a Resonant Extraction System in the Delivery Ring.

- Two Electro-static septum modules
- Two families of harmonic sextupole magnets (6 magnets total)
- Three horizontal tune ramp quadrupole magnets
- RF-knockout based spill feedback and control
- Spill monitoring



Parameter	Value
Spill duration	54 msec
Number of spills in a supercycle	8
Integrated spill intensity	10^{12} protons
Number of protons extracted per pulse (turn)	3×10^{7}
Time between pulses	1.695 μsec
Reset time between spills	5 msec
Spill rate variations	< 50%
Extraction time duty factor	32%

External Beamline

Mu2e External (M4) Beamline scope:

Design, procurement, fabrication and installation of the M4 beamline downstream of V907

M4 beamline includes:

- Extinction insert
- Diagnostic Absorber
- Final Focus

- Transport beam from Delivery Ring to Proton Target
- Extinction
- Diagnostic Absorber for beam commissioning & tuning
- Final focus and beam position control on target

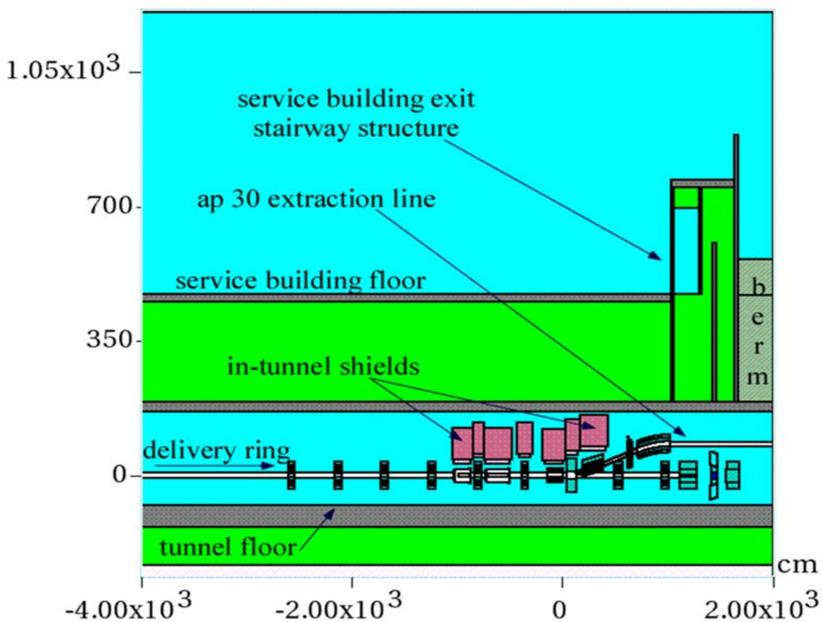
Extinction Section

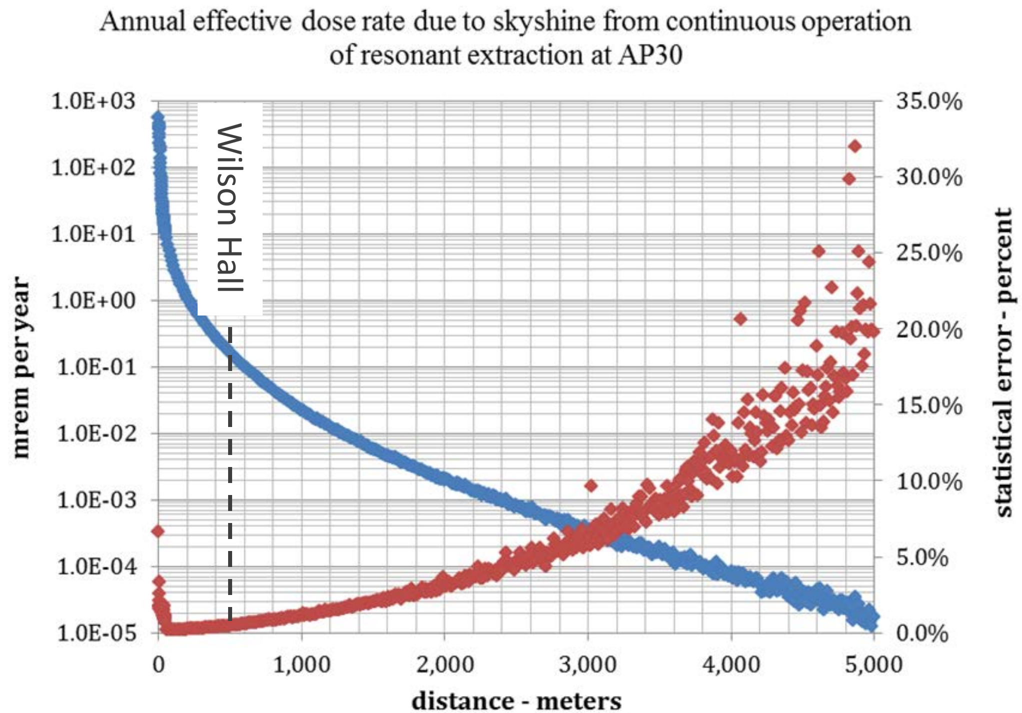
V907
M4-M5 split

Radiation Safety Design and Performance

The basic components of the Mu2e Accelerator Radiation Safety Upgrades are:

- Supplemental shielding of known loss points
- Total Loss Monitor (TLM) system of interlocked detectors to preclude unacceptable dose rates outside of beam enclosures



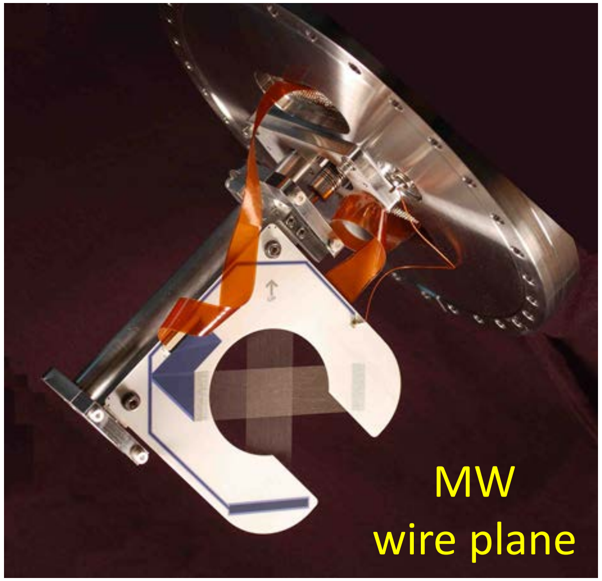


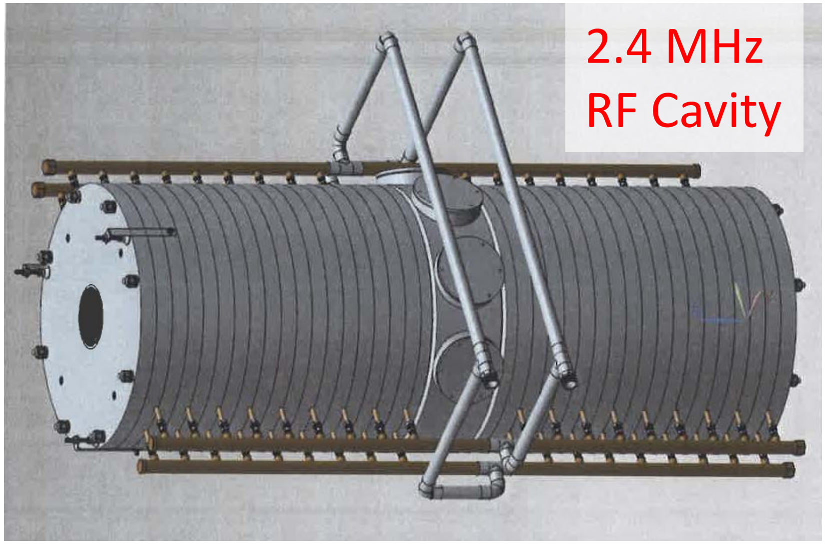
Extensive MARS modeling of beam losses during Mu2e operation has shown that the Mu2e Radiation System prevents unacceptable external radiation dose rates

Other Accelerator Systems

Also included in the Mu2e Accelerator Upgrades are:

- Accelerator Controls and Instrumentation
  - M4 beamline controls and instrumentation
  - Delivery Ring Abort controls
  - Delivery Ring beam intensity and tune measurement instrumentation
- 2.4 MHz Delivery Ring RF System
  - Design and Modeling
  - Low level RF system
  - RF Cavity and High Level amplification provided by the Recycler AIP





Improvements Since CD-1

Improvements since CD-1

Resonant Extraction

- Septum Plane Downselect: Foils chosen over wires
- Extraction Resonance Downselect: 3rd integer resonance selected over 2nd integer

Radiation Safety

- Received active shielding waiver (allows use of interlocked detectors)
- Received preliminary approval for the use of TLMs
- Received approval of the Mu2e preliminary shielding assessment

Target Station

- HRS redesign:
  - CD-1 Design All Bronze located inside the muon beamline vacuum
  - CD-2 Design Bronze, Stainless Steel, and water; located outside of the muon beamline vacuum
- Target remote handling system re-design

Improvements since CD-1 (Continued)

Extinction

- Removed “internal” extinction (not necessary to meet extinction requirements)
- Changed from two AC dipole harmonics to three (ensures that far out-of-time particles end up in the collimator and not in anything else)
- Beamline extinction section configuration change:
  - CD-1 Design: AC-Dipole followed by 5 collimators
  - CD-2 Design: 2 Hor. Collimators → AC Dipole → Hor. Collimator
- Removed upstream extinction monitor
- Extinction Monitor design downselect: Extinction Monitor design selection by the Mu2e collaboration and the Mu2e project

External Beamline

- Changed extraction to the diagnostic absorber from vertical to horizontal
- Lattice changes to accommodate reconfiguration of the extinction section

Value Engineering since CD-1

- Significant value engineering changes prior to CD-1
- Reduced amount of external beamline instrumentation by allowing for the early use of final focus section instrumentation for commissioning the extinction section
- New extinction section configuration uses two fewer collimators
- Elimination of upstream extinction monitoring
- Acquisition of most of target materials testing equipment from off-project sources (RAL)
- Lowered HRS costs by removing material at downstream (TS) end

RISKS

QUALITY ASSURANCE

ES&H

INTEGRATION

Risks

- **22** Accelerator Risks in Risk Register
  - All risks mitigated to the extent possible
  - **8** Threats
    - 4 High
    - 3 Medium
    - 1 Low
  - **2** Opportunities
  - **12** Retired Risks
- Detailed mitigation plans for all risks are documented in risk forms in the Mu2e doc DB and are linked from the Risk Register (docdb column)
- All risks are understood and under control
- Details on specific risks will be provided in the breakout session

Quality Assurance

Mu2e Accelerator Upgrades Quality Assurance involves all of the following:

- Use of Governing Lab and Project QA Standards
  - Fermilab Quality Assurance Manual (QAM)
  - Fermilab Engineering Manual
  - Mu2e Quality Management Plan (Mu2e-doc-677)
- Design Verification and Validation
  - Reviews
  - Magnet status tracking
  - Prototype testing
  - Beam testing
- Procurement & Fabrication Acceptance testing

ES&H

Accelerator beam enclosures

- Electrical hazards from exposed bus work.
- Mechanical hazards (sharp edges, protruding fixtures)
- Radiation hazards
  - Potentially lethal doses during beam operation
  - Residual radioactivity after beam operations
  - Radioactive surface and air contamination

Above ground hazards

- Radiation dose rates in excess of continuous occupancy limits during beam operation in Muon Campus service buildings, on or near associated Muon Campus beamline berms, and in the vicinity of the Mu2e proton target and the associated proton beam absorber.

➢ Radiation safety is a significant part of the Mu2e Project – it is a level 3 sub-project of Mu2e Accelerator Upgrades.

➢ These hazards are all discussed in the Mu2e Hazard Analysis Report (Mu2e-doc-675).

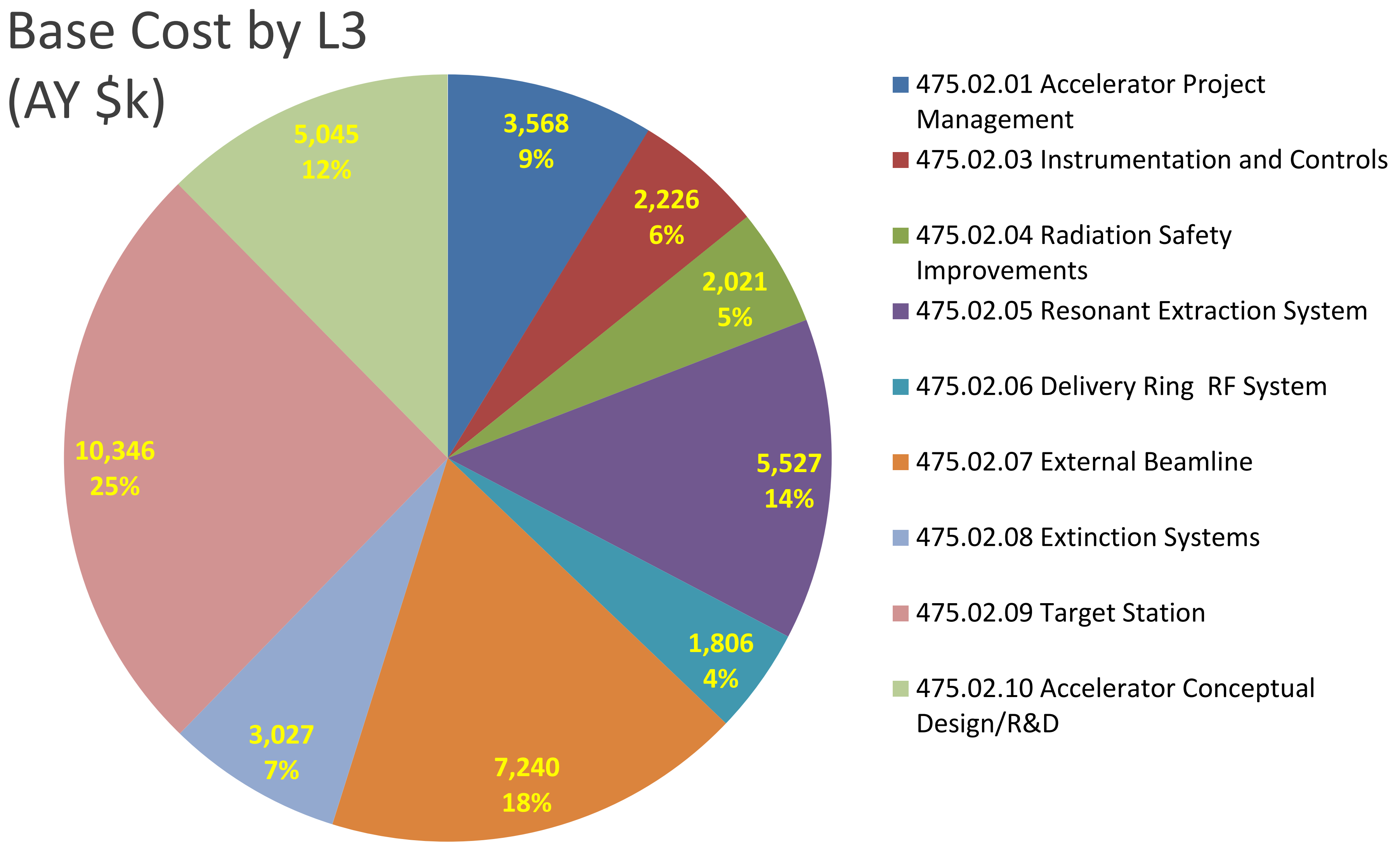
Integration and Interfaces

Mu2e Accelerator Systems Interfaces:

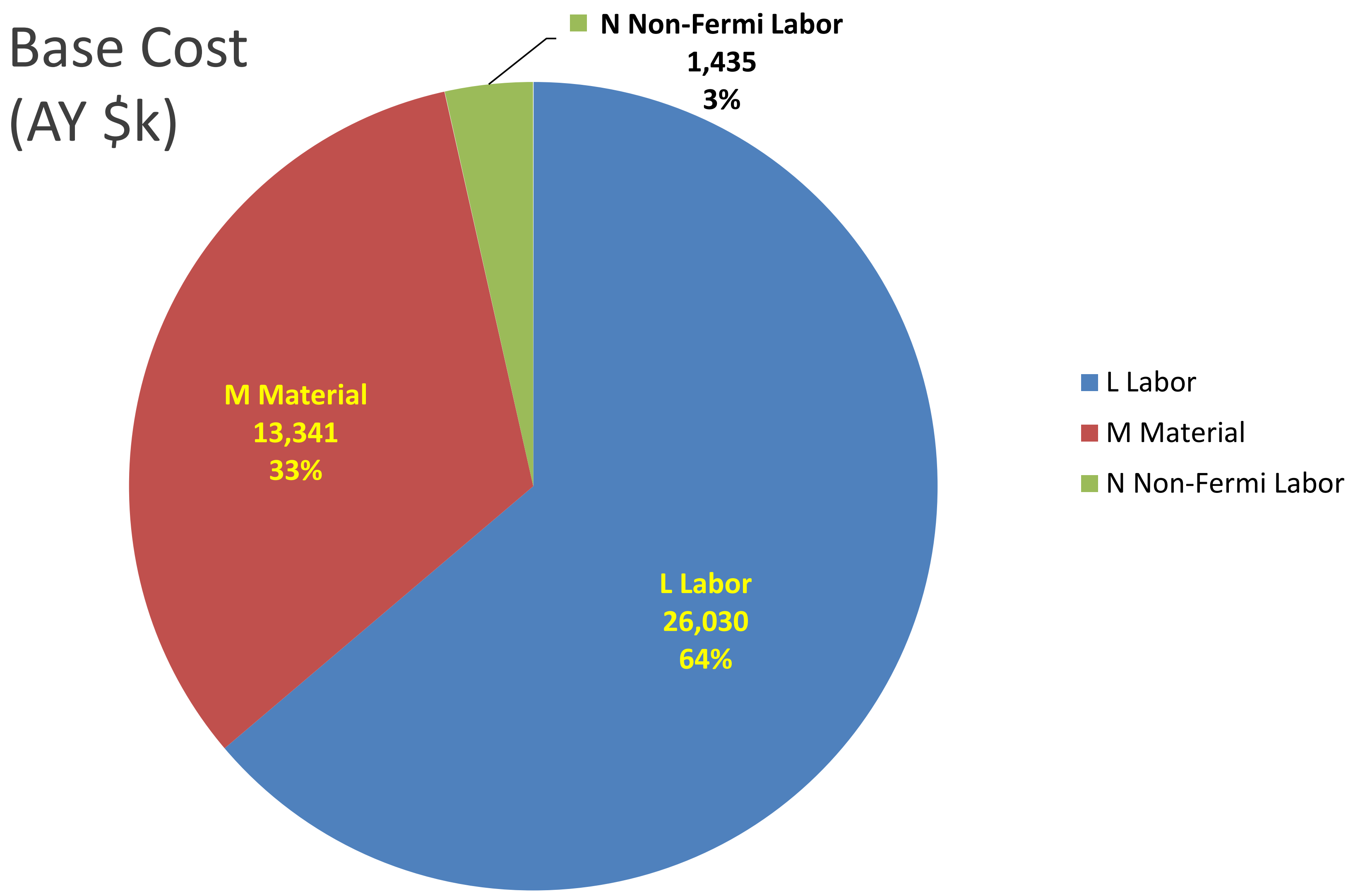
- External interfaces to the Solenoids, Muon Beamline, Conventional Construction, the g-2 project, and the Muon Campus AIPs
- Internal interfaces
  - Instrumentation & Controls ↔ Resonant Extraction, External Beamline
  - Radiation Safety ↔ Resonant Extraction, External Beamline, Target Station
  - Resonant Extraction ↔ External Beamline
  - External Beamline ↔ Extinction, Target Station
- Internal and external interfaces identified and described in the Accelerator Interface document, available on Review site (Mu2e-doc-1529).
- Interface Management:
  - Meetings: Weekly Target Station Meetings, Bi-weekly integration and Accelerator L3 meetings
  - Formal sign-off between owners of all external interfaces as part of final design requirements.
- Interfaces understood and under control.

Cost & Schedule

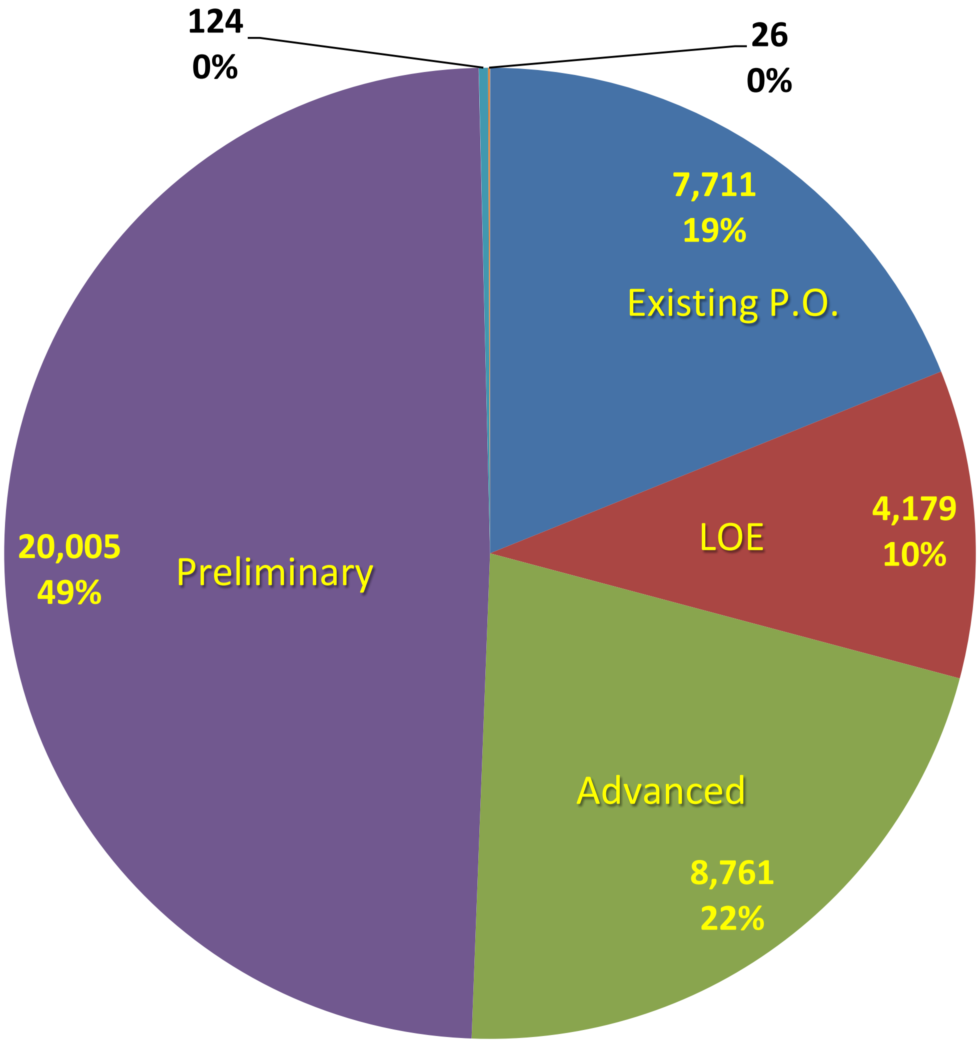
Cost Distribution by L3



Cost Distribution by Resource Type



Quality of Estimate



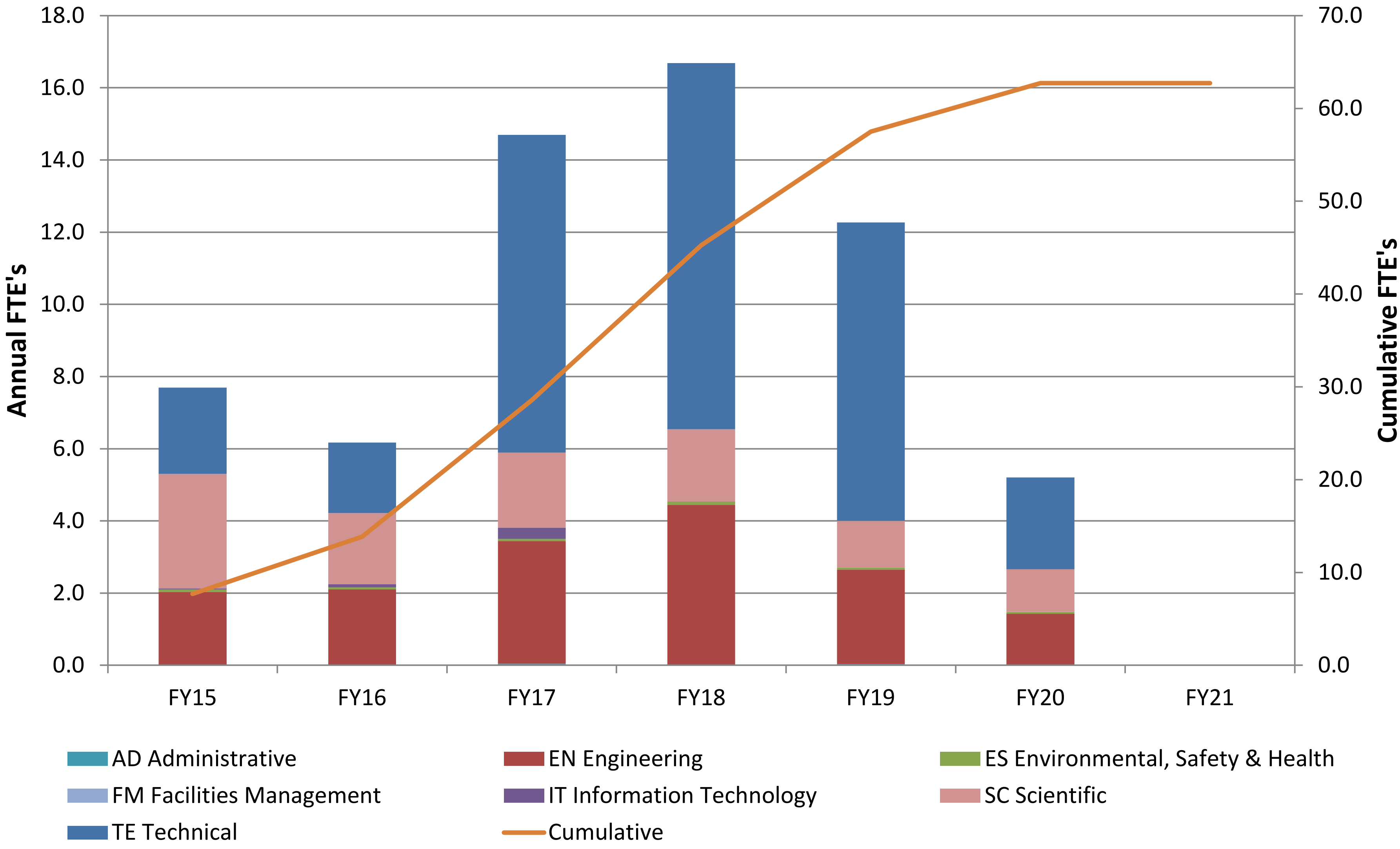
Base Cost by Estimate Type (AY $k)

- L1 Actual / M1 Existing P.O.
- L2 LOE Task / M2 Procurements for LOE/Oversight Work
- L3 / M3 Advanced
- L4 / M4 Preliminary
- L5 / M5 Conceptual
- L6 / M6 Pre-Conceptual
- L7 / M7 Rough Estimate Pre-Conceptual - Uncommon Work

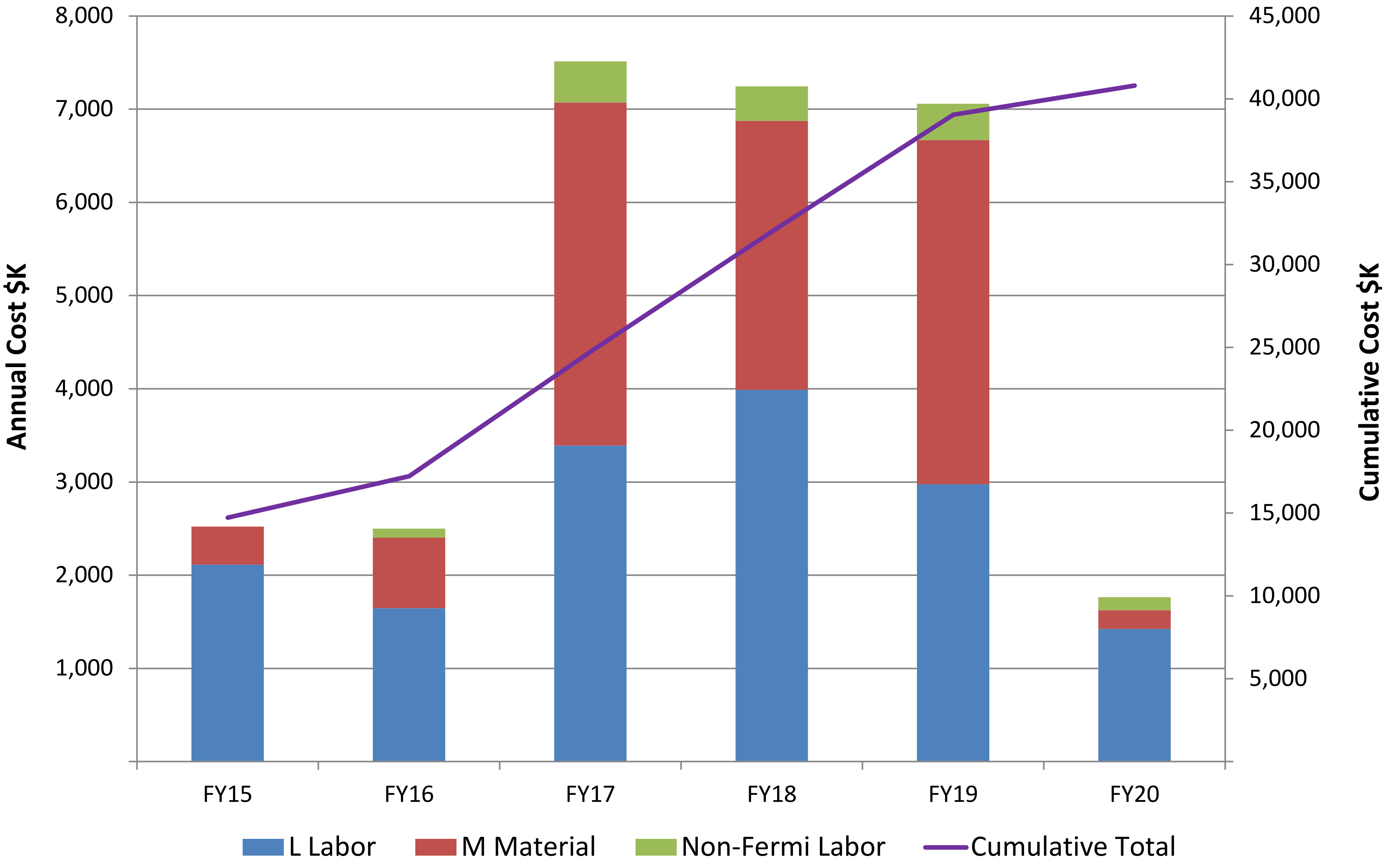
99.6% of estimates of Preliminary Design quality or better

Contingency Rules are in Mu2e-doc-459
(available on the review web site)

Labor Resources



Labor and M&S by FY



Mu2e

Cost Table

WBS 2 Accelerator

Costs are fully burdened in AY $k

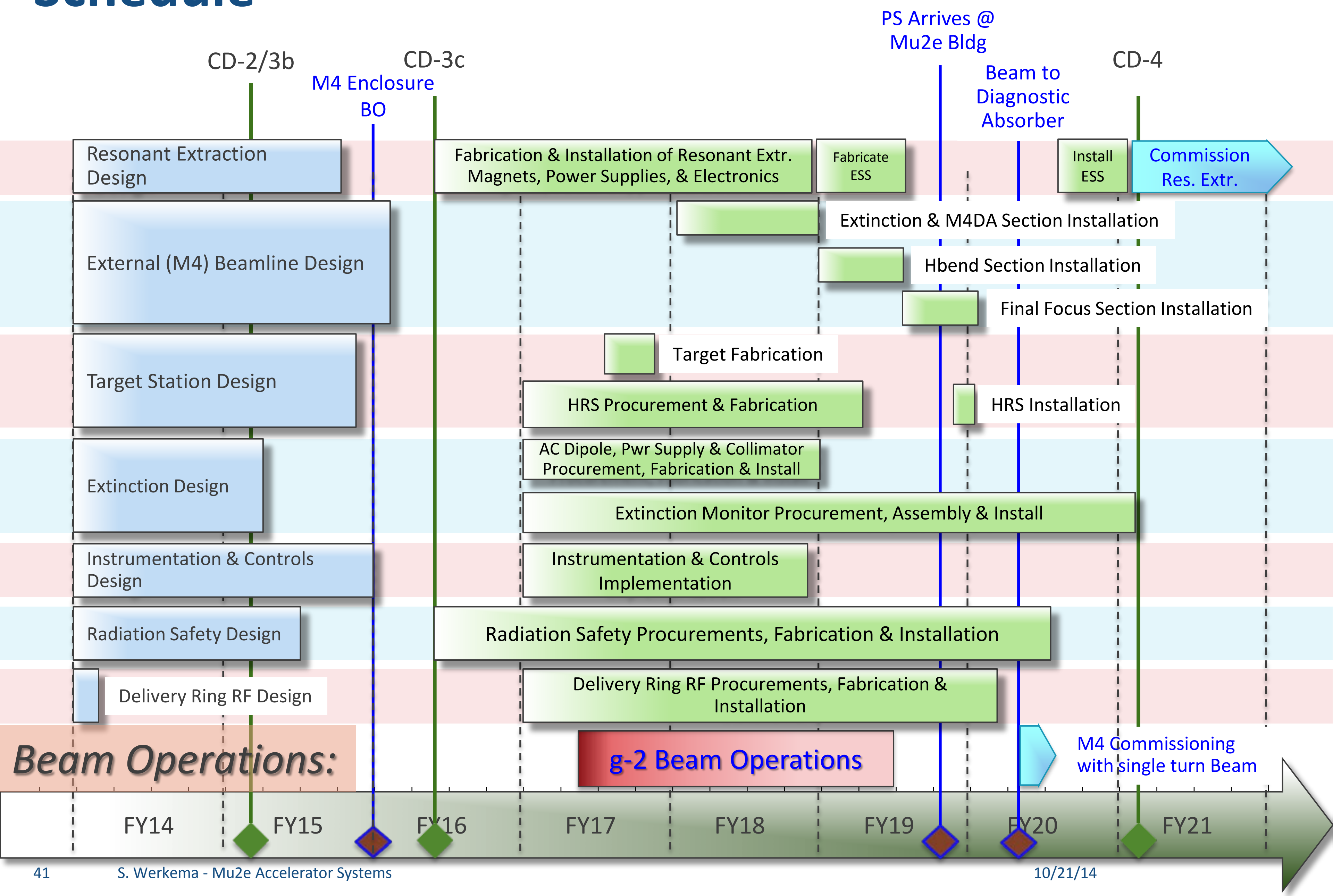
	Base Cost (AY K$)					
	M&S	Labor	Total	Estimate Uncertainty (on remaining budget)	% Contingency (on remaining budget)	Total Cost
475.02.01 Accelerator Project Management	74	3,494	3,568	360	15%	3,928
475.02.03 Instrumentation and Controls	655	1,571	2,225	482	26%	2,708
475.02.04 Radiation Safety Improvements	986	1,034	2,021	497	29%	2,517
475.02.05 Resonant Extraction System	1,638	3,889	5,527	1,616	35%	7,143
475.02.06 Delivery Ring RF System	114	1,692	1,806	389	25%	2,195
475.02.07 External Beamline	3,412	3,827	7,240	1,830	29%	9,069
475.02.08 Extinction Systems	1,374	1,653	3,027	740	33%	3,767
475.02.09 Target Station	5,863	4,483	10,346	2,706	32%	13,053
475.02.10 Accelerator Conceptual Design/R&D	660	4,386	5,045		n/a	5,045
475.02.99 Risk Based Contingency				814		814
Grand Total	**14,776**	**26,030**	**40,806**	**9,433**	**33%**	**50,239**

Major Milestones

Activity ID	Milestone Name	Milestone Date
47502.01.02.001020	T5 - Preliminary Design Tasks Complete	6/9/2014
47502.01.03.000130	TX2 - Beamline Enclosure Beneficial Occupancy	9/30/2015
47502.01.02.001045	T5 - Accelerator Final Design Complete	11/6/2015
47502.01.03.000020	T2 - M4 Enclosure Ready for Installation during g-2 beam operations	2/28/2017
47502.03.001050	T5 - Instrumentation & Controls Implementation Complete	9/4/2018
47502.05.02.001315	T5 - Resonant Extraction Electro-Static Septum Assembly Complete	7/11/2019
47502.05.001060	T5 - Resonant Extraction System Implementation & Close-out Complete	9/13/2019
47502.07.001240	T5 - Mu2e External Beamline Installation and Close-out Complete	11/25/2019
47502.06.001020	T5 - Delivery Ring RF Implementation and Closeout Complete	12/2/2019
47502.01.03.000100	T4 - Ready to Run Single Turn Extraction Beam to the Diagnostic Absorber	1/29/2020
47502.04.001080	T3 - Radiation Safety Improvements Complete	4/21/2020
47502.01.03.000120	T4 - Beam Established to Diagnostic Absorber for Objective KPP	4/22/2020
47502.09.001070	T4 - Target Station Complete	7/16/2020
47502.08.001100	T5 - Mu2e Extinction Systems Installation and Close-out Complete	9/21/2020
47502.01.03.001100	T4 - Implementation Tasks Complete (Ready for Verification that Key Performance Criteria are met)	9/21/2020

Total of 268 milestones in the Mu2e Accelerator Upgrades schedule

Schedule



CD-2/3b
M4 Enclosure BO
CD-3c
PS Arrives @ Mu2e Bldg
Beam to Diagnostic Absorber
CD-4
Resonant Extraction Design
Fabrication & Installation of Resonant Extr. Magnets, Power Supplies, & Electronics
Fabricate ESS
Install ESS
Commission Res. Extr.
External (M4) Beamline Design
Extinction & M4DA Section Installation
Hbend Section Installation
Final Focus Section Installation
Target Station Design
Target Fabrication
HRS Procurement & Fabrication
HRS Installation
Extinction Design
AC Dipole, Pwr Supply & Collimator Procurement, Fabrication & Install
Extinction Monitor Procurement, Assembly & Install
Instrumentation & Controls Design
Instrumentation & Controls Implementation
Radiation Safety Design
Radiation Safety Procurements, Fabrication & Installation
Delivery Ring RF Design
Delivery Ring RF Procurements, Fabrication & Installation
Beam Operations:
g-2 Beam Operations
M4 Commissioning with single turn Beam
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Summary

- The Design of the Mu2e Accelerator Systems meets the requirements set by the governing requirements documents
- Cost estimates for the Accelerator Systems are complete
  - 99.6% of the cost is understood at the Preliminary Design level or better
  - Risks are understood, are mitigated to the extent possible, and are under control
- All Interfaces are identified and defined
- Resource needs are understood
- ES&H has been embedded into all aspects of the project
- Responded to all recommendations from previous reviews
- Accelerator Systems are ready for CD-2

BACKUP SLIDES

Proton Target Positioning Requirements

Target dimension tolerances

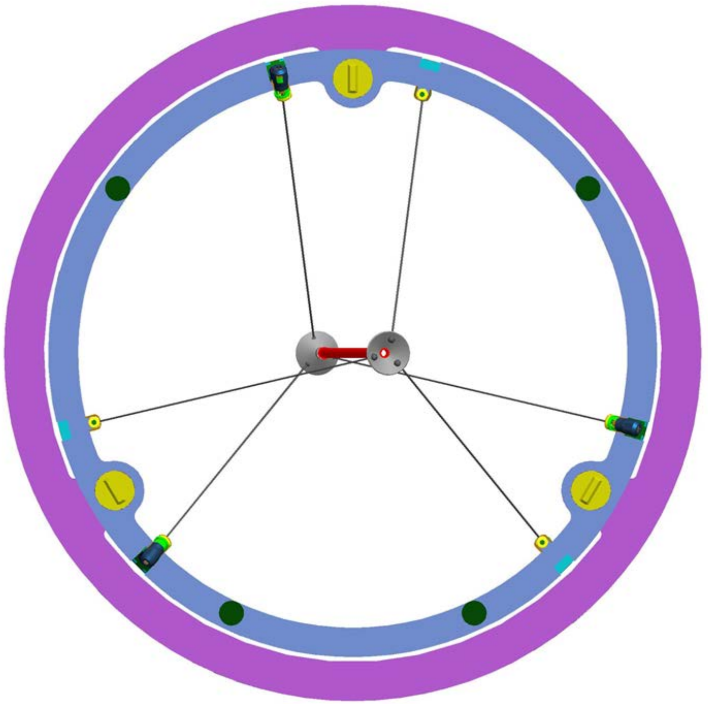
- Target Length = 16 cm $\pm$2 mm
- Target Radius = 3 mm $\pm$0.1 mm

Alignment of target with respect to PS/HRS

- Replacement target positioning repeatability: $\pm$0.25 mm
- Transverse placement w/resp. to PS axis: $\pm$5 mm
- Longitudinal placement along PS axis: $\pm$10 mm

Alignment of target with respect to the proton beam:

- Transverse beam positioning requirement: $\pm$0.5 mm
- Horizontal and vertical angle alignment: $\pm$0.2°



Nominal target and support structure and HRS inner wall viewed along the solenoid axis, looking in the proton beam direction.

The target is centered vertically in the HRS.

The target points horizontally off-axis by 14° (toward proton beam left) relative to the support ring in order to be properly aligned with the beam

PS Heat and Radiation Shield General Requirements

1. Production Solenoid Heat and Radiation protection
   a) Limit the continuous power delivered to the cold mass
   b) Limit the local heat load allowed anywhere within the superconducting coils
   c) Limit the maximum local radiation dose to the superconductor epoxy over the lifetime of the experiment
   d) Limit the damage to the superconductor's aluminum stabilizer and copper matrix
2. Production Solenoid field quality should not be degraded by materials used in the HRS
3. Production Solenoid forces during a quench should be minimized by the choice of HRS materials, if possible. The HRS electrical resistivity must be high to limit forces from eddy currents during a quench.
4. Transport Solenoid (TS1 coils) Heat and Radiation protection (see #1 above)
5. HRS thermal cooling system should limit the temperature on the surface of HRS. The inner surface holds the target support. The outer surface is adjacent to the PS cryostat and in contact in a few locations.
6. The HRS must also be adaptable to the design of a remote handling system for the pion production target.
7. Muon Yield should not be reduced significantly by the inner bore size of the HRS.
8. An acceptable shield design must avoid any line-of-sight cracks between components that point from the target to the inner cryostat wall and thus the magnet coils.

PS Heat and Radiation Protection Requirements

	Dynamic Heat Load [Watts]	Peak Power Density [μW/g]	Max. Lifetime Radiation Dose [MGy]	Peak DPA/yr [10^{-5}]
Specification	< 100	30	7*	4 to 6†
Estimated HRS Performance	24	13	5.2	2.4

* 7 MGy is a conservative limit on coil epoxy exposure, 10% of shear modulus lost due to radiation damage.

† This is the DPA damage per year from which RRR degrades to 100. After this RRR reduction we must warm-up and anneal.

Definitions:

DPA = Displacements per Atom (unit of radiation damage)

$\mathrm{RRR} = \frac{\rho_{300°K}}{\rho_{4.5°K}}$ = Residual Resistivity Ratio (want to be < 100)

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Proton Beam Absorber Requirements

Purpose: The proton beam absorber stops non-interacting primary beam and secondary particles downstream of the proton target.

Proton Absorber parameters for various beam conditions:

	Primary Beam	Diagnostic Beam	Accident Condition
Beam Power	8 kW (on target)	0.8 kW	8 kW
Total No. of Protons	8×10^{20}*	2×10^{19}	2×10^{19}
Duration of beam	Long Periods	Long Periods	< 10 min

Other Requirements:

- Absorber shielding sufficient to protect extinction monitor equipment from prompt radiation
- Absorber will include an albedo trap to protect PS hall equipment from secondary neutrons from absorber
- Sufficiently well shielded to protect workers in adjacent spaces from residual beam-off radiation
- Ground water and air activation less than FRCM limits

* Note: this is more than twice the required number of POT for physics running

Protection Collimator Requirements

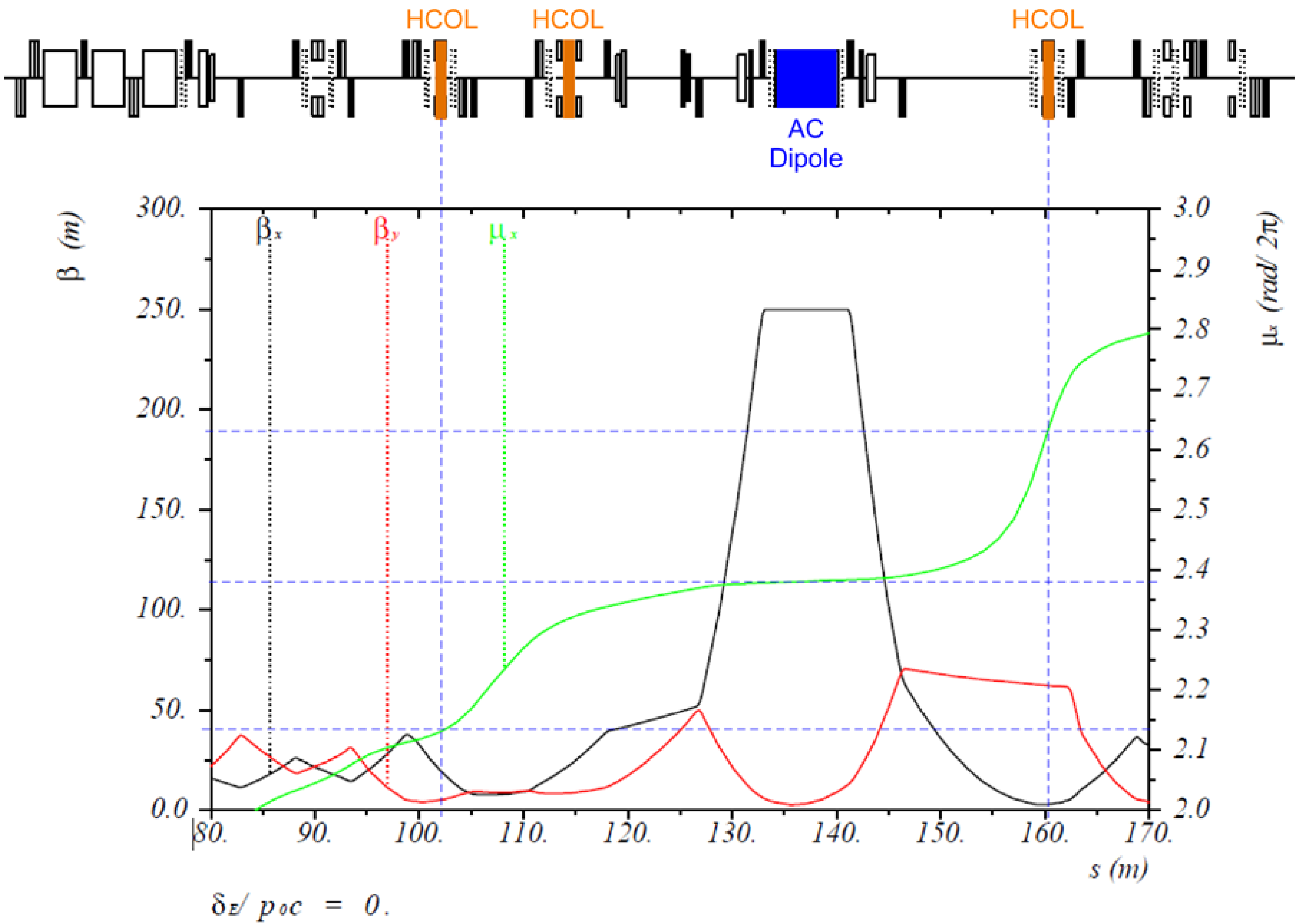
Purpose: prevent any interaction of primary proton beam with the HRS, PS cryostat, or PS coils that could result in significant thermal energy deposition or radiation damage.

Requirements:

- The Protection Collimator must be able to absorb full design beam power for at least 50 msec*
- The Protection Collimator must be able to continuously dissipate the energy deposited by the absorption of beam halo particles during normal operation
- The Protection Collimator inside diameter must be less than 80 mm (for elimination of extinction monitor backgrounds)
- Must be able to move out of the beam for target scans
- Must be constructed of non-magnetic materials (due to proximity to PS and TS)

*The TLM radiation safety system will remove the beam permit in less than 50 msec if all of the beam is being lost in this device

M4 Beamline Extinction Section Optics



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