Mu2e
(Accelerator Upgrades)

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NuFact-15, Rio De Janeiro

August 13, 2015

Goals and objectives

Mu2e proposes to measure the ratio of the rate of the neutrinoless, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus:

Mu2e TDR, arXiv:1501.05241

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

Has never been observed experimentally

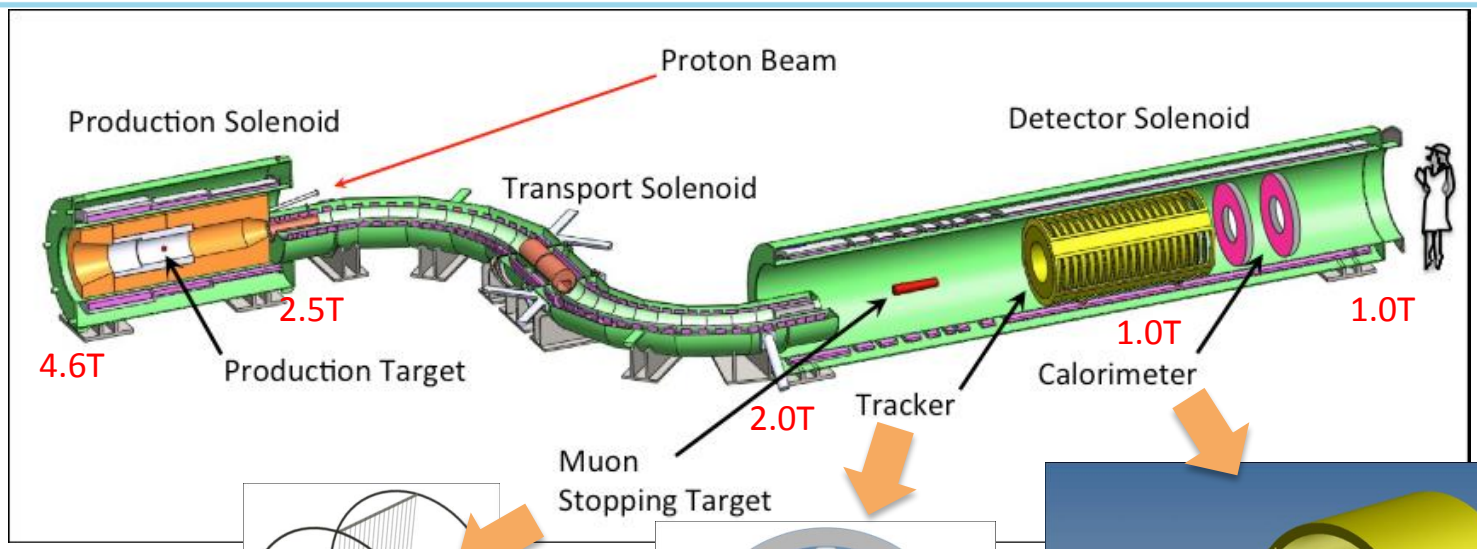
Unambiguous evidence of new physics

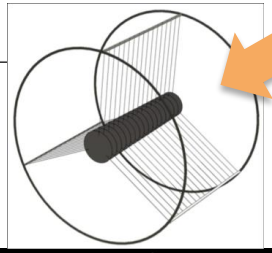
Clear event signature

Single event sensitivity

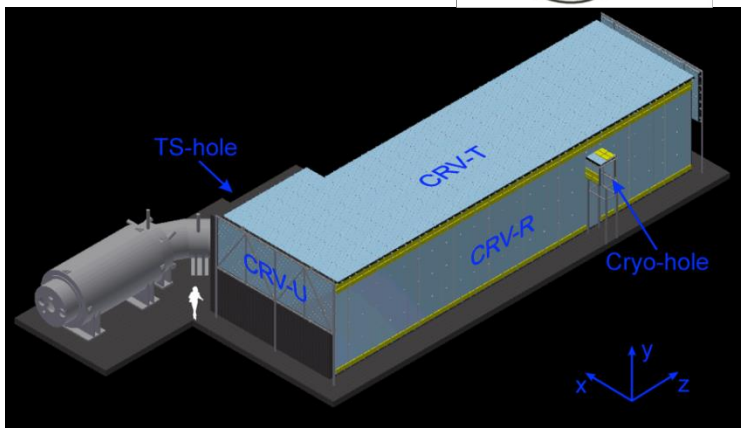
Improved sensitivity by ~4 orders of magnitude

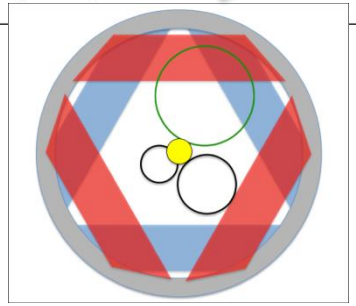
The Mu2e Experiment



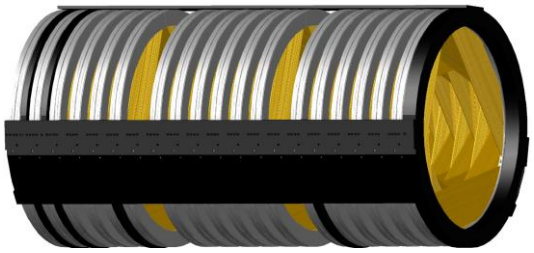


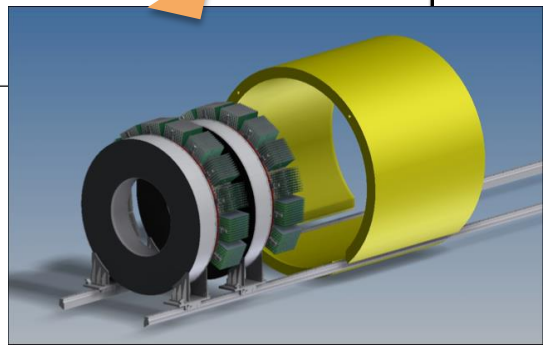
Cosmic Ray Veto





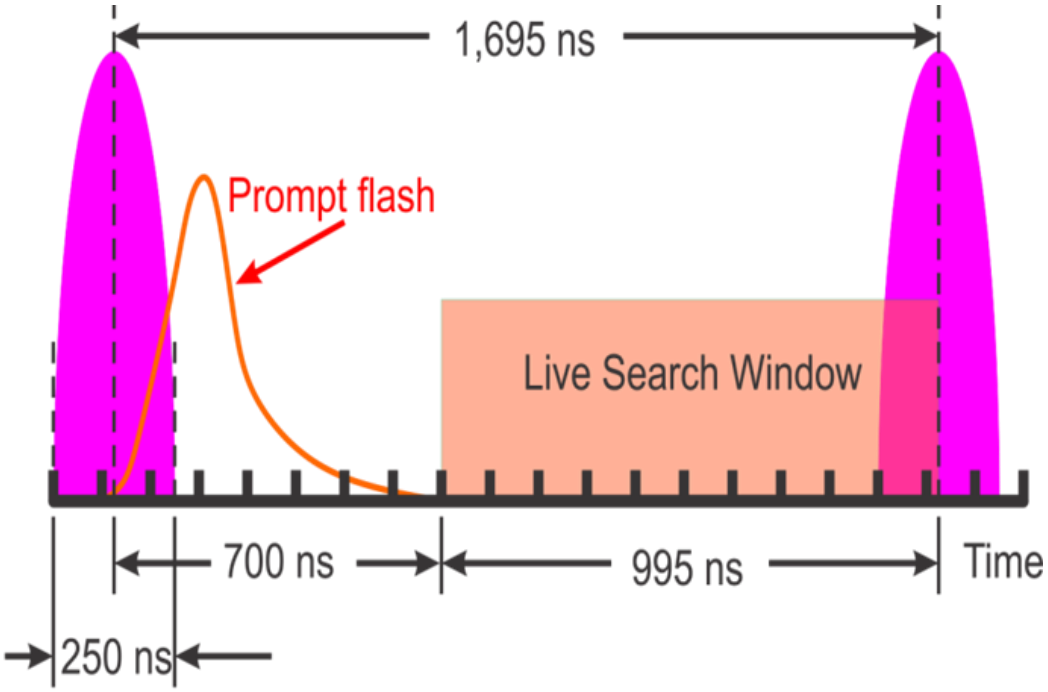
Tracker





Calorimeter

Mu2e beam timing requirements



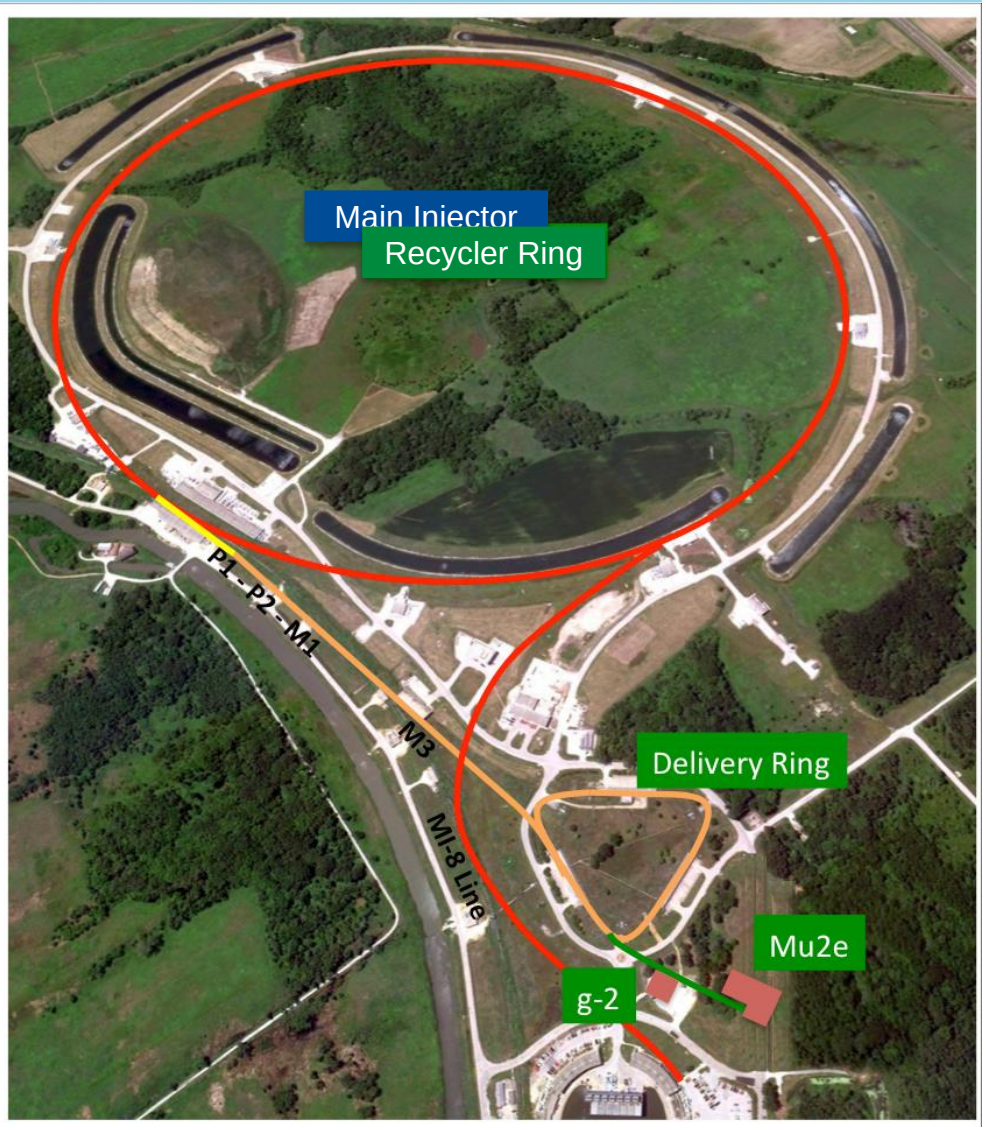
Pulsed beam
Detector dead time - 700ns
Detector Live time - 995ns
Extinction level - 10^{-10} relative to the pulse intensity

Mu2e beam requirements and parameters

Parameter	Design Value	Requirement	Unit
Booster repetition rate	15	>10.5	Hz
Main cycle time	1.333		sec
Number of spills in a cycle	8		
Total protons on target	3.6×10^{20}	3.6×10^{20}	protons
Time between beam pulses	1695	>864	nsec
Spill duration	35-54	>20	msec
Beamline Transmission Window	230	<250	nsec
Out-of-time extinction factor	10^{-10}	$\leq 10^{-10}$	
Average proton intensity per pulse	3.1×10^{7}	$< 5.0\times10^{7}$	protons/pulse
Maximum Pulse to Pulse intensity variation	50	50	%
Target rms spot size	1	$0.5 < \sigma < 1.5$	mm

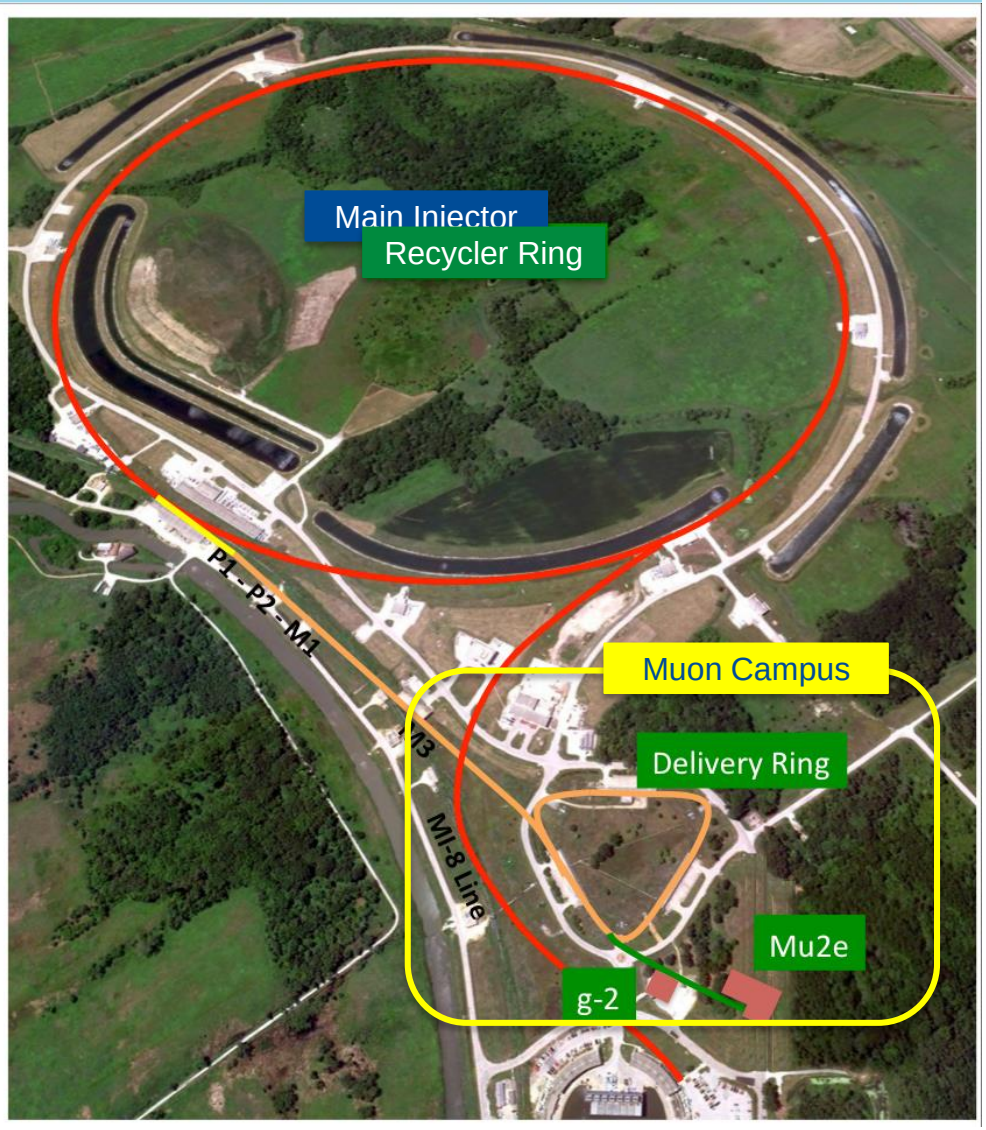
Beam delivery

- Enhancement of the FNAL Accelerator complex
- Repurposing the FNAL Anti-Proton source
- Muon Campus
- Mu2e upgrades



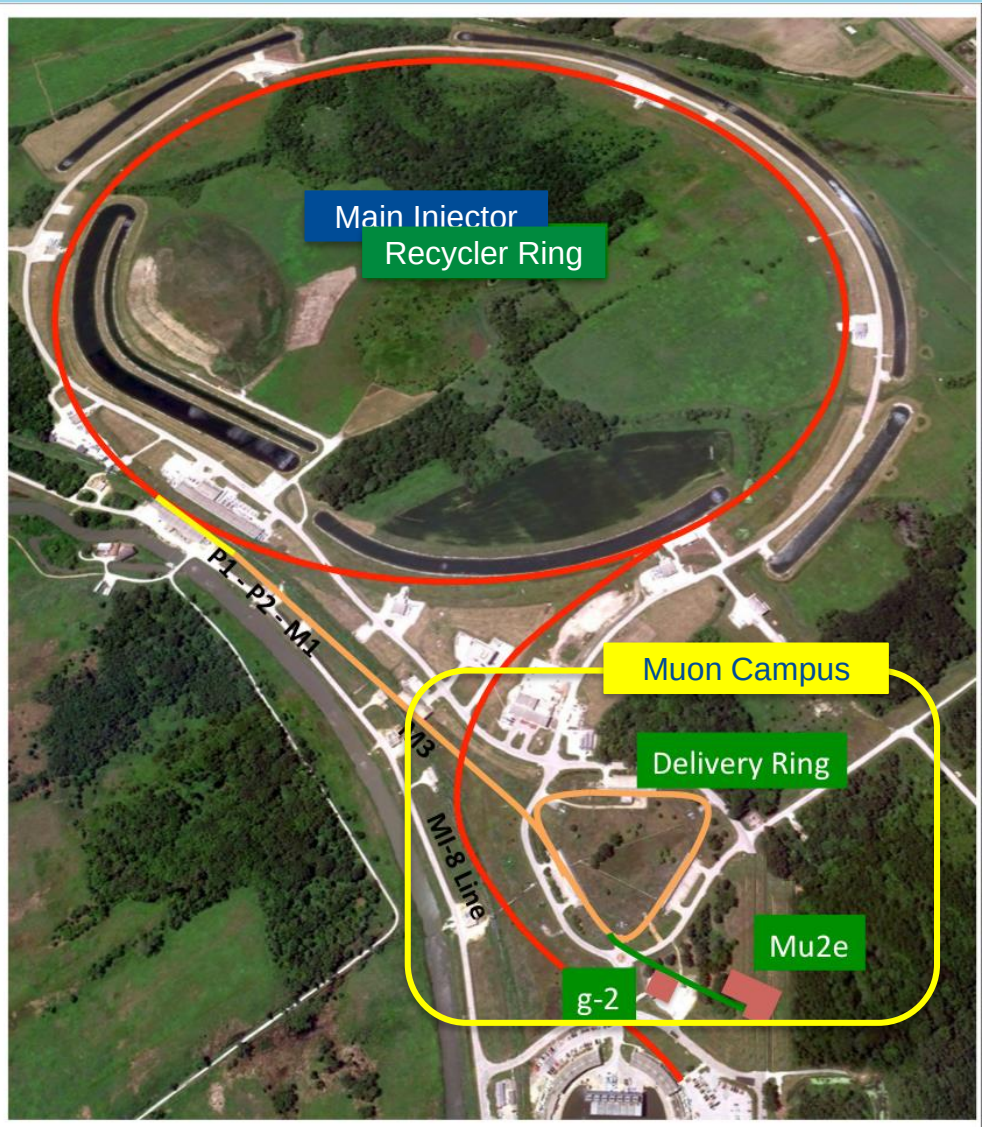
Beam delivery

- Enhancement of the FNAL Accelerator complex
- **Repurposing the FNAL Anti-Proton source**
  - Debuncher → Delivery Ring
  - Muon Campus
- Muon Campus
- Mu2e upgrades



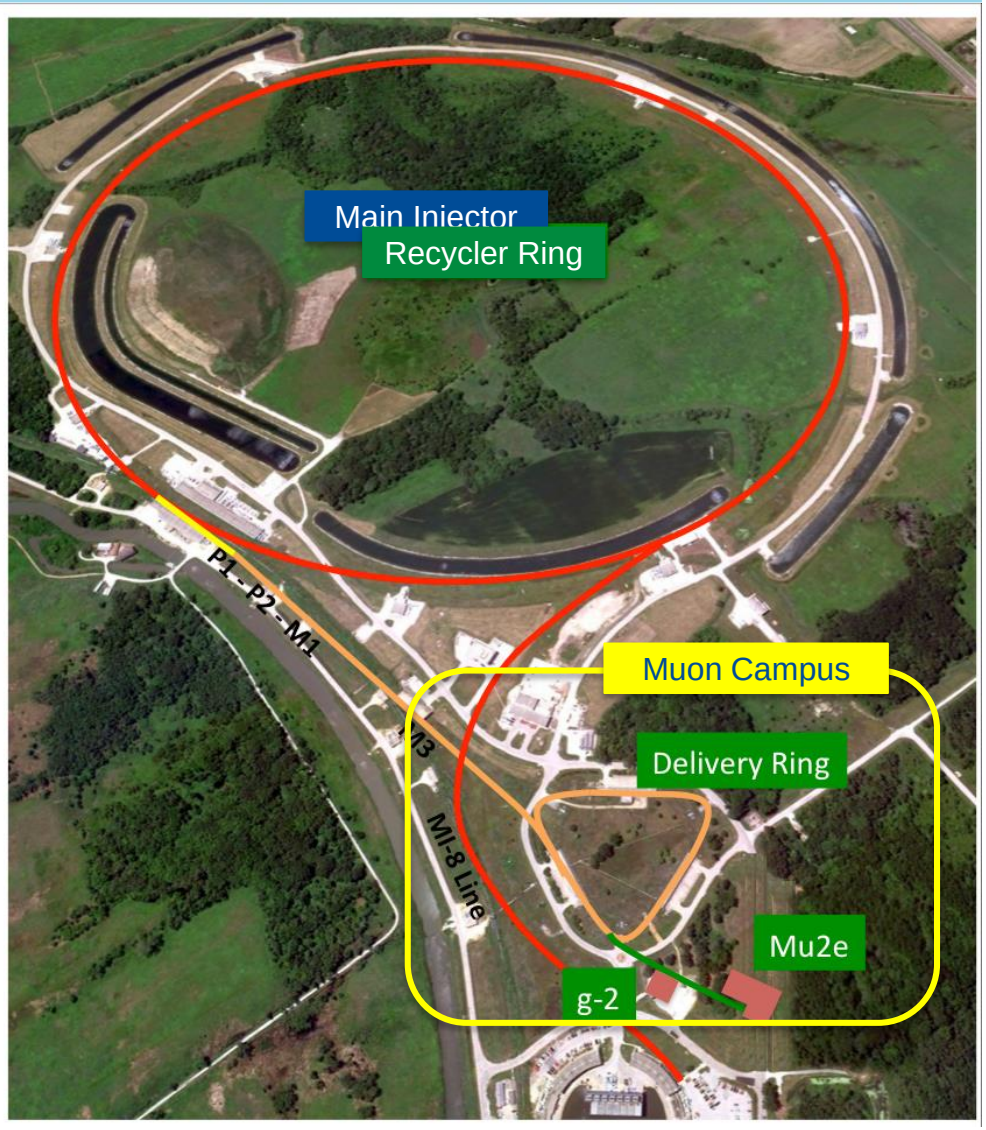
Beam delivery

- Enhancement of the FNAL Accelerator complex
- Repurposing the FNAL Anti-Proton source
- **Muon Campus:**
  - RF 2.4MHz RF upgrade
  - Transport to DR
  - Delivery Ring Upgrades
- Mu2e upgrades



Beam delivery

- Enhancement of the FNAL Accelerator complex
- Repurposing the FNAL Anti-Proton source
- Muon Campus
- **Mu2e upgrades**
  - Delivery Ring RF
  - Controls /Instrumentation
  - Resonant Extraction
  - External Beam line
  - Extinction System
  - Extinction Monitoring
  - Radiation Protection
  - Target Station

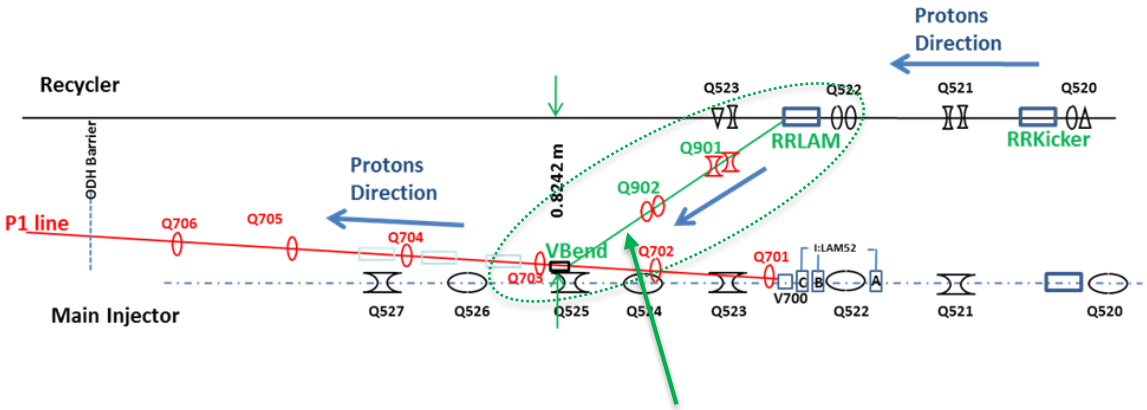


RF systems

- Muon Campus:
  - Recycler needs a new 2.4MHz RF system to rebunch the 53MHz beam batch structure into 4 bunches before sending them to the MC.
  - Using existing cavity design, modified for CW operation (1kW losses)

- Mu2e
  - Needs 2.4 MHz RF system in the Delivery Ring to maintain the bunch structure. Same cavities, coming early.

Beam Transport from RR (external)



A new beam line to route beam from Recycler to Delivery Ring
Being implemented as we speak!

Transport Recycler→ Delivery Ring is a complex beam line with several elements that have multiple functions: P1→P2→M1→M3→DR
The DS part of the M3 line is being redesigned and rebuilt for the g-2.
Upstream transport needs to be redesigned to match this new insertion.

Delivery Ring Upgrades

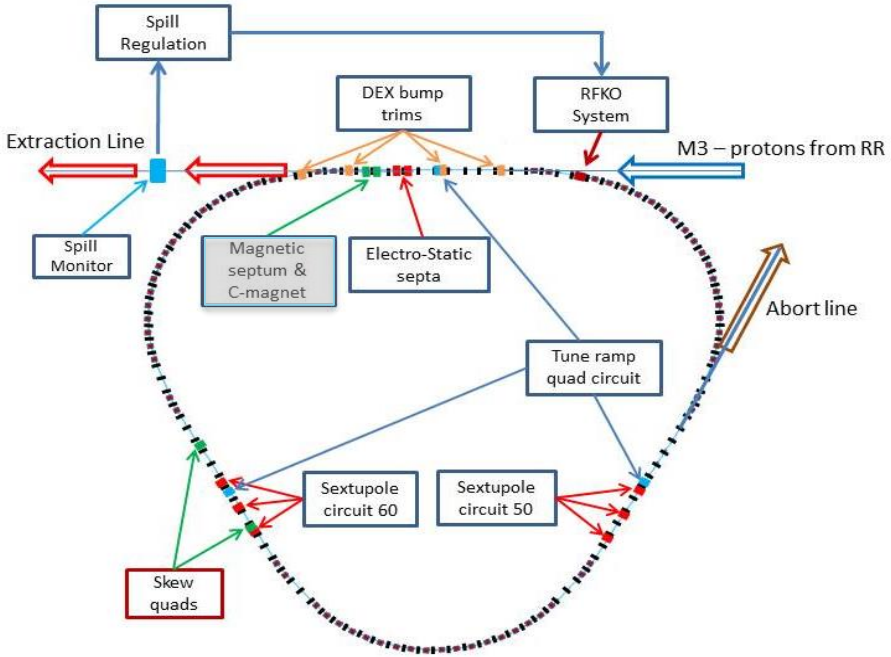
- Accumulator equipment removal
- Removing old equipment in the Delivery Ring:
  - Stochastic cooling
  - RF hardware
- New Injection/Extraction/Abort
- New power infrastructure
- Cable trays cleaning and re-routing
- Controls/Instrumentation upgrades

AP30 straight in Collider run

AP30 straight now

Resonant Extraction

Extr. efficiency	**98%**
Spill uniformity	**50%**
Resonance order	3
Operation point	9.65/9.73
Max. intensity	1e12 p
Spill duration	35-54ms
Duty factor	32%



Essential:

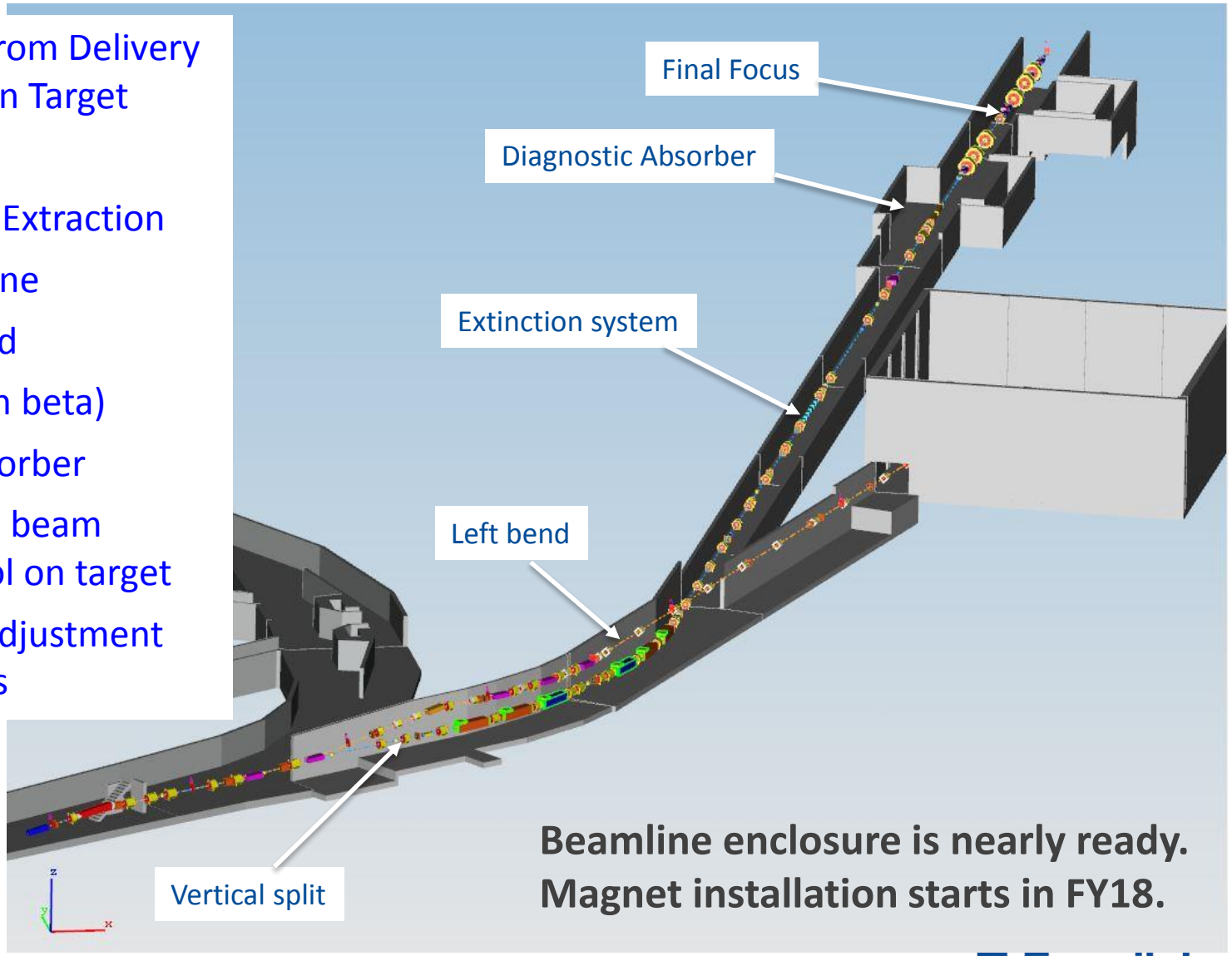
- Dynamic orbit control at the ESS
- RFKO in spill regulation loop

Will require long commissioning time
Technical design nearly complete
Production funding starts in FY17

External Beamline (M4)

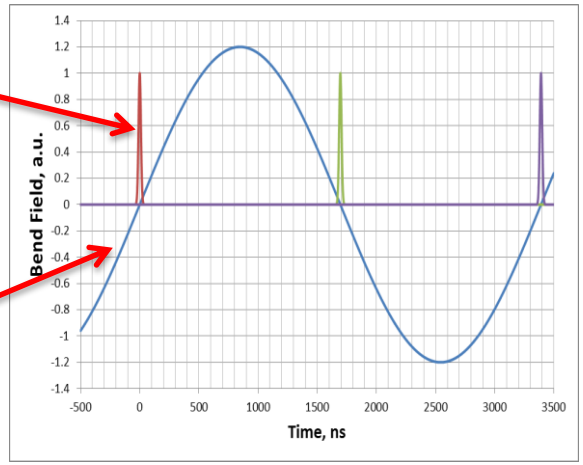
Transport beam from Delivery Ring to Proton Target

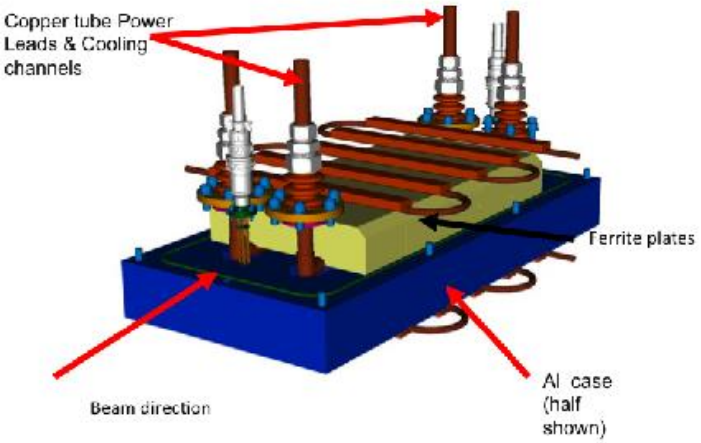
- Matching with Extraction
- Split with g-2 line
- Horizontal bend
- Extinction (high beta)
- Diagnostic Absorber
- Final focus and beam position control on target
- Provide orbit adjustment for target scans

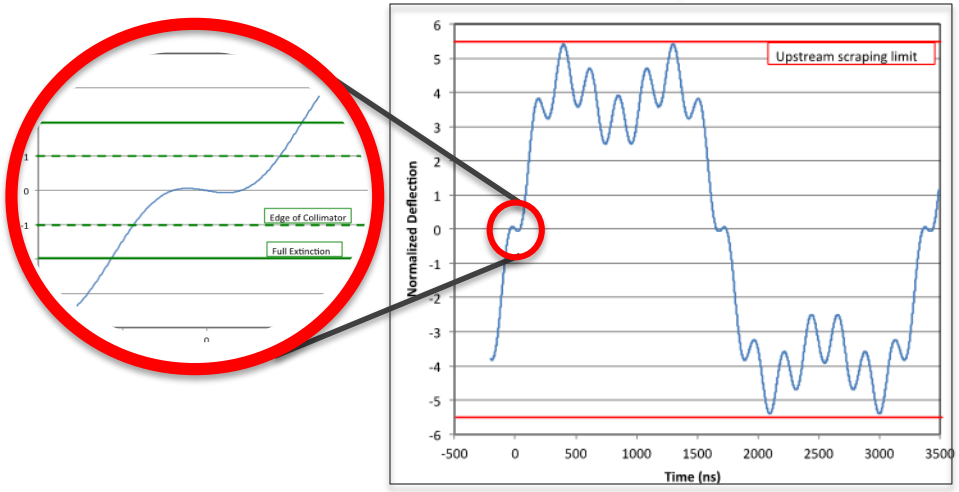


Extinction system

- 10^{-10} suppression of out-of-time beam
- Assume 10^{-3} - 10^{-5} already present
- Achieved by deflecting out-of-time beam in the AC-magnet (10^{-7})
- High beta at AC-magnet
- Collimation US and DS of AC-magnet
- 3 harmonics of AC excitation



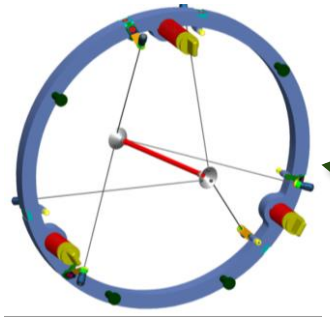




Target station

- Target
- Heat & Radiation Shield (HRS)
- Proton Absorber
- Protection Collimator
- Target Remote Handling

The most complex part of the Accelerator Upgrades



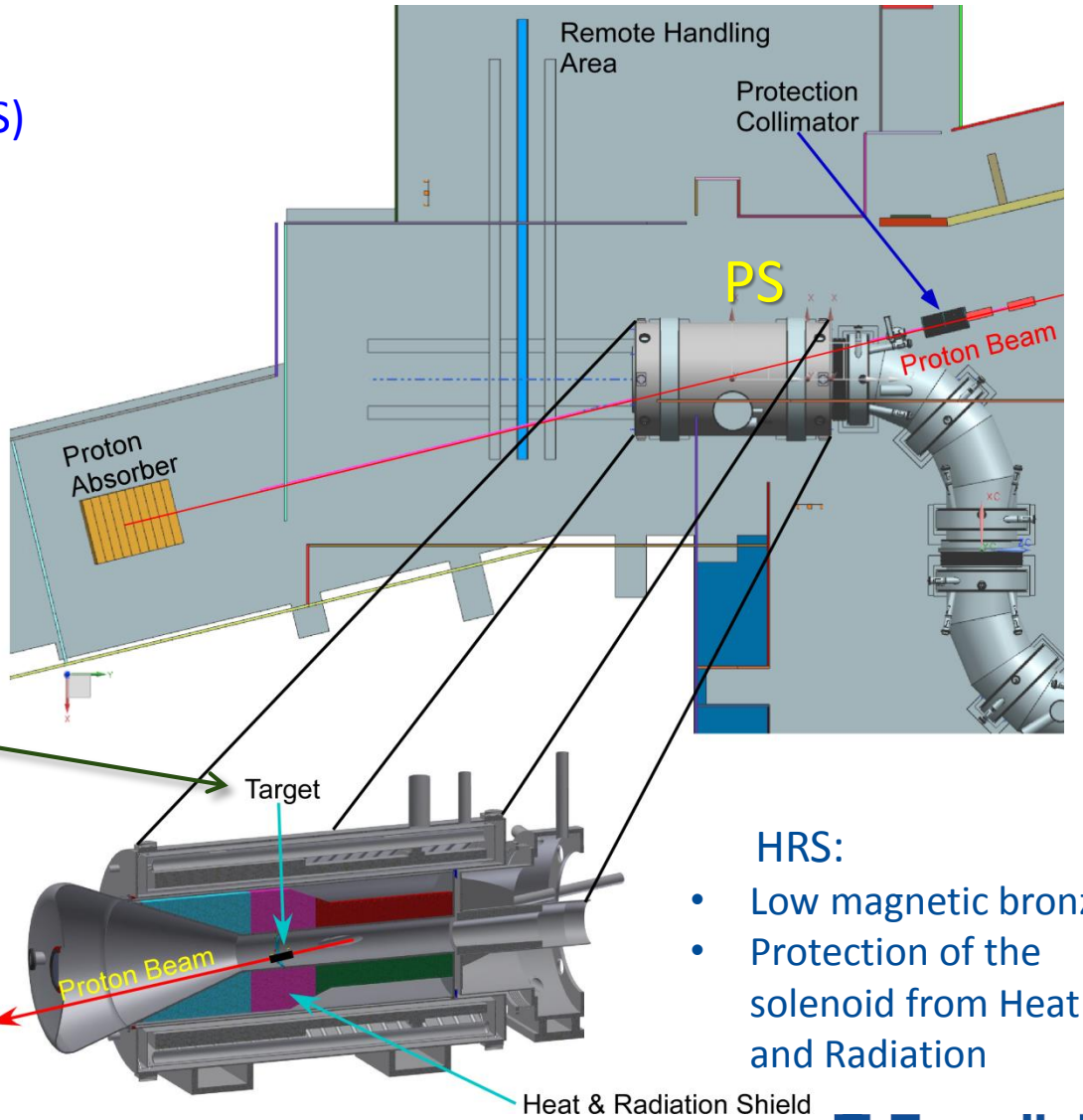
Target:

D=6mm, L=16cm Tungsten

"Bicycle wheel" suspension

0.6 kW heat load

Radiation cooled - 1700° C



HRS:

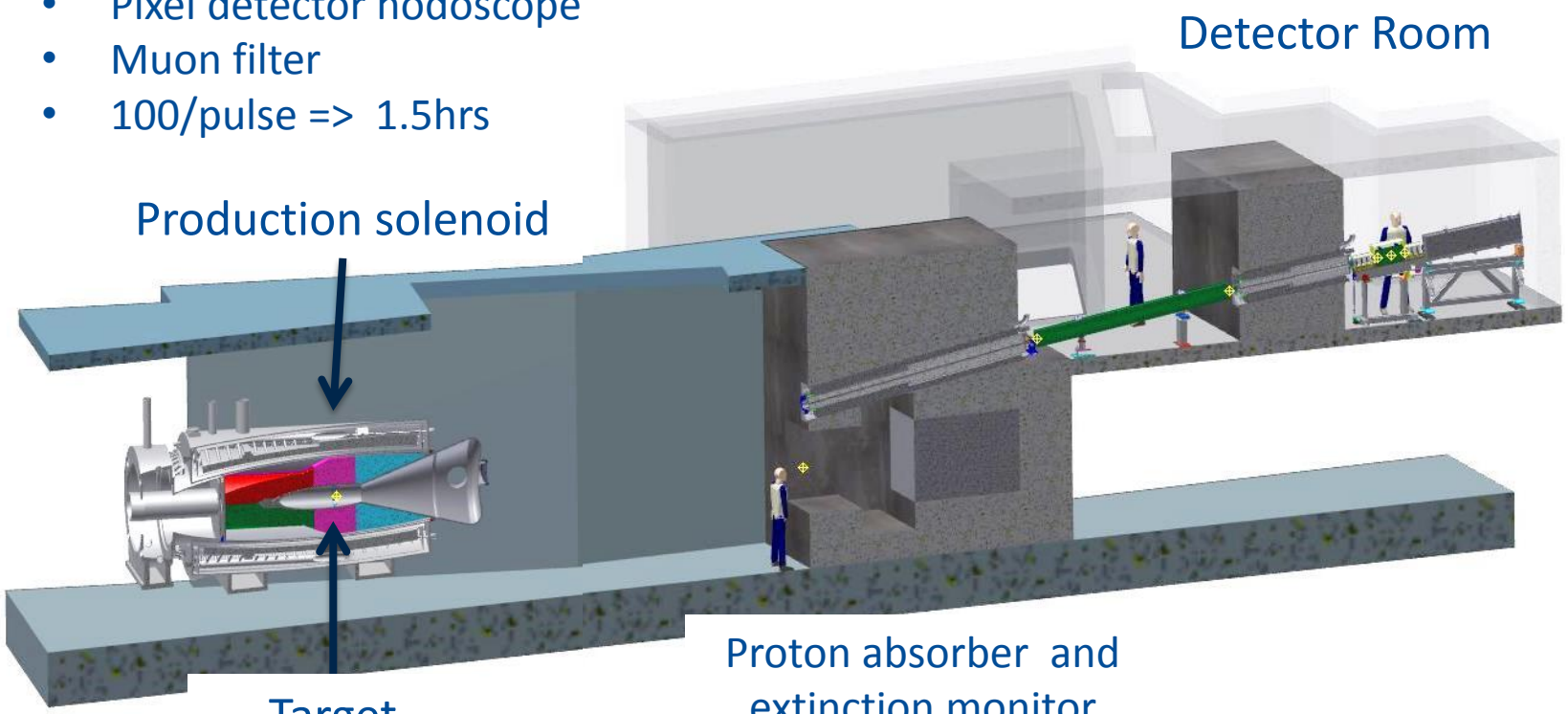
- Low magnetic bronze
- Protection of the solenoid from Heat and Radiation

Fermilab

Extinction Monitoring

Sampling secondaries:

- Secondaries from the Target
- 4.5 GeV/c momentum
- Permanent magnet
- Pixel detector hodoscope
- Muon filter
- 100/pulse => 1.5hrs



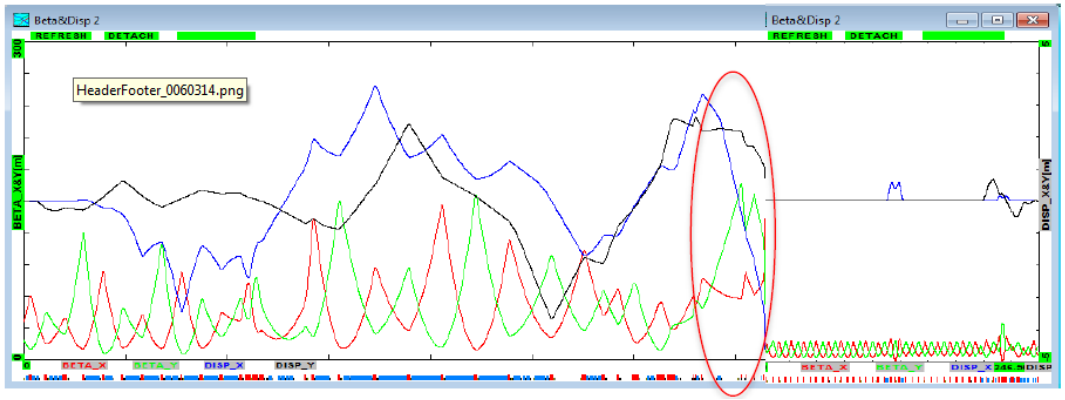
Civil Construction

Conclusions

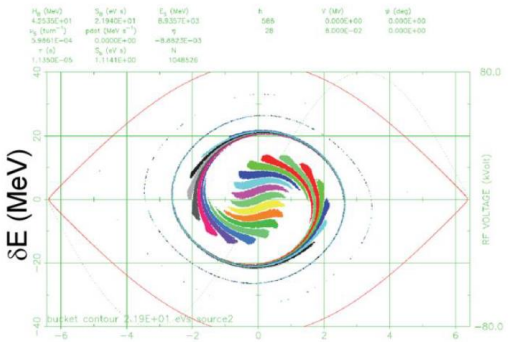
- Mu2e project is finishing technical design and is on track for general production authorization milestone.
- Civil Construction for Mu2e is in a good progress
- Accelerator Upgrades for Mu2e is a complex campaign building new facilities and utilizing many external upgrades of the Fermilab existing machines/beamlines.
- Mu2e Accelerator Upgrades subproject is well on track to start construction and will be ready to start beam commissioning in FY2020.

Extra Slides

Miscellaneous

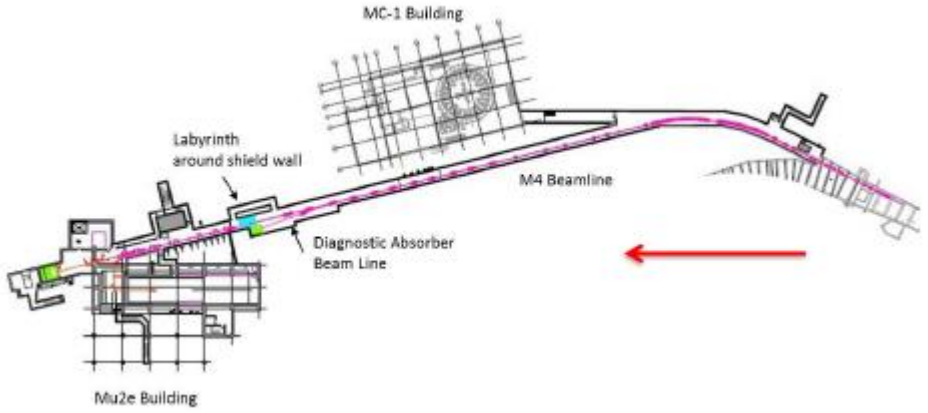


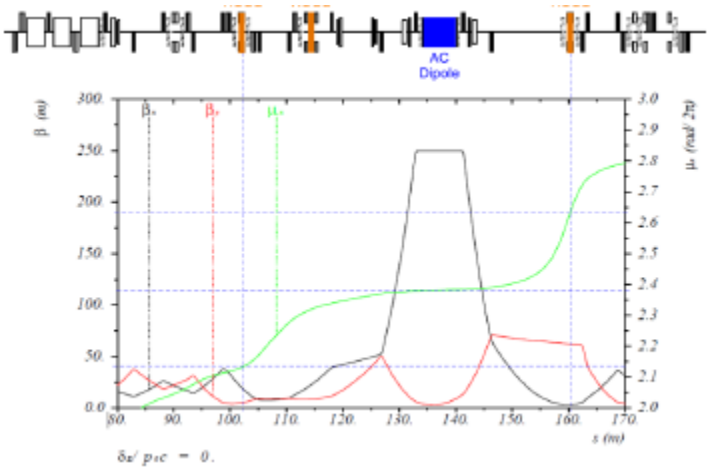
Transport line upgrades

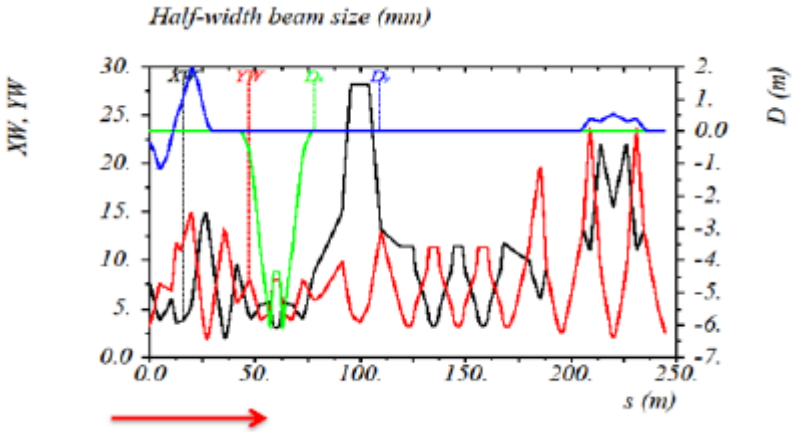


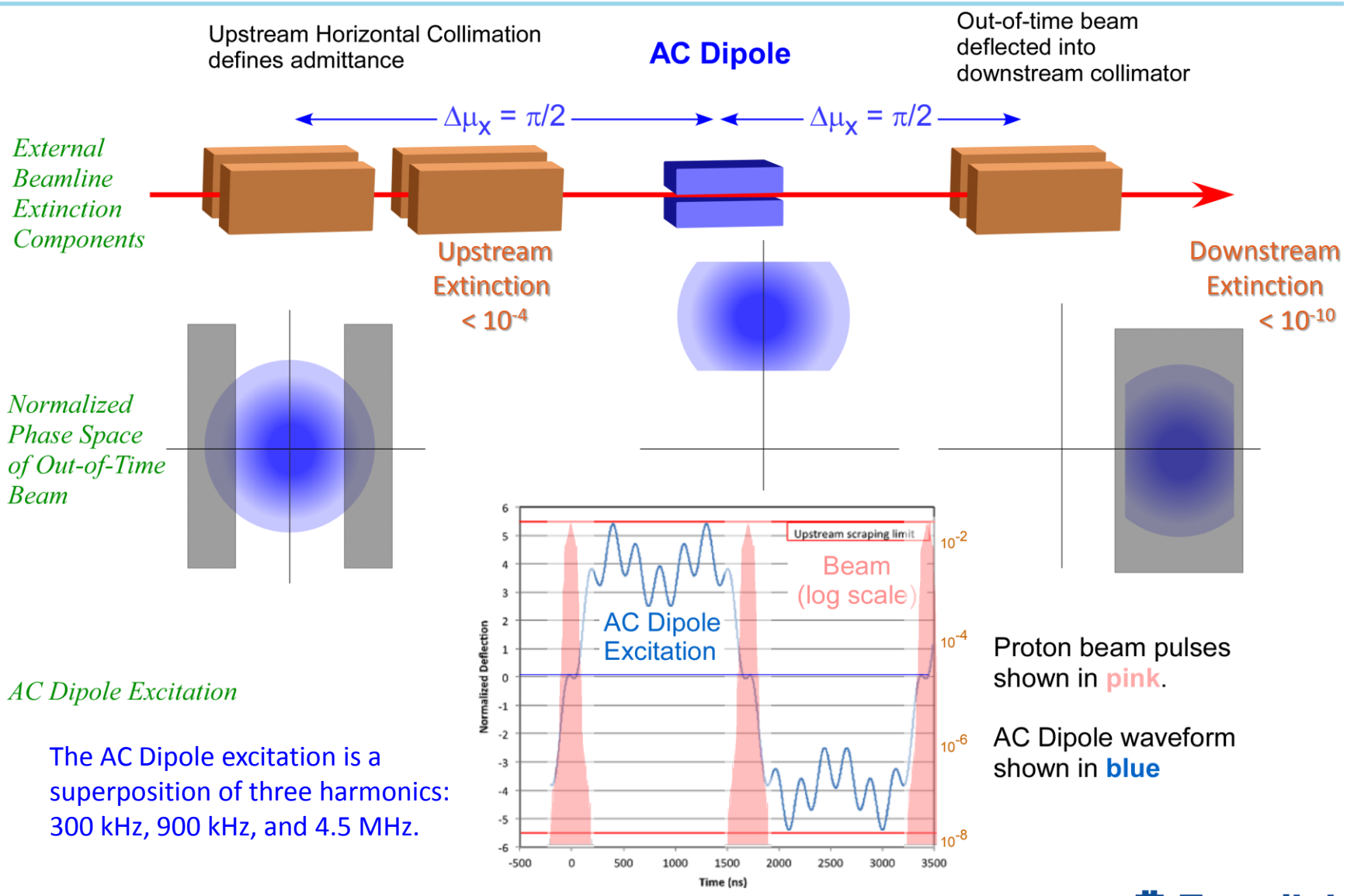
Bunch rotation in the RR

External beam line optics

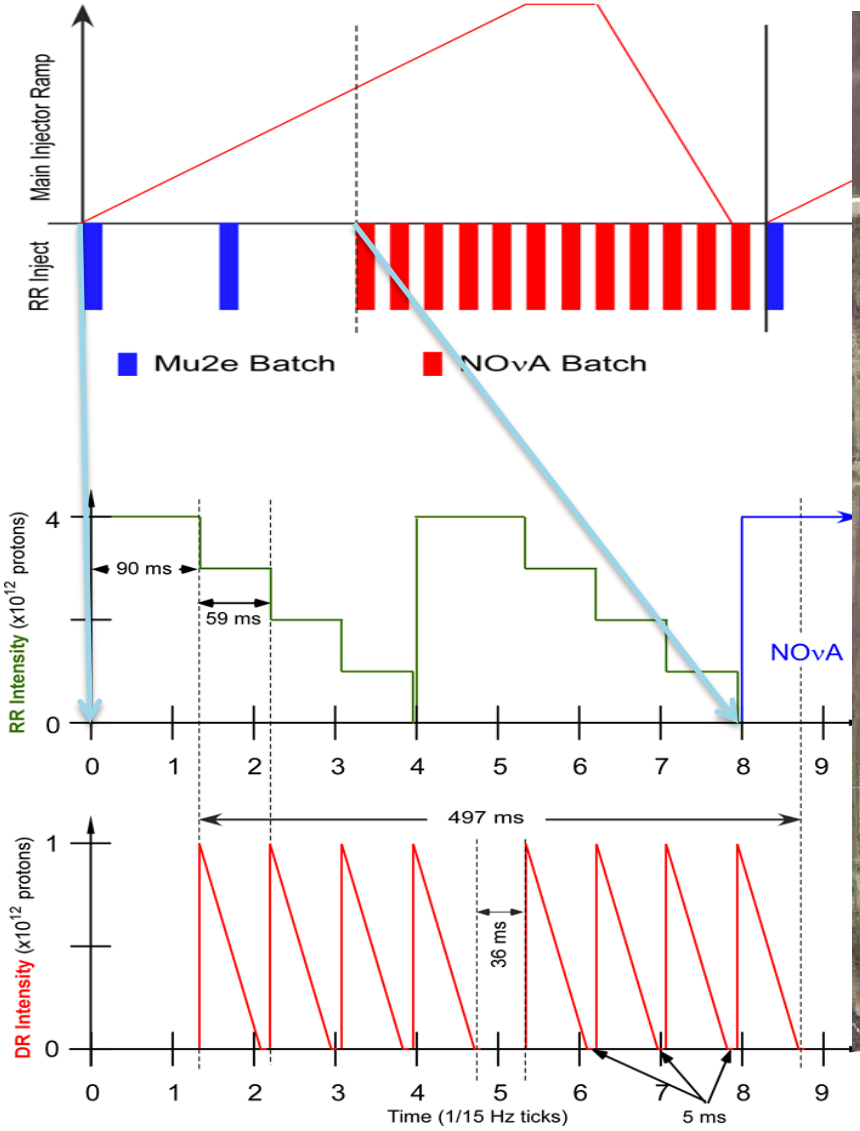


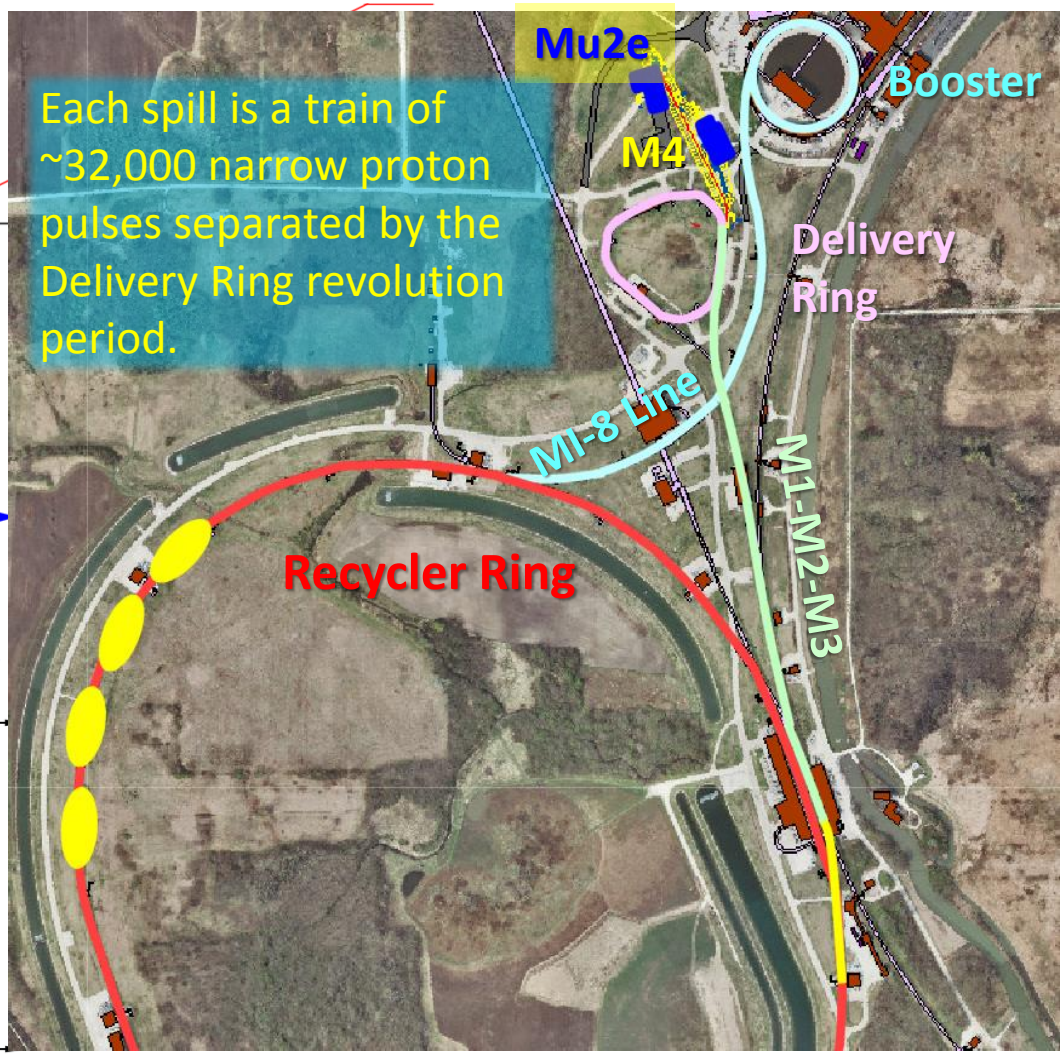





Upstream Horizontal Collimation defines admittance
AC Dipole
Out-of-time beam deflected into downstream collimator
$\Delta\mu_x = \pi/2$
$\Delta\mu_x = \pi/2$
External Beamline Extinction Components
Upstream Extinction < 10^{-4}
Downstream Extinction < 10^{-10}
Normalized Phase Space of Out-of-Time Beam
Upstream scraping limit
Beam (log scale)
AC Dipole Excitation
Normalized Deflection
Time (ns)
AC Dipole Excitation
Proton beam pulses shown in pink.
AC Dipole waveform shown in blue
The AC Dipole excitation is a superposition of three harmonics: 300 kHz, 900 kHz, and 4.5 MHz.

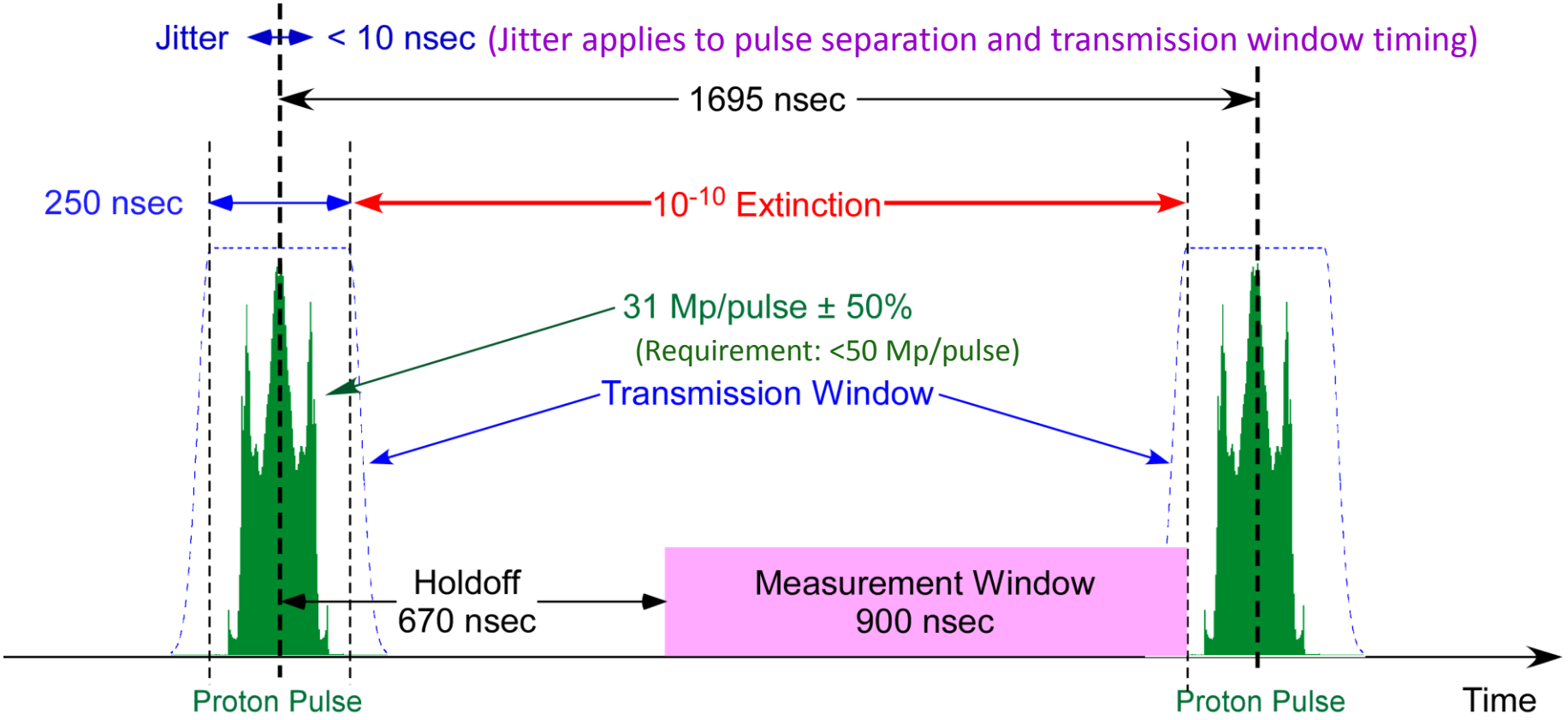
Collider cycle diagram





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

Fermilab


Jitter
< 10 nsec (Jitter applies to pulse separation and transmission window timing)
1695 nsec
250 nsec
10-10 Extinction
31 Mp/pulse ± 50%
(Requirement: <50 Mp/pulse)
Transmission Window
Holdoff
670 nsec
Measurement Window
900 nsec
Proton Pulse
Proton Pulse
Time