# Future Accelerator Upgrades and Muons at Fermilab

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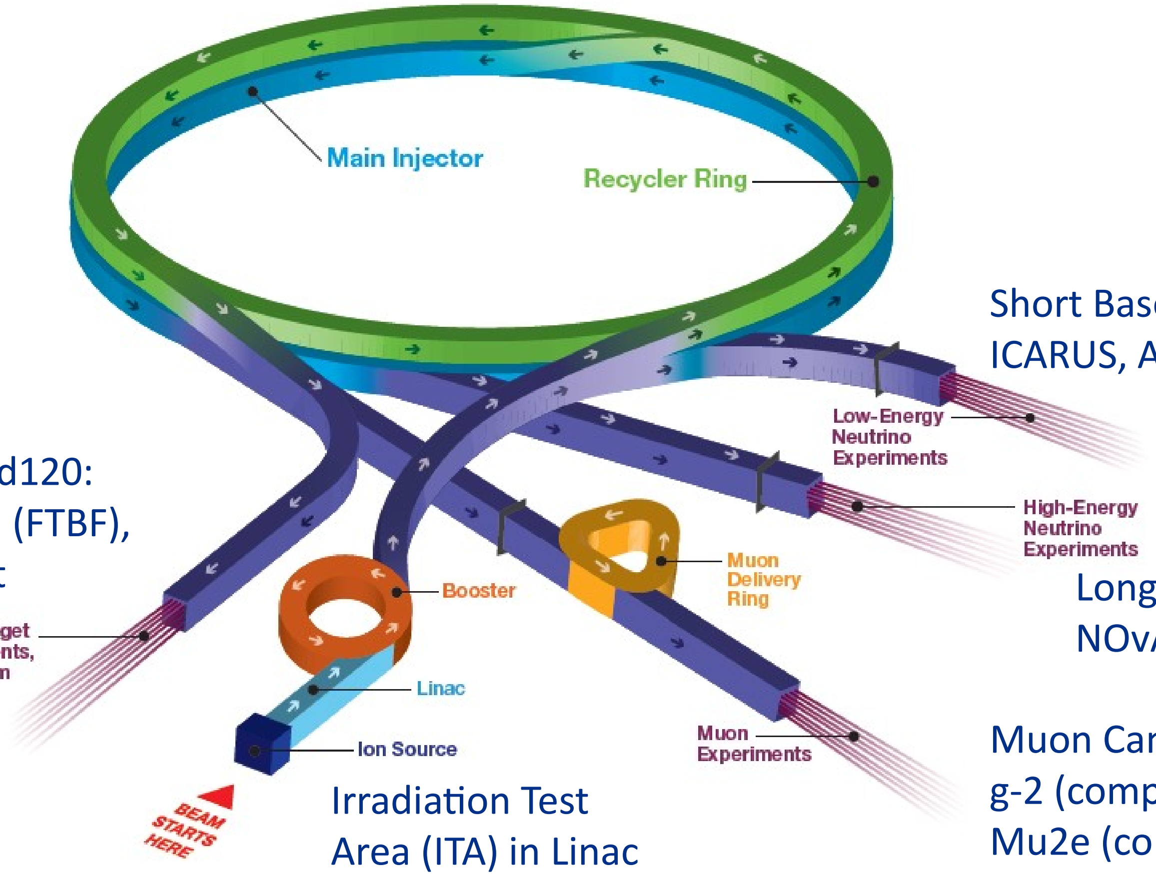
# Overview

- How we do protons to muons at Fermilab today
- How we expect things to evolve in the next ten years
- Gazing into the crystal ball…

# You must keep this constraint in mind

Since the end of Tevatron running, *neutrino physics* has driven the proton economics at Fermilab, and that *will* remain the key driver for the next 30+ years!

# Cartoon of the current accelerator complex




SwitchYard120:
test beam (FTBF),
SpinQuest

Short Baseline Neutrino:
ICARUS, ANNIE, SBND

Long Baseline Neutrino:
NOvA

Irradiation Test
Area (ITA) in Linac

Muon Campus:
g-2 (completes this year),
Mu2e (commissioning)

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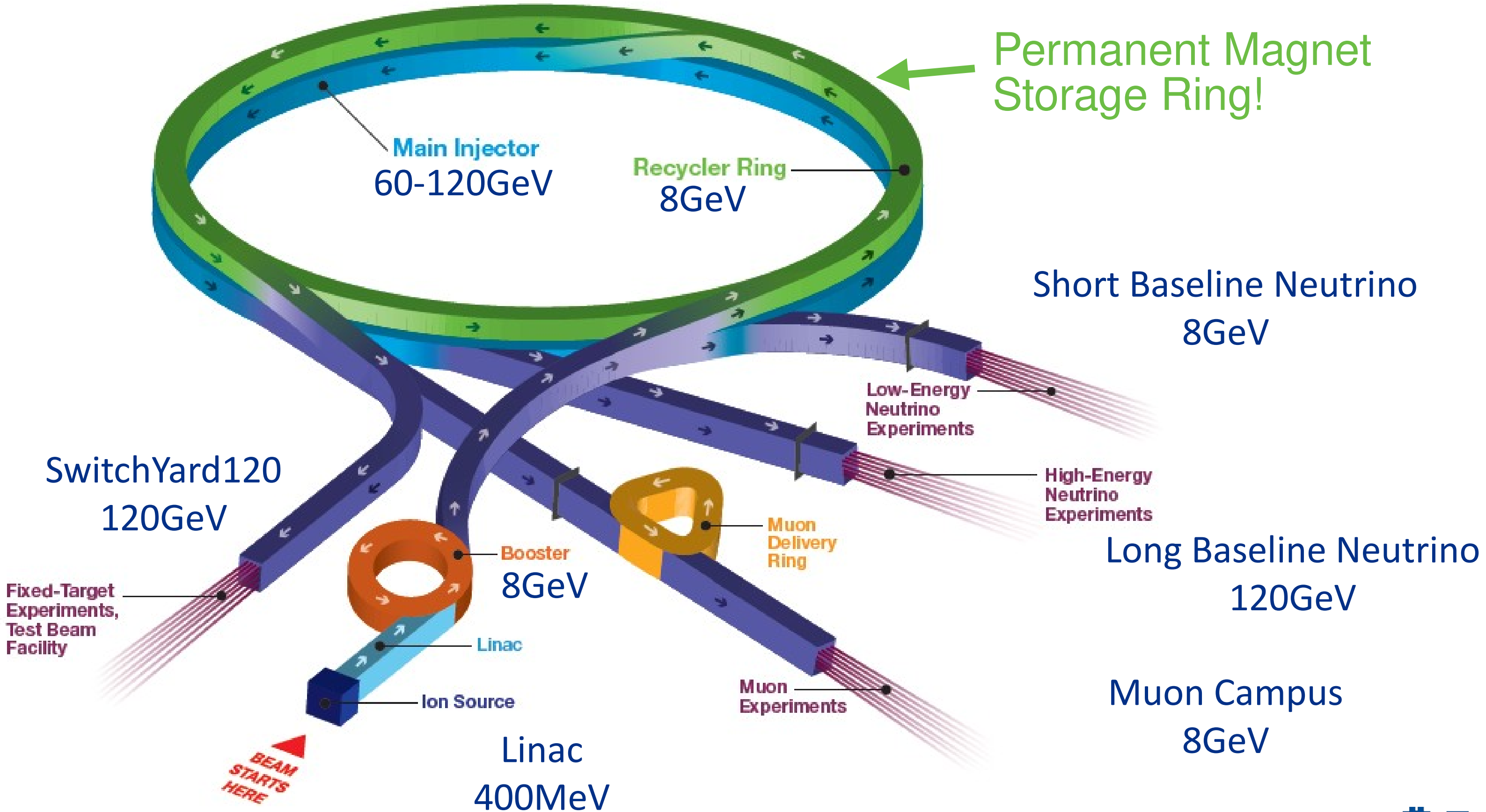
From M. Convery

# Cartoon of the current accelerator complex

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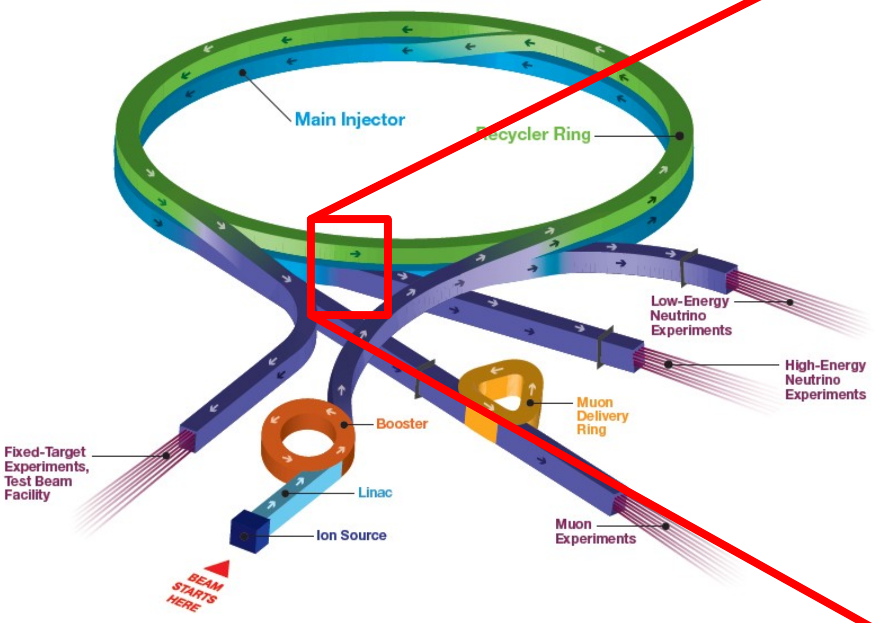
# Reminder that these cartoons hide a wealth of complex and interesting science and engineering




# Reminder that these cartoons hide a wealth of complex and interesting science and engineering

Recycler Ring

NuMI Extraction Line

Main Injector

# They also hide a vast hierarchy of scales!

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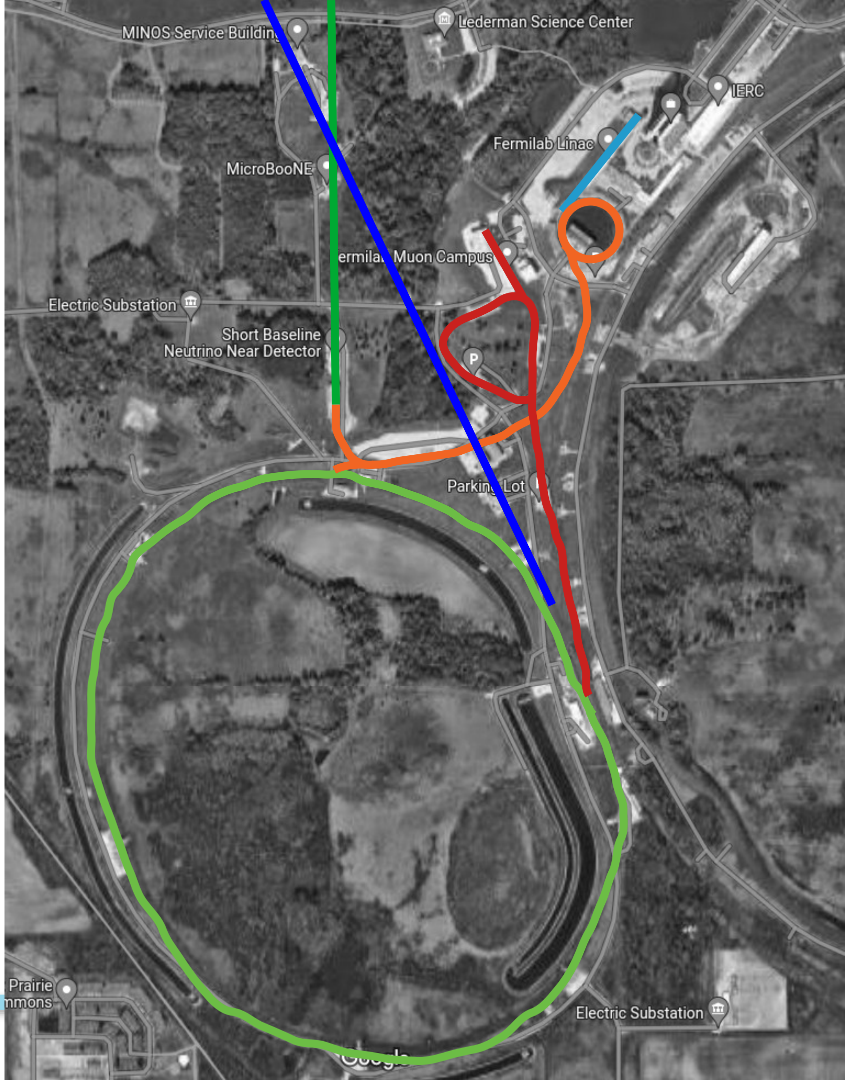
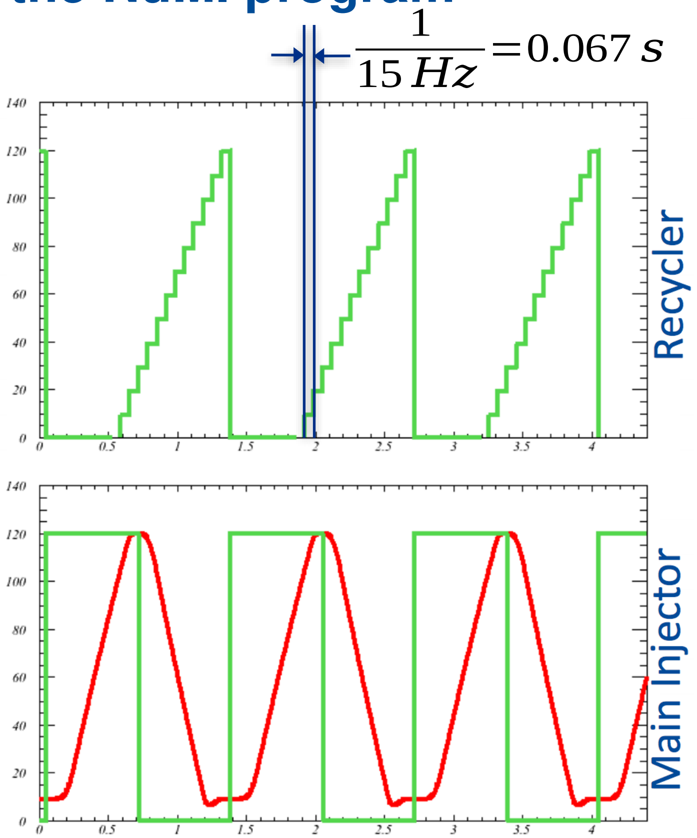
- Linac (400MeV)
- Booster (8GeV)
- RR/MI (8GeV/120GeV)
- Muon Campus (3.094GeV/8GeV)
- BNB (8GeV)
- NuMI (120GeV)



# The accelerator timeline is organized around the NuMI program

- $H^-$ linac (1970, 1993, 2012)
  - 400 MeV linac ~20mA
- Booster synchrotron (1970)
  - $H^-$ stripping injection (1978)
    - 16 turns to ~4.7x$10^{12}$ p per pulse
  - Resonant Ramp from 0.4 to 8 GeV at 15 Hz
- Recycler (1998)
  - 3.3 km permanent magnet 8 GeV ring
  - Slip-stacking 12 Booster batches, ~56x$10^{12}$ p
  - Also re-bunches beam for Muon Campus
- Main Injector (1998, but!)
  - 8 to 120 GeV ramp, cycle time 1.133*-1.4 s



1.33s cycle shown

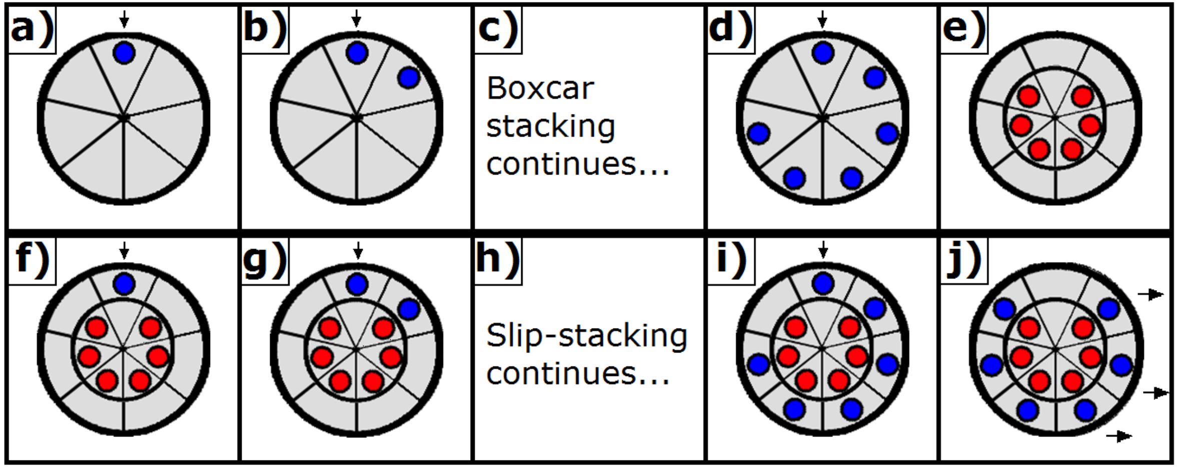
* 1.067s has been demonstrated recently!

From M. Convery

# Stacking beam in the Recycler is the key timeline constraint

- Slip stacking is a method of injecting multiple beams at different momenta into the same circular machine.
  - We combine slip stacking with boxcar stacking to stuff beam into the Recycler

7x as many 53MHz RF buckets in RR/MI as in Booster (588/84) … 81 filled buckets per transfer




- These manipulations require 13 ticks of the Booster clock
  - 12 for injection, one for extraction



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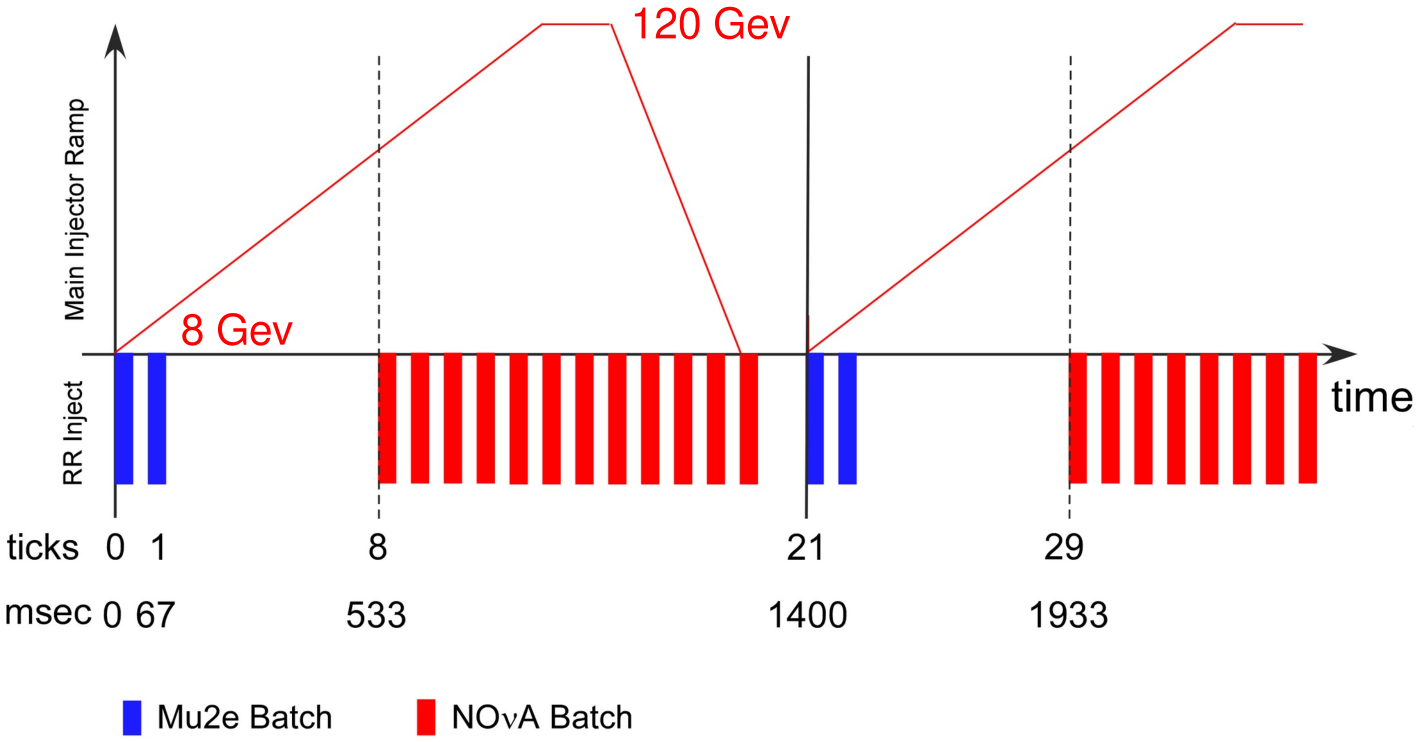
# All our machine timelines are built around moving 12 successive Booster batches to the MI – how does this impact muons?




1 tick = 1/15 sec

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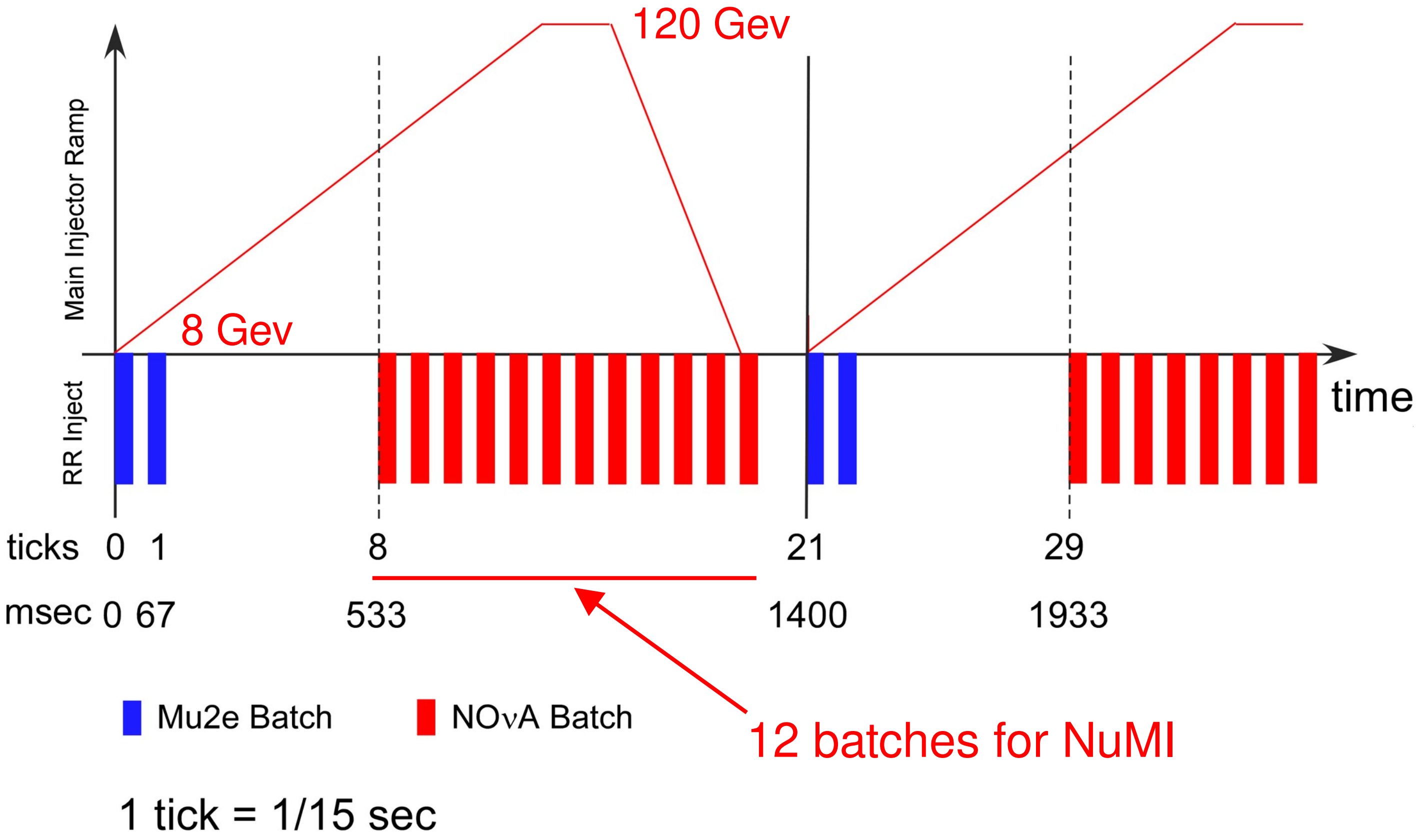

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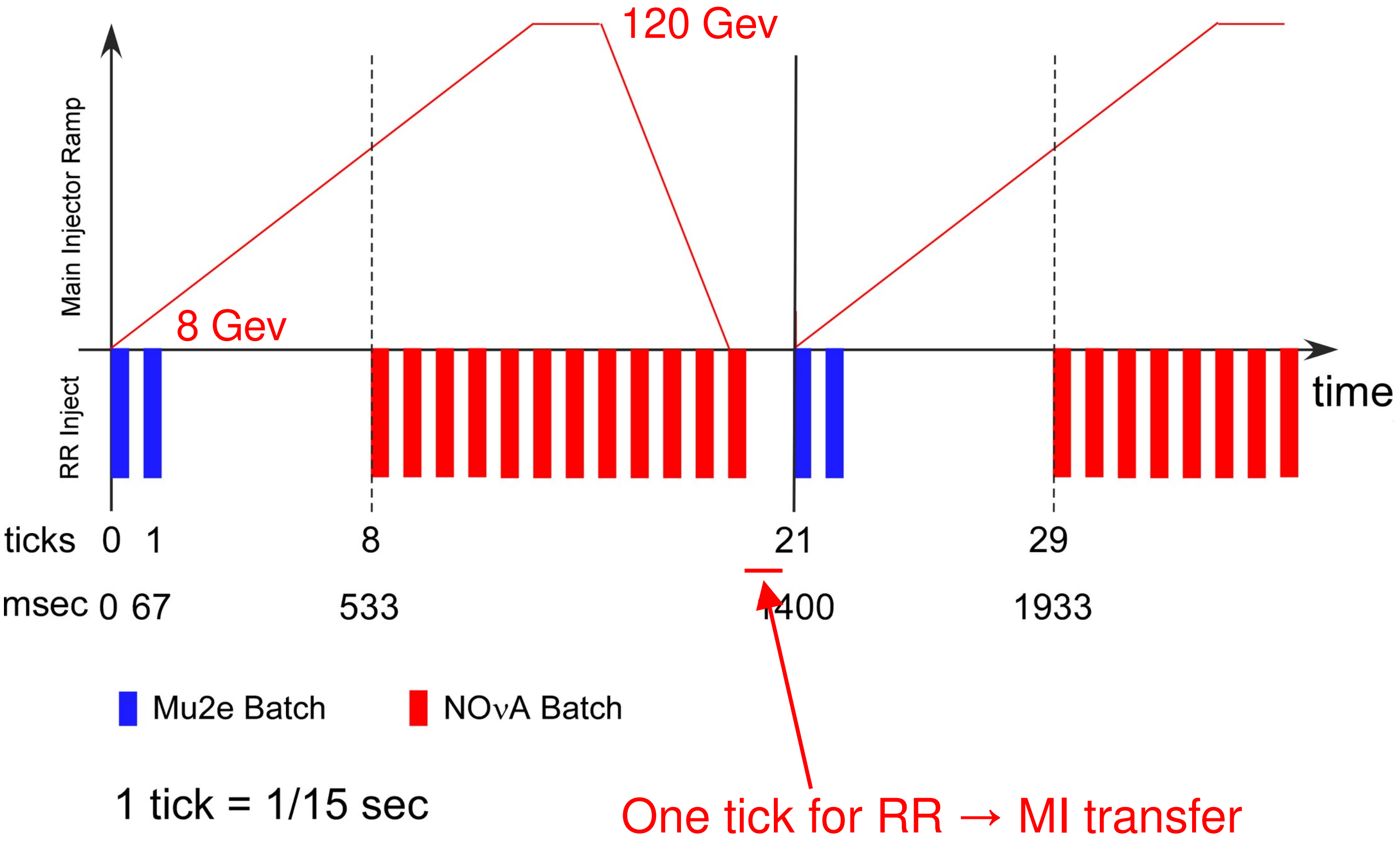

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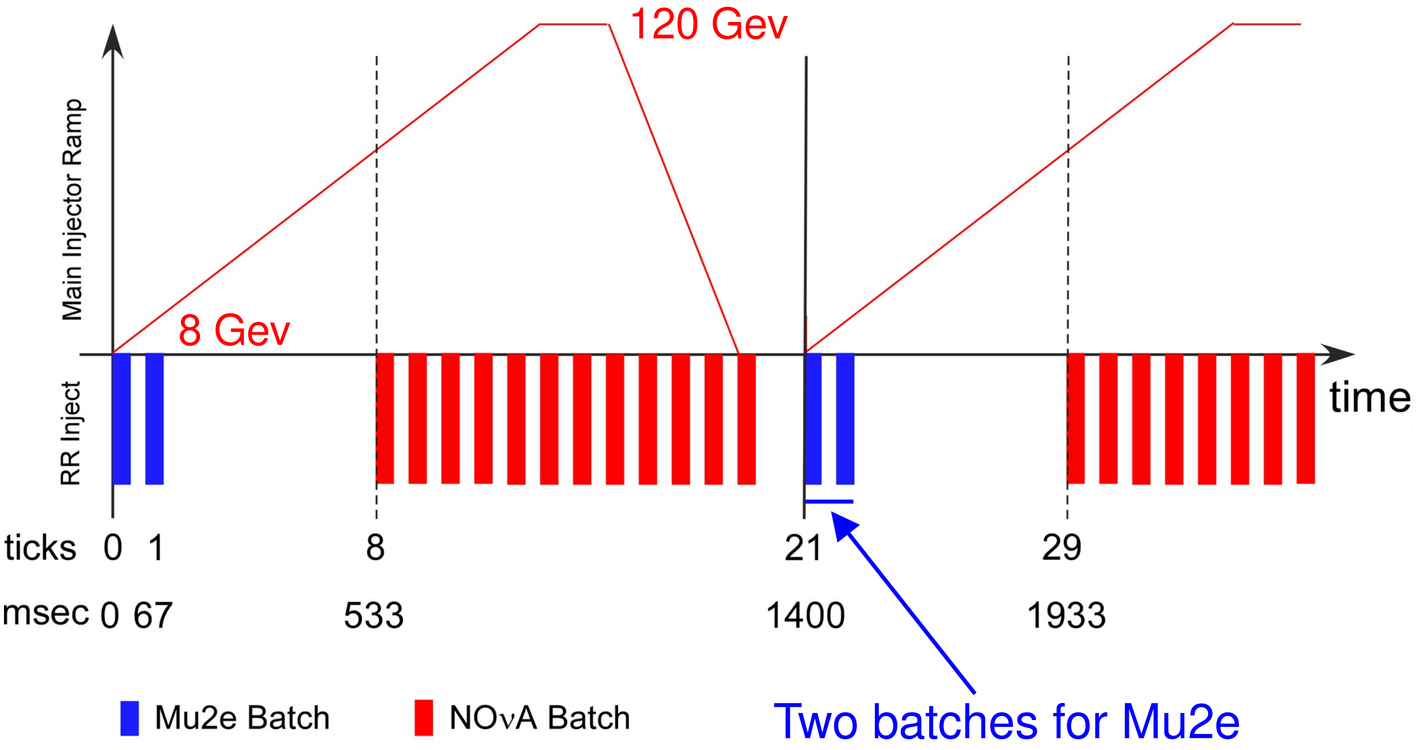


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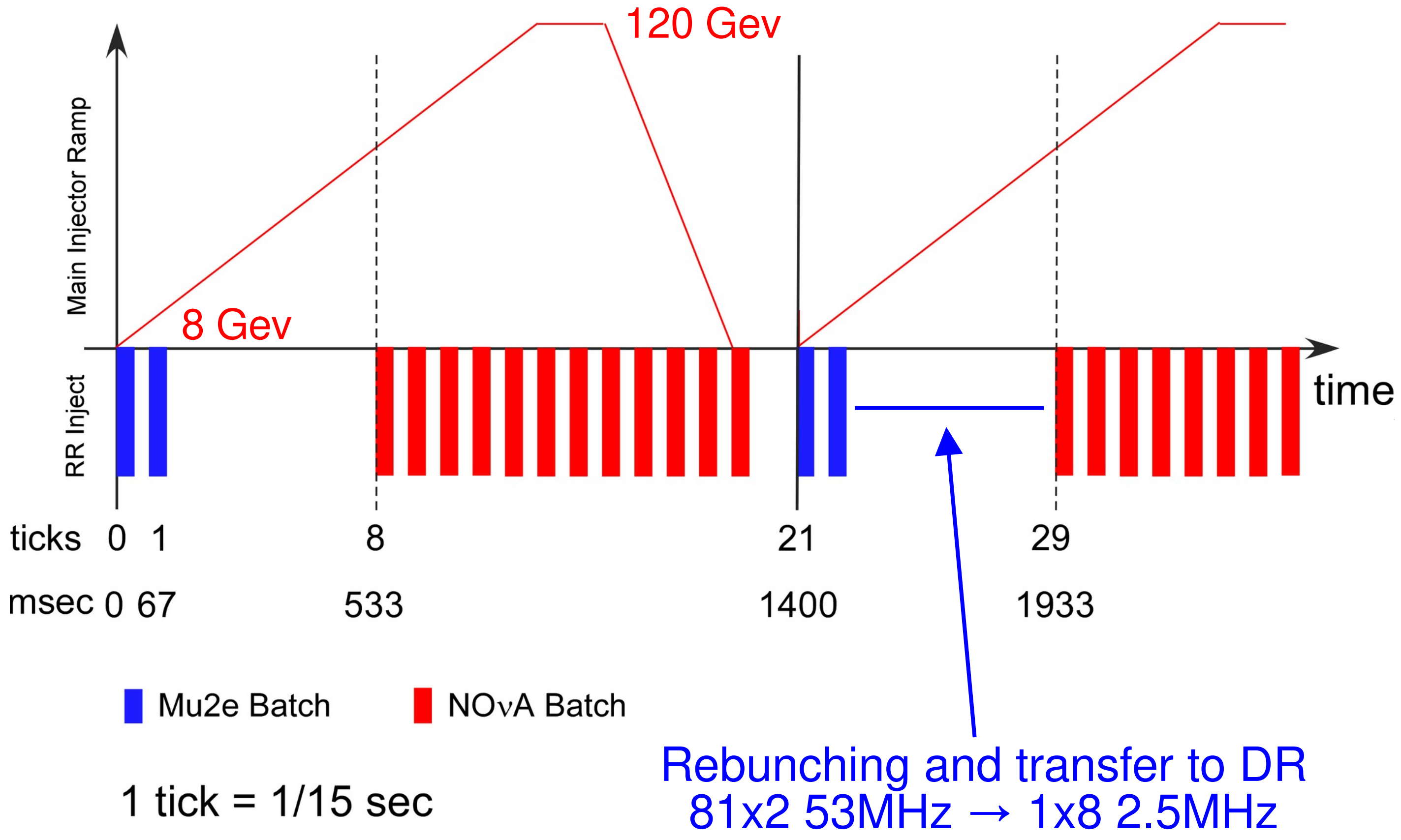
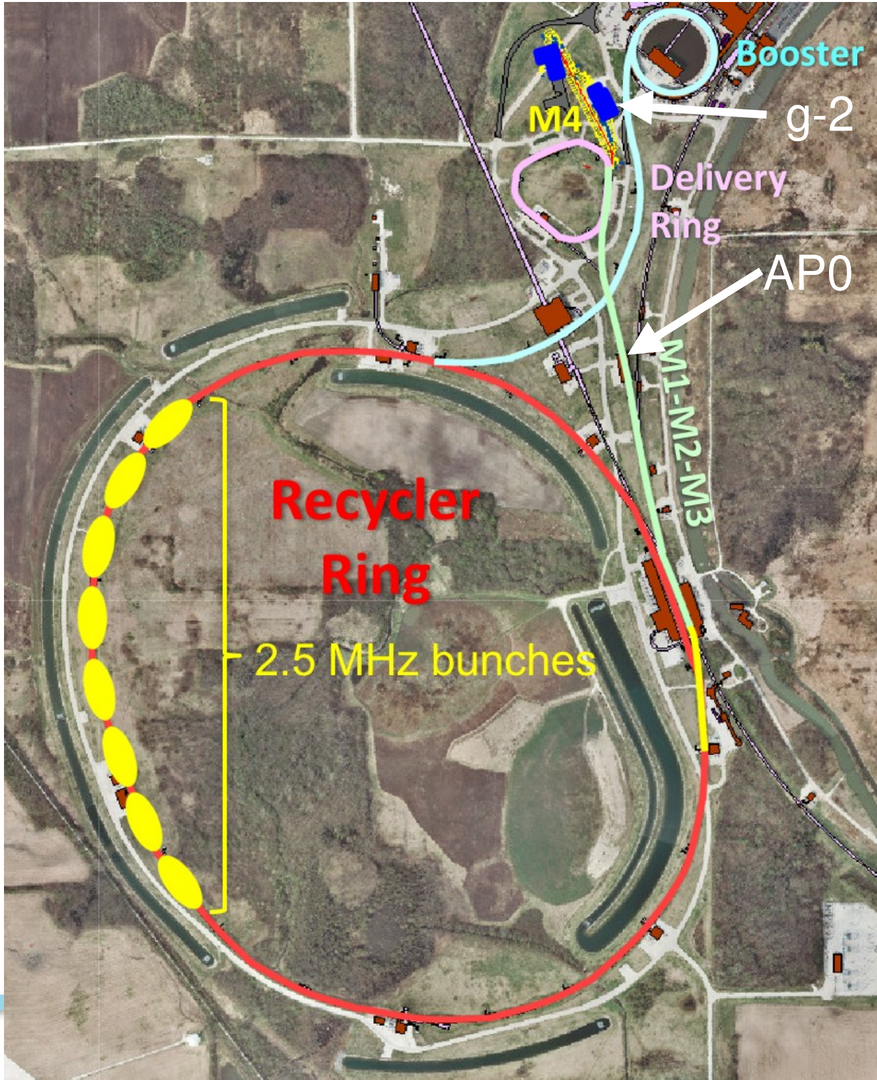


# Muon beam to g-2 is produced at the AP0 target – the old $\overline{p}$ facility

- The rebunched beam pulses are extracted from the RR
- Muons are produced at the AP0 target facility
- The secondary beam is injected into the DR
- DR acts as a long decay line that also separates p/π/μ by TOF



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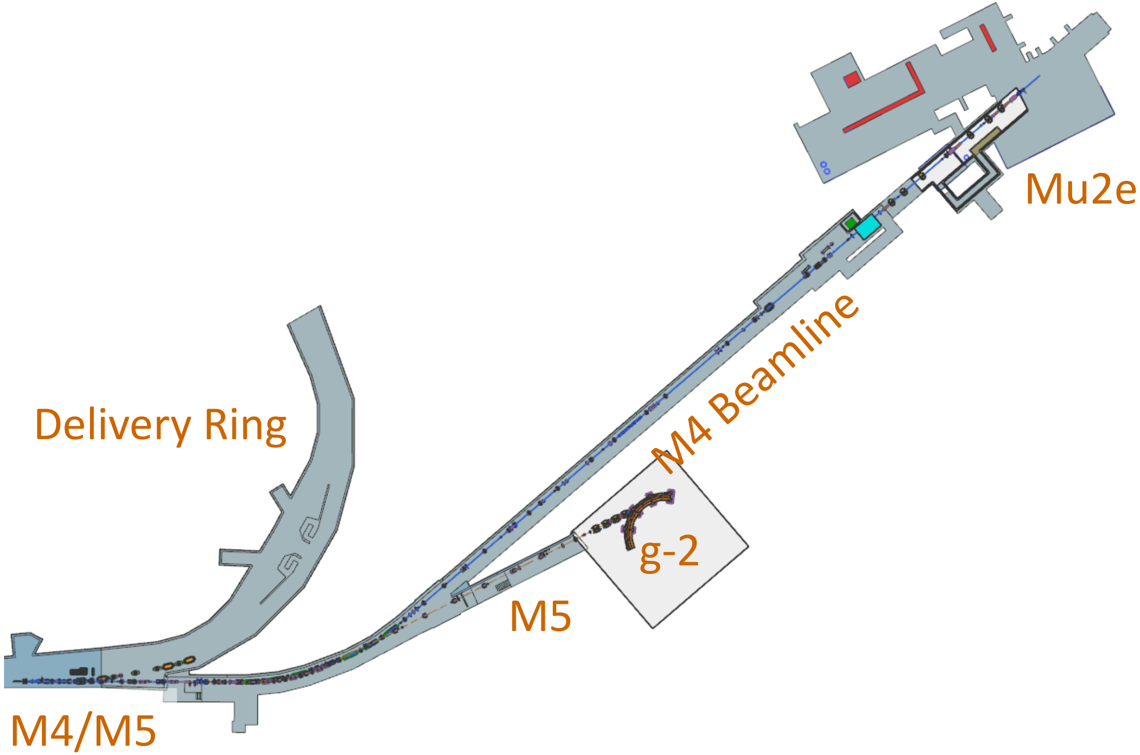
- The rebunched beam pulses are extracted from the RR
- Muons are produced at the AP0 target facility
- The secondary beam is injected into the DR
- DR acts as a long decay line that also separates p/π/μ by TOF
- Muons are fast extracted to the g-2 storage ring, while everything else is dumped to the abort





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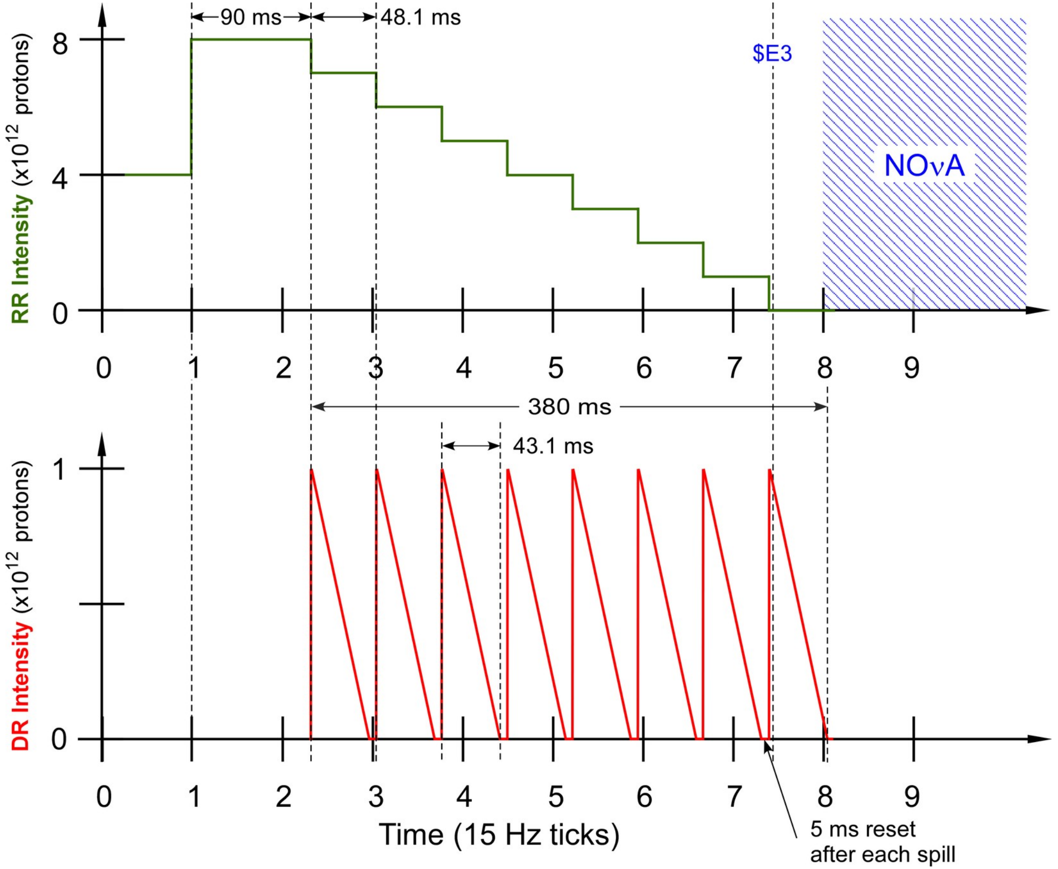
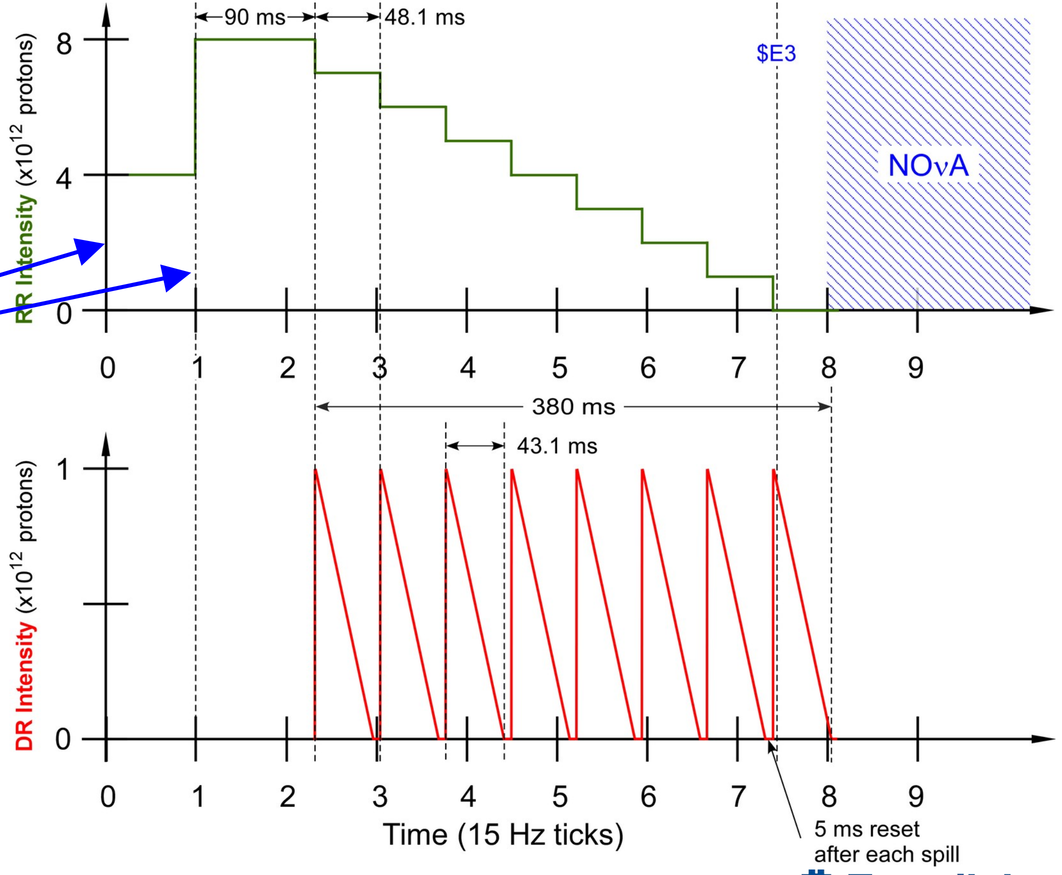
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks



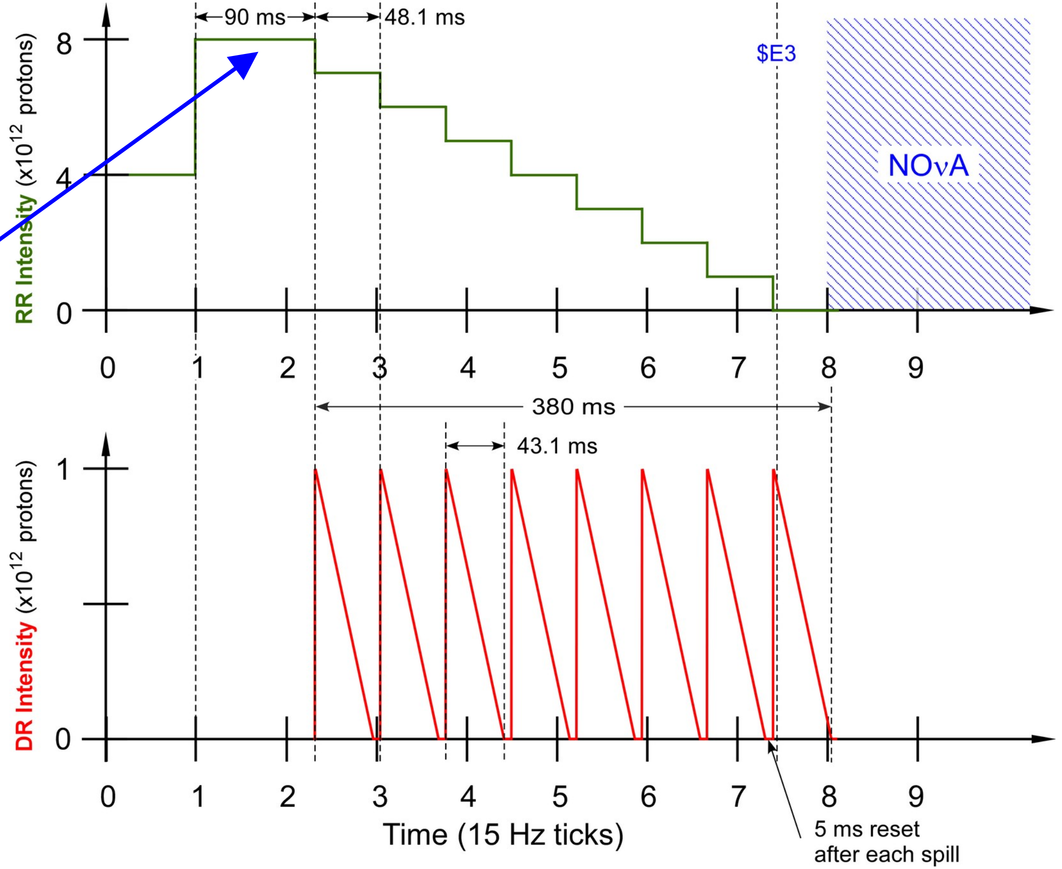
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks

Two batches from Booster



# Beam to Mu2e is resonantly extracted from the DR over 8 ticks

Rebatching takes >1 15Hz tick!!!



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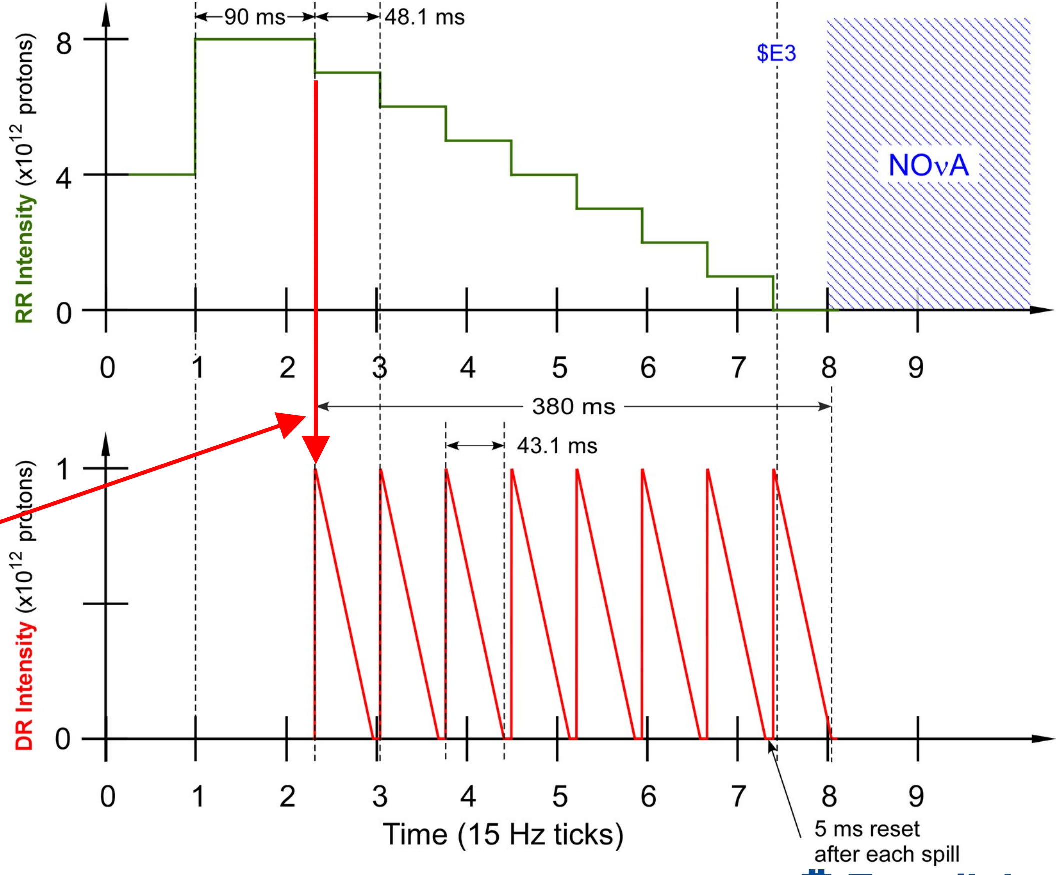
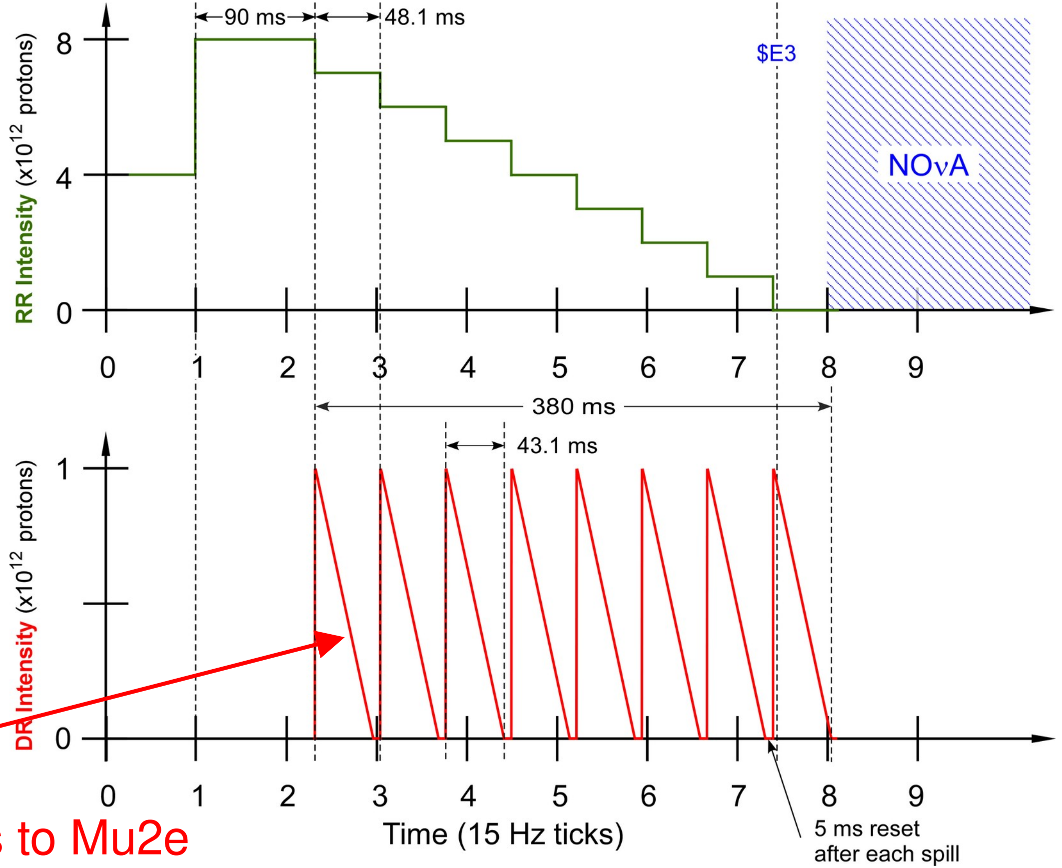



Move one of the new batches to DR
2.5MHz → 2.36MHz!

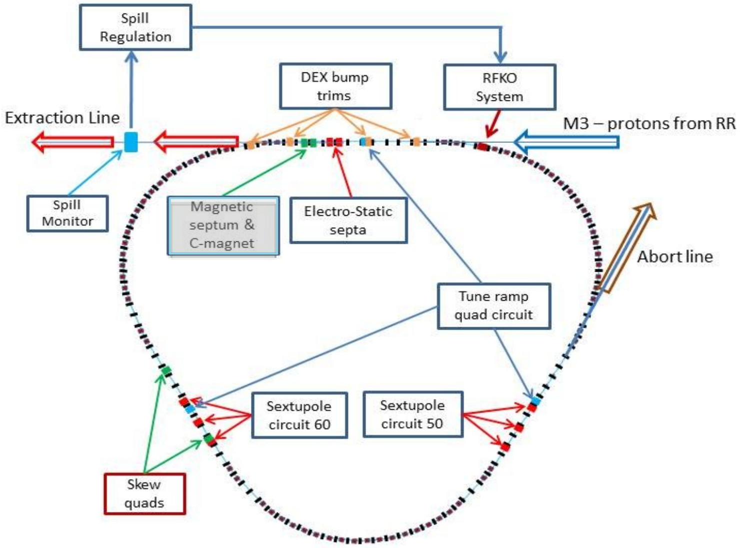
# Beam to Mu2e is resonantly extracted from the DR over 8 ticks

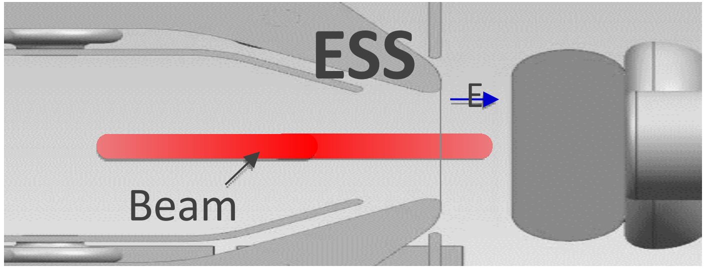



Resonant extraction ~25-30k pulses to Mu2e

# Mu2e resonantly extracts from the delivery ring

- Quadrupoles intentionally drive a 1/3 integer resonance in the horizontal tune.
- Sextupoles induce a controlled beam instability.
- Septum foils peel off a bunch each turn.
- Dynamic spill regulation control is accomplished by tune corrections and RFKO.
- Full extraction occurs over ~25-30k turns.
- Remaining beam is dumped, and the cycle starts again.



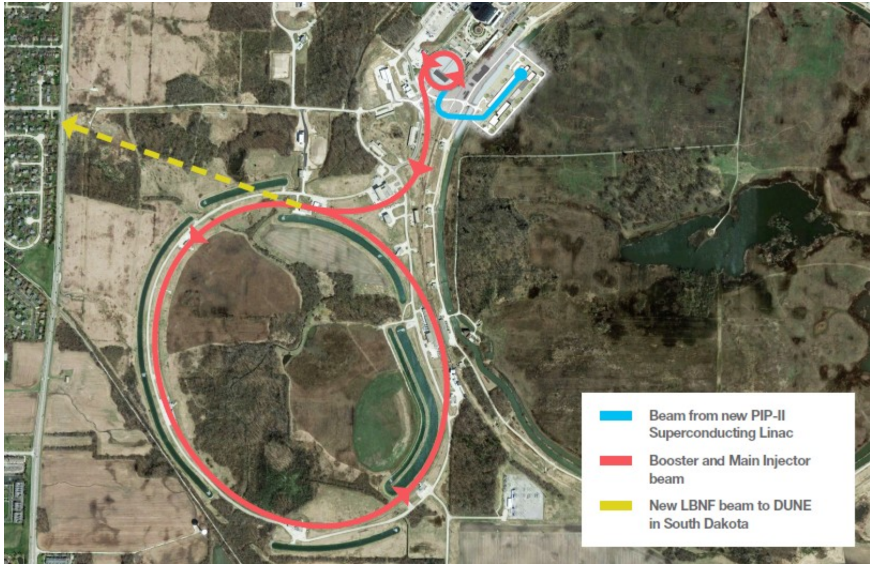

The delivery ring orbital period – 1695ns – drives the interpulse spacing in Mu2e, and is a nearly ideal match to the muonic aluminum lifetime of 864ns.

# Moar power!!!!!

- If you want to maximize power delivered to NuMI, you would operate a 13 tick timeline … which would leave only one batch for other physics!
  - At 15Hz, we have been running a 17 tick (1.133s) timeline for the last month, leaving 4 ticks for other experiments
    - 1.133s is driven by the rate we can safely/reliably ramp the MI
    - BNB, Muon g-2
    - Too short for Mu2e running!
    - But, averages 960kW to NuMI!
  - We have demonstrated a 16 tick (1.067s) timeline
    - Averages 1020kW to NuMI!
    - Needs more work on MI side for safe/reliable operation … but it's coming soon
    - This is probably the mode we will operate in until Mu2e comes online in 2026

# The next decade will be defined by PIP-II and LBNF 1.2MW

- PIP-II Project provides
  - New SRF linac for injection into Booster at 800 MeV (presently 400 MeV)
  - Booster cycle rate upgraded to 20 Hz from 15 Hz ← This already has uncertain impact on Mu2e!
  - Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI
  - CW capable, 1.6MW @ 800MeV
- LBNF/DUNE-US Project provides
  - New proton beamline for up to 2.4 MW
  - Target systems for 1.2 MW
  - Shielding and absorber for up to 2.4 MW



# PIP-II is currently under construction

# Fermilab is committed to both LBNF and Mu2e running!

- The current slate of programs will run through 2027
  - NuMI, BNB, Mu2e, SY120, MTA/ITA, FTBF
- The complex will shutdown from 2027-2029 for the PIP-II tie-in
  - Legacy Linac retires; MTA/ITA no longer available; Future BNB running is undecided
- LBNF beamline and target hall will be ready in 2031
  - Slow ramp up to 1.2MW on target
- Fermilab is committed to running beam to Mu2e through 2033
  - How exactly we do that in the 20Hz Booster era is not yet clear
- Then what?

# We want even more beam power to experiments

- LBNF Phase II wants double the beam power on target – 2.4MW
  - But will still use less than 2% of PIP-II beam capacity!
- We can’t get there directly, even with PIP-II
  - Limited by Booster power handling!
- Fermilab has proposed a phased approach of reliability improvements and accelerator upgrades
  - P5, DOE, etc.
- Meanwhile, various collaborations have made proposals to use some of that 98% of available PIP-II beam directly from the new Linac
  - PAR-BD
  - Mu2e-II (see talk by S. Müller in this conference)

# Accelerator Complex Evolution – MIT and BR

ACE-MIT

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power – 0.65s, 13 ticks @ 20Hz
  - Upgrading target systems for up to 2.4 MW – driven by absorber design!
  - Improving reliability of the Complex – FY22 was 41% → LBNF Target is 57%

ACE-BR

- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement – 2.4MW
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV – BD? SBN? AMF? (see talk by D. Hitlin in this conference)
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research – Muon Collider



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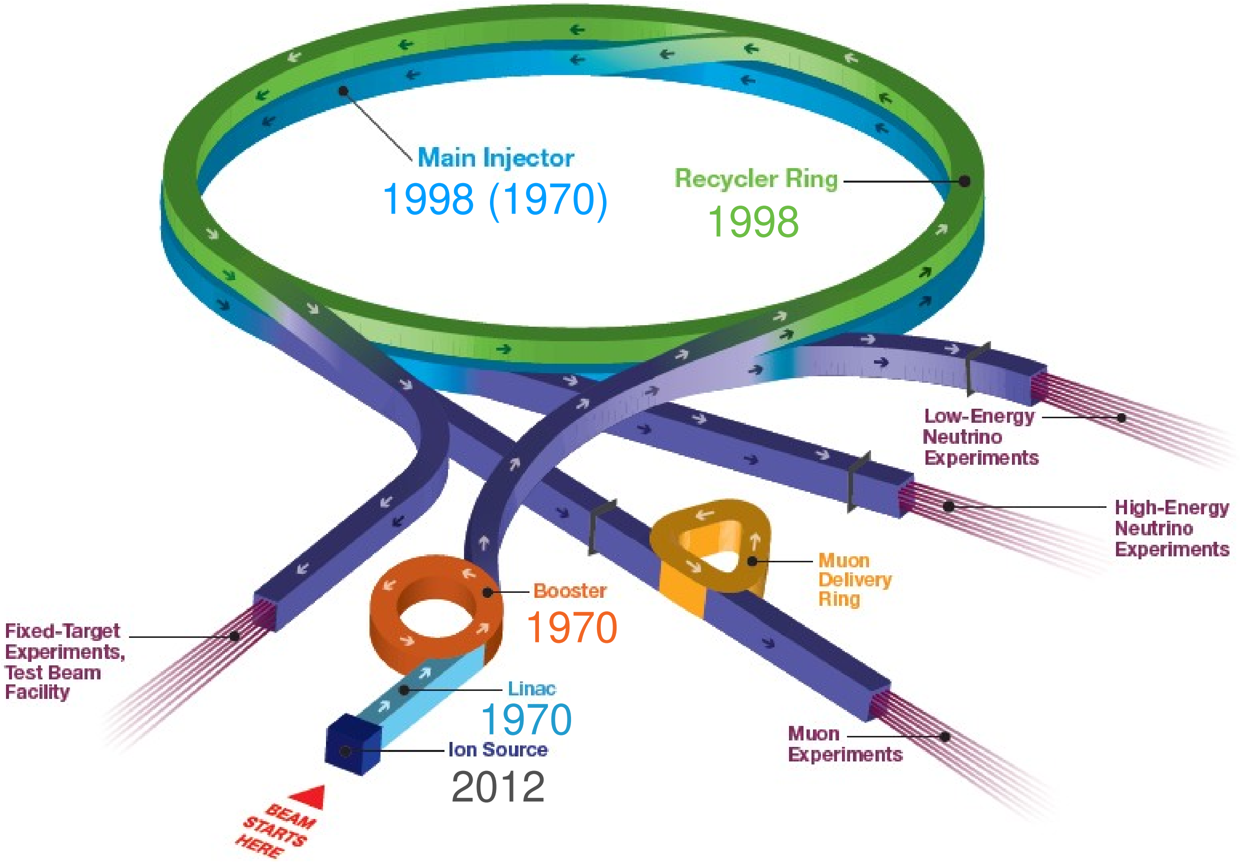
From M. Convery

# Another look at the Accelerator Complex



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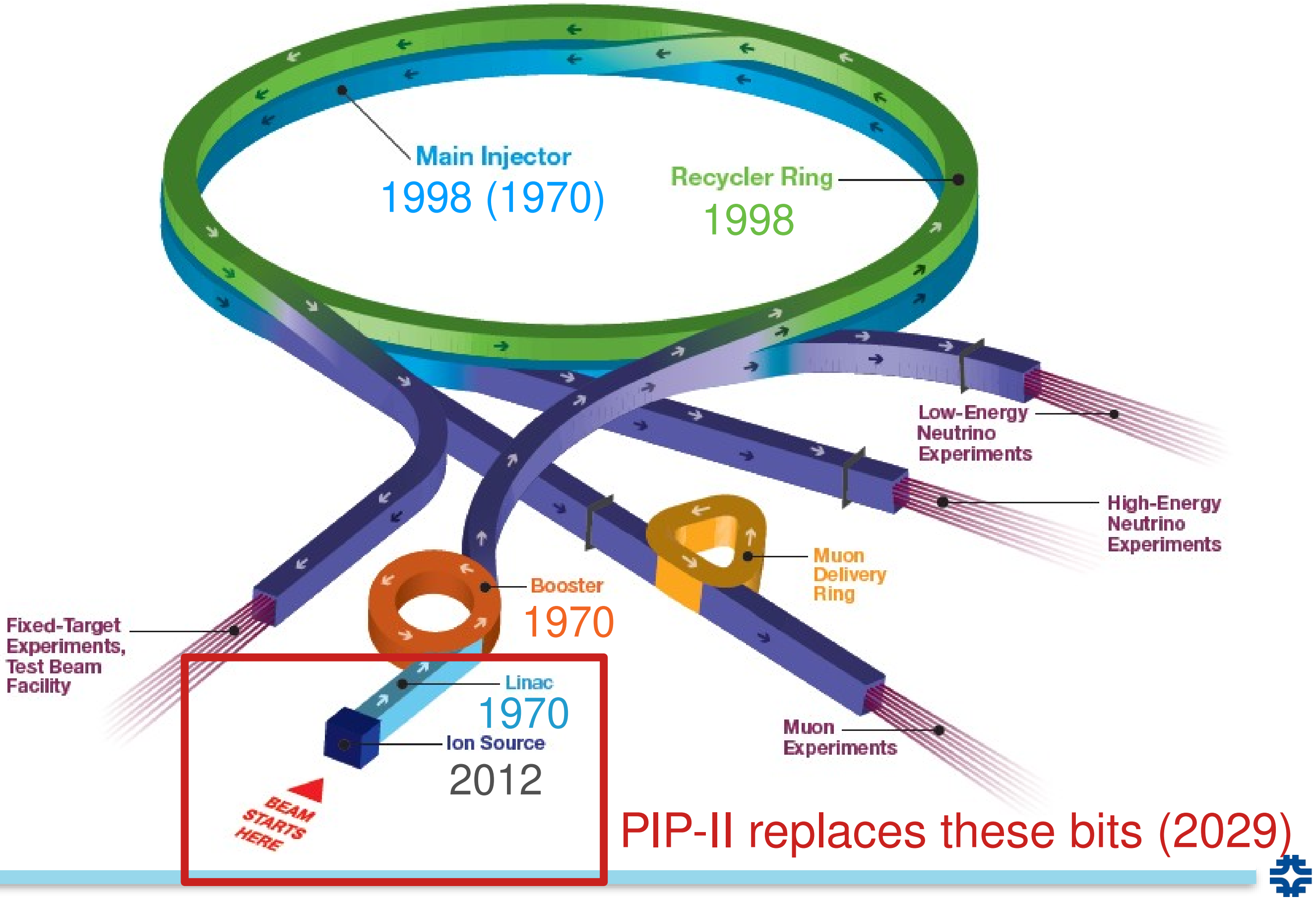

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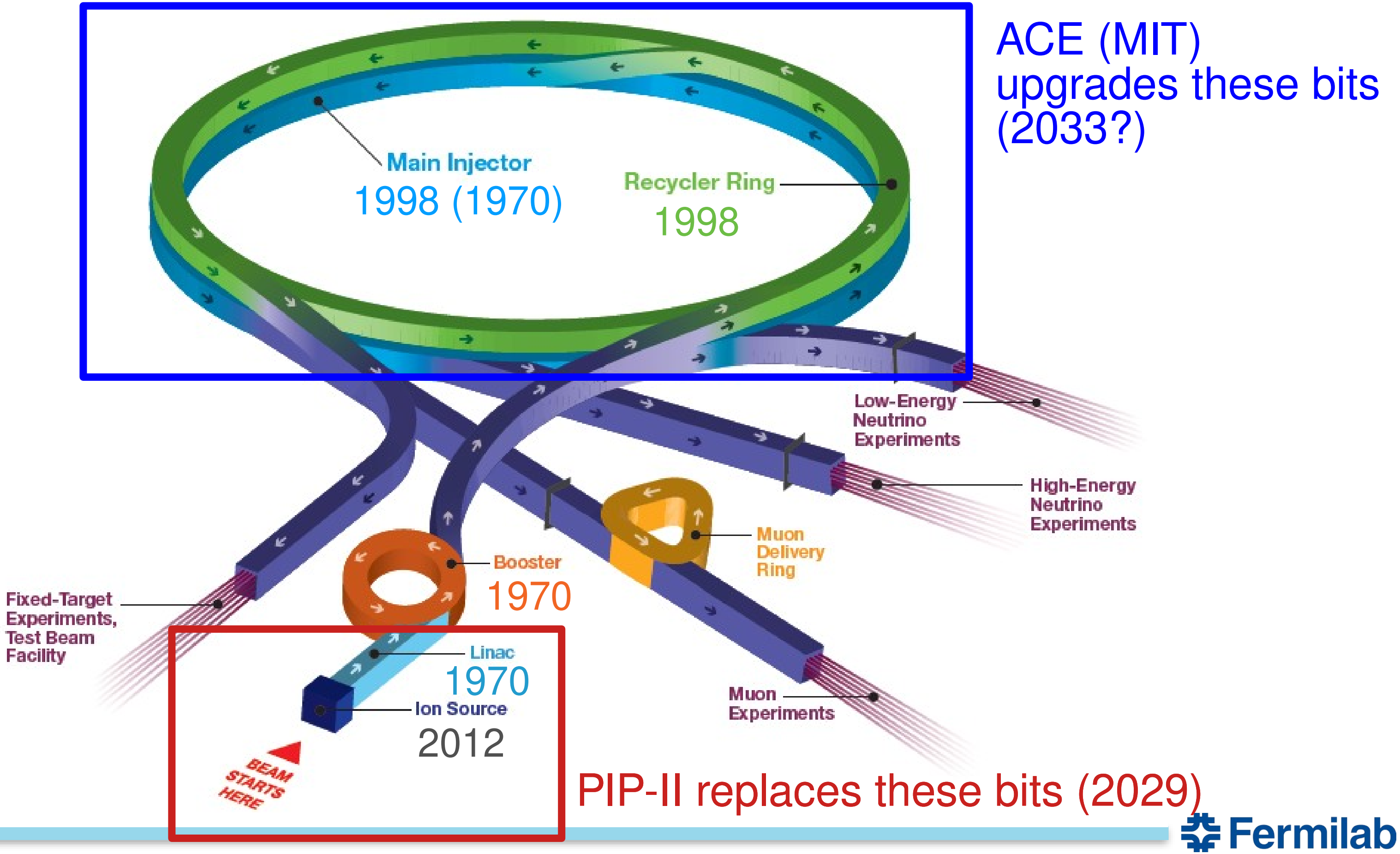

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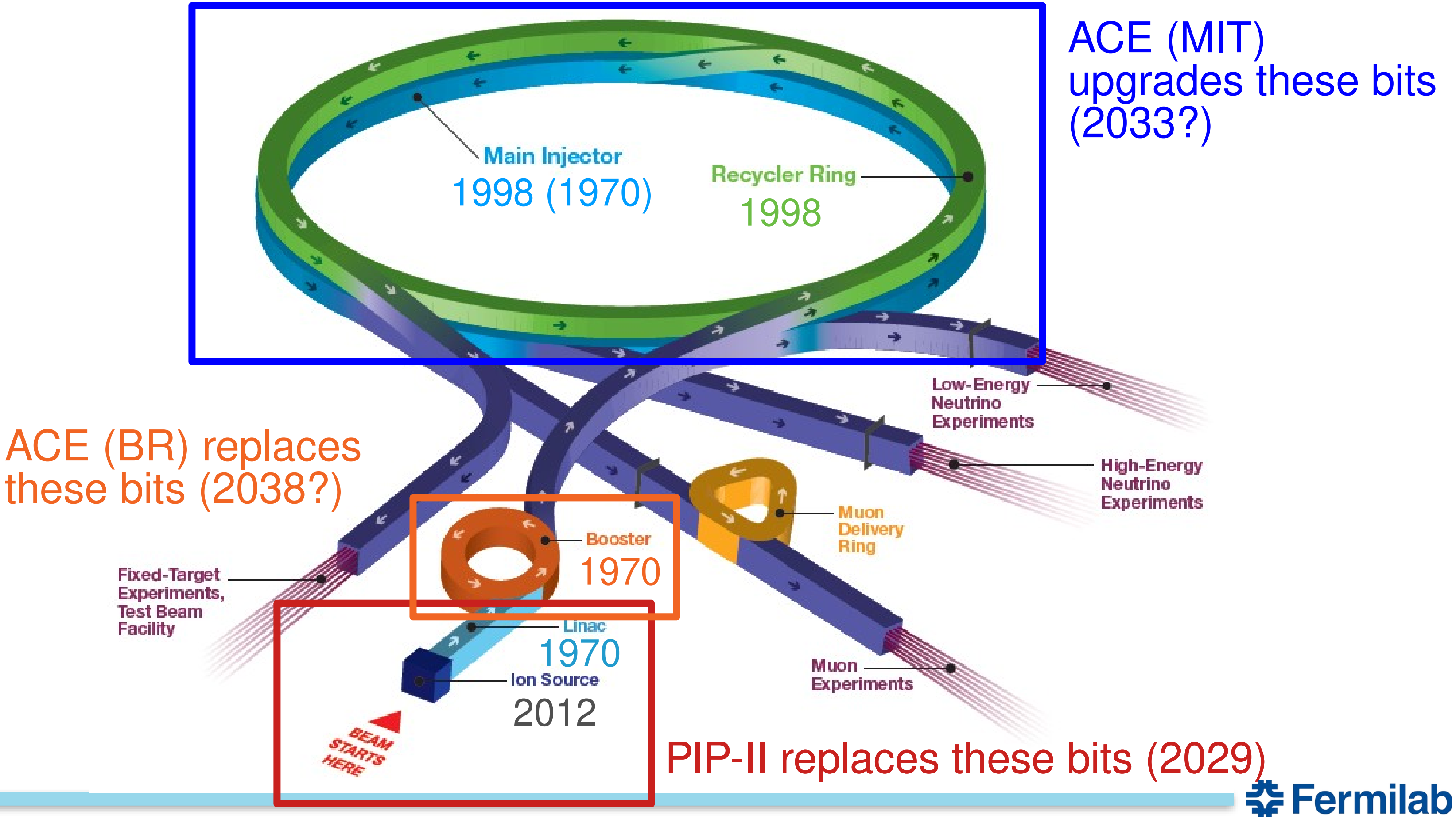

# ACE (MIT) will include

- Improved MI reliability by replacing original Main Ring (1970s vintage!) quadrupole magnets with robust new design
- Upgraded MI ramp power systems to enable faster cycle times – down to 0.65s
- Upgraded MI RF acceleration system to allow for more beam flux
- Upgraded LBNF target and horns to ensure reliable 2+ MW capability


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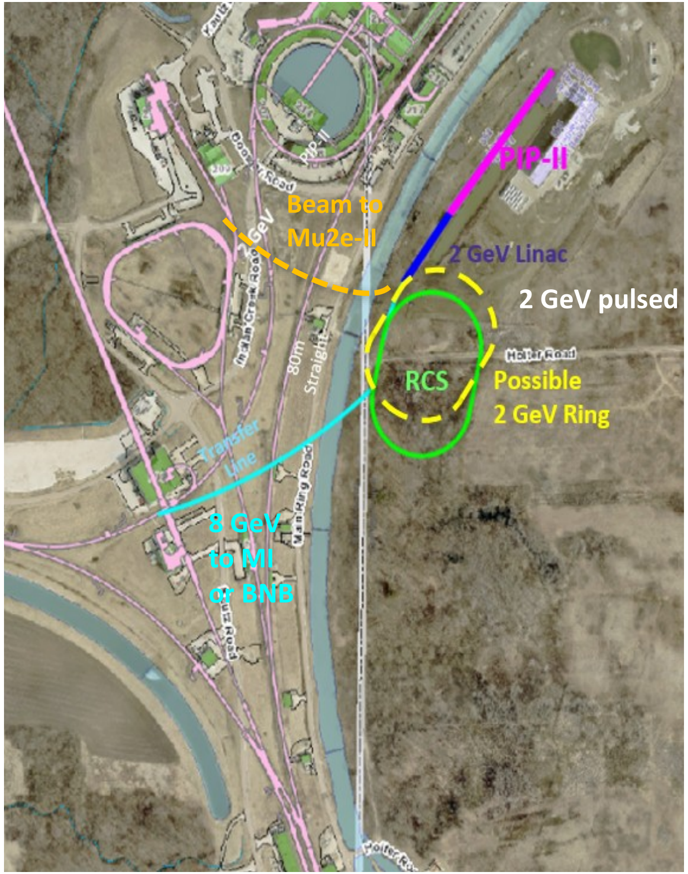
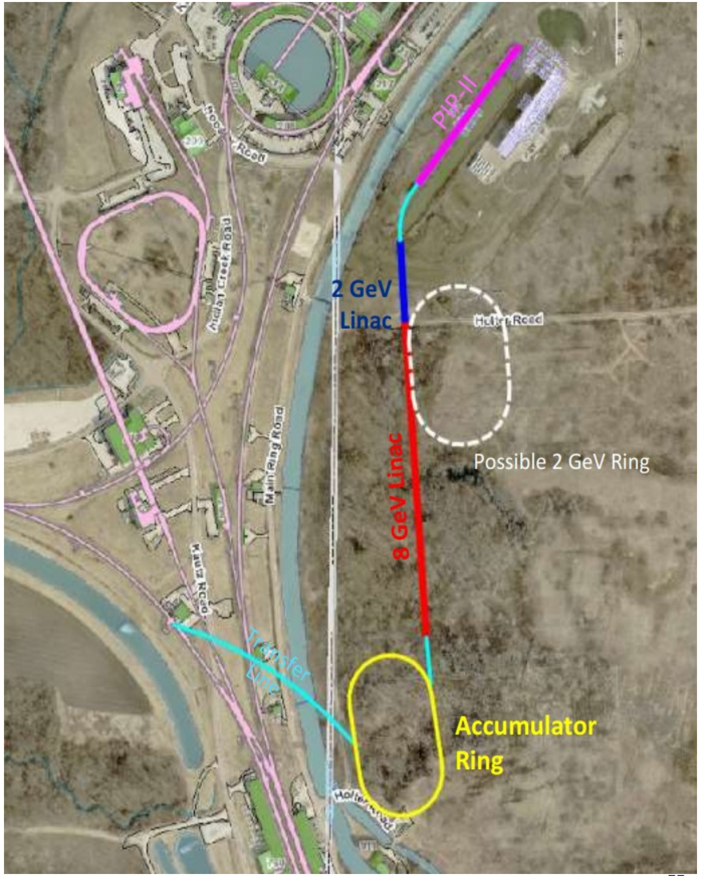
From A. Valishev

# ACE (BR) – replacing the Booster

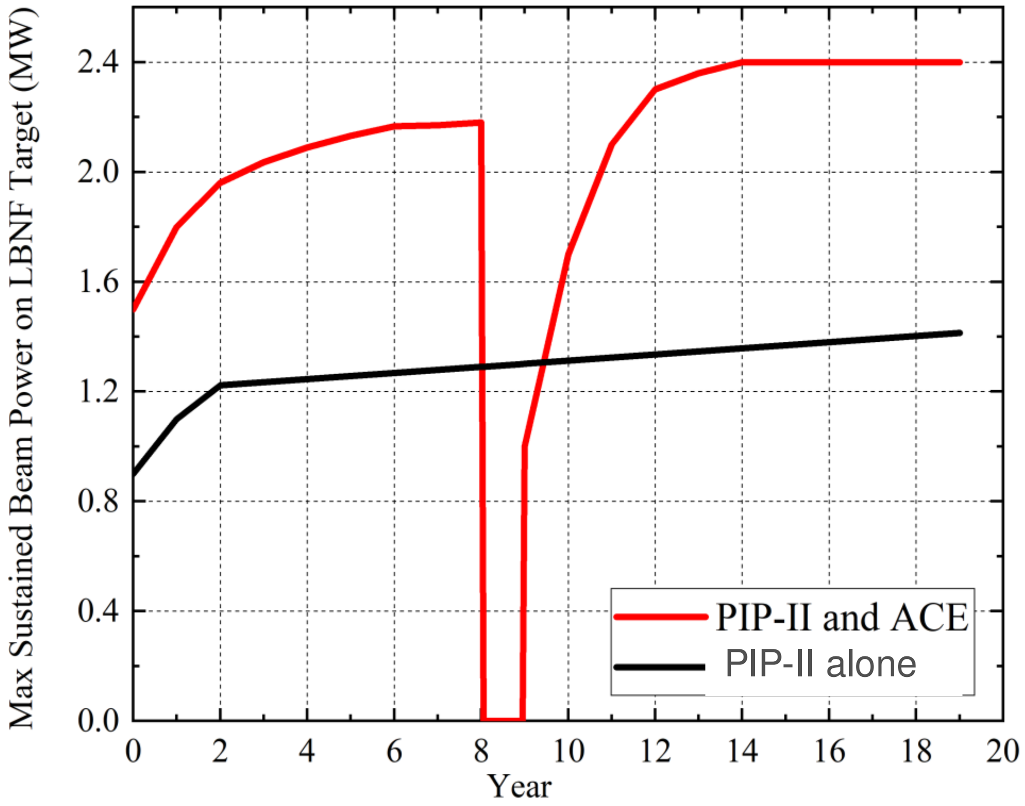
- Delivering more than 2.1MW to LBNF *and doing other physics* requires a replacement for the venerable Booster
  - PIP-II can in principle deliver 800MeV beam directly to experiments (Mu2e-II? PAR-BD?), but the rest of the complex will be maxed out to run LBNF … which will only use ~2% of the PIP-II capability!
- The PIU-CDG is evaluating various options for Booster replacement
  - Extended SRF Linac vs RCS at various energies
  - Choices will be informed by community input
    - Last week's ACE Science Workshop: https://indico.fnal.gov/event/59663/
  - And of course funding agency choices
- PIP-II plus a Booster replacement should work together to enable 2.4MW LBNF, many spigots for new experiments, and a platform for a potential future muon collider

# Various options under consideration – Linacs, RCSs, Accumulators, etc



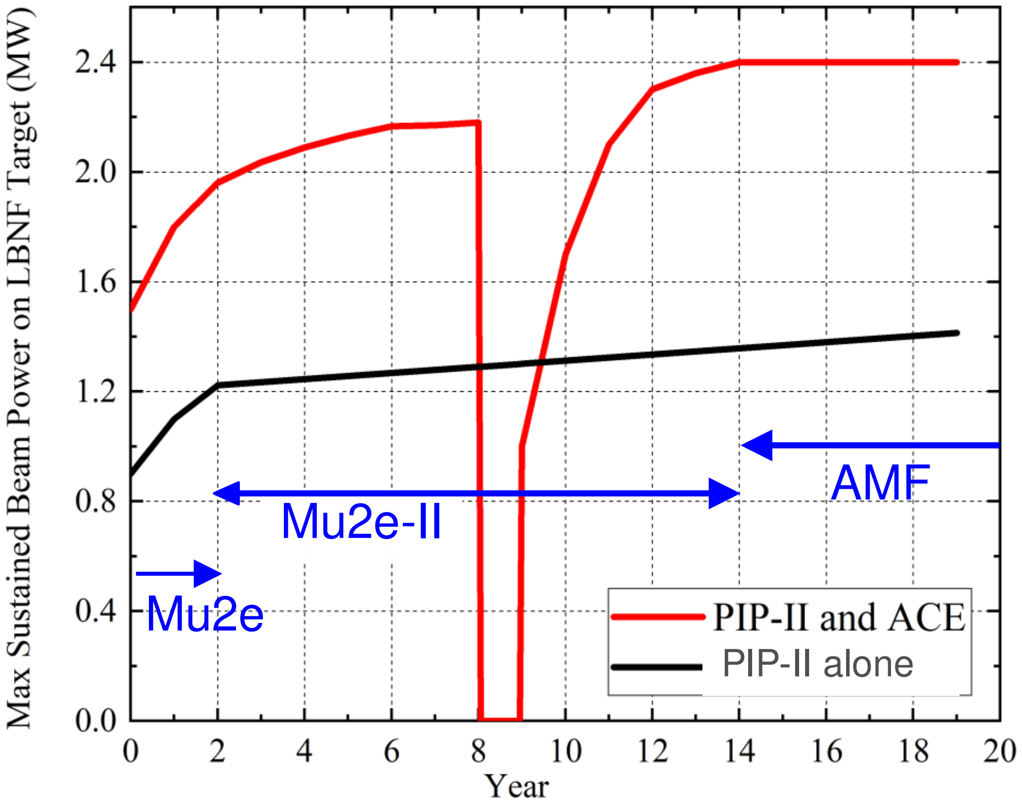



# A potential LBNF beam power delivery profile




- Year 0 = 2031, start of LBNF beam operations
- Year 2 = 2033, end of Mu2e beam operations
- Year 8 ~ 2039, shutdown for new Booster tie-in to MI

# A potential LBNF beam power delivery profile




A potential future scenario for muon physics at Fermilab?

# Thanks!

# 1 PHYSICS

## 1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

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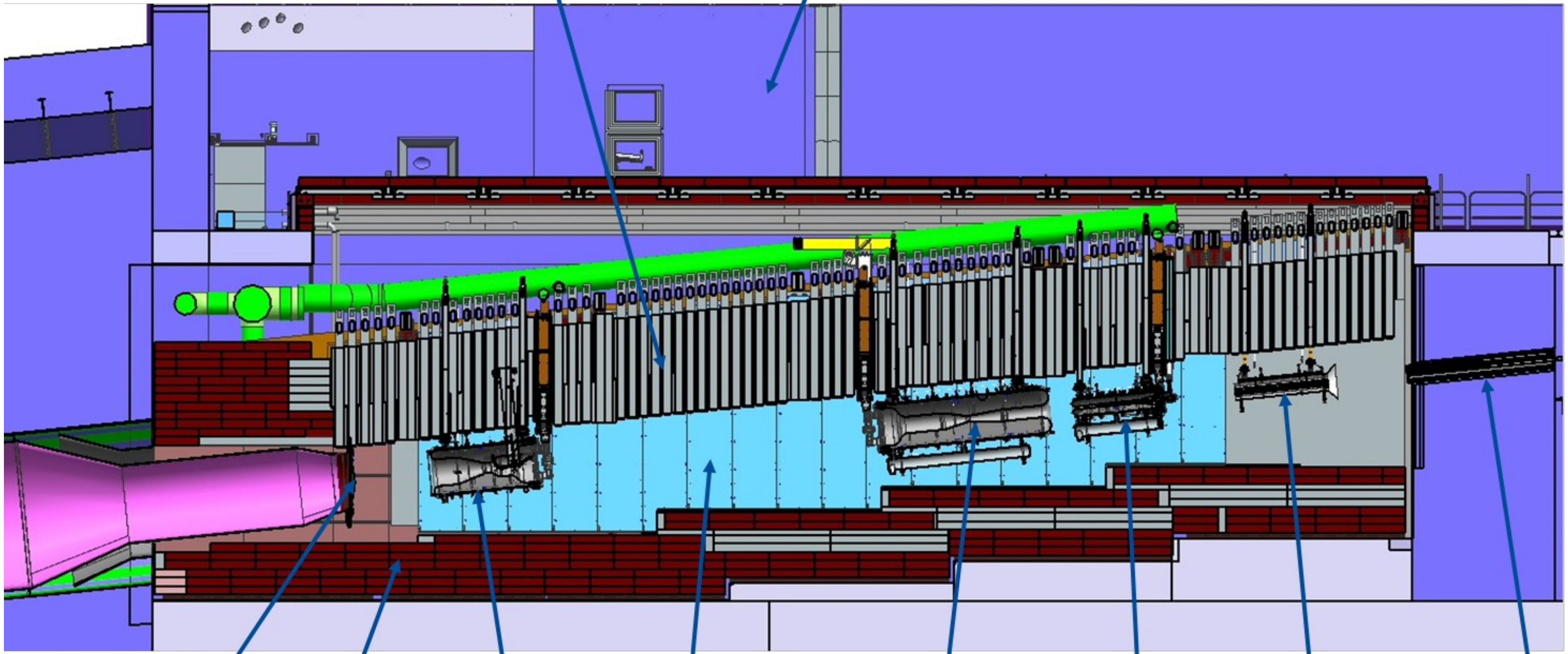
# Backup Slides

# LBNF target systems - Beam-Intercepting Device Inventory



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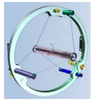
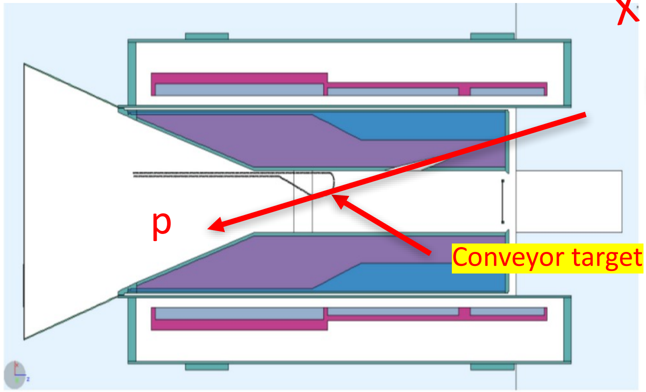
# RPF Experiment Targetry - Production target concept – Muon Program

X 140






X 2.5

?

X ?

?

Muon Collider 1 to 4 MW
??
300 kW in C target at 8 GeV

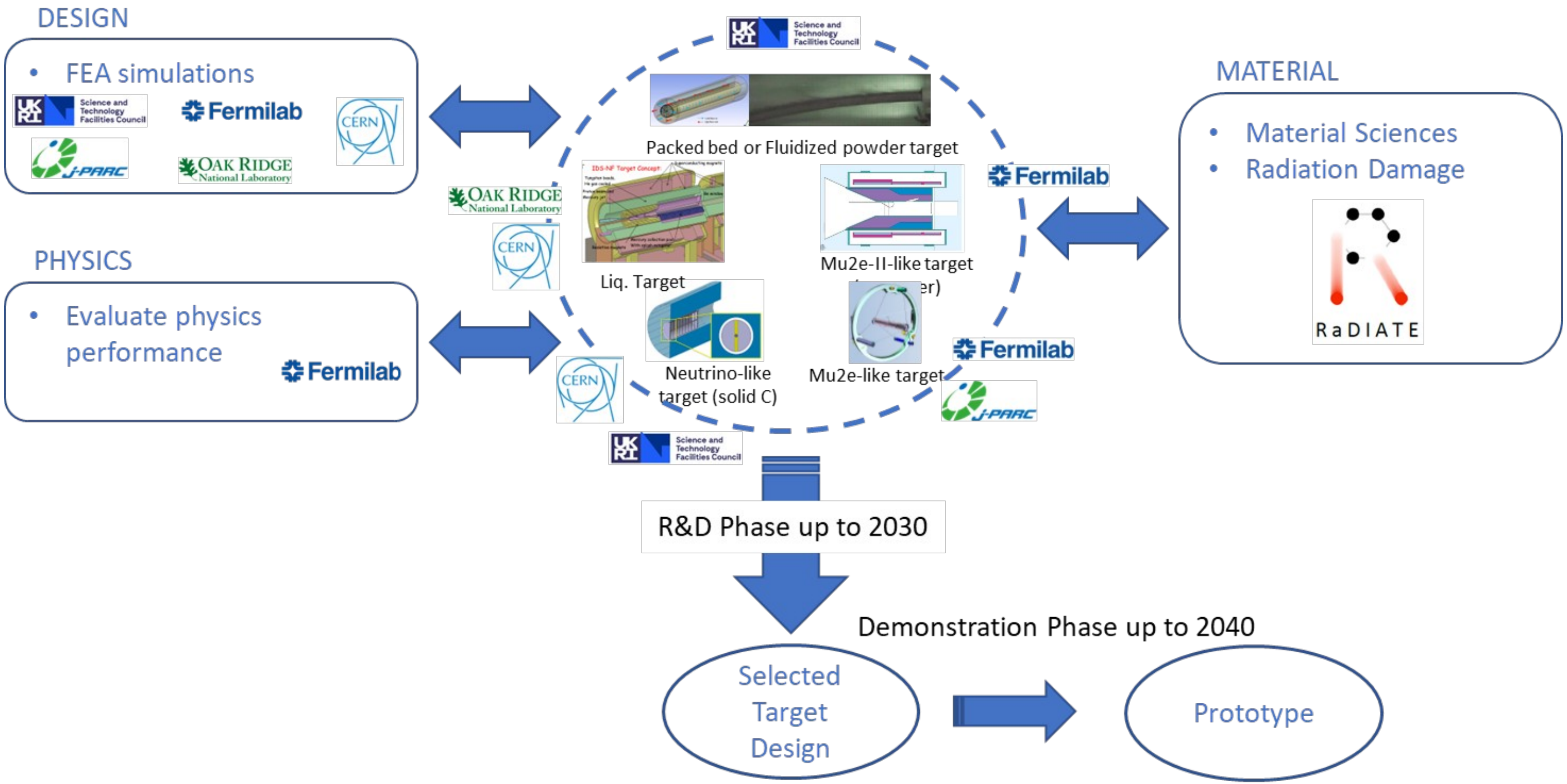
AMF Target core ?
??
250 kW in target at 800 MeV

Mu2e-II Target core C, W, WC, SiC,…?
~ 10 mm x 200 mm
100 kW in target at 800 MeV

Mu2e Target core Tungsten
6.3 mm x 220 m
700 W in target at 8 GeV

More power density = More challenges

# RPF Experiment Targetry – R&D Approach for Muon Collider

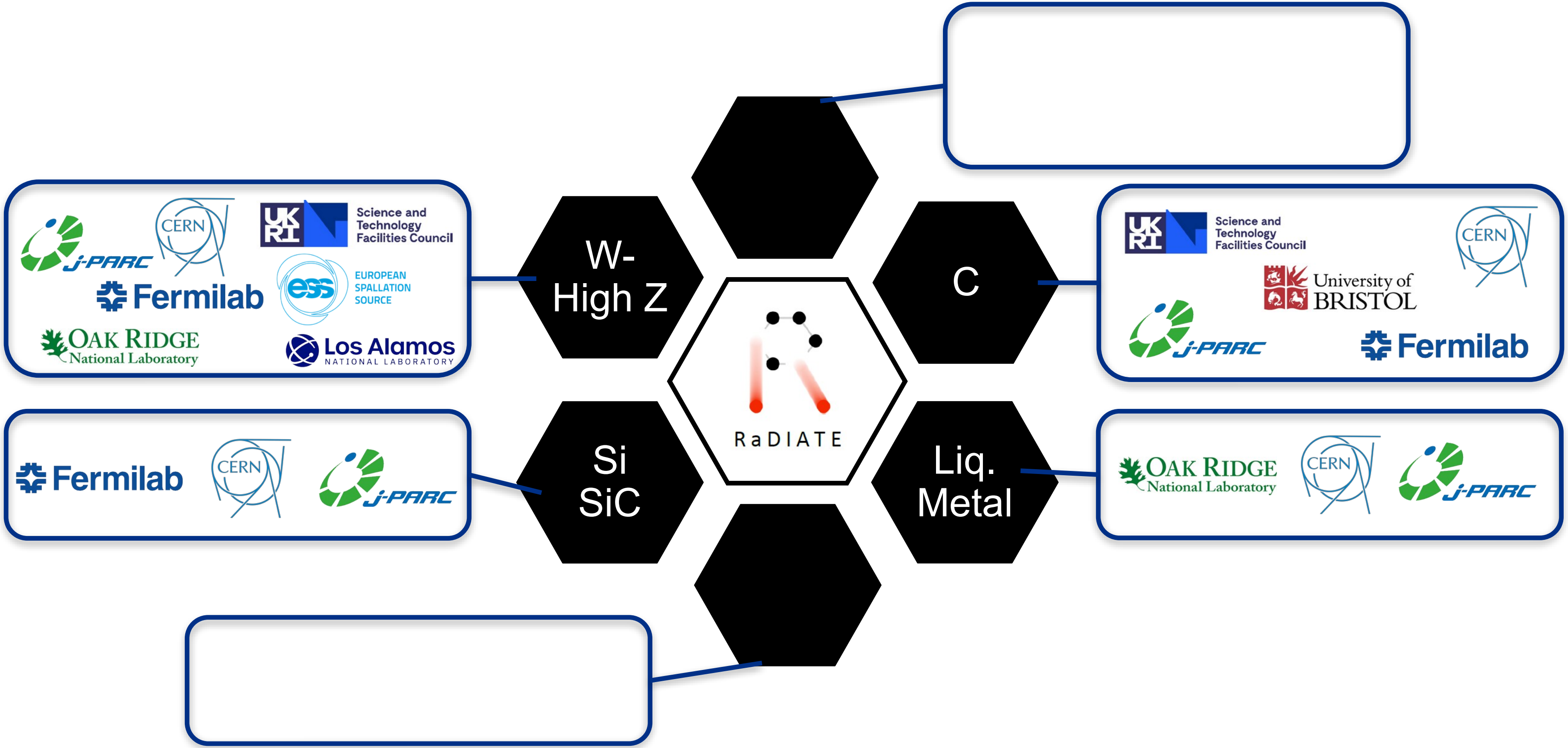


# How can Muon Targetry Fit into Fermilab HPT R&D?

- Funding streams:
  - General Accelerator Research and Development (GARD) - Pre-conceptual design / and Material R&D
  - Operations/Projects fund design and construction
  - Partners: RadiATE support and IKC
- Focus has been on neutrino beams and accelerator components
  - ➢ Can certainly be extended to other HEP applications

  Fermilab HPT R&D so far focused on fixed target made of graphite, beryllium, Ti-alloys, High entropy alloys and ceramic nanofiber
    - ▪ High-Z material with very short muon bunches
      - ⇨ Not part yet of HPT R&D program
      - ⇨ R&D already ongoing through RaDIATE collaboration
    - ▪ High efficiency cooling and/or novel concept need to be developed
      - ⇨ Not part yet of HPT R&D program
      - ⇨ More R&D needed through our RaDIATE collaboration
  - ➢ Design development:
    - ▪ Unproven concept exist for 100 kW (Mu2e-II) but will require significant R&D effort
    - ▪ For AMF, no idea how to build a MW scale target
      - ⇨ Synergies with Muon Collider R&D paths

# Potential Materials for Muon Production Targets and related R&D



# Tools Needed to Support R&D Program

- High energy beam irradiation
  - Highly activated material

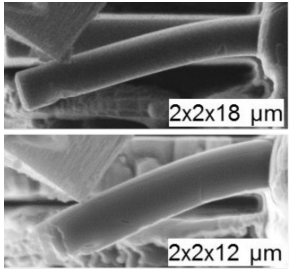
**→ Need to develop PIE: hot cells and specific characterization equipment**

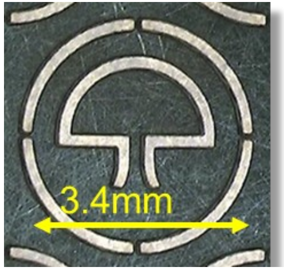
  - High energy p Low dpa rate p long irradiation time (order of months) p Expensive
- Alternative radiation damage method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
  - Few heavy ion irradiation facilities around the world

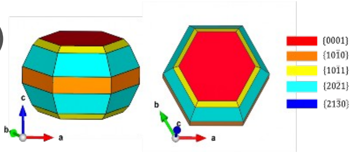
**→ Need more development of such facilities with higher intensity**

- Ab initio and molecular dynamics (MD) modeling
  - still not yet mature enough to model atomistic changes to micro-structural evolution to macro-properties of real-world materials. Prediction of fundamental response of various material classes to irradiation helps steer material choices and experiment design for future irradiation studies
    - Modeling of He gas bubbles in Beryllium and of novel material radiation behavior (HEAs)

**→ Need to develop this expertise at FNAL**



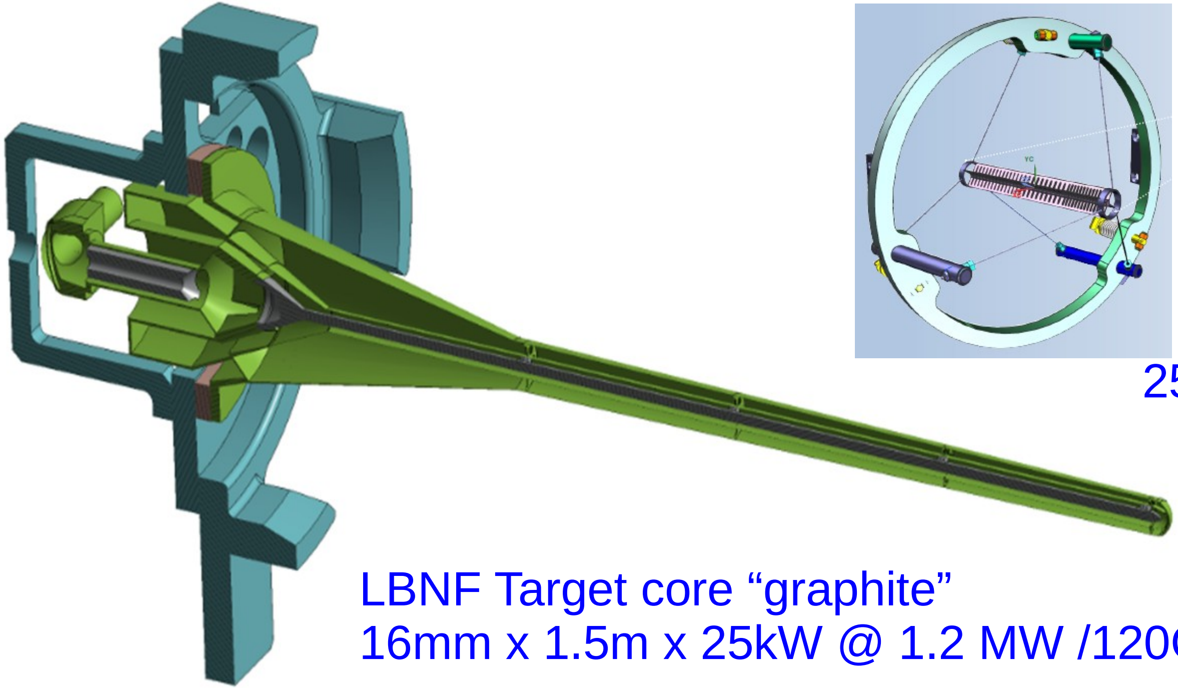



# Comparison of Mu2e Target and LBNF 1.2MW Target

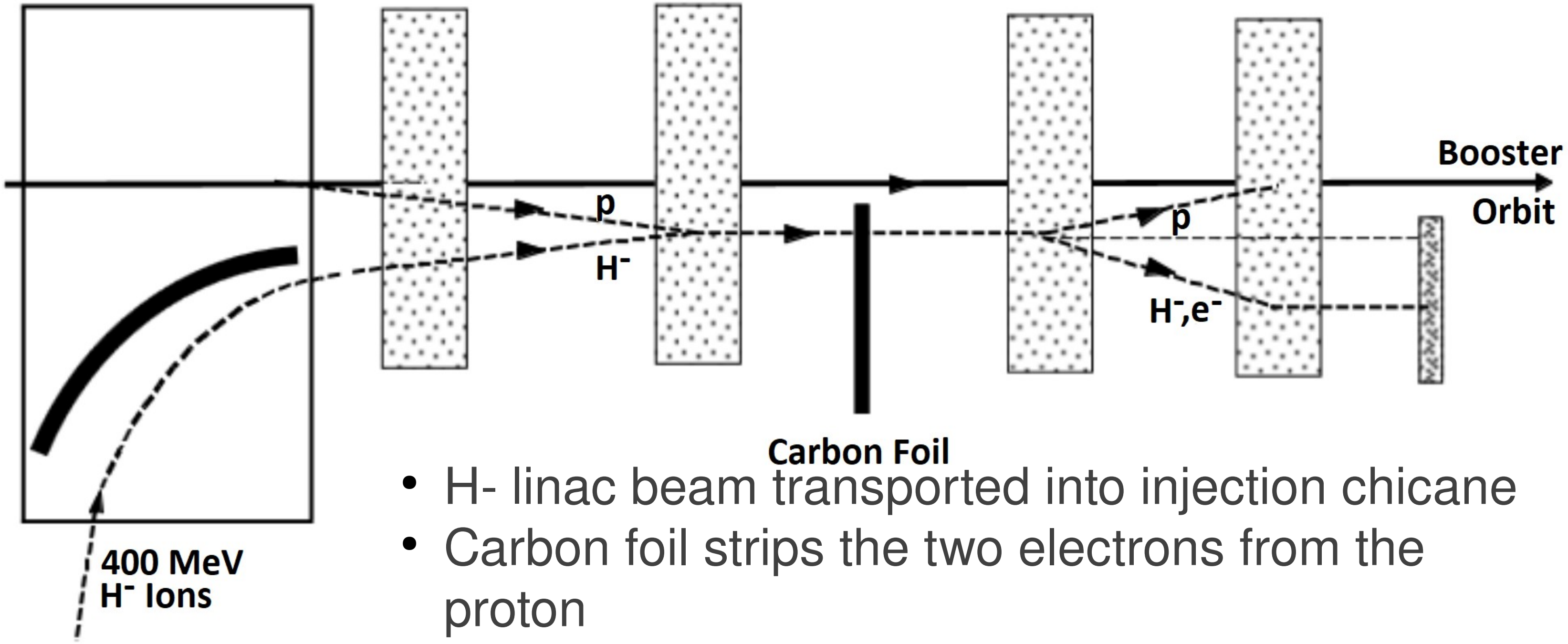
Mu2e Target Core, "tungsten"
6.3mm x 220mm x 700W @ 8kW/8GeV

250kW @ 1MW/800MeV



LBNF Target core "graphite"
16mm x 1.5m x 25kW @ 1.2 MW /120GeV

# H- Injection process into a ring




- H- linac beam transported into injection chicane
- Carbon foil strips the two electrons from the proton
- Proton beam accumulates in the ring
- Unstripped H- ions are sent to an absorber.



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From J. Eldred