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Mu2e Project Overview

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Mu2e Accelerator Radiation Safety Improvements Design Review

20 October 2015

Outline

- The Mu2e Experiment
- The Muon Campus
- The Mu2e Project Accelerator Systems
- Construction Progress
- Schedule Overview

The Mu2e Experiment

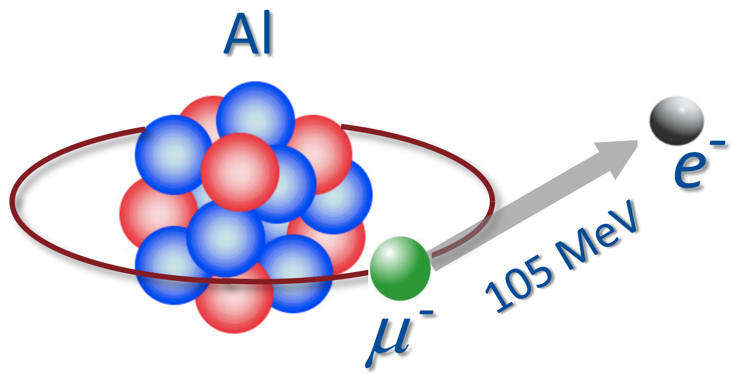
Charged Lepton Flavor Violation

- The Mu2e experiment will attempt to detect Charged Lepton Flavor Violation (CLFV)
- CLFV is a process involving charged leptons ($e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$) that violates the conservation of the number of leptons of each flavor

Ordinary muon decay is not CLFV

$$\mu^- \to e^- \; \bar{\nu}_e \; \nu_\mu$$

	μ^-	e^-	$\bar{\nu}_e$	ν_μ
L_μ:	1	0	0	1
L_e:	0	1	-1	0



$$\mu^- N \to e^- N$$

	$\mu^- N$	$e^- N$	
L_μ:	1	0	$\Delta L_\mu = -1$
L_e:	0	1	$\Delta L_e = 1$

Both L_μ and L_e are not conserved in this process

If this is observed, it is evidence physics beyond the Standard Model

What Mu2e Measures

The Mu2e experiment will measure the ratio of the number muon captures in aluminum that produce a conversion electron to the number of those that are captured in the ordinary way. This ratio is designated "$R_{\mu e}$"

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + \left(A,Z\right) \rightarrow e^- + \left(A,Z\right)\right)}{\Gamma\left(\mu^- + \left(A,Z\right) \rightarrow \nu_\mu + \left(A,Z-1\right)\right)}$$

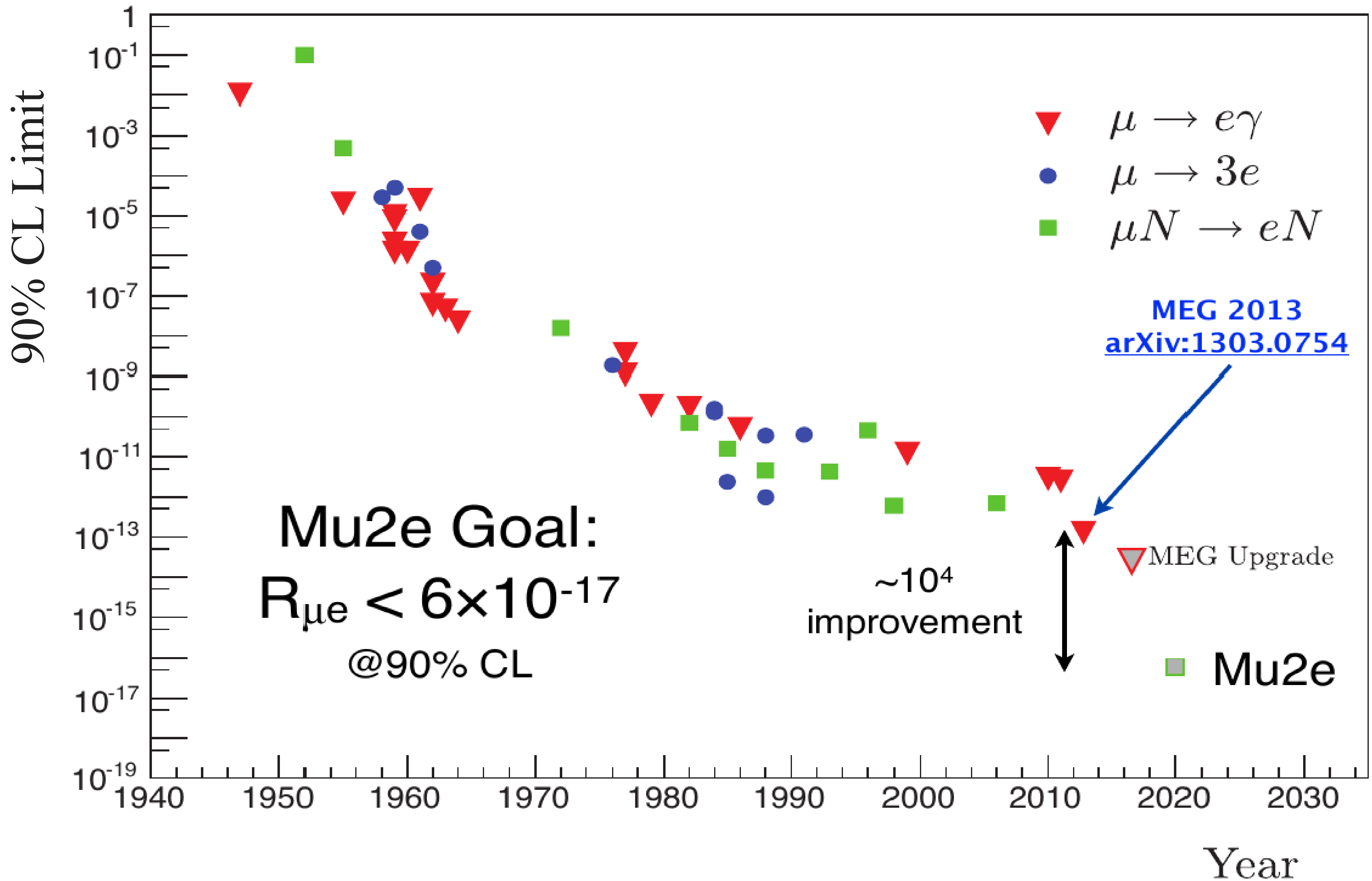
← *Rate of CLFV* $\mu \rightarrow e$ conversion

← μ capture rate

Mu2e goal for 10^{18} stopped muons:

- Single event sensitivity = 2.87×10^{-17} (i.e. one observed event yields $R_{\mu e} = 2.87\times10^{-17}$)
- 90% CL $R_{\mu e}$ Limit < 6.0×10^{-17}

Results of Previous CLFV Searches



Mu2e Apparatus

The Mu2e apparatus consists of three superconducting solenoids joined together to make a continuous whole

Production Solenoid

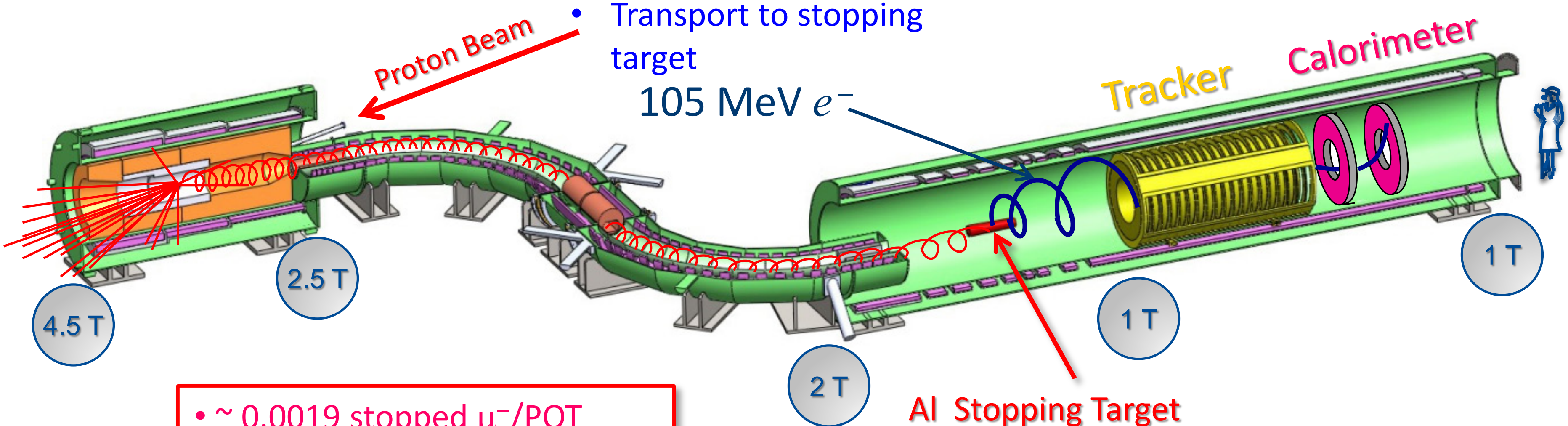
- Contains proton target
- Magnetic mirror – reflects secondaries back toward transport solenoid

Transport Solenoid

- Collimation
- Momentum and charge selection
- Transport to stopping target

Detector Solenoid

- Contains stopping target
- Tracker (straws)
- Calorimeter (BaF_2 crystals)



- ~ 0.0019 stopped μ^-/POT
- 10^{10} Hz of stopped muons

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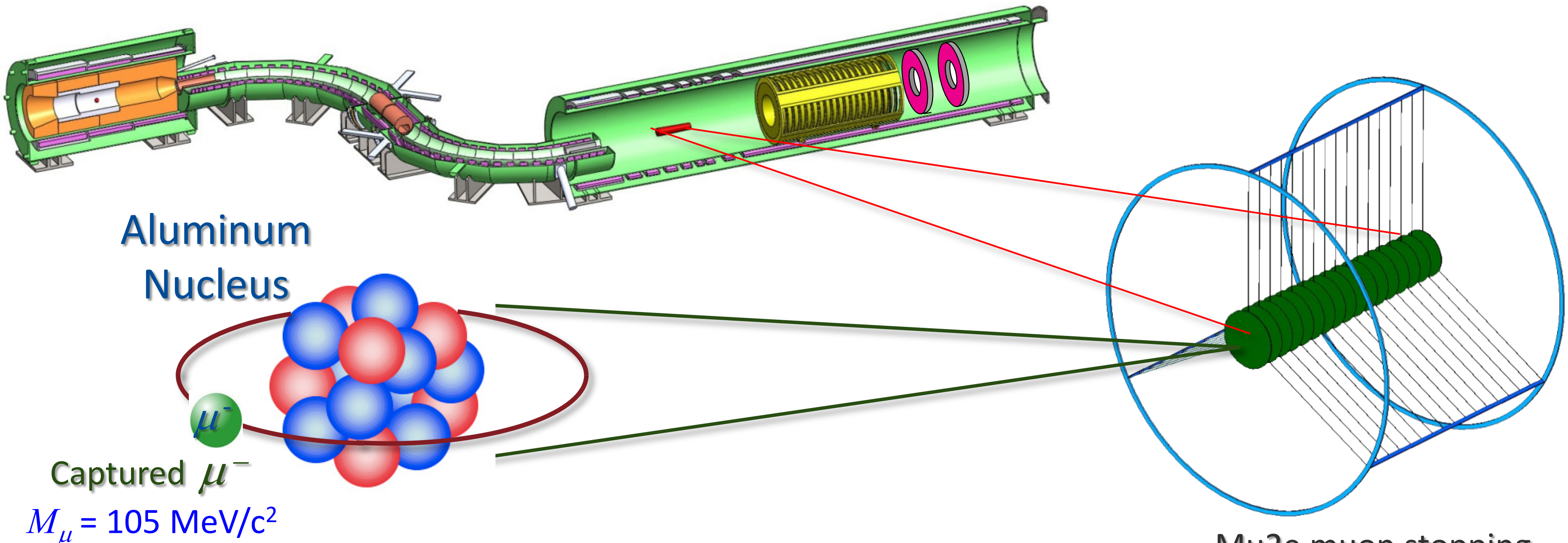
Stopping Muons



Mu2e muon stopping target

- 17 Al 200 μm foil disks
- Disk radii decrease from 83 mm to 65 mm in downstream direction

- A muon that is stopped in the Mu2e target is captured into an atomic orbital state of an aluminum nucleus
- The muon quickly ($\lesssim$ psec) transitions* to the 1S state where its wave-function overlaps the nucleus

* A target monitor counts nuclear transition photons

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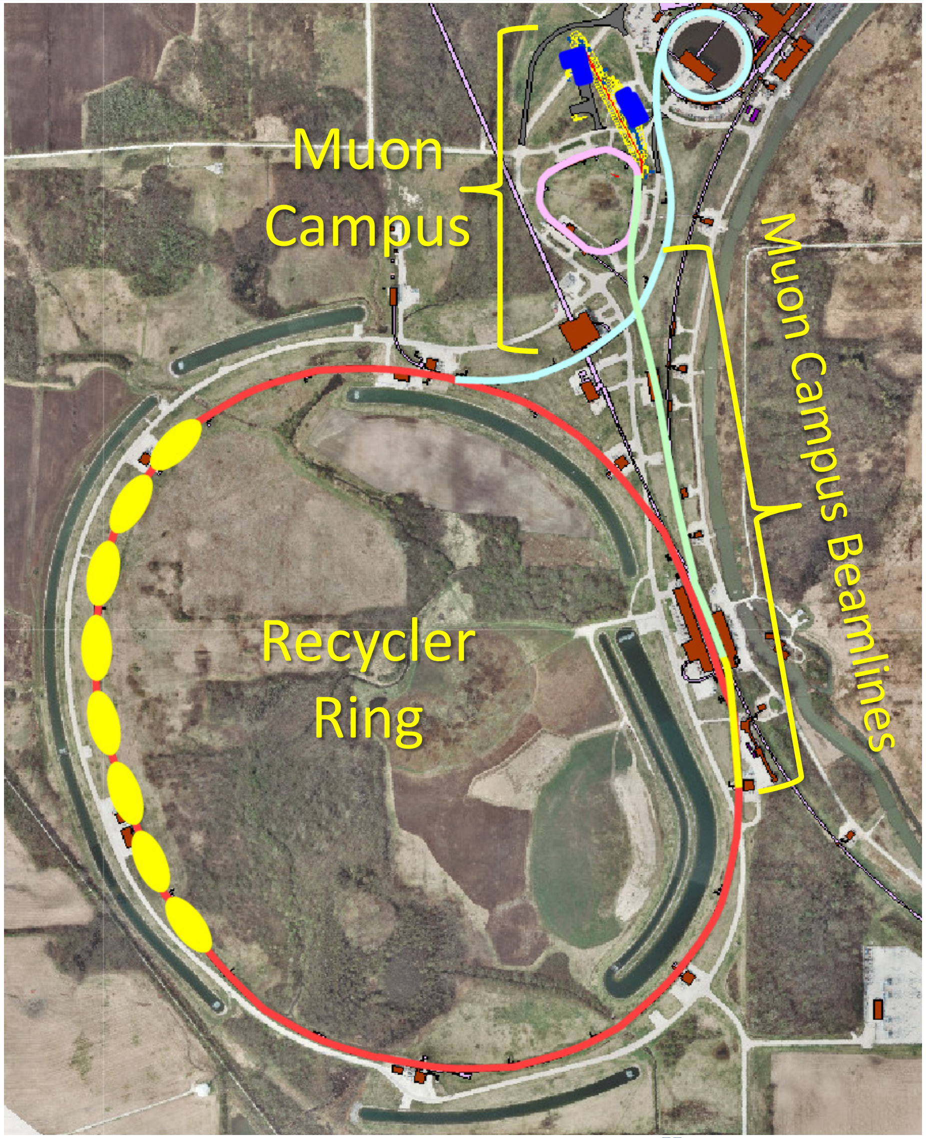
The Muon Campus

Acquisition of Beam for Mu2e



Accelerator timeline for Mu2e proton beam delivery

- Spill duration: 43.1 msec
- Interval between spills 48.1 msec
- Duty Factor: 27.1%
  (Total Spill Time/Length of Cycle)
- Peak Delivery Ring proton intensity: 1.0×10^{12}

The Muon Campus

DOE Projects, AIPs, GPPs

Building the Muon Campus requires the following projects:

1. DOE Projects
   - Muon g-2
   - Mu2e
2. AIPs (Accelerator Improvement Projects)
   - Recycler RF
   - Beam Transport
   - MC Cryo Plant
   - Delivery Ring
3. GPPs (General Plant Projects)
   - MC-1 Building
   - Beamline Enclosure
   - MC Infrastructure Upgrade

Muon Campus Upgrades Required for the Mu2e Experiment but not on the Mu2e Project

Accelerator Upgrade	Project
MI-8 beamline to Recycler Ring Injection	NOvA Project
Recycler Ring 2.5 MHz RF system	Recycler RF AIP
Delivery Ring 2.4 MHz RF Cavities and HL Amps & Cooling	Recycler RF AIP
Single bunch extraction from Recycler Ring	Beam Transport AIP
Beamline aperture upgrades	Beam Transport AIP
AP1, AP2, AP3 to M1, M2, M3 conversion & upgrade	Beam Transport AIP
Beam transport instrumentation & infrastructure	Beam Transport AIP
Beam transport controls	Delivery Ring AIP
Delivery Ring Injection	Delivery Ring AIP
Delivery Ring Abort	Delivery Ring AIP
Delivery Ring infrastructure	Delivery Ring AIP
Delivery Ring Controls and Instrumentation	Delivery Ring AIP
D30 straight section reconfiguration	g-2 Project
Delivery Ring Extraction (except ESS)	g-2 Project
Extraction line (M4) to M5 split	g-2 Project
M4 beamline enclosure	MC Beamline Enclosure GPP

The Mu2e Project Accelerator Systems

Mu2e Accelerator Systems Scope Overview

475.02.08.03 Extinction Monitor

475.02.09 Target Station

475.02.07 External (M4) Beamline

475.02.08.02 Extinction

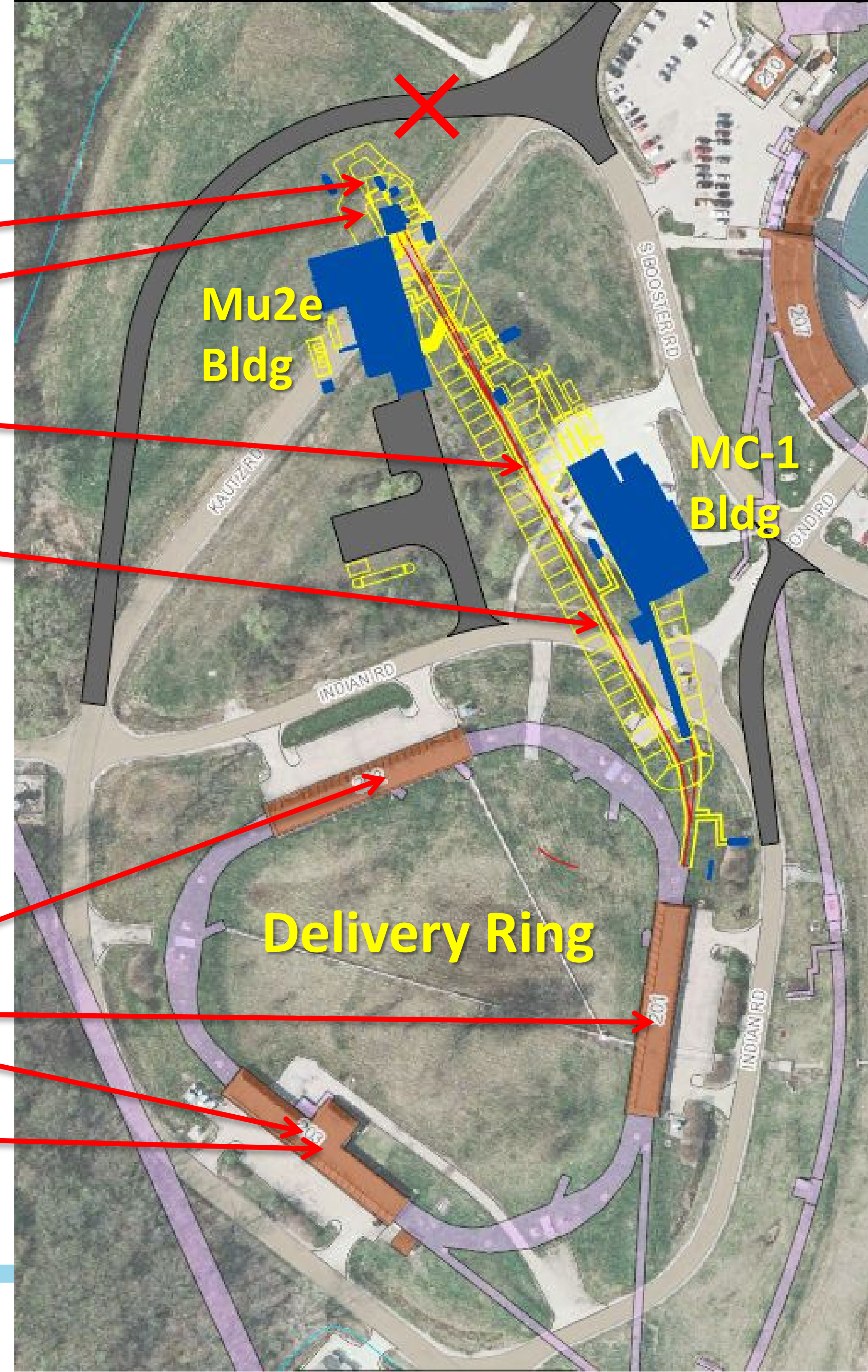
475.02.03 Instrumentation & Controls

475.02.04 Radiation Safety

Everywhere

475.02.05 Resonant Extraction

475.02.06 Delivery Ring RF



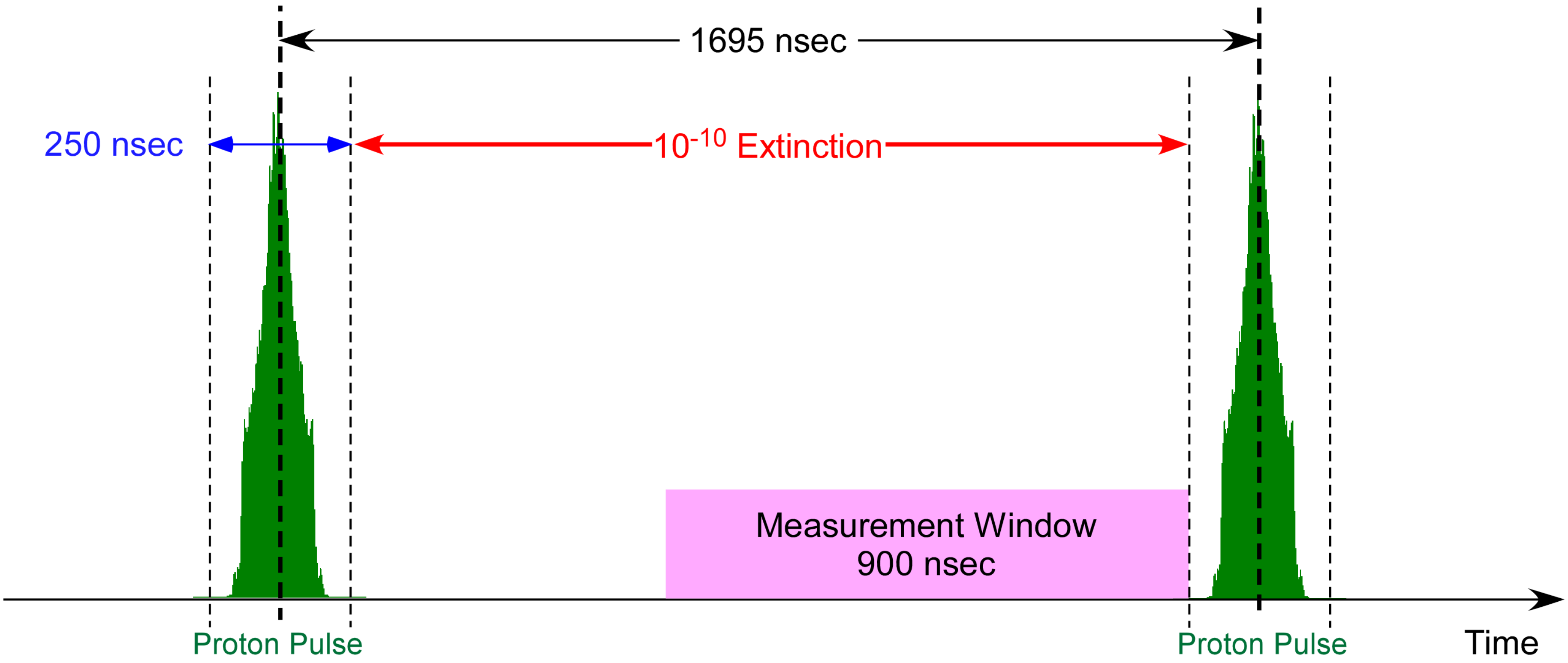
Mu2e Proton Beam Requirements

	Parameter	Design Value	Requirement	Unit
3-4 year run	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}	$< 5.0 \times 10^{7}$	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

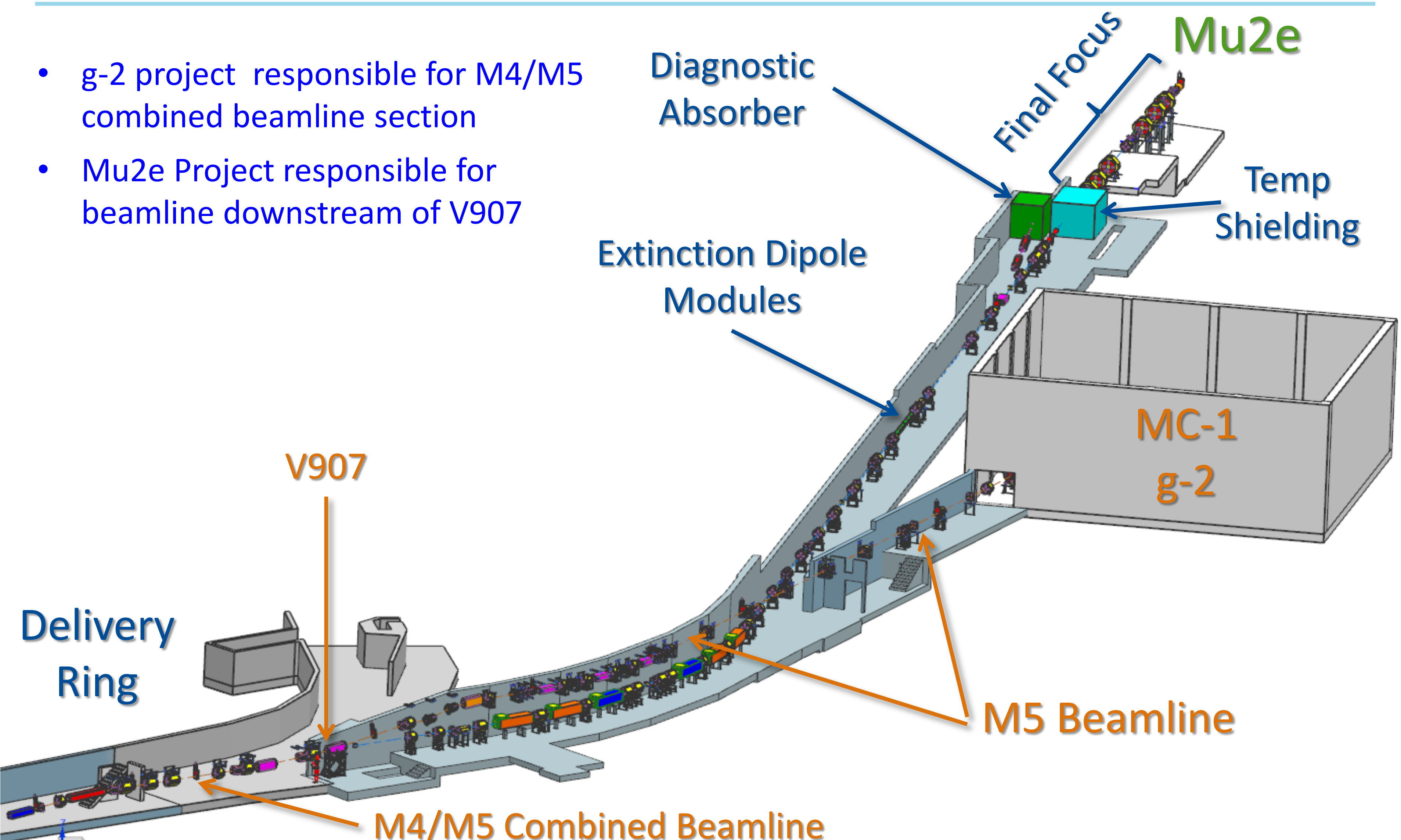
Two successive proton pulses on the Mu2e target (out of ~30,000 per spill)

- Each pulse contains ~40×10^6 protons
- Extinction = No. of out-of-time protons / No. of in-time protons

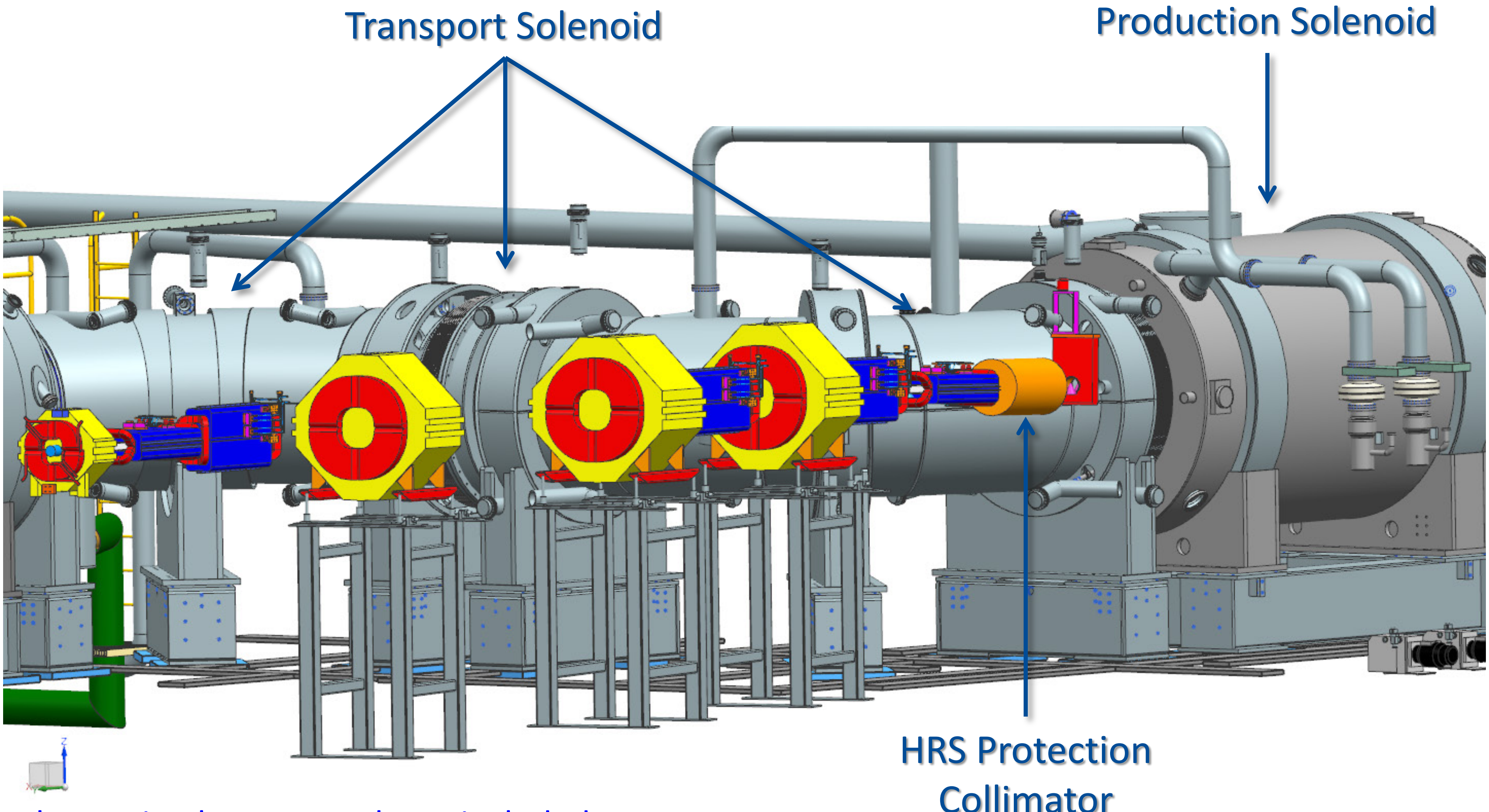


External (M4) Beamline Layout

- g-2 project responsible for M4/M5 combined beamline section
- Mu2e Project responsible for beamline downstream of V907

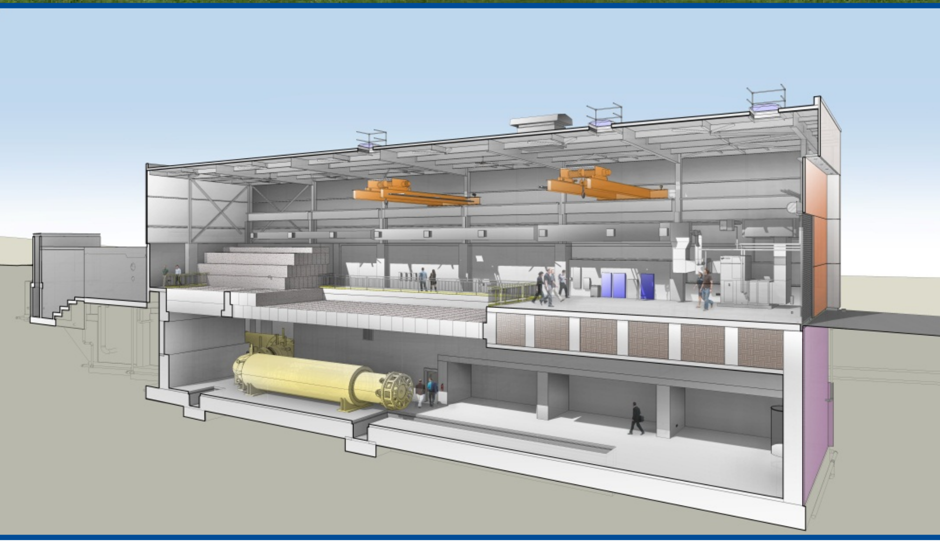


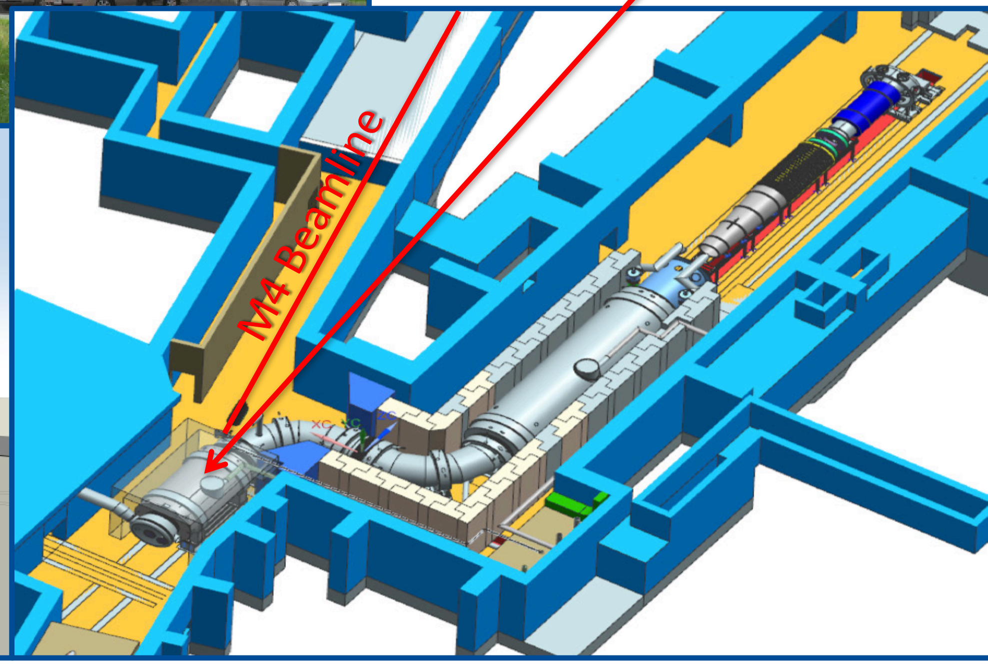
M4 Beamline / Production Solenoid Interface



beampipe has not yet been included

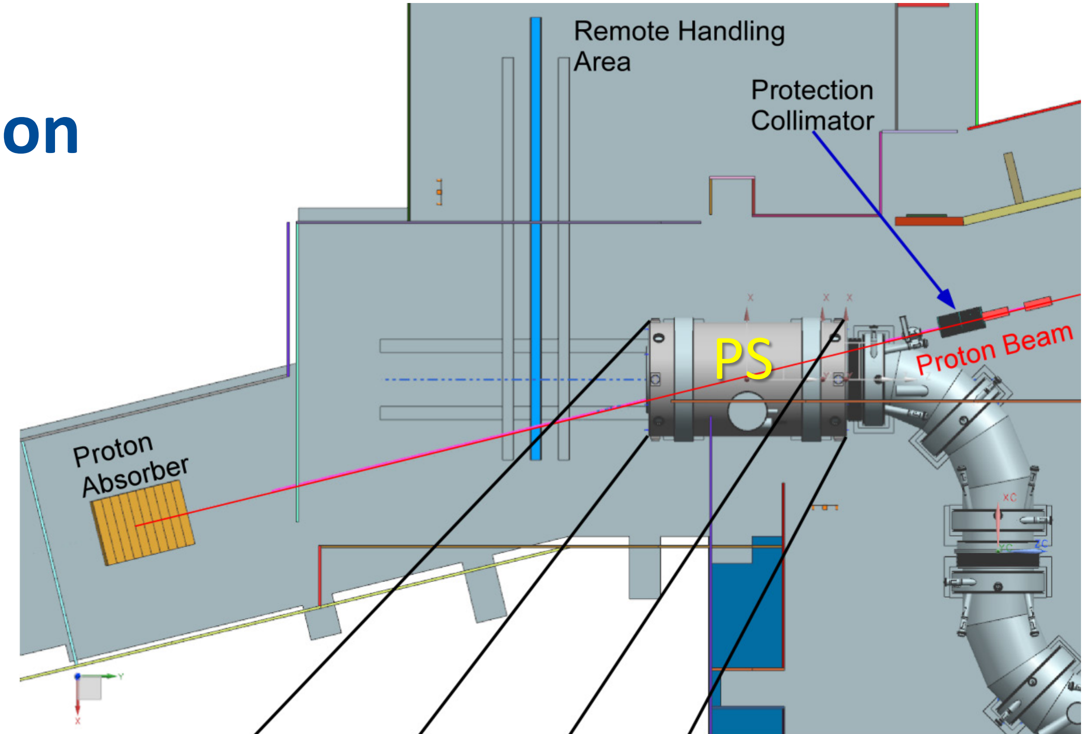
The Mu2e Building

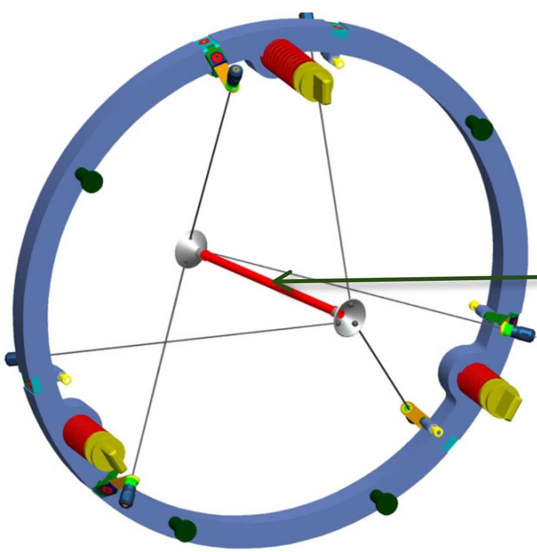


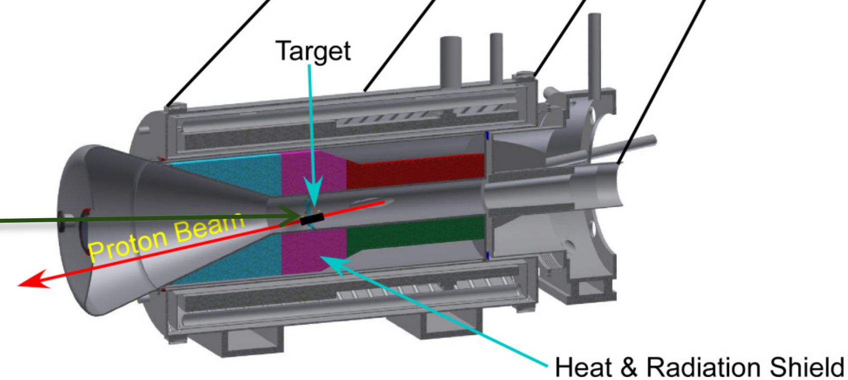


Mu2e Proton Target Station

- Target – located inside the Production Solenoid (PS)
- Heat & Radiation Shield (HRS)
- Proton Absorber
- Protection Collimator



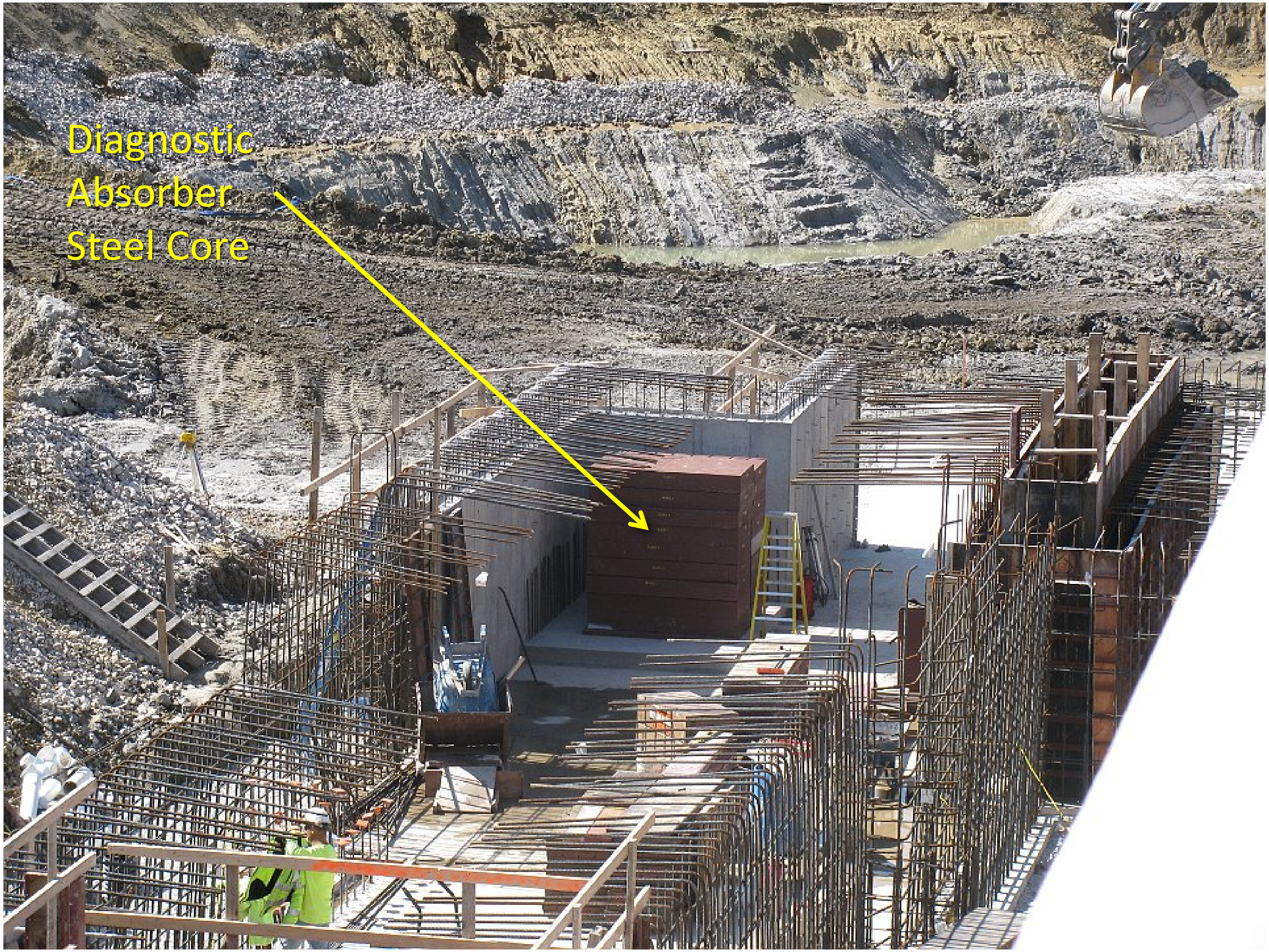




Construction Progress

M4 Enclosure Construction

M4 Beamline Enclosure construction – Diagnostic Absorber



Pouring Mu2e building floor slab

- Looking east toward g-2 Building

Framing the walls in the proton target station area of the Mu2e building

Concrete floor complete

Framing and pouring the walls

Target Proton Beam Absorber Air Manifold

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Saturday, 17 October 2015

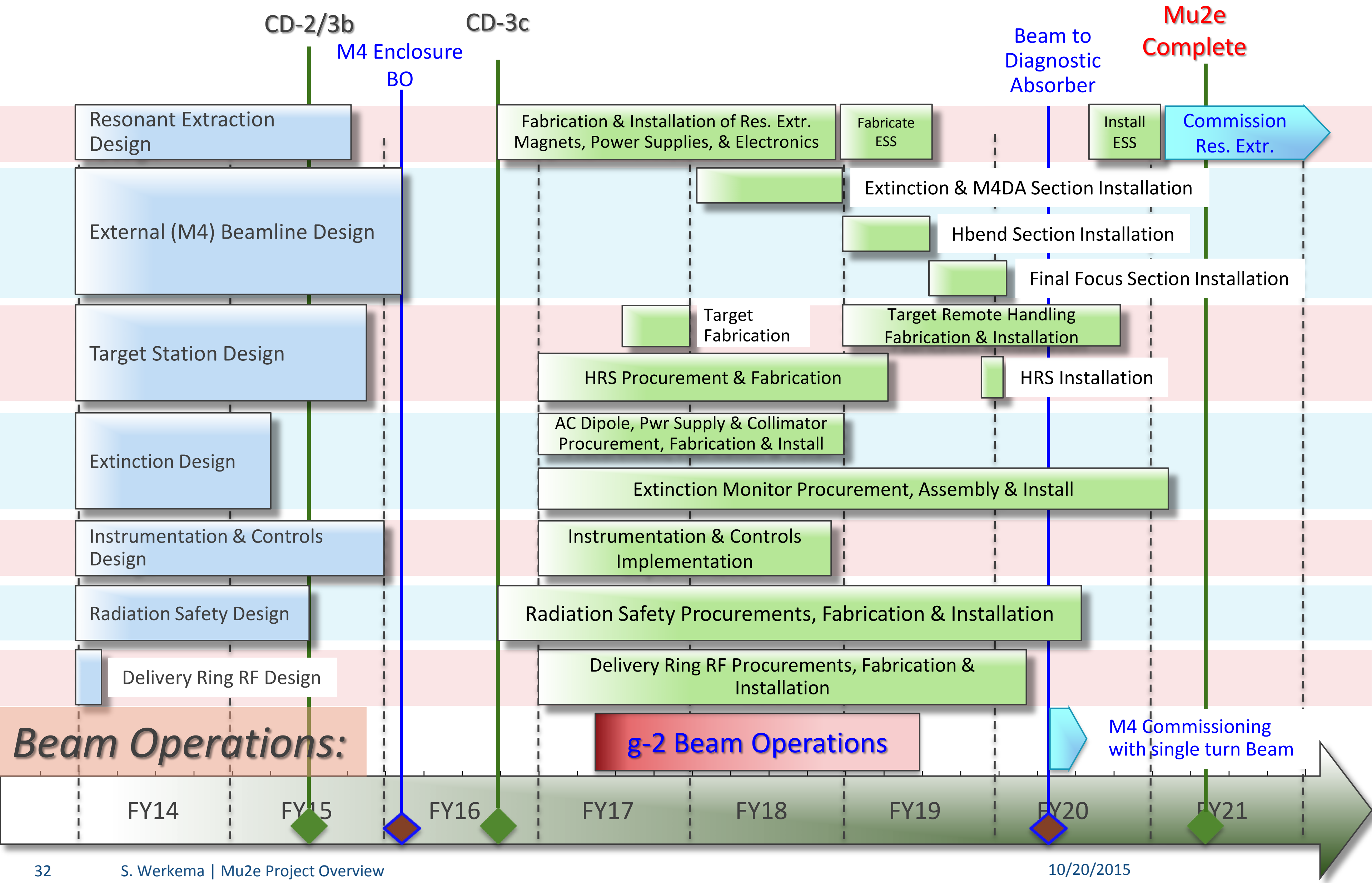
Why Start Building Construction before Design is Complete?

- Generally, this is a very bad thing to do
  - Removes the flexibility to accommodate unforeseen design issues that might be alleviated by building changes
  - Once an A&E firm is retained, building design changes are expensive. Once a construction contract is awarded changes become even more costly
  - The building becomes a design constraint as soon as concrete is poured

- The Muon Campus and Mu2e projects did this because:
  - Allows early start on projects necessary for g-2 – early g-2 running simplifies accelerator commissioning for Mu2e
  - Construction costs were relatively low and projected to trend up when this decision was made

Schedule

Mu2e Accelerator Schedule



Significant Milestones

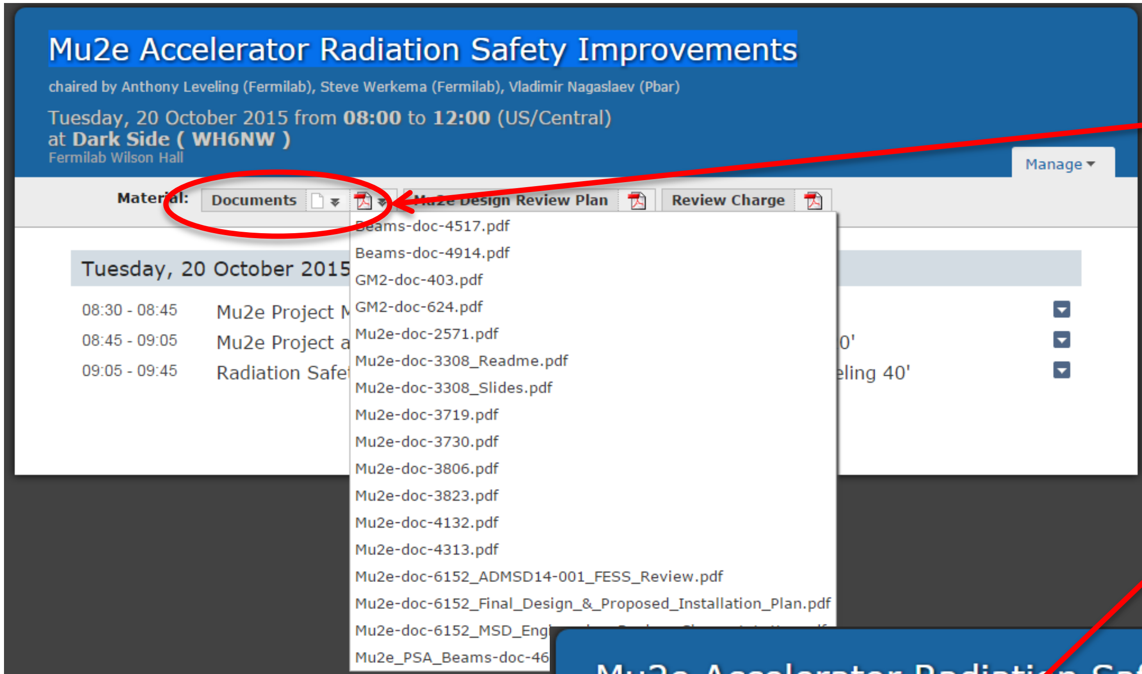
Milestone	Date
Diagnostic Absorber Installation Complete	March 2015
M4 Beamline Enclosure Beneficial Occupancy	Nov 2015
DOE CD-3c Approval	June 2016
Start of Muon g-2 Run	May 2017
Ready to run beam to diagnostic absorber	June 2020
M4 Beamline commissioned to Diagnostic Absorber	Sept 2020
Start electro-static septum installation	Oct 2020
DOE CD-4 Approval	May 2021

Muon Campus Program Cost

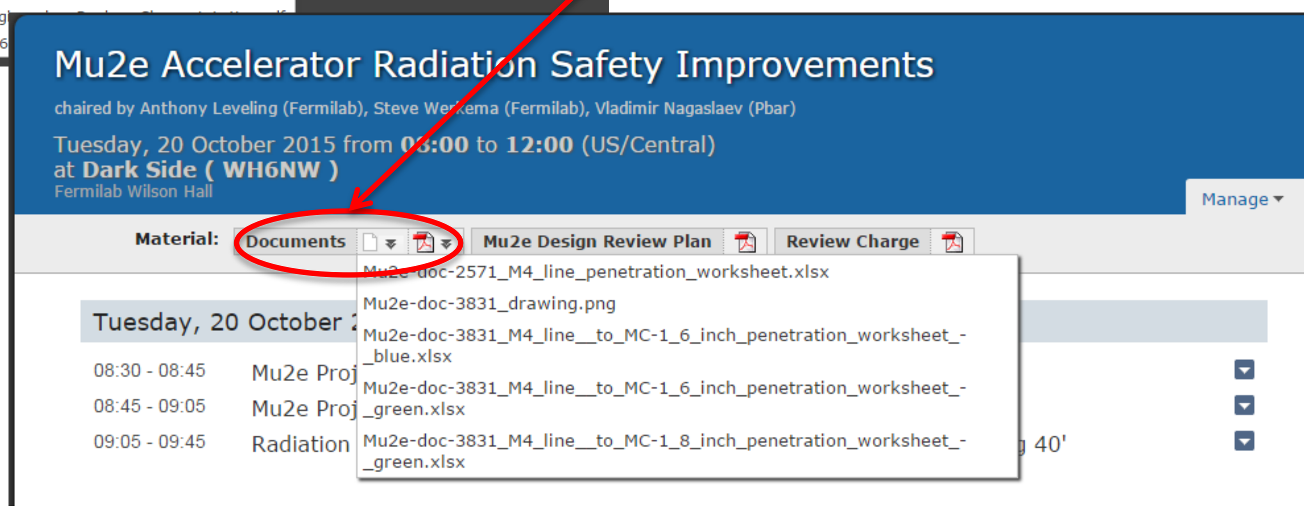
Project	Total Project Cost ($M)	Accelerator Costs ($M)
Muon g-2 Project	46.4	22.2
Mu2e Project	271.0	50.2
Recycler RF AIP	9.7	9.7
Beam Transport AIP	6.2	6.2
Delivery Ring AIP	9.3	9.3
Cryo AIP	9.7	9.7
MC-1 Building GPP	9.0	
Beam Enclosure GPP	9.7	
MC Infrastructure GPP	1.0	1.0
Total	372.0	108.3

All costs are base cost + estimate uncertainty (contingency)

Access to documents



Two drop-down lists under "Documents"



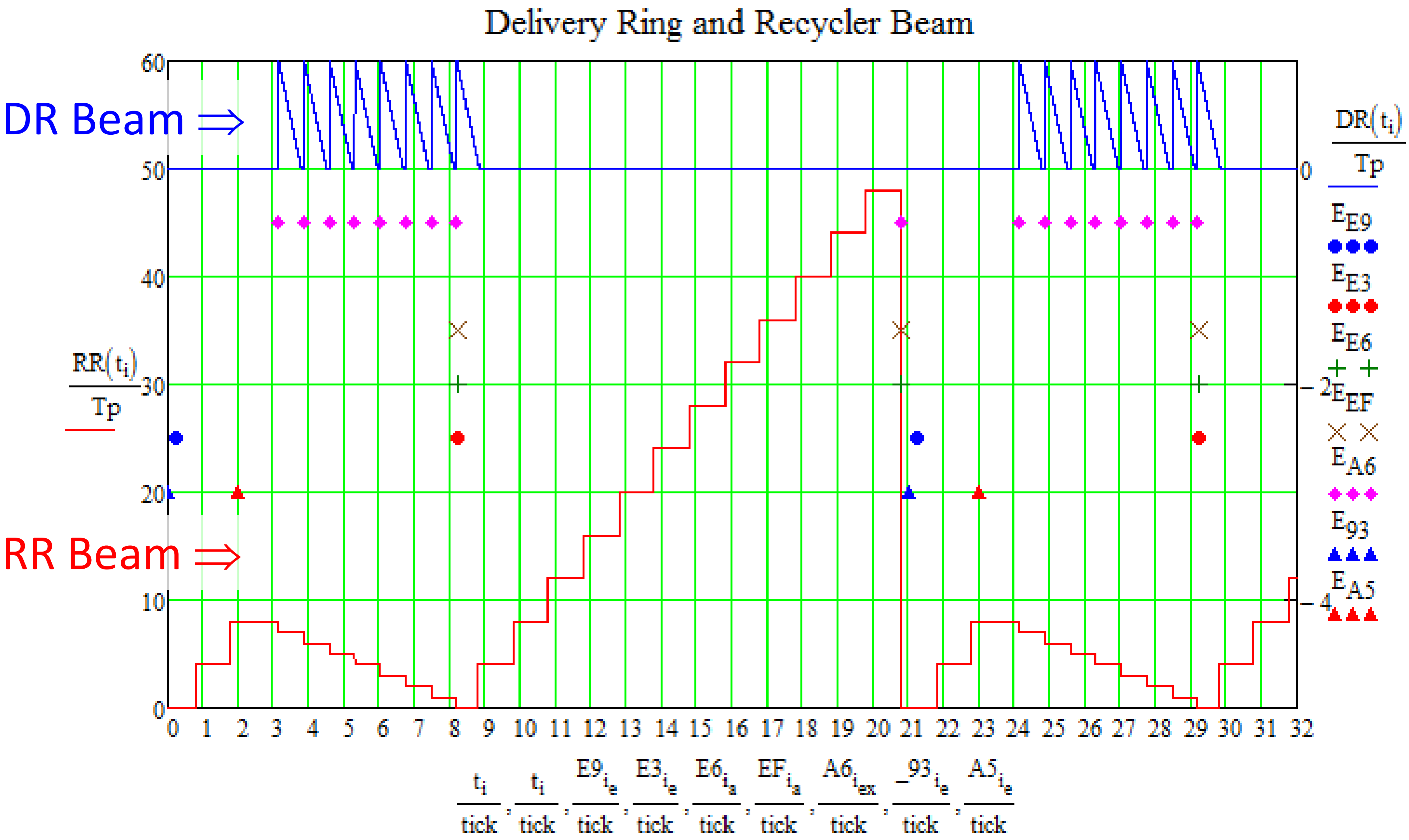
All documents referenced in Tony Leveling's talk should be available on the review Indico site

Conclusion

- Thank you for your helping us by participating in this review
- The Mu2e project is in the final stages of completing its final design
  - We expect to begin our CD-3c reviews in ~March of next year
- We would very much appreciate your advice on how we should best focus our attention in preparation for these reviews

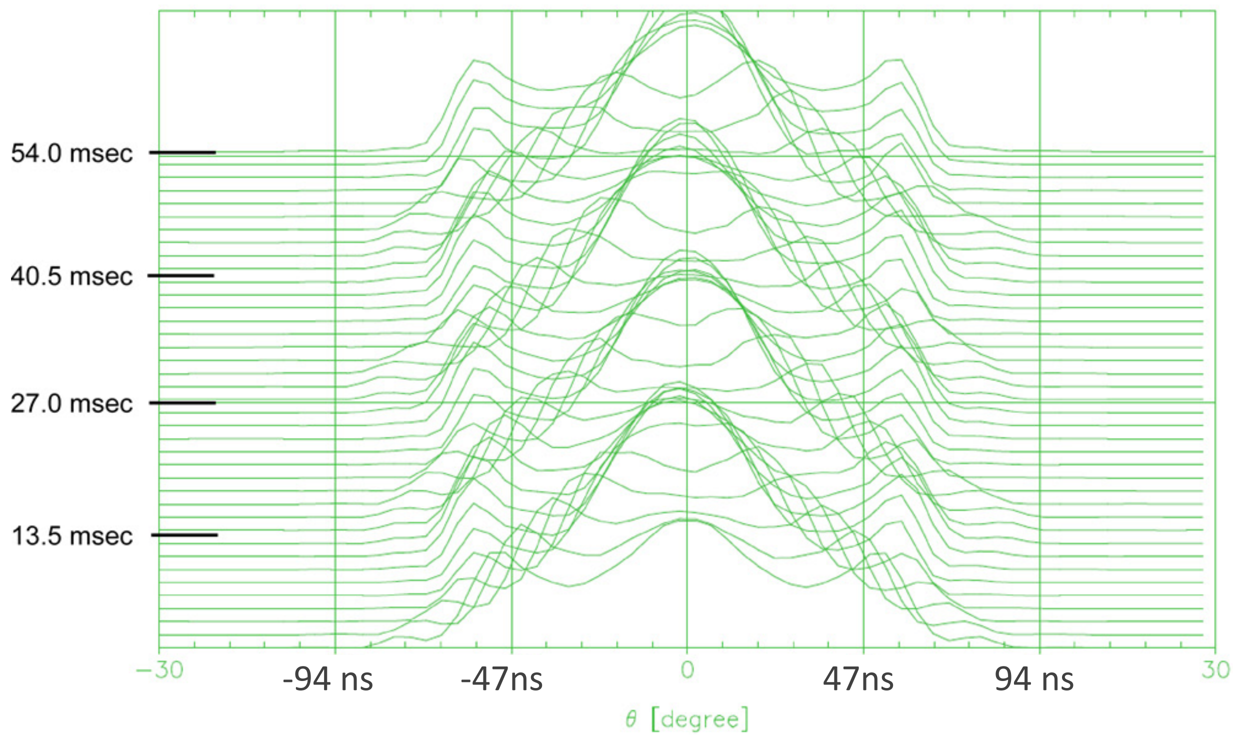
Backup Slides

Mu2e / NOvA Accelerator Timeline Model



Delivery Ring Bunch Shape Variation in Time

The re-bunched beam from the Recycler is poorly matched to the 2.4 MHz RF bucket in the Delivery Ring. Thus, the beam tumbles in the bucket. The bunch shape changes at twice the synchrotron frequency (T_{synch} = 25.6 msec).



Waterfall display of the variation of the proton bunch time profile as the bunch rotates in the 2.4 MHz RF bucket. A trace is plotted every 1.35 msec over the course of the spill. The vertical axis is time relative to the start of the spill. The horizontal axis is Delivery Ring phase (1° = 4.708 nsec).