Fermilab

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Muon Campus pion operations

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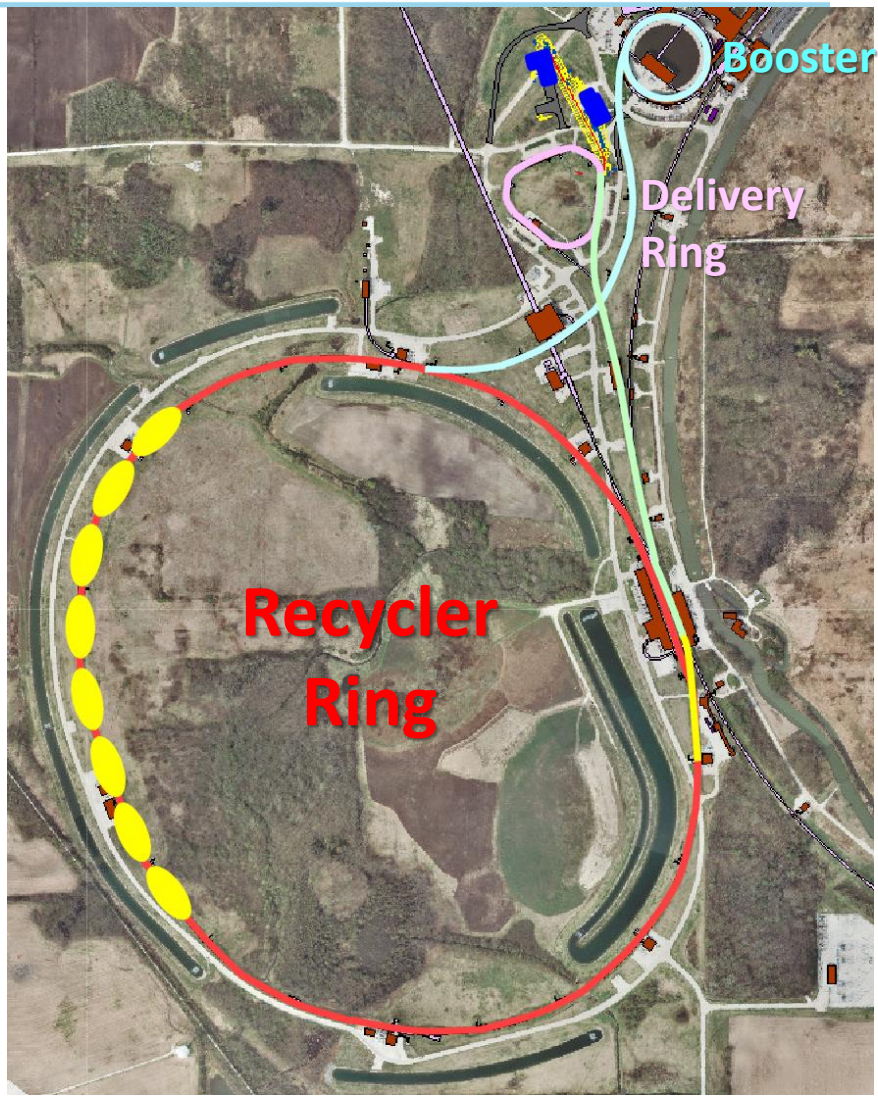
Outline

- Summary of current beam operation to g-2
  - Beam path to the Muon Campus and bunch formation
- Differences between running Mu2e and g-2
  - Beam transport to Delivery Ring
  - Extraction process
- Differences between g-2 at BNL and FNAL
- Pions for neutrino mass measurement
  - Very low intensity at very high frequency
- Pions for lifetime measurement
  - Highest intensity possible

Proton delivery to the Muon Campus

- 750 keV protons from the Pre-Accelerator are sent to the Linac, then accelerate to 400 MeV
- 400 MeV protons are transported from the Linac to the Booster and accelerated with 52.8 MHz RF (84 bunches) over 33 ms to 8 GeV
- 8 GeV protons are transported from the Booster to the Recycler via MI-8
- 8 GeV protons are injected into the Recycler, then the above process is repeated so that there are two “batches” of beam in the Recycler
- The 52.8 MHz RRRF system is turned off and a 2.5 MHz system “rebunches” the 168 bunches into 8 bunches approximately 120 ns long
- The 8 bunches are each transported from the Recycler to the Muon Campus via the P1 & P2 Lines
- The process is repeated for 16 bunch operation



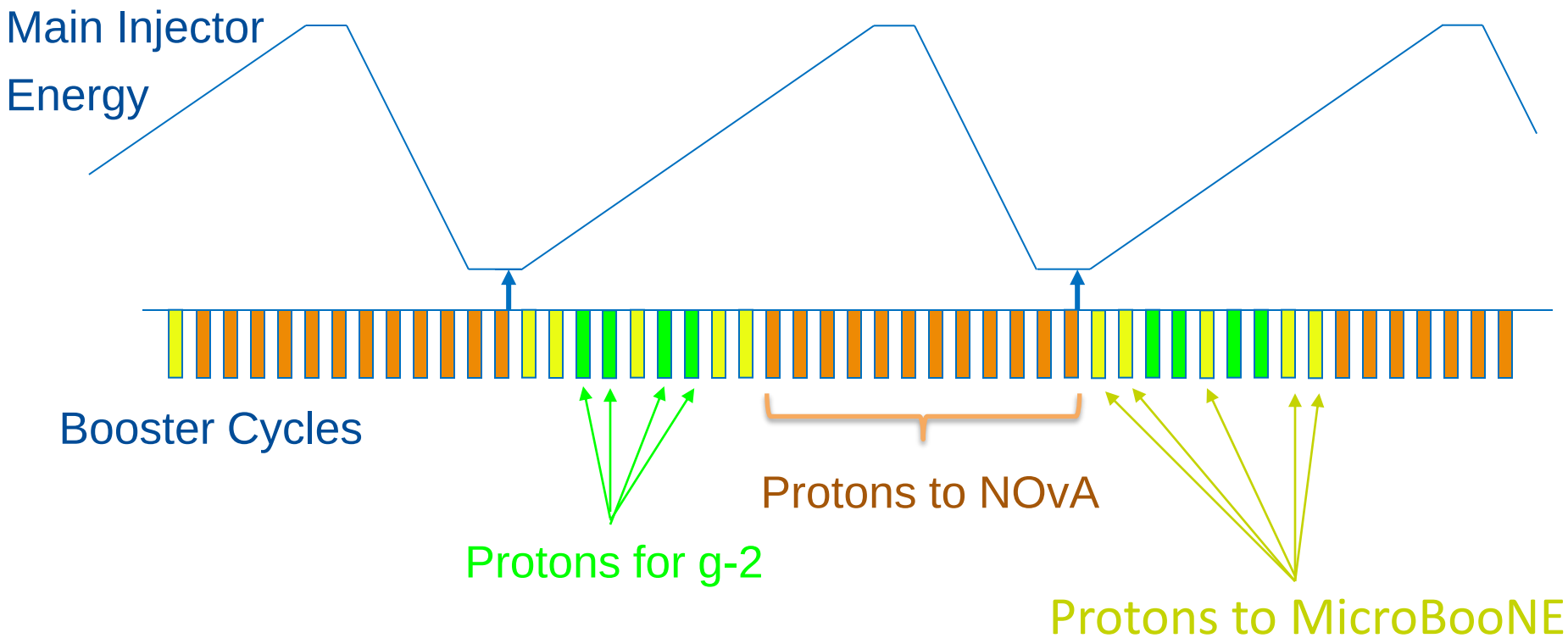
Beam delivery timeline for g-2

21 Booster cycles per NOvA cycle (1.4 sec, 15 Hz)

12 NOvA cycles stored in Recycler before transfer to MI

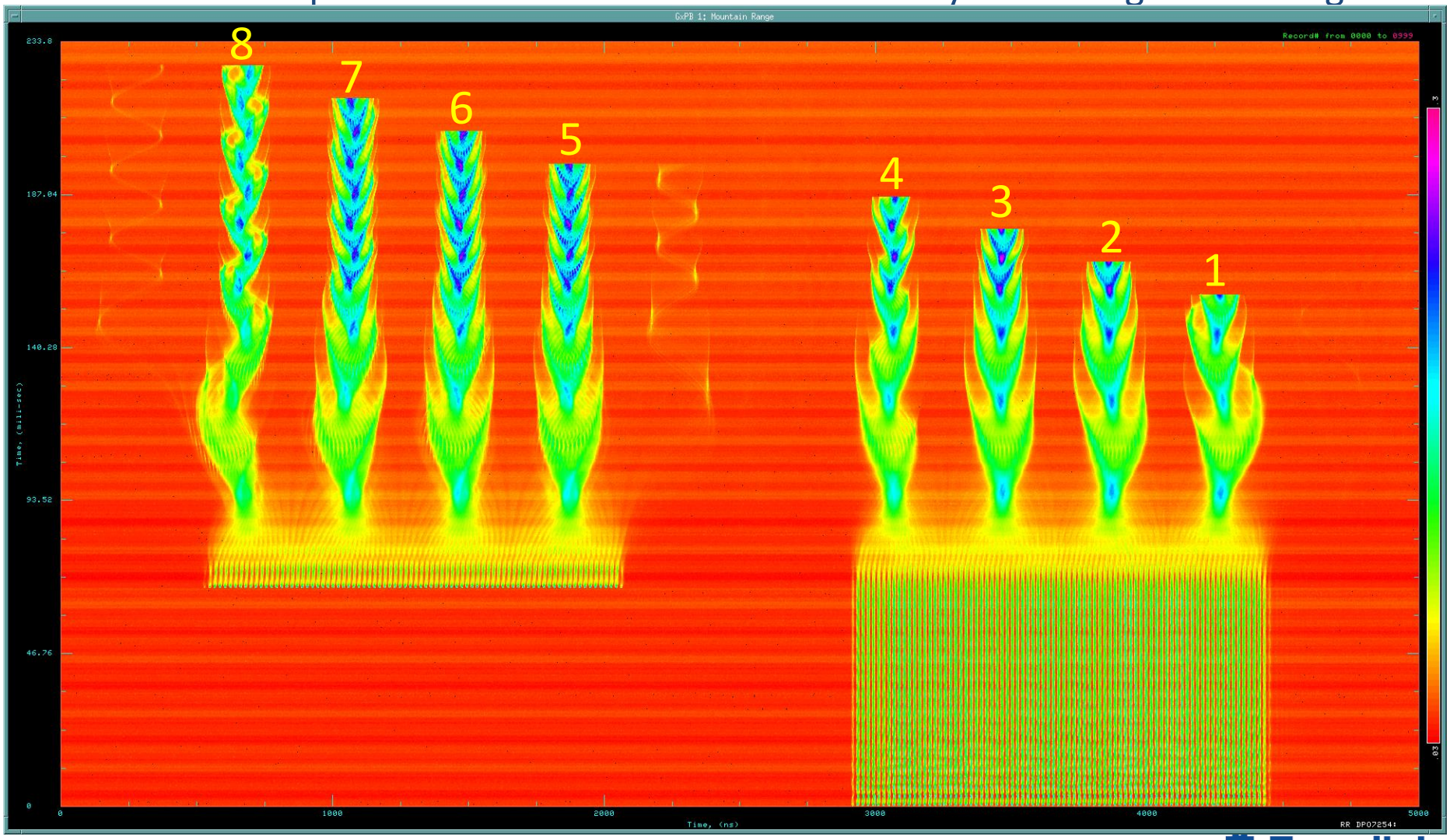
Remaining 9 Booster cycles available for other experiments

Nova can run with 1.2 second cycle time



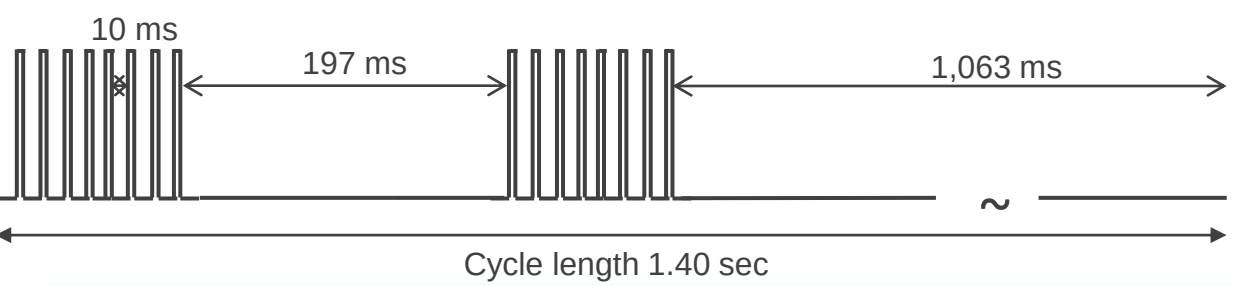
Recycler bunch formation

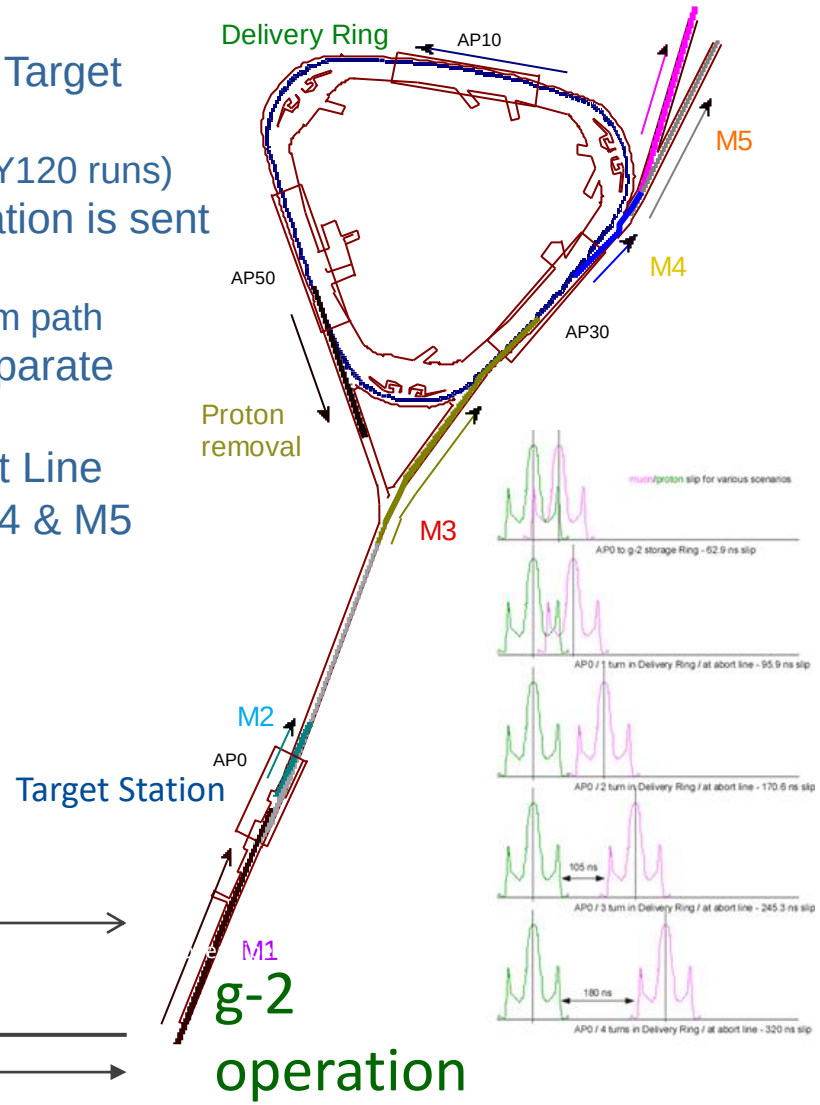
Waterfall plot of two 84 bunch “batches” in Recycler during rebunching



The differences between g-2 and Mu2e

- g-2 – 3.1 GeV Muons
  - Protons from the Recycler are sent to the AP-0 Target Station via P1, P2 and M1
    - 1E12 protons per pulse at 11.4 Hz (less when SY120 runs)
  - A 3.1 GeV secondary beam from the Target Station is sent into the M2 and M3 Lines
    - Pions decay to muons along the secondary beam path
  - Beam circles the Delivery Ring four times to separate protons from muons in time
  - Secondary protons are kicked into the DR Abort Line
  - Muons are extracted and sent to through the M4 & M5 Lines to the g-2 Experiment





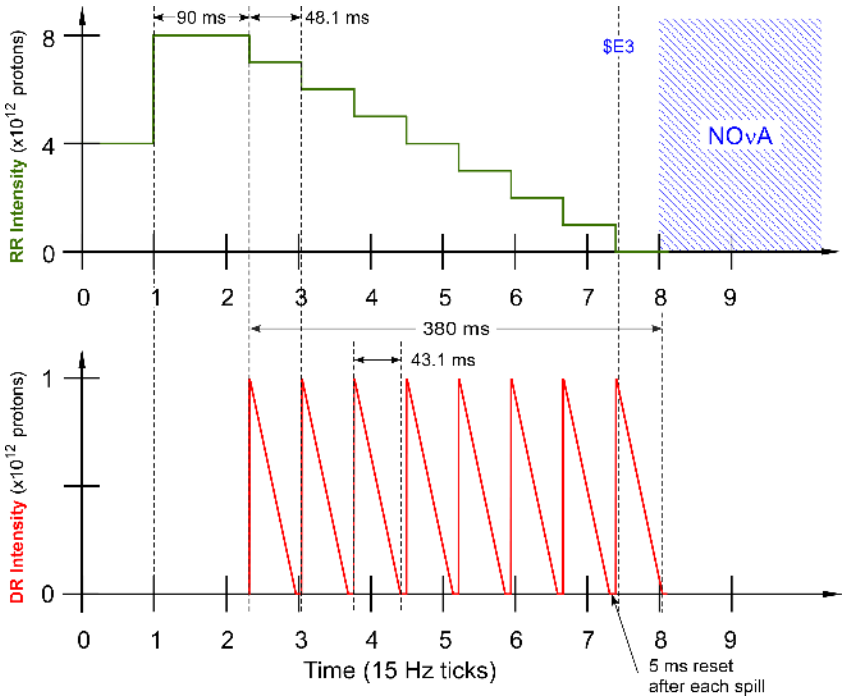
The differences between g-2 and Mu2e

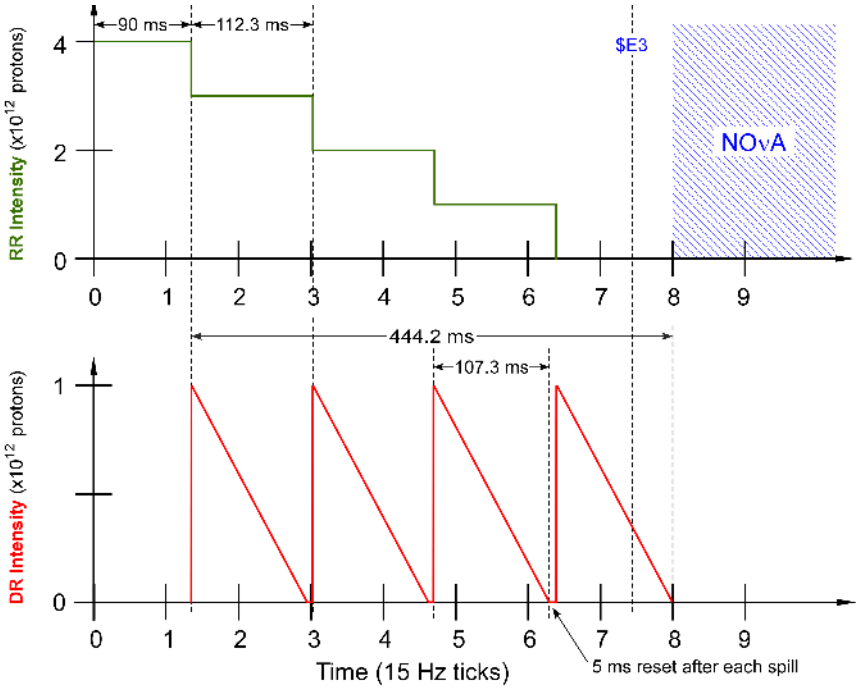
- Mu2e – DR resonantly extracted 8 GeV protons
  - Protons from the Recycler bypass the Muon Target Station via the upstream M3 Line
    - Recycler to Delivery Ring beam path is through P1, P2, M1 and M3 beamlines
  - 1E12 protons per pulse at 2.86 Hz (initially 4 pulses every 1.33 seconds over 444 ms, beam off 889 ms)
  - Protons circulate in the Delivery Ring for 43 ms and are resonantly extracted
    - Protons remaining at the end of spill are sent to Delivery Ring Abort
  - Beam is extracted with two electrostatic septa and a Lambertson
    - Protons are transported from the Delivery Ring to Mu2e via the M-4 Line
    - M-4 Line ends at Mu2e Target in the Production Solenoid

Mu2e operation

Delivery Ring resonant extraction to Mu2e

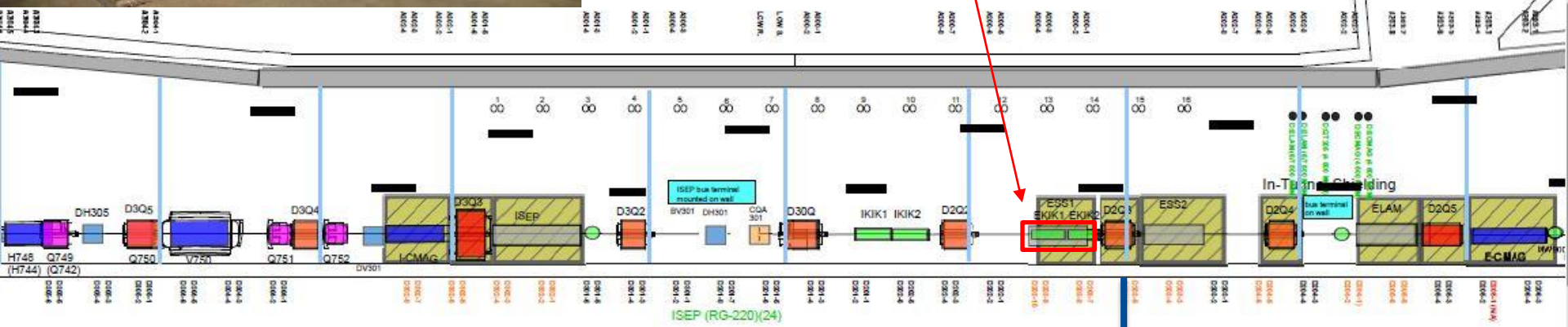
- Mu2e – resonant extraction pulse timeline
  - Design rate of 1E12 protons per pulse at 6.0 Hz (8 pulses every 1.33 seconds)
    - Duty cycle 26% (8 x 43.1 ms every 1.33 seconds)
    - 140 ns long proton bunch repeating every 1,695 ns
  - Reduced rate of 1E12 protons per pulse at 3.0 Hz (4 pulses every 1.33 seconds)
    - Duty cycle 32% (4 x 107.3 ms every 1.33 seconds)
    - 140 ns long proton bunch repeating every 1,695 ns

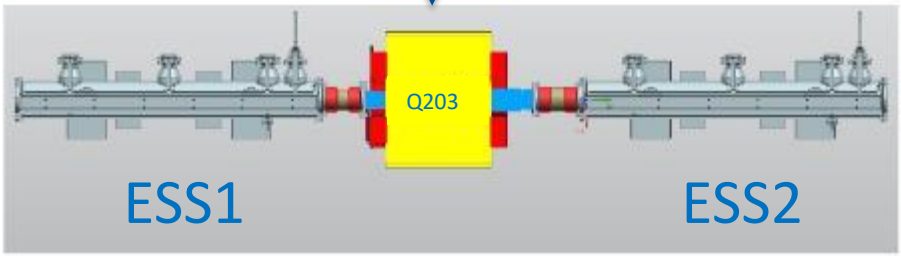




D30 straight section and extraction devices

Upstream Mu2e electrostatic septa will be located where Extraction Kicker is now



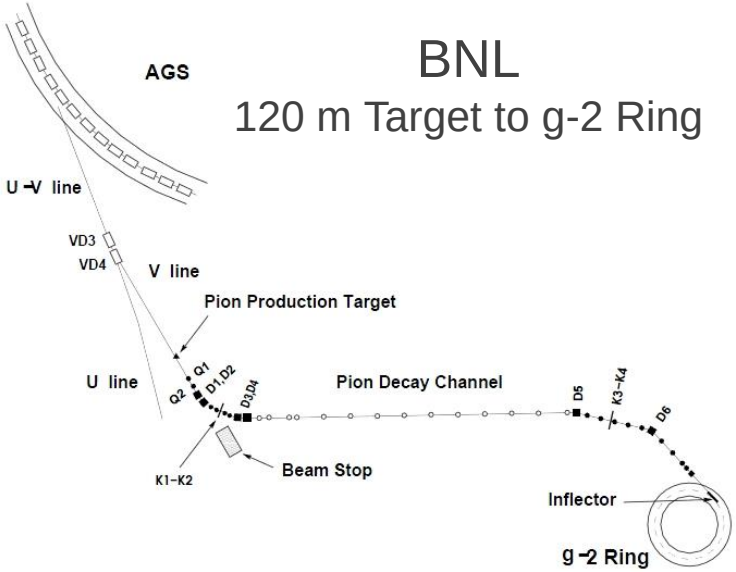


Differences between g-2 at BNL and FNAL

- BNL
  - AGS capable of both single turn and resonant extraction
  - Relatively short path length from target to g-2 Ring
  - Protons reduced, but not removed
- FNAL
  - Recycler not capable of resonant extraction, used for NuMI production
  - Relatively long path length from target to g-2 Ring
  - Proton removal possible, but greatly lengthens path length to g-2 Ring
  - Delivery Ring will have resonant extraction for Mu2e

BNL

120 m Target to g-2 Ring

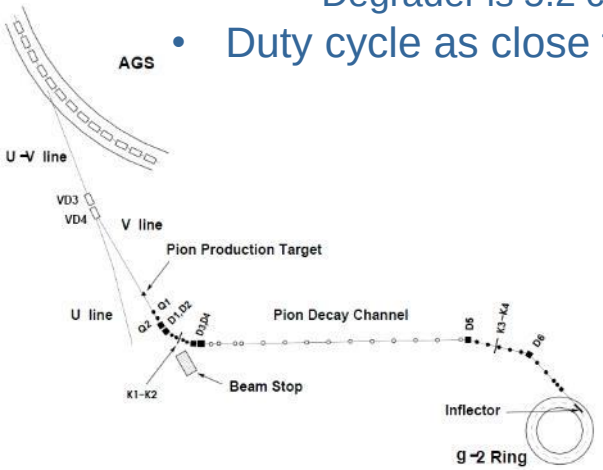


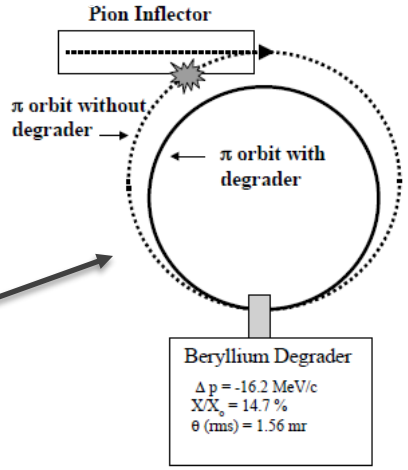
FNAL

420 m Target to g-2 Ring
(2,440 m with proton removal)

Muon Neutrino mass measurement – 2000 Numass proposal

- Very low pion intensity, but at high frequency
  - Each muon must be referenced unambiguously to its parent pion
  - Proposal calls for one pion every 300 ns (3.3E6 pions/second)
- Proposed accelerator configuration at BNL
  - Slow resonant extraction from AGS
    - Dedicated mode with 10 GeV protons, 5.1 second cycle with 3.6 second spill
    - Shared operation with another experiment at 25 GeV (required new extraction device)
  - Beam delivered to Pion production target, as with g-2 operation
  - 120 m path length from target to ring
- Injection into g-2 Ring
  - Pions are injected at 16 MeV/c above capture momentum of 3094 MeV/c
  - Energy degrader located 180° from Inflector provides -16 MeV/c momentum kick
    - Degrader is 5.2 cm thick beryllium
  - Duty cycle as close to 1 as possible





Numass in the Muon Campus - challenges

- Present g-2 modes of operation won't work
  - Very low pion count and proton removal, but extremely low rates (10 Hz?)
  - "Straight through" operation increases pion count, includes protons, rates still low
- Recycler and Main Injector are occupied with loading beam for NoVA
  - Primary use of 8 GeV Recycler is to load Main Injector for NOvA (eventually LBNF)
    - g-2 and others make use of pause between NuMI cycles
  - Recycler could have resonant extraction system, but total beam with NOvA poses problems
    - AP-0 Target Station would need to operate DC, existing Li lens and magnet won't work
    - 2/7 Recycler circumference populated with beam, 11.1 us revolution period, 0.25 sec spill
- Resonant extraction to external Target Station in M5 Line
  - Delivery Ring will use resonant extraction in Mu2e configuration
  - Extremely daunting target station design challenge due to radiological issues
  - Pion beam will have larger momentum spread than g-2 Ring momentum acceptance unless momentum collimation scheme is devised

M5 Line to g-2

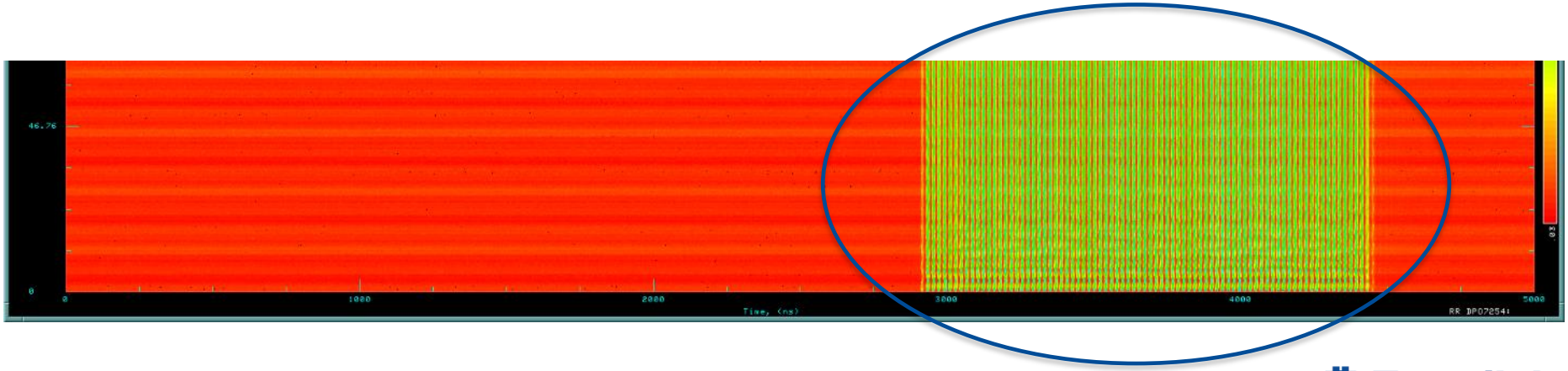
M4 Line to Mu2e

Delivery Ring “Mu2e-like” resonant extraction to Numass

- Mu2e – resonant extraction pulse timeline
  - Design rate of 1E12 protons per pulse at 6.0 Hz (8 pulses every 1.33 seconds)
    - Duty cycle 26% (8 x 43.1 ms every 1.33 seconds)
    - 140 ns long proton bunch repeating every 1,695 ns
  - Reduced rate of 1E12 protons per pulse at 3.0 Hz (4 pulses every 1.33 seconds)
    - Duty cycle 32% (4 x 107.3 ms every 1.33 seconds)
    - 140 ns long proton bunch repeating every 1,695 ns
- Proton rates to M5 target station in each scenario
  - 140 ns long proton pulse of 3.9E7 every 1,695 ns
    - 153.0 KHz rate
  - 140 ns long proton pulse of 1.6E7 every 1,695 ns
    - 190.4 KHz rate
- Assuming 1E-6 pions to g-2 Ring per proton on target
  - 15 to 40 pions per pulse (too many) at 153.0 KHz rate (low compared to proposal)
- Beam intensity on target can be as low as 1E11 per pulse
  - 1.5 to 4.0 pions per pulse (close) at 190.4 KHz rate (low compared to proposal)

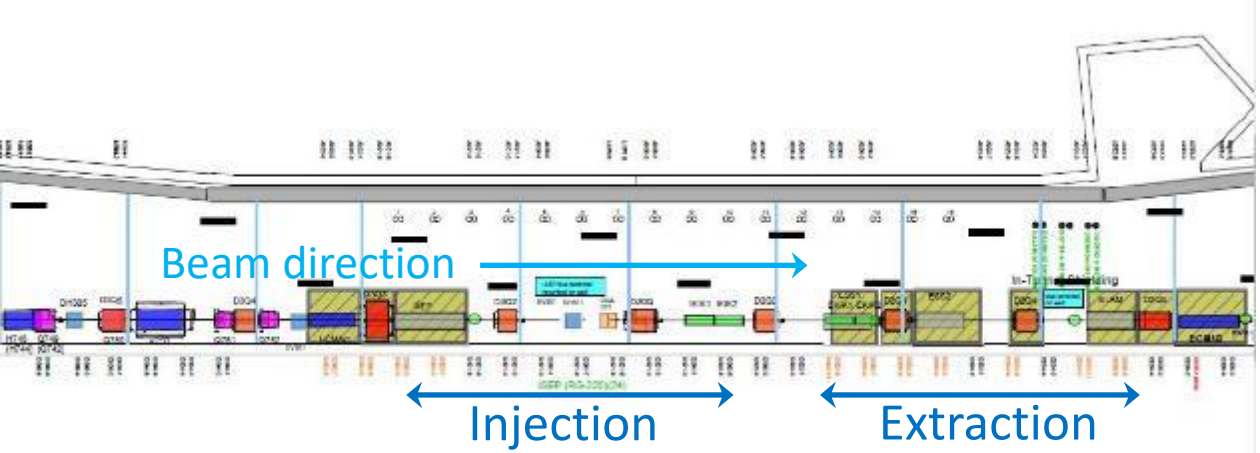
Delivery Ring alternate resonant extraction to Numass

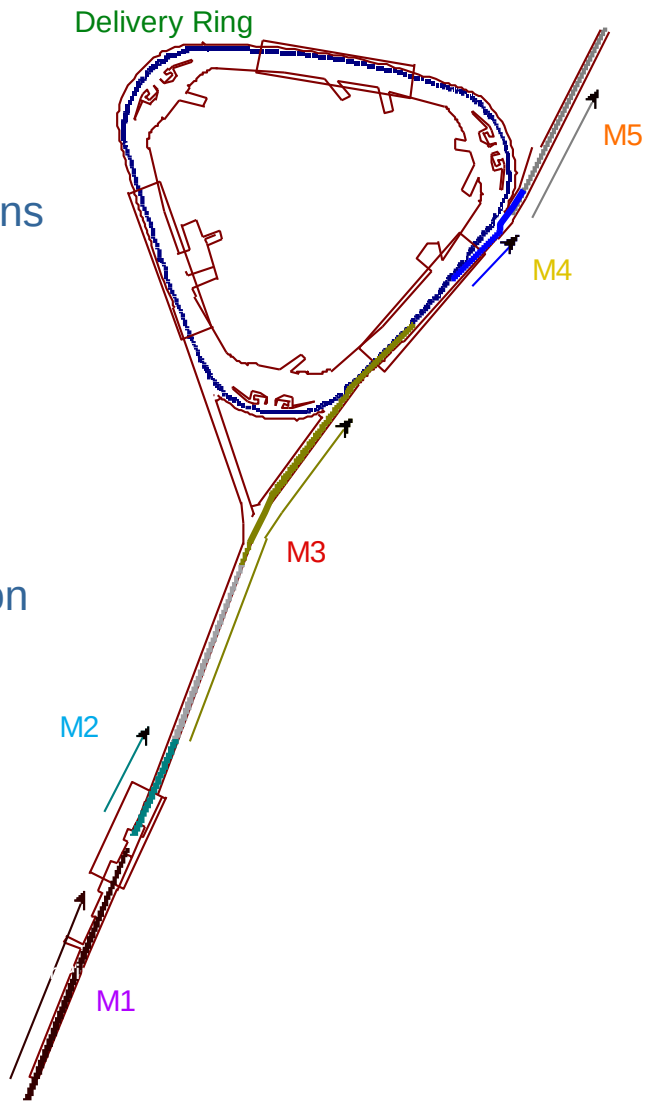
- No bunch formation in Recyler
  - 84 53 MHz Booster bunch sent directly to Delivery Ring (H=90 at 53 MHz)
    - Requires a longer PFL for the Delivery Ring Injection Kicker
    - 4E12 protons per transfer every 1.33 seconds (or multiples of 1.33 seconds)
    - Allow beam to partly debunch (spread out), followed by 1 second spill (or 2.33 second spill if beam is delivered every other NuMI cycle)
- Proton rates to M5 Target Station in this scenario
  - 4E12 protons/second
  - Can reduce proton intensity by factor of 10, reduces rates but improves rad issues
- Assuming 1E-6 pions to g-2 Ring per proton on target
  - 4E6 pions per second
  - Distributed over time pretty evenly, some 53 MHz micro-structure (19 ns)



Pion operating scenarios for lifetime measurements

- A variation on the g-2 operating scenario looks the most promising
  - Pion yield from AP-0 Target Station is relatively high
  - Using AP-0 Target Station greatly simplifies preparations for operation
  - Decay length is an issue, distances are long
- Running “straight through” Delivery Ring D30 straight section shortens path length
  - Injection is upstream of extraction in D30
  - Injection and Extraction kickers can be fired together
  - Eliminating turns in Delivery Ring also means no proton removal





Pion operating scenarios for lifetime measurements

- Path length in current g-2 scenario leaves few pions to MC-1 Ring
  - Roughly only one pion after traveling 2,440 m from Target (173 m decay length)
- Can use “straight through” path that eliminates DR revolutions
  - 420 m path length from target to g-2 Ring
  - Up to 1E6 pions per fill (based on 1E-6 π+ to g-2 Ring per POT)
  - Probably 5E5 pions per fill more realistic, based on M5 to g-2 dispersion mismatch
  - Considerable contamination from other particles
- Particle contamination
  - Protons, positrons, muons, deuterons
  - Perhaps 75% of particles aren’t within momentum acceptance of g-2 Ring
  - Removing off-momentum particles would greatly reduce radiological issues

DIKTYS STRATAKIS *et al.* PHYS. REV. ACCEL. BEAMS **20,** 111003 (2017)

TABLE II. Number of secondary particles at different Fermilab Muon Campus locations, where these values are normalized to the POT.

	p, all	π^+, all	μ^+, all	$\mu^+, \Delta p/p = \pm 2\%$	$\mu^+, \Delta p/p = \pm 0.5\%$
End of M3	1.37×10^{-4}	1.87×10^{-5}	2.68×10^{-6}	1.19×10^{-6}	3.26×10^{-7}
DR (Turn 1)	8.02×10^{-5}	5.06×10^{-7}	9.50×10^{-7}	8.40×10^{-7}	2.59×10^{-7}
DR (Turn 2)	7.94×10^{-5}	2.72×10^{-8}	9.15×10^{-7}	8.16×10^{-7}	2.54×10^{-7}
DR (Turn 3)	7.89×10^{-5}	1.93×10^{-9}	8.83×10^{-7}	7.89×10^{-7}	2.47×10^{-7}
DR (Turn 4)	7.88×10^{-5}	$<10^{-9}$	8.54×10^{-7}	7.65×10^{-7}	2.39×10^{-7}
End of M5		$<10^{-9}$	7.80×10^{-7}	6.80×10^{-7}	2.08×10^{-7}

Pion operation conclusions

- Numass could work, in principle
  - Mu2e-like bunch delivery scheme has drawbacks
  - Direct injection of 84 bunch train from Booster gives most uniform spill
  - A target station in the M5 Line would be very challenging to design and build
  - Would use existing resonant extraction hardware for Mu2e
  - Need simulation effort to get realistic pion yield estimates
  - Lower proton intensity per spill may make radiological issues tolerable
  - Momentum collimation scheme would be needed for smaller momentum bite
  - Recycler resonantly extracted protons to modified AP-0 Target Station possible
- Pion lifetime experiment could also work, if protons can be tolerated
  - Uses existing AP-0 Target station and “g-2 like” beam transfer process
    - 140 ns bunch structure as is used for g-2
  - No turns in Delivery Ring due to long path length required for proton removal
  - Mixed beam of protons, muons, pions, positrons and deuterons sent to MC-1 Ring
  - Momentum collimation scheme would help minimize rad levels in MC-1
  - Need critical Target Station components to be left after g-2 ends