Introduction to Fermilab's Accelerators and Beams (Present and Future)

Jason St. John
Accelerator Division
54th Annual Users Meeting, 2021.08.02

Outline

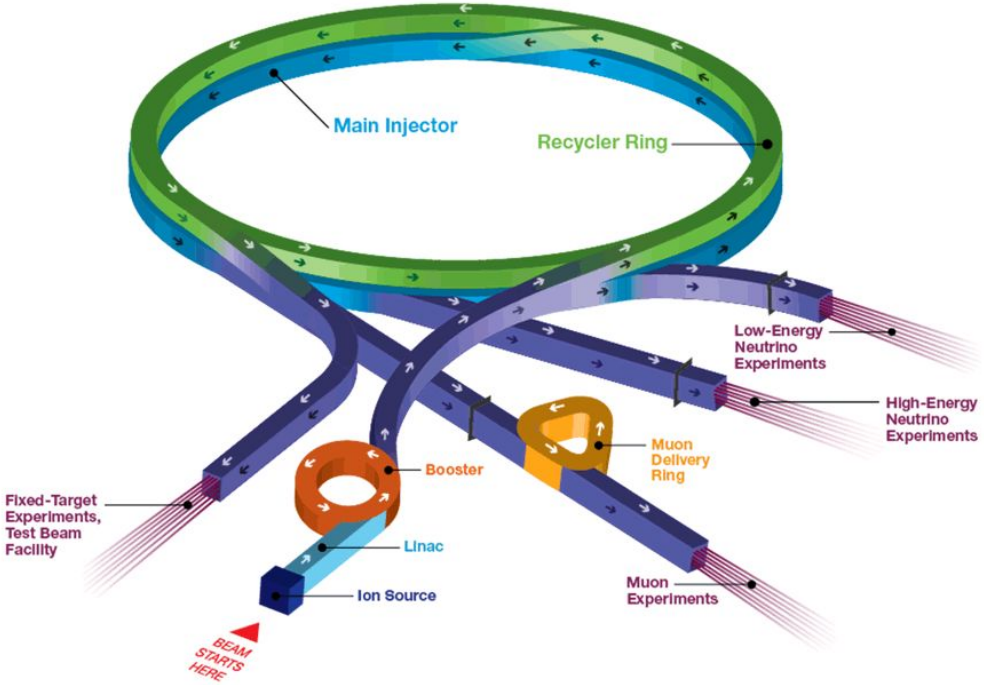
Accelerators: Linac & Booster (Proton Source)

- Beam: MTA
- Beam: Booster Neutrino Beam

Accelerators: Main Injector & Recycler

- NuMI
- Switchyard

Fermilab Accelerator Complex



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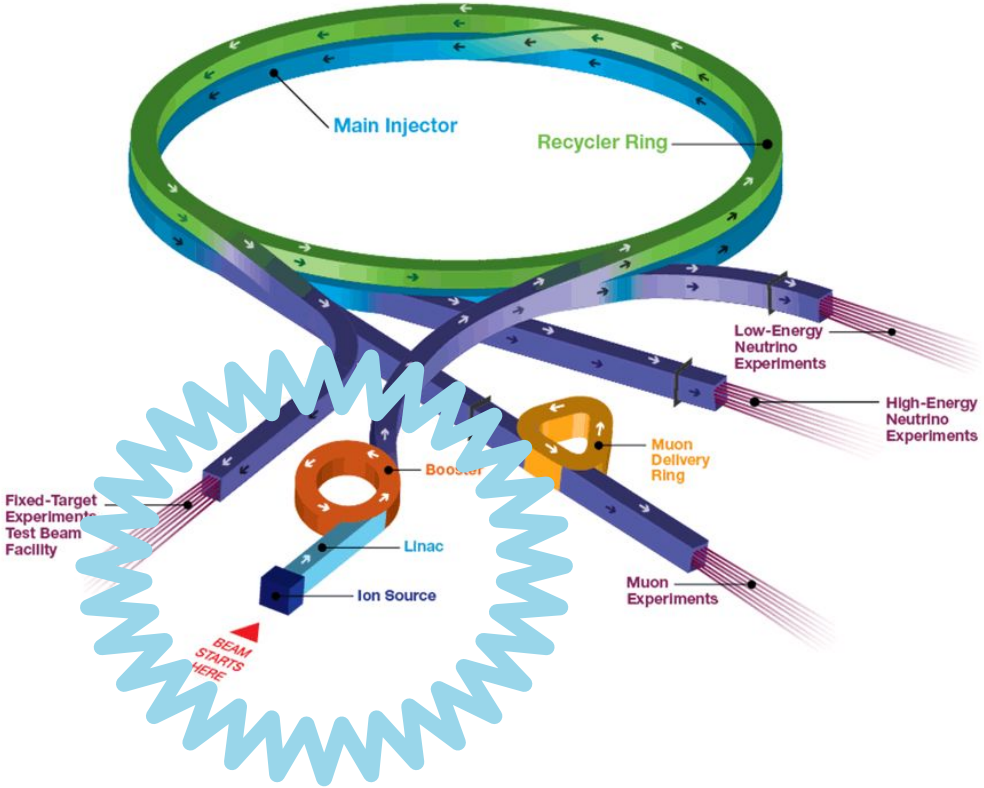
Fermilab Accelerator Complex



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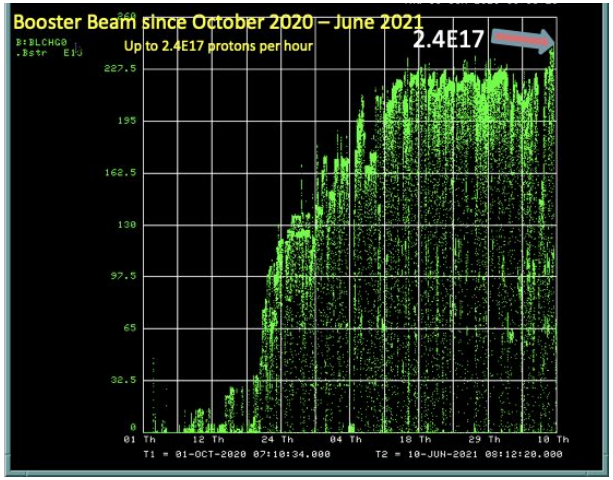
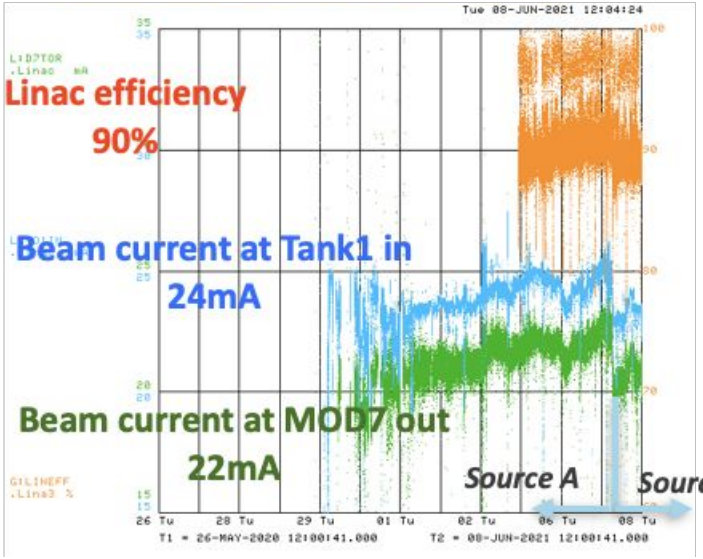
Proton Source: Linac & Booster

Good year for AD/PS: PreAcc, Linac and Booster despite COVID-19.

Big thanks to RF, MSD, Instrumentation, Controls, and Ops for their support.



Operation (last 54 weeks)



- New digital longitudinal damper system being commissioned.
- New Wide-bore RF cavity installed and running.
- New digital LLRF system being commissioned.
- New diagnostics installed in LEBT and MEBT.
- New computer simulations on injection, transition crossing, and bunch rotation.
- Very productive Booster studies:
  - Source of RF cavity phase error found & fixed.
  - ½-integer corrections revealed interesting physics.
  - First hints of e-cloud in Booster.

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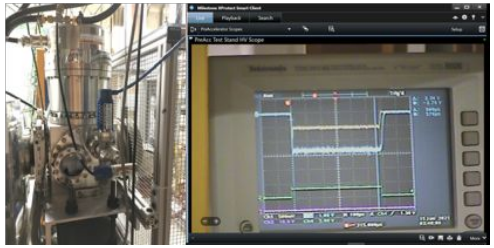
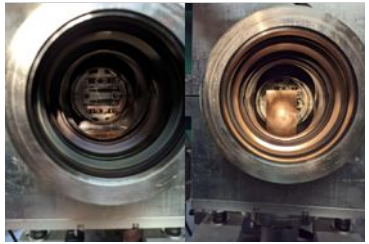
Proton Source: Linac & Booster

Magnetron source @ 600 us possibly for PIPII



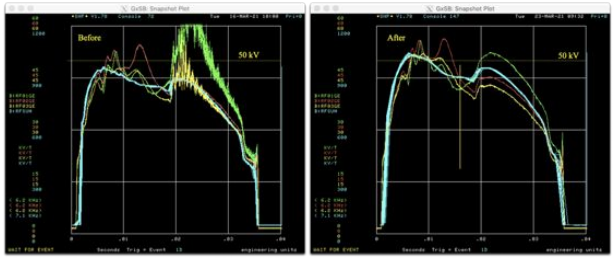
New LEBT collimator for beam measurements



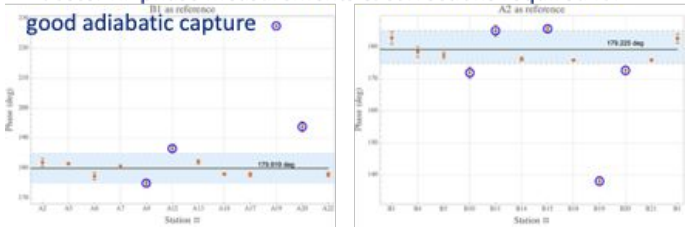
New MEBT BPM, halo and current monitor

Setting up for gradient magnet tests at E4R for PIPII

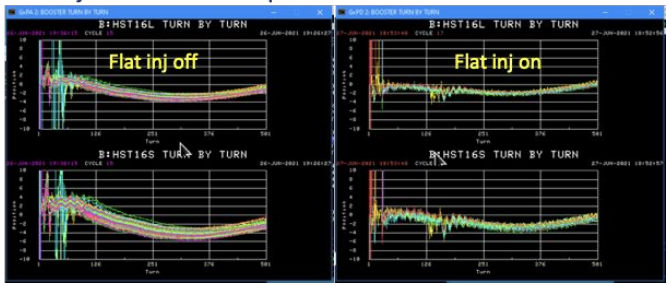
All Booster RF running above 50 kV required for PIPII



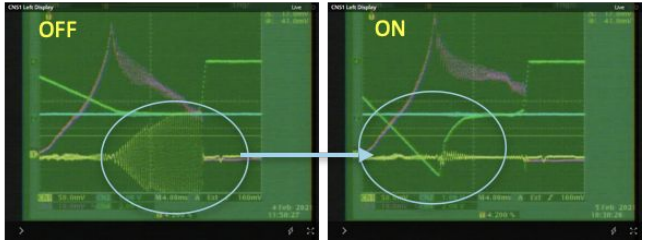
Booster RF phase measurements & corrections required for good adiabatic capture



Flat injection studies required for PIPII



Mode 2 dampers required for high intensities



New digital LLRF system for Booster (required for PIPII)

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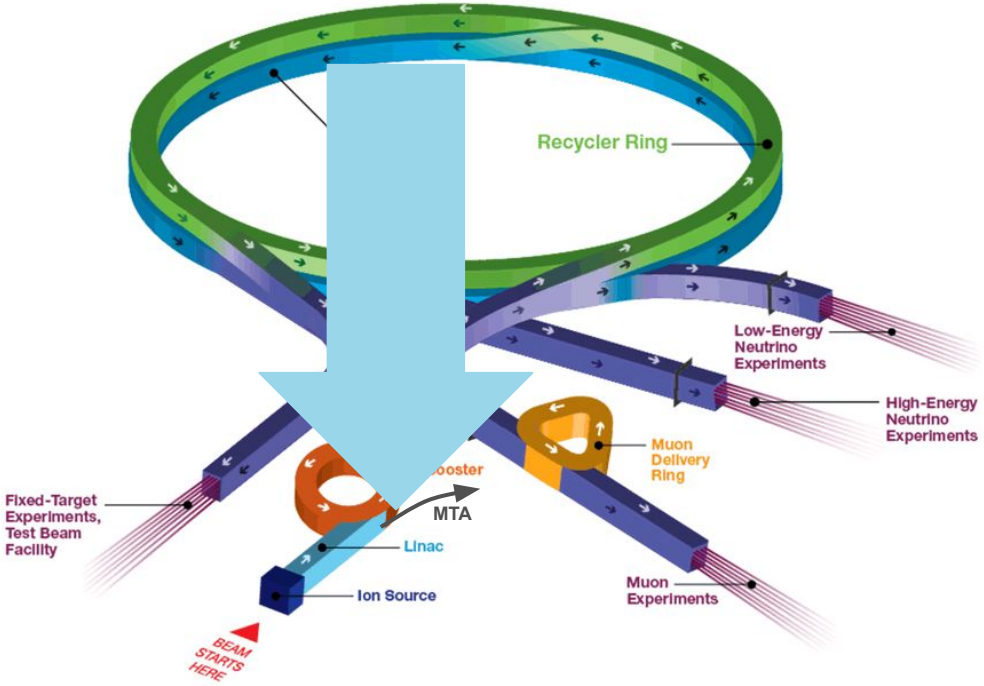
Fermilab Accelerator Complex



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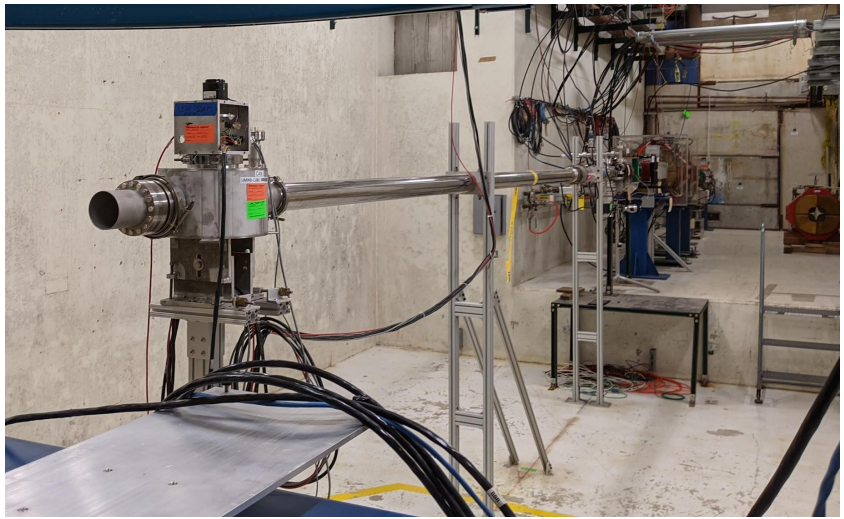
N
Kaulz Rd
Shielding
Cave
Front
Porch
Absorber
Beam
Alcove
Exp. Hall
Access Pit
S
Google
Imagery ©2020 Google, Imagery ©2020 U.S. Geological Survey, Map data ©2020
20 ft

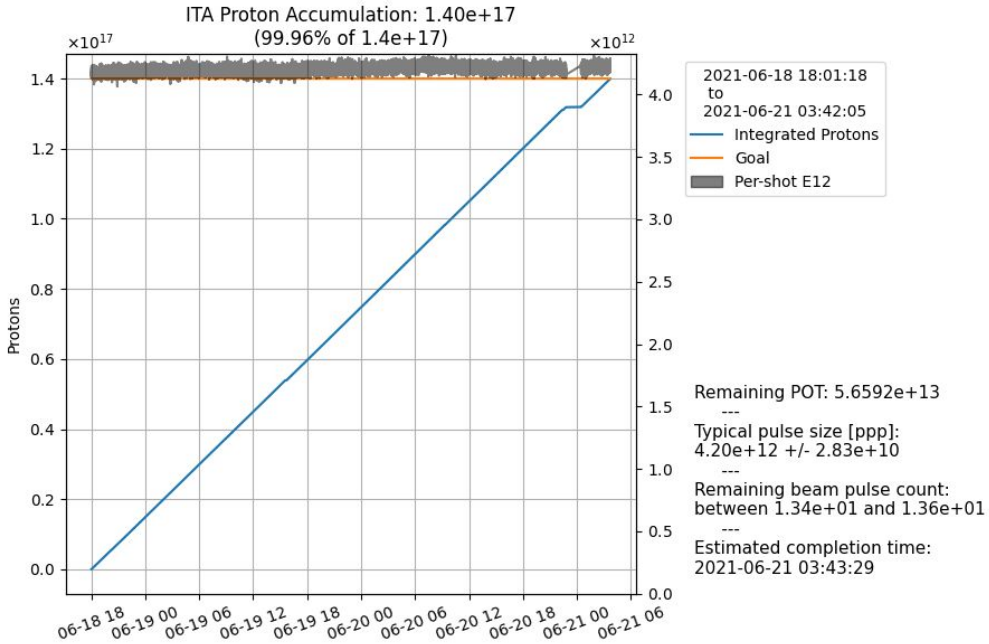
MTA: 400 MeV Testing Area

New shielding assessment safely allows high rate 400 MeV beam

Changes to timeline generator to allow multipulse operations:

~6.4e16 particles / 24 hrs





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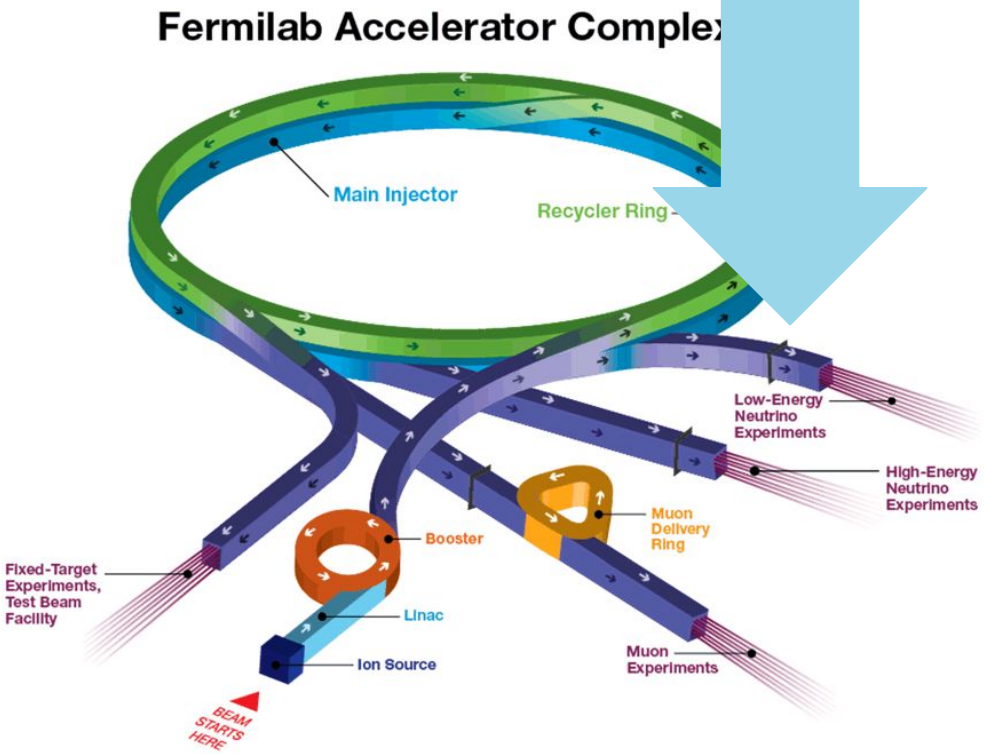
Fermilab Accelerator Complex
Main Injector
Recycler Ring
Low-Energy Neutrino Experiments
High-Energy Neutrino Experiments
Muon Delivery Ring
Booster
Fixed-Target Experiments, Test Beam Facility
Linac
Ion Source
Muon Experiments
BEAM STARTS HERE

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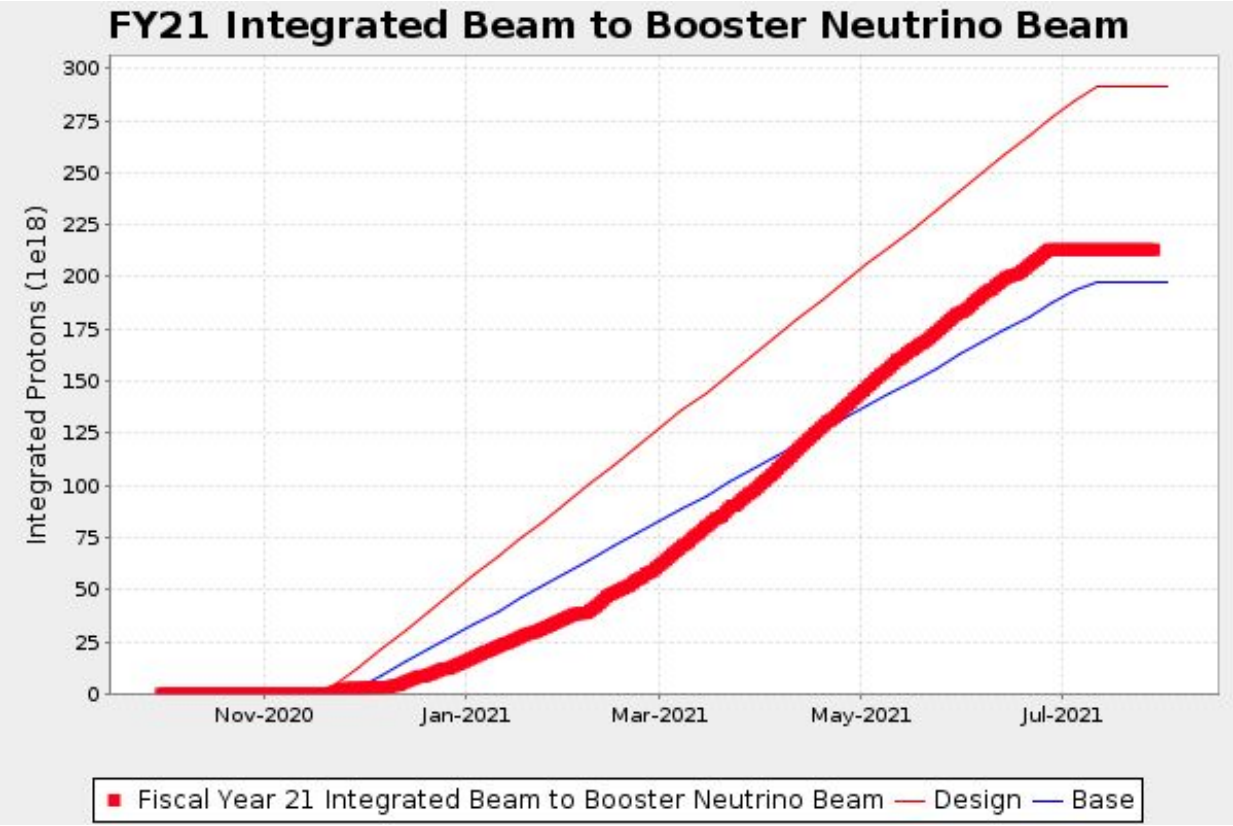
Booster Neutrino Beam (BNB)



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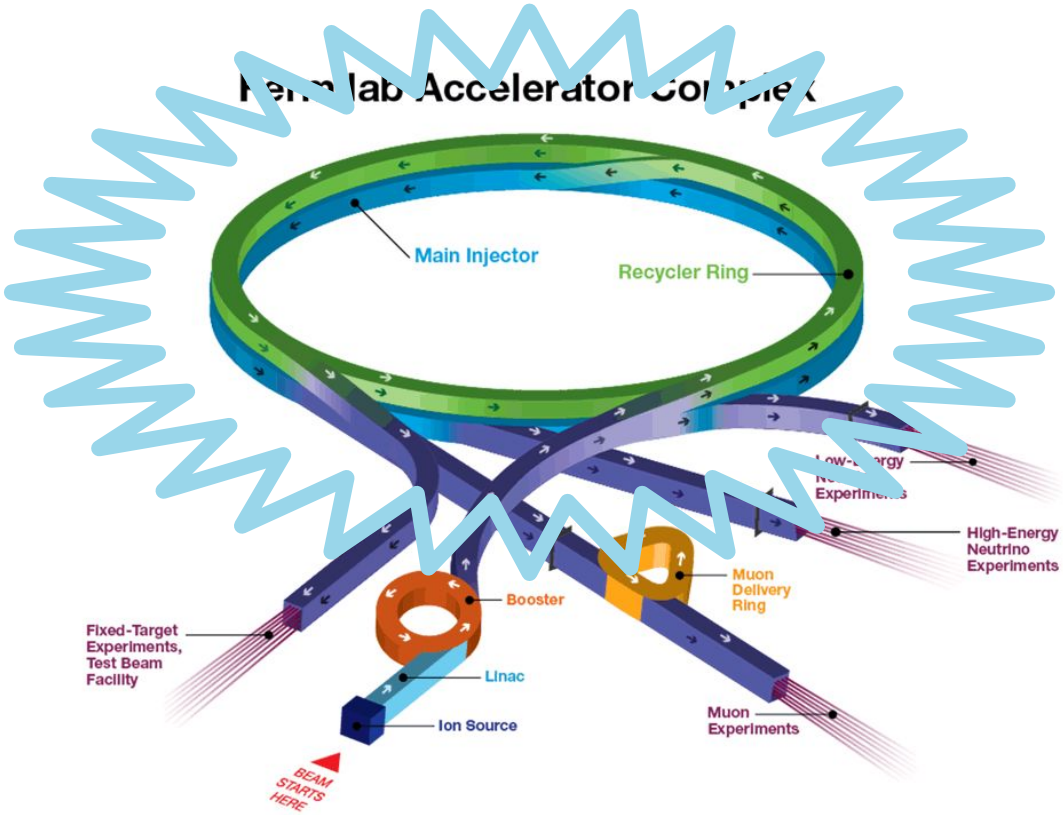
Main Injector
Recycler Ring
High-Energy
Neutrino
Experiments
Muon
Delivery
Ring
Booster
Fixed-Target
Experiments,
Test Beam
Facility
Linac
Ion Source
Muon
Experiments
BEAM
STARTS
HERE

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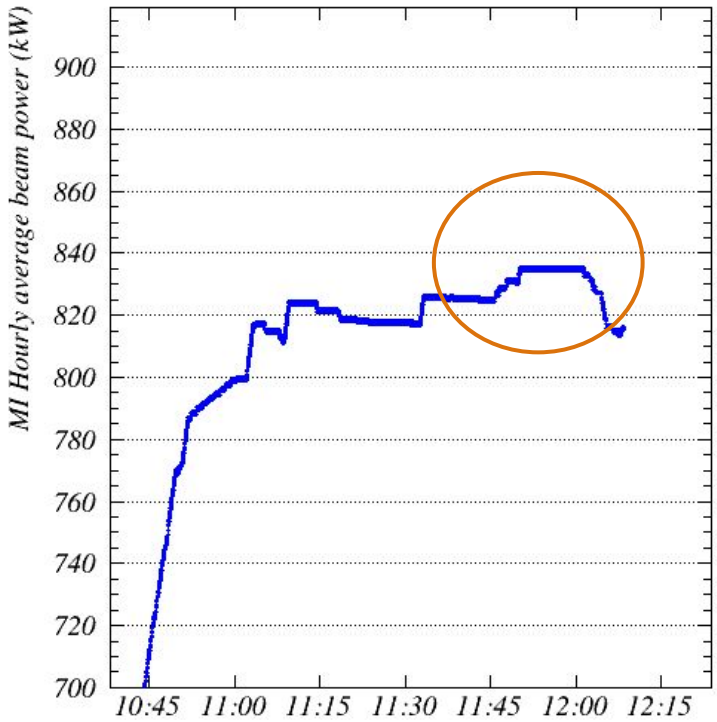
Main Injector Sets Beam Power Record

Monday 2021-06-14 11:50:09 - 12:50:09



With SY120 and g-2 not running this morning, we set a new hourly average beam power record in Main Injector. In fact, we set a new hourly average beam power record on 48 separate occasions this morning, the most recent of which was 835 kW, for the hour between 11:50:09 and 12:50:09.

Typical running during this morning's beam power attempt was around 850 kW; the average was reduced by a couple of clusters of beam loss trips on the MI-8 collimators.

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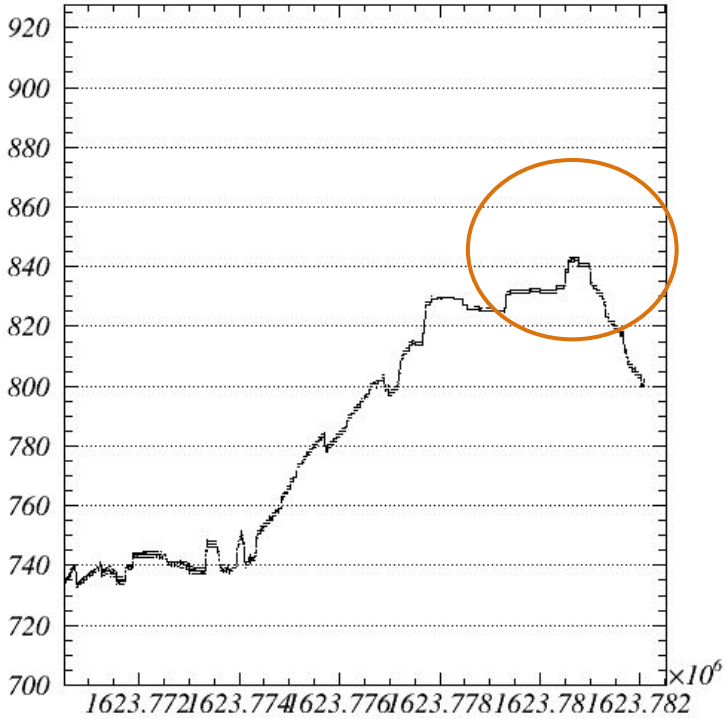
Main Injector Sets Beam Power Records

Tuesday 2021-06-15 13:11:37 -14:11:37



...and then beat that record again the next day!

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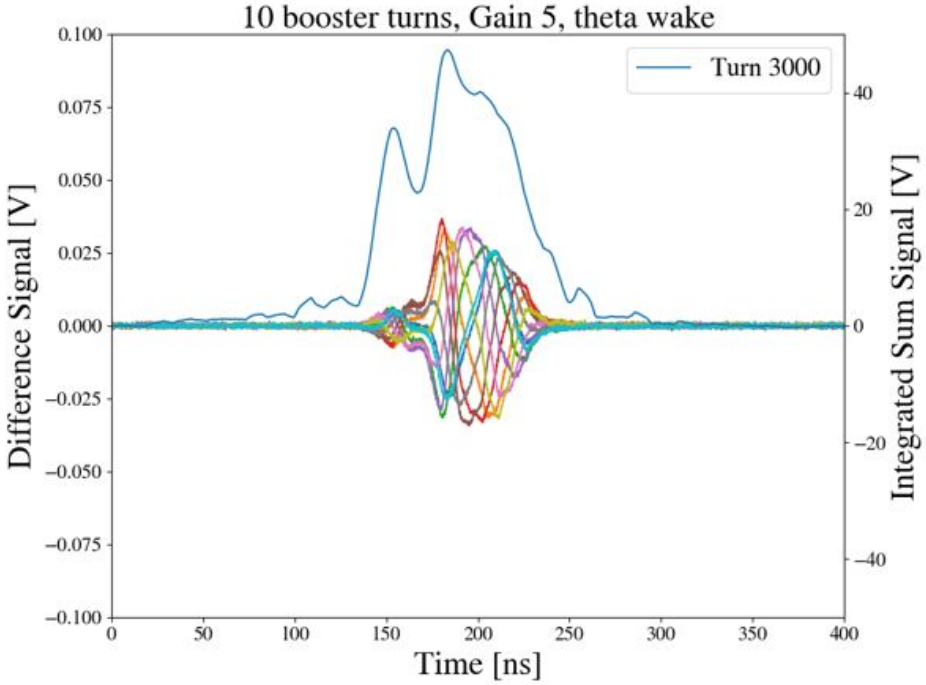
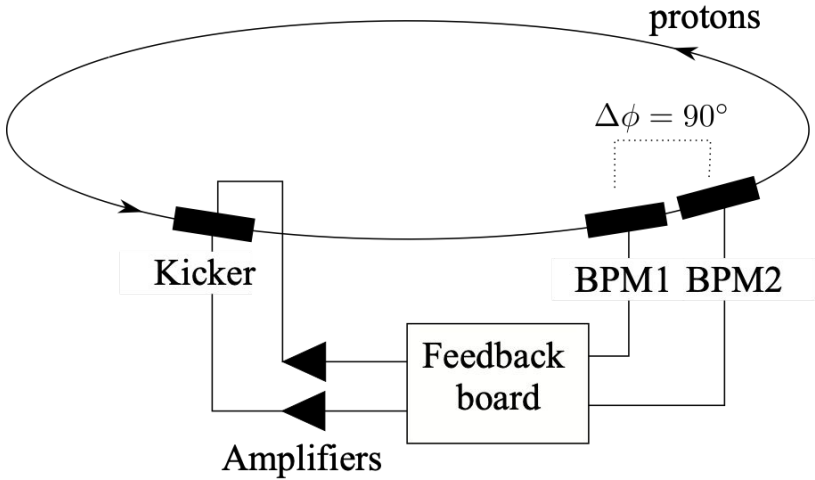
Recycler: Wakefield Studies for High Space Charge





← Example of excited instability measured by diagnostic

- Difference signal is proportional to intensity times vertical position
- Integrated sum signal shows longitudinal bunch profile

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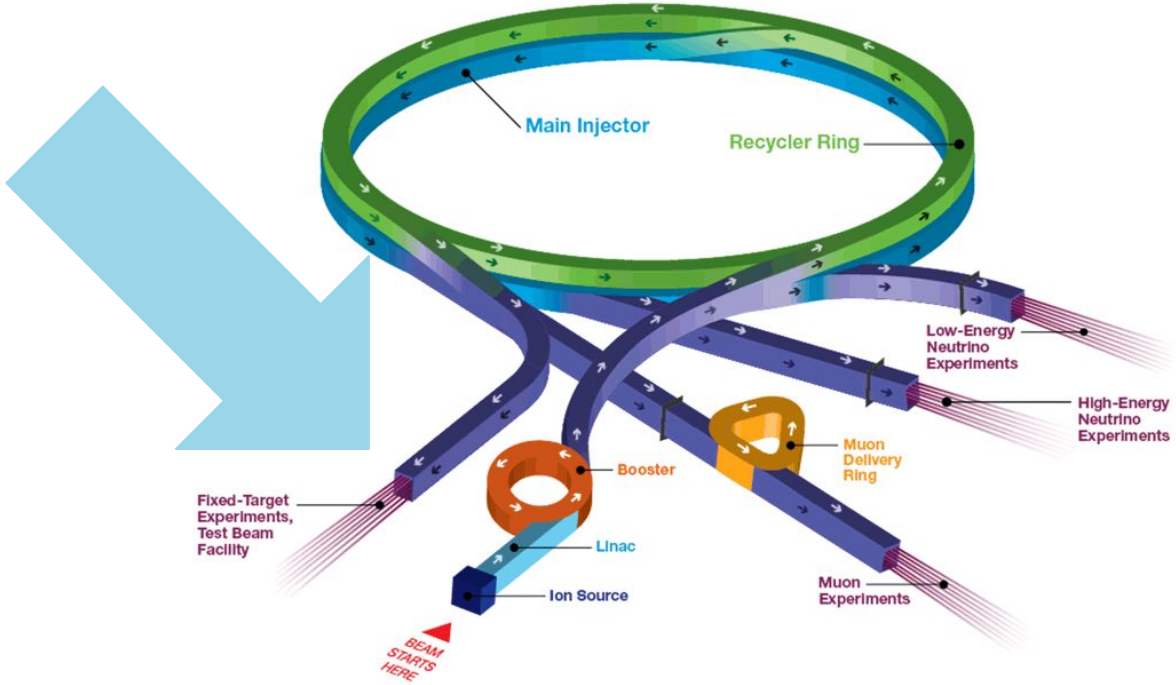
Fermilab Accelerator Complex



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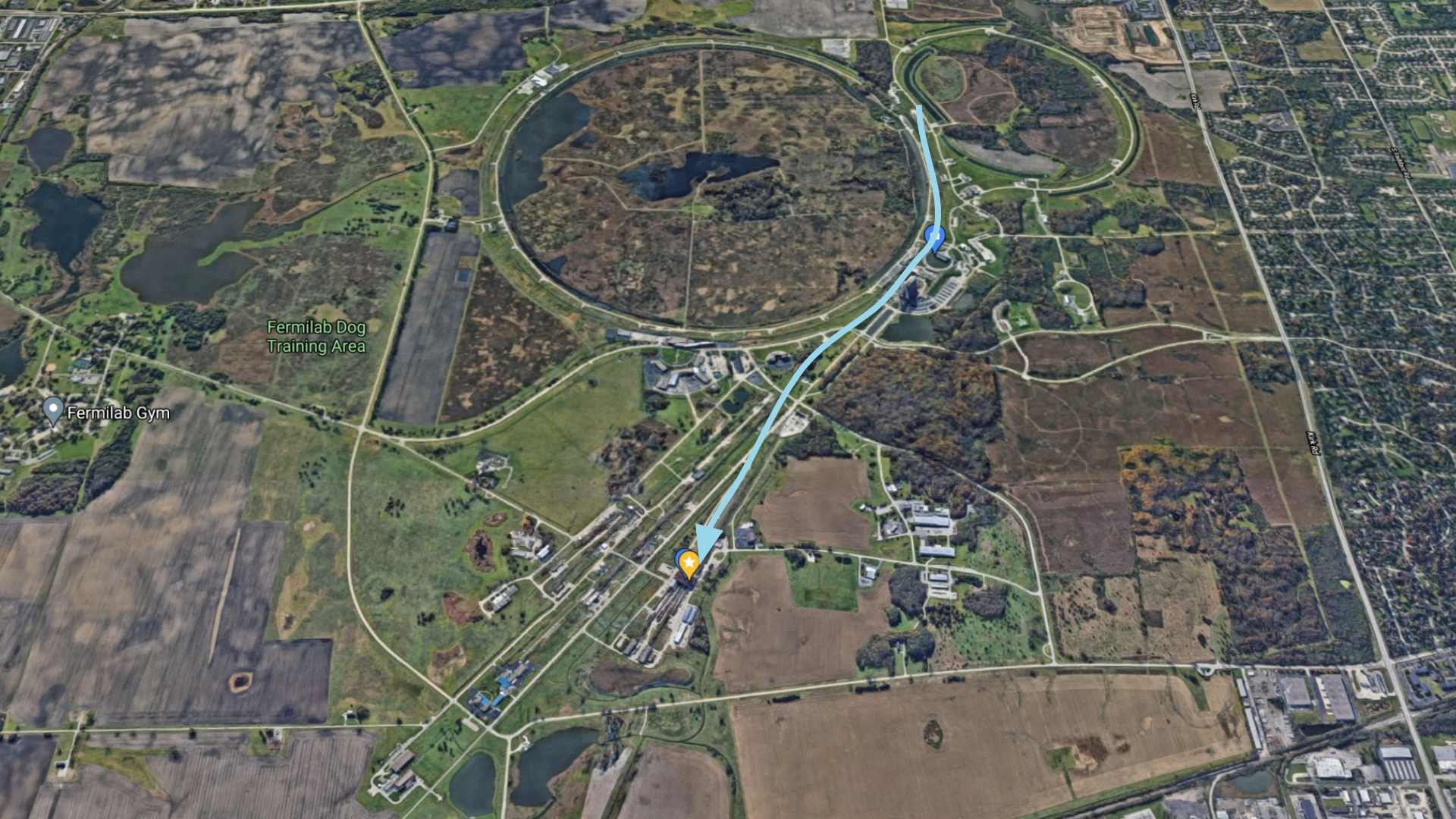
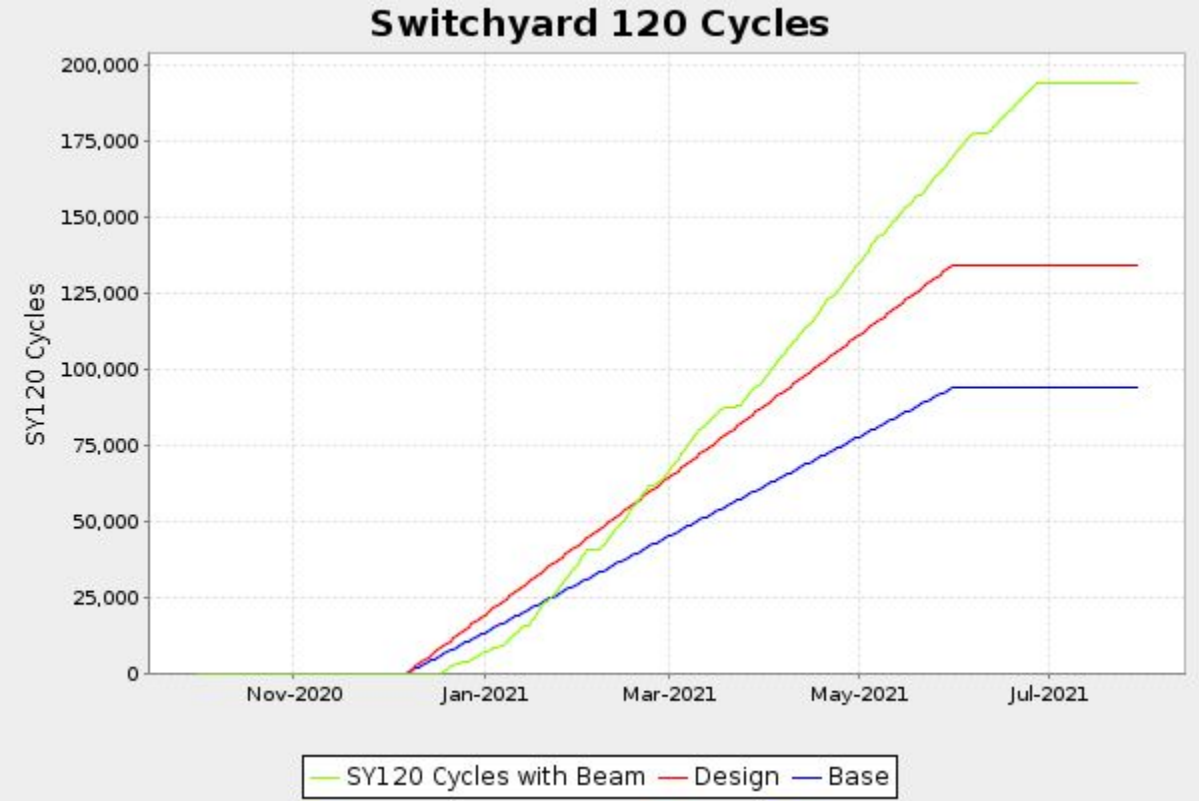

Fermilab Dog
Training Area
Fermilab Gym

Switchyard



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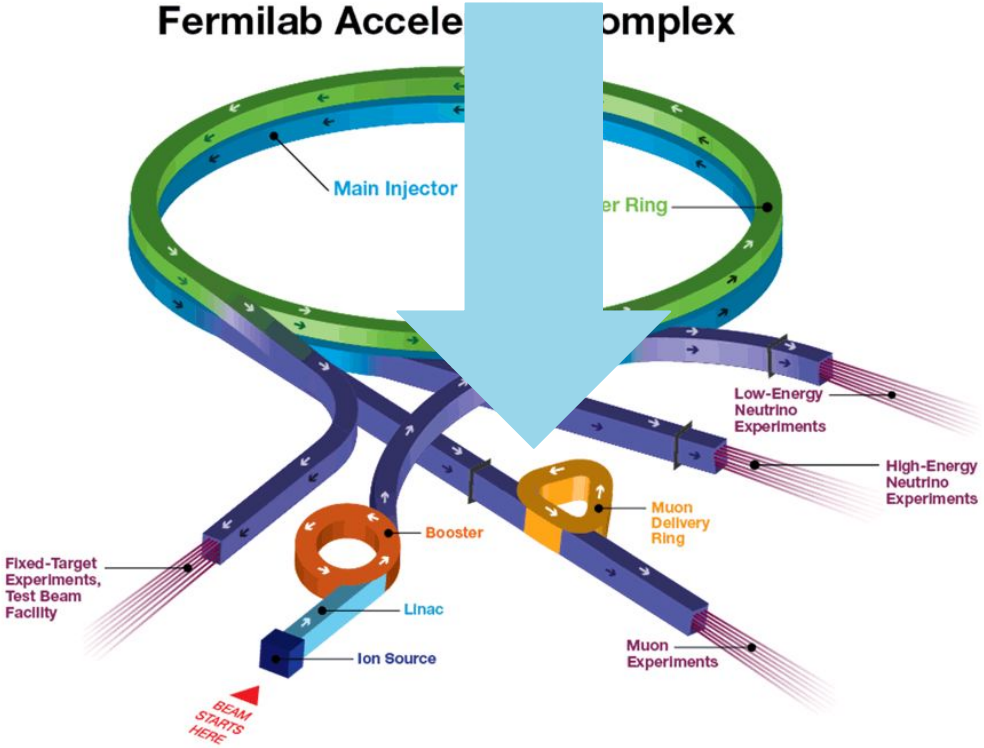
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BEAM
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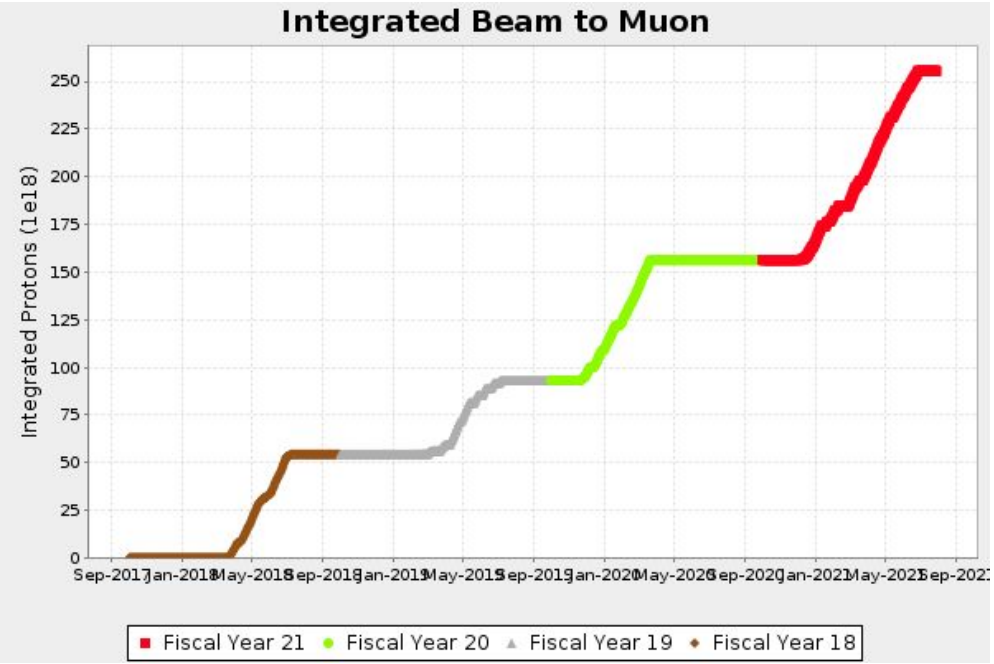
Muon Campus: g-2 beam



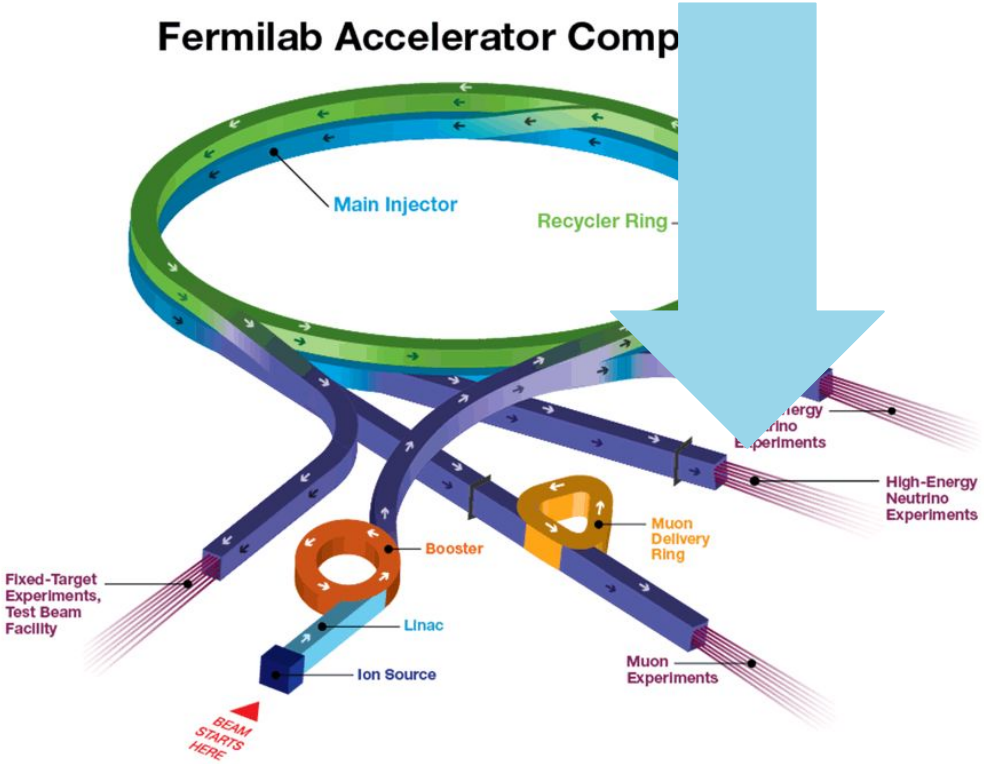
Completed Run 4 - Beam delivered 85% of the time requested.

- Run 1 (FY18) 2 * BNL data set
- Run 2 (FY19) 2 * BNL data set
- Run 3 (FY20) 3 * BNL data set
- Run 4 (FY21) 5.5 * BNL data set

Total to date: 12.9 * BNL data set

Muon Campus: mu2e Beam

First production mu2e target assembly to be installed in the experiment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BEAM
STARTS
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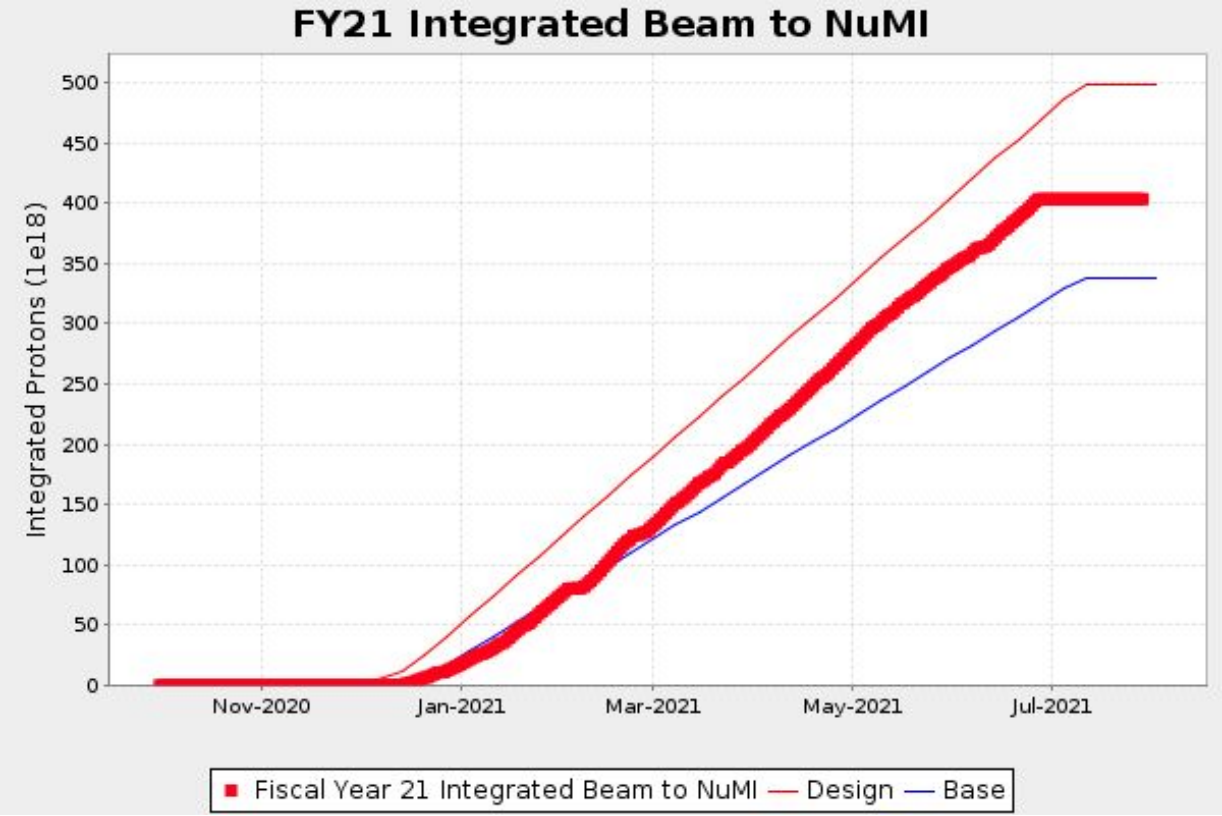
NuMI: Neutrinos from the Main Injector



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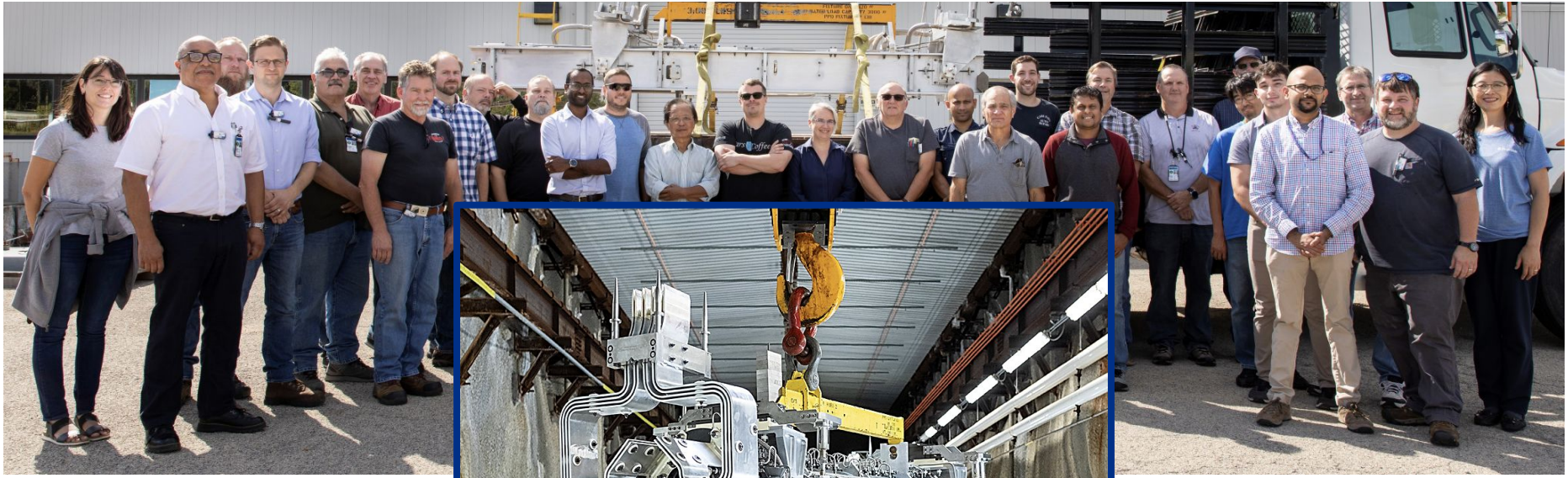
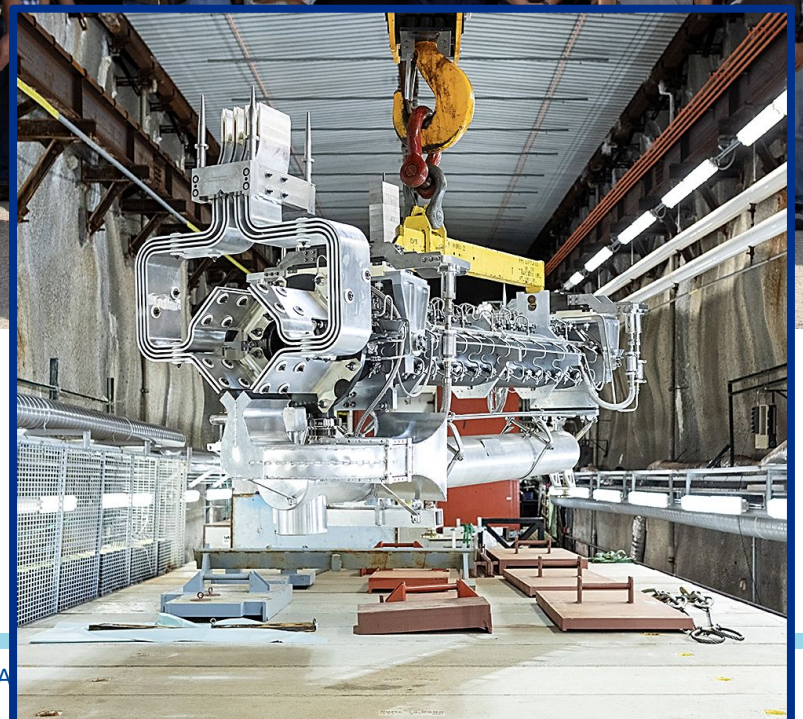
NuMI Target System Upgraded for Megawatt Beam Operation





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NuMI Target System Upgraded for Megawatt Beam Operation

Objective reached:

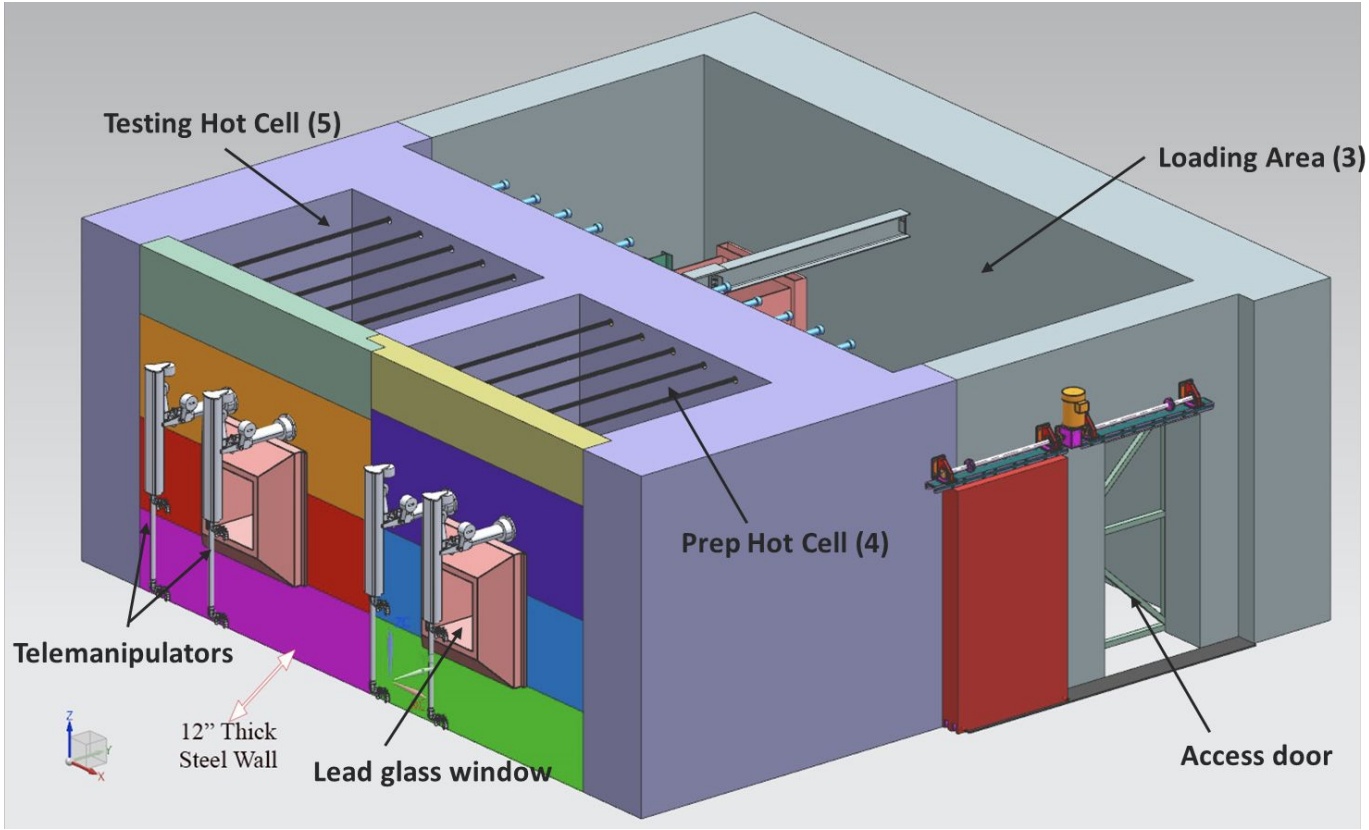
- Capable of accepting 6.5E13 protons/spill at 120 GeV, 1.2 sec cycle time

Project scope:

- Improve and replace Target Hall components / support systems

Upgrade for 1 MW	Risk Mitigation
• MARS / FEA simulations for all beamline components • 1 MW target • 1 MW horn 1 • Stripline air diverter T-block & HVAC ductwork • Target & Horn 1 RAW system • Target chase cooling and air handling system	• Horn 1 module drive mechanism changeout • Absorber intermediate cooling system HX • MI-65 condensate rerouting • Target chase supplemental shielding • Hadron monitor and gas system • Target module drive mechanism • MINOS surface dry cooler • Decay pipe US window repair mechanism

High-Power Targetry R&D



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Fermilab Accelerator Complex
Main Injector
Recycler Ring
Low-Energy Neutrino Experiments
High-Energy Neutrino Experiments
Muon Delivery Ring
Booster
Fixed-Target Experiments, Test Beam Facility
Linac
Ion Source
Muon Experiments
BEAM STARTS HERE

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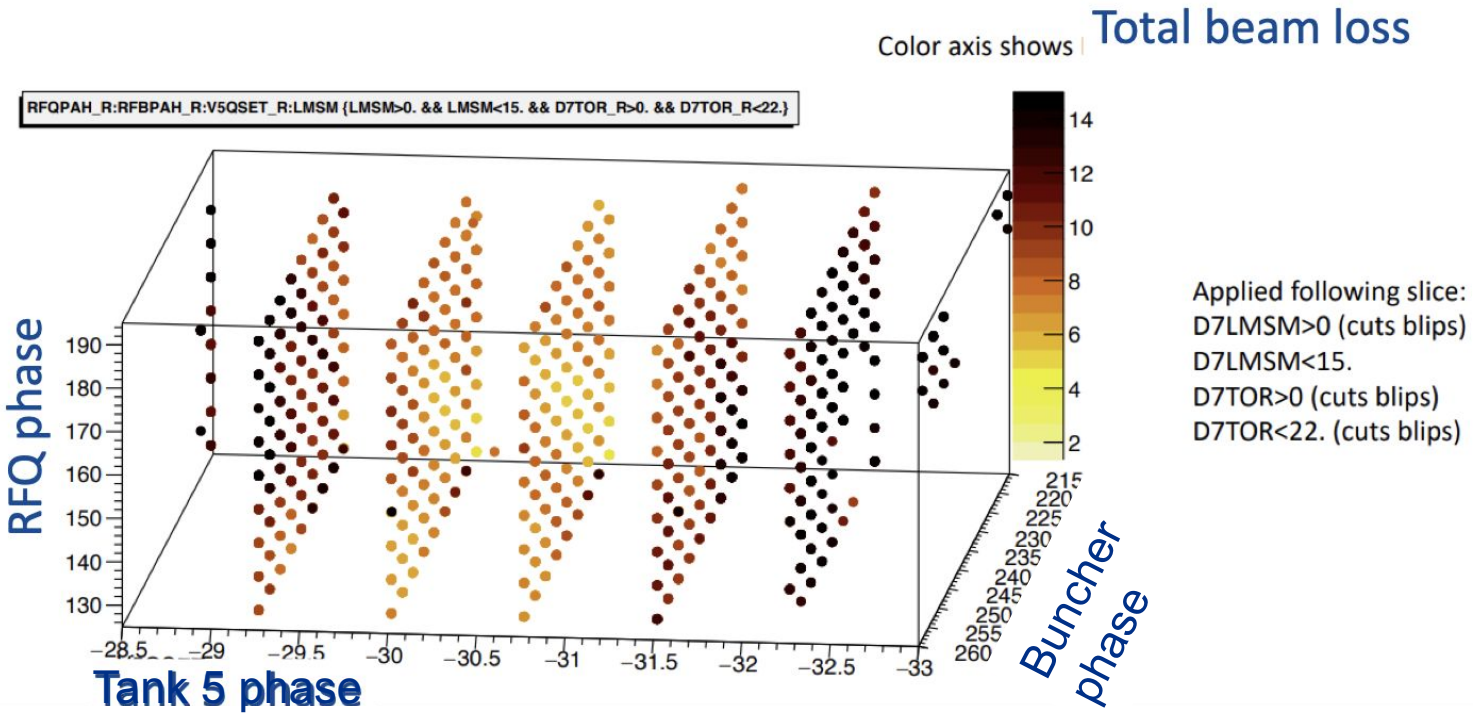
AD AI: Machine Learning for the Accelerators

- Real-Time Linac RF Phase optimization
  - Minimize losses in real time with fine adjustments to RF phase settings
- L-CAPE
  - Predicting & Preventing Linac beam outages with anomaly detection
- AI GMPS
  - High-Precision Regulation of the Booster GMPS (bending magnets) via FPGA
- READS (Real-Time Edge AI for Distributed Systems):
  - Reducing beam aborts with intelligent and semi-autonomous operations by deploying de-blending and de-noising techniques to decouple overlapping beam losses in the Main Injector enclosure, increasing the overall uptime of the Recycler Ring
  - Improving the real-time spill regulation with the use of reinforcement learning algorithms for guided operations optimization thereby increasing the Spill Duty Factor of slow spill extraction

ML Linac Accelerator Cavity Phase Tuning

3-phase scan 06/29/2021: D7LMSM



Applied following slice:
D7LMSM>0 (cuts blips)
D7LMSM<15.
D7TOR>0 (cuts blips)
D7TOR<22. (cuts blips)

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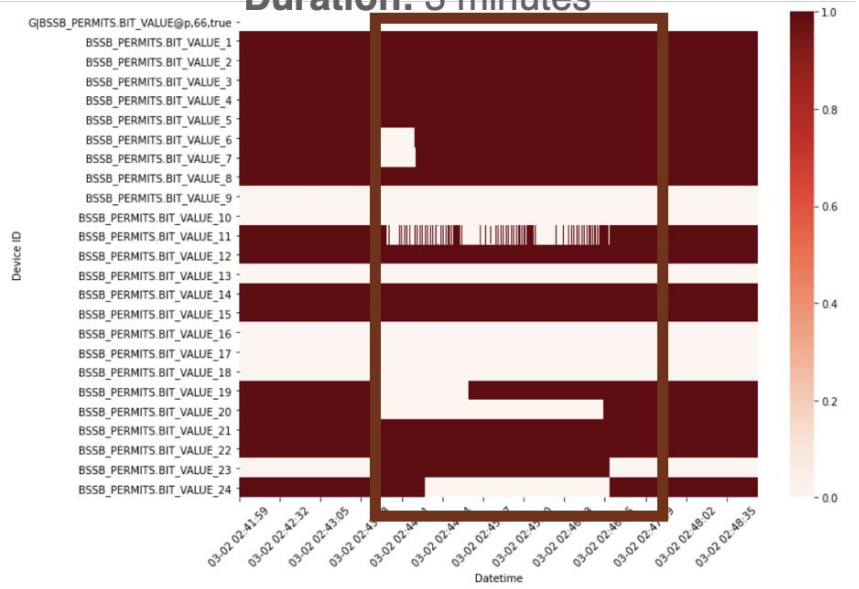
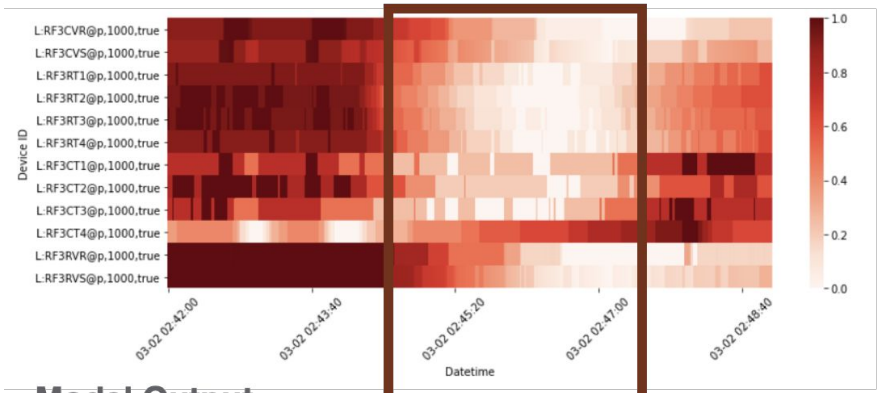
L-CAPE: Linac Condition Anomaly Prediction of Emergence

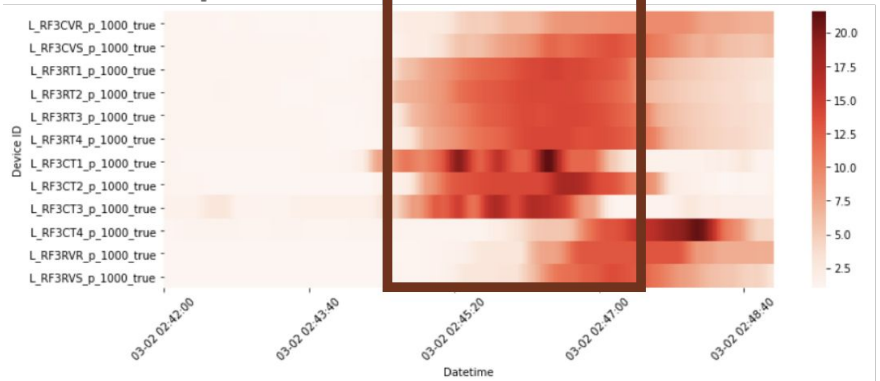
Fault: LRF3 Driver Anode OL
Reported: 2021-03-02 02:44:00
Duration: 3 minutes



Actual Data



Model Output



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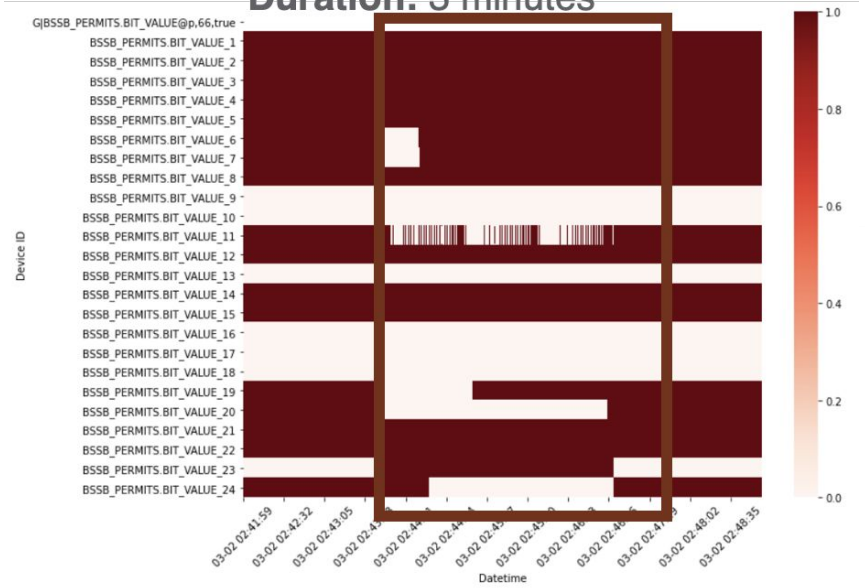

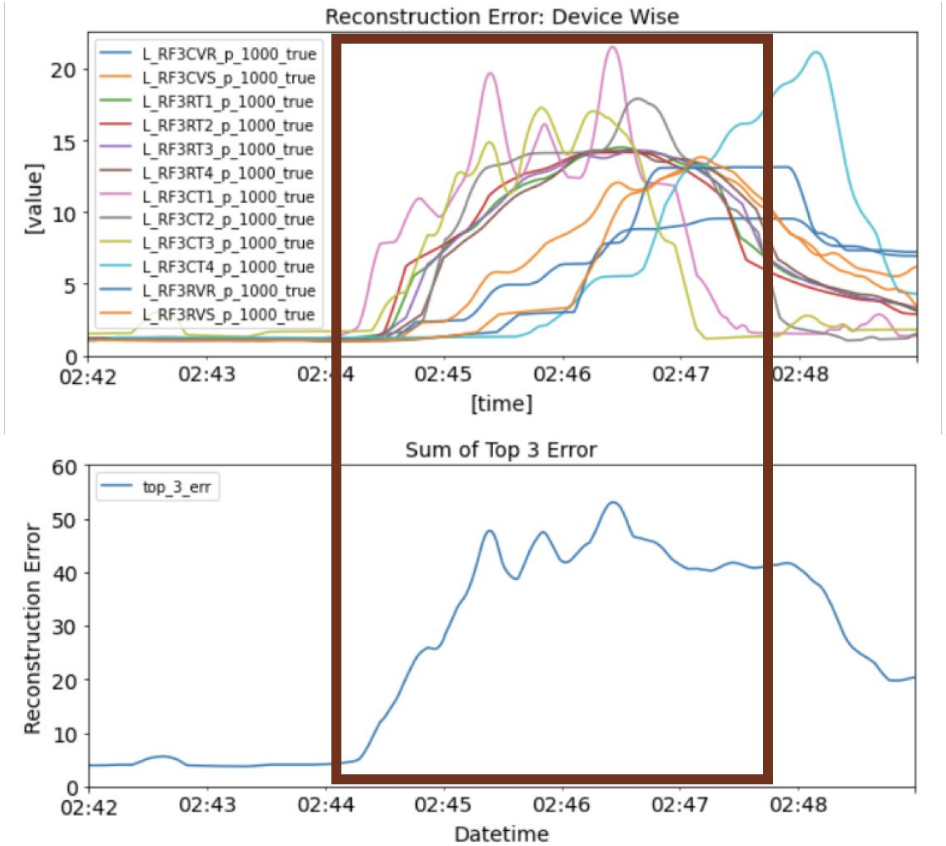

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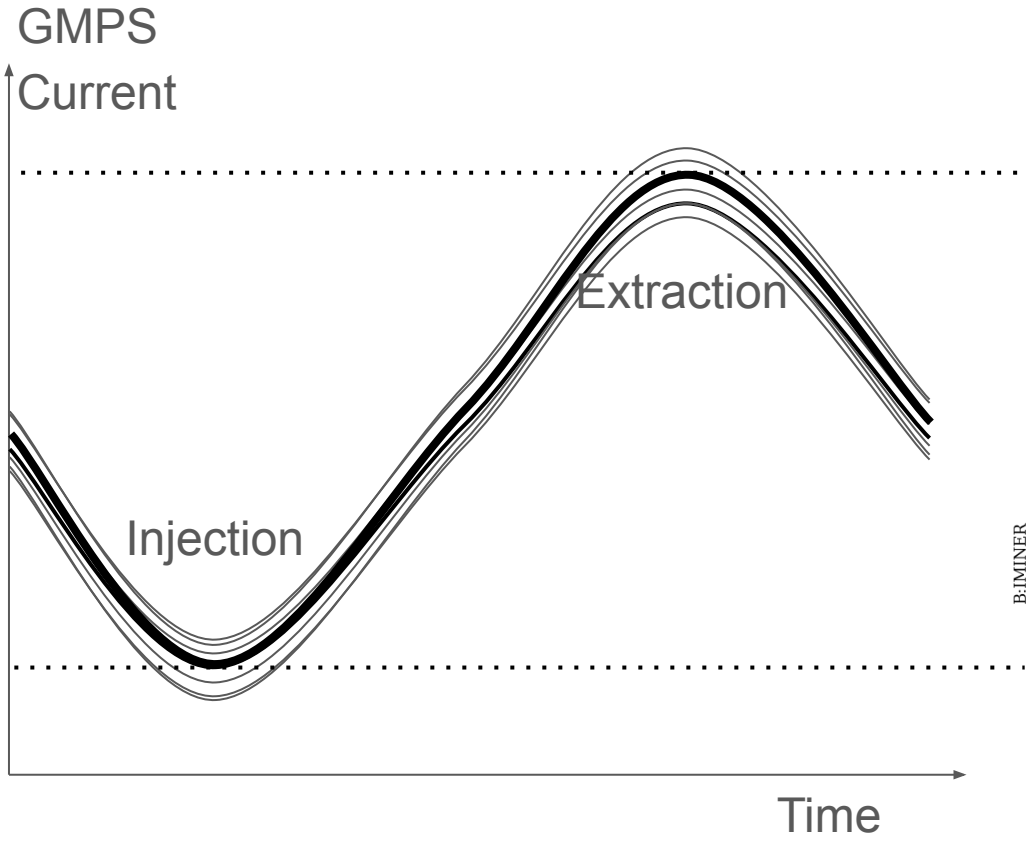
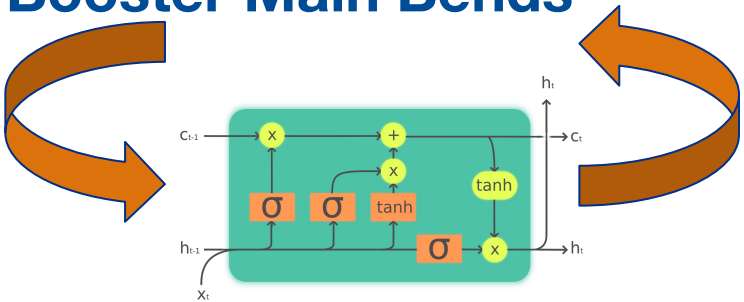
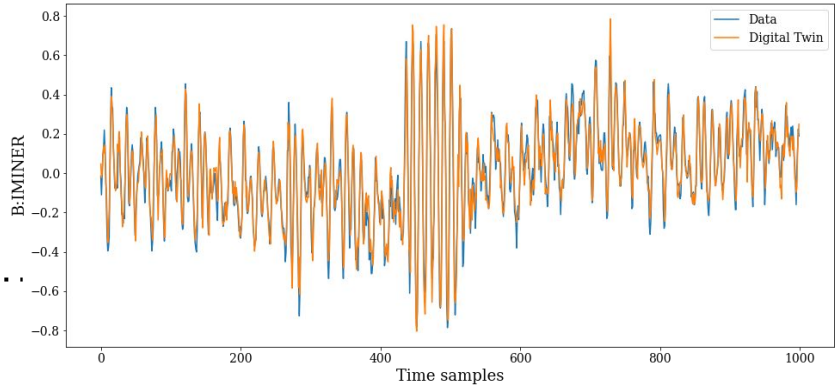
AI GMPS: Precision Regulation for the Booster Main Bends





Legend: Layer Pointwize op Copy



B:IMINER = 10*(Setting - obsMax)

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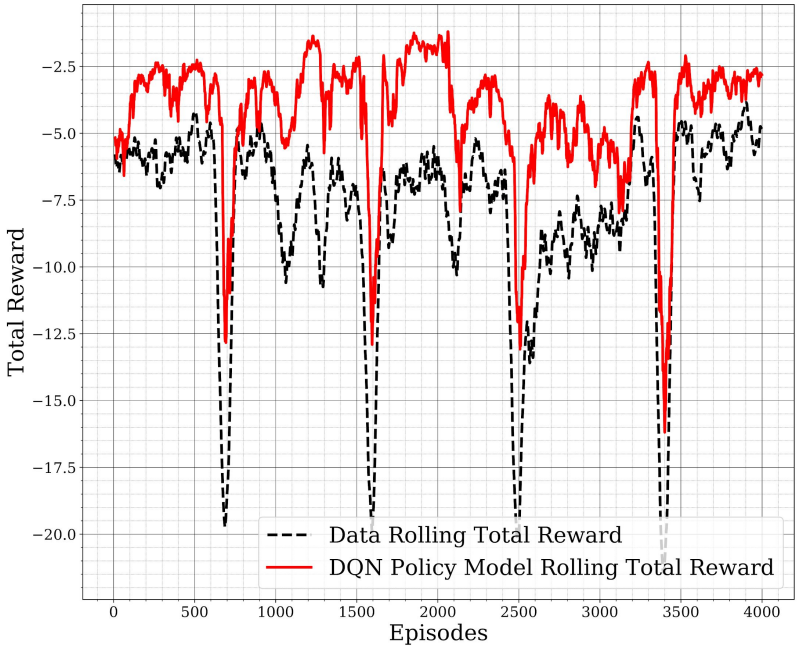
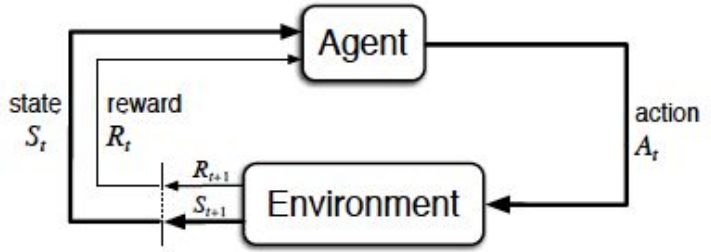
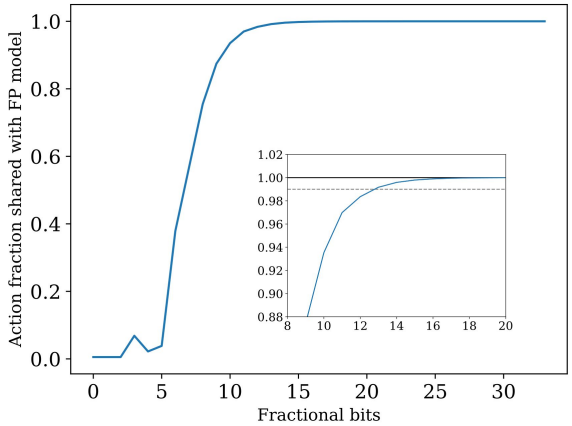
AI GMPS: Precision Regulation for the Booster Main Bends

Consecutive episodes of 50 GMPS cycles at 15 Hz.







Reported at multiple conferences and soon, Physics Review AB

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READS: Beam Loss Deblending

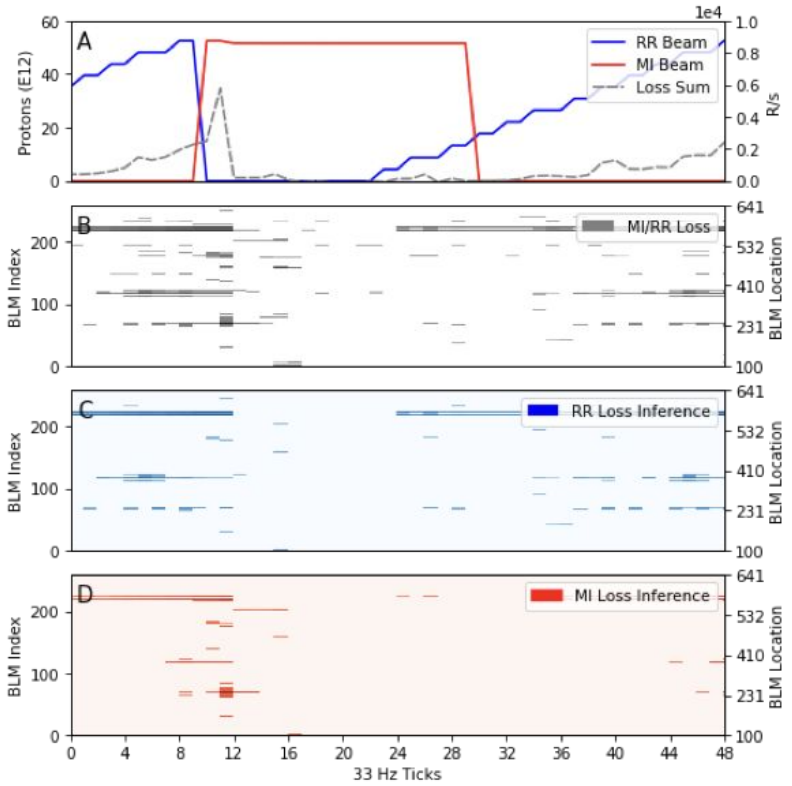
Real-time Main Injector and Recycler machine beam loss attribution using Machine Learning

Status

- Sample dataset collected year-round from machine operations and studies data (15-33 Hz)
- Various model architectures are under investigation.
  - Preliminary models have been trained from sample dataset
  - Many show great promise

FPGA-based VME bus reader cards (“Pirate Cards”) designed and manufactured to stream remote BLM readings at much higher rates.

  - Currently being tested
  - Will ultimately provide final training dataset
- Central real-time FPGA based inference node under development
- Published work progress at IPAC’21, paper MOPAB288



Example of preliminary model inference / beam loss attribution

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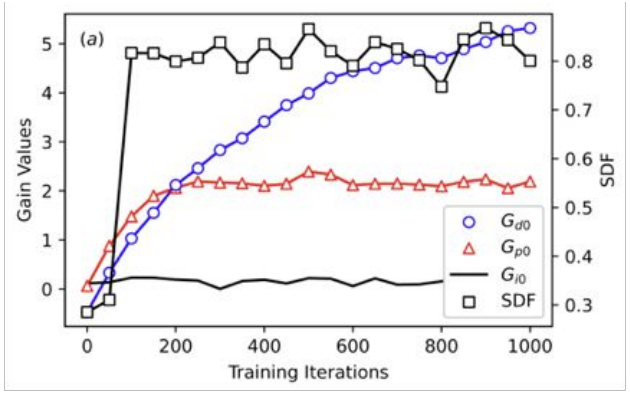
READS: Mu2e Slow Spill Regulation

Future Mu2e slow spill regulation using Machine Learning

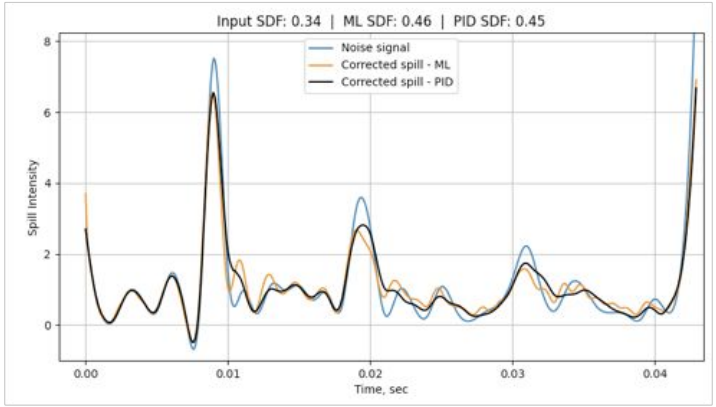
Status

- Using differentiable slow spill simulation code to generate simulated extractions and corrections
- Have explored two ML regulation schemes
  - PID gain optimization using ML
    - Preliminary model converges on optimal PID gain values
    - Consistently achieves high spill duty factors in simulation
  - Direct ML regulation
    - Preliminary model ingests last n corrected spill observations and generates the next correction
    - Currently performs on-par with standard PID method

Published work progress at IPAC'21, paper THPAB243



PID gain optimization: Evolution of PID gains during training



Direct ML regulation: Optimized PID regulation vs ML regulator

Fermilab

Thank You!