Fermilab's Muon Campus: Status, Experiments, and Future

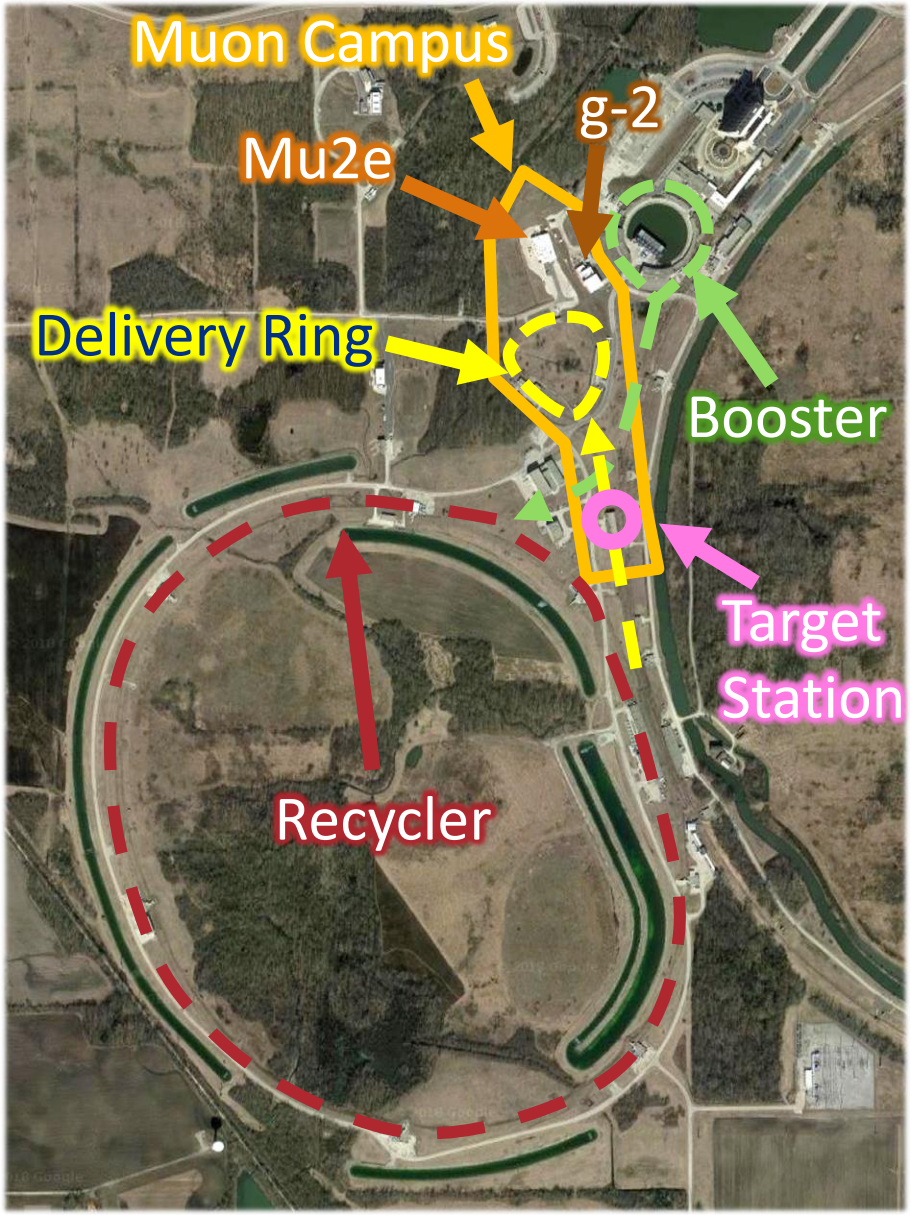
Steven Boi

NuFact 2022: WG4 Muon Physics

August 5th, 2022

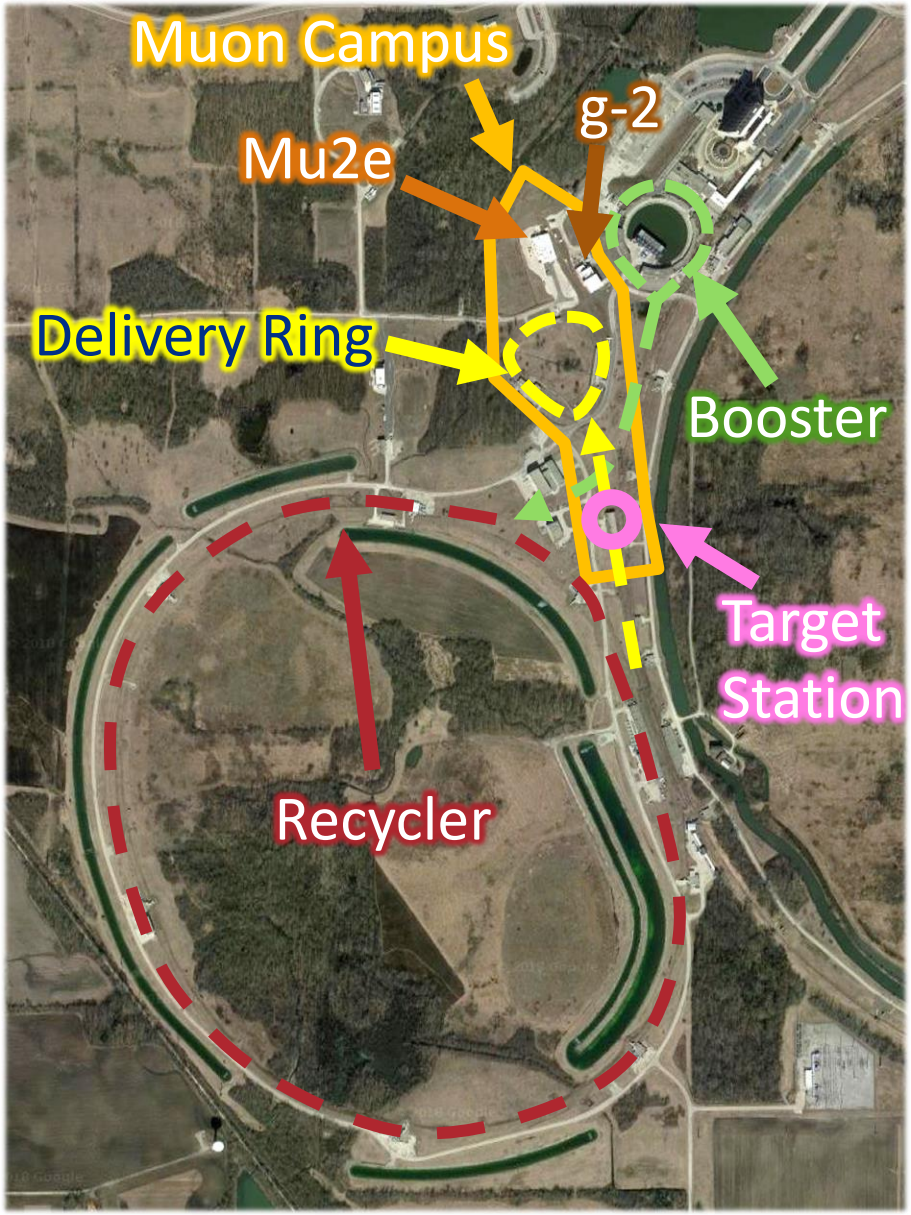
Fermilab's Muon Campus

- Originally the Antiproton Source during the Tevatron-era, the Muon Campus makes use of much of the existing infrastructure.
- Booster provides 8 GeV protons.
- The 120 GeV Main Injector is now the Recycler, forming 8 GeV proton bunches.
- Target Station was for $\bar{p}$ production, now for μ production for g-2.
  - Mu2e-mode bypasses target.



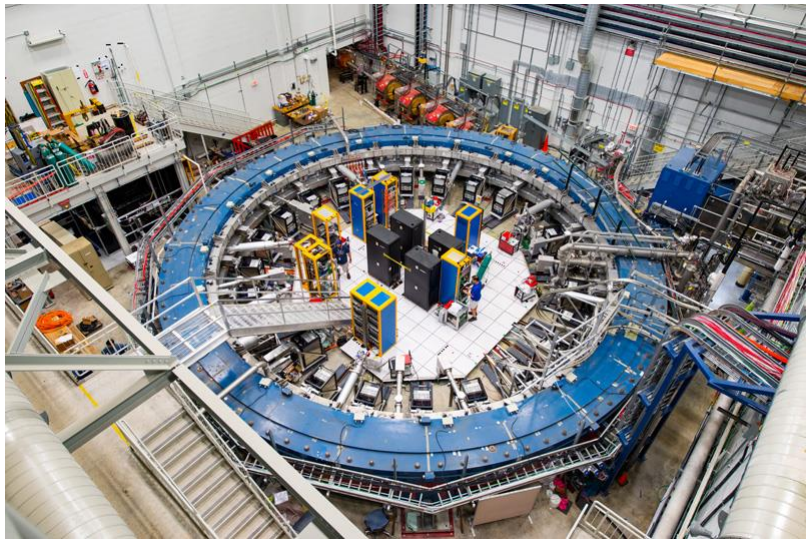
Fermilab's Muon Campus

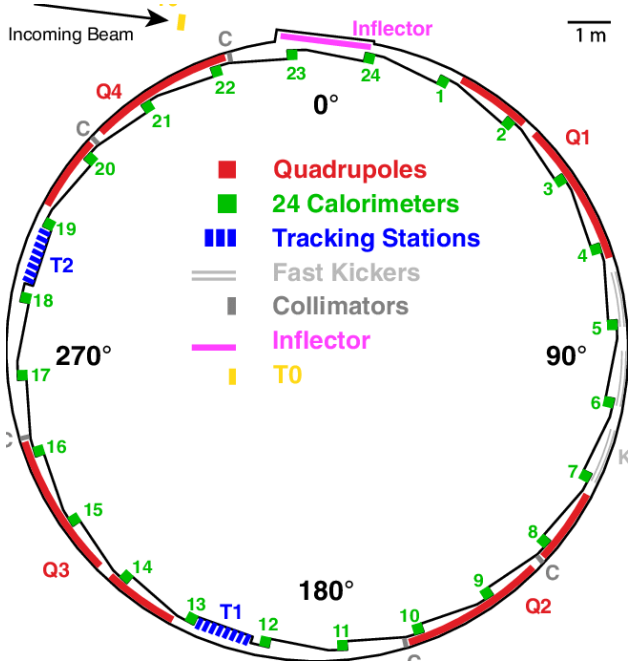
- The $\bar{p}$ accumulator was removed.
- The $\bar{p}$ debuncher is now the Delivery Ring.
  - Debuncher injection line repurposed as DR abort.
  - 505 m in length, 1.695 μs revolution period.
- Two new transport lines were constructed, the M4 and M5, for beam delivery to Mu2e and g-2.



Muon Campus Experiments

- Muon g-2
  - Precision measurement of the anomalous magnetic moment of the muon: $a_\mu = \frac{g_\mu - 2}{2}$
  - Where g_μ is the gyromagnetic ratio of the muon: $\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{S}$

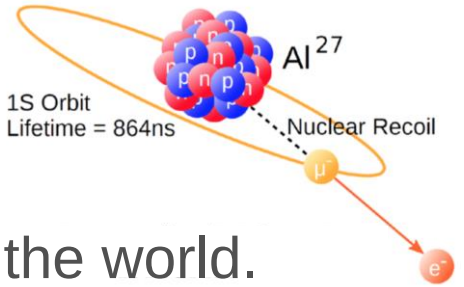




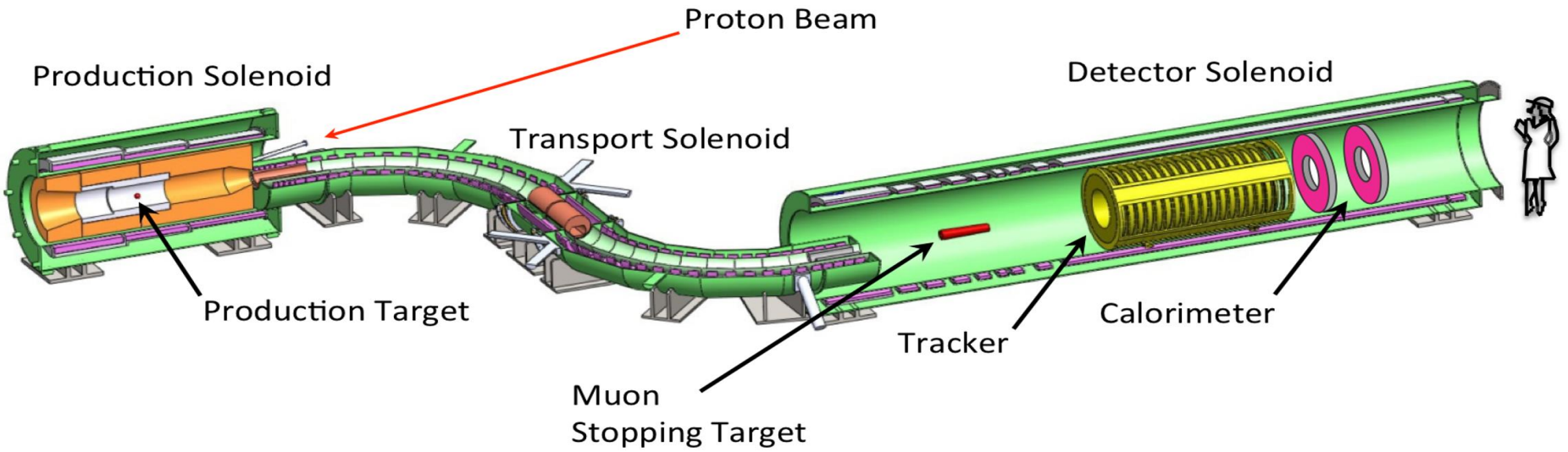
Muon Campus Experiments

- Muon-to-Electron Conversion Experiment (Mu2e)
  - Searching for neutrino-less muon to electron conversion in the presence of an aluminum nucleus.

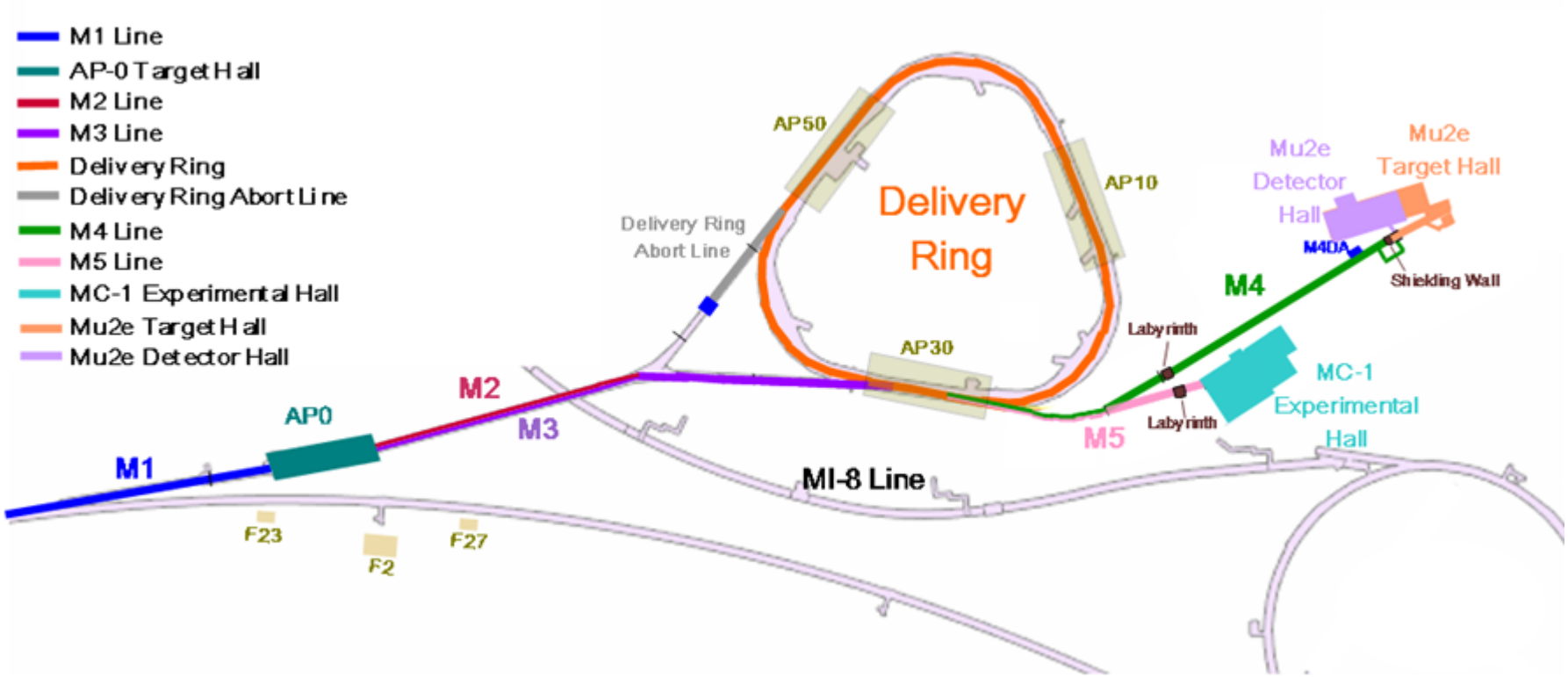
$$R_{\mu e} = \frac{\Gamma\left(\mu^- + (A,Z) \rightarrow e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)\right)}$$



  - Will be one of the most intense muon beams in the world.



Muon Campus Beam Lines

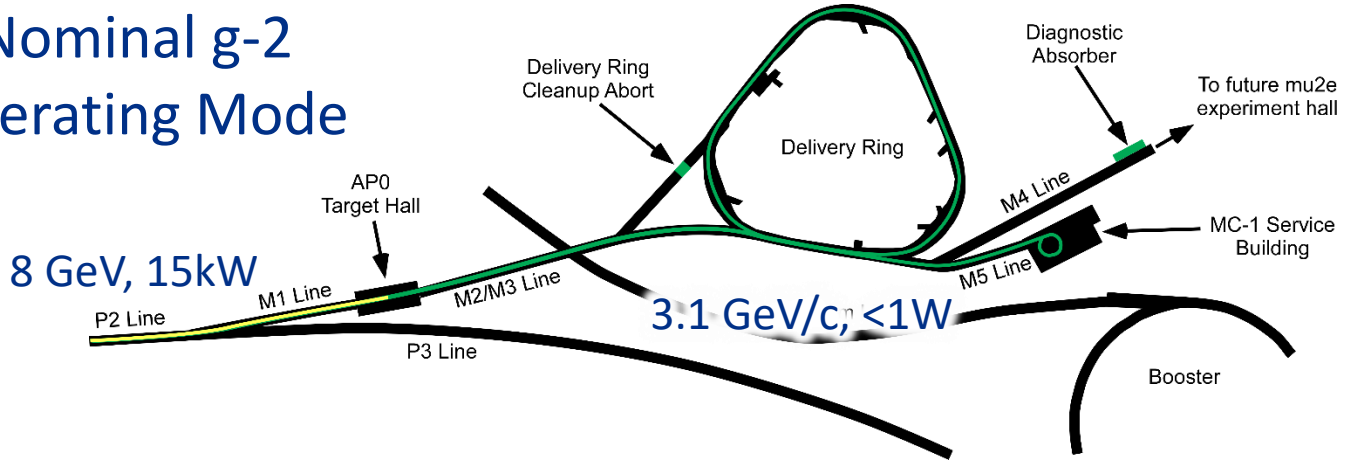


Fermilab

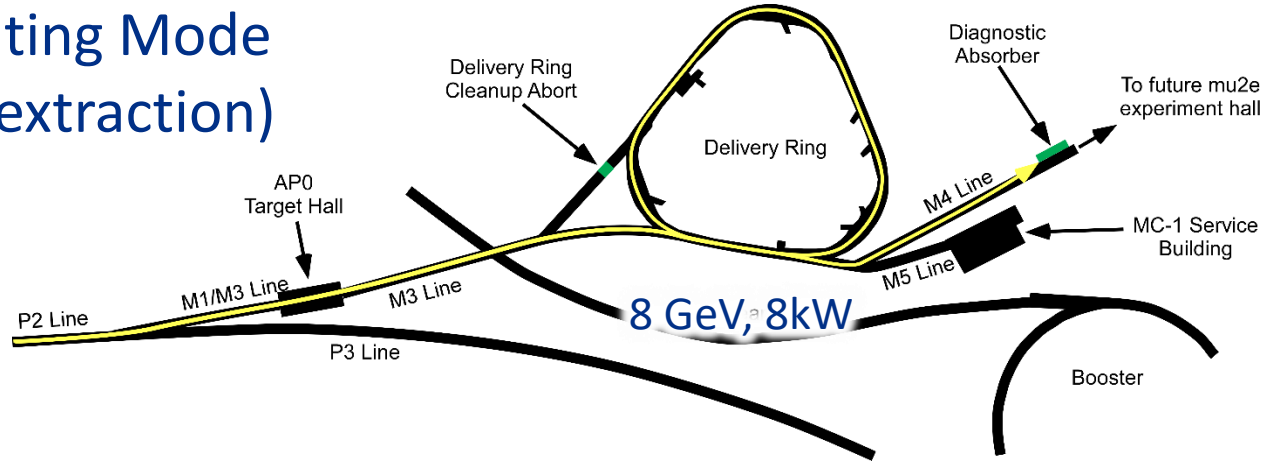
Operating Mode Comparison

- Primary Proton Beam
- Secondary Beam

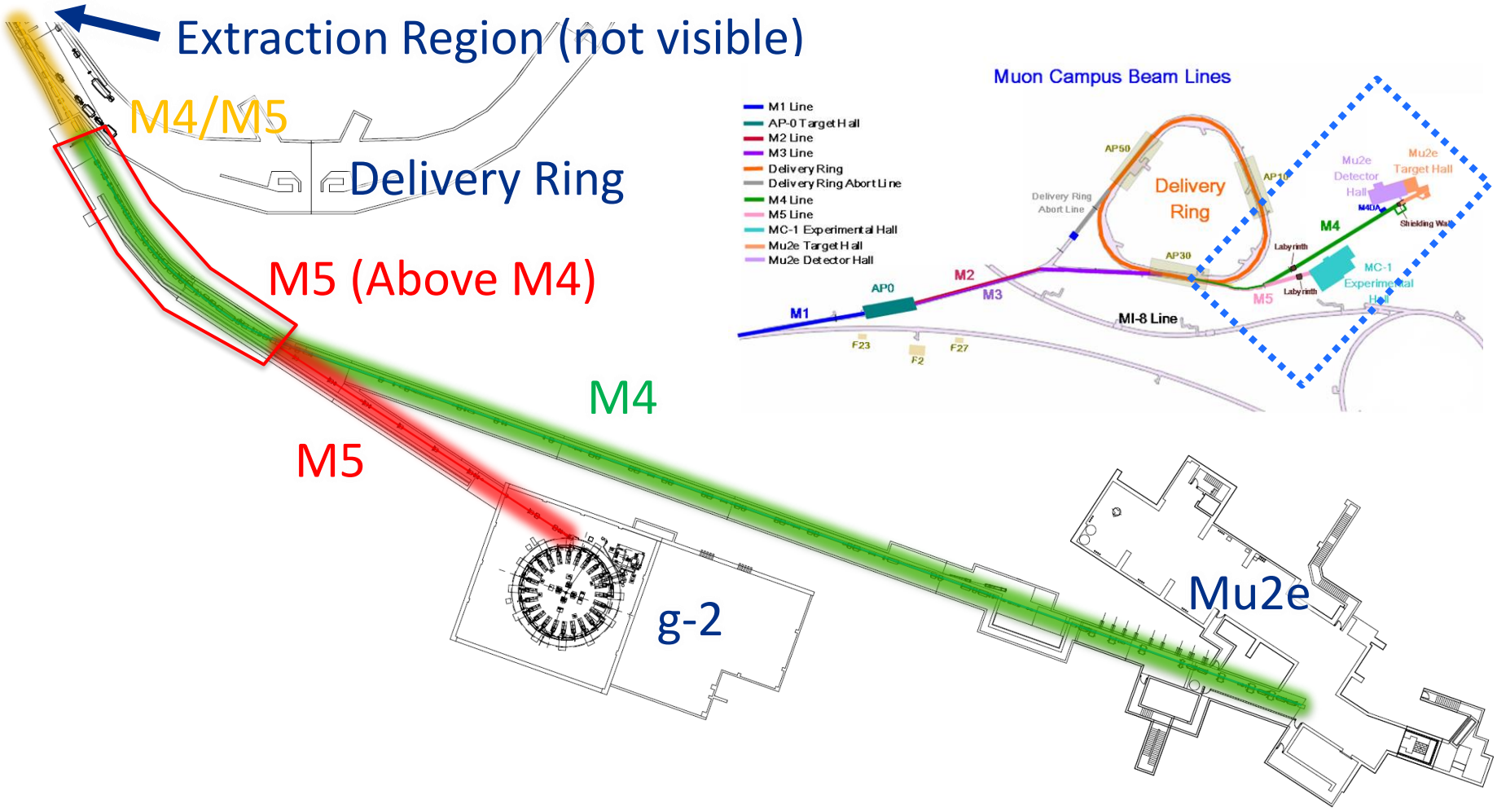
Nominal g-2 Operating Mode



Nominal Mu2e Operating Mode (slow extraction)

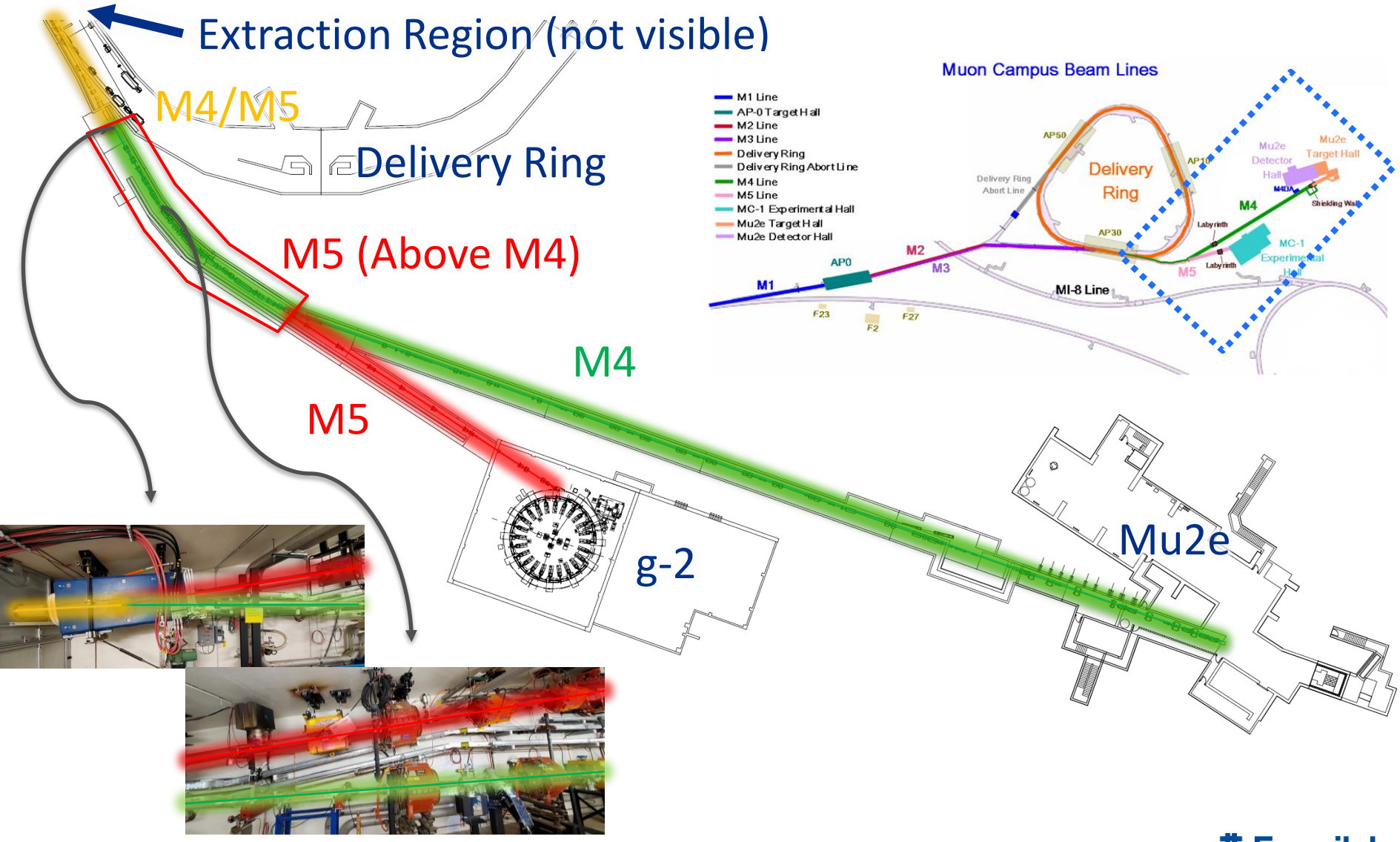


M4/M5 Beamlines



Fermilab

M4/M5 Beamlines



Fermilab

Beam Transport

M4 Beamline

- Resonant extraction from the DR.
- Transport:
  - 8.9 GeV/c, 8kW proton beam
  - $\epsilon = 30$ π-mm-mrad (95%)
  - Momentum spread (±1% @ 95%)

M5 Beamline

- Extraction of μ^+ beam from the DR.
- Transport:
  - 3.1GeV/c, <1W secondary μ^+ beam
  - Momentum spread (±2% @ 95%)
  - Average polarization >90%
  - Yield of $>7\times10^{-7}$ μ/POT

Muon Campus Status

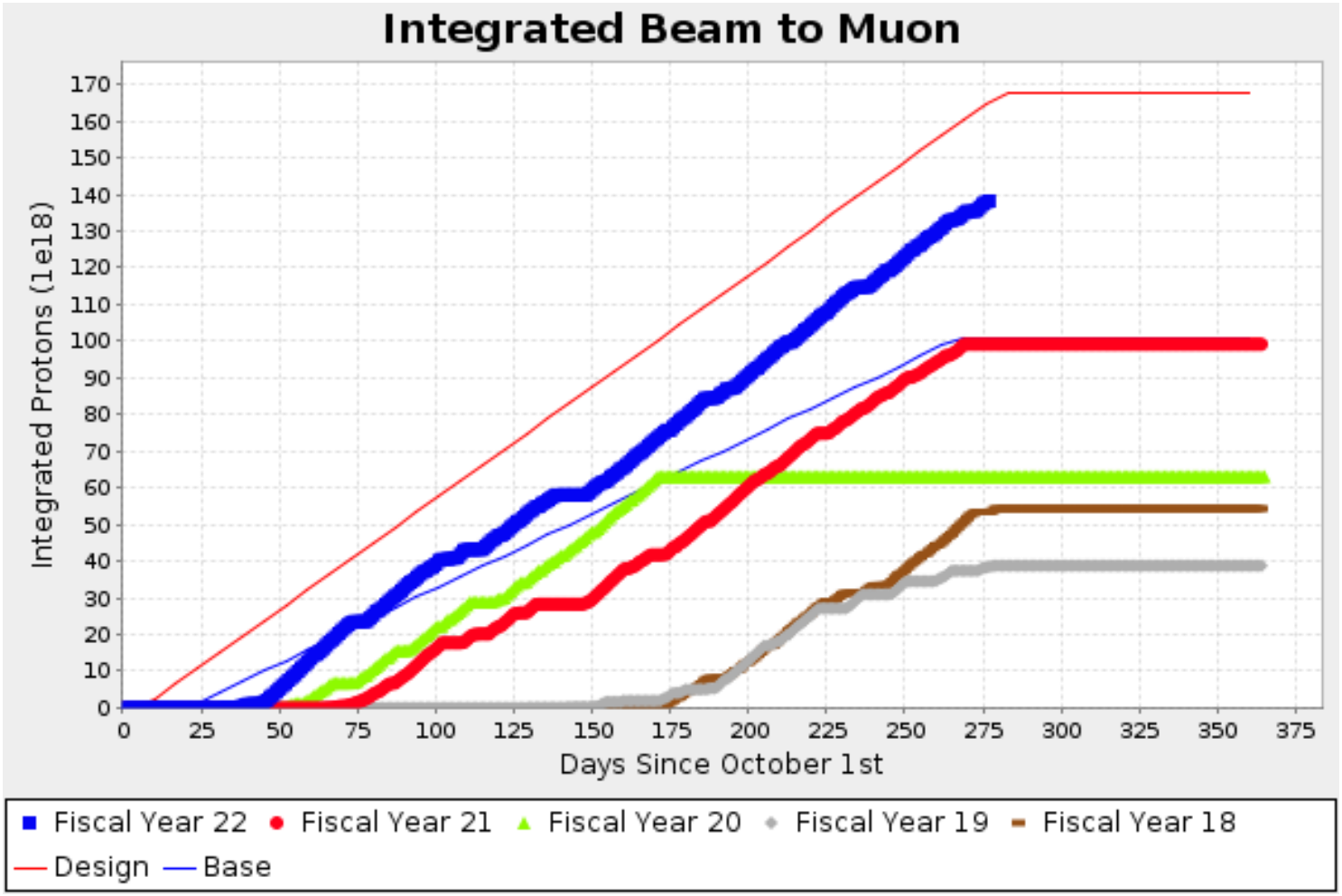
- At the time of this presentation, g-2 completed its ‘final’ run.
  - It was anticipated that an additional μ^- run would take place after the accelerator complex summer shutdown, but this is not happening as of July 1st, 2022.
  - Additional μ^+ run will take place (Run 6), with priority lower than Mu2e commissioning.
- The Muon Campus is unable to run g-2 and Mu2e simultaneously.
- Operations are currently shifting to Mu2e-mode, which involves commissioning the rest of the M4 beamline.
  - As of April 22nd, 2022, proton beam was successfully delivered to the Diagnostic Absorber.

Muon Campus Status: g-2 Mode

- 8 GeV proton bunches (10^{12} protons/bunch) are sent to the target station from the Recycler (15.4kW).
- From the target station, only 3.1 GeV/c particles are propagated.
  - Mostly p, some π, and few μ.
  - μ-beam comes from π decay.
- Proton contamination is removed by making 4 turns in the DR and sent to abort.
- μ^+ are extracted to g-2.

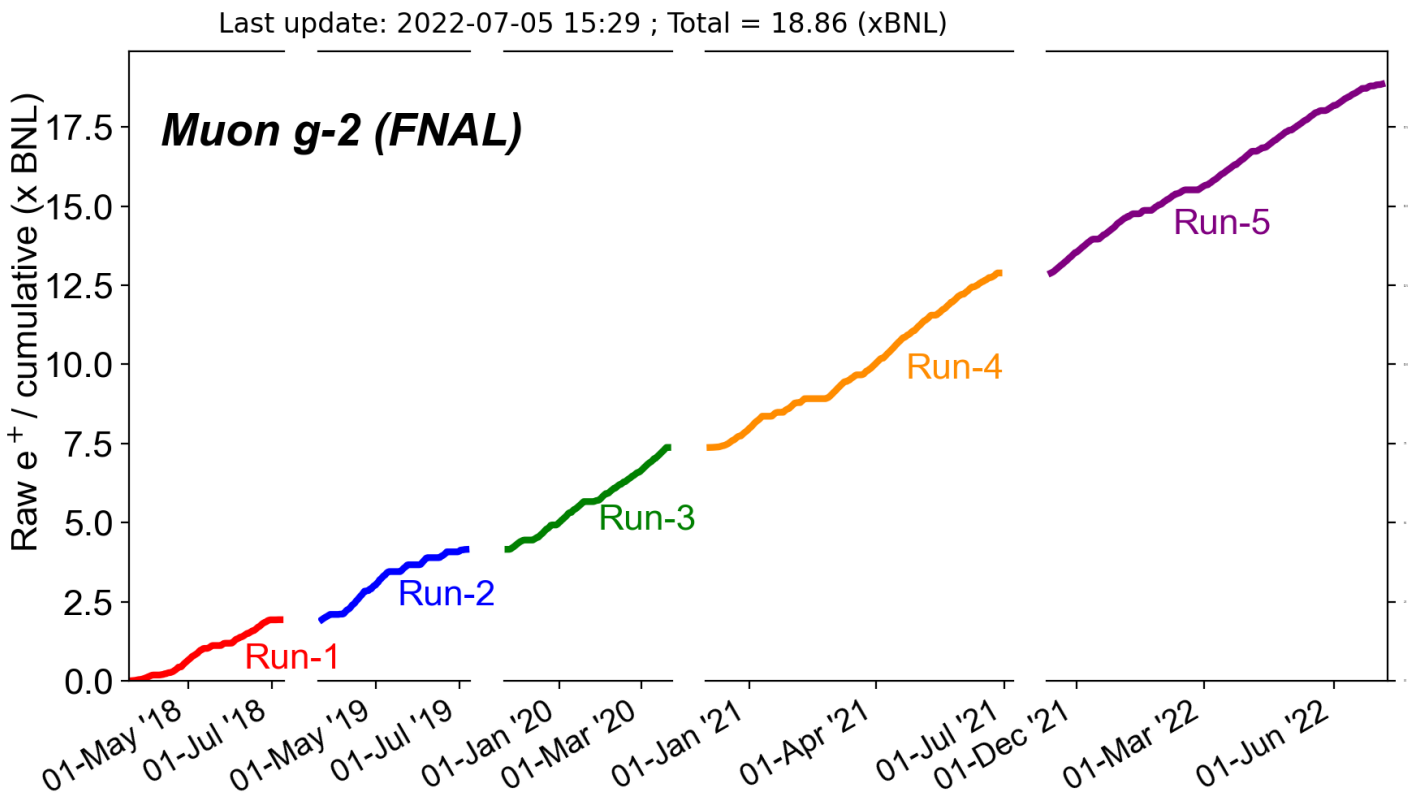
Muon Campus Status: g-2 Mode

- Better beam delivery than previous years for g-2 run 5.



Muon Campus Status: g-2 Mode

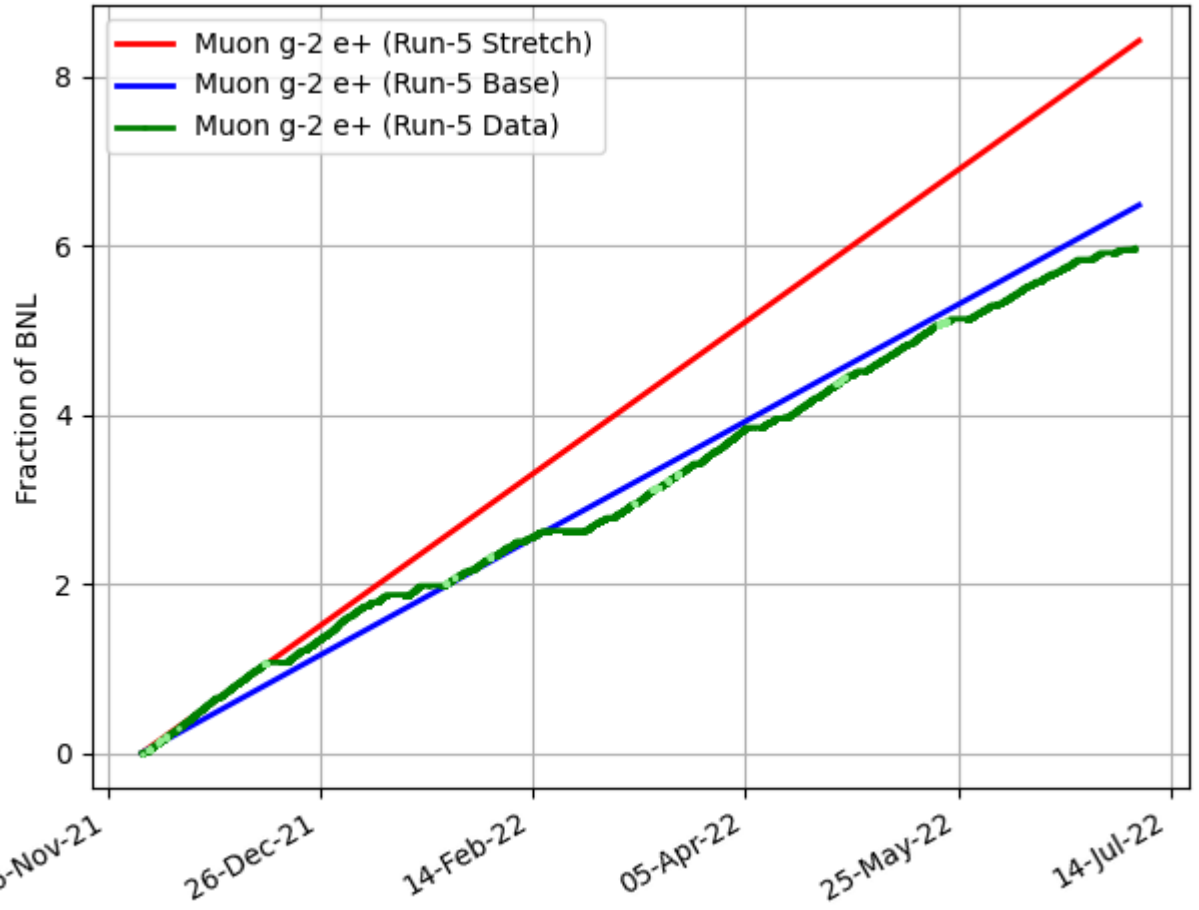
Integrated Decays in units of ×BNL



Fermilab

Muon Campus Status: g-2 Mode

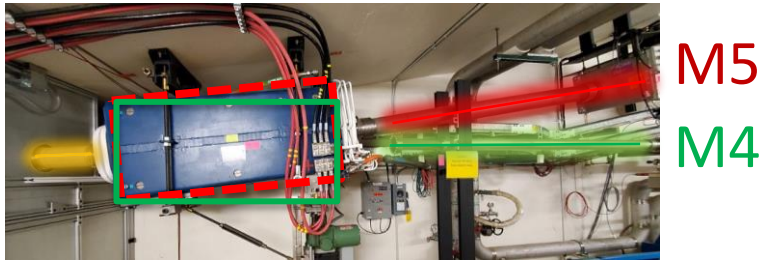
Integrated Decays in units of ×BNL



Fermilab

Switching to Mu2e Operations

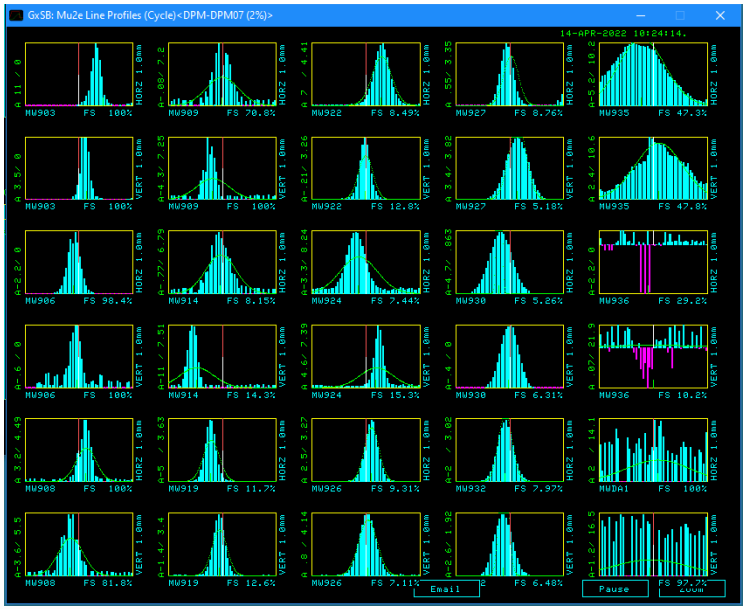
- Because Mu2e and g-2 are not able to run simultaneously, some operational changes must be made.
- Protons from the Recycler will bypass the Target Station and head straight into the Delivery Ring.
  - Protons are to be resonantly extracted from the Delivery Ring and sent to the Mu2e production target.
- Vertical bend magnet at the end of the shared M4/M5 line will be aligned with the M4 beamline.

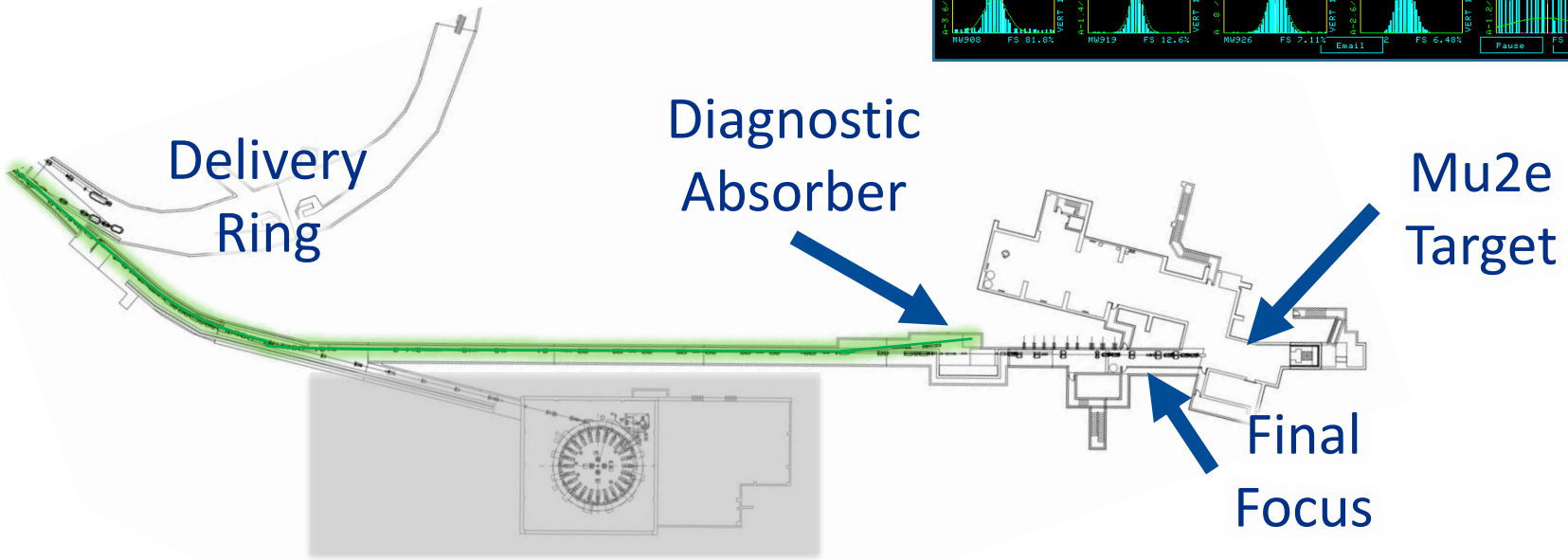


- It is intended for the Muon Campus to be fully operating in Mu2e-mode in FY2024.

M4 Beamline Status

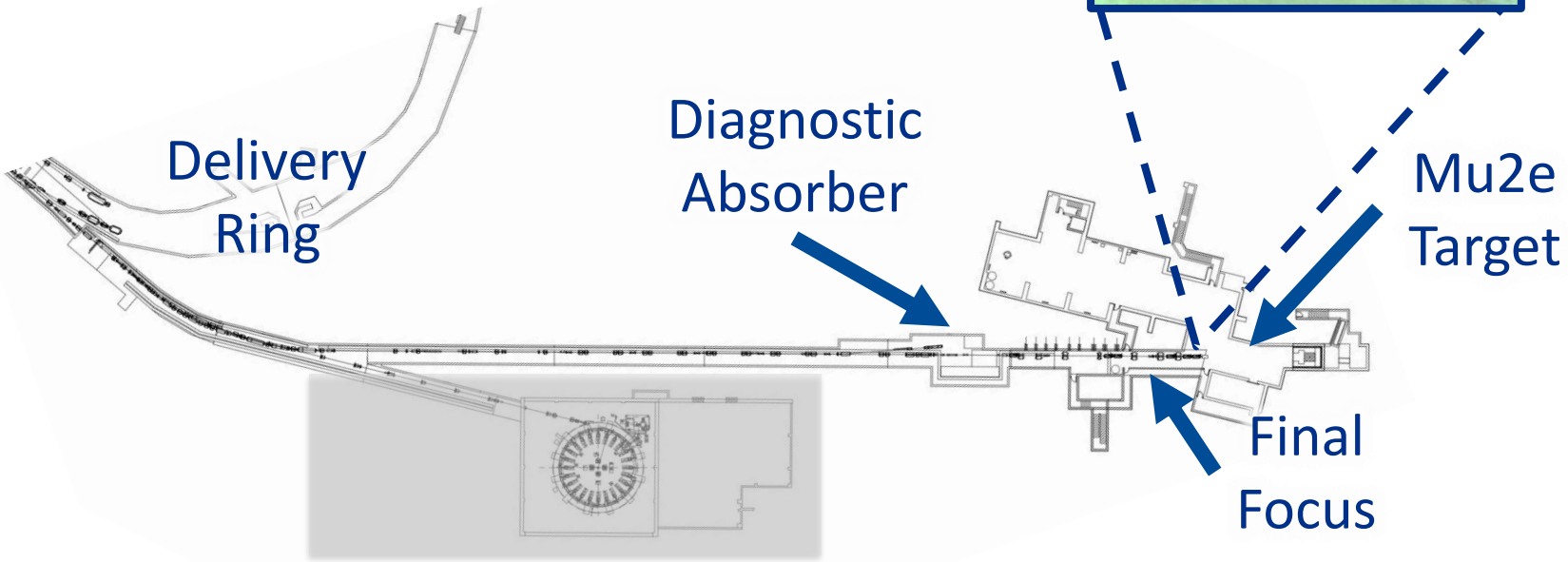
- Current Status:
  - First proton beam to Diagnostic Absorber on April 14th, 2022.
    - A Key Performance Parameter for Mu2e.





M4 Beamline Status

- Current Status:
  - Final Focus installation is nearing completion.
  - Commissioning studies to resume after 2022 Summer Shutdown.



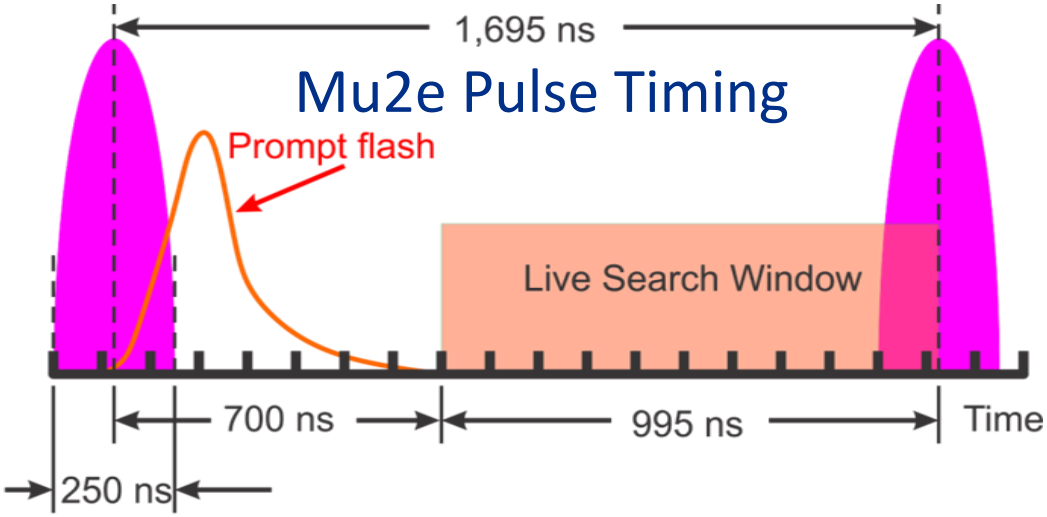
Fermilab

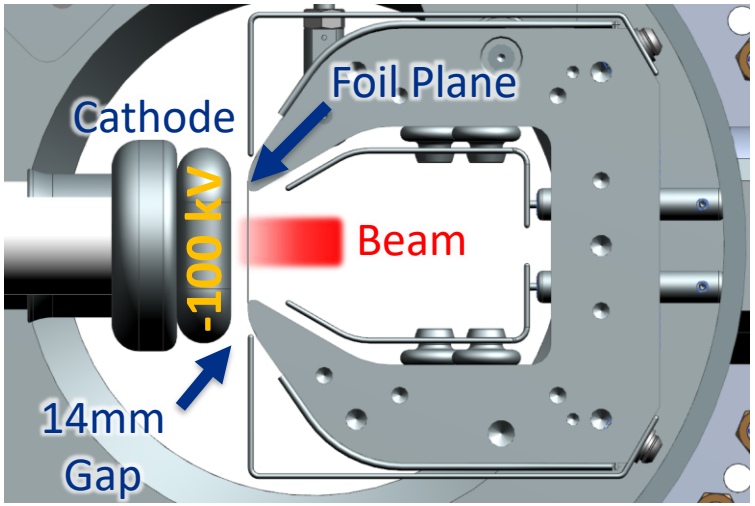
M4 Beamline Challenges

- Challenges:
  - Commissioning 1/3-Integer Resonant Extraction.
  - Ensuring adequate beam extinction.
  - More…

Resonant Extraction

- Mu2e requires a pulsed beam structure, resonant extraction is employed to provide this.
- Continuous beam extraction is achieved by creating a resonance that destabilizes part of the beam in a controlled manner.
- The disturbed portion of the beam is pulled away by a narrow, high-potential field.
  - Electrostatic Septum (ESS)





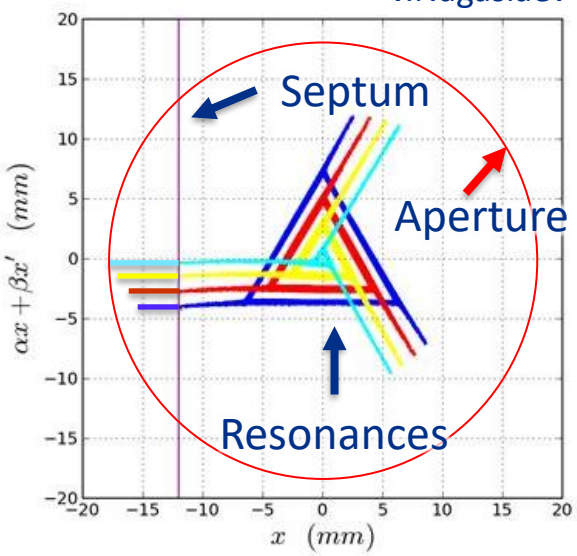
S.Werkema

Fermilab

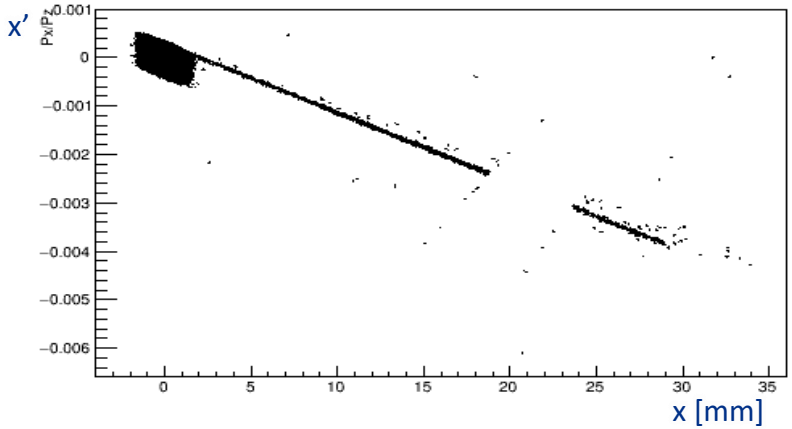
Resonant Extraction

- Resonant Extraction is not a clean process, which results in losses and scattering from the foil plane.
- The result is beam halo that enters the acceptance channel of the M4 beamline.
  - This halo can be steered into the downstream acceptance channel by the extinction system.

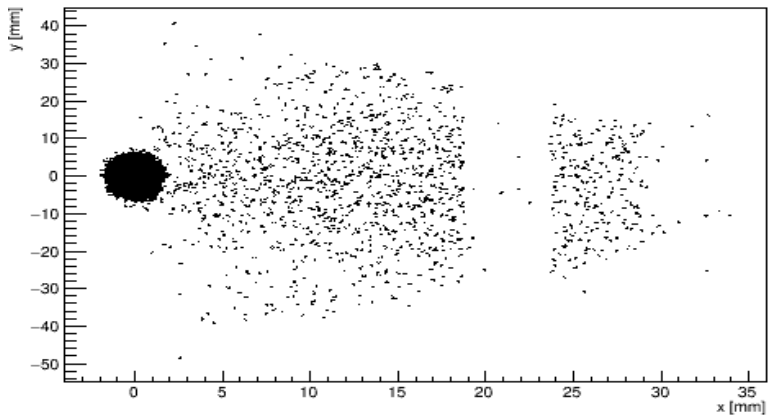
V.Nagaslaev



x’ : x



y : x



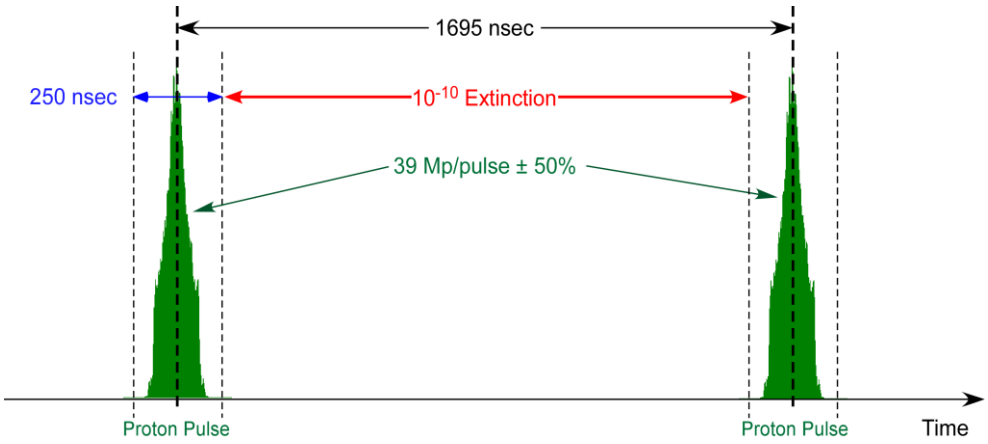
Fermilab

Extinction

- Mu2e requires a pulsed beam structure with no less than a 10^{-10} inter-pulse beam extinction.

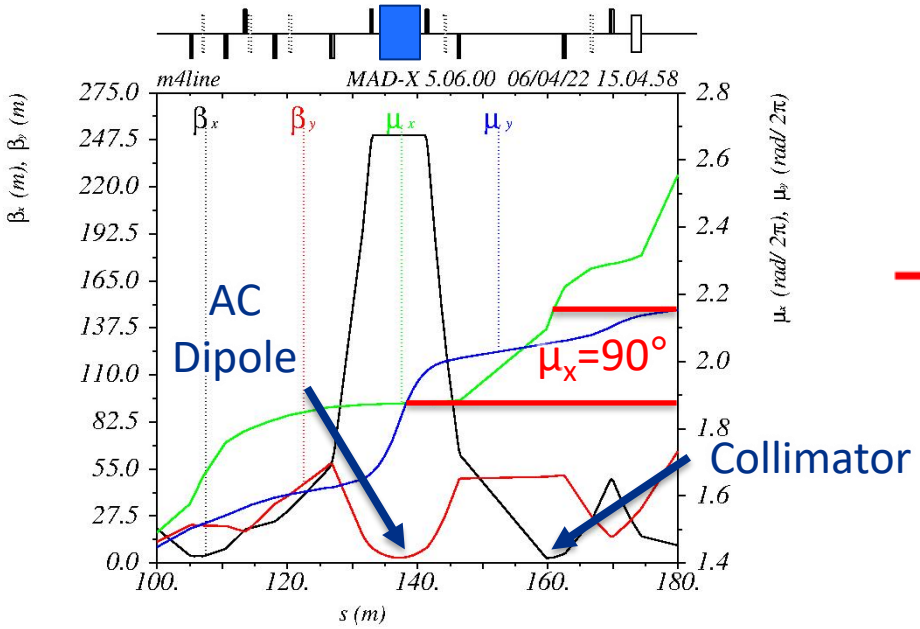
$$\frac{Out\ of\ time\ beam}{Total\ beam\ on\ target} < 10^{-10}$$

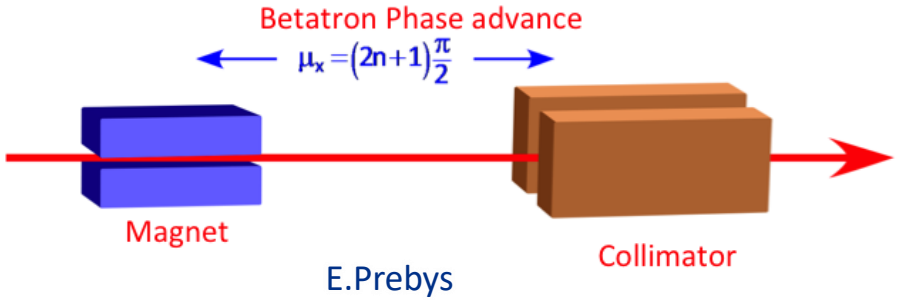
- Natural beam extinction on the order of 10^{-5} is achieved by the extraction method from the DR.
  - Out-of-time beam may develop because of space charge, beam-gas interaction, or beam loading effects on the RF.
- An additional 10^{-7} can be achieved by the employing a resonant dipole extinction system.



Extinction

- An alternating current dipole located in a high-beta region will “sweep” out-of-time beam into a collimator (COL931), which is at a 90° phase advance downstream.
  - In-time beam should be fully transmitted.

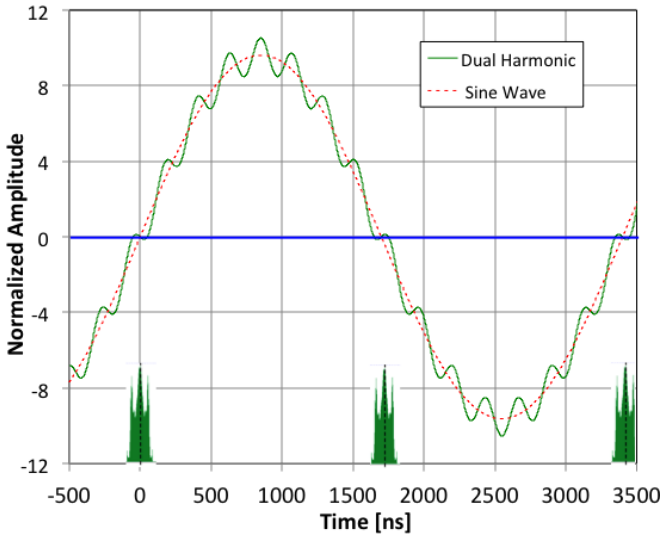


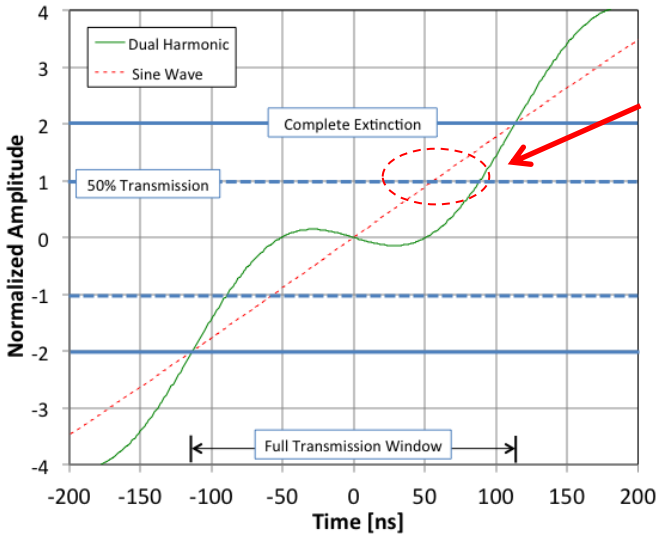


Extinction

E.Prebys

- AC dipole is driven by two harmonics:
  - 300 kHz (half bunch frequency) to sweep out-of-time beam into the downstream collimator.
  - 4.5 MHz (15th harmonic) to maximize transmission of in-time beam.
- If extraction halo is not removed, it can be steered into the acceptance channel!





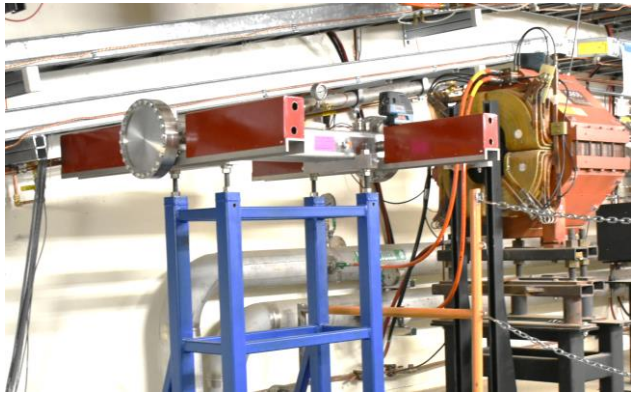
Single harmonic would hit collimator too soon.

Fermilab

Extinction & Collimation

- Two collimators in the M4 Line are used to remove the extraction halo before it reaches the extinction system.
- COL907: removes most of the extraction halo.
  - Placed as far upstream as possible.
- COL924: removes any remaining scattered particles.
  - Placed 90° in phase advance upstream of the AC dipole.
- The collimators have adjustable jaws to optimize collimation.

COL907



COL924

M4 Challenges

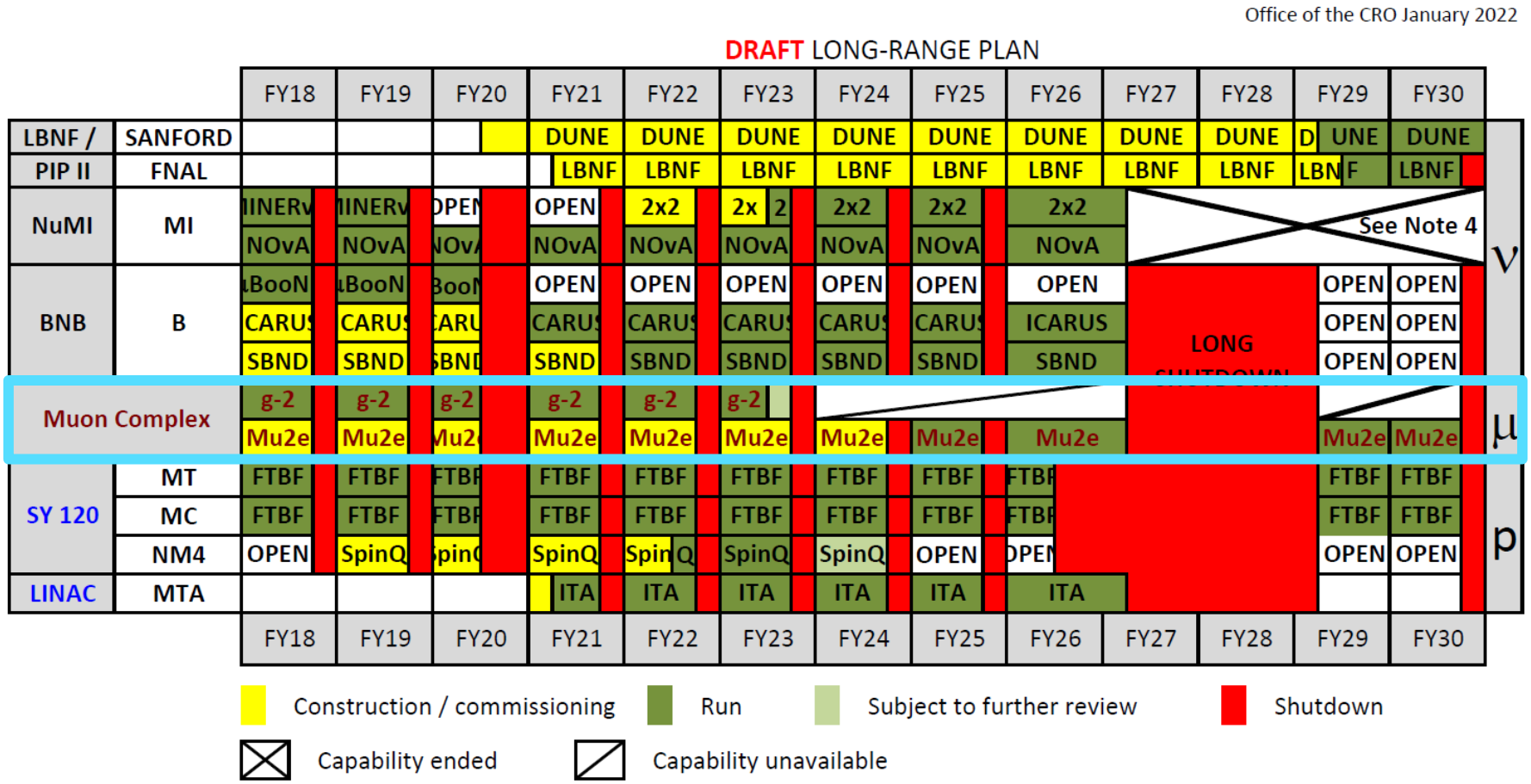
- Resonant Extraction faces mostly technical challenges.
  - Power supplies, vacuum controls, etc.
  - Delivery Ring was not designed for RE.
    - A lot of machine time needed for commissioning.
    - Need to reduce losses as DR was not designed for significant beam loss.
  - Currently the extraction septum is not installed and cannot be until fully finished with g-2.
- Extinction system needs to be installed and tuned to maximize in-time beam transmission while guaranteeing elimination of out-of-time beam to a $<10^{-10}$ level.
- Radiation from upstream extraction halo collimation requires additional shielding.

Final Remarks

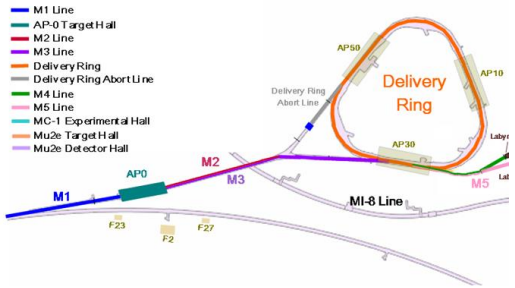
- g-2 is quickly approaching its end of life after many successful years of running.
  - There will be an additional μ^+ run (Run 6).
- The muon campus cannot run Mu2e and g-2 simultaneously, so operations are now shifting towards Mu2e-mode.
- There are some challenges that must be met to successfully transition to Mu2e-mode:
  - Commission Resonant Extraction.
  - Commission extinction system.
- On 4/14/22, the first protons were sent down the M4 beamline to the diagnostic absorber.
  - Only a short section of the line, the Final Focus, will need to be assembled to transport beam to Mu2e.

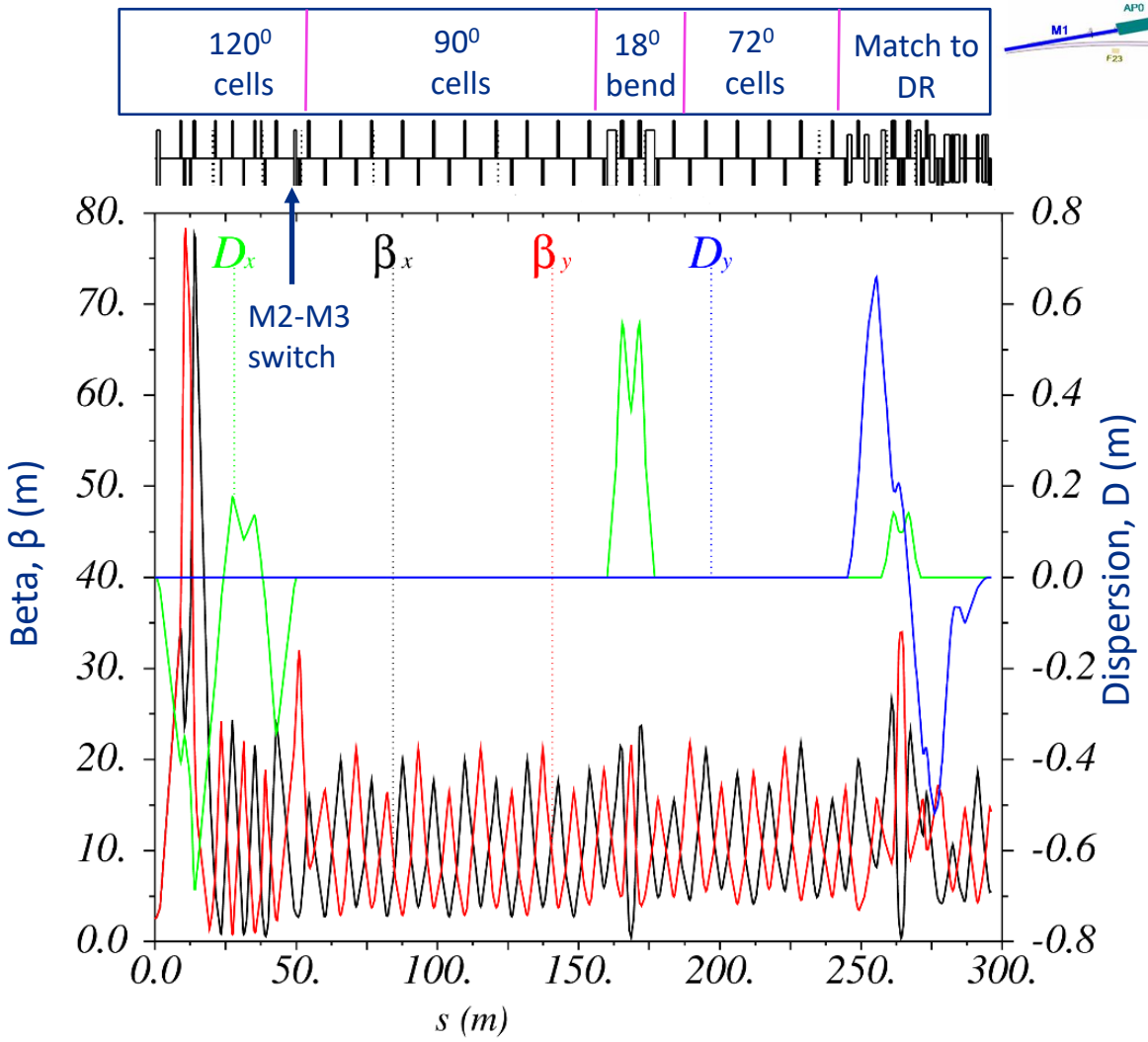
Backup

Lab Schedule



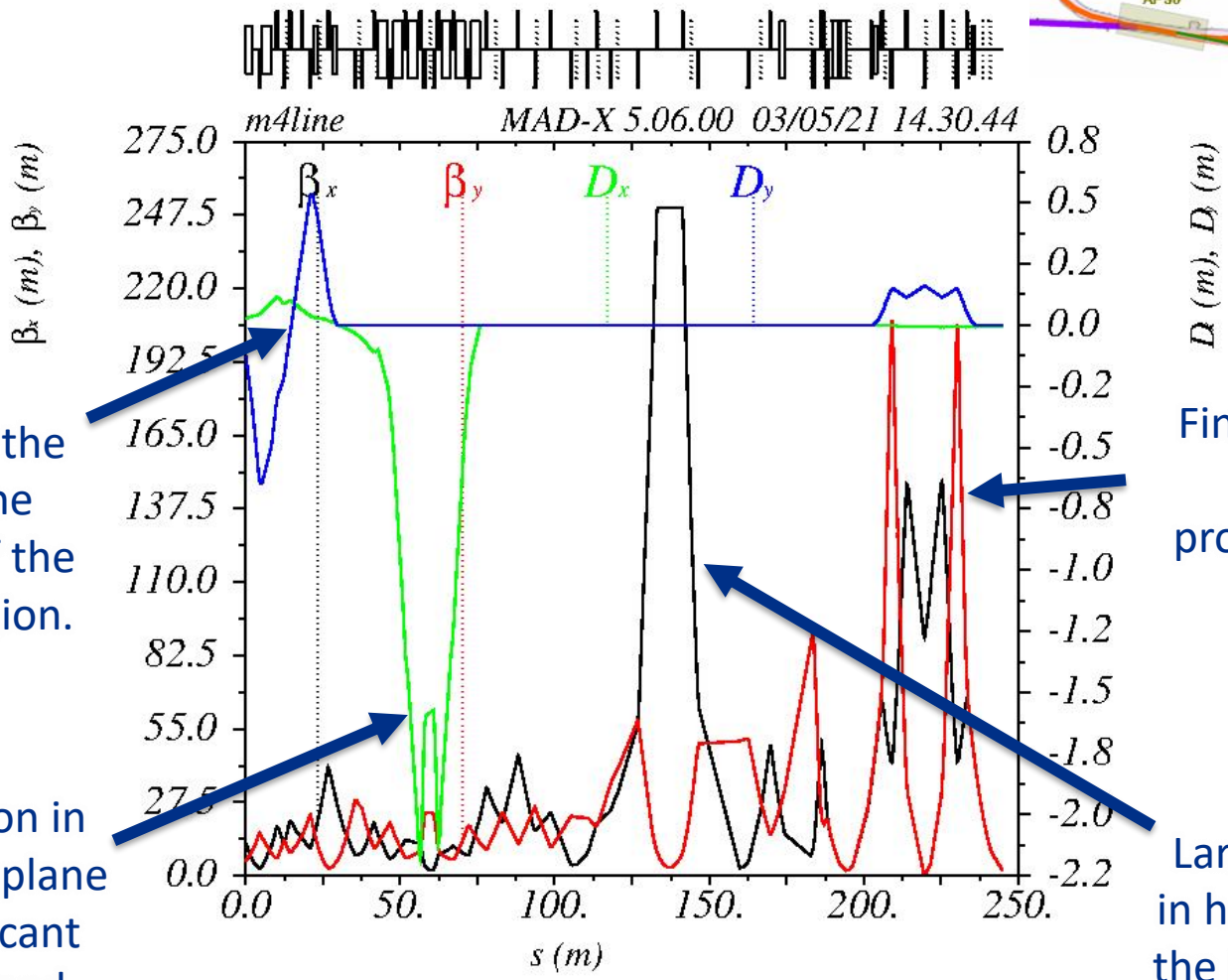
M2/M3 Optical Functions





Fermilab

M4 Optical Functions



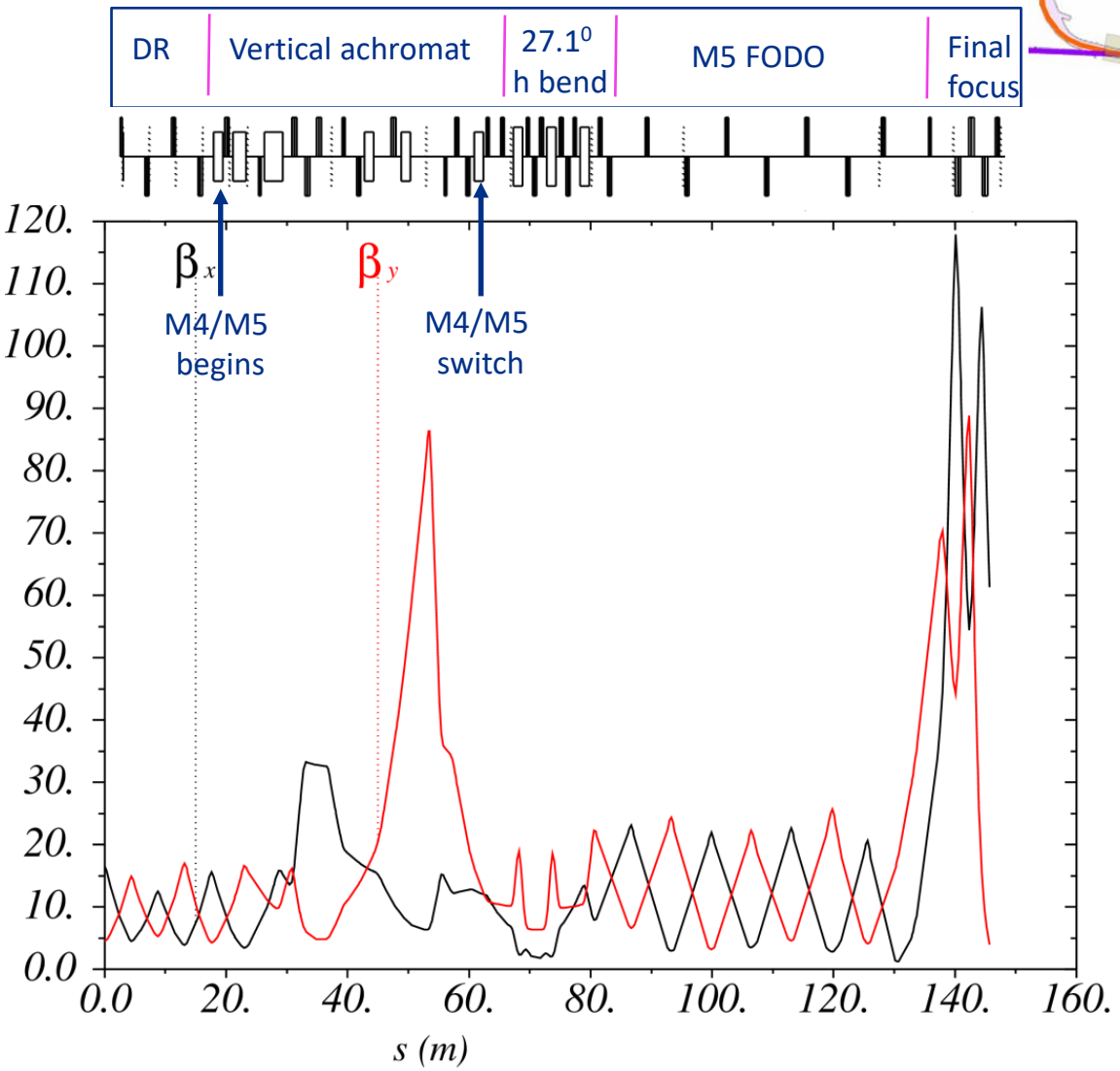
Dispersion in the vertical plane coming out of the extraction region.

High dispersion in the horizontal plane due to significant horizontal bend towards Mu2e.

Final focus before the Mu2e production target.

Large Beta function in horizontal plane in the Extinction region.

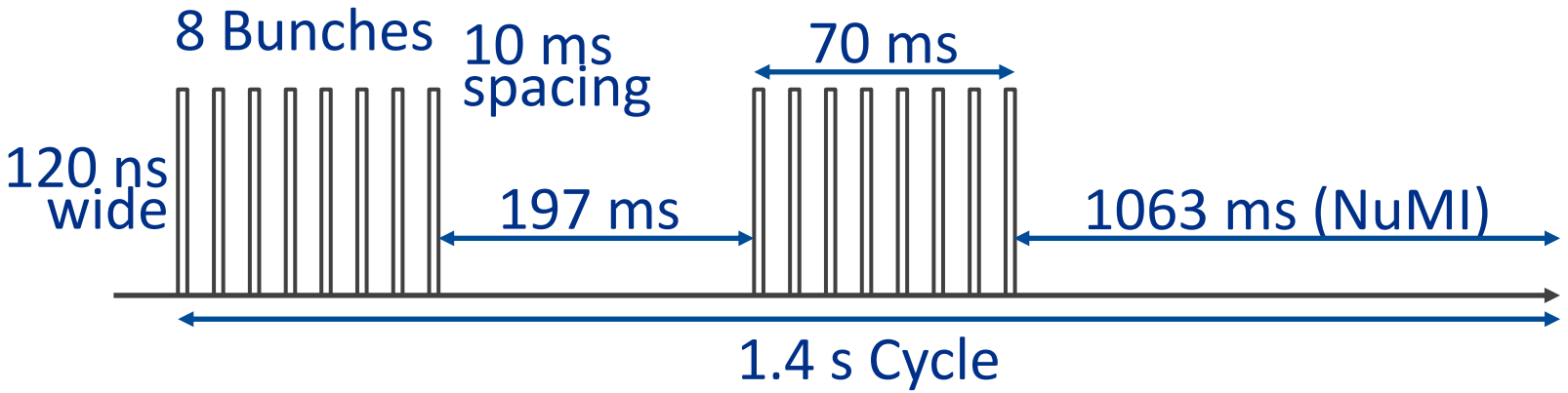
M5 Optical Functions



Fermilab

Timeline Changes

- g-2 Macro-time Structure, Recycler to Target



- Mu2e Macro-time Structure, Recycler to Delivery Ring