Summary of Red Team Discussion of May 23rd

D. Glenzinski

30 May 2019

Introduction – Recall

- The Fermilab Directorate initiated discussions in early March to develop a strategy for mitigating the project contingency issues
  - Established a “Red Team” to review project proposals

- All possibilities are currently being considered…
  - **Pay for some parts of the project scope with other money**
    (e.g. use operations funding to pay for some equipment)
    (e.g. use research funded personnel to replace technical or engineering effort)
  - **Add money to the project via “buybacks”**
    (e.g. purchase the spares “from” the project)
    (e.g. reimburse the project for HAB)
  - **Remove scope from the project so that it costs less**
    (e.g. stage or de-scope the experiment)
  - **Re-Baseline**
    (solution of last resort)

The Mu2e Collaboration is in the best position to make informed choices.

We asked the EB to develop acceptable ”staging” options
(cf. S. Miscetti presentation 25-April doc-db-25728)

Introduction

- We met with the Red Team on 23-May-2019
- Agenda
  - **Project Contingency vs Remaining Estimate Uncertainty and Risks** (Ron Ray)
  - **Exploration of Possible Descoping Options for the Mu2e Experiment** (Doug Glenzinski) mu2e-doc-db26292
- Red Team:
  - G. Bock, J. Butler, M. Convery, P. Czarapata, P. Derwent, C. Ginsburg, A. Klebaner, M. Lindgren (chair), H. White
  - Ex officio – J. Frieman, J. Lykken, T. Meyer, R. Tschirhart, Ron, Julie, Jim, Doug

Red Team Charge

Available in doc-db-26292

Charge for the Mu2e Red Team
20 May 2019

Recently, primarily owing to significant issues associated with the solenoids, the Mu2e Project has incurred significant calls on contingency. The total remaining contingency corresponds to <20% of the ETC. Although the project is over 2/3 complete, significant estimate uncertainties and risks remain. The Project has been asked to analyze the remaining estimate uncertainties and risks, and to develop a plan that would, with high probability, enable a successful completion of the project within its current baseline. All reasonable mitigation strategies should be considered, including a reduction of objective project scope, a transfer of objective project scope to other funding sources, and buyback opportunities that increase the available contingency.

Based on materials provided by the project via written reports and/or presentations, this team is asked to address the following questions:

1) Are the costs associated with the remaining estimate uncertainty and risks appropriate and well understood? Are there missing risks that might carry significant costs or schedule delays? Are there mitigations that have not been implemented that might significantly reduce threat impacts to the project?

2) Does the project have in place the appropriate processes for managing and tracking its risks and contingency spending?

3) Has a thorough analysis of descope options been performed? For the proposed descope options: Are they consistent with the KPPs? Do they still allow the experiment to achieve important physics goals in a timely manner with high confidence? Are there additional significant descope options that have not been explored or included in the project plan?

4) Has a thorough analysis of scope transfers been performed? For the proposed transfer options: Are they consistent with the KPPs? Has potential alternative funding been identified or is it reasonable to expect that it can be identified in a timely manner? Do they represent a scope of work that could be reasonable accomplished using the proposed alternative source of funding in a timely manner?

5) Have all reasonable buyback opportunities been identified? For the proposed buyback opportunities: Are they fair and legitimate requests?

Relevant Charge Question for the Collaboration Exercise

> 3) Has a thorough analysis of descope options been performed? For the proposed descope options: Are they consistent with the KPPs? Do they still allow the experiment to achieve important physics goals in a timely manner with high confidence? Are there additional significant descope options that have not been explored or included in the project plan?

This talk summarizes the talk I gave to the Red Team to address the above charge question. At the end I summarize their comments/questions and discuss our next steps.

Our Process

- In mid-March we engaged the Mu2e Executive Board to
  - Help brainstorm possible mitigations
  - Help prepare so that we can participate in discussions with Fermilab in an informed and well-considered manner
  - Nb. EB is an advisory board to the spokespersons
    - 6 elected positions (staggered 2y terms)
    - Plus, Chair of the Institutional Board, Project Manager and Deputy PM, Young Mu2e Representative (elected by YM), and the Office of Equity Diversity and Inclusion Representatives

- Timeline
  - Kick-off meeting with EB (19-March)
  - Email announcement to Collaboration (20-March)
  - Several EB meetings to discuss (19-Mar : 20-May)
  - Discuss current status with Collaboration (25-Apr)
  - Finalize documentation for discussion with FNAL (mid-May)
  - Continue studies and discussions as needed

Executive Board Participation

- Initial email and kick-off meeting straddled election for new EB… spokespersons decided to keep both old+new EB members engaged
  - Oksuzian, Murat, Miscetti (chair), Hitlin, Ginther, Echenard, Dhongia, Byrum, Brown, Bernstein + Whitmore, Ray, Goodenough, Brown, Dukes
  - Additional expert input from: Werkema, Lamm, Kasper, Gaponenko
  - Incorporates expertise from all the major sub-systems of the experiment including the solenoids and accelerator beam line

- We asked EB for any ideas to help mitigate the project contingency… but particularly sought their input for ways to reduce the project cost
  - Consider scenarios in which our first physics run uses a less-capable experiment… Which systems can be reduced or (partially) delayed and still allow us to achieve significant physics goals?
  - Subject to some important ”ground rules”

Ground Rules

Our ultimate goal remains unchanged – explore $\mu \rightarrow e$ conversion with a sensitivity ~10^4 better than SINDRUM-II

- Consider "staging" scenarios that have a straight-forward path to recovering full capabilities
- Ensure first physics run confidently enables a world's best sensitivity
  - Current World's Best: $R_{\mu e}(Au) < 7 \times 10^{-13}$ @90% CL (SINDRUM-II)
  - We have competition: COMET-I expects x100 improvement by ~2023
- Ensure we remain a discovery experiment… keep background small
- Brainstorm a wide variety of possibilities… don't worry about implications for cost, schedule, partnerships, etc
  - These things will be assessed in a second pass by the Project in consultation with other relevant Stakeholders

EB Process

- Systematically go through each sub-system and brainstorm possibilities
  - In total, >45 options/ideas were identified across all sub-systems
- Engage Project to identify those options that offer significant savings
- For those “significant savings” options, obtain additional information
  - Engage experts to further understand feasibility and implications
  - Perform simulation studies as needed
- Summarize findings in a memo (mu2e-doc-db-26289)
  - A draft was sent to the Red Team on 22-May-2019

EB – Change the Run Plan

- Run at reduced beam intensity for an extended period
  - Take advantage of reduced rates and occupancies to realize savings
  - Still allows us to reach compelling sensitivity within first year of running (nb. at full intensity: match SINDRUM-II in ~100 minutes, x100 better in ~7d)
  - Use LBNF/PIP-II Shutdown to recover full capability

FY	Weeks of Physics Beam	Beamline Uptime	Fraction of time spent on Special Runs	Physics Run Time (s)	POT at nominal intensity	SUM(POT) at nominal intensity	assumed intensity relative to nominal	POT weighted by intensity	SUM(POT) weighted by intensity	Notes
2023	26	0.80	0.30	8.81E+06	5.03E+19	5.03E+19	0.5	2.52E+19	2.52E+19	Assumes an additional 14w of beam for commissioning
2024	34	0.85	0.30	1.22E+07	6.97E+19	1.20E+20	0.5	3.49E+19	6.00E+19	
2025	40	0.90	0.30	1.52E+07	8.69E+19	2.07E+20	0.8	6.95E+19	1.30E+20	
2026	LBNF / PIP-II Shutdown									
2027										
2028	40	0.90	0.30	1.52E+07	8.69E+19	2.94E+20	1.0	8.69E+19	2.16E+20	
2029	40	0.90	0.30	1.52E+07	8.69E+19	3.81E+20	1.0	8.69E+19	3.03E+20	
2030	40	0.90	0.30	1.52E+07	8.69E+19	4.67E+20	1.0	8.69E+19	3.90E+20	

nb. nominal total POT from the TDR: 3.6e20

Mu2e Project Key Performance Parameters

Table 2.1 Key Performance Parameters

Parameters	Threshold Performance	Objective Performance
Accelerator	Accelerator components are acceptance tested at nominal voltages and currents. Components necessary for single-turn extraction installed. Shielding designed for 1.5 kW operation delivered to Fermilab and ready for installation. All target station components are complete, delivered to Fermilab and tested. Heat and Radiation Shield is installed in Production Solenoid. Other components are ready to be installed after field mapping.	Protons are delivered to the diagnostic absorber in the M4 beamline. Shielding designed for 8 kW operation delivered to Fermilab and ready for installation.
Superconducting Solenoid	The Production, Transport and Detector Solenoids have been cooled and powered to the settings necessary to take physics data.	The Production, Transport and Detector Solenoids have been cooled and powered to their nominal field settings.
Detector Components	Cosmic ray tracks are observed in the Tracker, Calorimeter and a subset of the Cosmic Ray Veto and acquired by the Data Acquisition System after they are installed in the garage position behind the DS. The balance of the CRV counters are at Fermilab and ready for installation.	The cosmic ray data in the detectors is acquired by the Data Acquisition System, reconstructed in the online processors, visualized in the event display and stored on disk.

- From the Project Execution Plan (mu2e-doc-db-1172), Table 2.1
- KPPs offer limited scope contingency

Mu2e Project Key Performance Parameters

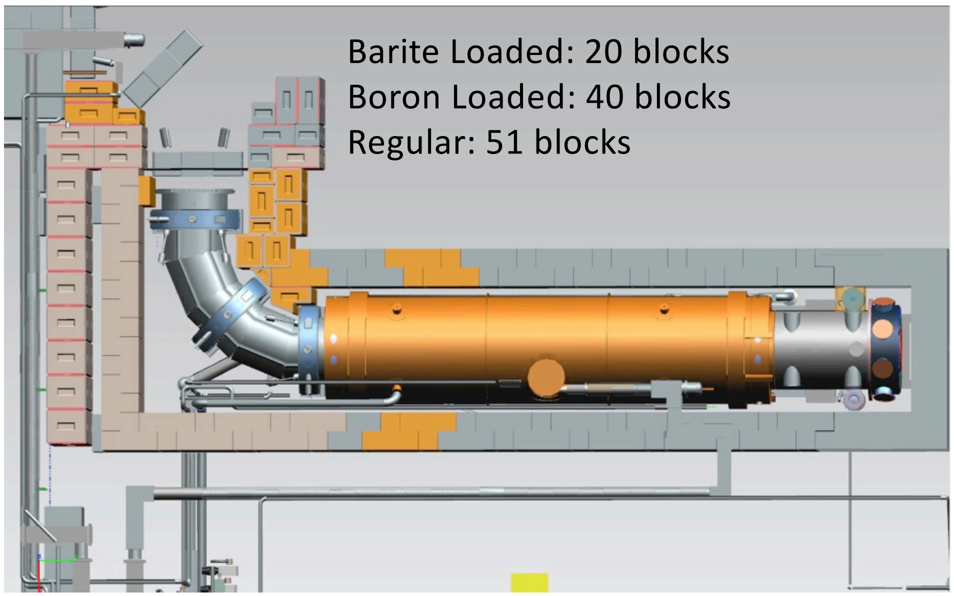
Table 2.1 Key Performance Parameters

Parameters	Threshold Performance	Objective Performance
Accelerator	Accelerator components are acceptance tested at nominal voltages and currents. Components necessary for single-turn extraction installed. Shielding designed for 1.5 kW operation delivered to Fermilab and ready for installation. All target station components are complete, delivered to Fermilab and tested. Heat and Radiation Shield is installed in Production Solenoid. Other components are ready to be installed after field mapping.	Protons are delivered to the diagnostic absorber in the M4 beamline. Shielding designed for 8 kW operation delivered to Fermilab and ready for installation.
Superconducting Solenoid	The Production, Transport and Detector Solenoids have been cooled and powered to the settings necessary to take physics data.	The Production, Transport and Detector Solenoids have been cooled and powered to their nominal field settings.
Detector Components	Cosmic ray tracks are observed in the Tracker, Calorimeter and a subset of the Cosmic Ray Veto and acquired by the Data Acquisition System after they are installed in the garage position behind the DS. The balance of the CRV counters are at Fermilab and ready for installation.	The cosmic ray data in the detectors is acquired by the Data Acquisition System, reconstructed in the online processors, visualized in the event display and stored on disk.

At reduced intensities can reduce shielding

At reduced intensities may be able to employ a “lesser” detector and still achieve physics goals

Mu2e – External Shielding



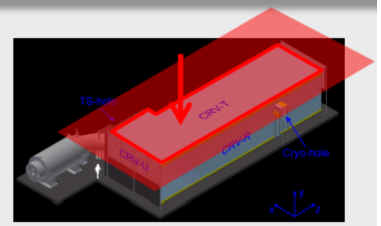
- Main role is to reduce rates in cosmic-ray veto (CRV) system from neutron-induced interactions
  - Neutron sources: production target, middle collimator, stopping target, muon beam stop
- Baseline configuration optimized over several years of detailed simulation work and measurements

- Significant cost savings available by eliminating specialty concretes

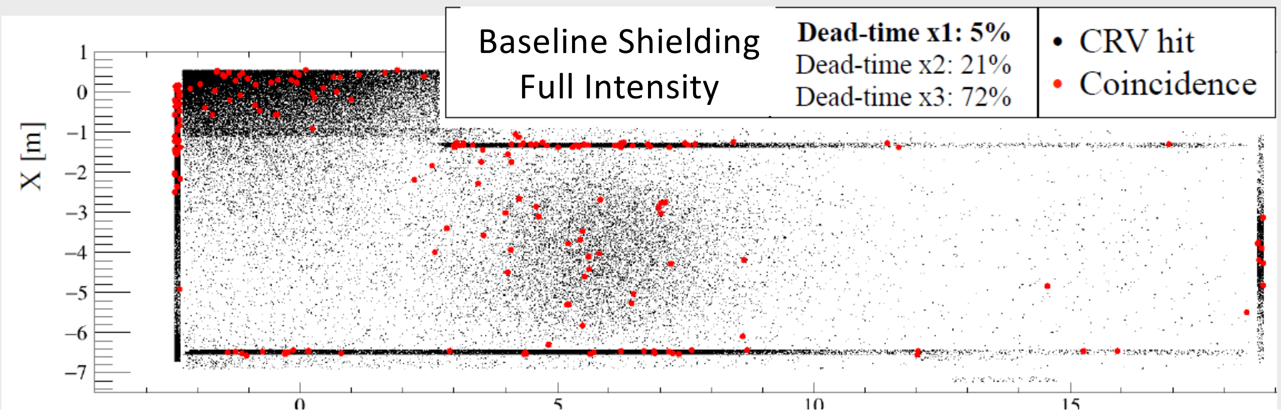
Impact of Reduced External Shielding on CRV Deadtime

Dead-time: regular concrete

- As part of "de-scope" option, we consider a shielding design with regular concrete only
- Upstream region is covered by borated poly
- The dead-time and rates are higher in the upstream region and around the stopping target
- The dead-time is within the requirement
- The rates are above the required 1 MHz value



Y. Oksuzian
Mu2e-doc-db-8627

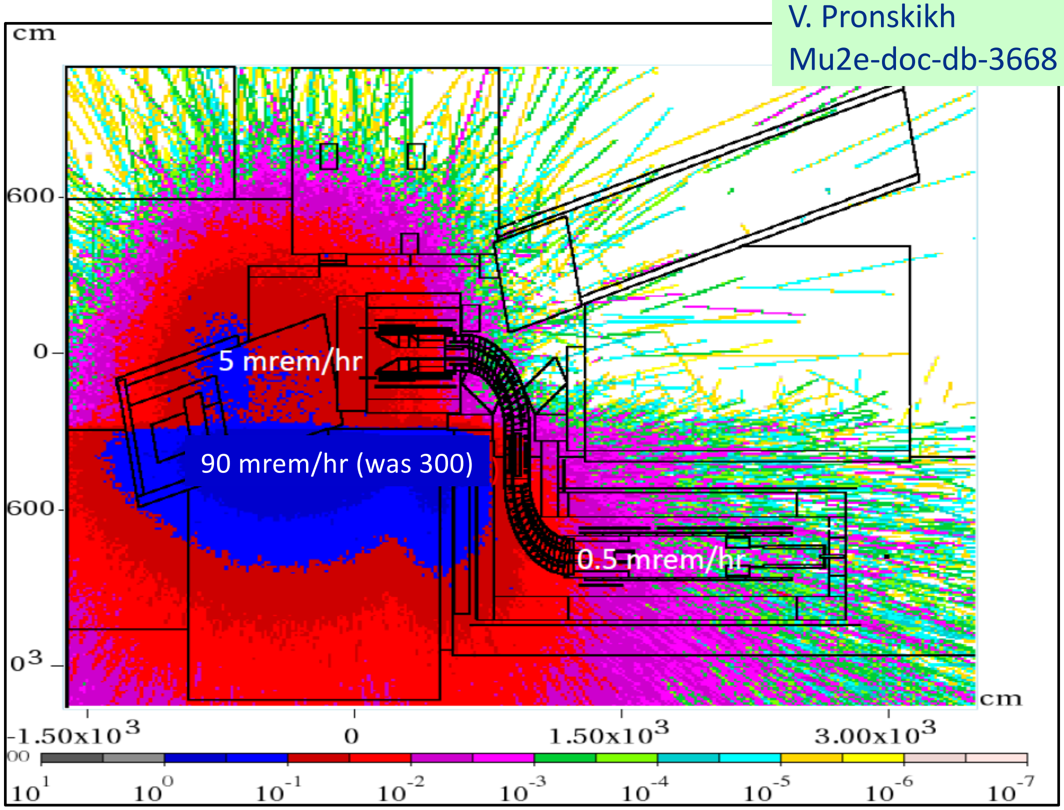


- At reduced intensity can keep dead-time <10% with external shielding package that eliminates specialty concrete
  - nb. still requires the borated poly sheets

For All Regular Concrete Shielding	Full Average Intensity	50% Average Intensity
Dead-time at x1 occupancy	5%	2%
Dead-time at x3 occupancy	72%	11%

Residual radiation levels with reduced hatch shielding

V. Pronskikh
Mu2e-doc-db-3668



At Full Intensity, but using only 3' of hatch shielding instead of the 6' currently in Project baseline

- At reduced intensity, can likely reduce hatch shielding and still meet radiation safety requirements
  - Will be confirmed with updated simulations
- Reducing hatch shielding by x2 would increase the CR-induced background by ~10% (cf. CDR)

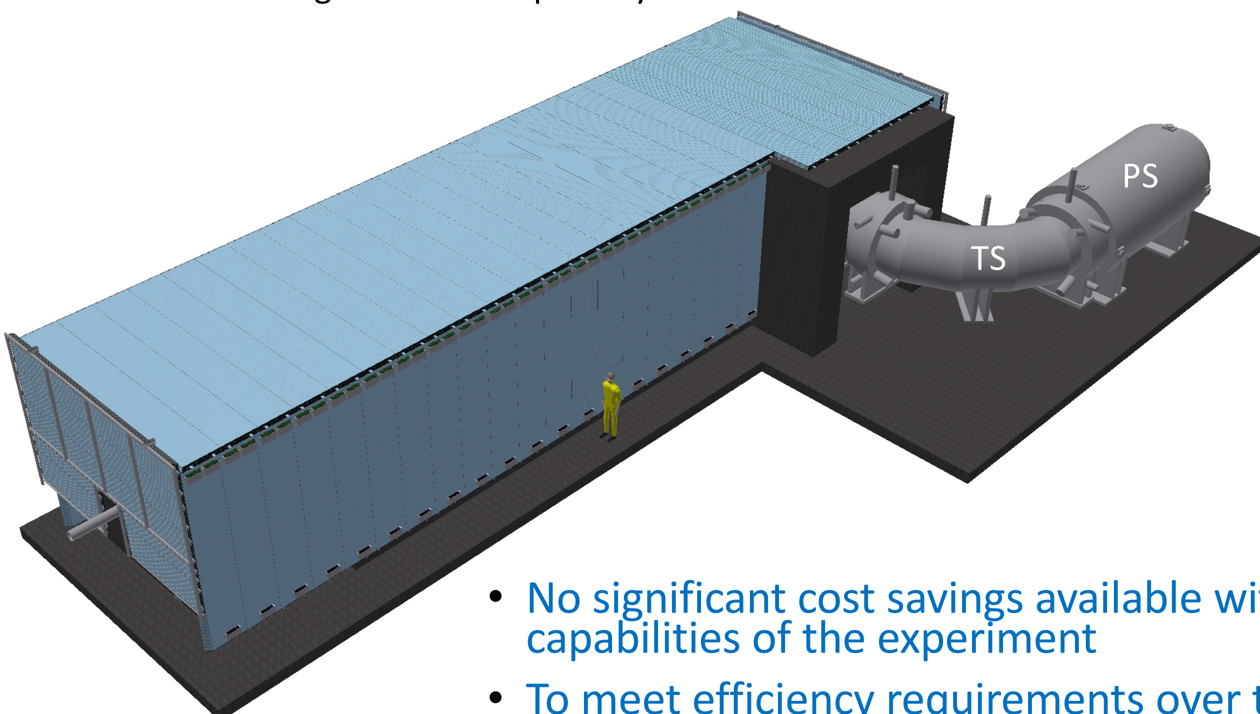
Mu2e Shielding

- Can utilize “lesser” shielding options during reduced intensity running without significant impact on the science capabilities of the experiment
  - ~$1.7M in savings

- For full intensity running, we expect to need upgrades to the shielding
  - Can optimize the required upgrades based on experience gained with low intensity running

Mu2e Cosmic-Ray Veto

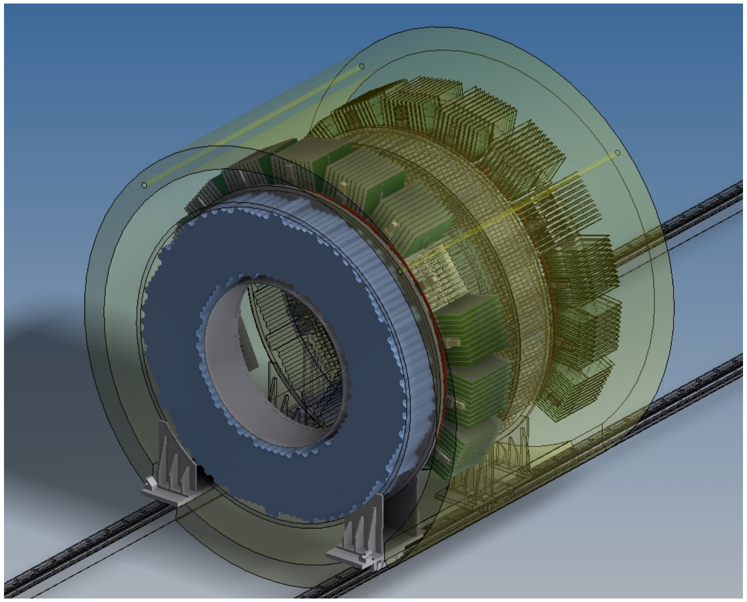
Without the veto system, ~1 cosmic-ray induced background event per day



- CR-induced background
  - Largest background source
  - It scales with run time
  - Requires Veto eff. > 99.99% over the lifetime of the experiment
  - Scintillator was extruded in 2018 and is aging
  - ie. *Running at reduced intensity for an extended period exacerbates the challenges*

- No significant cost savings available without jeopardizing science capabilities of the experiment
- To meet efficiency requirements over the extended run period, we may need to upgrade certain portions of the CRV to maintain sufficient light yields – will be informed by *in situ* experience

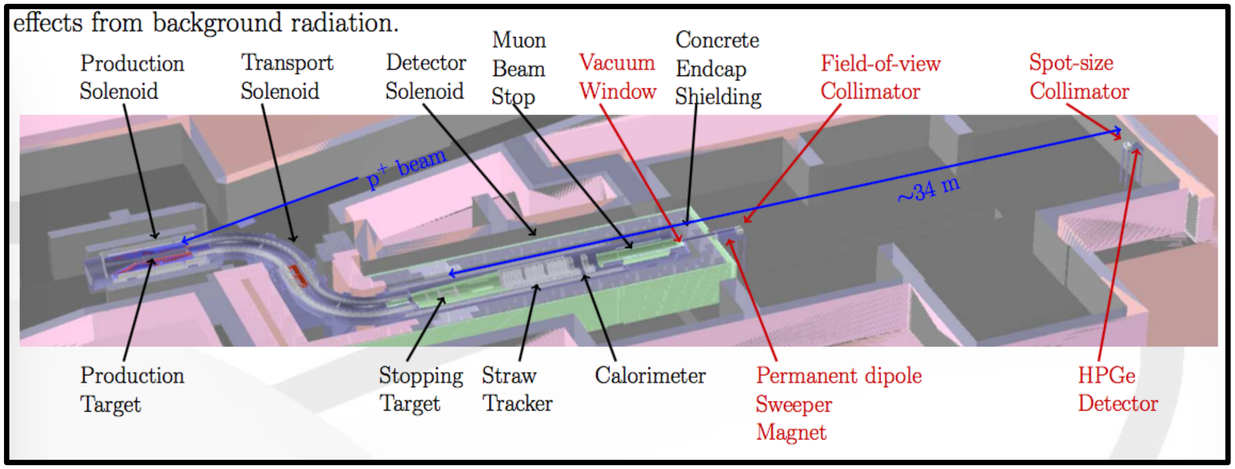
Mu2e Calorimeter



- Provides PID, fast trigger, and t0
  - CR and pbar backgrounds x7 without PID
- Large in-kind contribution from INFN, smaller from JINR
- Crystals 67% delivered, SiPMs 100%
- Calibration systems in-hand or in-kind
- Eliminating 2nd disk (30% eff. Reduction) requires re-engineering mechanical supports, transportation & installation fixtures, etc.

- Can eliminate outer crystals with small impact to physics capabilities
  - ~$95k savings less the costs associated with aluminum “filler” bars

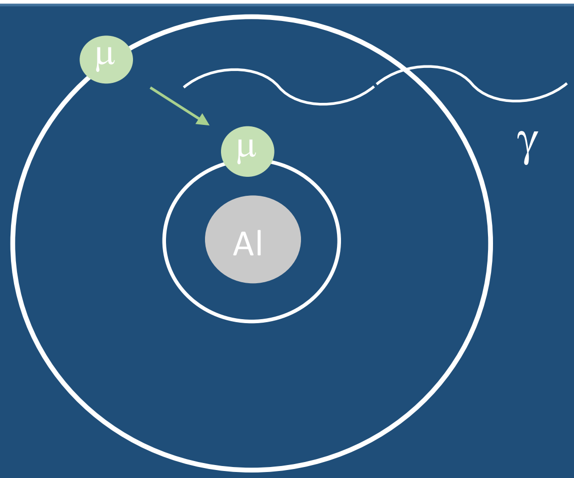
Mu2e Stopping Target Monitor



- Our luminosity monitor
  - Provides only direct evidence of muonic Al atoms by observing characteristic γ lines
  - Provides muon arrival time information
- HPGe, cooling, DAQ provided in-kind (STFC)
  - Already procured

- Can eliminate some of the infrastructure associated with the STM without significant impact to the physics capabilities during reduced intensity running
  - ~$50k in savings
- We expect to need to recover full capabilities prior to full intensity running

Mu2e - Stopping Target Monitor



A) Prompt
- ^{27}Al(2p → 1s)
- 80% of μ stops
- 347 keV
- $\tau_{1/2}$ < ps

B) Semi-Prompt
- ^{27}Al(μ, νnγ)^{26}Mg
- 50% of μ captures
- 1809 keV
- $\tau_{1/2}$ = 864 ns

C) Delayed
- ^{27}Mg(β decay)^{27}Al*→^{27}Al
- 9% of μ captures
- 844 keV
- $\tau_{1/2}$ = 9.5 m, 35 ps

- Stopped muons promptly (10^{-15} s) cascade to ground state, emitting photons at given energies
- The muon capture process also produces photons at characteristic energies
- These photons used to monitor number of stopped muons

Mu2e – Extinction Monitor

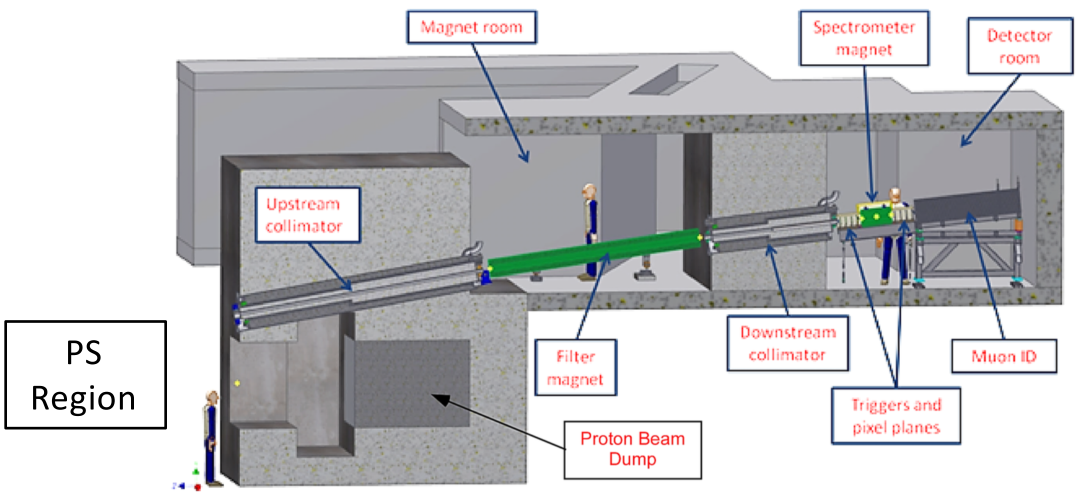
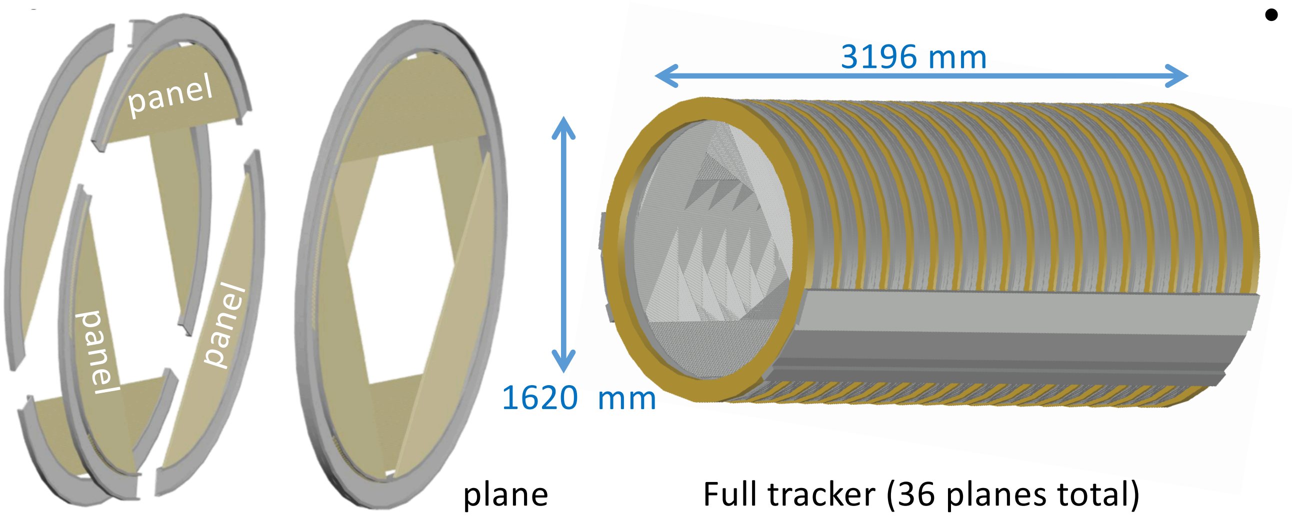


Figure 4.116. The components for the target extinction monitor

- Monitors proton beam
  - Provides proton arrival time distribution at the target
  - Measures extinction (at 10^{-10} to 10% in 4h)
  - Essential to verify quality of proton beam
  - Prompt backgrounds steep function of pulse width and extinction
  - Pixel planes in-hand, assembled

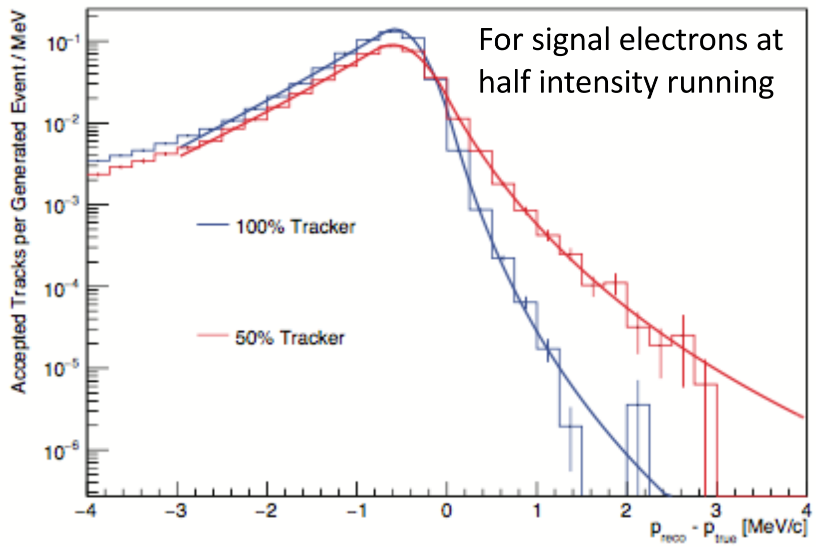
- Can eliminate muon range stack without impacting physics capabilities
  - at the cost of reducing capability to understand any surprises that may arise
  - ~$50k in savings

Mu2e - Tracker



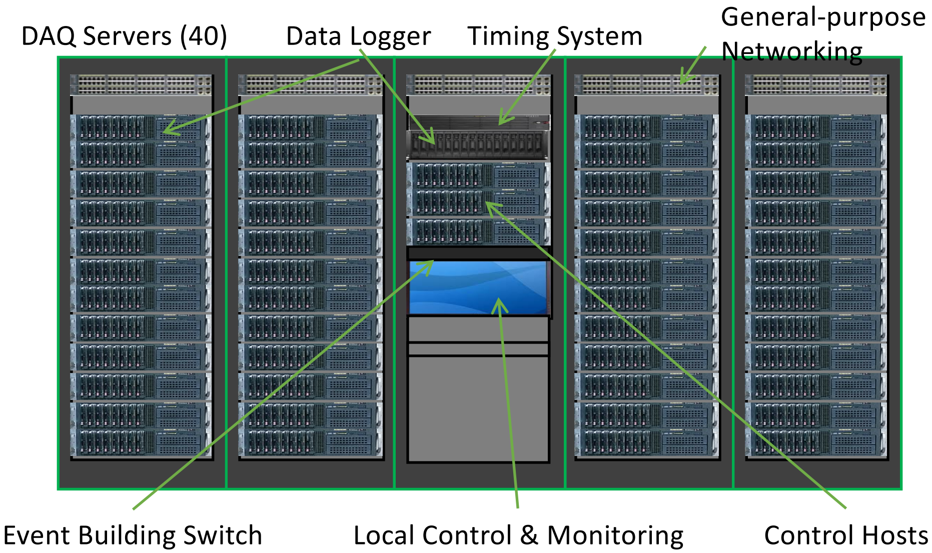
- Provides precision determination of E_e
  - DIO background falling as E^5… stringent resolution requirements
  - Must operate in high occupancy environment
  - Optimal # planes ~44… current baseline already reflects previous value engineering exercise… moved us from a performance plateau to the knee
- May be able to eliminate some fraction of the planes while incurring an "acceptable" degradation in physics performance during the reduced intensity running period
  - nb. a ~25% reduction in no. of tracker planes would provide ~$500k savings
  - At this stage, I would characterize this as having a Very High risk of failure
  - Requires O(6 mo.) of detailed studies to develop this option and reduce associated risk
- Will need full tracker for full intensity running in order to accomplish science goals

First look at a reduced tracker



- As an extreme case, we generated a signal sample with 50% tracker
  - 30% reduction in signal efficiency
  - Order of magnitude increase in fraction of events with $\Delta P > 1$ MeV/c
  - Additional impacts have not been evaluated (e.g. DIO background, trigger filter performance) would require significant O(6 mo) additional effort

Mu2e – Trigger & DAQ



- Clock distribution, control, CPU farm
  - Data is streamed to cpu farm where software filters select events to save
  - Baseline number of servers is bare minimum
  - Baseline plan utilizes collaboration effort to develop TDAQ software
  - 2y effort required to develop filters that meet bw requirements
  - Any reduction in tracker or calorimeter will impact trigger performance

- No significant cost savings is available – baseline already aggressively VE'd

Summary (For the Red Team)

- Collaboration performed a thorough investigation of descope options
- Have proposed a modified run plan
  - Extended running at 50% intensity with a “lesser” experiment
  - Use LBNF/PIP-II shutdown to recover full capabilities
  - Will achieve important physics goals in a timely manner

FY	Weeks	90% CL on $R_{\mu e}$	vs SINDRUM-II	5σ on $R_{\mu e}$
2023	26	17×10^{-16}	$\times 350$	32×10^{-16}
2024	34	7.1×10^{-16}	$\times 850$	14×10^{-16}
2025	40	3.0×10^{-16}	$\times 2000$	5.8×10^{-16}
LBNF/PIP-II shutdown	—	—	—	—
2028	40	1.7×10^{-16}	$\times 3500$	3.8×10^{-16}
2029	40	1.3×10^{-16}	$\times 4600$	2.8×10^{-16}
2030	40	1.0×10^{-16}	$\times 6000$	2.5×10^{-16}

Assumes full tracker.

Assumes we’ve recovered full performance capabilities during shutdown.

  - Offers “immediate” savings of $1.7M
  - Additional savings *may* be possible at the level of $100s k… would require significant studies esp. for possible tracker reductions

Red Team Comments & Questions

- Their overall impression:
  - “collaboration has clearly done a careful and thorough job”
  - “aside from the reduced shielding there doesn’t appear to be any significant cost savings available without introducing significant risk to the science goals”
  - “$1.7M in savings by itself will not be enough to put the project on sound financial footing”
- Their homework for us:
  - Breakout cost savings for hatch, barite, and boron shielding separately.
  - Provide size of hatch blocks. Could steel work in the hatches?
  - Quantify the costs associated with recovering full capability at a later date.
- They are working on a report– due 15-June to Tim Meyer

Next Steps

- Obtain answers to Red Team questions

- Spokespersons will generate a next version of the report that:
  - Addresses the comments/questions received from the collaboration
  - Includes the answers to the Read Team questions
  - Includes the KPPs and associated discussion
  - Includes estimates of cost savings
  - Is tailored to a higher-level audience (FNAL Directorate, DOE, INFN, STFC, etc)

Backup Slides

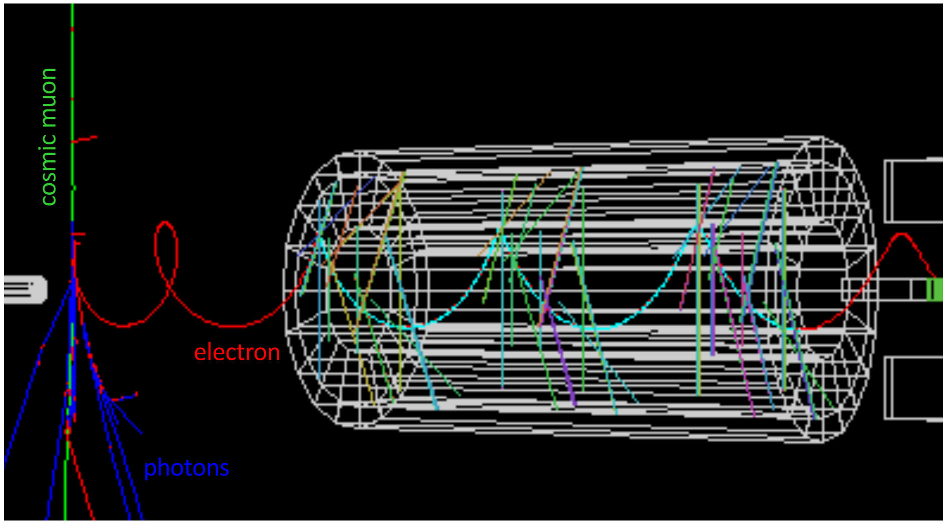
Mu2e Backgrounds

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.04
	Cosmic Ray induced	0.21
Total Background		0.41

Assuming 6.7e17 stopped muons in 6e7 seconds of run time at full beam intensity and nominal detector performance.

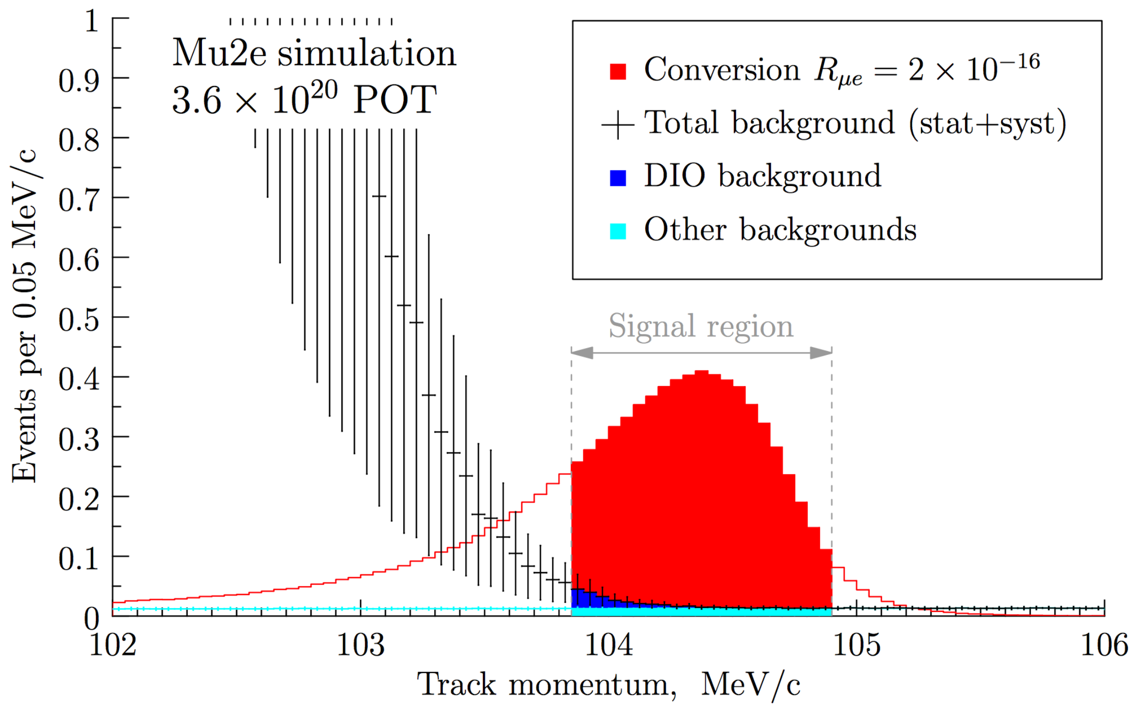
- Scales with the number of stopped muons
  - DIO strong function of spectrometer resolution
- Scales linearly with the extinction performance
- Cosmic background scales with run time

Mu2e Dominant Backgrounds



- Cosmic μ can generate background events via decay, scattering, or material interactions
  - Suppressed with high efficiency veto counters

After full data set (projection)



- Discovery sensitivity for all $R_{\mu \rightarrow e} > 2 \times 10^{-16}$!