Accelerator Physics (R & D)

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Outline

- Introduction
- Operations: current status & achievements
- Plans: 2022-2027 and long-term
- Summary

Introduction

- Fermilab Accelerator complex produces world's most powerful ν beams, along with muon & test beams

Fermilab Accelerator Division: Missions

Delivering beams for research

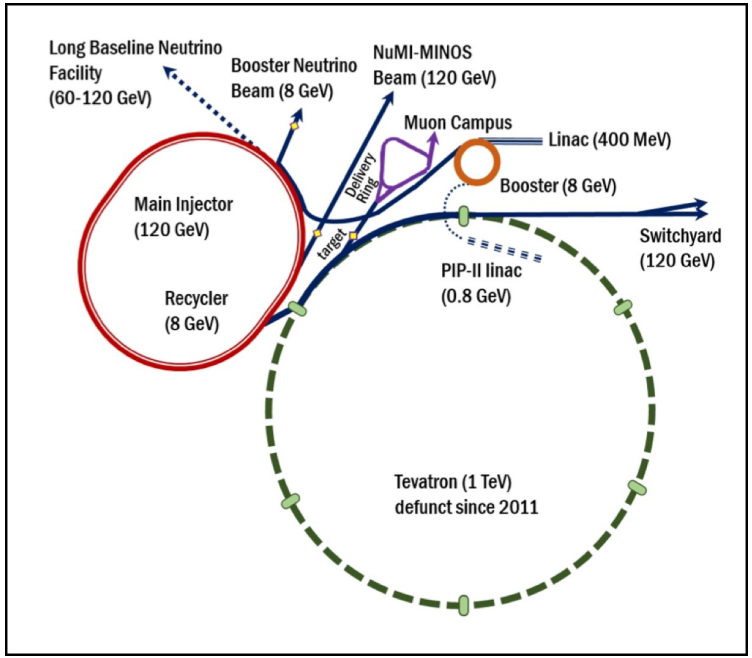
- NOvA neutrino oscillation experiments
- Short Baseline neutrino experiments
- Mu2e, g-2 experiments
- Detector R&D

Upgrading accelerator complex/beam line/ targets to extend scientific reach

- Proton Improvement Plan-II (PIP-II)

Conducting accelerator physics research

- Optical stochastic cooling at FAST-IOTA
- Research on High Power Target systems
- Robotics for remote handling
- Application of machine learning



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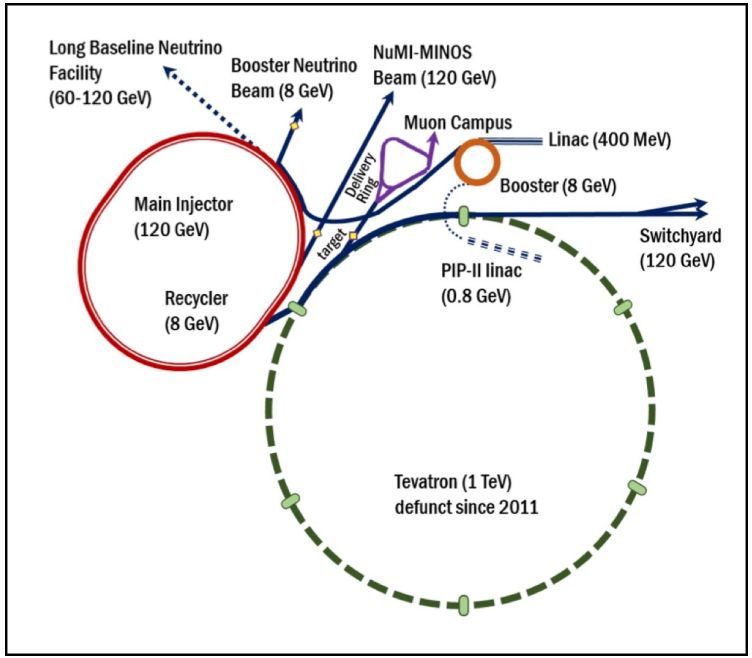

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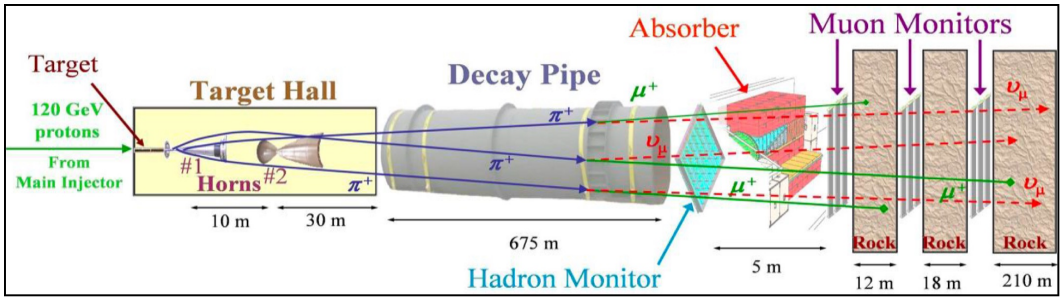
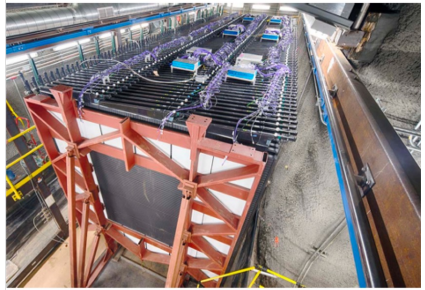
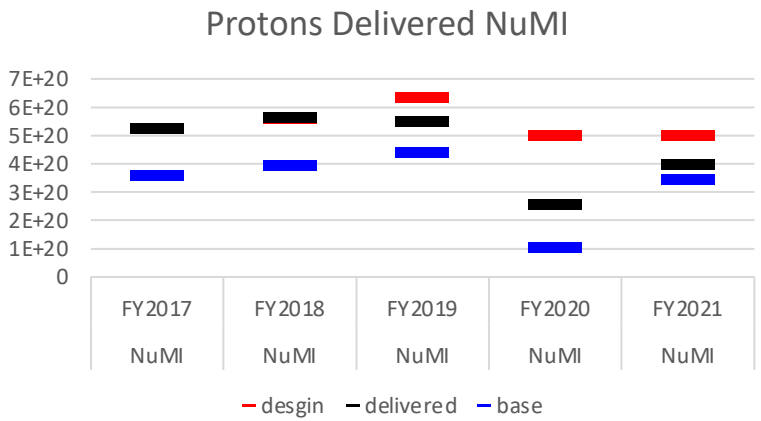
NuMI Operations





- Neutrinos at Main Injector (NuMI) beam line **provides 120 GeV protons for present long baseline neutrino program** (NOvA)
- Proton delivery goals over last 5 years met



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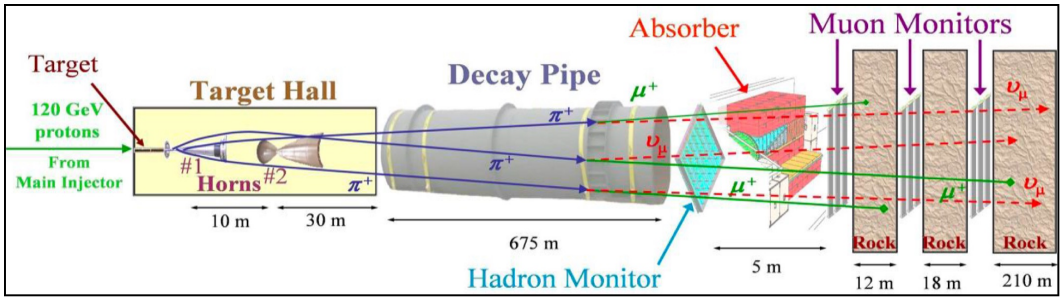
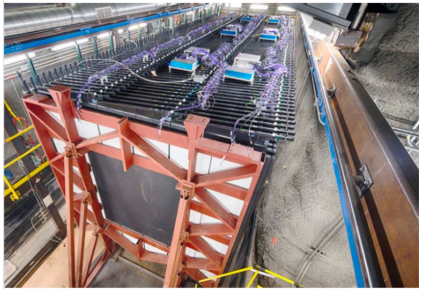
NuMI Target Upgrade





- NuMI 1 MW target installed
- Upgraded 1 MW horn installed, upgraded cooling system
- Radiation hardened hadron monitor installed
- Installation of higher capacity pumps, heat exchangers, piping and instrumentation to handle extra cooling required

NuMI beam parameter — Present target goal

	NuMI Design	NOvA	1 MW upgrade
Proton beam energy	120 GeV		
Beam power (kW)	400	700	1 MW
Energy Spectrum	Low Energy	Medium Energy	
Cycle time (s)	1.87	1.33	1.2
Protons per spill	4.0×10^{13}	4.9×10^{13}	6.5×10^{13}
Spot Size (mm)	1.0	1.3	1.5
Beam pulse width	10 microsec		

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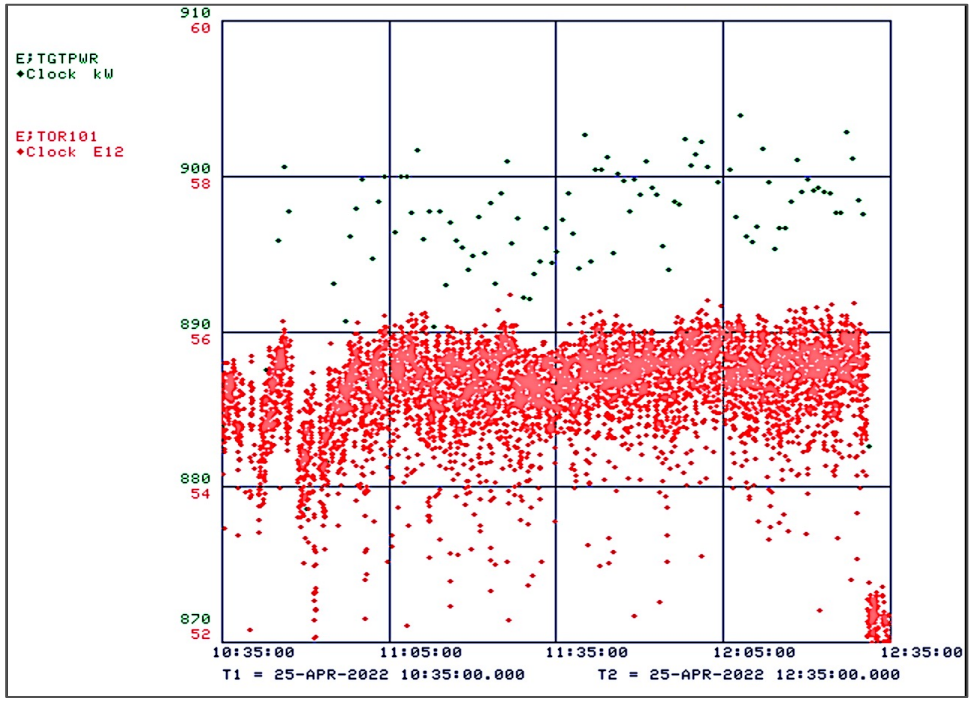
NuMI Target Upgrade



Beam power will gradually increase to 1 MW as several upgrades and studies are performed

NuMI beamline adequately shielded for >1 MW, transported 893 kW average beam power for 1 hour, record set on April 25, 2022!

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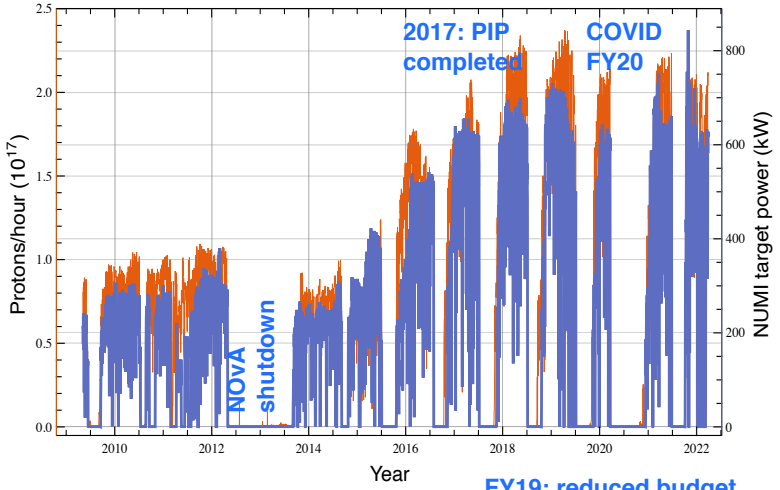
Proton Flux compared to NuMI Target Power

- **Proton source:**
  - **Record flux: 2.56 E17 pph in June 2018**
  - Without SY, BNB, and Muon, Proton Source capable of delivering beam of 900 kW for NuMI
- **Main Injector/Recycler:**
- Various improvements resulted in loss reduction & close to 900 kW beam power
  - ➢ RR collimators
  - ➢ Diode damper
  - ➢ 1.2 s & off-center injection (for PIP-II)

Power on target and protons/hour from May 2009 until today



FY19: reduced budget.
5 days on, 9 days standby from May 6

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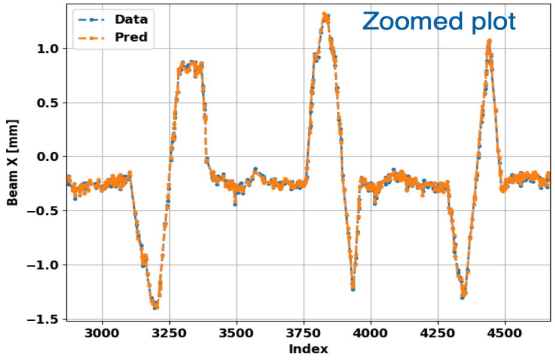
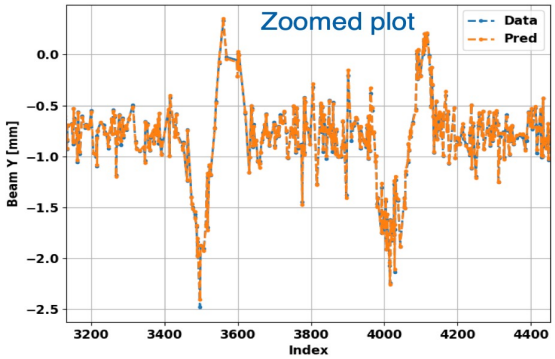
Application of Machine Learning
Predicting Beam Position: NuMI proton beam on target





- A Machine Learning application to predict NuMI beamline parameters
  - beam position
  - horn current
  - beam intensity

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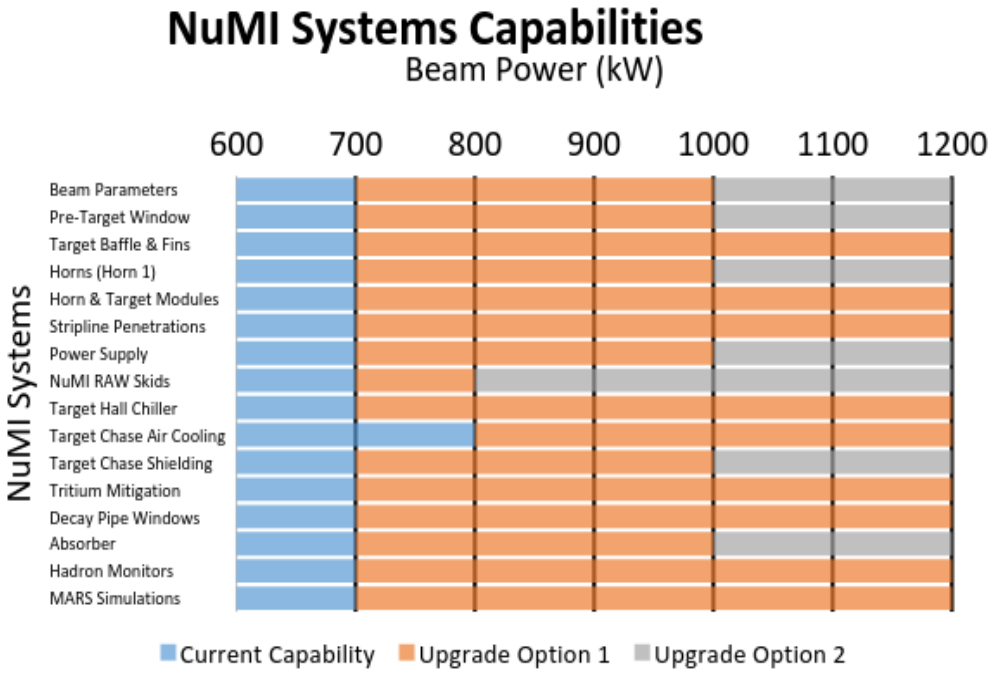
NuMI Plans: 2022 - 2027

- Five-year plan: continue delivering beam!
- Upgrade “orbit verifier” before spare parts are unavailable
- Proton source: utilizing 8hrs dedicated machine time every month for further improvements on delivering higher beam power
- Beam line expertise is being shared amongst new hires

NuMI Plans on Megawatt Upgrade Project

- Continuing work to increase beam power on target
  - Goal 1-MW beam operation
- Understanding NuMI beam optics
- Quality control of neutrino event



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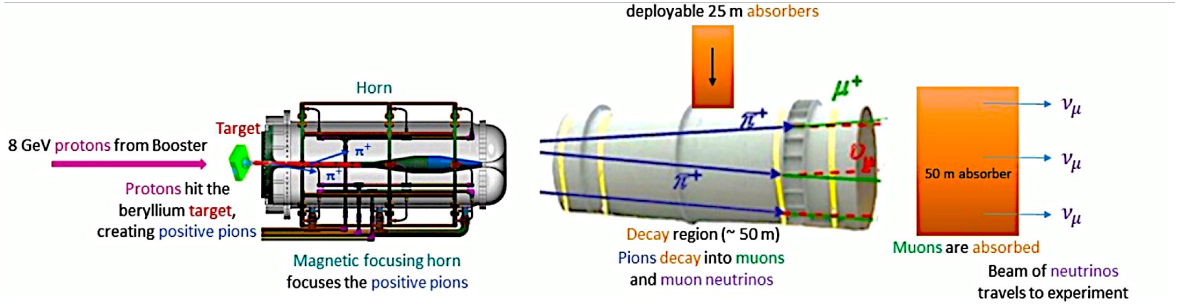
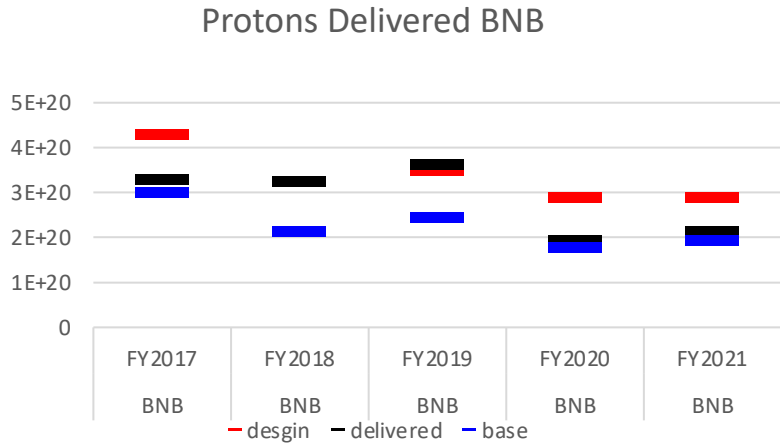
BNB Operations & Plans: 2022-2027



Booster Neutrino Beamline (BNB) provides 8 GeV protons for **short baseline neutrino program**

- MicroBooNE completed
- ANNIE, ICARUS in operations
- SBND online next year
- Will run program until~2026 (long shutdown for PIP-II/LBNF)

- Proton delivery goals met
- Five-year plan: continue delivering beam!
- Present long-range plan indicates no LBNF era operations



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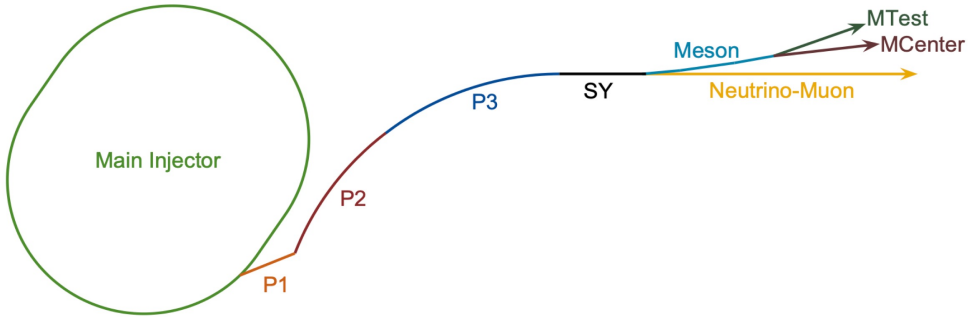
SY120 Operations



- SY120 provides 120 GeV beam to Meson Area & Neutrino Muon Area
- Meson Area services Fermilab Test Beam Facility, which provides a platform for new particle detection techniques and instrumentation development
  - MTest houses short-term experiments (~O weeks)
  - MCenter houses long-term experiments
- Neutrino Muon Area services a single facility, currently E1039 (SpinQuest)
  - E906/SeaQuest concluded in 2016
  - E1039 (an upgrade to E906) will likely run in FY2023

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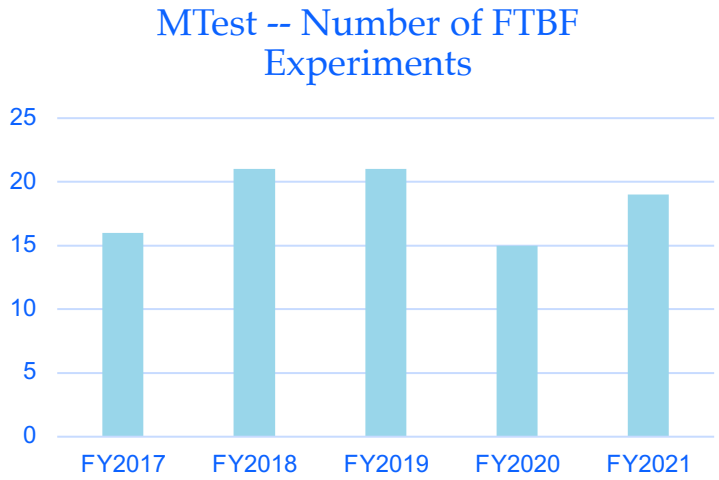
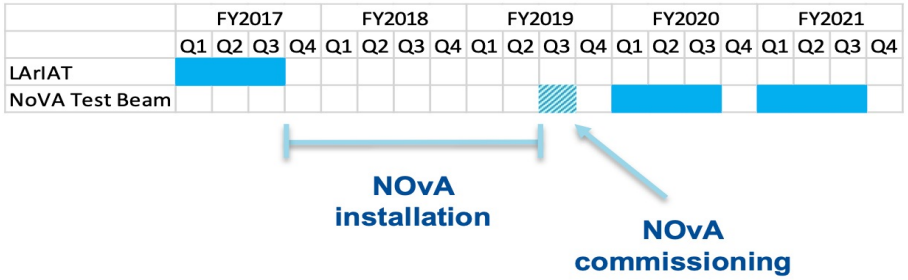
SY120 Plans: 2022 - 2027

- Five-year plan: continue delivering beam!
  - NM NOT scheduled to operate after SpinQuest
  - Meson Area scheduled to run into LBNF era
  - Implement modernization of SY and Meson Area





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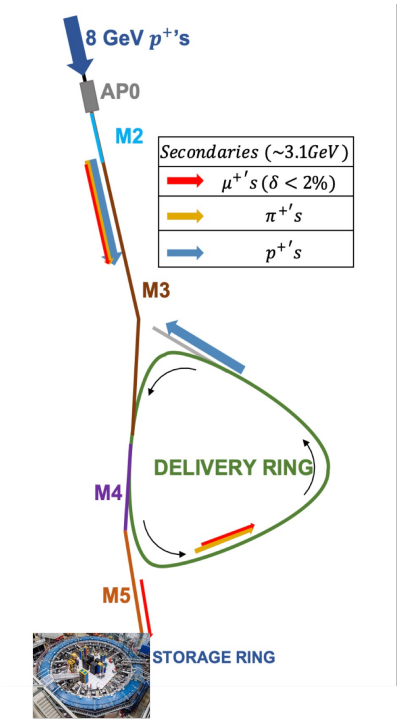
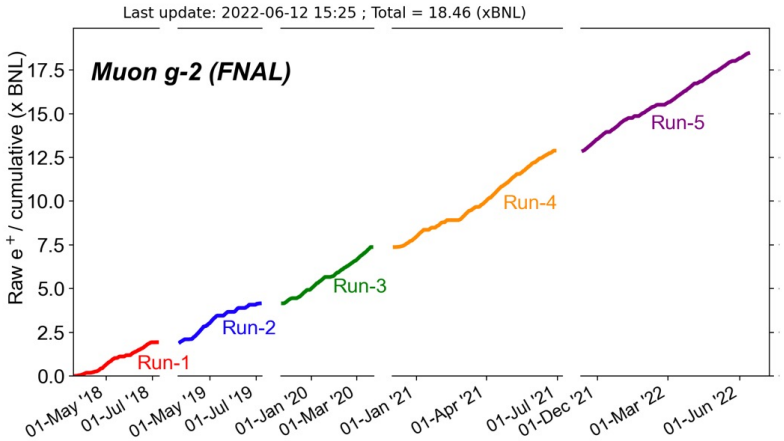
Muon Campus Operations



Schematic layout of the beam delivery system to Muon g-2

- **Delivered high impact physics results from Run 1 data!**
- Muon g-2 commissioning b/w June 2017 & March 2018

  → First observation of precessions of muons
- Run 1 physics data collected b/w March 2018 & June 2018



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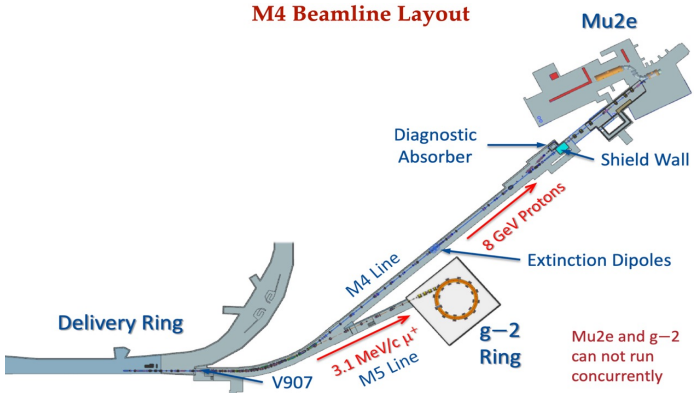

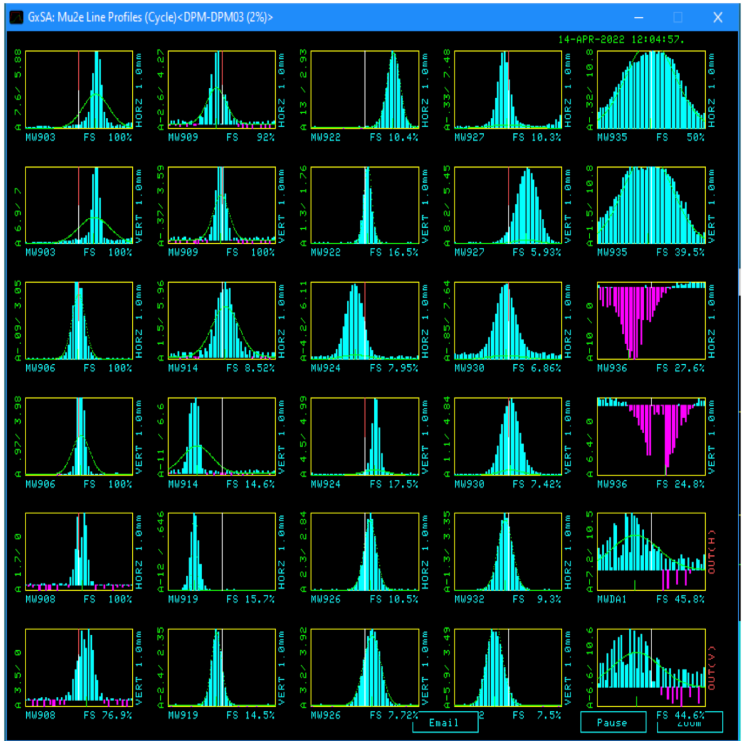

- Mu2e commissioning behind original schedule
- Commissioned beam to Diagnostic Absorber for first time!
- Satisfies Mu2e project key performance parameter
- Plan to upgrade a toroid in diagnostic absorber line to monitor beam intensity

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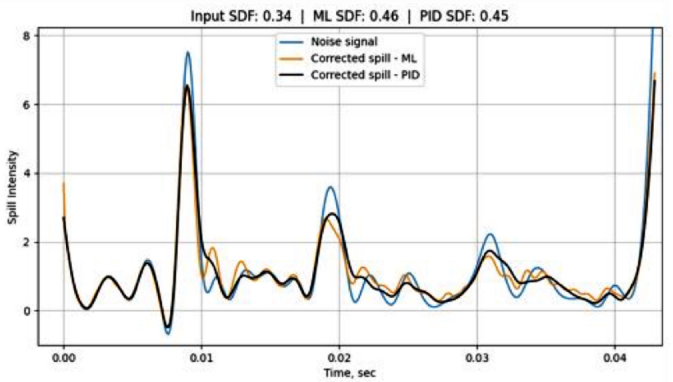
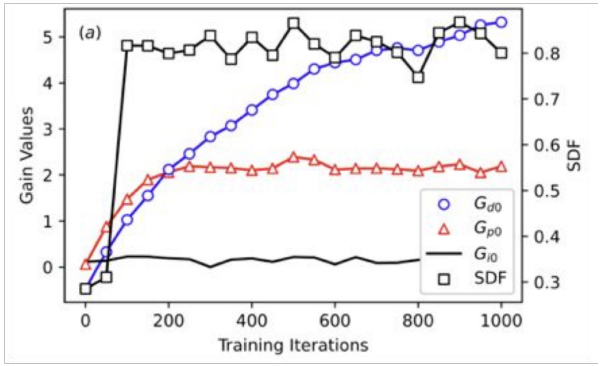
Mu2e Target

Unique target has been built, testing of target at AP0, with Mu2e like beam underway, radiatively cooled

Work underway on Mu2e target remote handling

Mu2e Slow Spill Regulation with Machine Learning





Comparing different ML regulation schemes: optimized PID regulator vs ML regulator

- READS (Real-Time Edge AI for Distributed Systems):
  - Improve real-time spill regulation with reinforcement learning algorithms for guided operations optimization
  - Increases Spill Duty Factor of slow spill extraction

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Muon Campus Plans: 2022- 2027

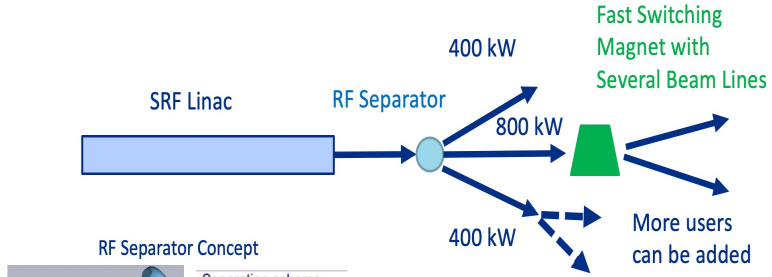
- FY2023: Run 6 for Muon g-2, μ^-run
- Muon g-2 will finish taking data after FY2023
- Mu2e : installation and commissioning starting in 2023
- Mu2e : beam commissioning and physics data taking in 2026
  - X 1000 improvement over current limit by 2027
  - X10000 improvement over current limit by the end of decade

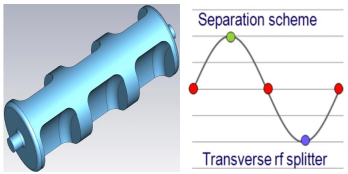
Long-Term Run Plan

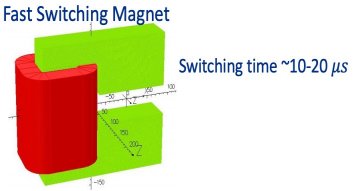
- PIP-II Linac will provide:
  - Beam power
  - Flexibility
  - Reliability

Accelerator upgrades needed for PIP-II:

  - In Booster:
    - ➢Collimators, longitudinal dampers, transverse dampers
  - In Main Injector/Recycler:
    - ➢New MI8 collimators
    - ➢Aperture upgrades







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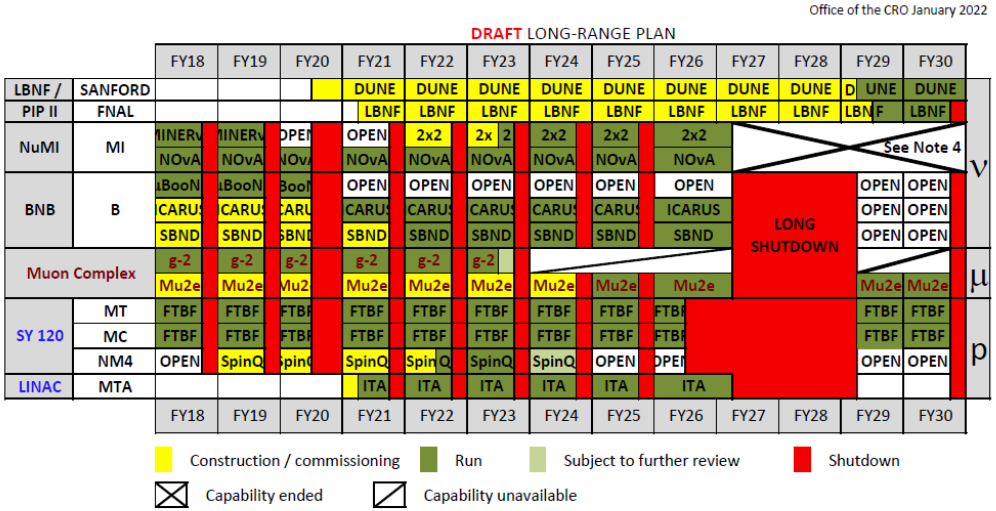

Projects	Design beam power	Period
BNB	30 kW	2002 - 2027
NuMI	700 kW – 1 MW	2004 - 2027
Muon g-2	20 kW	2017 - 2023
Mu2e	8 kW	2025 -
LBNF/DUNE	1.2 MW	2029 -

- Plan for complex to be down for ~two years for PIP-II and LBNF starting in January 2027
- ACNET is current accelerator controls system - ACORN (Accelerator Controls and Operations Research Network) project proposed
- Additional target/horn fabrication & target materials R&D capability planned

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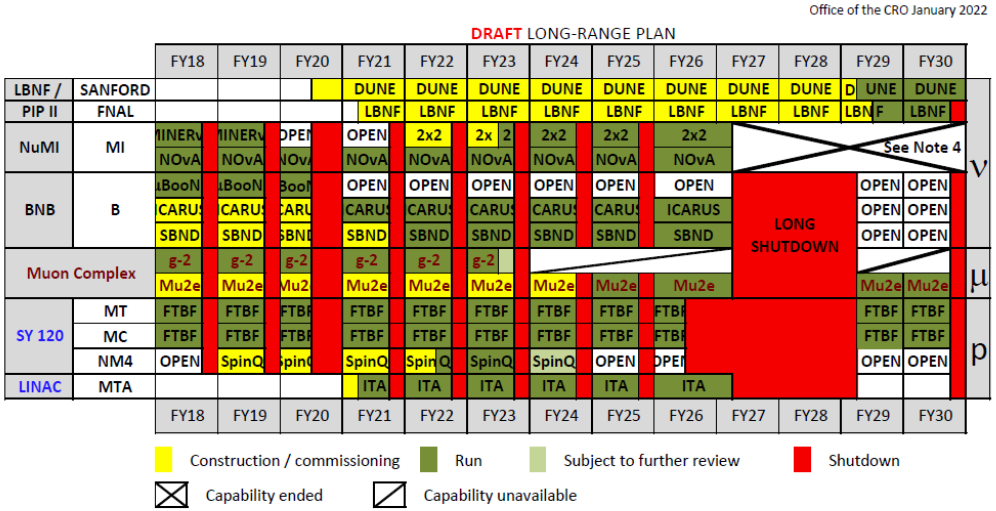
Long-Term Run Plan



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Mu2e-II	100 kW	2033 (?)-
LBNF2	2.4 MW	2035 (?) -
800 MeV Expt	1.6 MW	2030 (?)-
2 GeV Expt	4 MW	2035 (?)-
8 GeV Expt	0.8 – 1.6 MW	2035 (?)-

The Multi-Megawatt Frontier

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Summary

- NuMI 1 MW target, upgraded horn installed, NuMI orbit verifier modernization is planned
- BNB horn power supplies will be modernized
- Modernization of SY and Meson Area is planned
- Muon Campus & g-2 will likely to be reconfigured for negative muon run during FY2023 Run6
- COVID has introduced a “new normal”: teleworking, emphasis on shared knowledge, closer collaboration
- A new generation being hired to continual success and transition into LBNF era
- **We have successfully operated to deliver on the missions while also working to build the future of the laboratory**