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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

The Fermilab Muon Campus: Present Operation and Future Plans

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J-PARC Seminar

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In partnership with:

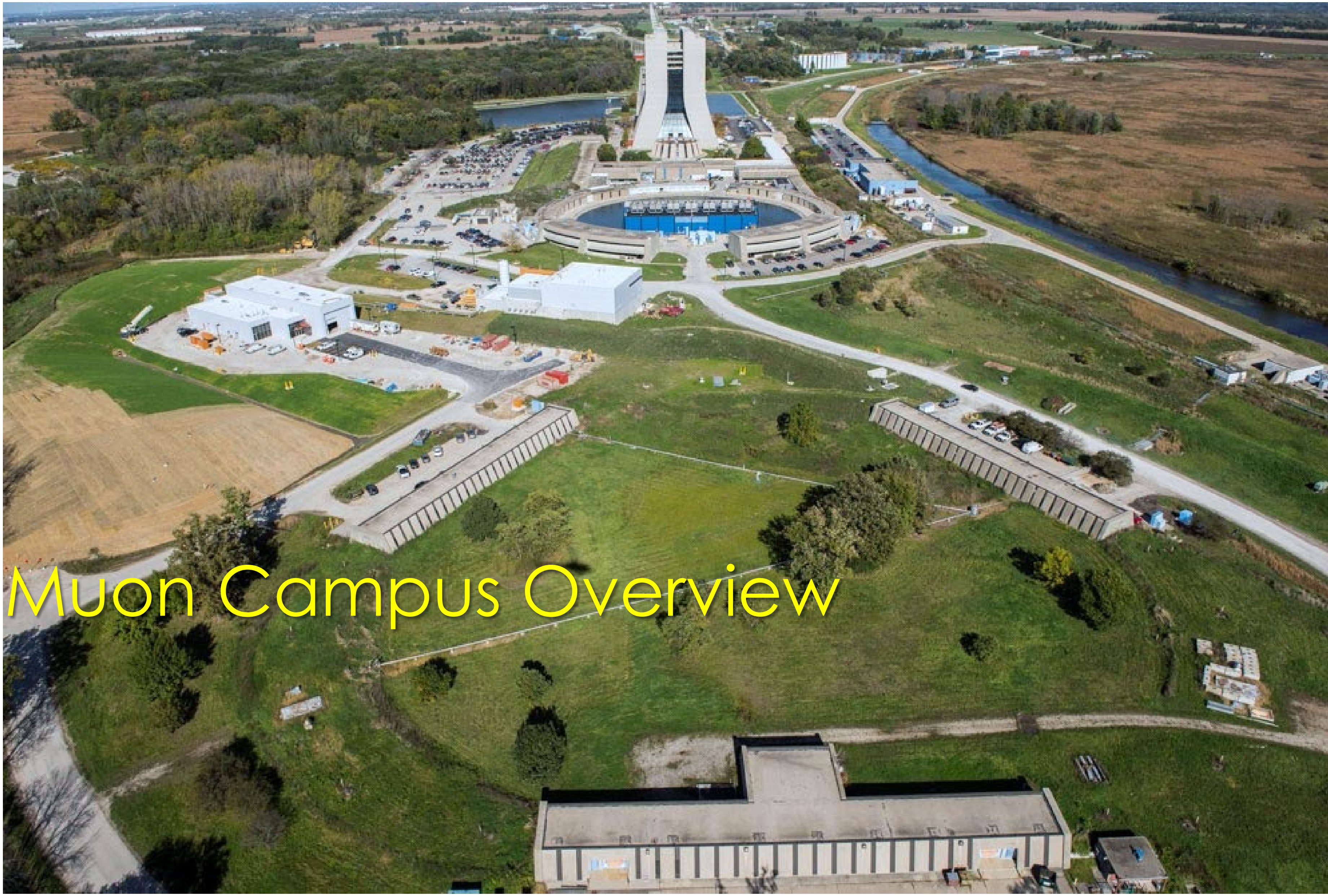
μ g-2

Mu2e μ e

Outline

- Overview of Muon Campus – Bird's Eye View (Literally)
- Muon g-2:
  - the physics & experimental technique
  - the beam
  - data taking status
  - future plans
- Mu2e:
  - the physics & experimental technique
  - the beam
  - construction status
  - future plans
- Conclusion

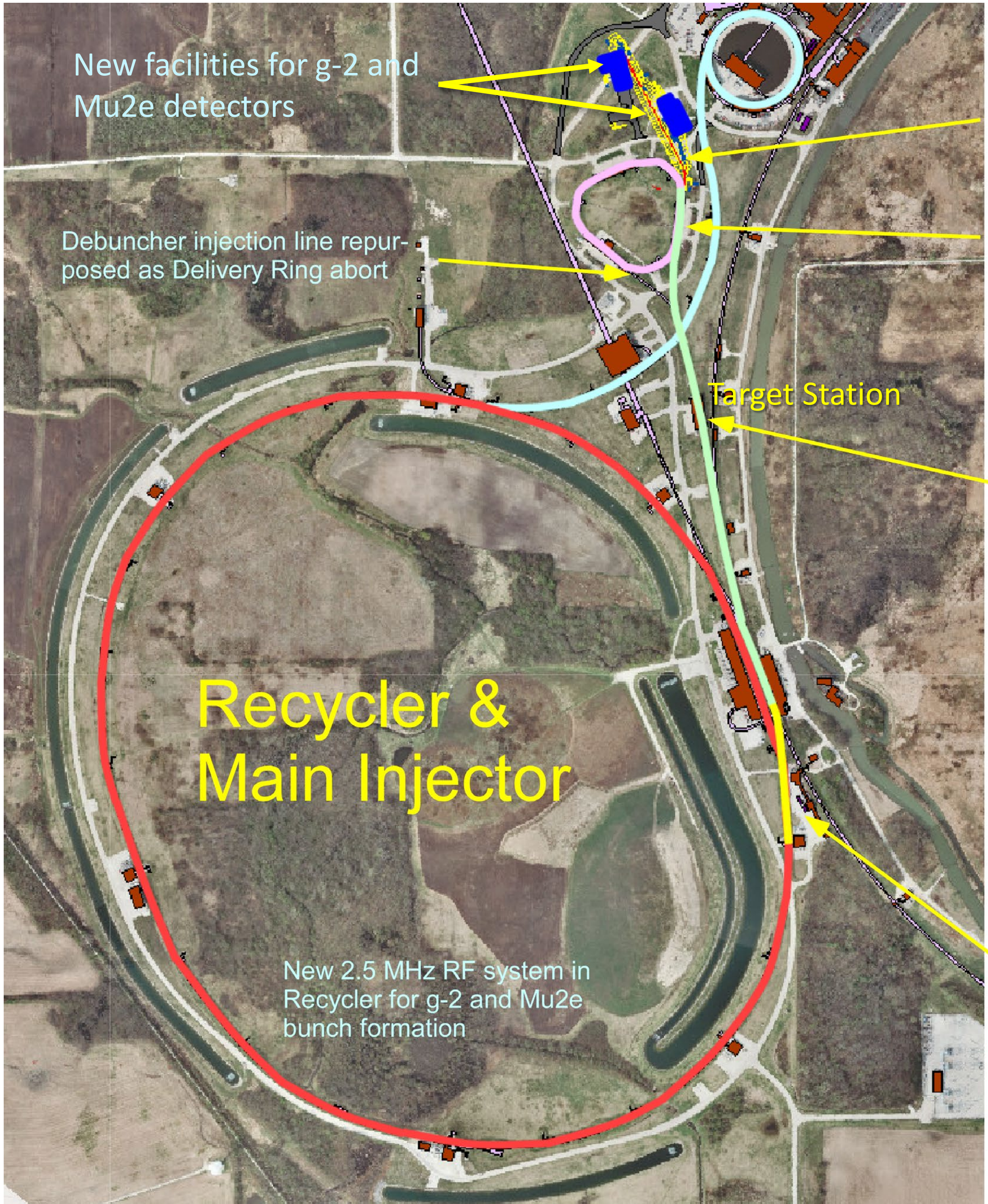
Muon Campus Overview



Pre-Muon Campus

- Before the Muon Campus there was the Fermilab Antiproton Source.
- The triangular shaped beam enclosure of the $\bar{p}$ source contained the antiproton Debuncher and Accumulator rings.
- At peak performance, the Antiproton Source produced 2.5×10^{11} antiprotons/hour for the Fermilab collider program.
- Collider program ended in September 2011.
- In 2011, the future site of g-2 and Mu2e was a parking lot.

Antiproton Source → Muon Campus



New M4 and M5 beamlines for beam transport to Mu2e and g-2

Antiproton Accumulator Ring removed

Antiproton Debuncher repurposed as Delivery Ring

120 GeV protons on target for antiproton production

Replaced by

8 GeV protons on target for muon production for g-2

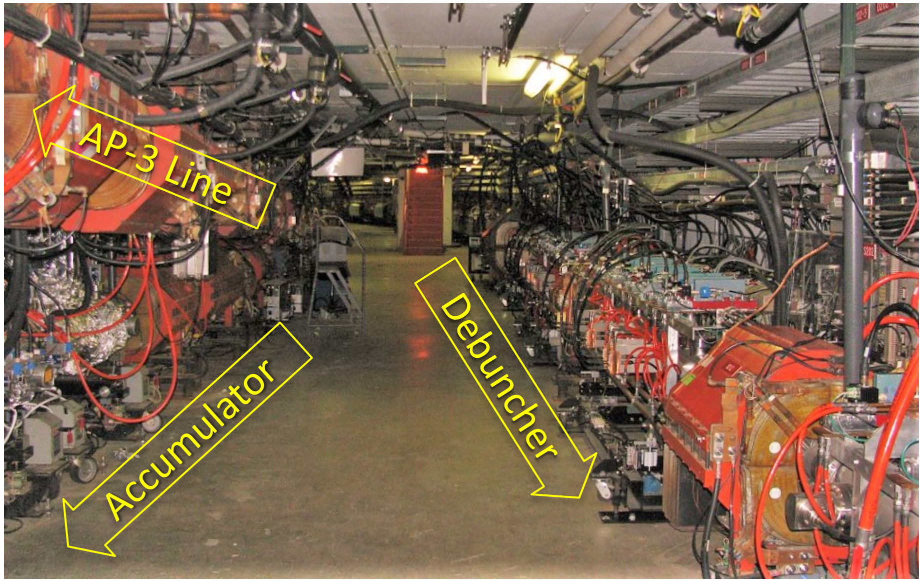
8 GeV transport for Mu2e bypasses target

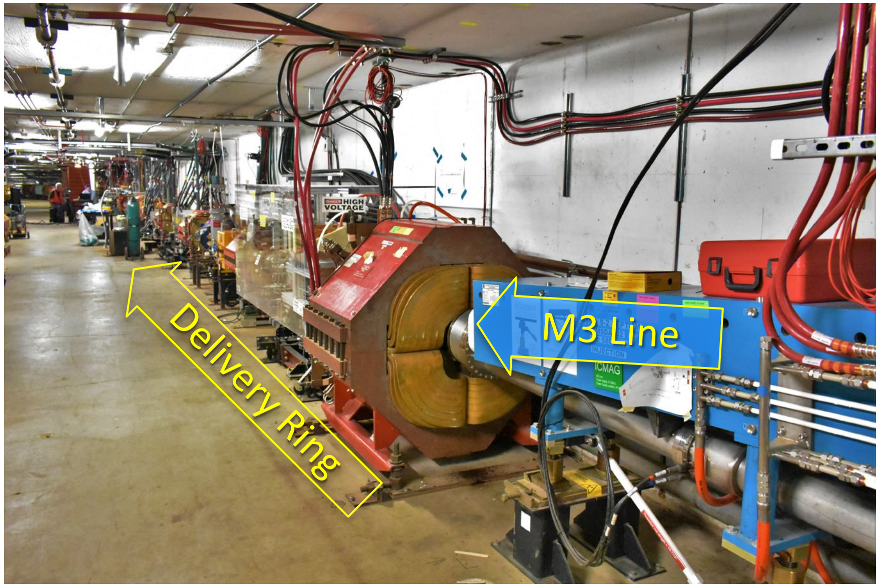
120 GeV extraction from Main Injector for antiproton stacking

Replaced by

8 GeV extraction from Recycler for Muon Campus

Demolition & Reconstruction – D30 Straight Section



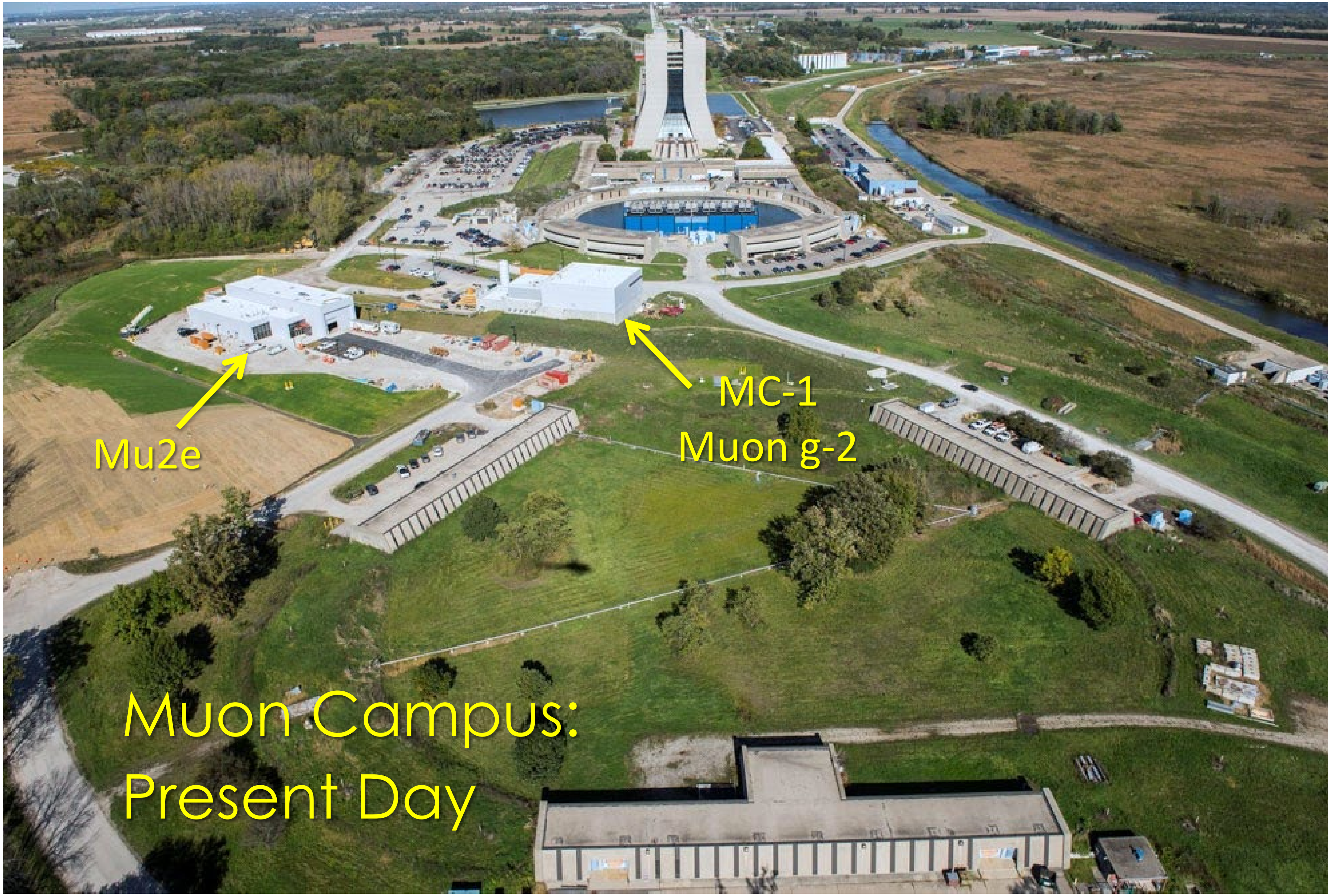


Antiproton Source

Muon Campus

- Accumulator Removed
- Debuncher repurposed
- AP-3 rebuilt/renamed to M3
- Polarity reversed

All upgrades required for g-2 running completed Spring 2018


MC-1
Muon g-2
Mu2e
Muon Campus:
Present Day

The Muon g−2 Experiment

Muon g–2

- The Muon g–2 experiment measures the "anomalous" magnetic moment of the muon, usually written a_μ
- a_μ is defined as: $$a_\mu = \frac{g_\mu - 2}{2}$$
- g_μ (the g in g–2) is the gyromagnetic ratio of the muon in

$$\boldsymbol{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\mathbf{S}$$

a_μ is not very interesting in and of itself. The value of this measurement derives from the fact that a_μ can be measured to high precision *and* calculated from Standard Model processes with high precision.

Thus, a precision measurement of a_μ is a potential probe into physics beyond the Standard Model.

A Hint of New Physics

The difference between the calculated value of a_μ from the standard model (a_{SM}) and the measured value (a_{Expt}) suggests the possibility of new physics.

- $a_{SM} = 116\ 59\boxed{1\ 823}(43)\times 10^{-11}$
- $a_{Expt} = 116\ 59\boxed{2\ 089}(63)\times 10^{-11}$

This is a statistically interesting difference.

$$a_{Expt} - a_{SM} = 266(76)\times 10^{-11} \rightarrow 3.5\sigma$$

What must be added to the Standard Model to make $a_{SM} = a_{Expt}$?

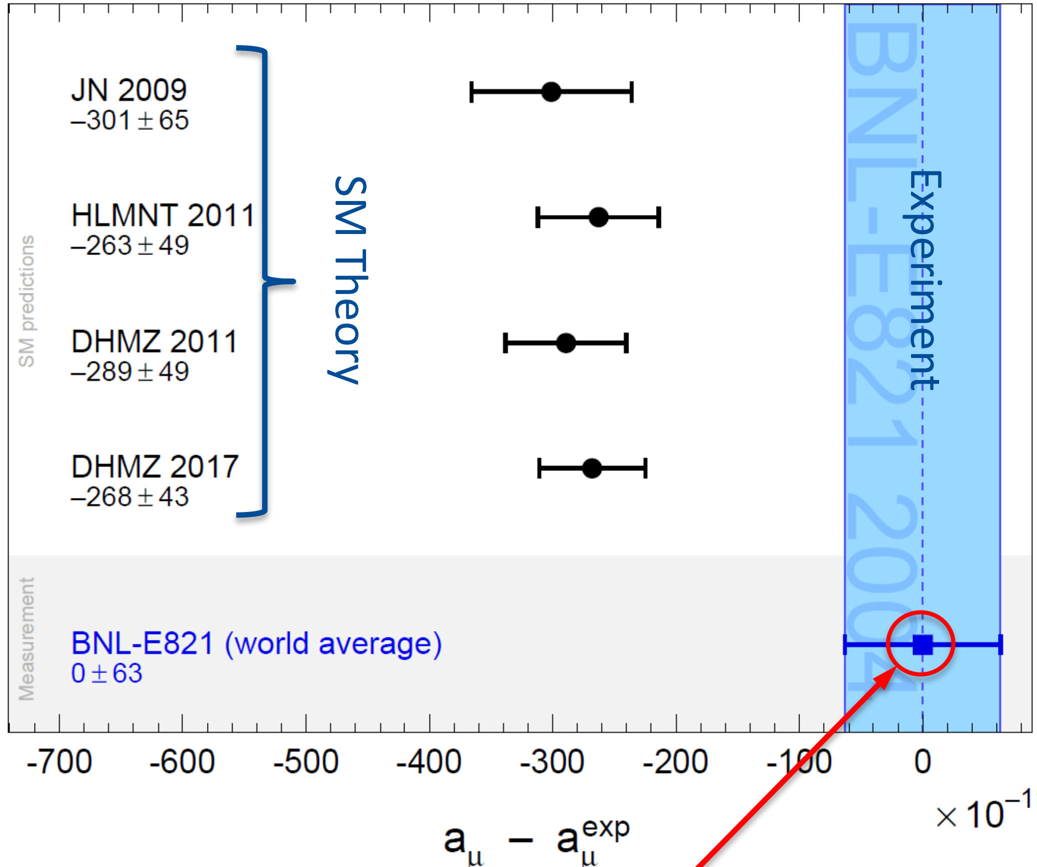
Theory vs Experiment

$$\Delta a_\mu = a_\mu^{Expt} - a_\mu^{SM} = 266(76)\times 10^{-11}$$

- Presently there is a 3.5σ difference between theory and experiment.
- *If* the central value of a_μ^{Meas} does not appreciably change, the Fermilab Muon g−2 Experiment will enhance this difference to 6σ (does not include possible reduction of the theoretical uncertainty).
- The goal of the Muon g-2 Experiment is to reduce the experimental uncertainty in Δa_μ from 63×10^{-11} to 16×10^{-11}.

A. Hoecker and W.J. Marciano (Particle Data Group) Phys. Rev. D 98, 030001 (2018) with 2019 update, sec. 57.

Comparison of theoretical calculations of a_μ with measurement



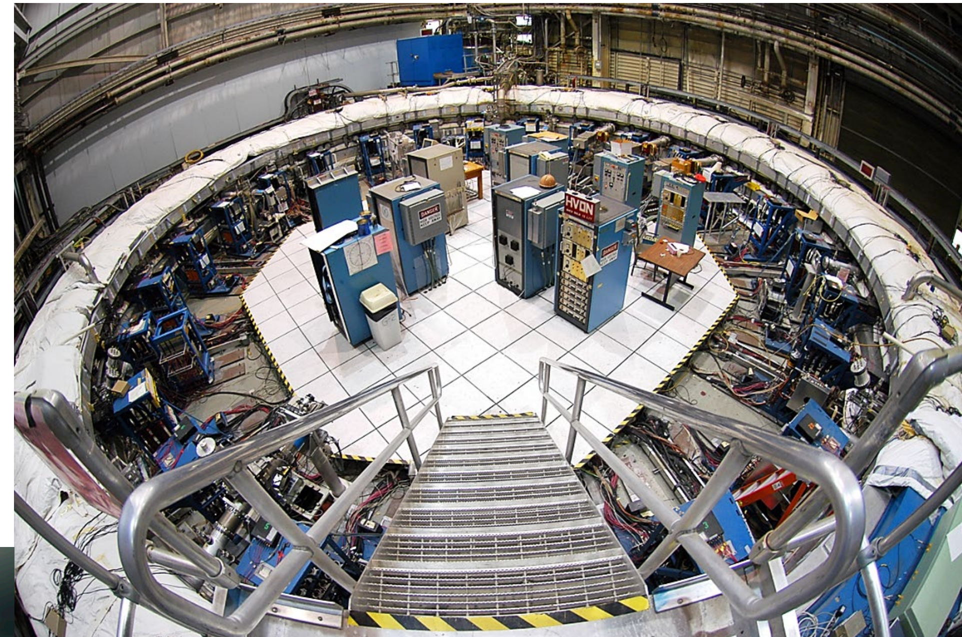
Fermilab Muon g-2 goal:
$a_\mu^{Expt} - a_\mu^{SM} = 0 \pm 16 \times 10^{-11}$

4× reduction in experimental uncertainty

Measuring g−2: Historical Background of Muon g−2

The Muon g−2 experiment has an impressive pedigree:

- Three CERN experiments
  (~1961 – 1979)
- BNL Experiment E821
  (1984 – 2000)
- FNAL Experiment E-989
  (2017 – 2021)



BNL Experiment E821 muon storage ring

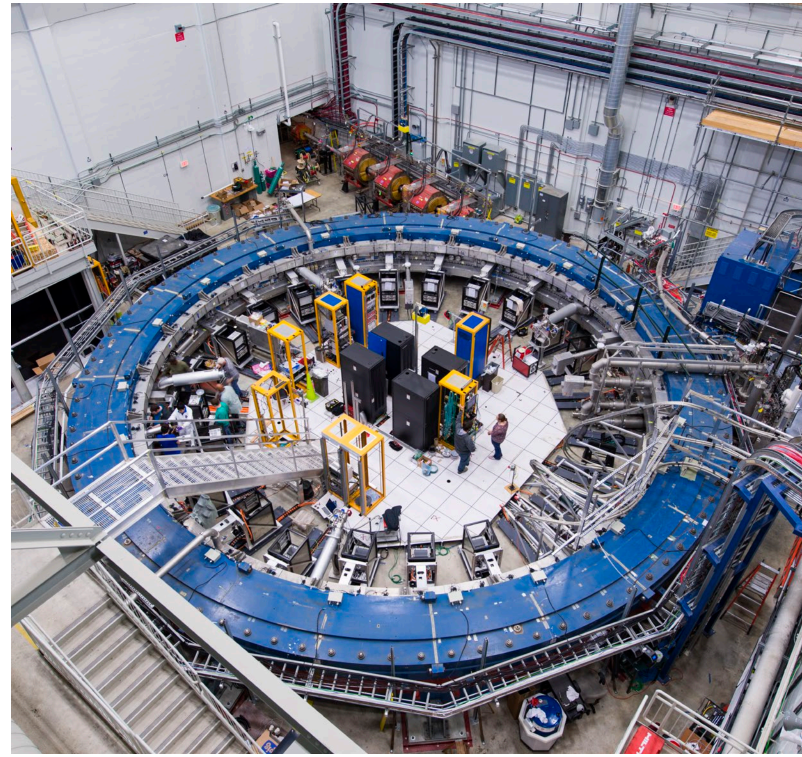
The ring was transported to Fermilab by barge and by truck during the summer of 2013.

It now resides in the MC-1 building of the Fermilab Muon Campus.

Moving g–2 to Fermilab

Installation of the BNL E821 muon storage ring into the MC-1 building at Fermilab.

July 2013



Completed and operational –

g–2 storage ring in its new home in the Fermilab Muon Campus.

Measuring $g_\mu - 2$

Very straight-forward procedure (straight forward to contemplate, difficult to do):

Capture a polarized muon beam into an orbit in a uniform magnetic field and analyze the time evolution of the muon magnetic moment.

There are two motions:

- Cyclotron rotation of the muon momentum

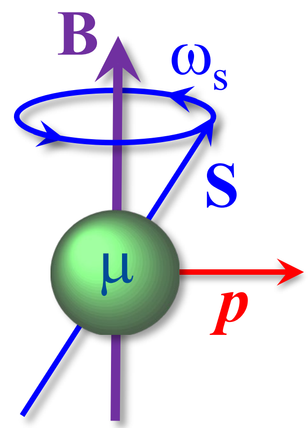
$$\omega_c = \frac{eB}{m_\mu c}$$

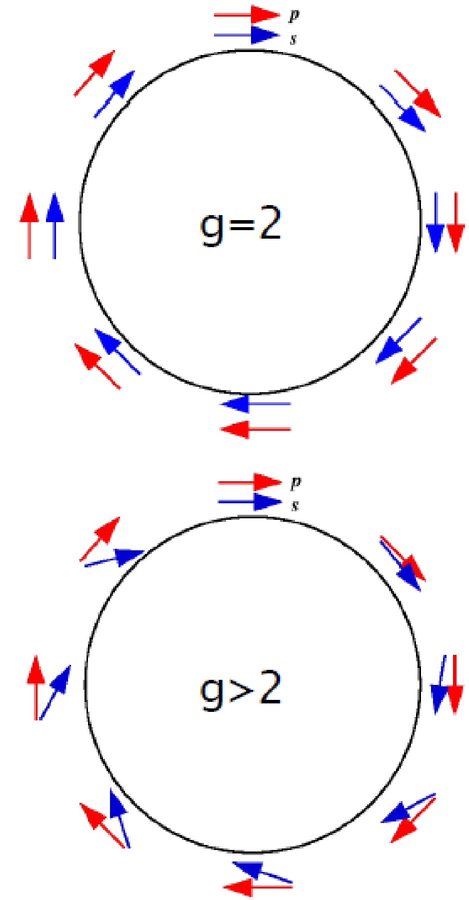
- Larmor precession of the muon spin

$$\omega_s = g_\mu \frac{eB}{2m_\mu c}$$

- The difference ($\omega_a \equiv \omega_s - \omega_c$) is proportional to $g_\mu - 2$

$$\omega_a = \omega_s - \omega_c = \left(\frac{g_\mu - 2}{2}\right)\frac{eB}{m_\mu c} = a_\mu \frac{eB}{m_\mu c}$$





<u>If B is well known</u>, $g_\mu - 2$ is determined by measuring ω_a

The Muon Beam

- Bunches of 10^{12} protons from the Recycler Ring are targeted on the former Antiproton production target.
- The beamlines downstream of the target transport 3.1 GeV/c secondaries. The muon beam is derived from the decay of the pions in this secondary beam.
- >90% of pion decay muons will be polarized along the momentum vector of the muon (this is a fortuitous consequence of the V-A nature of weak decay).
- The secondary beam circulates in the Delivery Ring for ~4 turns (6.8ms) – pions decay, protons slip in time relative to μ^+ beam.
- Protons are aborted prior to extraction
- Pure, polarized μ^+ beam extracted into M5 beamline to g-2 ring.

Why 3.1 GeV/c ?

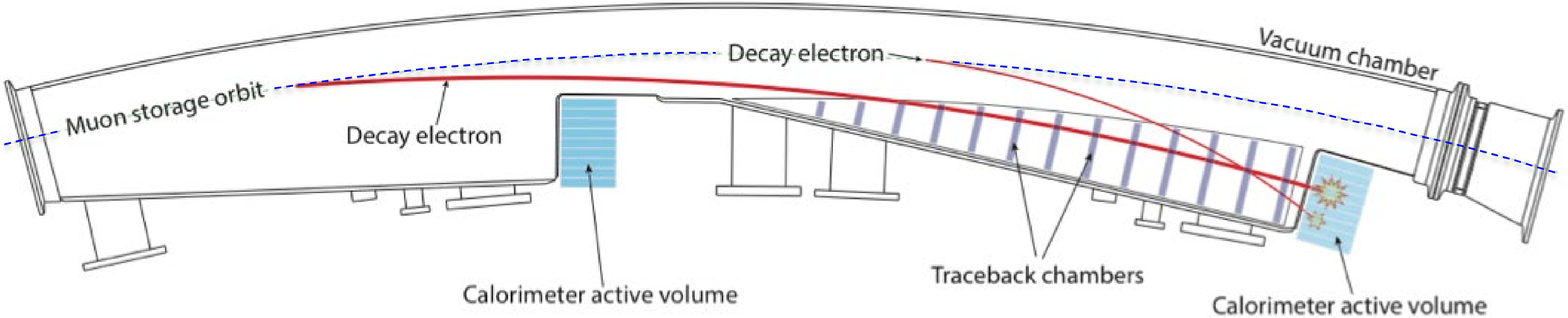
- Muon beam focusing in the g-2 ring is accomplished by electrostatic quadrupoles. The electric field from these quadrupoles affects the muon spin precession frequency:

$$\boldsymbol{\omega_a} = \frac{e}{m_\mu}\left[a_\mu \mathbf{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}\boldsymbol{\beta}\times\mathbf{E}\right]$$

- At $\gamma = 29.3$ (p = 3.094 GeV/c) the $\boldsymbol{\beta}\times\mathbf{E}$ term vanishes, greatly simplifying the relationship between ω_a and a_μ.

Recall: a_μ = 0.0011659…

Measuring ω_a



Segment of g-2 storage ring

- g–2 muon storage ring: instrumented magnetic dipole
- The muons circulating in the muon storage ring decay into neutrinos and positrons: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- 24 calorimeter stations situated around the inside of the muon storage ring detect the decay positrons.
- The direction of the resulting positron is correlated with the direction of the muon spin – Therefore, the number of positrons counted in each detector is modulated at the precession frequency ω_a.

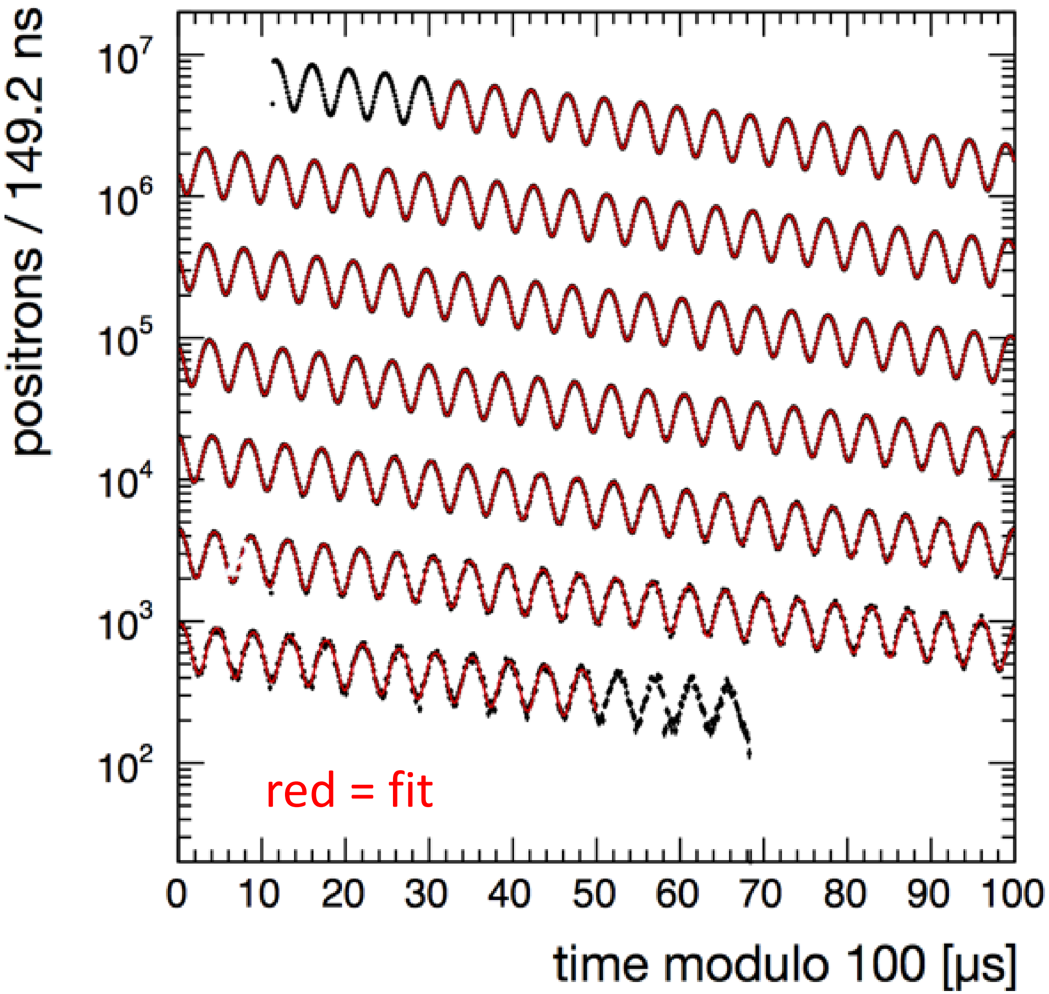
Spin Precession Analysis

- Muon decay positrons are counted in each of the calorimeter stations
- ω_a can be extracted from a fit to*

$$N(t) = N_0 e^{-\lambda t}\left[1 - A\cos\left(\omega_a t + \phi_0\right)\right]$$

λ contains muon beam loss due to muon decay and other beam loss mechanisms.

- The actual analysis used is beyond the scope of this talk.



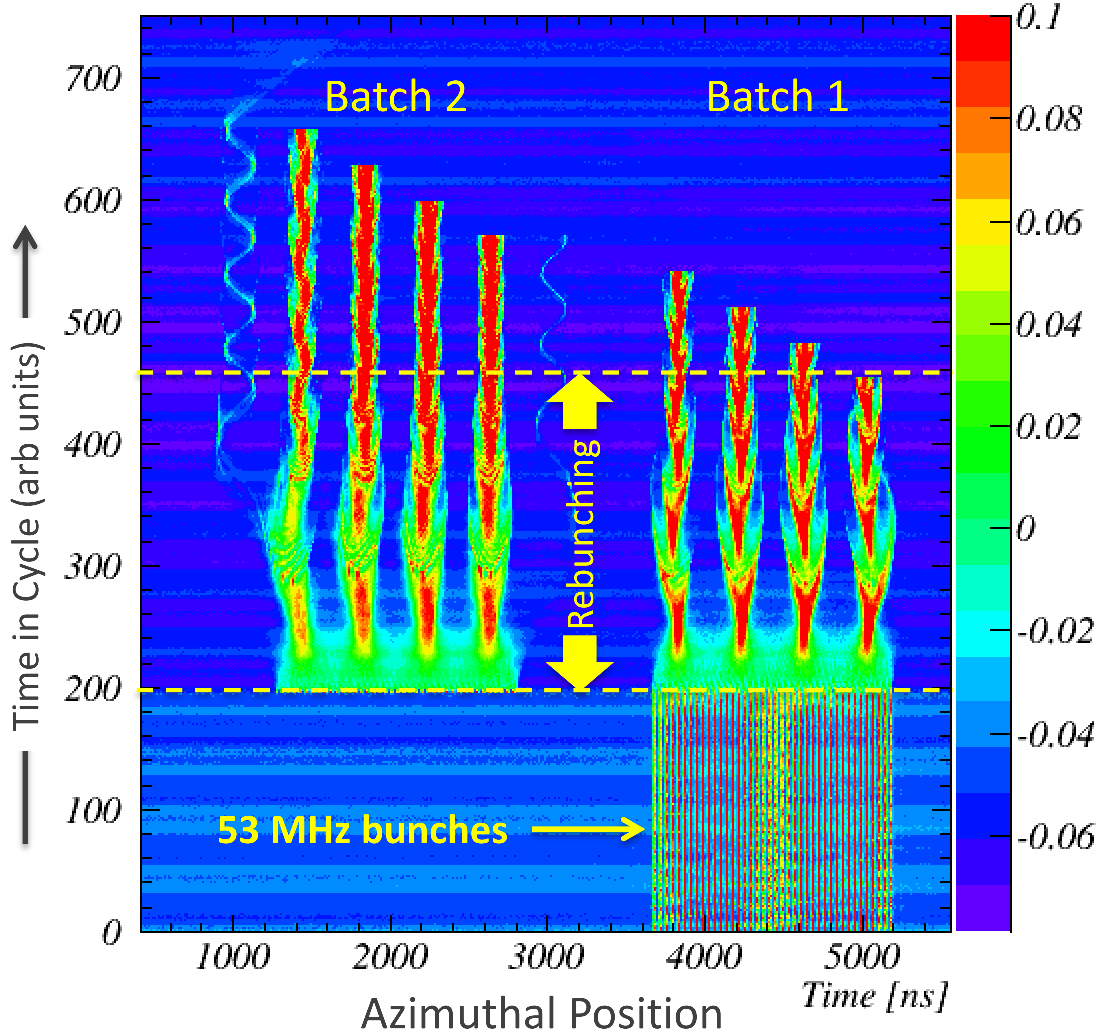
* The functional forms used in the actual analysis are much more complicated than the simple form shown here

Chris Polly

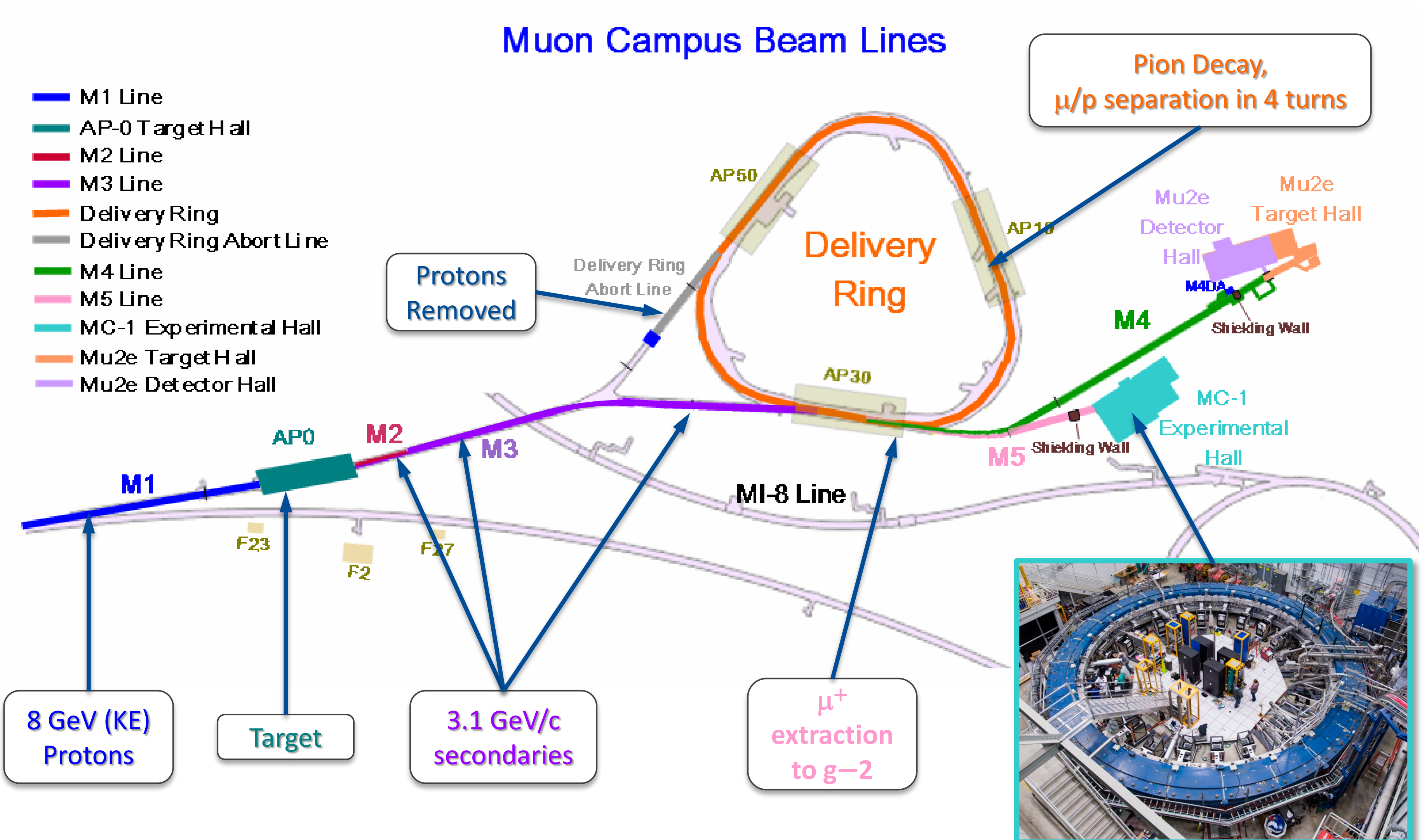
Muon g-2 Beam Delivery Details

Recycler Ring 2.5 MHz Rebunching

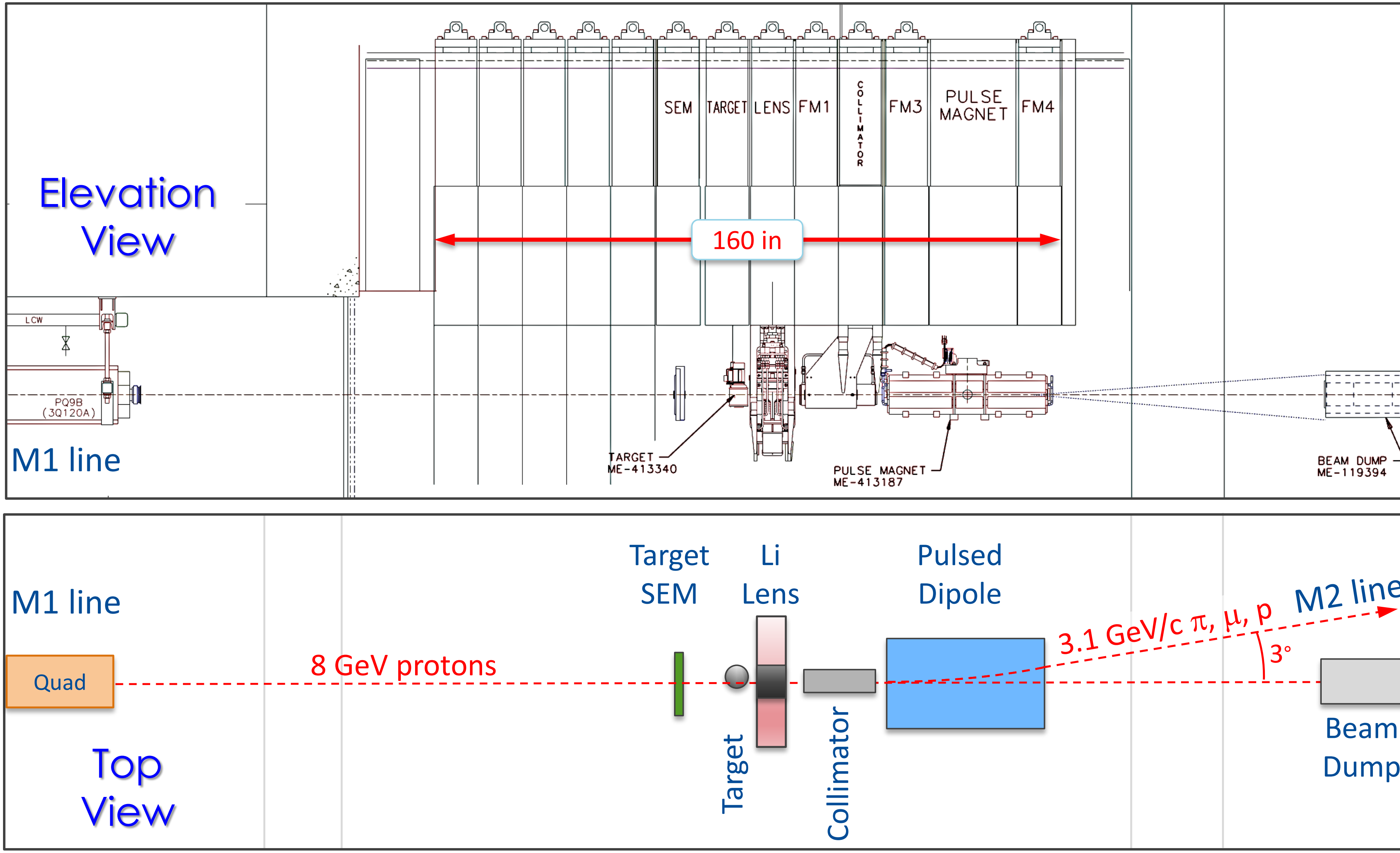
- First batch(4×10^{12} protons) injected into Recycler at t = 0.
  - 84 53 MHz bunches/batch
- Second batch injected at t = 200
- Rebunching ramp plays immediately after 2nd bunch injected
  - 53 MHz RF turned off
  - Adiabatic bunching with 2.5 MHz for 90 ms
  - After rebunching, 8 2.5 MHz bunches are circulating in Recycler
- First bunch (10^{12} protons) extracted to g−2 target at t = 460
- 2.5 MHz bunches extracted, one-at-a-time, every 10ms



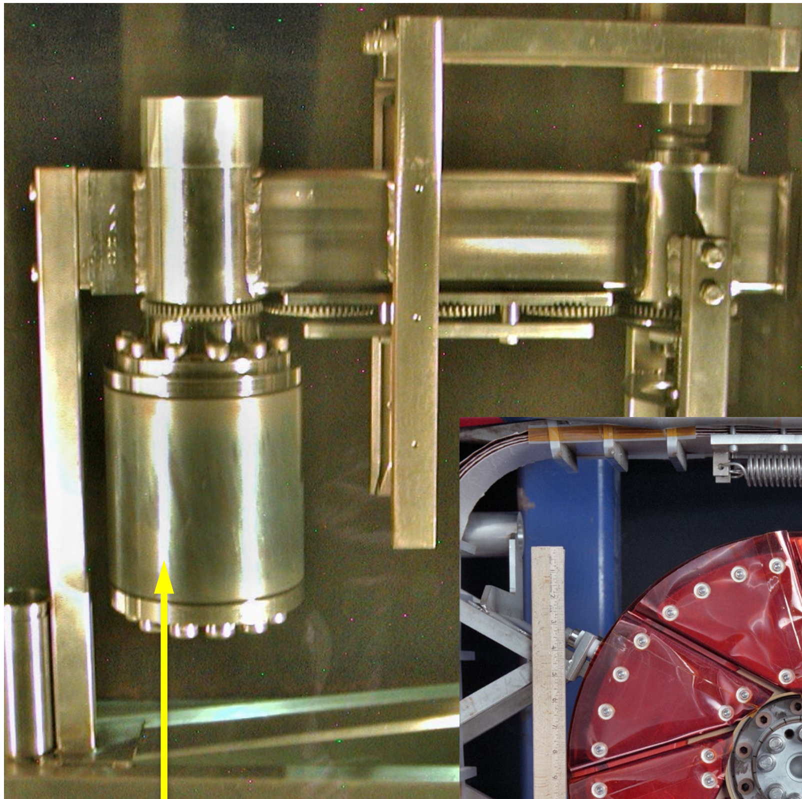
Muon Campus Beam Transport



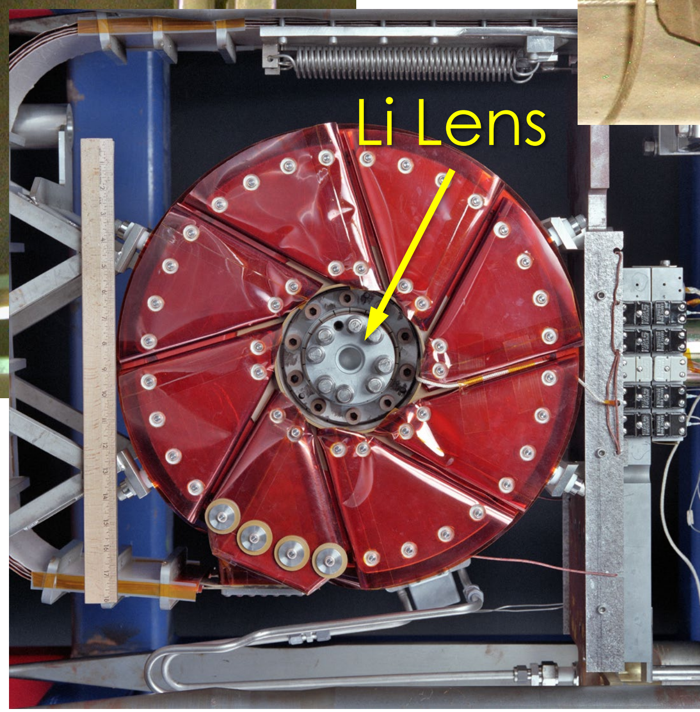
Target Station

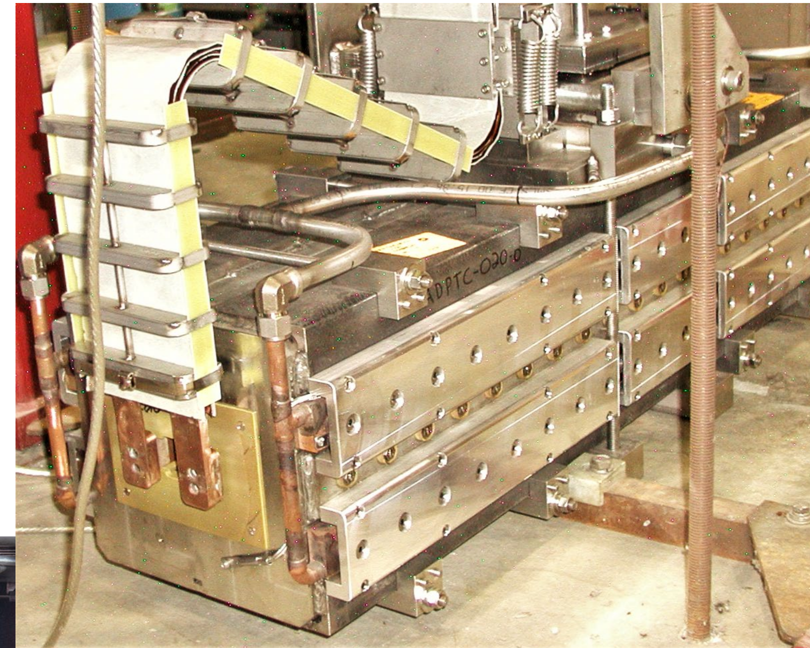


Target Station Components



Target





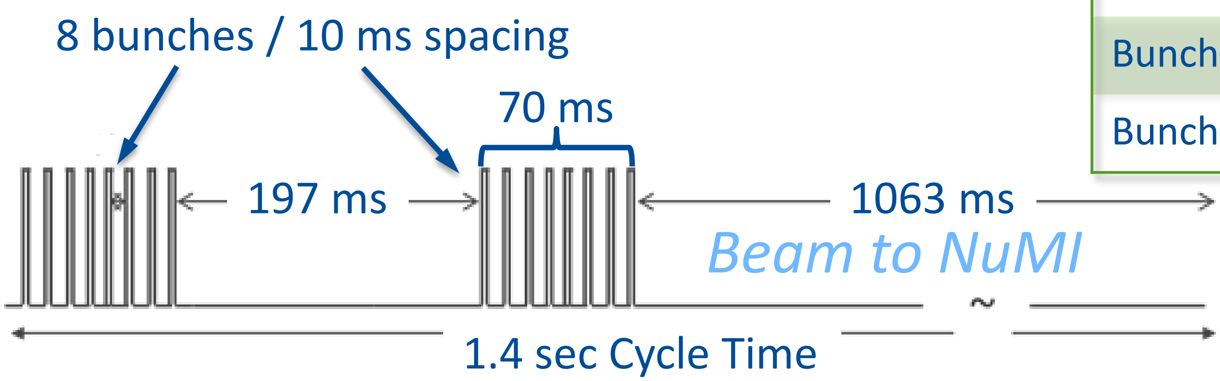
Pulsed Magnet

All target station equipment is reused Antiproton Source equipment

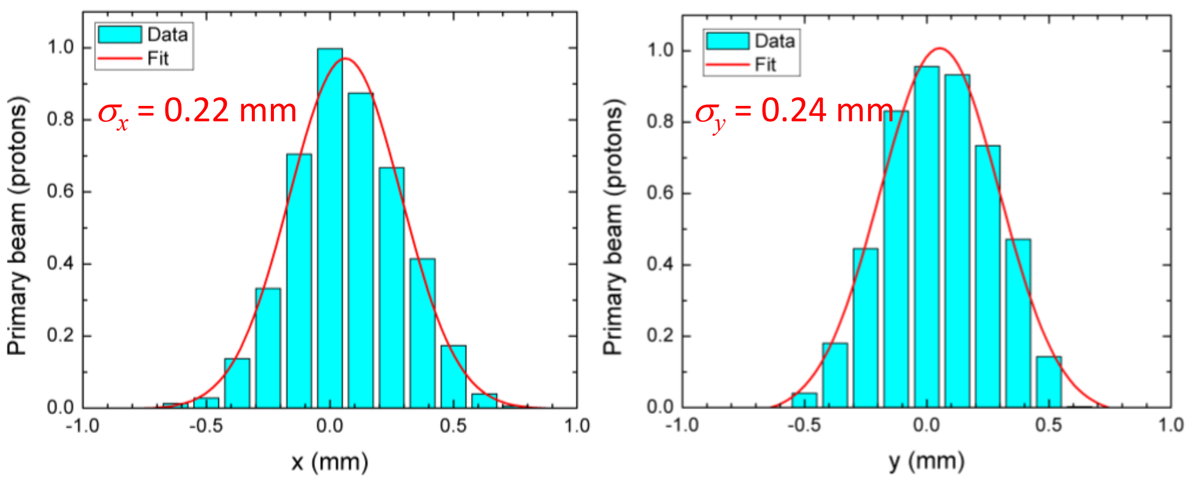
Proton Beam on Target

Parameter	Value
Protons per Bunch	10^{12}
Average Bunch Rate	11.4 Hz
Bunch time width (σ)	120 ns
Bunch transverse width (σ)	0.25 mm

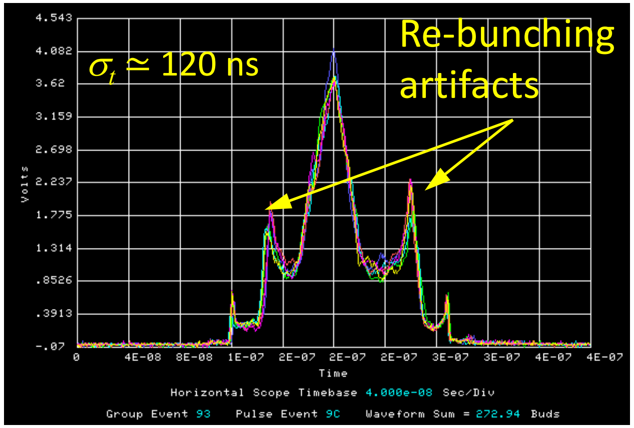
Macro-time structure



Transverse structure

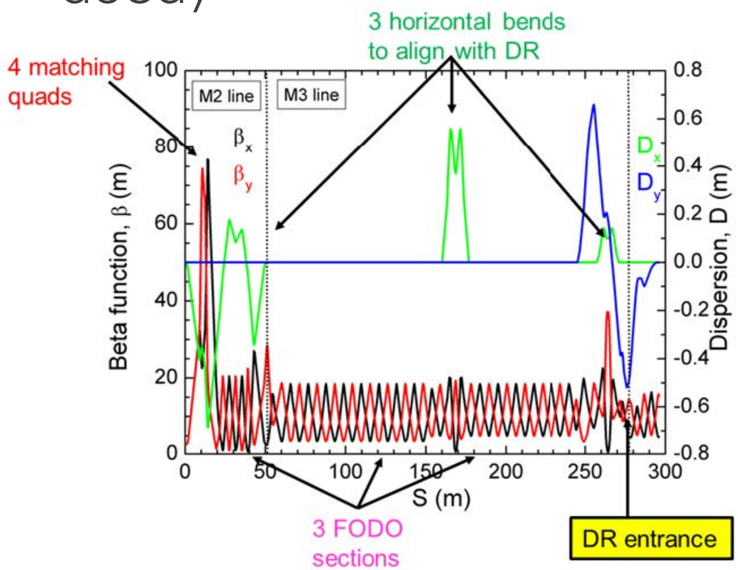


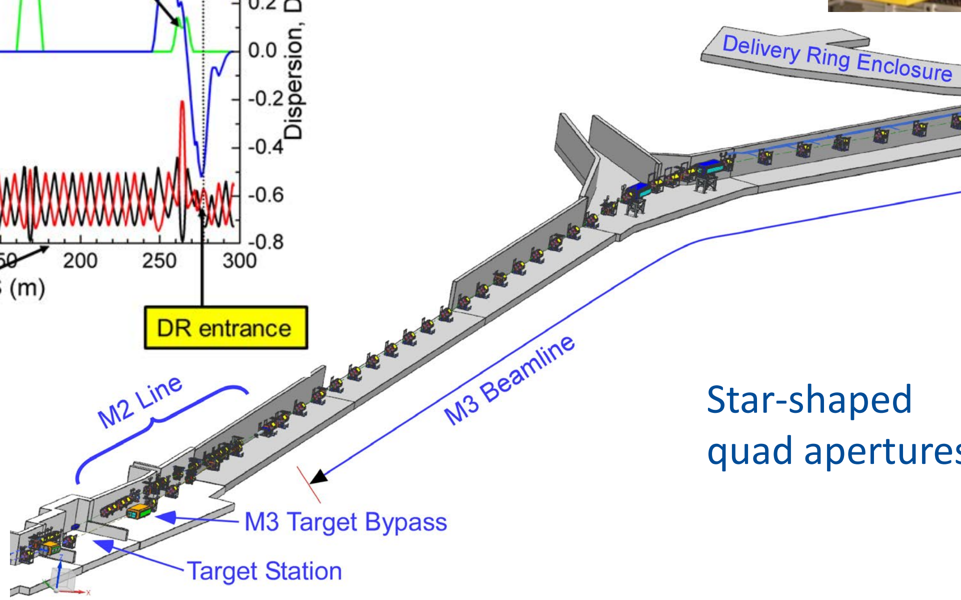
Micro-time structure



Beam Transport from Target to Delivery Ring

- M2 and M3 beamlines have high density of large aperture quadrupole magnets
- High acceptance for forward muons from pion decay





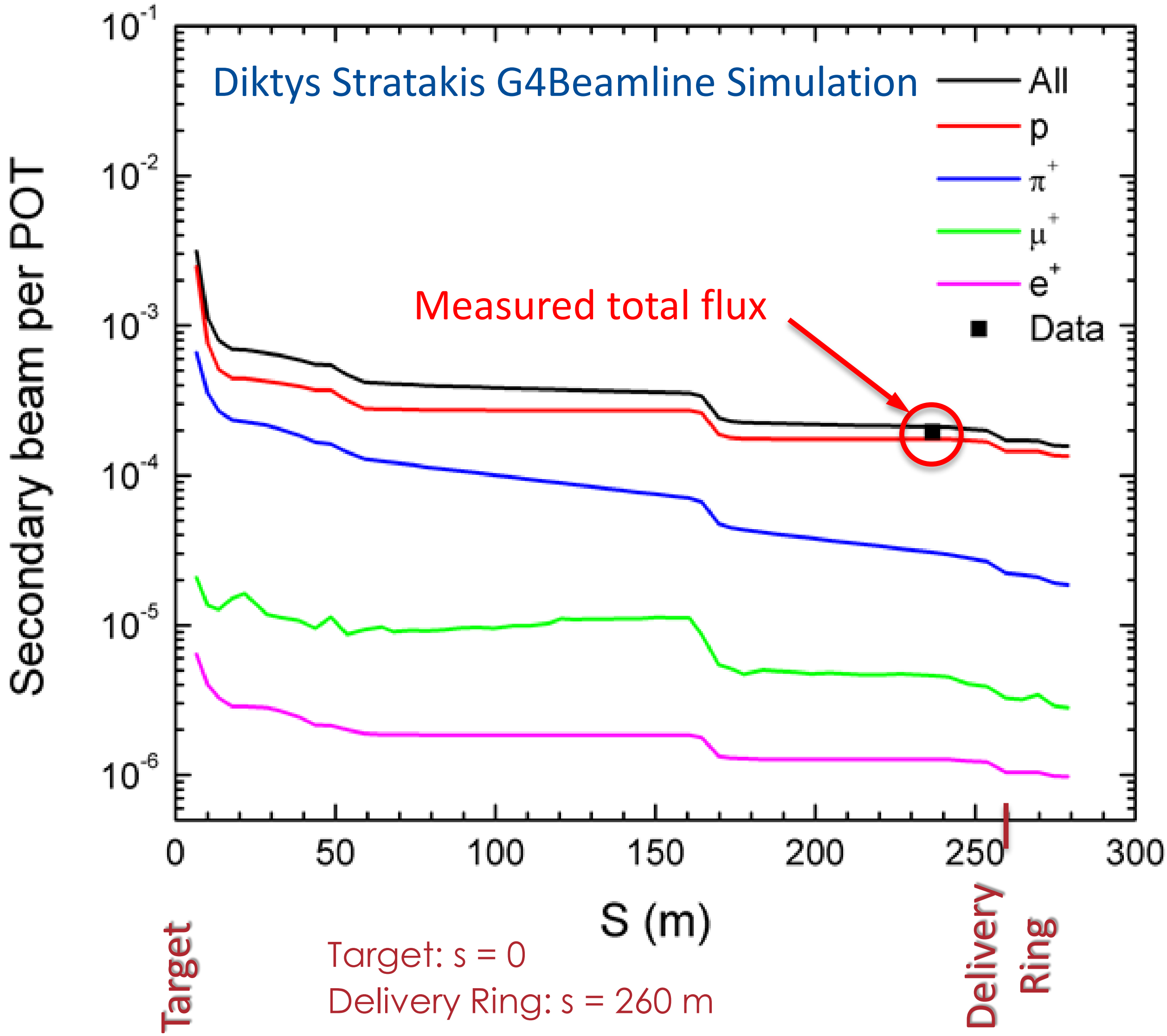
Star-shaped quad apertures

Diktys Stratakis

Transport Efficiency from Target to Delivery Ring

Measured intensity matches simulation

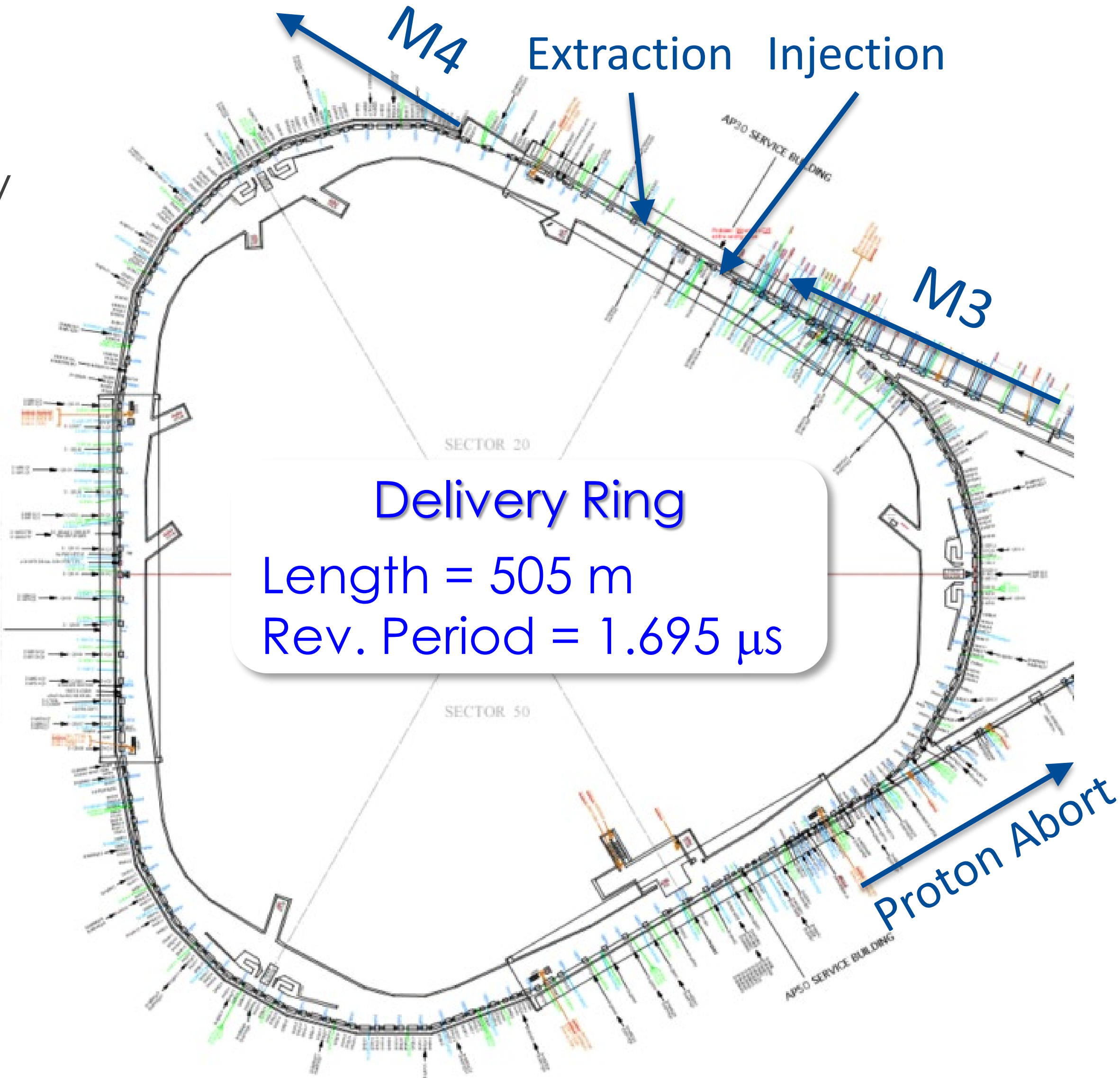
- Secondary flux is primarily protons
- 70% of pions decay before reaching the Delivery Ring.
- 2.7×10^{-6} μ^{+}/POT reach the Delivery Ring



Target: s = 0
Delivery Ring: s = 260 m

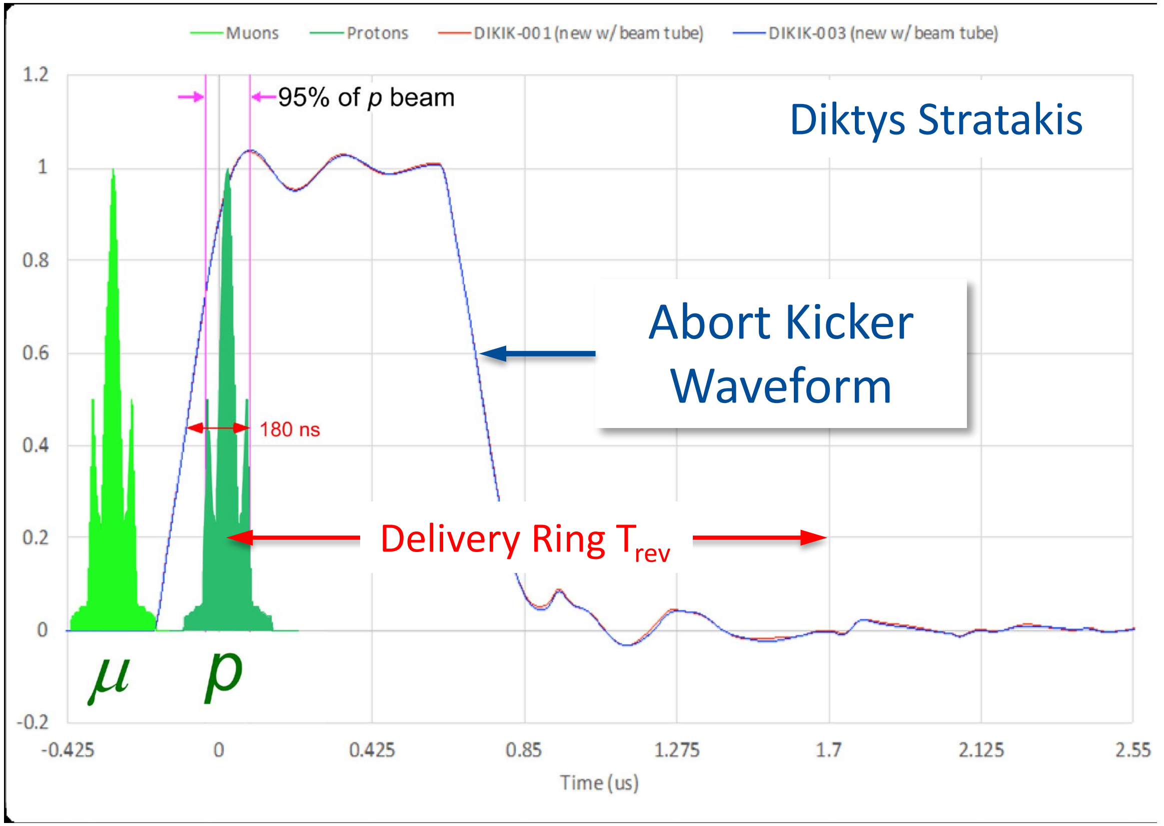
Proton Removal

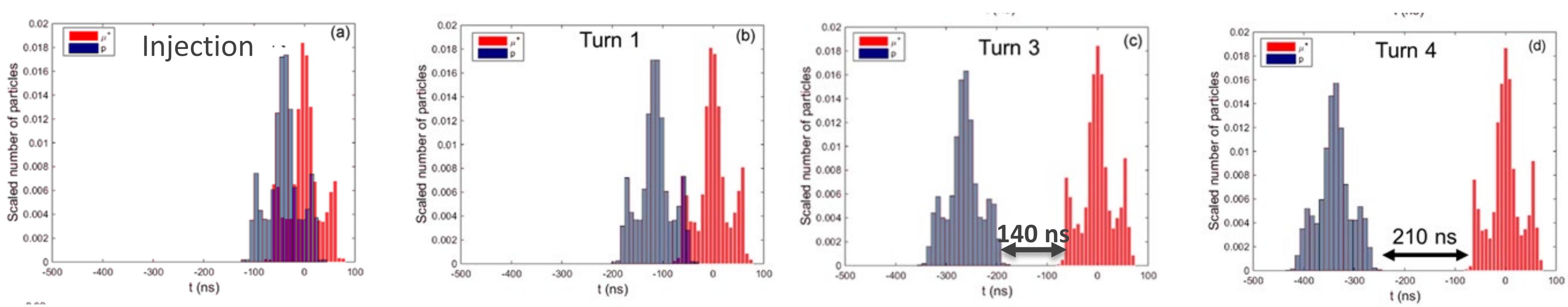
- Secondary Beam is transferred to the Delivery Ring. At Delivery Ring injection the beam composition is:
  - 89% protons
  - 8% pions
  - 2% muons
- After 4 turns, only protons and muons remain
- The protons are sent to a beam dump prior to extraction of the remaining muons to g-2



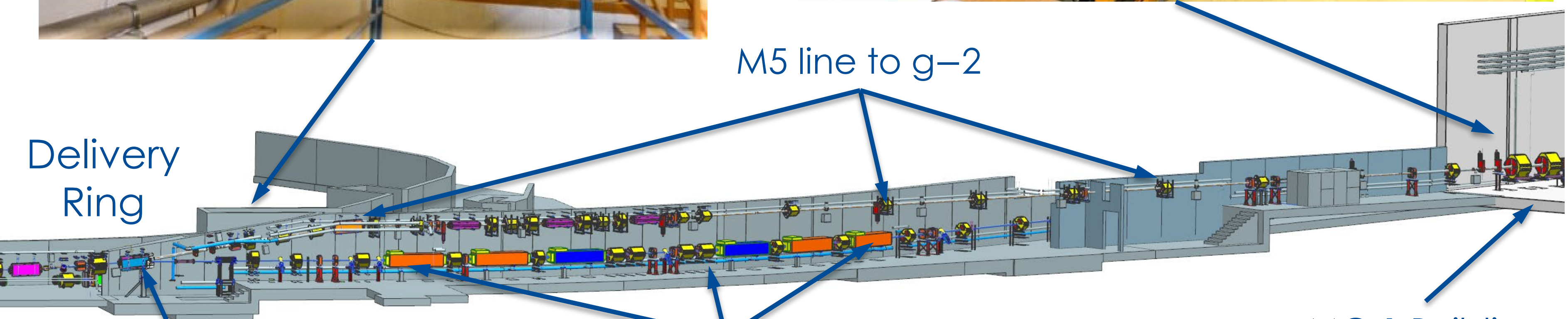
Proton Removal

- 3.1 GeV/c Muons and protons separate longitudinally at a rate of 75 ns per Delivery Ring turn
- By turn 4 the separation exceeds the rise time of the abort kicker (~180 ns)
- The remaining muon beam is extracted to g-2

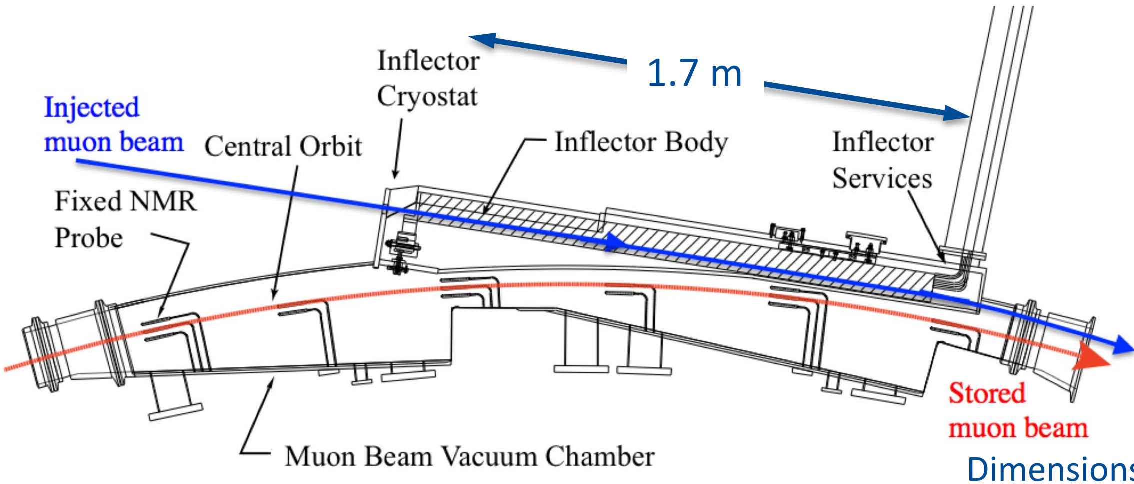


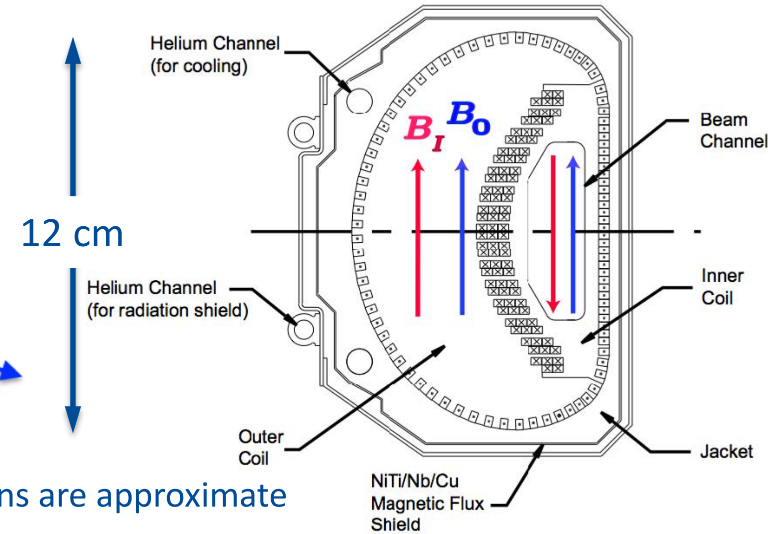


Transport from Delivery Ring to g–2



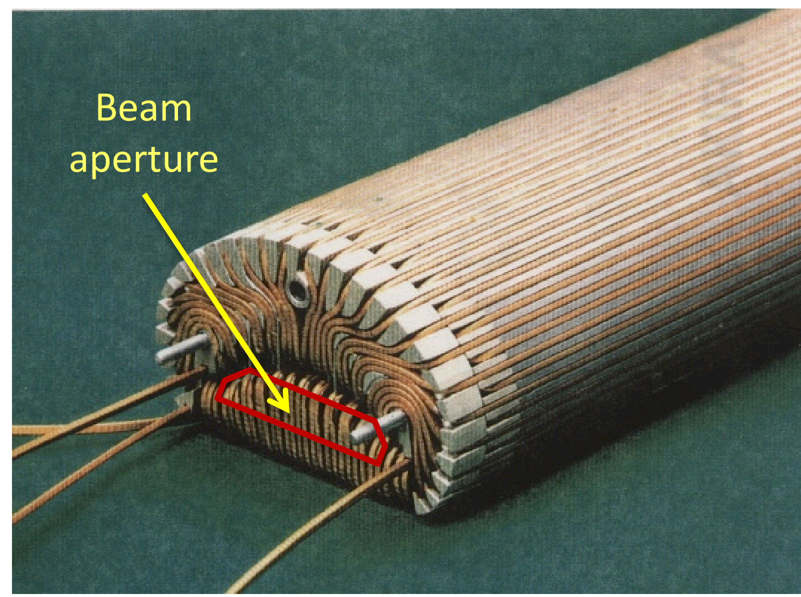
Injection into the Muon Storage Ring



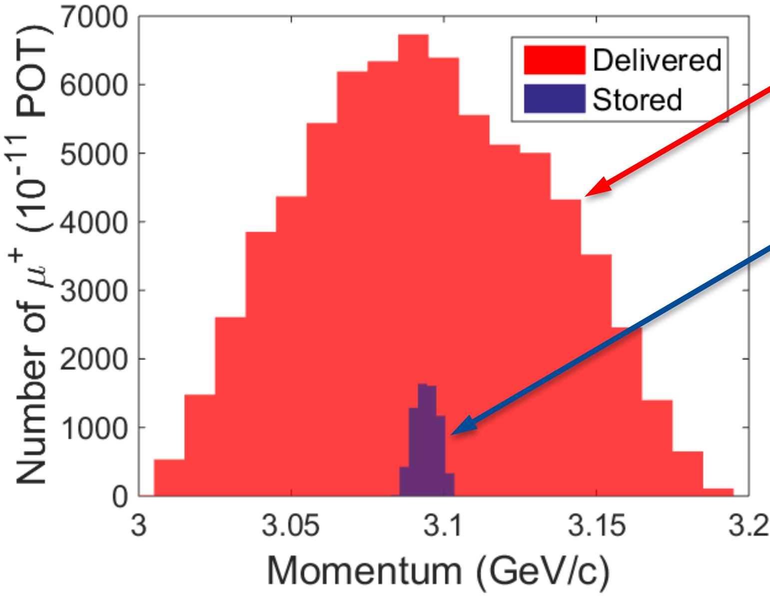


Injection into the muon storage ring is facilitated by a super conducting inflector.

- The purpose of the injector is to cancel the field of the storage ring dipole along the injection channel.
- The beam aperture is occluded by super conducting coil windings
- Muon transmission efficiency is 2-4%
- An "open ended" inflector is being build that is expected to increase transmission efficiency to ~30%



Performance Enhancement with Passive Absorbers

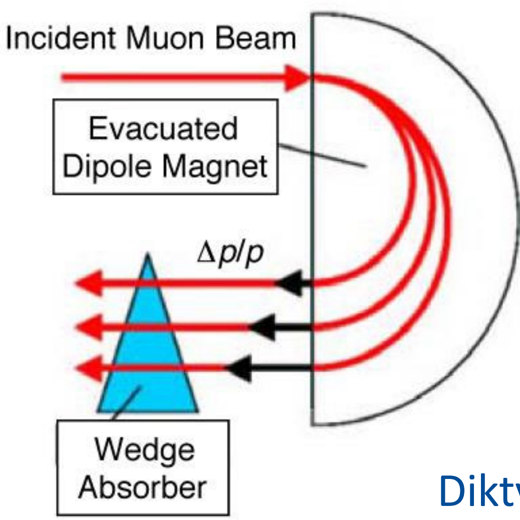


$$\frac{\sigma_p}{p} = \pm 1.26\%$$

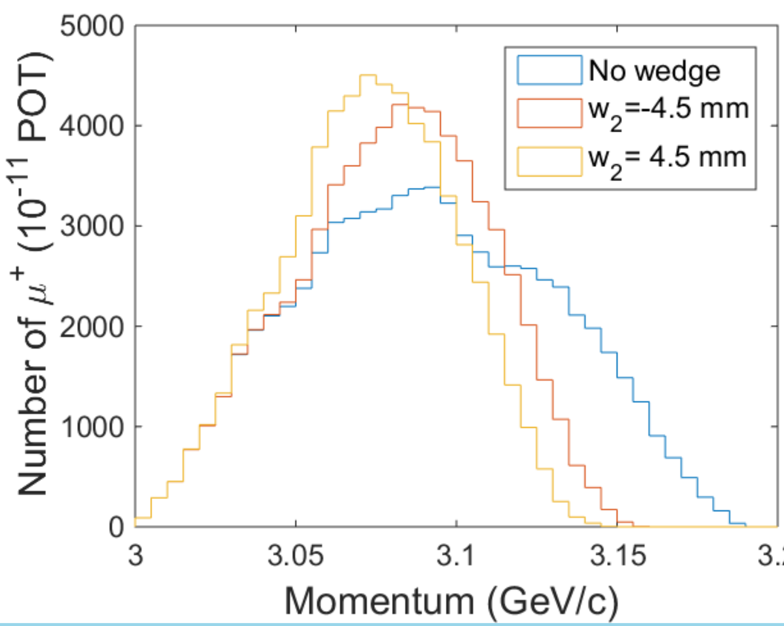
$$\frac{\sigma_p}{p} = \pm 0.12\%$$

The g-2 muon storage ring accepts only a small fraction of the longitudinal phase space delivered to the ring.

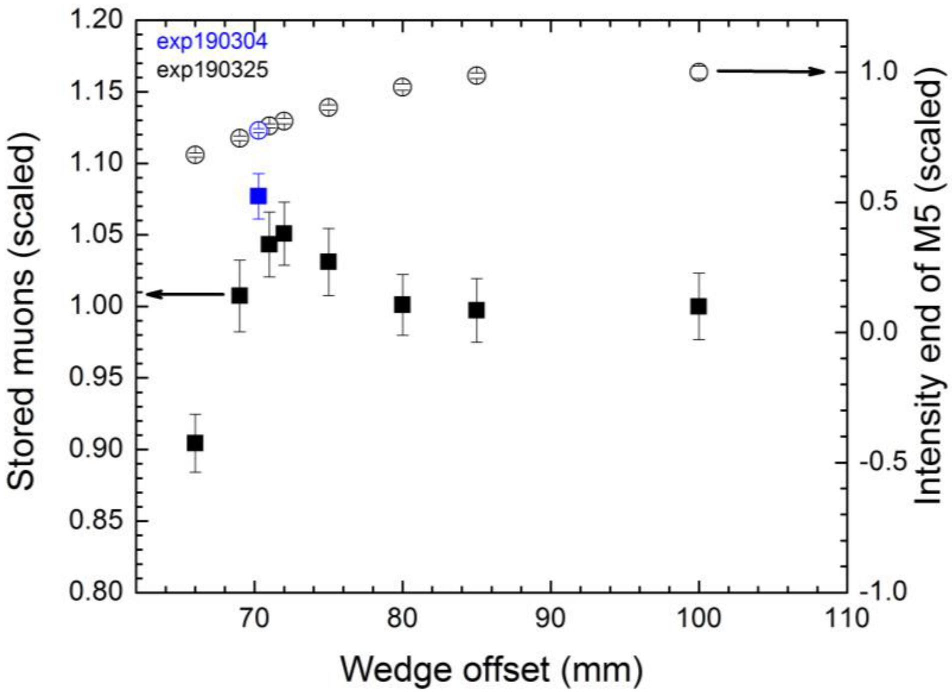
Improvement can be obtained by placement of a wedge absorber in high dispersion upstream of the ring.

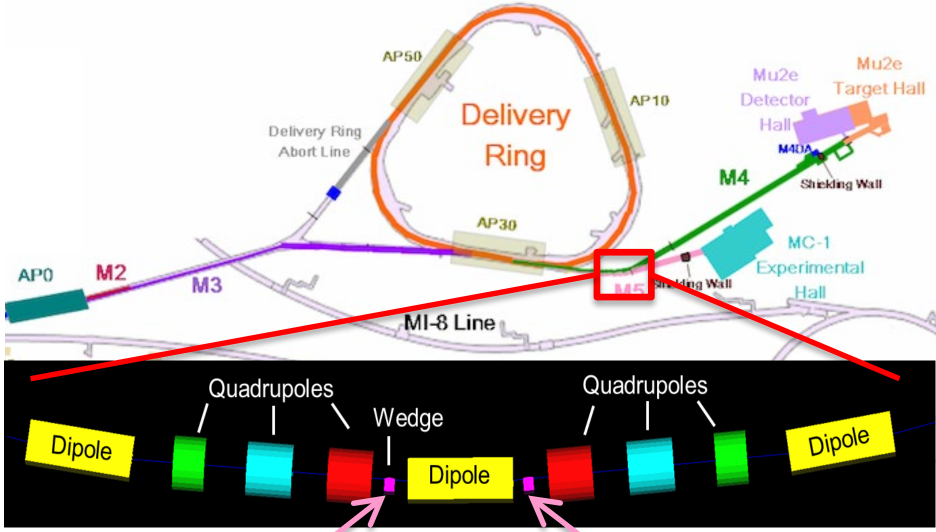


Diktys Stratakis

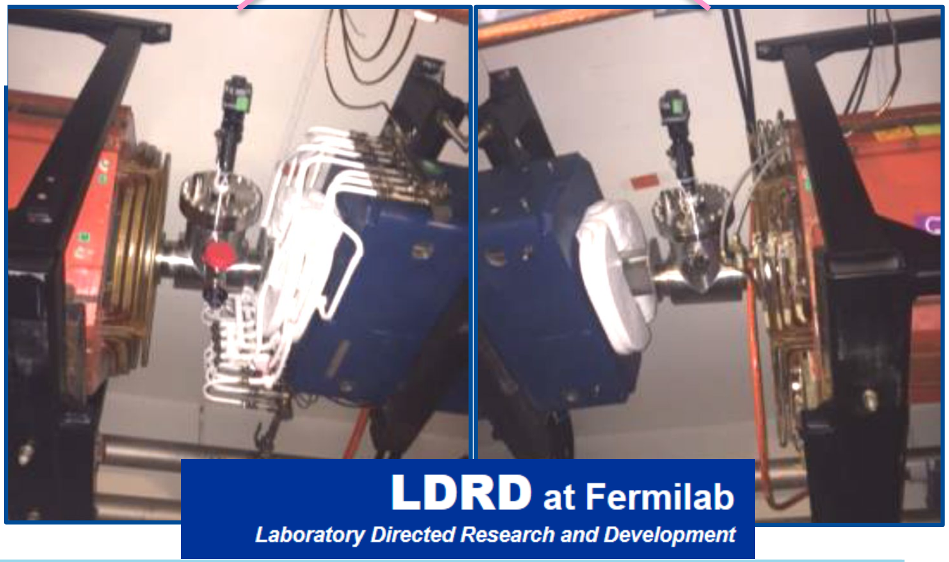


Proof -of -principle test with a polyethylene wedge





- Proof-of -principle experiment performed.
- Demonstrated gain of up to 8% in stored muons with a polyethylene wedge.
- Wedges installed funded from an LDRD. Diktys Stratakis is the PI.



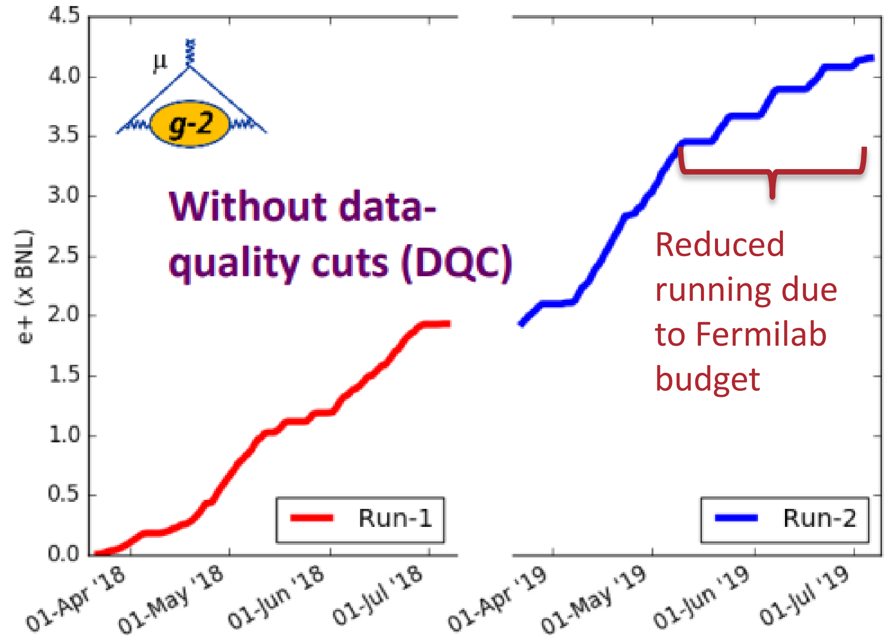
g−2 Status and Plans for the Future

Data Collection

- The goal of Muon g−2 running at Fermilab is a fourfold improvement in the measurement of a_μ over the BNL E821 result.
  - BNL E821 precision: 0.54 ppm
  - Fermilab goal: 0.14 ppm
  - Goal requires 21.5×BNL statistics

- Two runs so far:
  - Run 1 (2018) 1.9×BNL E821 in raw statistics
  - Run 2 (2019) 2.2×BNL E821 in raw statistics
  - At the end of Run 2 data collection rate was approximately one BNL data set every month of runtime – for normal running conditions.
- Two future runs planned for 2020 and 2021

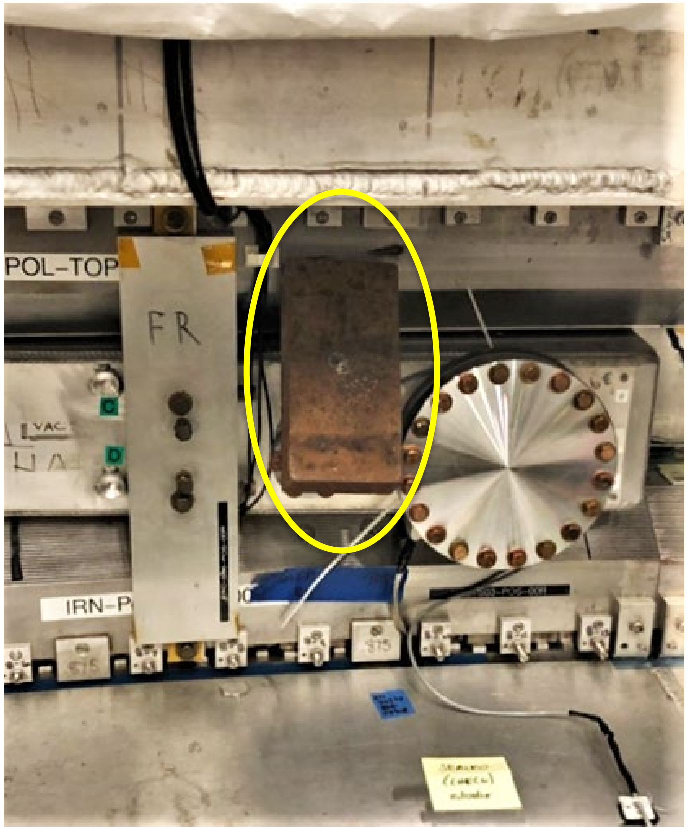
  With stable running and planned improvements the combined statistics of all four runs could approach 22×BNL E821 data set.



Dave Herzog

Difficulties Encountered During g–2 Runs 1 and 2

- Late start for Run I due to vacuum issues
- Unable to operate storage ring injection kickers at design voltage. Caused downtime and unstable running.
- Muon Ring Hall climate control problems affecting field stability
- Safety incident
- Late start for Run II due to recovery from safety incident and technical issues
- Diminished run time in Run II due to insufficient lab operating budget.
- Two Li Lens failures – one good spare remains. Lowered lens gradient by 15% to reduce heating ⇒ 30% loss in flux.

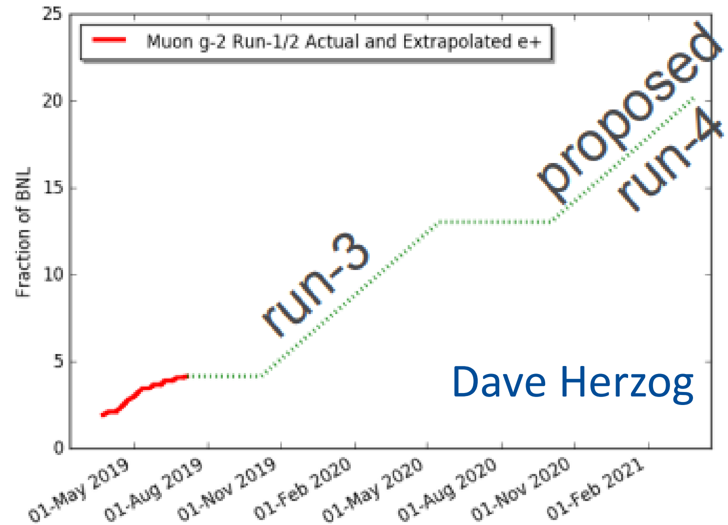


The brick

No one was hurt. Damage was minor. Significant downtime was required to re-establish and ensure safe operating.

g–2 Plans for the Future

- Two more runs in 2020 and 2021
- Inflector upgrade expected to increase muon flux by 30%.
- No published results yet – but we should be seeing something soon.



Collaboration meeting Nov 20
-- *maybe* #1 will shortly follow

1st publication (>1 x BNL statistics)

2nd publication (3 x BNL statistics)

3rd publication (10 x BNL statistics)

Final publication

CY18 | CY19 | CY20 | CY21 | CY22

Chris Polly – October 2019

The Mu2e Experiment

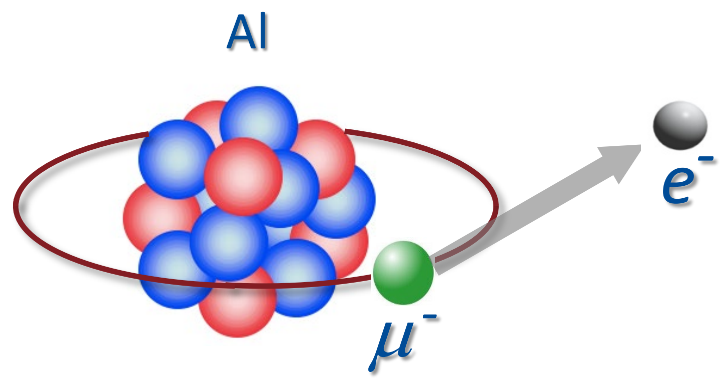
Charged Lepton Flavor Violation

Charged Lepton Flavor Violation (CLFV)

- The Mu2e experiment endeavors to detect one particular channel of Charged Lepton Flavor Violation (CLFV)
- 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
- The signal the Mu2e experiment is designed to detect is the coherent conversion of a muon into an electron in the field of an Aluminum nucleus.

The Signal



$$\mu^- N \rightarrow e^- N$$

L_μ:	1	0
L_e:	0	1

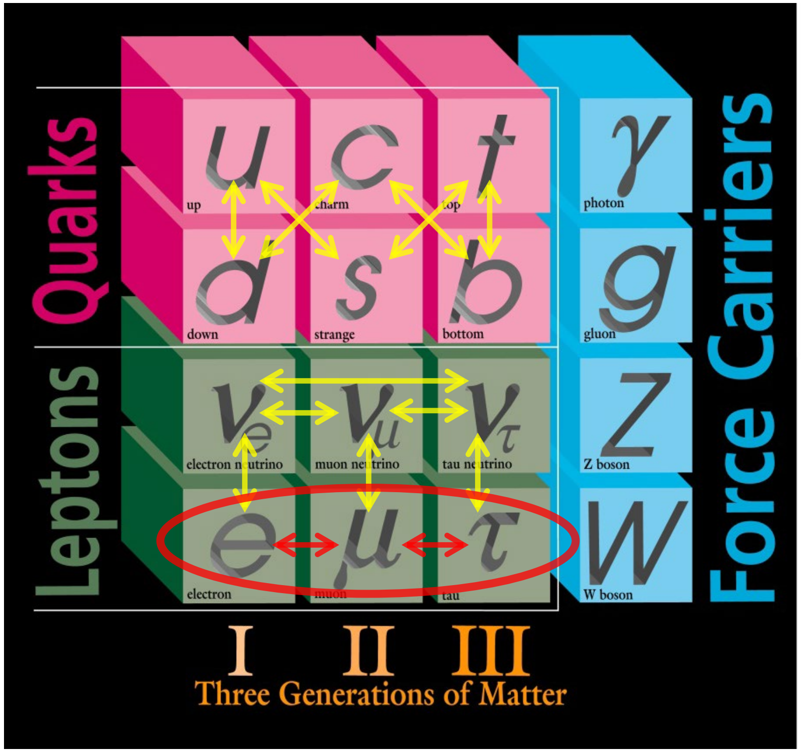
Both L_μ and L_e are not conserved in this process

Why Mu2e? – The Significance of Observing CLFV

- A large variety of quark flavor changing processes have been observed and understood in terms of the Standard Model.

  The CKM (Cabbibo-Kobayashi-Maskawa) matrix gives the quark flavor couplings:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- Lepton sector flavor changing processes observed to be more limited

  Weak decay: $\ell^{\pm} \to W^{\pm}\,\nu$

  Neutrino Oscillations

- Why shouldn't *charged* leptons mix?

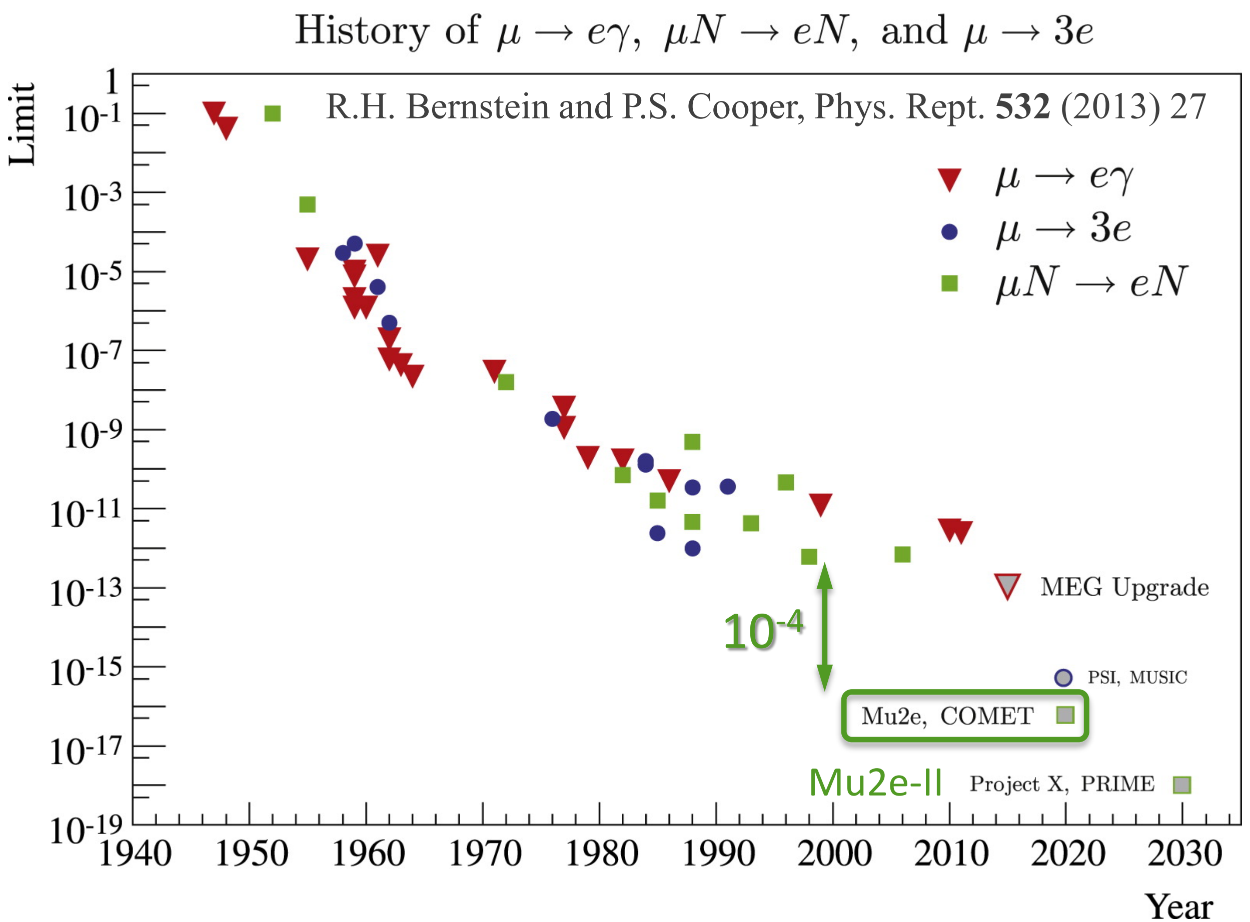
  The Standard Model predicts $e \leftrightarrow \mu \leftrightarrow \tau$ mixing, but the rates are negligible.

  BR$(\mu \to e\,\gamma) \lesssim \mathcal{O}(10^{-52})$

  This is unmeasurable by any known technology.

Any detection of $\mu^- \to e^-$ is an unambiguous indication of physics beyond the Standard Model

History of Muon CLFV



$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \longrightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \longrightarrow Anything)}$$

Current best limits:

SINDRUM 1988
BR($\mu \to 3e$) < 1×10^{-12}

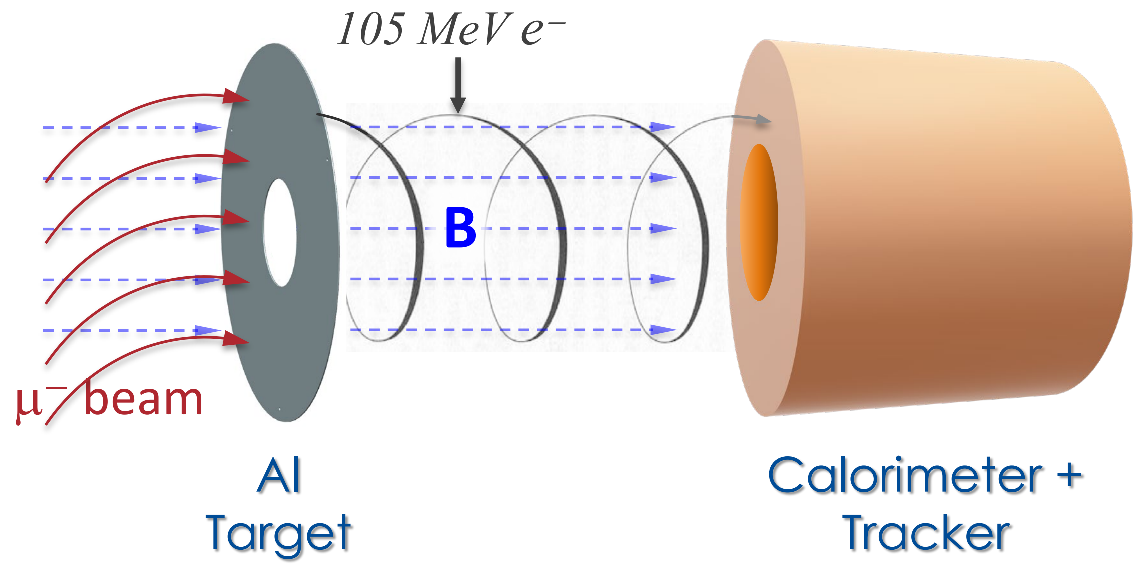
SINDRUM-II 2006
$R_{\mu e} < 6.1\times10^{-13}$

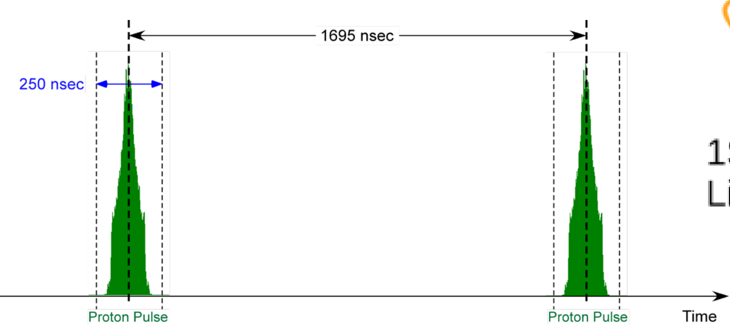
MEG 2016
BR($\mu \to e\gamma$) < 4.2×10^{-13}

Mu2e Goal
$R_{\mu e} < 8\times10^{-17}$

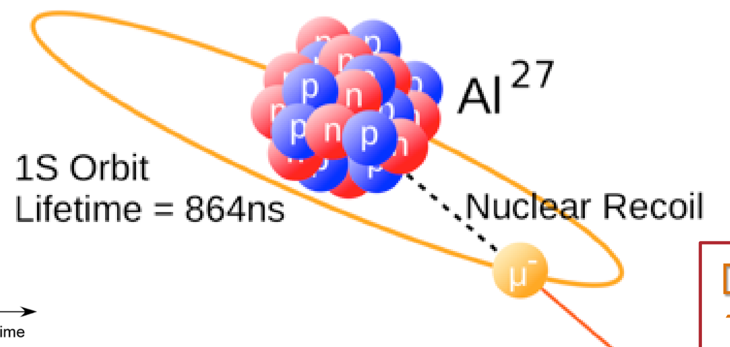
Mu2e Experimental Technique

- Low momentum pulsed μ^- beam (<100 MeV/c)
- Aluminum target
- Solenoidal magnetic field
- e^- tracking and calorimetric energy measurement for identification of conversion electrons





Pulsed Primary Beam



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} \\ = 104.96\ \mathrm{MeV}$$

Discovery signal:
104.96 MeV electron

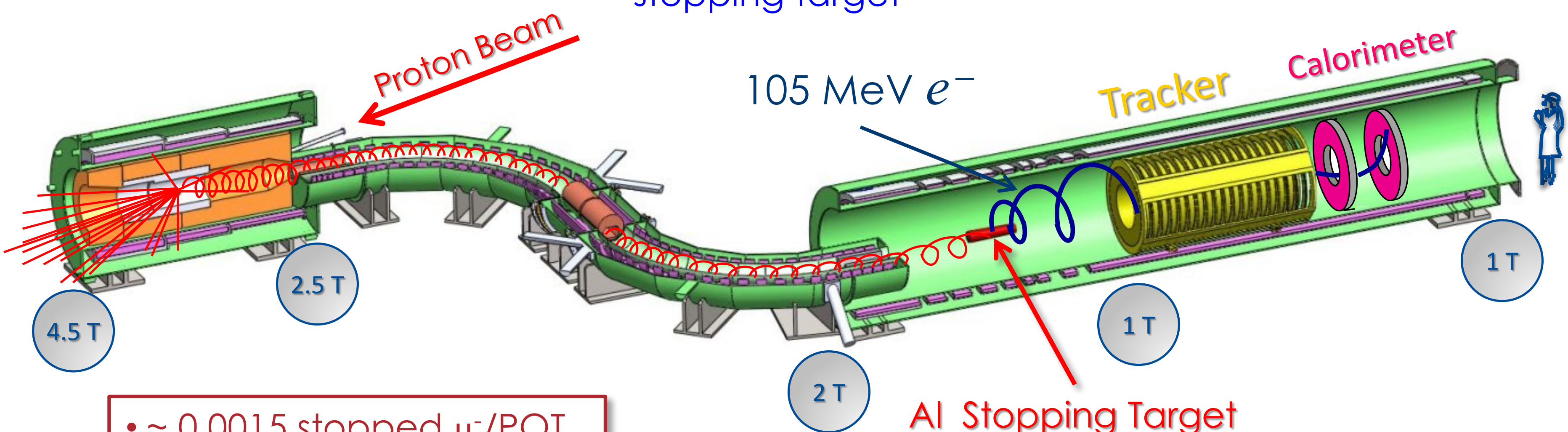
Mu2e Apparatus

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

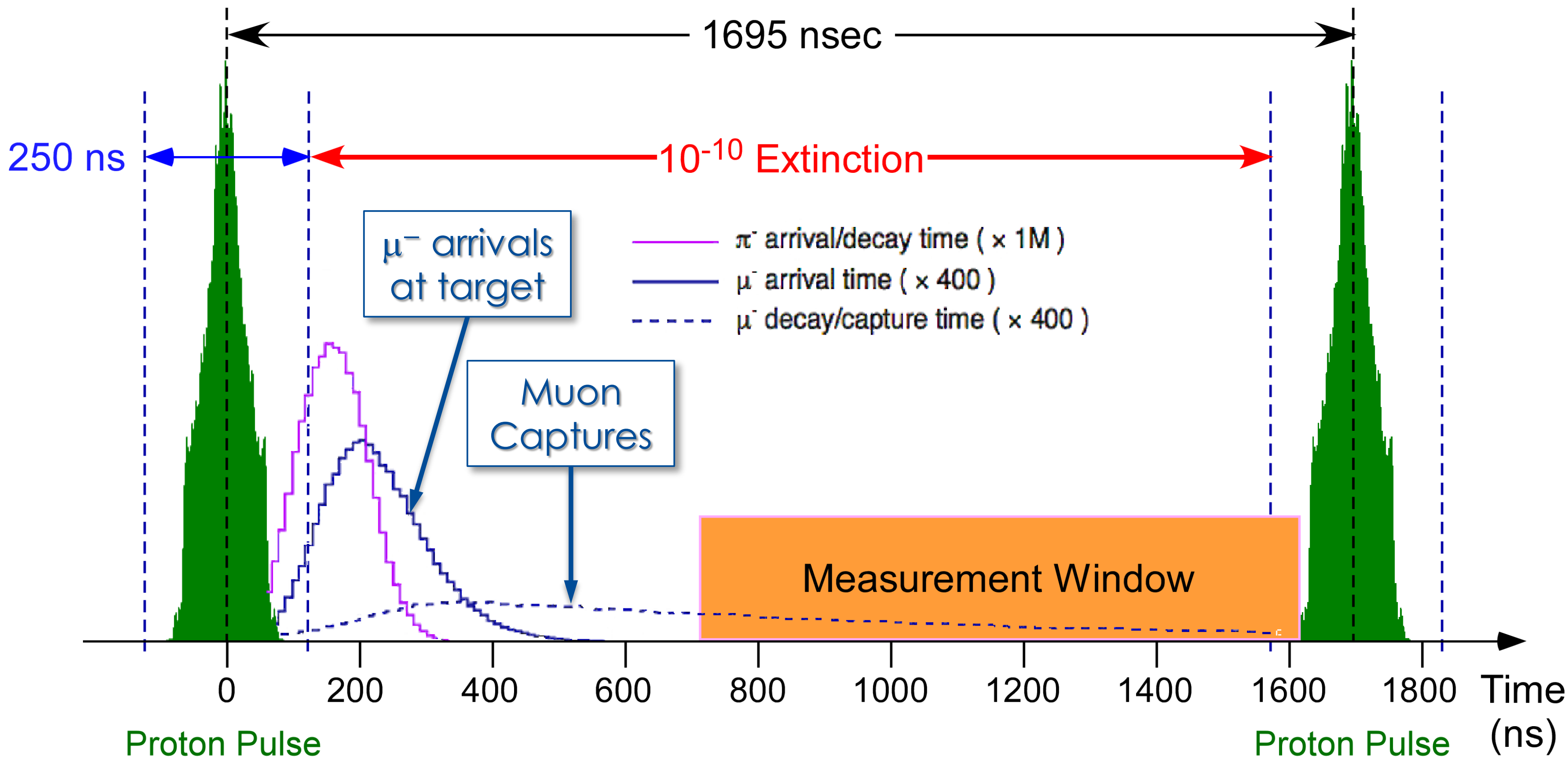
Transport Solenoid
- Collimation
- Momentum and charge selection
- Transport to stopping target

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



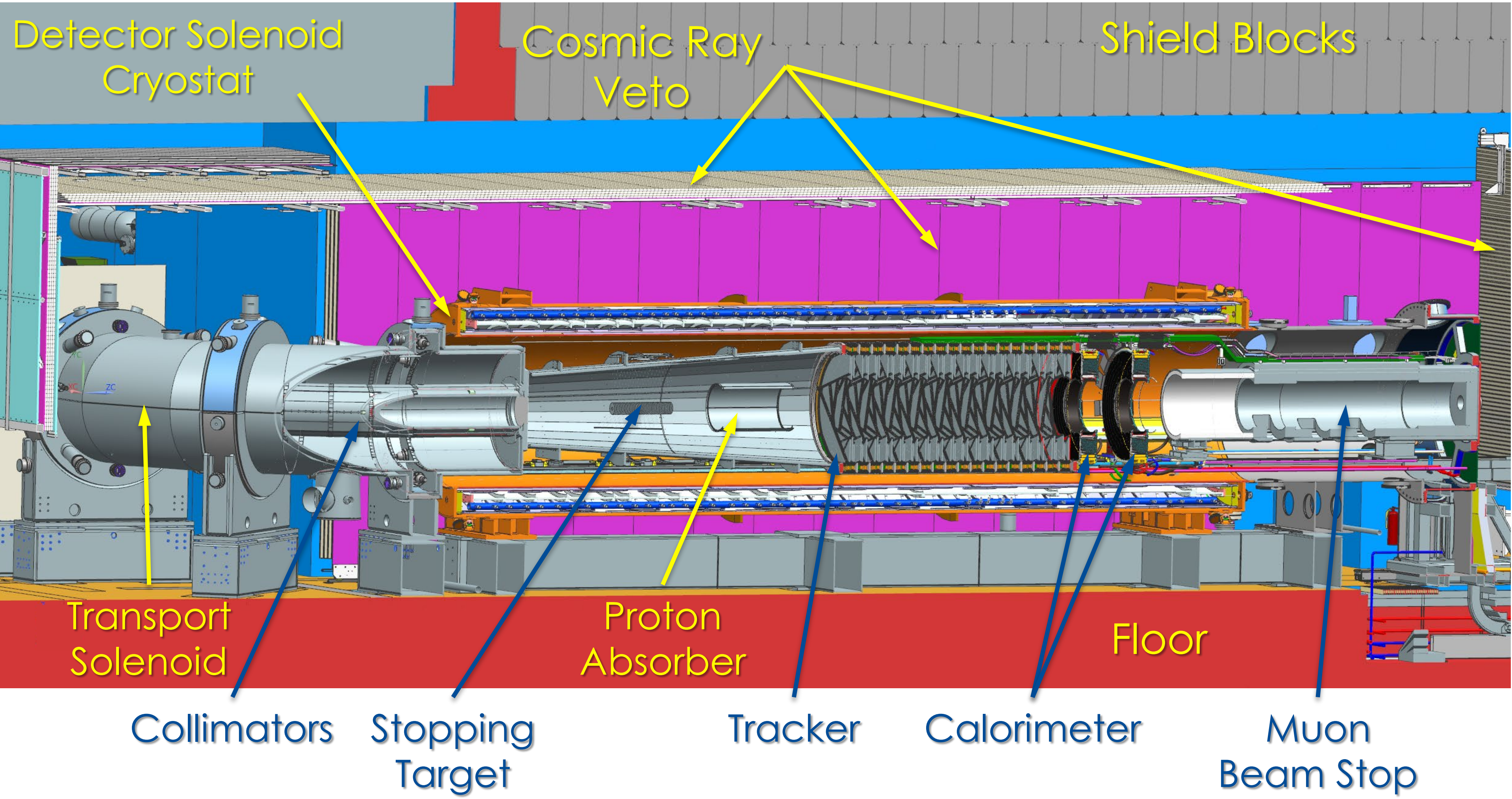
- ~ 0.0015 stopped μ^-/POT
- 10^{10} Hz of stopped muons

Reduction of Prompt Backgrounds



- Beam flash decays within 600 ns
- Live gate begins after prompt signal is gone
- $\tau(\mu^-)$ in Al = 864 ns >> prompt background duration
- Out-of-time backgrounds reduced by 10^{-10} extinction factor

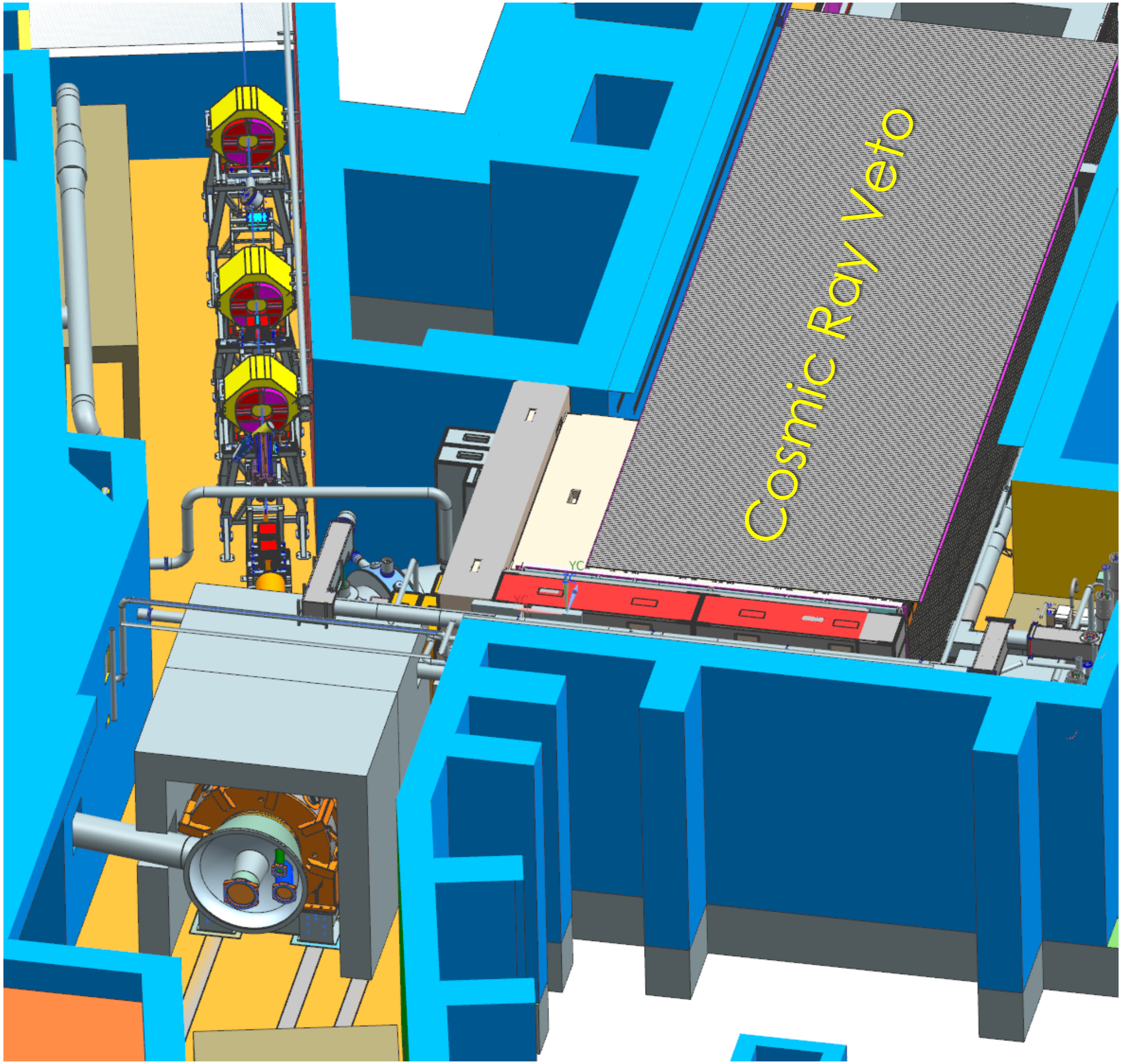
Mu2e Detector Layout



Mu2e Facility Layout

After installation of the solenoids and detectors, most of the apparatus is surrounded by shielding and covered by Cosmic Ray Veto detectors.

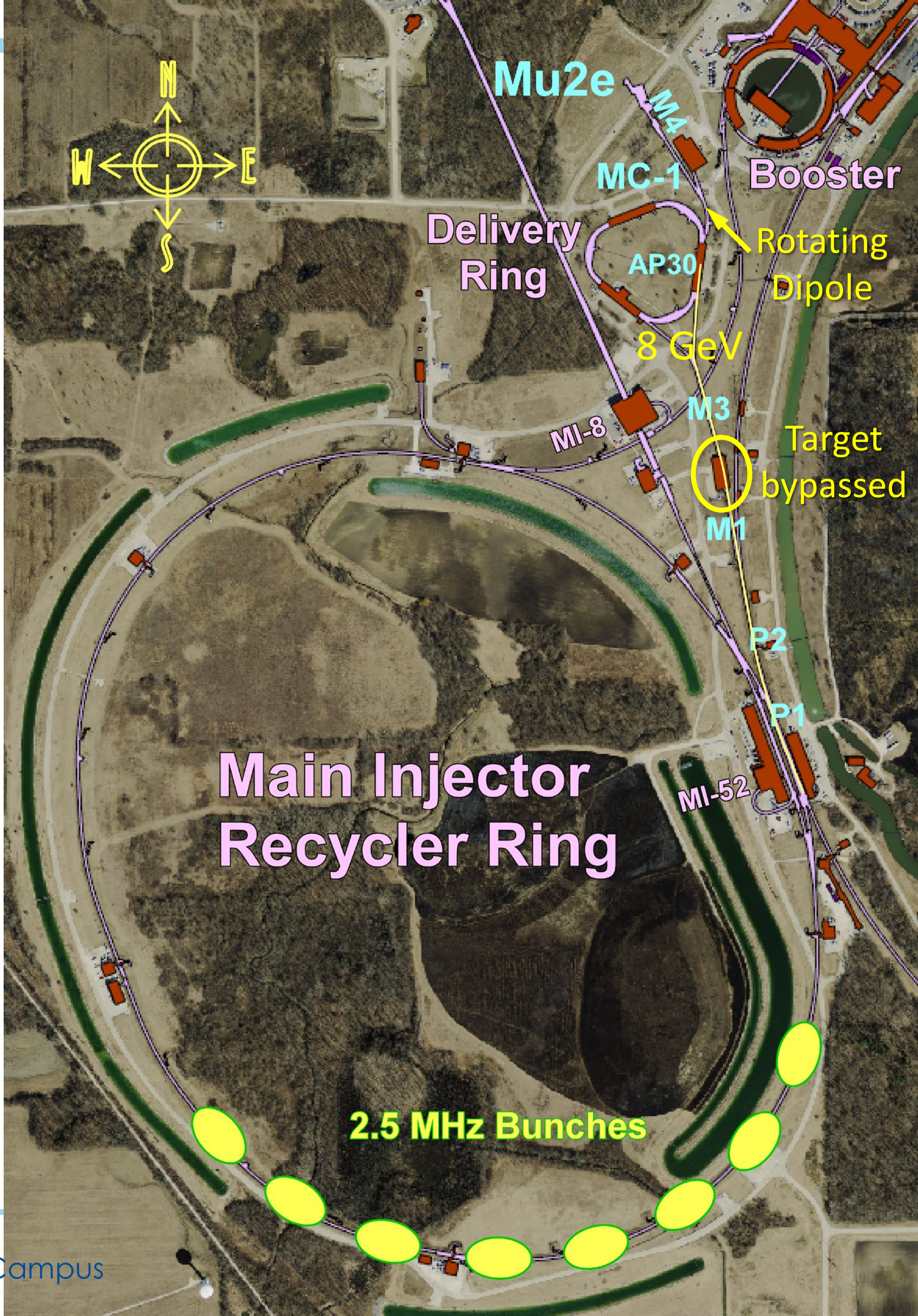
The Cosmic Ray Veto hides all of the interesting equipment, but without it we would see one CR induced conversion-electron like event per day.



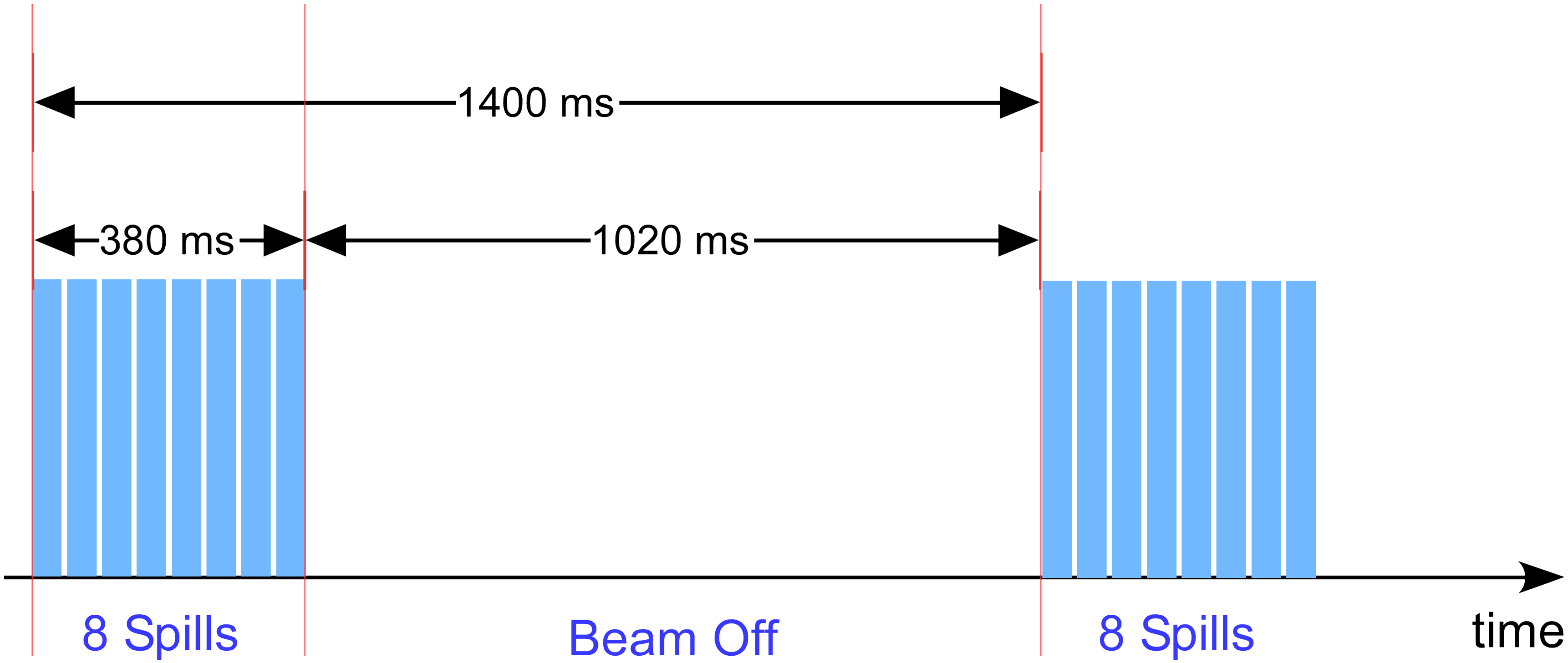
Beam Delivery to Mu2e

Proton Beam to Mu2e

- The delivery of proton beam from the Fermilab accelerator complex to the Muon Campus is similar to that of g−2.
- The target used by g−2 is bypassed
- Each 8 GeV / 2.5 MHz proton bunch is synchronously transferred to the Delivery Ring where the beam is resonantly extracted to the Mu2e proton target via the M4 beamline.
- A vertical dipole is rotated to direct beam to Mu2e via the M4 line rather than to g−2 via the M5 line.



Mu2e Proton Beam Time Structure – Design Beam Power

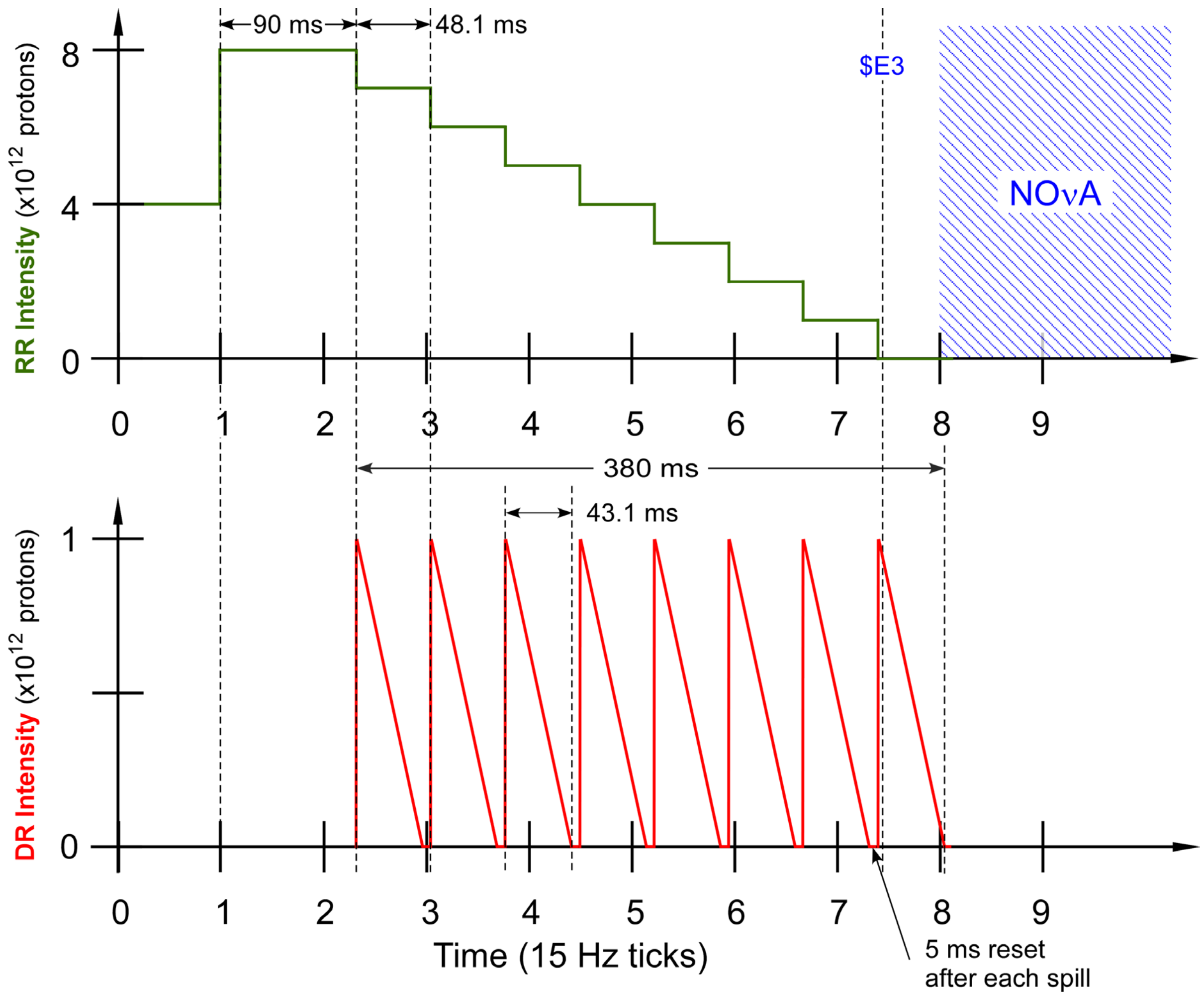


- Each of the 8 bunches from the Recycler is slow spilled to Mu2e over an interval of 380 ms
- After the 8th spill the Recycler is used for NuMI/NOνA slip-stacking

Mu2e Proton Beam Time Structure – Design Beam Power

Detailed Structure

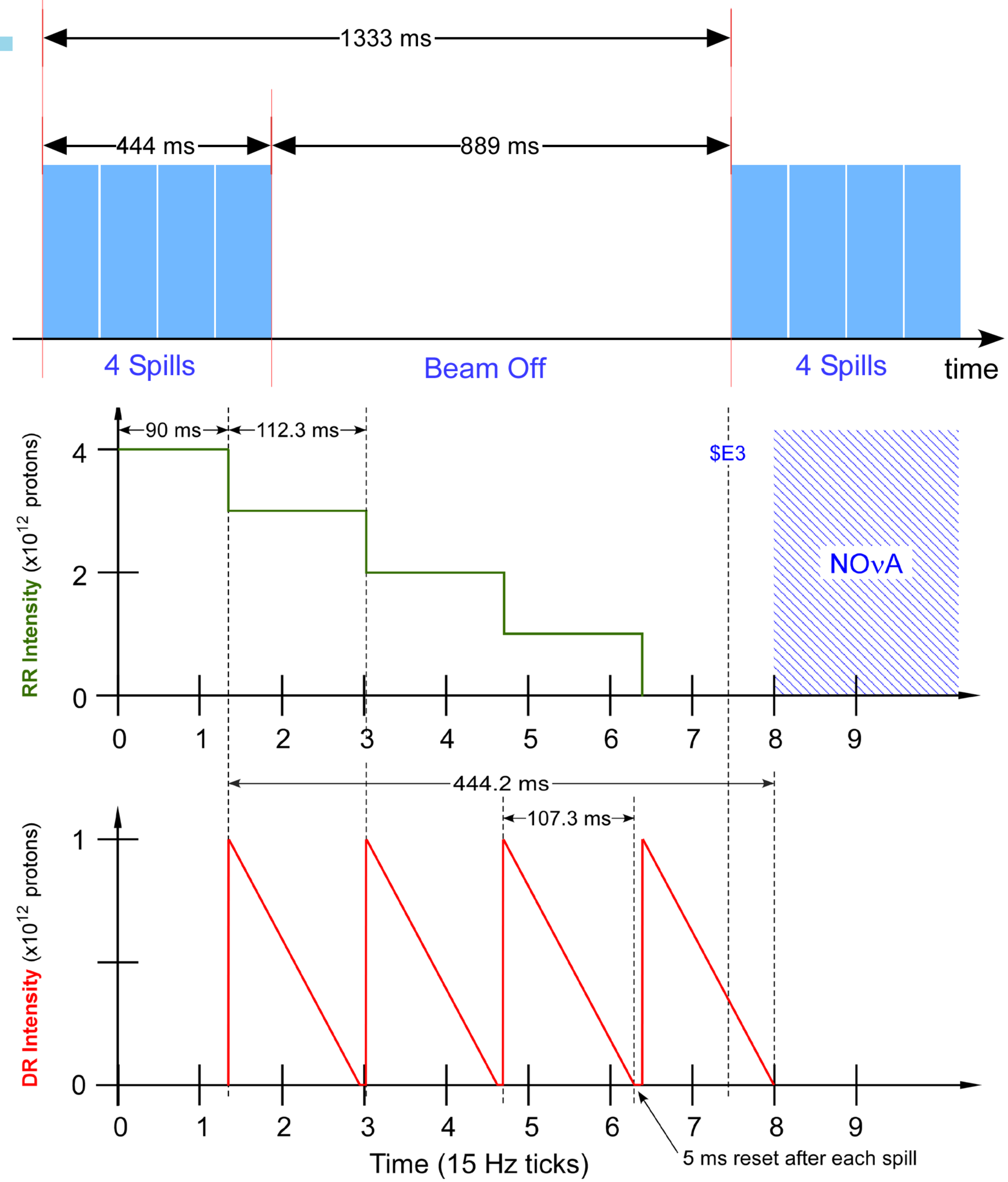
- 90 ms rebunching ramp begins after 2nd Proton batch injected into Recycler
- The resulting 8 bunches are extracted every 48 ms
- Each spill is 43 ms long with a 5 ms reset between spills



Reduced Intensity Running

- The first couple of years of running will be at reduced intensity
- For this period, only one proton batch from the Booster will be transferred to the Muon Campus for Mu2e.
- Consequently, there are only four spill of much longer duration

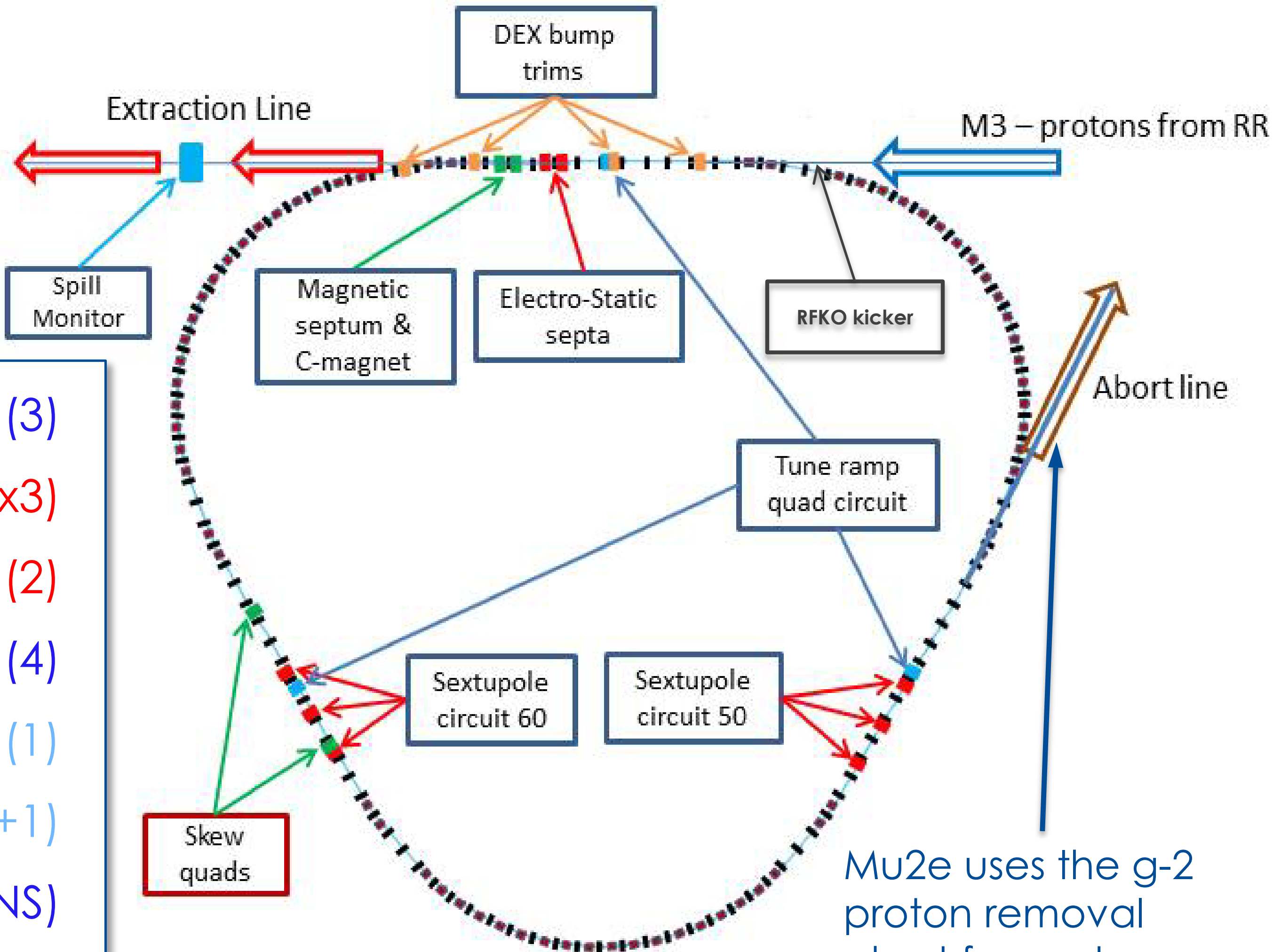
⟹ More on this later



Mu2e Resonant Extraction – Delivery Ring Equipment

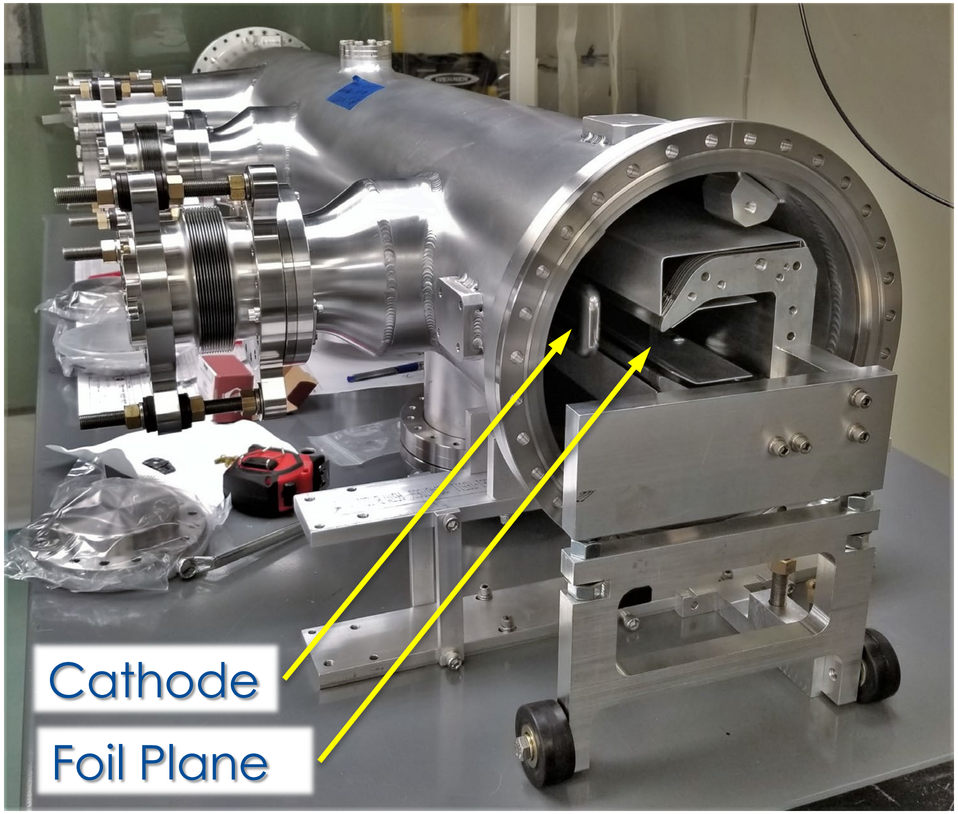
Installed by Mu2e:

- Tune ramp quads (3)
- Sextupoles (2x3)
- Electro-static Septa (2)
- DEX bump trims (4)
- RFKO kicker (1)
- Spill Monitor (1+1+1)
- Spill Regulation (NS)
- Skew quads (2)



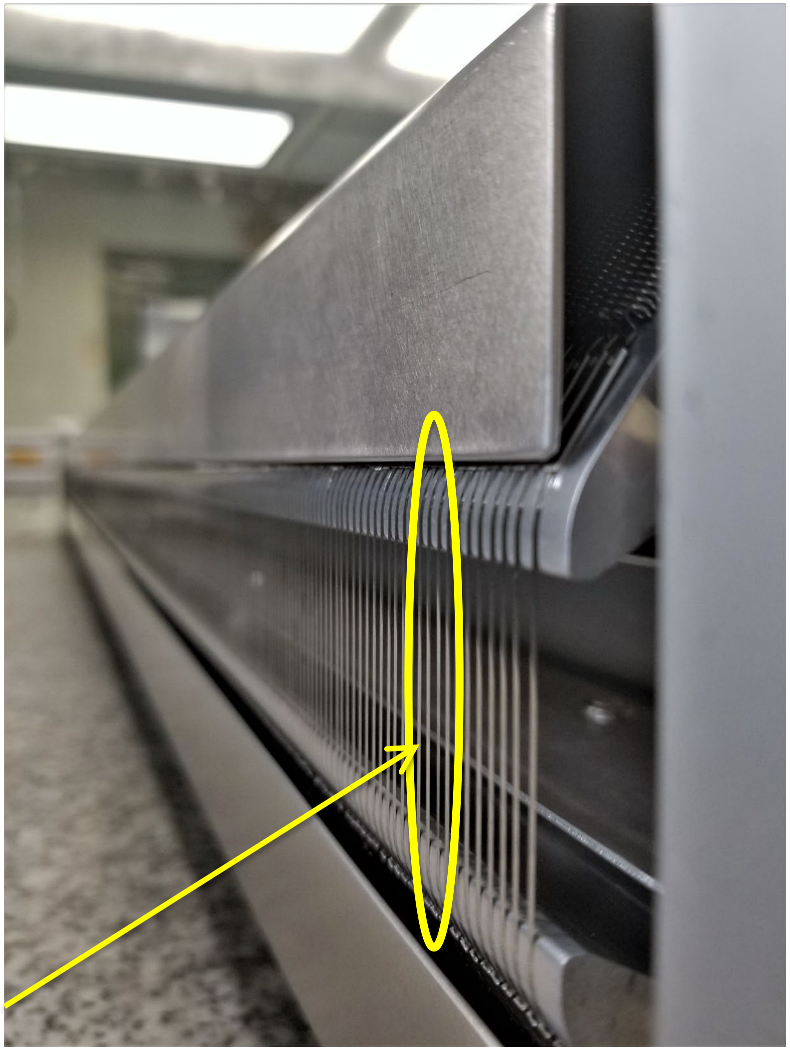
Mu2e uses the g-2 proton removal abort for post-extraction clean-up

Electro-static Septum Prototype Construction



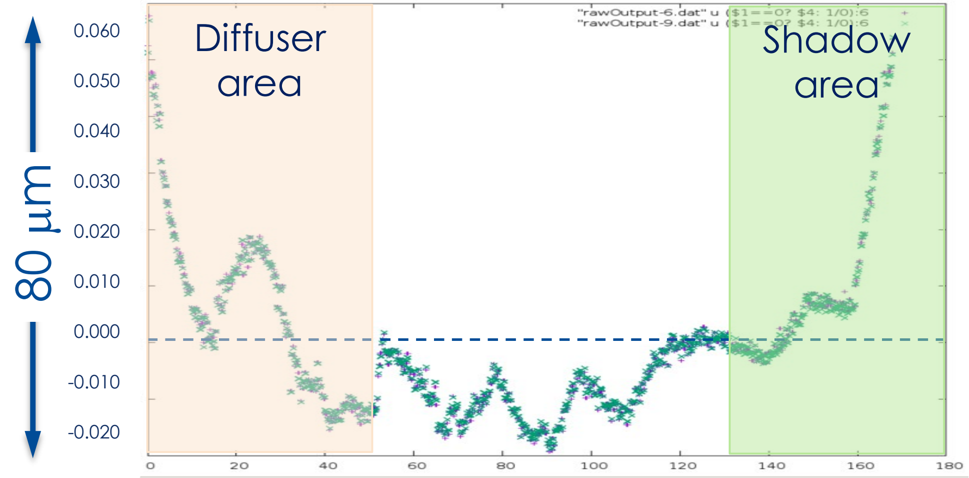
ESS Prototype Assembly

Yes, we know about this one



ESS Foil Plane

Foil Plane Measurements



Septum Plane Profile

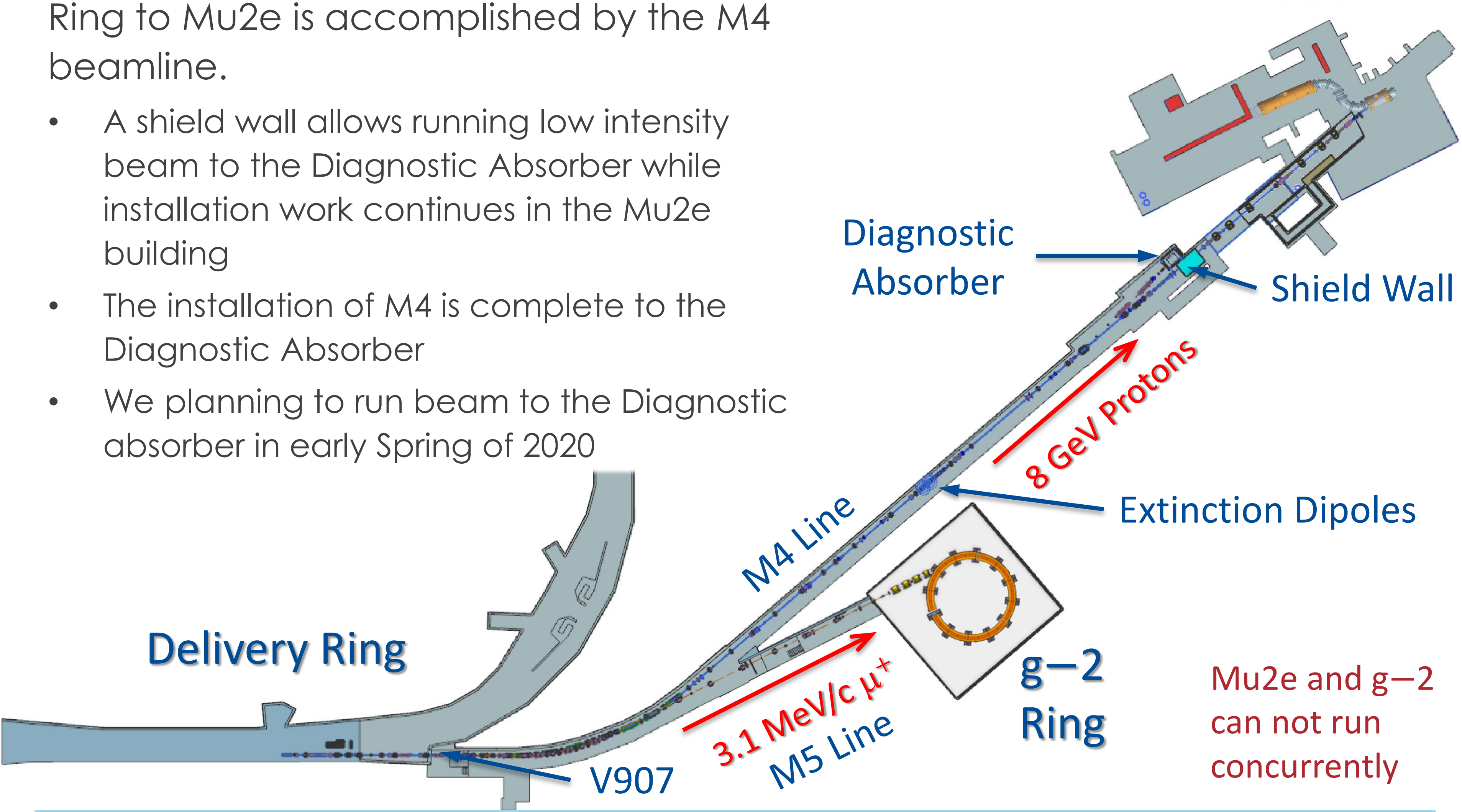
Foils

- 1 mm wide × 25 μ thick
- Material: Tungsten (alloyed with Re)
- Effective thickness goal: 50 μ

M4 Beamline Layout

Proton beam transport from the Delivery Ring to Mu2e is accomplished by the M4 beamline.

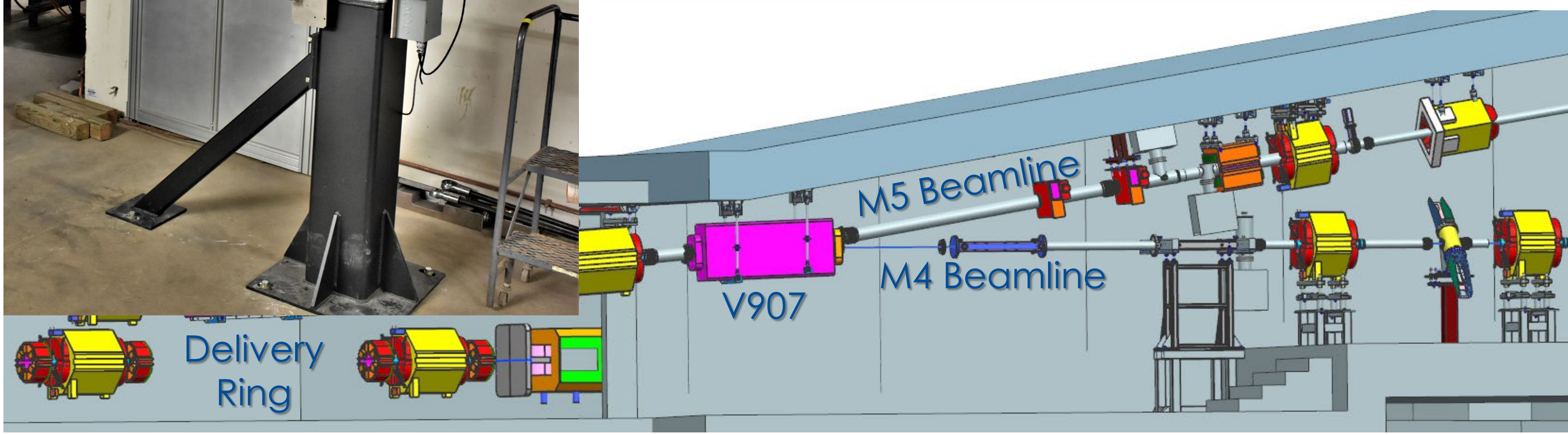
- A shield wall allows running low intensity beam to the Diagnostic Absorber while installation work continues in the Mu2e building
- The installation of M4 is complete to the Diagnostic Absorber
- We planning to run beam to the Diagnostic absorber in early Spring of 2020



Mu2e and g−2 can not run concurrently

Rotating Dipole to Switch Between g–2 and Mu2e

V907 is a vertical dipole
- pitched up to run muon beam to g-2
- pitched down to run protons to Mu2e

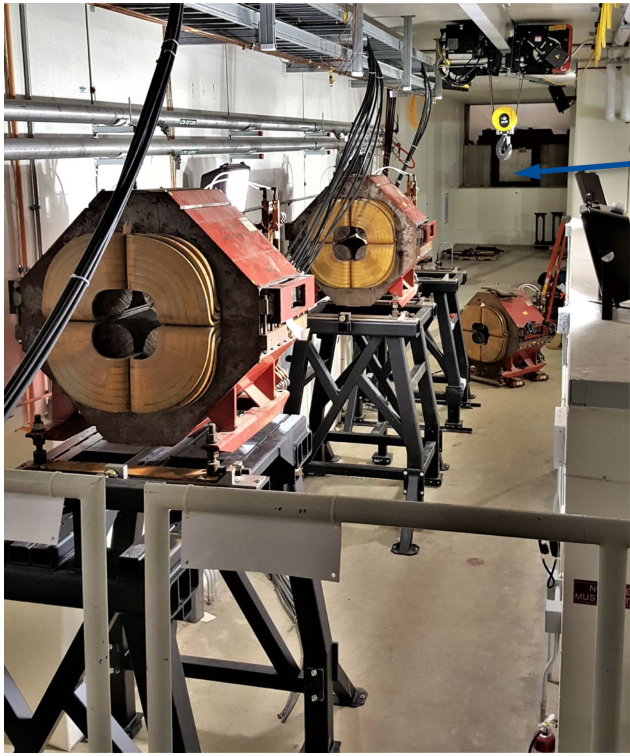


M4 Beamline Construction

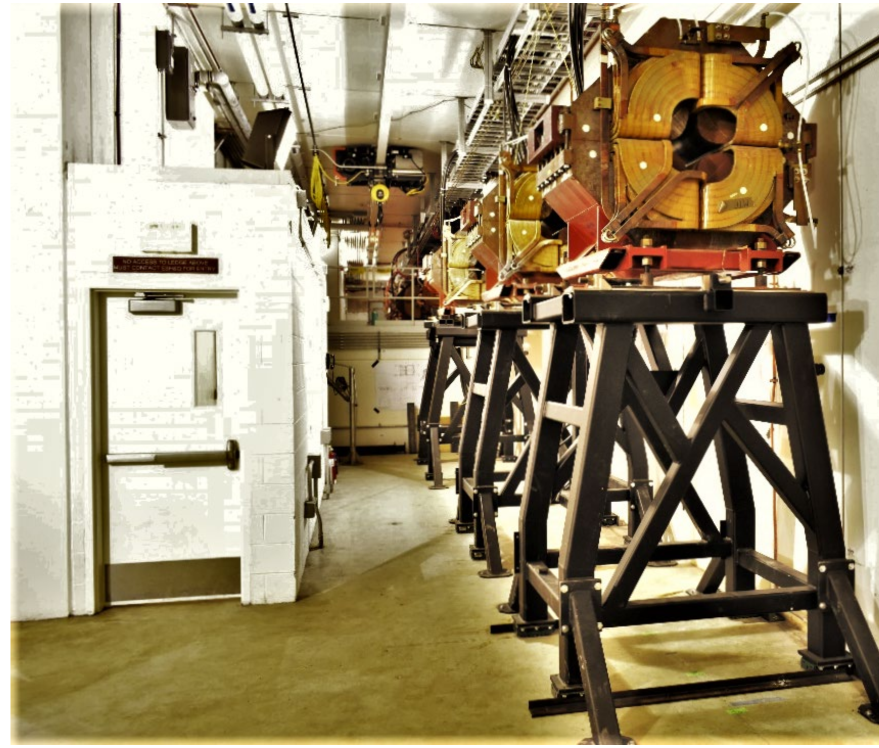
Portion of beamline leading up to the diagnostic absorber.

This part of the M4 beamline is now complete and under vacuum.

M4 Beamline Construction Progress – Final Focus



Target Dump



Final focus quadrupole installation

Viewed looking downstream toward proton target

Final focus quadrupoles

Viewed looking upstream from Production Solenoid

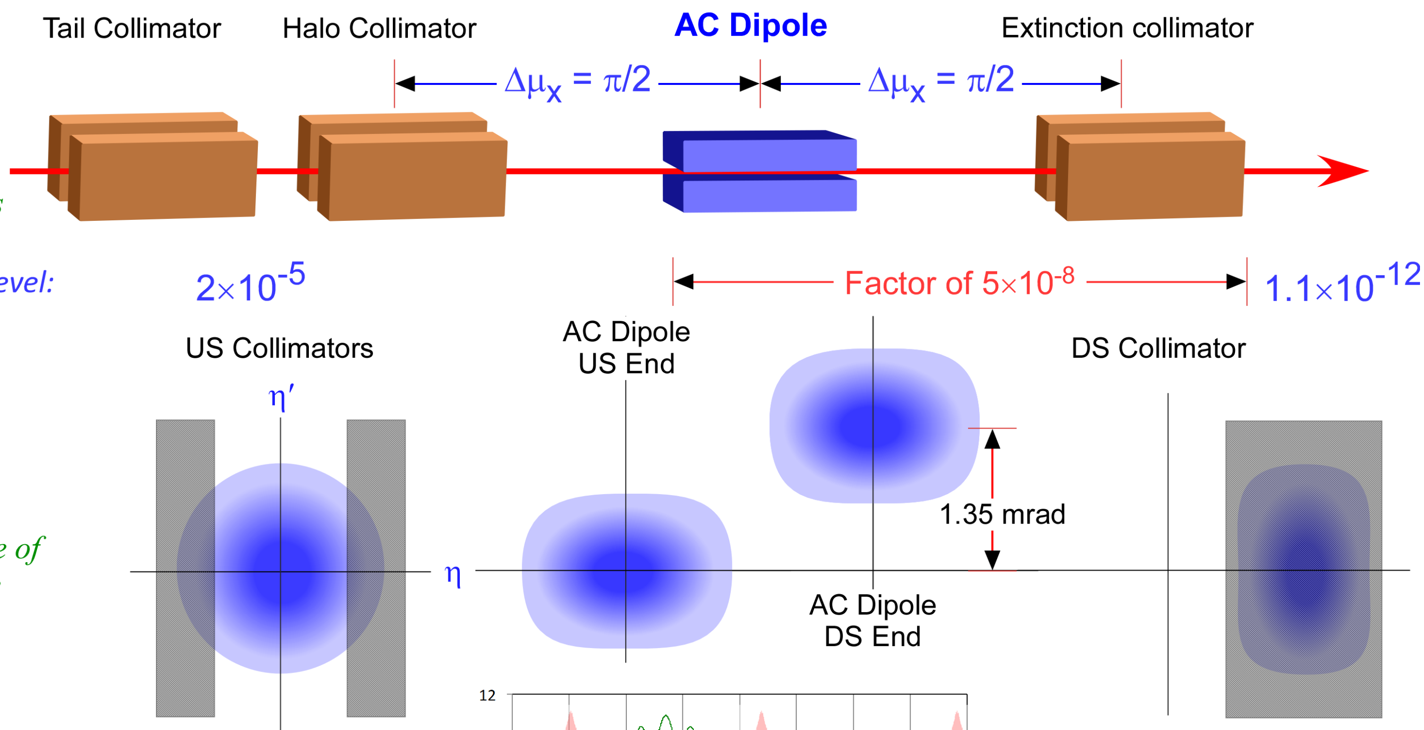
The final focus section is the only part of the M4 beamline where significant installation work remains

Extinction

External Beamline Extinction Components

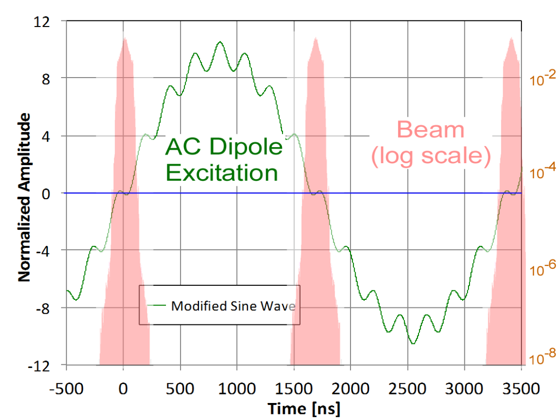
Extinction Level:

Normalized Phase Space of Out-of-Time Beam



AC Dipole Excitation

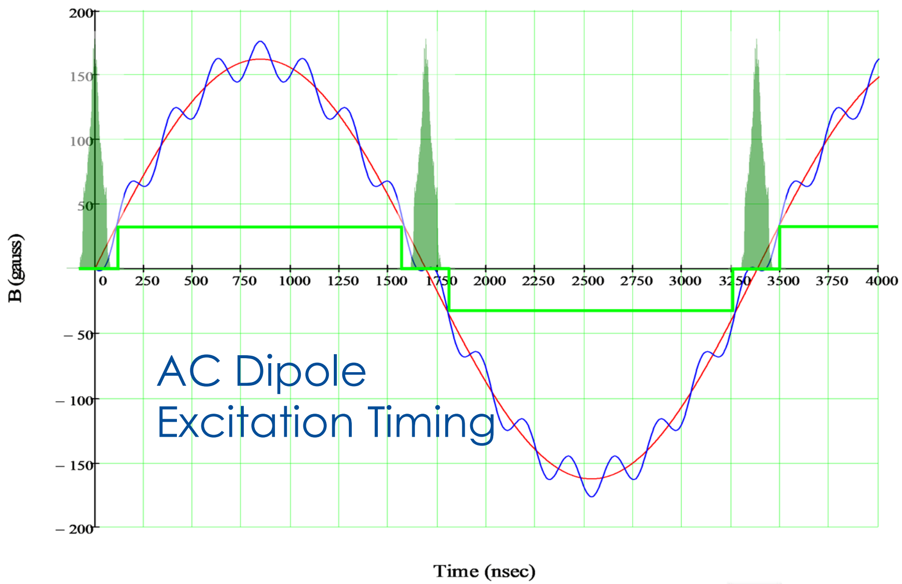
The AC Dipole excitation is a superposition of two harmonics: 295 kHz and 4.4 MHz that aresynchronized to the beam.



Proton beam pulses shown in pink.

AC Dipole waveform shown in green

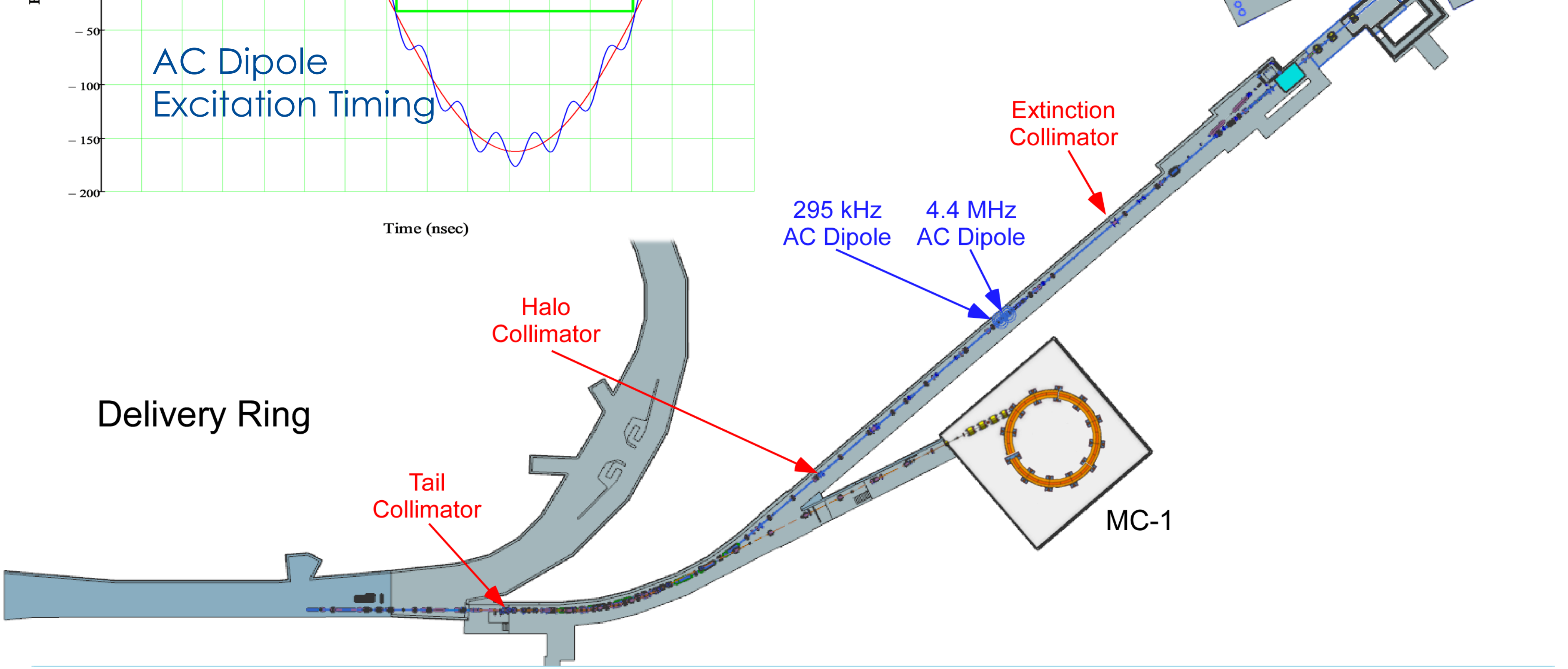
Extinction System Layout



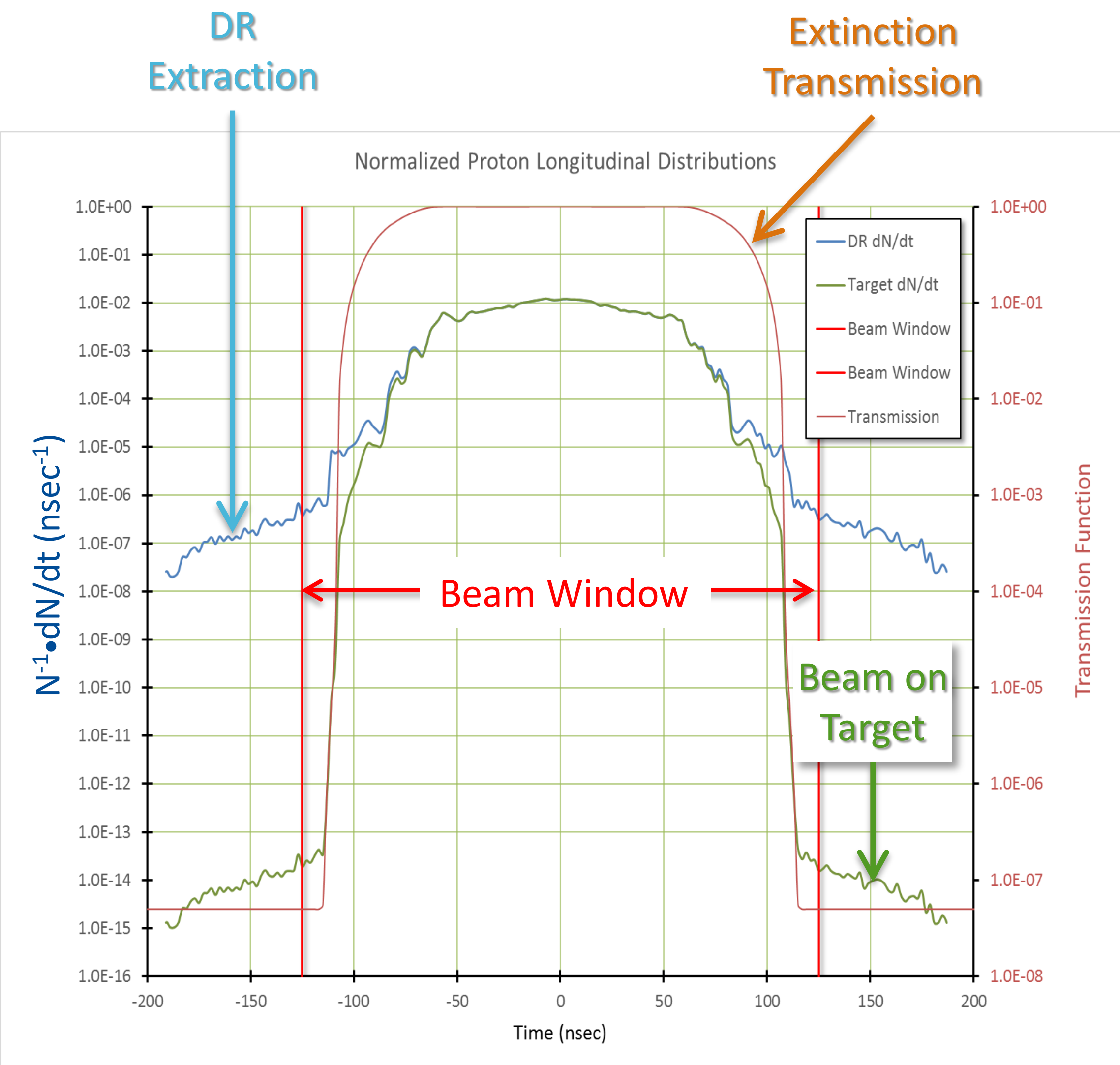
Delivery Ring f_{rev} = 590 kHz

AC Dipole components:

- 295 kHz
- 4.4 MHz



Extinction Simulated Performance



Simulation Results

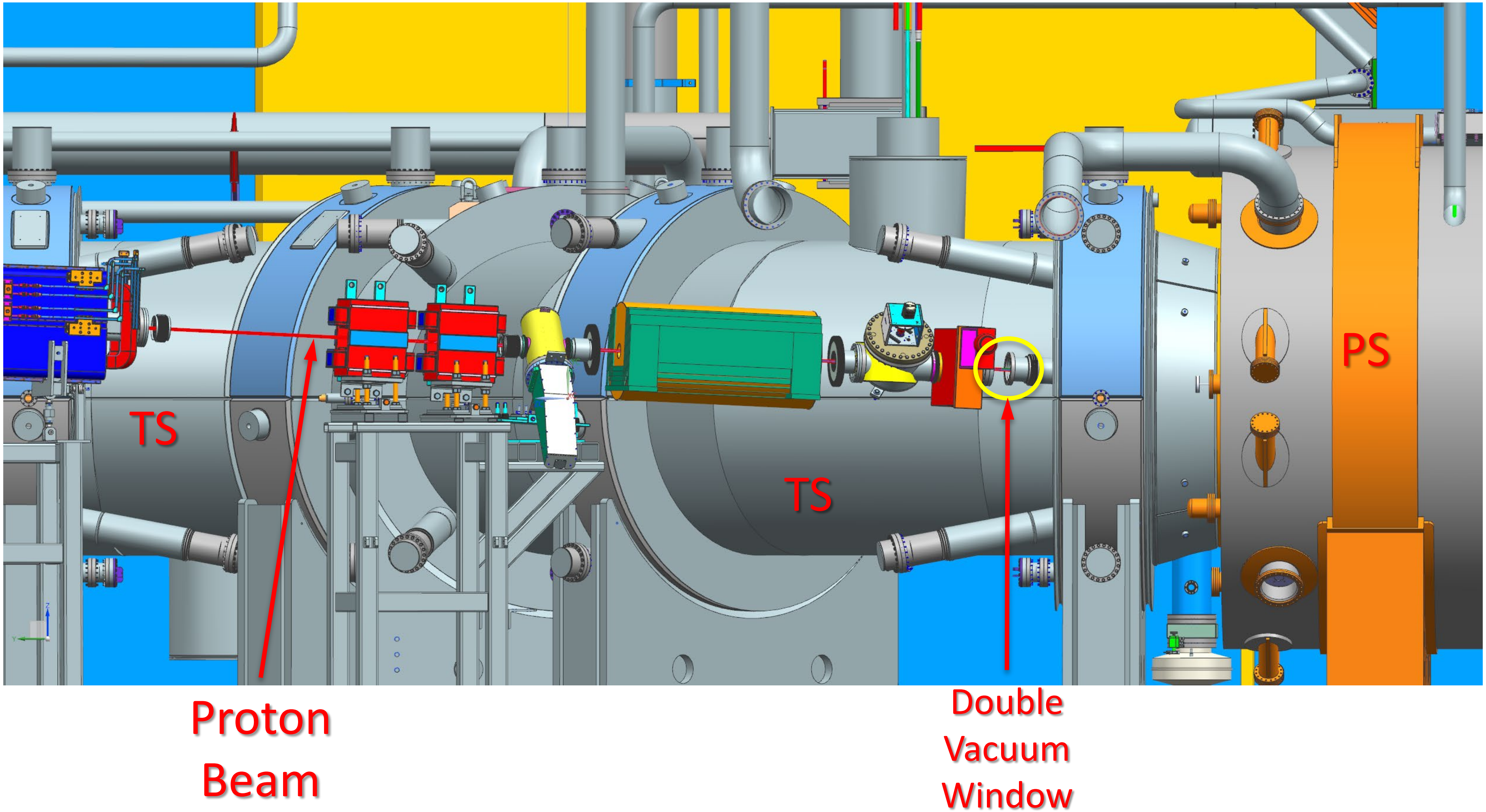
Fraction of DR extracted beam outside of ±125 ns:	2.1×10^{-5}
In-time beam transmission:	99.5%
Beam line extinction:	$<5\times10^{-8}$
Total extinction:	**1.1×10^{-12}**
Extinction Requirement:	$<1.0\times10^{-10}$

Almost two order of magnitude margin

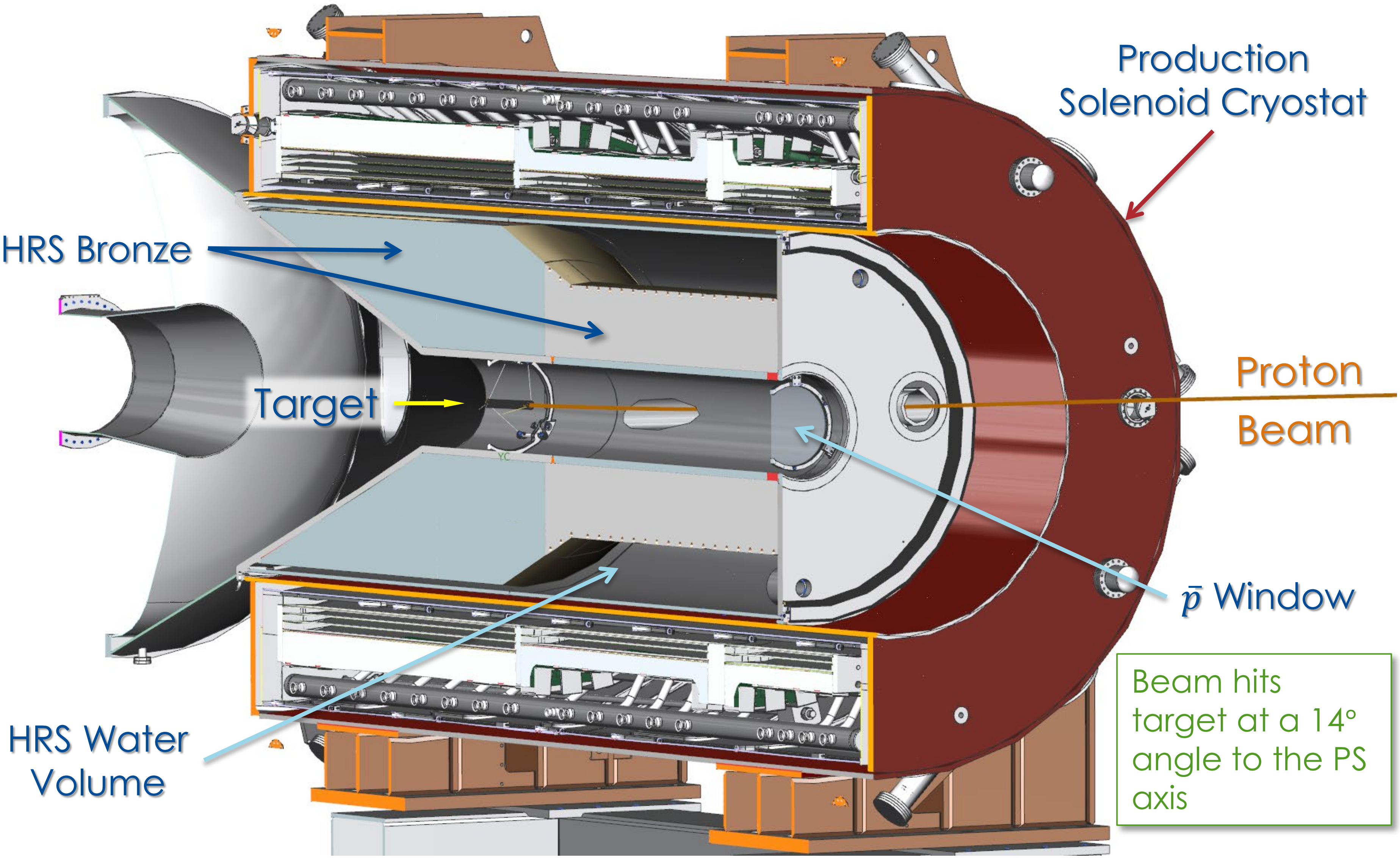
Note: the extinction system is required to provide an extinction factor of 10^{-7}. Meeting the 10^{-10} requirement of the Mu2e experiment depends on the extinction already present in the beam extracted from the Delivery Ring.

Transport into the Production Solenoid

Proton beam enters the Production Solenoid (PS) by way of a beam channel embedded in the Transport Solenoid (TS)



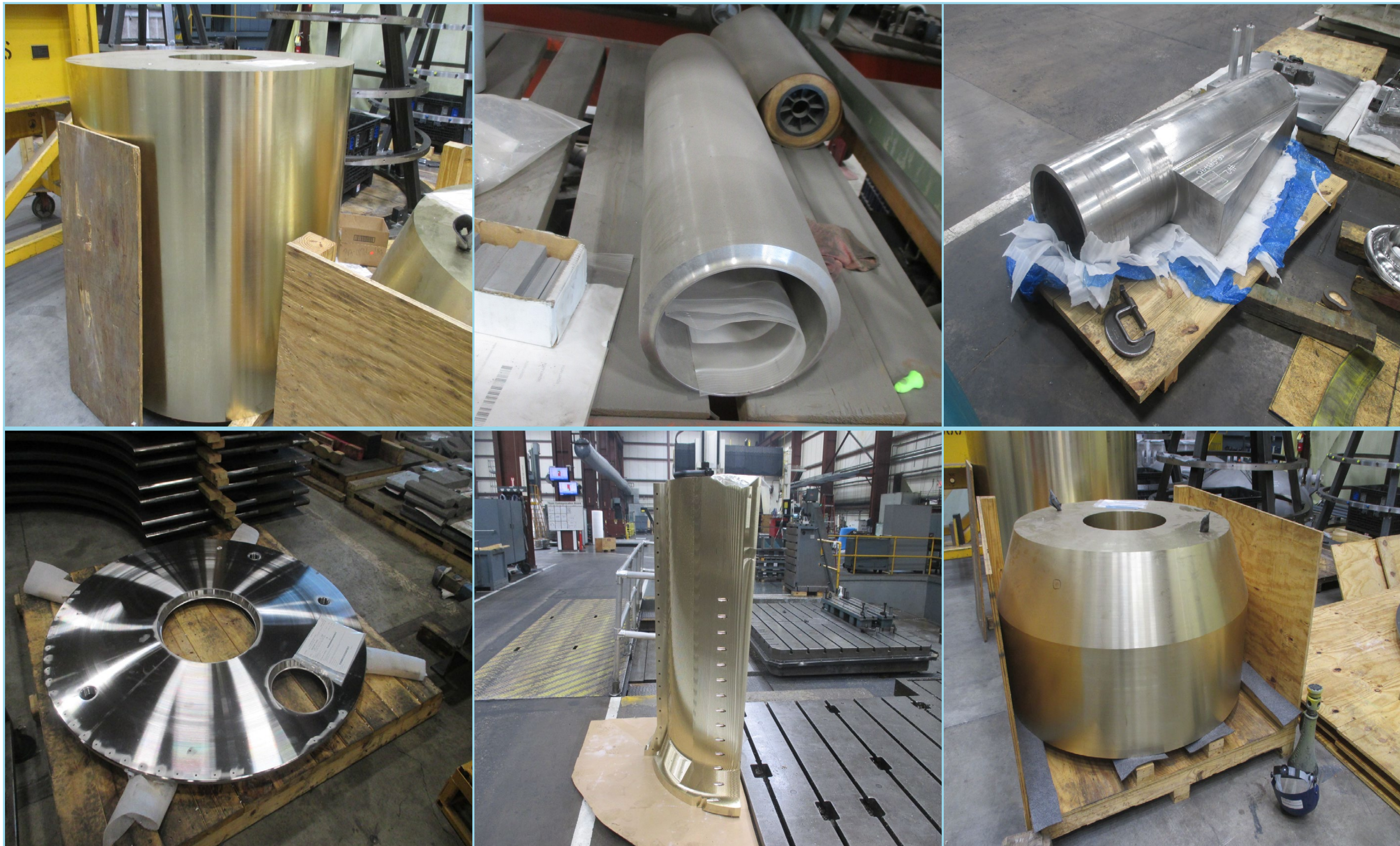
Heat and Radiation Shield (HRS)



Beam hits target at a 14° angle to the PS axis

HRS Fabrication

Delivery Expected in February 2020

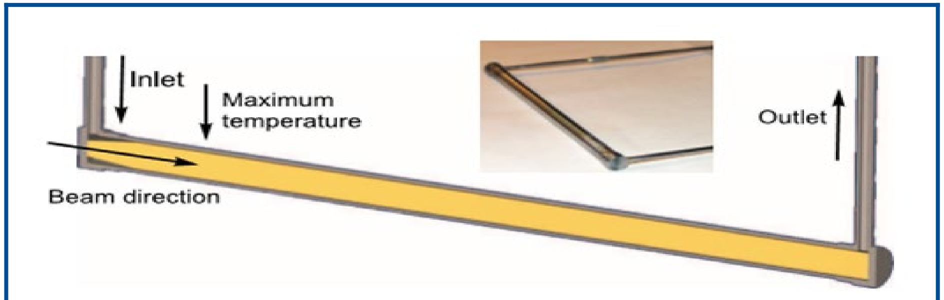


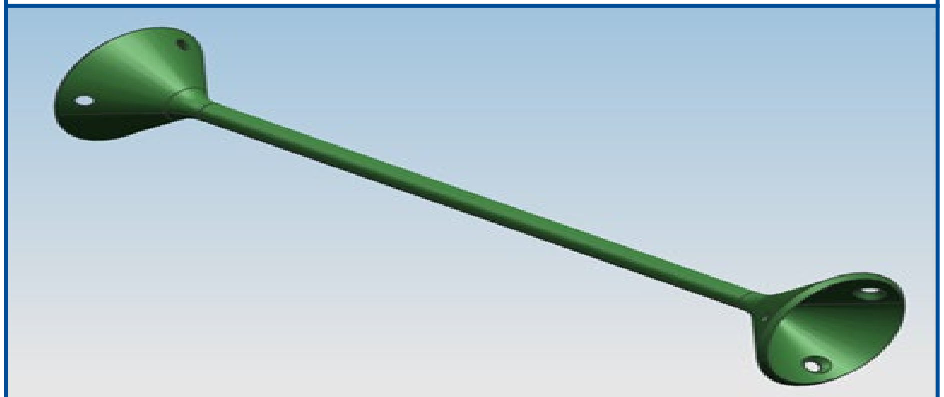
Pictures courtesy of Major Tool & Machine, Indianapolis, IN

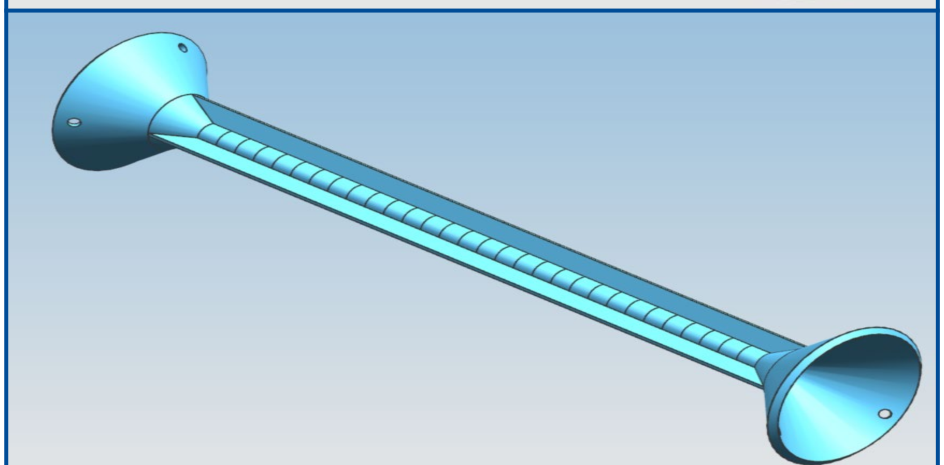
Proton Target

- Late in 2011 the decision was made to reduce the proton average beam power from 25 kW to 8 kW – this was done to reduce costs
- At that time we began investigating the possibility of implementing a radiatively cooled target rather than the original water-cooled gold target
- In 2012 we abandoned water cooling and incorporated radiative cooling into the design of the Mu2e proton target
- We chose tungsten as the target material
- At the time the radiative cooling decision was made, we had no idea of the magnitude of the technical challenges that we would face – there were many occasions to doubt the wisdom of our decision
  - fatigue stress from the cyclic 1 Hz ⊕ 20 Hz time structure of the beam
  - oxidation at high temperature (peak temp. at design beam power = 1700°C)
  - water cycle erosion of tungsten ($2W + 3O_2 \rightarrow 2WO_3$)
  - recrystallization of tungsten above ~1300°C
  - ductility of tungsten at high temperature gives rise to creep anywhere there is a bending moment (i.e. gravity and support structure)

Initial Target Design Attempts





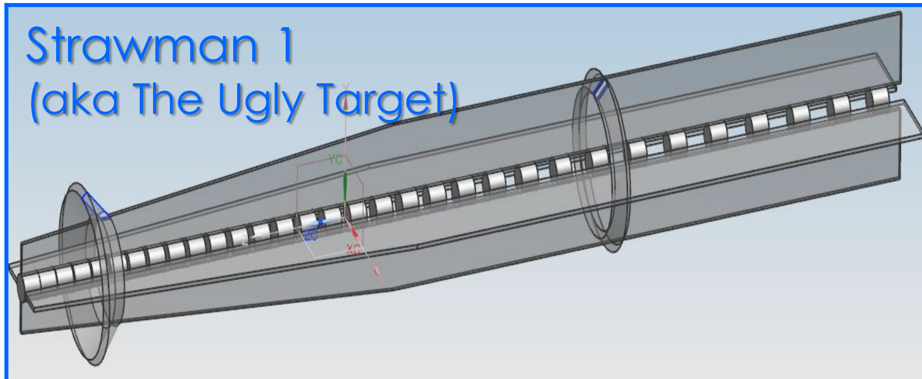


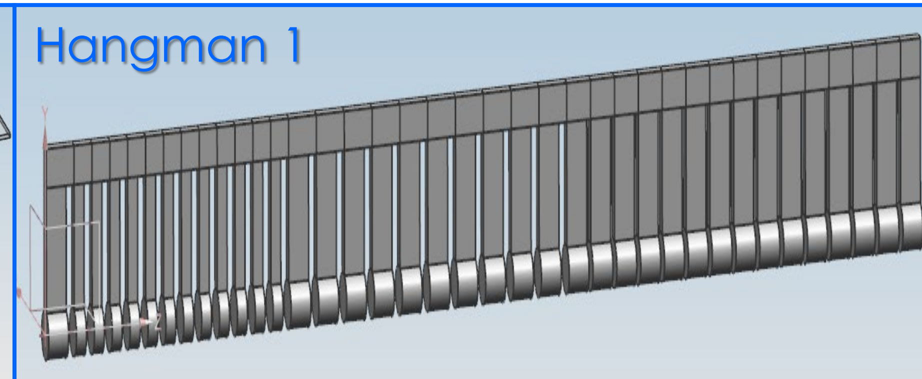
Mu2e Proposal target (c. 2008)
- Titanium encased gold
- Water cooled
- 25 kW beam power

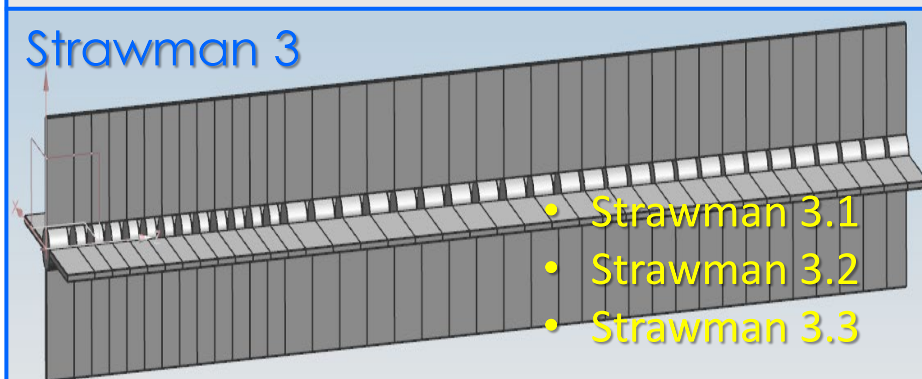
Baseline Design Target (2012-14)
- Tungsten
- Radiatively cooled
- 8 kW beam power
- 0.001626 μ/POT

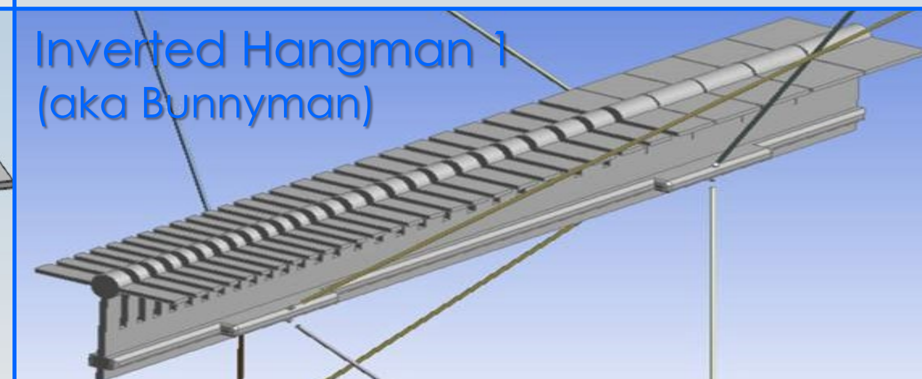
T1 Milestone Target (2018)
– we built this one
- Tungsten rod + 3 fins
- Radiatively cooled
- 8 kW beam power (would not last the required one year lifetime)
- 0.001521 μ/POT
- Completed 26 July 2018

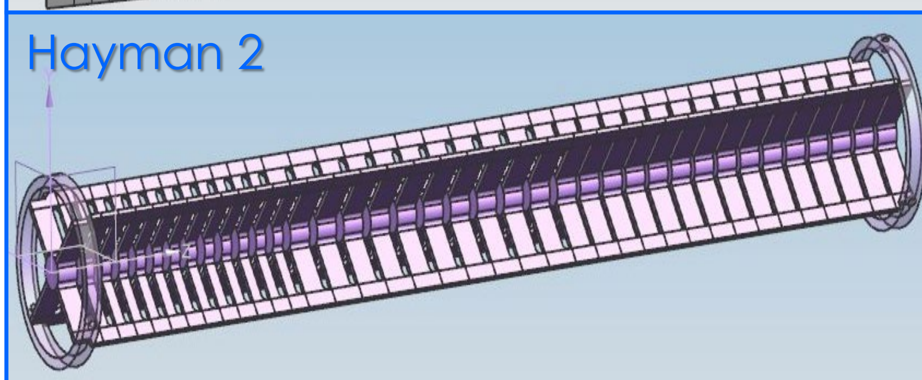
A Year of Target Design Iterations





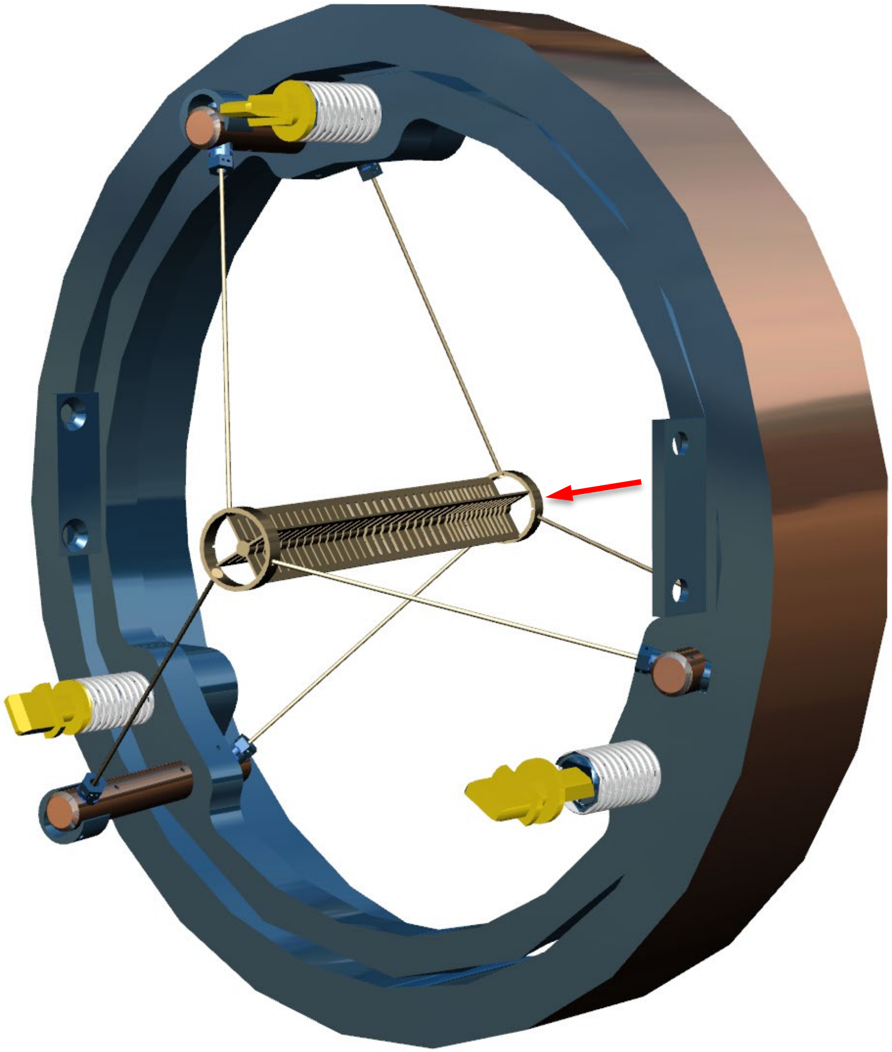




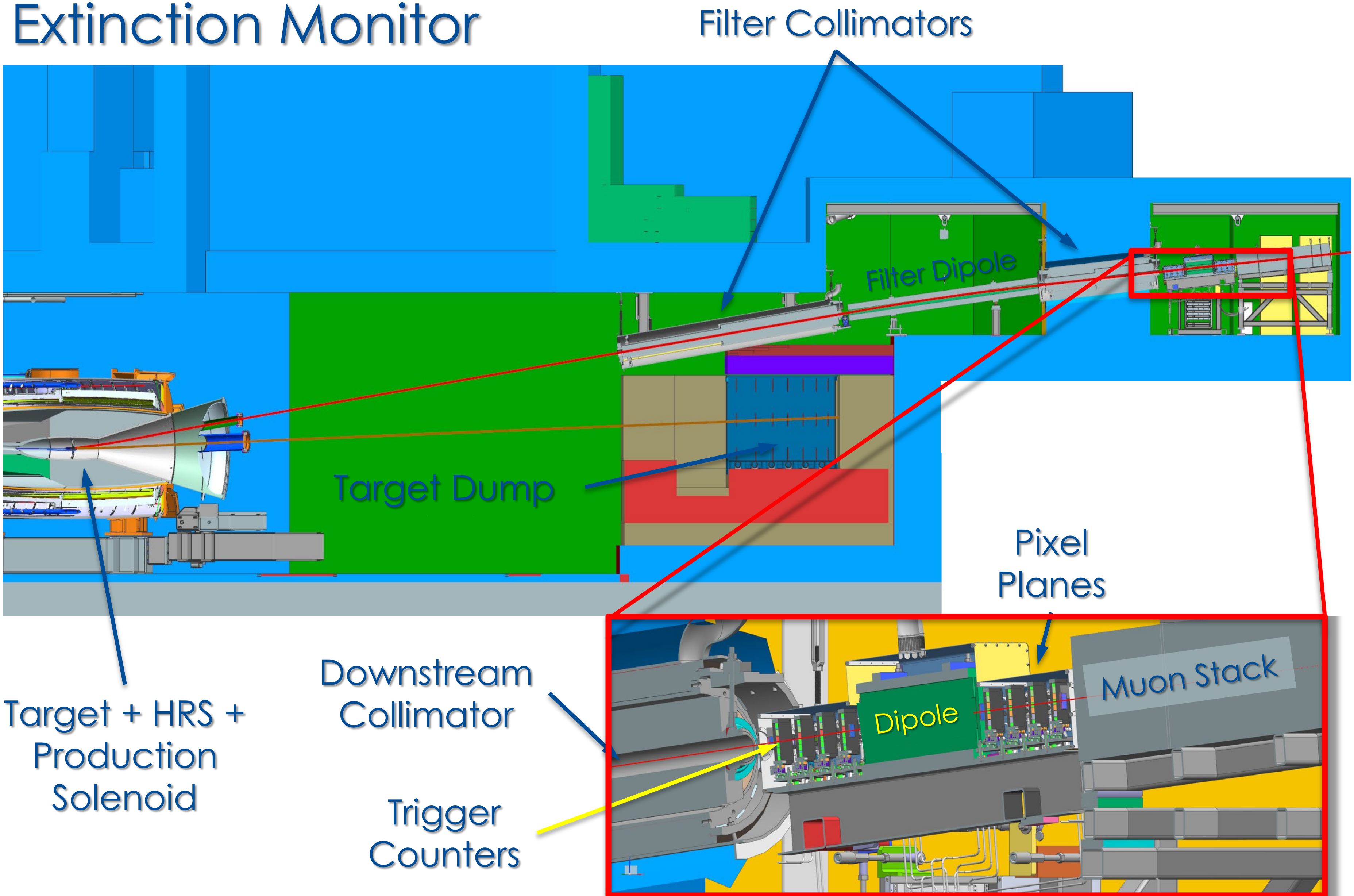


Final Target Design

- Radiatively cooled
- Peak temperature = 1130°C
  (@ 8 kW proton beam power)
- Variable length segmented core and fins to control longitudinal temperature profile
- Four 1mm thick × 13mm tall fins, angled to minimize interference with Extinction Monitor view of target.
- Extended mounting bars on outside ring to minimize bending moment on target
- Stopped muon yield = 0.0015 μ/POT
- *Ready to start procurement and fabrication after final reviews*



Extinction Monitor



Mu2e Construction Status & Future Plans

Mu2e Detector Hall Today

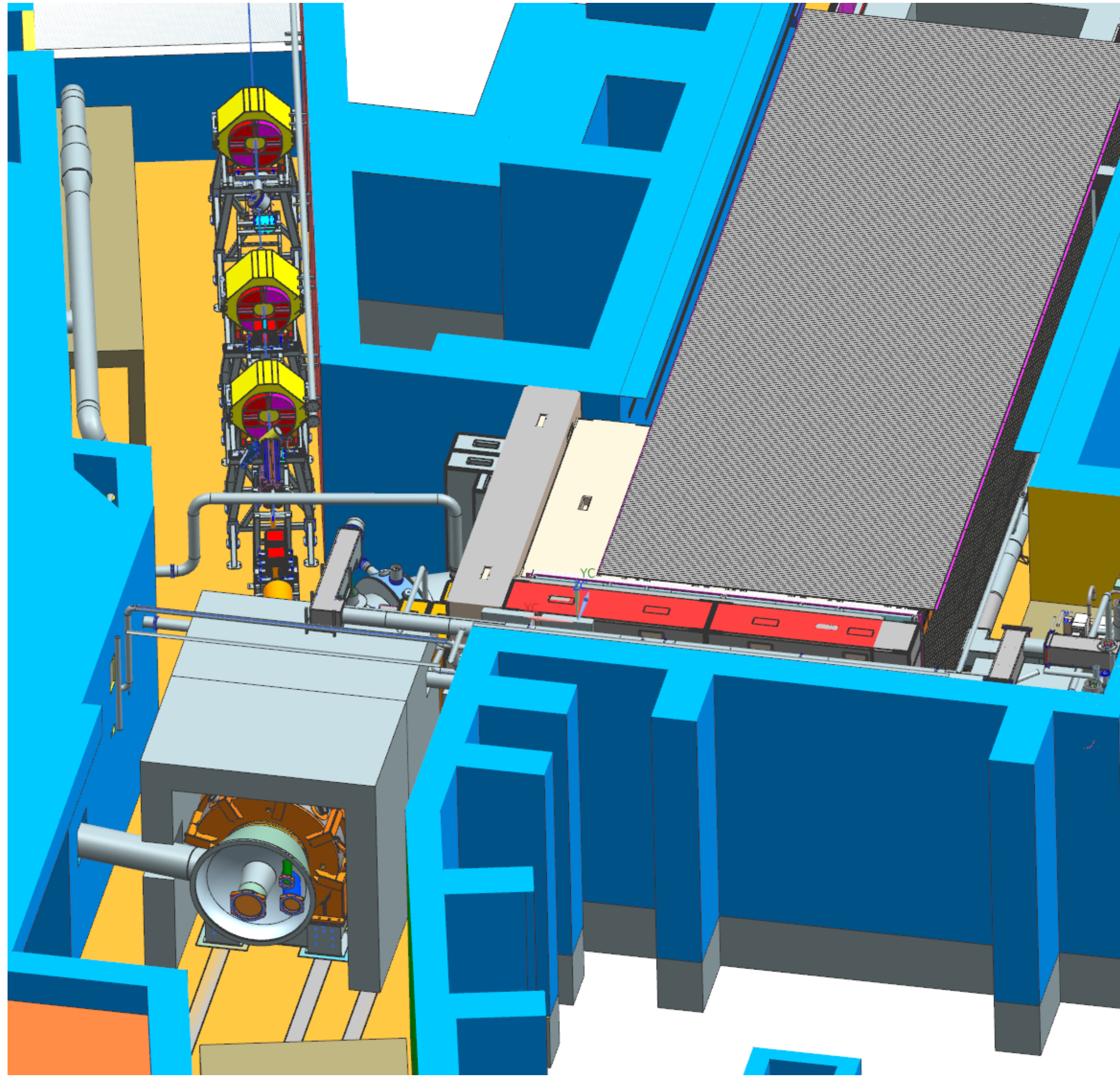
This is the present state of solenoid and detector installation in the Mu2e building.

We have much work to do!

A Little over Two Years from Now

Mu2e should be ready to begin commissioning with beam in approximately two years. Before then we will:

- Install and field map all of the solenoids
- Install the muon stopping target, tracker, and calorimeter in the Detector Solenoid
- Install HRS and the proton target inside of the Production Solenoid.
- Cover the entire apparatus with concrete shielding
- Install the Cosmic Ray Veto



Solenoid Financial Setbacks

There have been two serious setbacks associated with the Mu2e solenoids:

1. General Atomics had to completely revise the way the PS and DS superconducting coils were wound resulting a significant cost overrun and schedule delay
   – $3.1 M over budget
   – 2 year delay (this is extremely expensive)
   – More cost overruns and delays are likely
   – The good news: Coil winding issues appear to have been resolved
2. Vendor bid for the TS cryostat was significantly above our original estimate
   – $2.5 M over budget

Mu2e Project and Collaboration Response to Cost and Schedule Issues

To cut costs, there was an effort to investigate areas where some project scope could be deferred until later (and funded off-project)

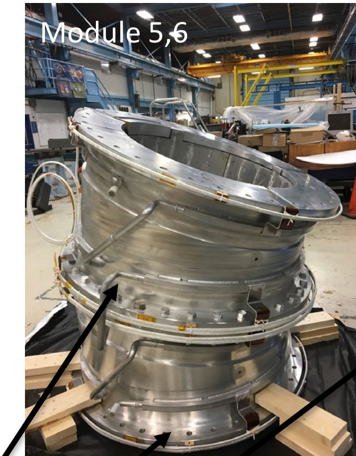
- The following changes were adopted:
  - The specialty concrete shielding around the detector will be implemented with ordinary concrete (saves $1.7 M)
  - Reduce the number of installation hatch shielding blocks by 50% (saves $0.4 M)
  - Eliminate cold testing of the assembled TS magnets (saves $0.5M) (Note: individual modules are still tested)
- Fermilab has agreed to by back the solenoid cryo-testing facility built by the project ($6M)
- *The shielding compromises will require running at ½ of design beam power until the shielding can be upgraded*

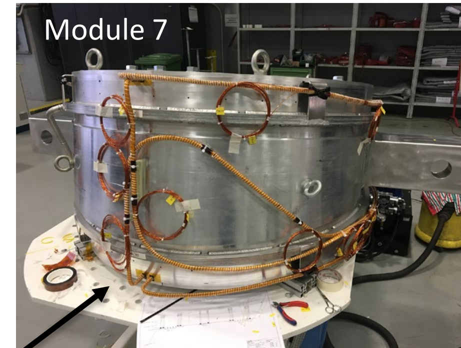
Progress

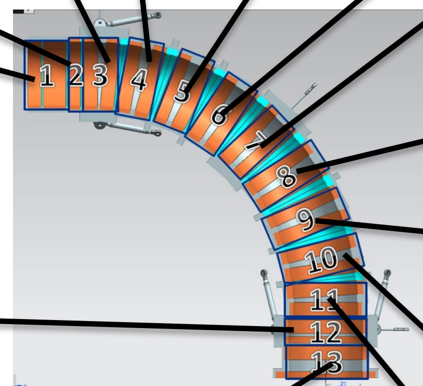
Despite the setbacks, there has been significant progress toward completion of the Mu2e project

- Superconducting coil winding of the DS and PS is proceeding
- TS cold mass and cryostat fabrication are nearing completion (April 2020)
- Mu2e detectors are well into the fabrication process

Transport Solenoid Cold Mass Production – TSu

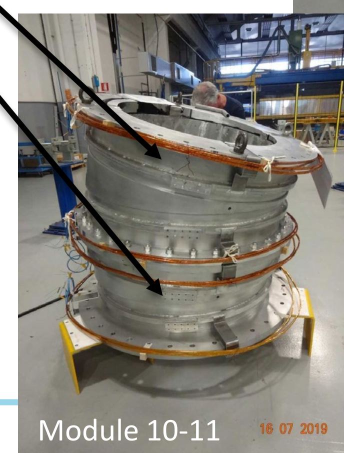






First half of TSU delivered to FNAL

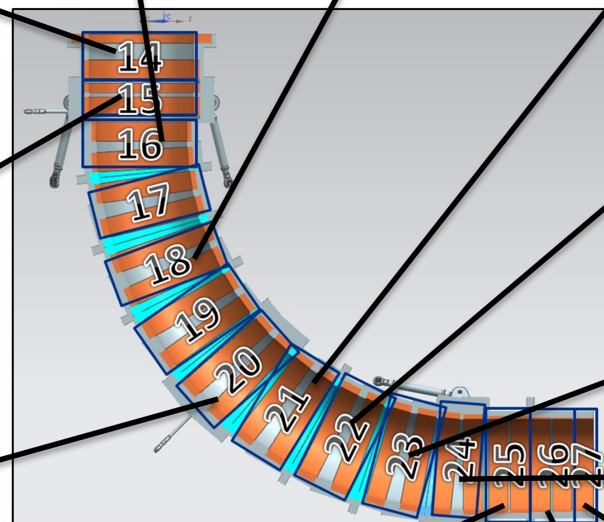
Progress on second half moving forward at a good pace.



Transport Solenoid Cold Mass Production – TSd

Module 16
- Rough machining completed

Module 18
- Rough machining completed



Module 24
- Rough machining completed
- Welding completed

Module 25
- Rough machining completed

Module 27
- Rough machining ongoing

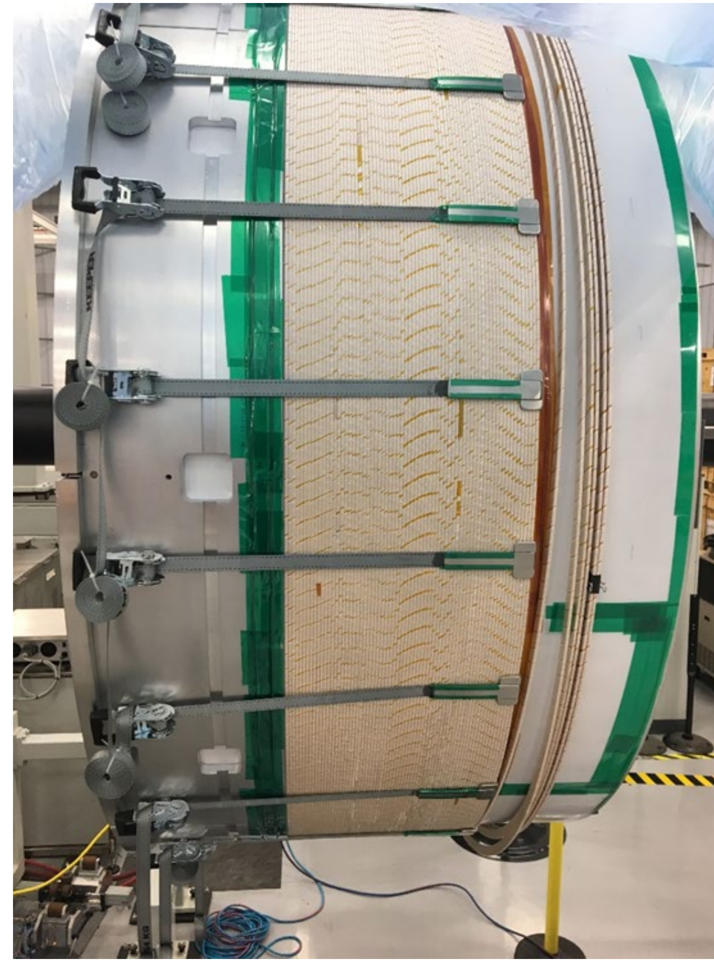
Module 26
- Rough machining completed
- Welding completed

Expect cold mass completion in April 2020

Work is ongoing on 12 out of 14 TSD modules

Production and Detector Solenoid Progress

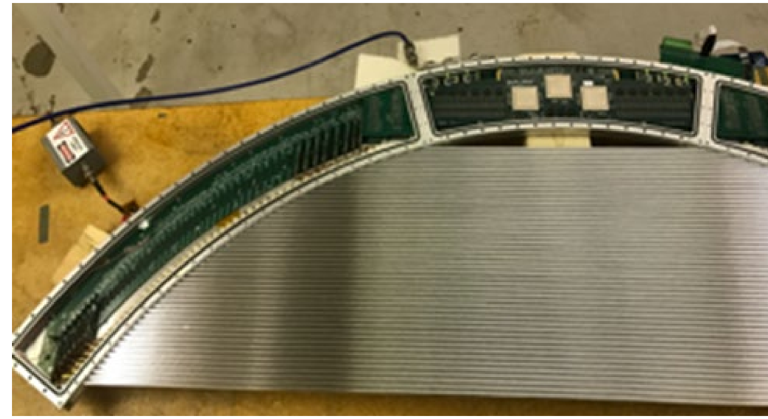
Production Solenoid Cryostat



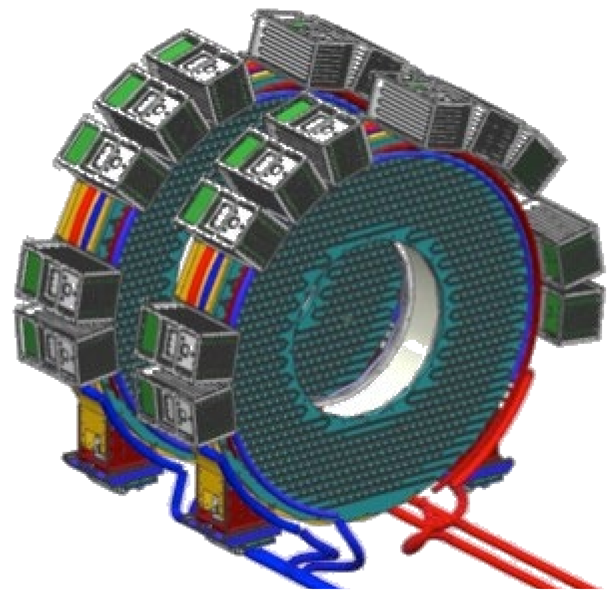
Superconducting conductor wound on a section of the Detector Solenoid

Detector Status

- Tracker
  - Difficulties getting into routine panel production mode
  - All straws have been procured
  - Expected completion: August 2021
- Calorimeter
  - Received 1185 out of 1450 BaF_2 crystals
  - Expected completion May 2021
- Cosmic Ray Veto
  - 83 panels covering an area o 335 m^2
  - High efficiency (0.9999 CR veto factor)
  - One of the last components to be installed



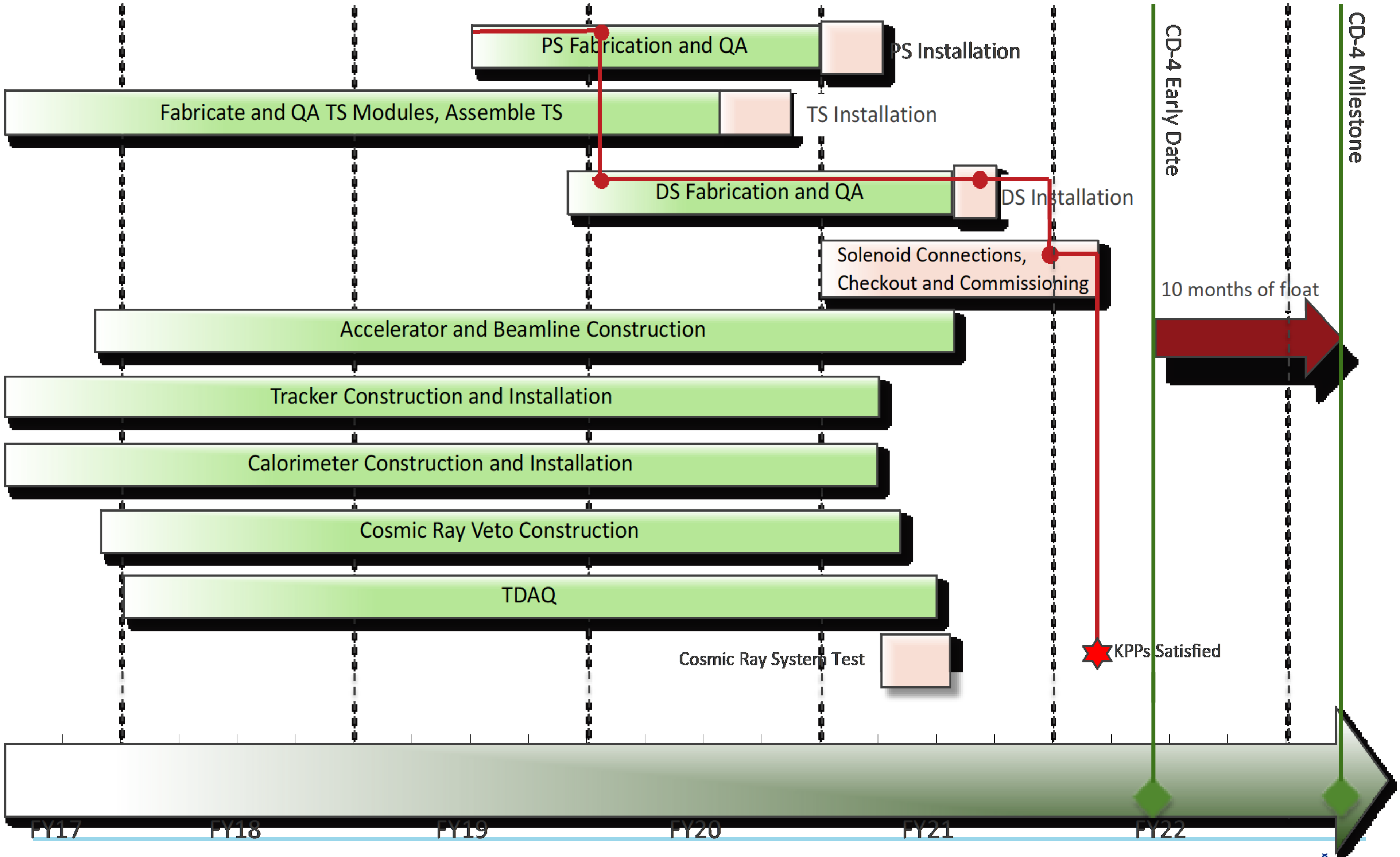
Installation of front end electronics on a new tracker panel



Mu2e Electro-Magnetic Calorimeter

Mu2e Project Schedule

BCR074 Baseline Schedule



Mu2e Milestones

March 2020	Low intensity beam to Diagnostic Absorber
October 2020	Production Solenoid delivered to Fermilab
February 2021	Transport Solenoid at Mu2e Building
April 2021	Detector Solenoid delivered to Fermilab
July 2021	g–2 running complete (allows ESS installation)
January 2022	Solenoid preliminary field maps complete
January 2022	Mu2e project complete (CD-4)
August 2022	Detectors inserted into Detector Solenoid
Spring 2023	First beam to Mu2e proton target

Summary & Conclusions

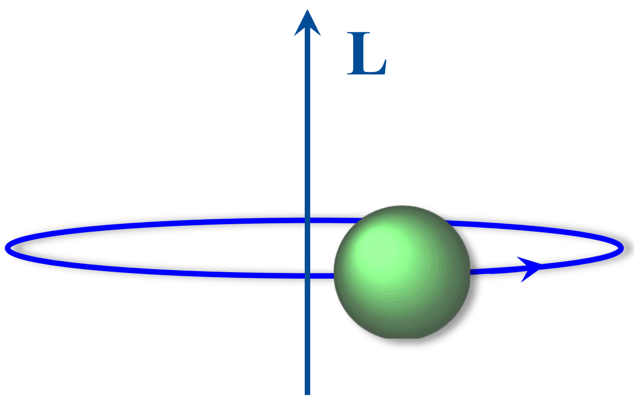
Summary & Conclusions

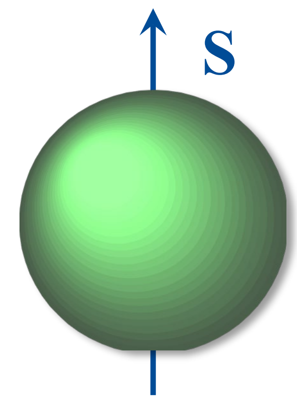
- The transformation of the Tevatron era Antiproton Source into the Fermilab Muon Campus is nearing completion
- The Muon g–2 experiment was the first to take advantage of the new facility
  - 2 Runs complete
  - ~4× Brookhaven E821 data set acquired
  - Two more runs planned in 2020 and 2021 – good prospects for achieving the goal of 22 × BNL sample
- Mu2e is making good progress toward completion of its construction phase
  - First beam to the Diagnostic Absorber in Spring 2020
  - Project completion in early 2022 followed by first beam to the proton target in Spring of 2023
- Both experiments have the ability to serve as definitive indicators of physics beyond the Standard Model

Extra Slides

The Gyromagnetic Ratio of a Muon, g_μ

$g_\mu \equiv$ ratio of the magnetic moment of a particle due to its spin to that of a classical particle of the same charge and angular momentum





Magnetic Moment ($\boldsymbol{\mu}$) of a classical point muon (mass m_μ) with charge e and angular momentum $\mathbf{L}$:

$$\boldsymbol{\mu} = \frac{e}{2m_\mu c}\mathbf{L}$$

Magnetic Moment ($\boldsymbol{\mu}_s$) of a real muon with intrinsic spin angular momentum $\mathbf{S}$:

$$\boldsymbol{\mu}_s = g\frac{e}{2m_\mu c}\mathbf{S}$$

Note: a "real" muon probably is not a green sphere.

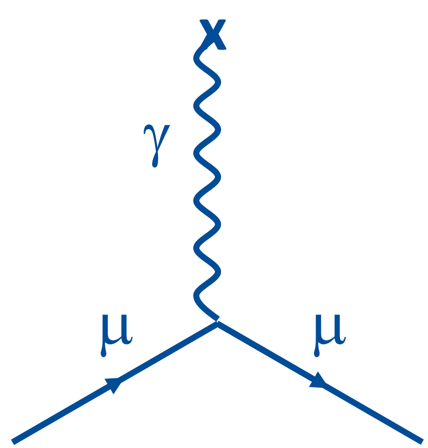
The Value of g_μ (the easy part)

$$g_\mu = 2\left(1 + \frac{\alpha}{2\pi} + \cdots\right)$$

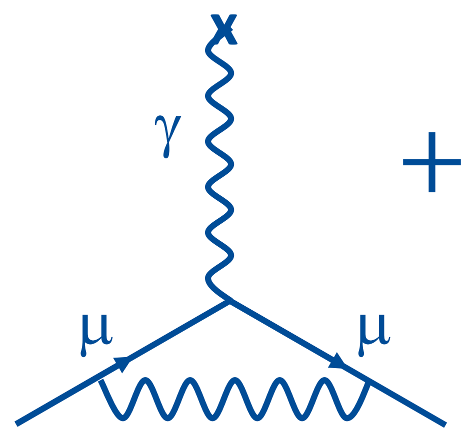
Dirac Equation

1st Order QED "Schwinger term"

$=$



$+$



$+ \cdots$

The "2" in g−2

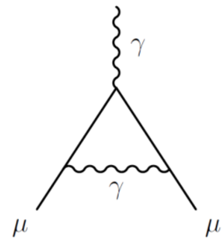
$$= 2 + 0.00232 + \cdots$$

The Value of g_μ (Other Contributions)

There are many Standard Model (SM) processes that contribute to the magnetic moment of the muon that must be added to the g_μ expansion.

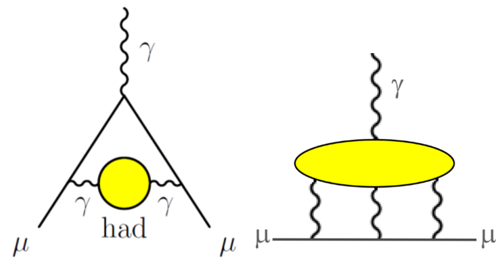
\+ Higher order QED $\quad \mathcal{O}(10^{-3})$

$g_{QED} = 233{,}169{,}438(16)\times10^{-11}$



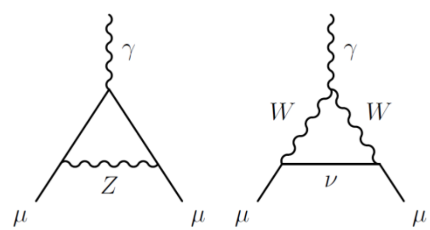
\+ Hadronic contributions $\quad \mathcal{O}(10^{-7})$

$g_{Had} = 13{,}911(101)\times10^{-11}$



\+ Electro-weak contributions $\quad \mathcal{O}(10^{-9})$

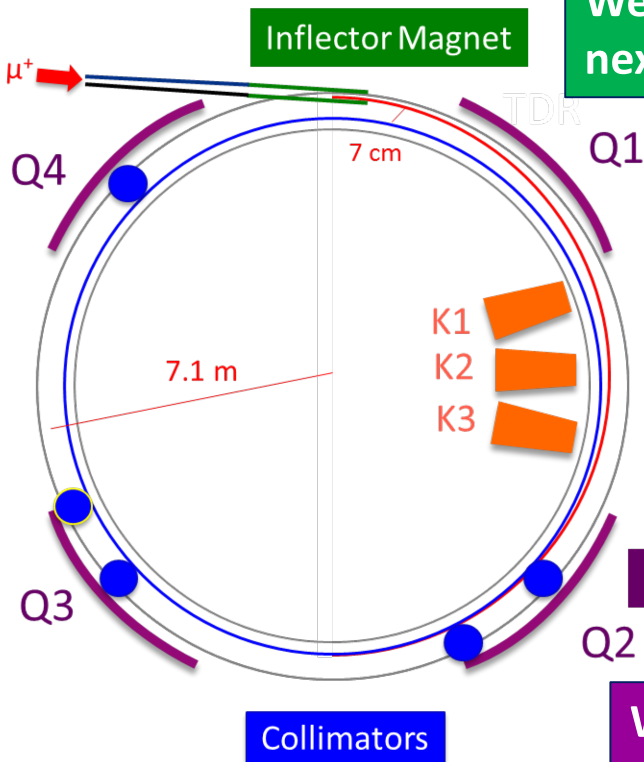
$g_{EW} = 308(2)\times10^{-11}$



$= \quad g_{SM} = 2.00\ 233\ 183\ 657(101)$

Muon g–2 Challenges

g–2 Ring injection and storage components that are not yet optimized



We would like to put in new Open Ended next summer to increase the Rate by 30%

We continue to improve this challenging system to increase Kick

Kicker magnets **x3 (40-55 kV)**
radially centers beam

Focusing quadrupoles **15-28 kV**
vertically focuses beam

Working on increasing max Voltages and adding Novel RF system for scraping and CBO reduction

Dave Hertzog

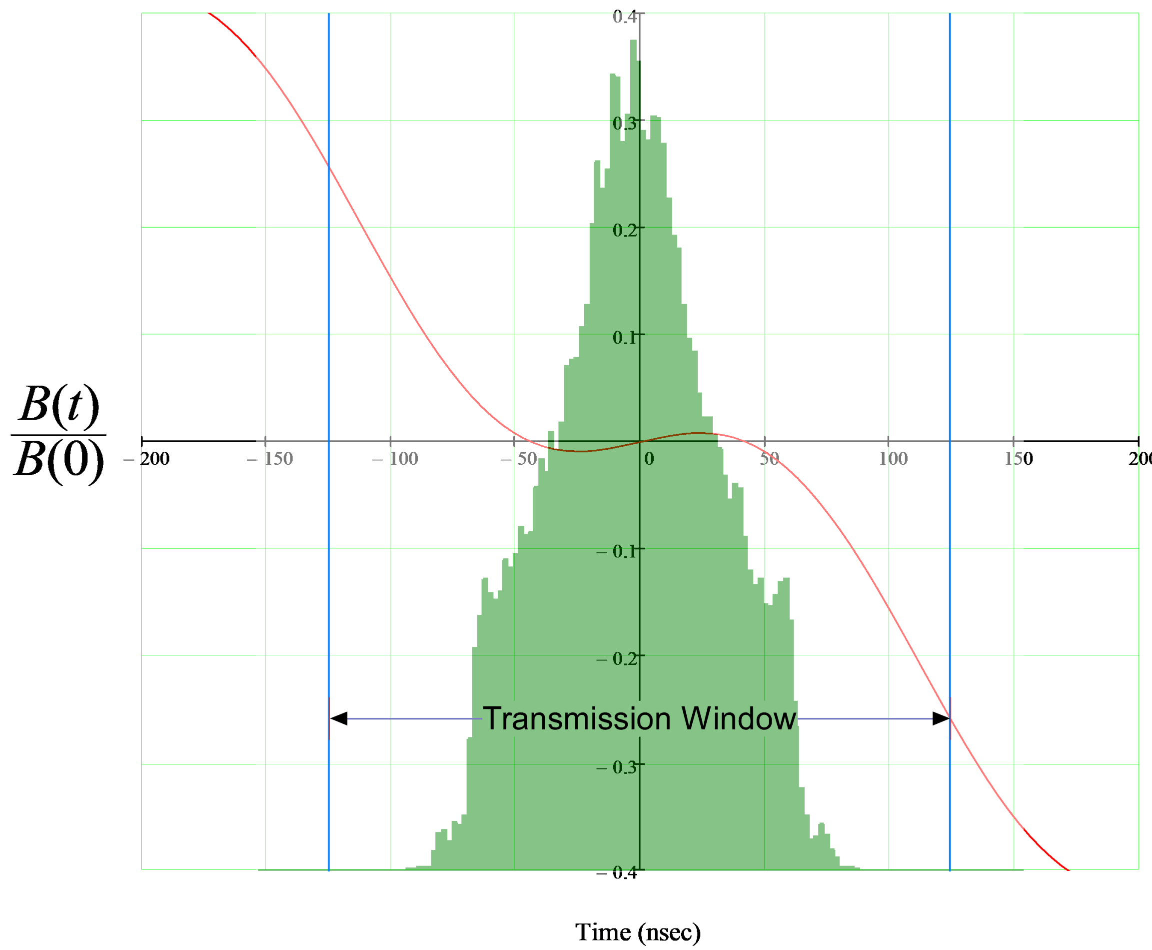
Mu2e Muon Stopping Target

- 37 Al foils
- Foil spacing: 22.2 mm
- Foil thickness: 0.1 mm
- Foil radius: 75 mm
- Center hole radius: 21 mm

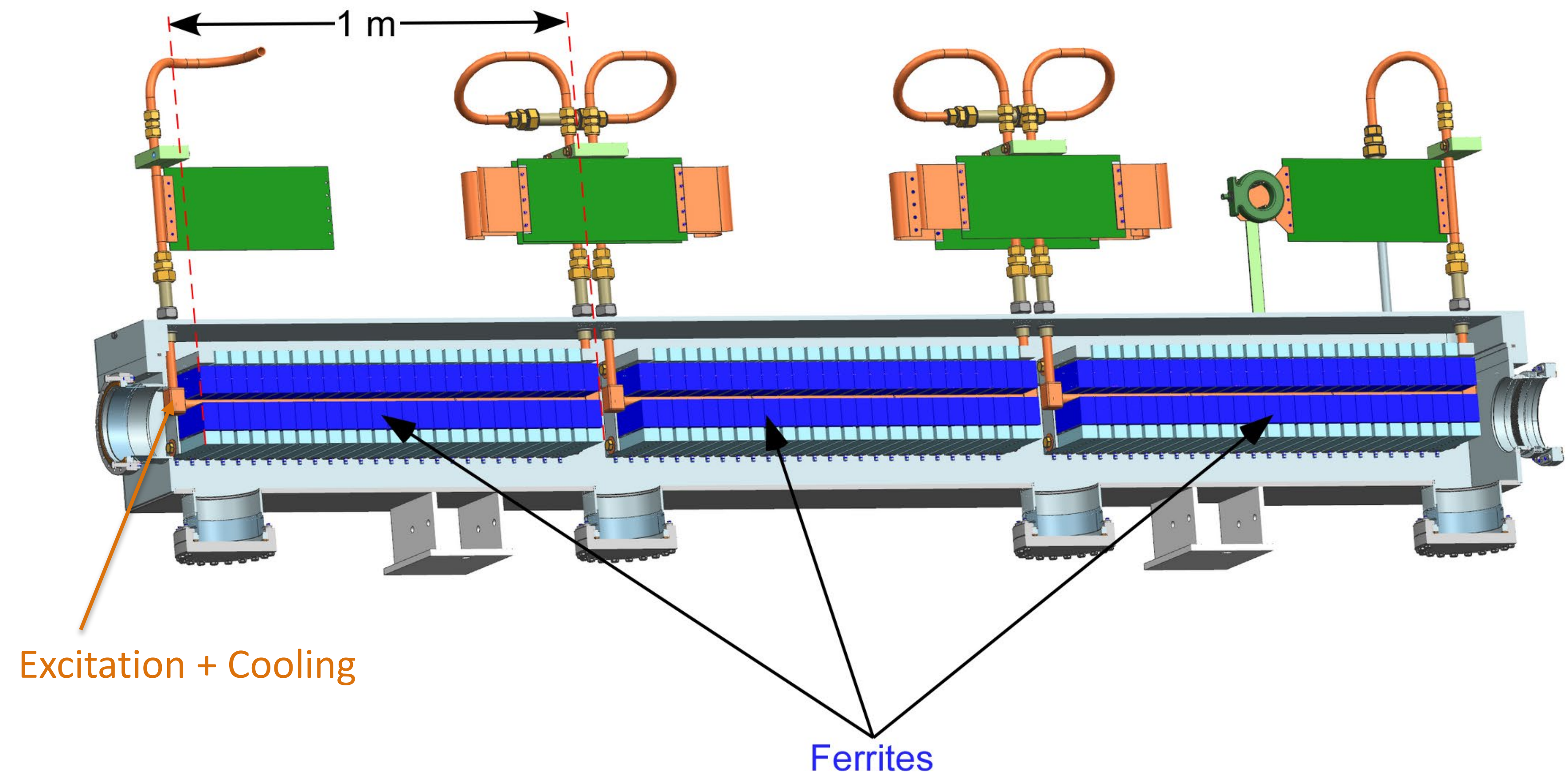
Prototype

AC Dipole – Beam Synchronization

Average proton beam longitudinal distribution superimposed on the AC Dipole dual harmonic excitation.



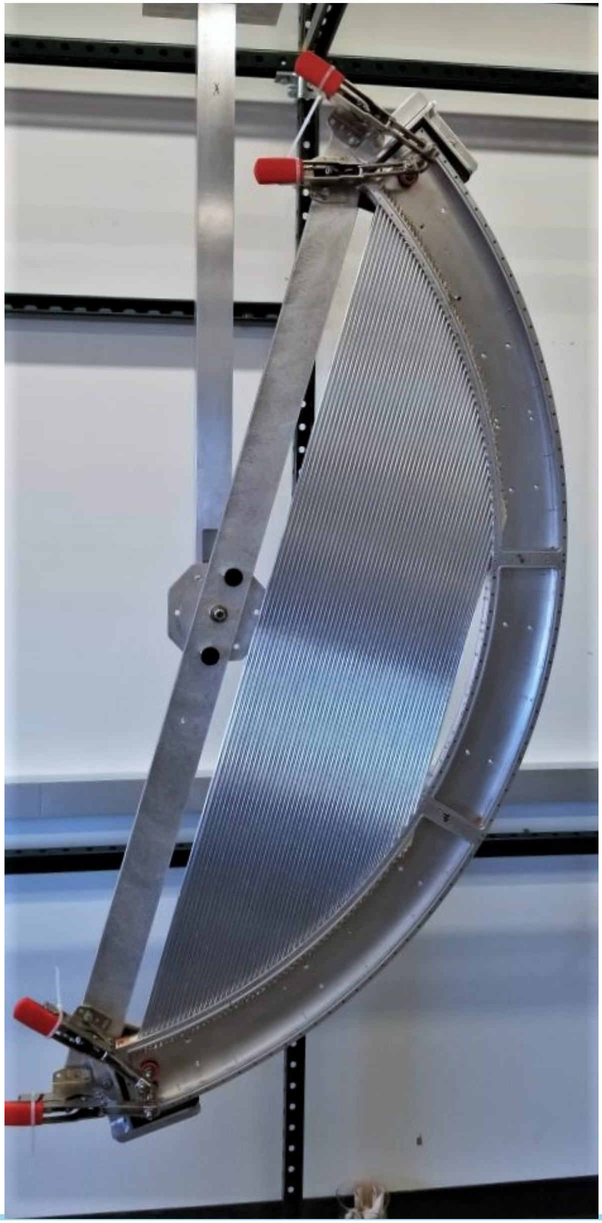
Extinction AC Dipole Magnet (1 of 2)



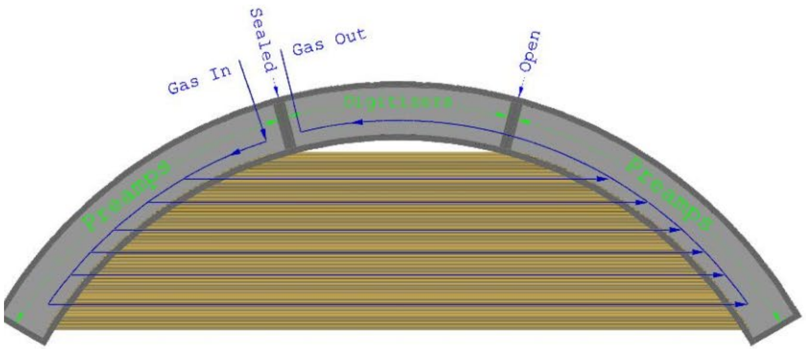
Cross-section of one AC Dipole magnet consisting of 3 individual modules

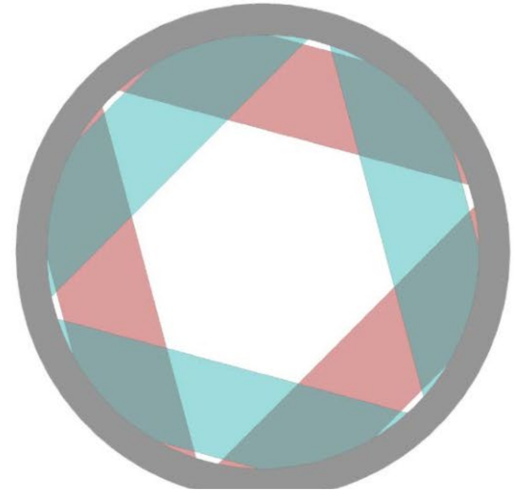
Tracker Panel Fabrication at the University of Minnesota

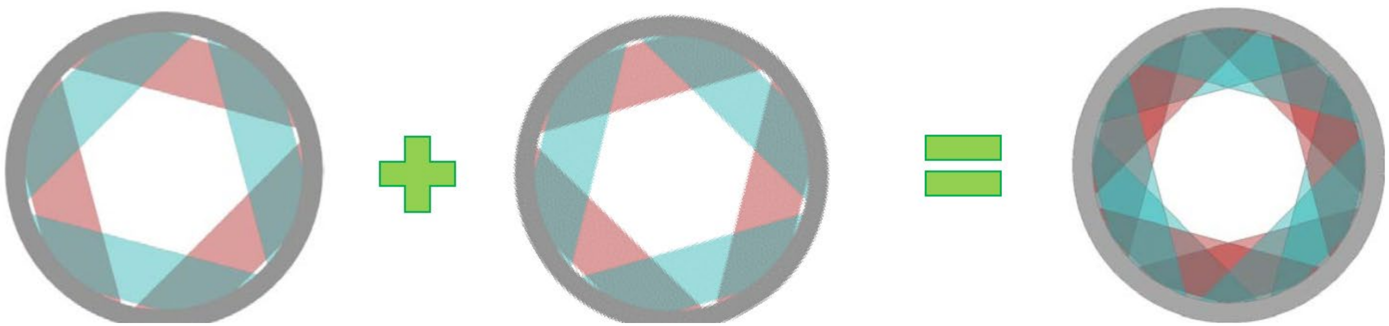
Partially completed panel



The Mu2e Tracker







- Self-supporting “panel” consists of 96 straws, 2 layers, 48 straws/layer
- 6 panels assembled to make a “plane”
- 2 planes assembled to make a “station”
- Rotation of panels and planes improves stereo information
- >20 k straws total