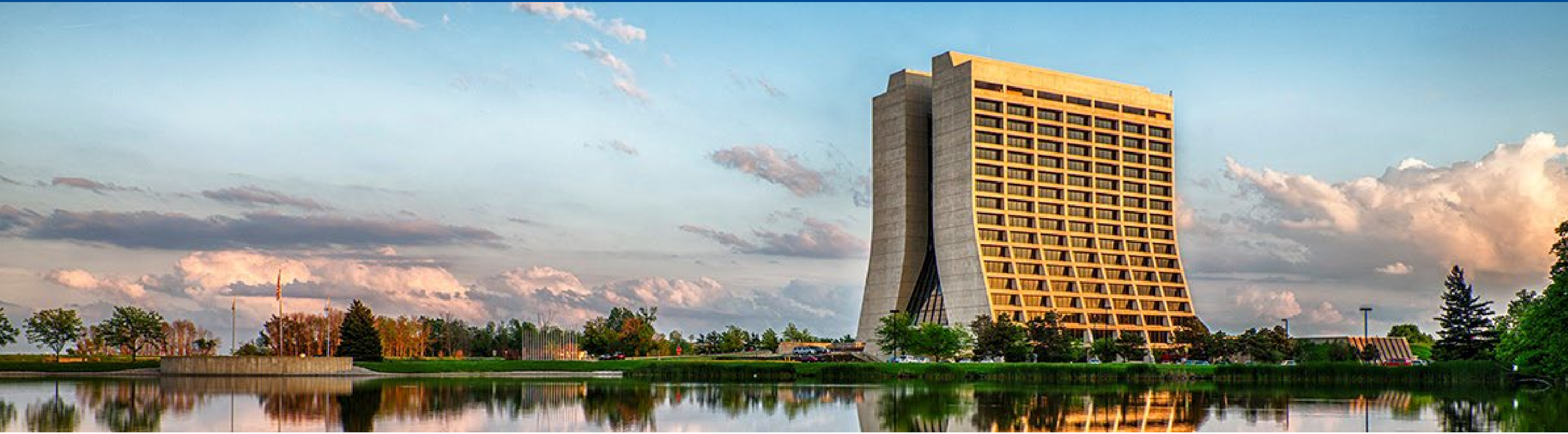
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science



The Fermilab Accelerator Complex

Robert Zwaska, Fermilab

Muon Collider Accelerator School, 2025

6 August 2025

Summary

- Fermilab Accelerators have run for decades and are now at a turning point
  - Decades-long plans are being put into action
  - New Challenges and opportunities emerge on an almost daily basis

- The Long Shutdown is approaching in ~ 2027
  - Install LBNF & PIP-II
  - Retire Linac & NuMI
  - Integrate improvements to the complex: ACE-MIRT, AIPs, UIP, ACORN

- Planning for the Future
  - R&D into accelerator physics and technology
  - Complex upgrades for new experiments, and perhaps a collider

Fermilab at a Glance

- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

As Fermilab moves into its second 50 years, its vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

The Fermilab research community

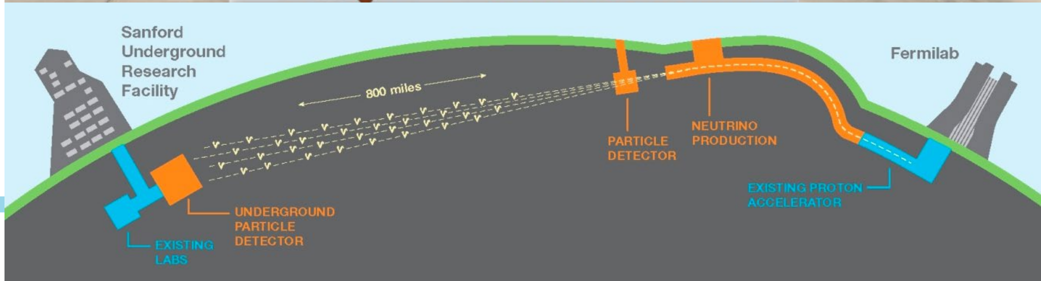
- More than 4,000 scientists in 55 countries use Fermilab and its particle accelerators, detectors and computers for their research
- More than 2,200 scientists from 175 U.S. universities and labs in 41 states
- Fermilab is attracting and training the next generation of a diverse HEP scientific workforce: 114 postdocs, 273 graduate students, 52 undergraduate interns
- Fermilab scientists also work at CERN, Sanford Underground Research Facility (SURF), SNOLAB, Cerro Tololo Inter-American Observatory, South Pole Telescope, NOvA Ash River Laboratory, Matter-wave Atomic Gradiometer Interferometric Sensor

Fermilab follows the P5 strategy

- The flagship projects LBNF/DUNE/PIP-II, HL-LHC anchor the program and will take many years to realize
- Fermilab simultaneously pursues a broad research effort in HEP
- The goal is a continuous stream of exciting results that attract/build/retain a diverse user community and scientific workforce

Exploring the Quantum Universe

2014 → 2023



Fermilab Accelerator Complex

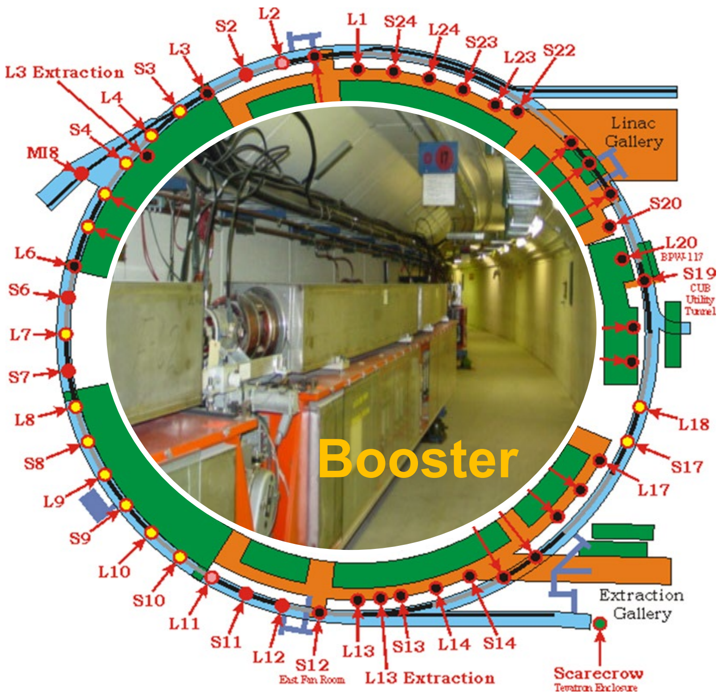
The Fermilab Linac

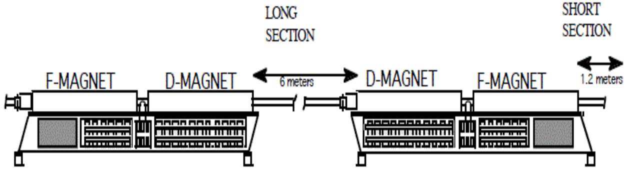
- Linear (copper) Accelerator
- Accelerates H^- ions
  - 750 keV → 400 MeV
    - Thousands to millions of volts
- Beam bunched at 200 MHz
  - ~ 1.5 Billion ions / bunch
- RF of 200 & 800 MHz
  - Distance between drift tubes changes with beam velocity
- Pulse length of ~ 80 μs
  - Many particles for short periods of time – more efficient operation
- To be retired Jan. 2028

Booster Overview

- H^- ions stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 msec
- Fast cycling synchrotron
  - Fast magnet ramping
  - Frequency of 15 Hz
- Single turn extraction
- Many pulsed devices requiring upgrade

Booster	
Circumference (m)	474
Harmonic Number	84
Kinetic Energy (GeV)	0.4 - 8
Momentum (GeV/c)	0.954 - 8.9
Revolution period (μsec)	$\tau_{(inj)}$ 2.77 – $\tau_{(ext)}$ 1.57
Frequency (MHz)	37.9 - 52.8
Batch size	4.5 E12
Focussing period	FDooDFo (24 total)





Combined Function Magnets

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Main Injector & Recycler

Main Injector: 120 GeV Fast-cycling synchrotron

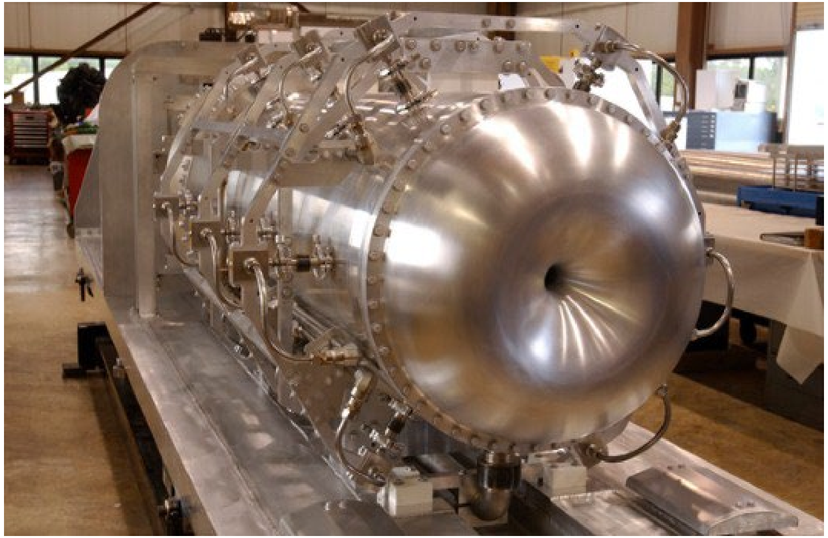
- 360 main dipole magnets
- 200 main quadrupole magnets
- 108 sextupoles, 66 octupoles, corrector dipoles/ qua extraction magnets
- Twenty 53-MHz RF cavities to accelerate beam
- 170 DC and 360 ramped magnet supplies with total pulsed magnet supplies

Recycler: 8 GeV Storage Ring

- Originally built for antiproton storage, repurposed for
- Combined function, permanent magnets
- RF cavities for stacking proton beams

Booster Neutrino Beam (BNB)

- Uses 8 GeV beam from the Fermilab Booster, operating since 2002
  - Up to ~ 30 kW of beam (5e12 ppp)
- Beryllium target integrated with single focusing horn
- Services a suite of experiments at Fermilab: the Short Baseline Neutrino (SBN) program
- BNB capability with PIP-II will be preserved after the long shutdown



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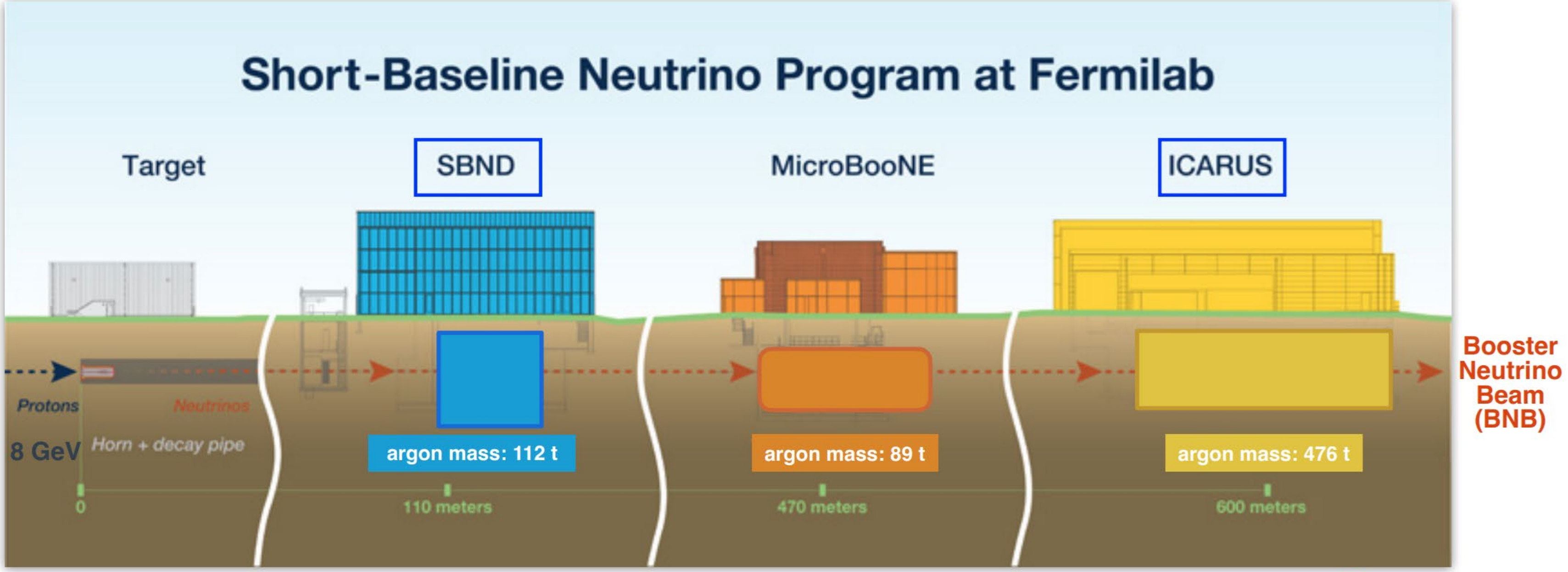
SBN Program



2015-2021
Large production of scientific results

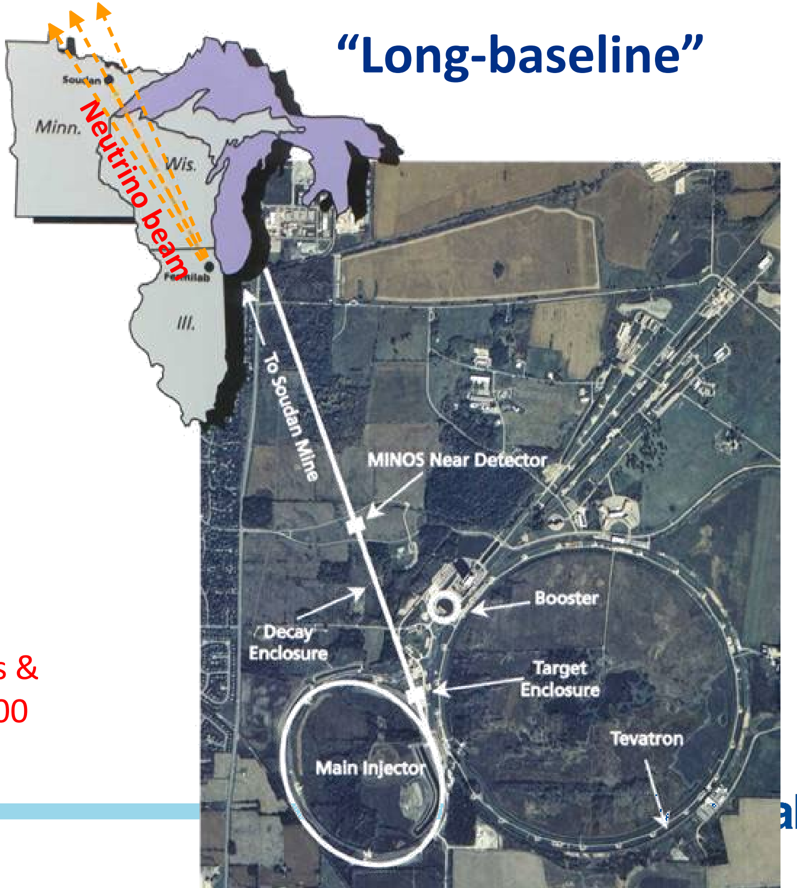
Beam composition:
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
$\nu_e + \bar{\nu}_e$ (0.5%)

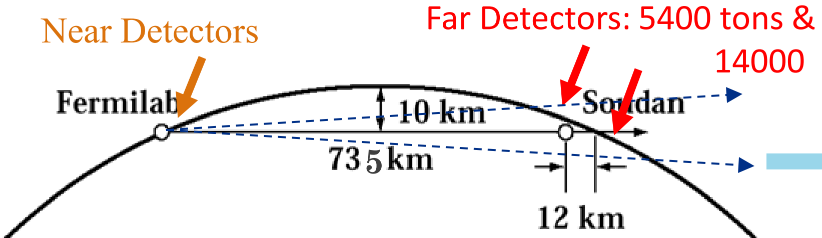
Mean ν_μ energy: ~0.8 GeV

The NuMI Facility: "Neutrinos (ν –> Nu) at the Main Injector"

- Intense muon-neutrino beam directed towards Minnesota
- Main Injector supplies 50–70e12 120GeV protons every 1.2 seconds
  - Designed for 400 kW, operated up to 900 kW
  - Multiple upgrade projects to 1 MW
- Each pulse produces about 2×10^{14} ν_{μ}
  - ~ 20,000,000 Pulses per year
  - Direct beam 3° down
- Commissioned in 2005, expect to run to ~ 2027

"Long-baseline"

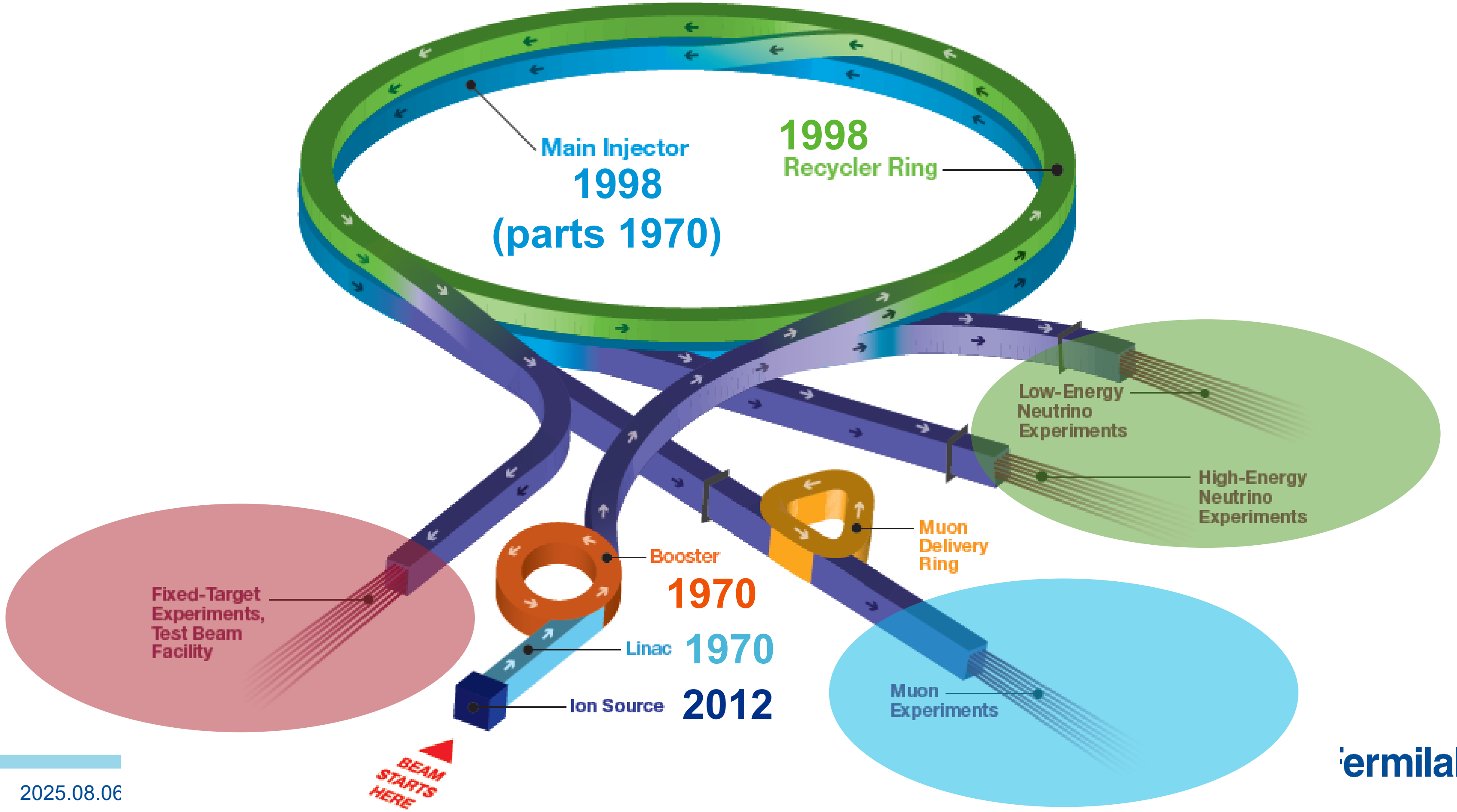




Mu2e: Muon to Electron Conversion Experiment

- Two transport solenoids were installed into the Mu2e experimental hall
  - Production Solenoid just installed
- Beamline has been commissioning
  - Electrostatic septa built & installed
  - AC Dipoles ready to commission
  - Goals for 2026:
    - Establish efficiency slow extraction
    - Develop extinction methods
  - Considering options for upgraded targets
- Plan to have a 6-9 month physics run before the long shutdown

Fermilab Accelerator Complex – National Users Facility



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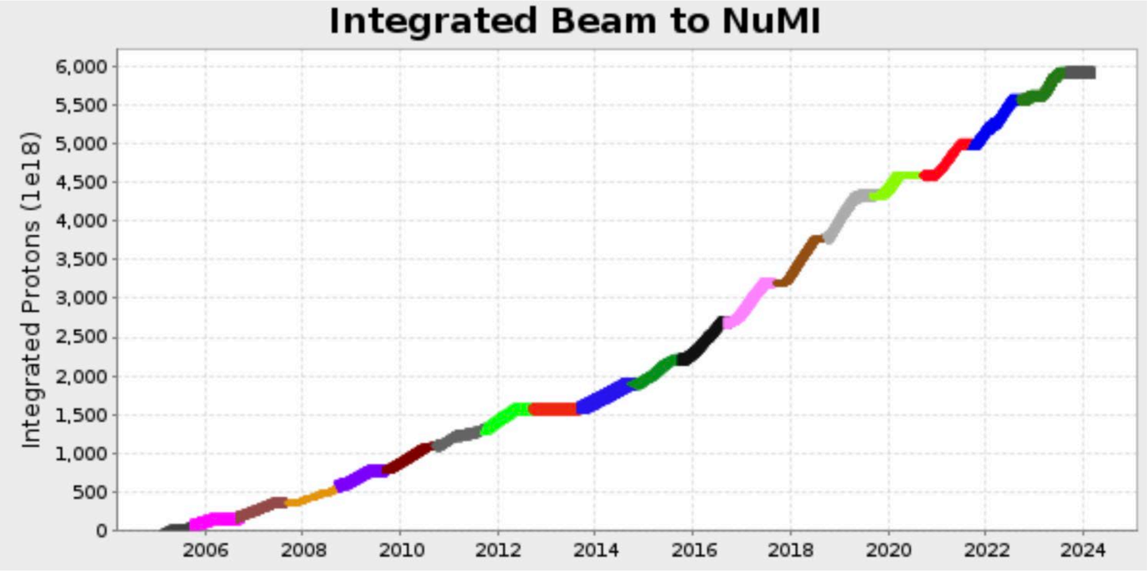
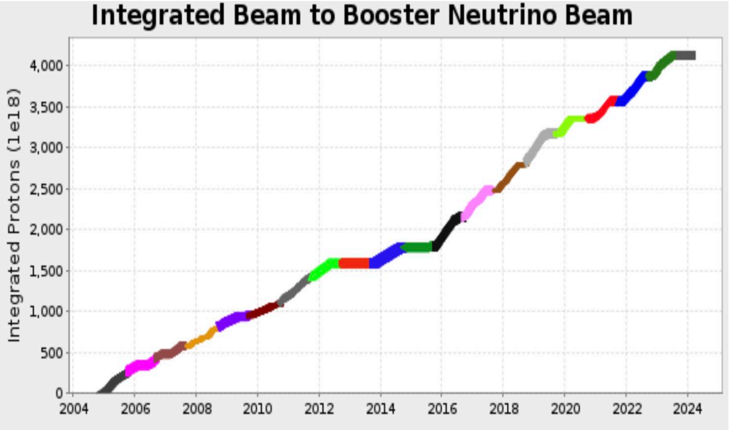
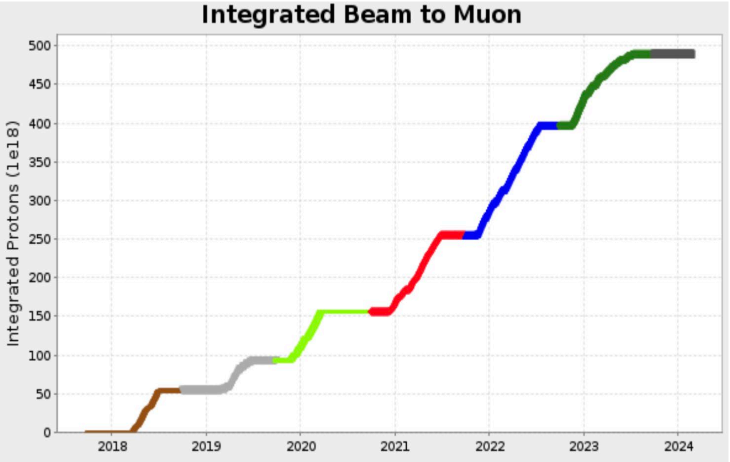
Accelerator Complex function - beam delivery to science users

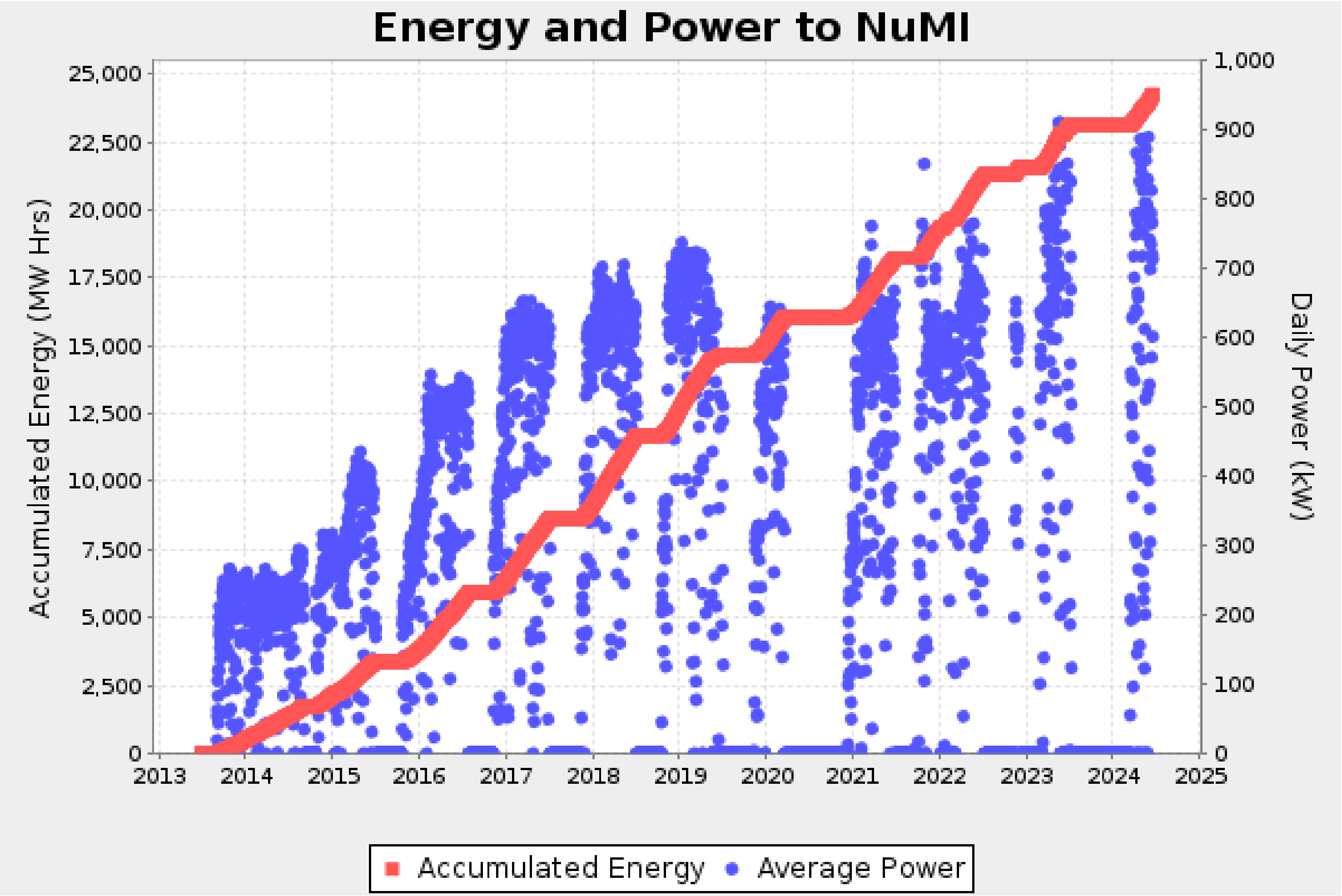






Protons-On-Target ∝ Power × Runtime × Uptime

Multiple experiments operate concurrently



Energy and Power to NuMI
Accumulated Energy (MW Hrs)
25,000
22,500
20,000
17,500
15,000
12,500
10,000
7,500
5,000
2,500
0
Daily Power (kW)
1,000
900
800
700
600
500
400
300
200
100
0
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Accumulated Energy
Average Power

NuMI Beam Power Evolution

- Started at 250 kW in the Tevatron operation
  - Increased to 400 kW with Slip Stacking

- NOVA / ANU upgrades incorporated Recycler to allow 700 kW beam

- Proton Improvement Plan (PIP) increased reliability and capability
  - Allowed BNB and Muon to operate simultaneously with NOvA @ 700 kW
  - True Booster pulsing of 15 Hz

- Intensity increases and MI ramp tweaks pushed towards 1 MW
  - Needed a target station capable

NuMI Megawatt Accelerator Improvement Project (AIP): 2018-2021

- Originally designed for 400 kW beam power, then upgraded to 700 kW with NOvA/ANU
- Megawatt AIP (Accelerator Improvement Project)
  - Upgrade of target, horns, and supporting systems to be capable of accepting 1 MW beam power through 2025
  - Completed in 2021 after 3 annual accelerator shutdowns to replace components

	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		

NuMI Target Systems Accelerator Improvement Plan (AIP): Target Station Upgraded for 1-MW Beam Operation

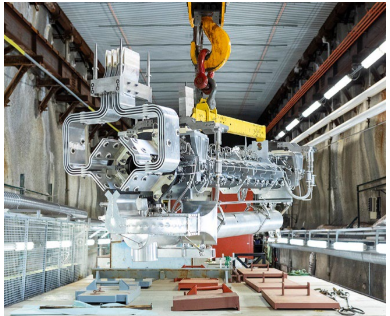
Objective reached: capable of accepting 6.5E13 protons/spill at 120 GeV, 1.2 sec cycle time

Project scope: improve and replace Target Hall components / support systems

Tasks completed in 2019 – 2022

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

NuMI Team



1-MW Horn-1 Installation

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1 MW Test Run: June 26, 2024

- AD was granted an 8-hr window for up to 4-hr of running exceeding One Megawatt
- Summer temperatures necessitated work during a cool and calm period
  - 4am June 26 was chosen, with June 27 as backup
- Individual machines pushed their capabilities to near-MW the few days before
- Full operations & machine teams reported at 4am along with technical department personnel at the appropriate locations
  - Security opened the East Gate early for this occasion
- At 6:53 machine conditions stabilized to allow 1 MW running, so the 4-hr period started at 5:53 am
  - Improvements were made over the next few hours and **1.018 MW** (1-hr average) was achieved at 8:21 am.
  - BNB ran at full intensity in this period. Experiment concluded at 9:30 am
- Much was learned from the run in terms of machine tuning and vulnerabilities.

1.018 MW

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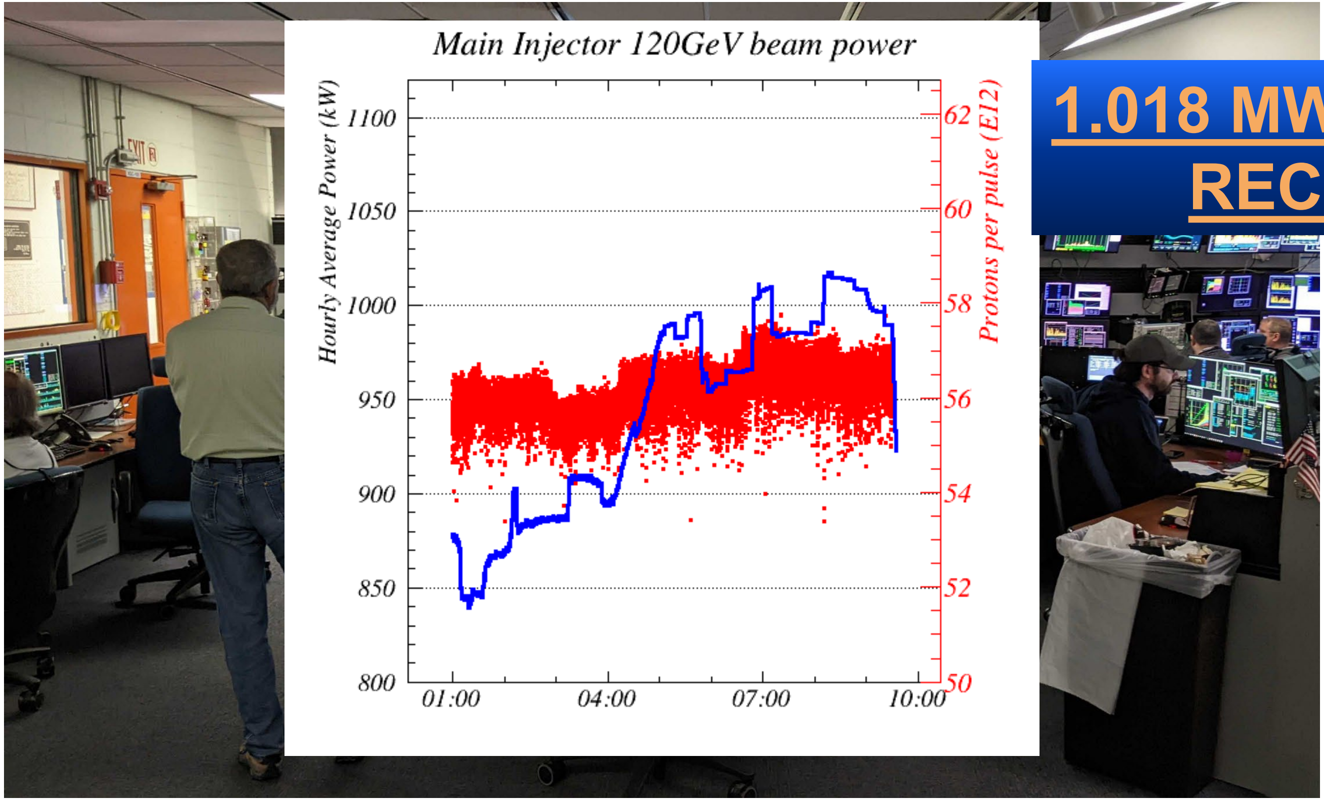
1.018 MW



1.018 MW POWER RECORD

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Fixed Target

- Original experimental purpose of Fermilab
- Beam directed onto stationary targets
- Results in a large shower of particles, useful for making beams of unstable particles
- Can give a very large number of interactions
- Resulted in the discover of the Upsilon and tau neutrinos, ampng many other results

PBar – the Antiproton Source

- 120 GeV protons impact a Ni target
  - ~ 1.6 x 10^{-5} usable antiprotons per proton
- Debuncher ring captures and cools antiprotons
  - Takes ~ 2 seconds
  - Collects the 8 GeV antiprotons
- Accumulator ring stores and further cools antiprotons
  - Stores them for hours, or even days
- "Stack" of antiprotons can get as large as ~ 10^{13}
- Further stored in the Recycler and cooled with electrons
- Major goal at Fermilab for years was to maximize antiproton production

The Tevatron

- Highest-energy collider for ~ 20 years
  - Likely the last proton-antiproton collider
- Superconducting magnets
  - Cooled with Liquid He
  - Field of 5 Tesla
- Collides counter-rotating beams of protons and antiprotons in a single beam tube
  - CoM energy of 1.96 TeV
  - Significantly more than fixed target
- Produces most everything
  - All the quarks (inc. top)
  - Z, W, all the leptons
  - Even the Higgs

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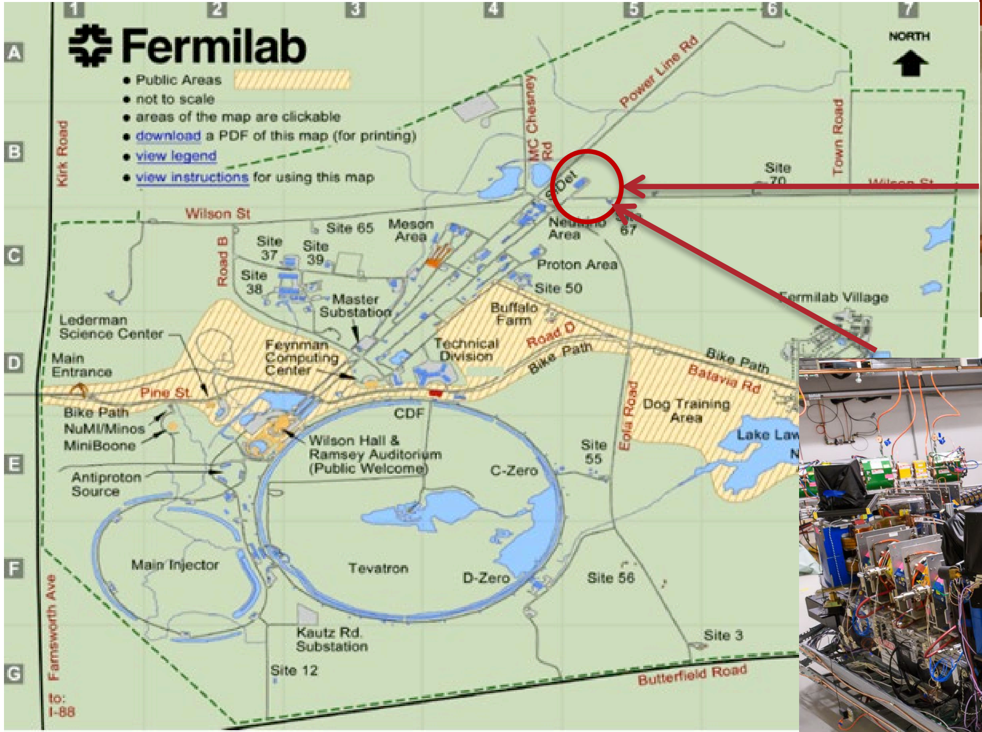
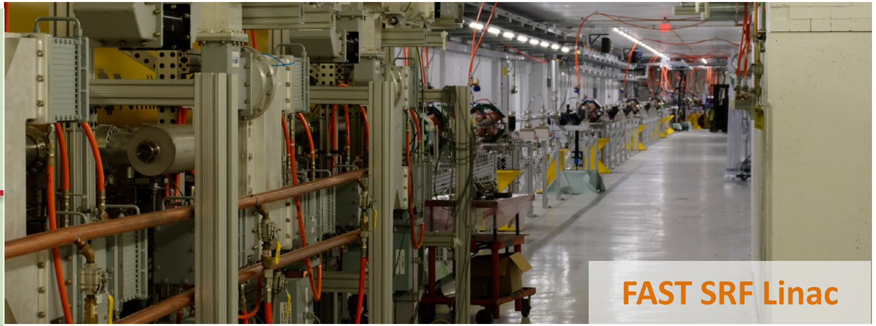
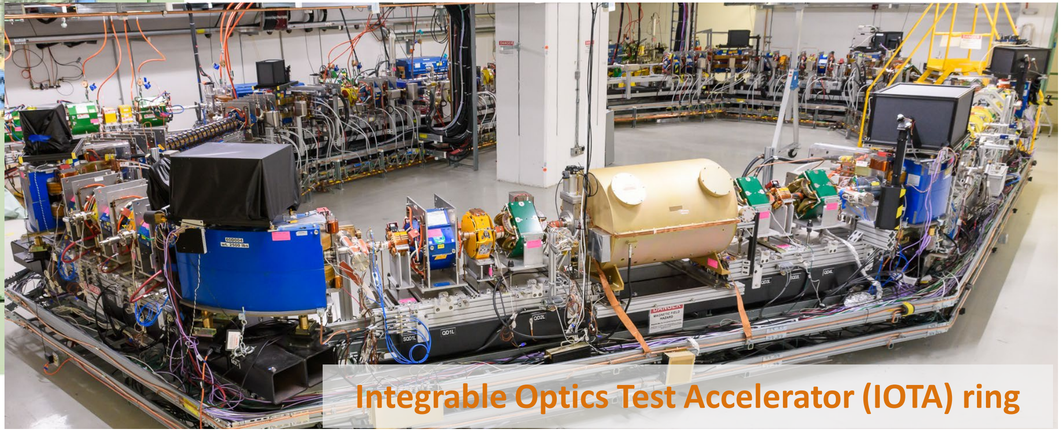
Fermilab Accelerator Science and Technology (FAST) facility



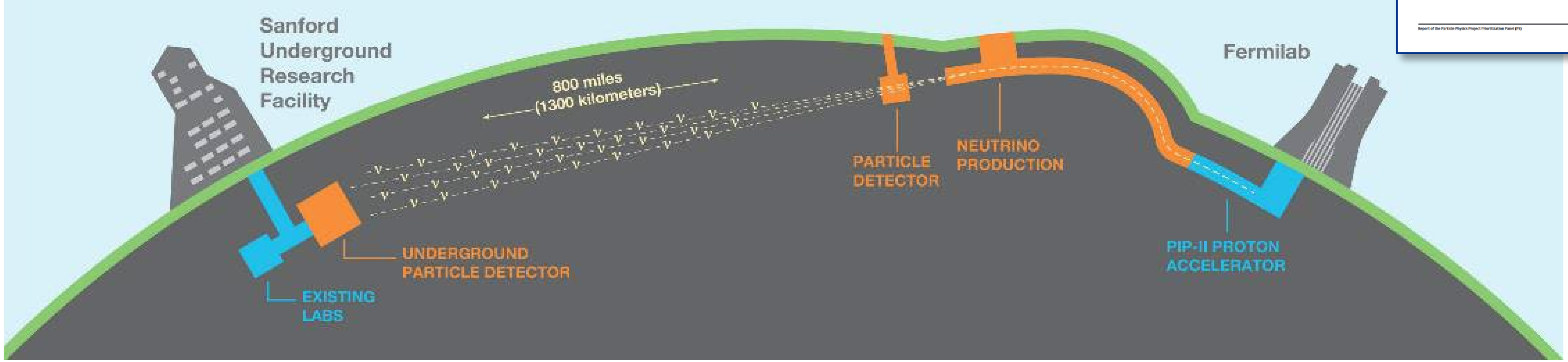


FAST SRF Linac



Integrable Optics Test Accelerator (IOTA) ring

Deep Underground Neutrino Experiment



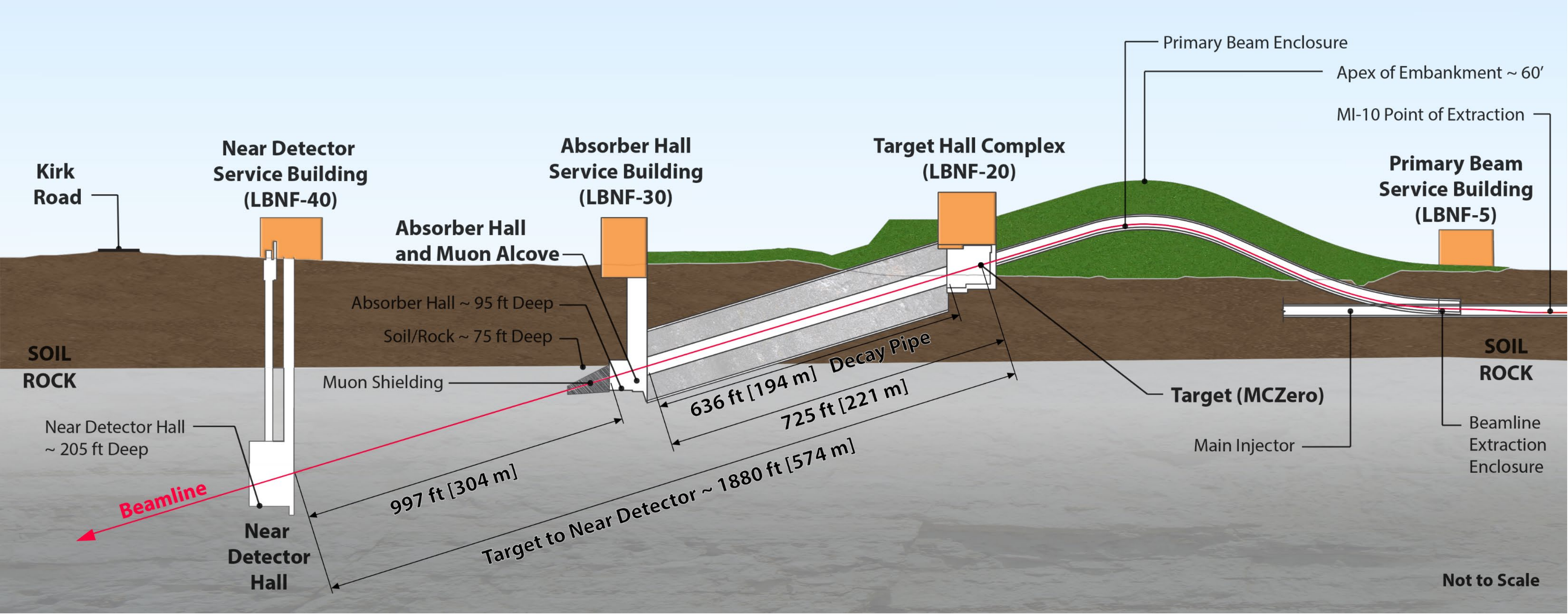
Origin of matter. Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?

Neutron star and black hole formation. Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.

Unification of forces. Investigate nucleon decay, advance unified theory of energy and matter.

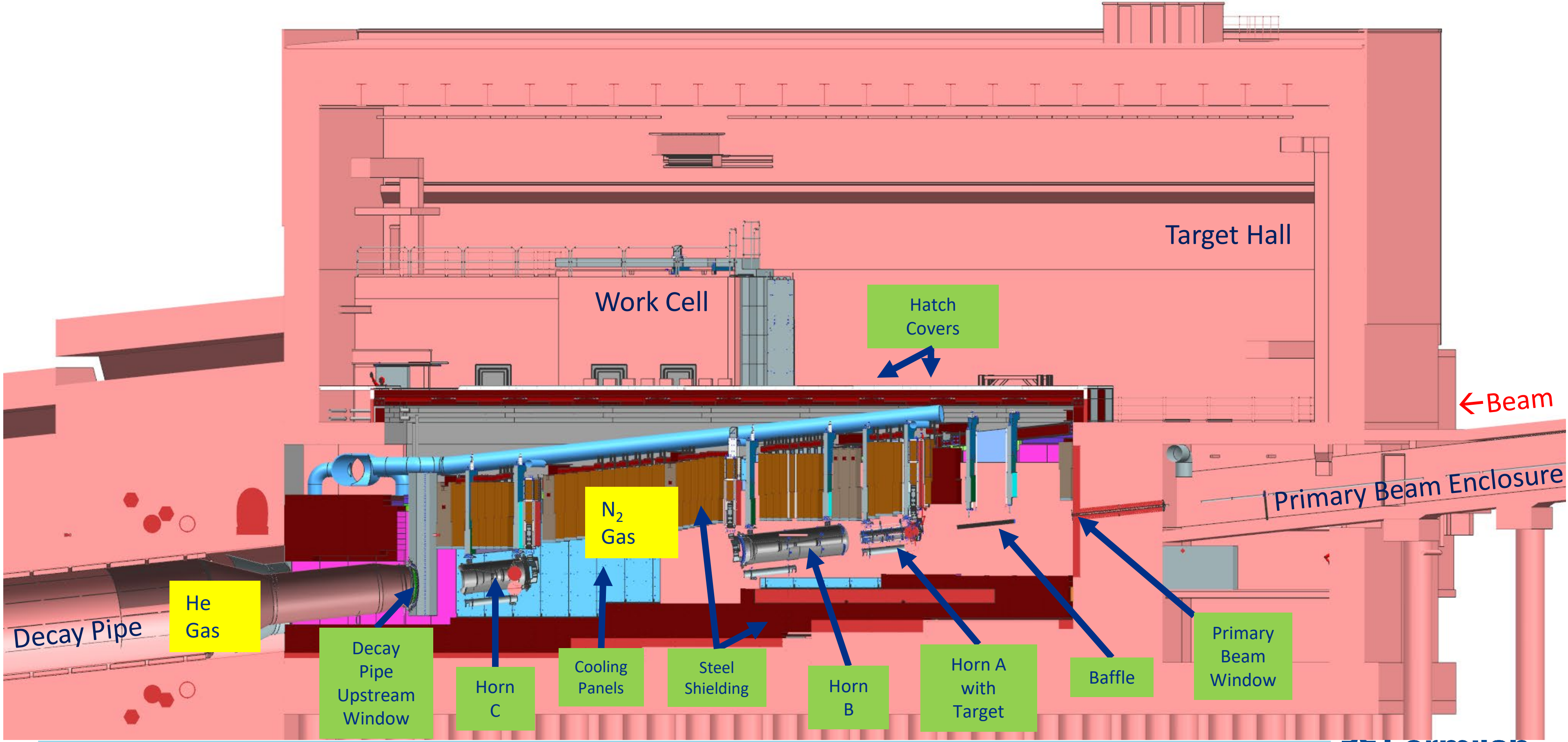
The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

The LBNF Beam



Facility designed for initial beam power of 1.2 MW, upgradeable to 2.4 MW

Section View of Target Complex – Target Hall



Proton Improvement Plan II (PIP-II)

- Increase Main Injector beam power to 1.2 MW.
  - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac => increase in Booster intensity.
    - Provide a platform to increase LBNF power to 2.4 MW
  - Provide path for a 100 kW Mu2e-II
  - Provide capability for 1.6 MW at 800 MeV, CW beam
  - Platform for high duty-factor / power operations to multiple experiments

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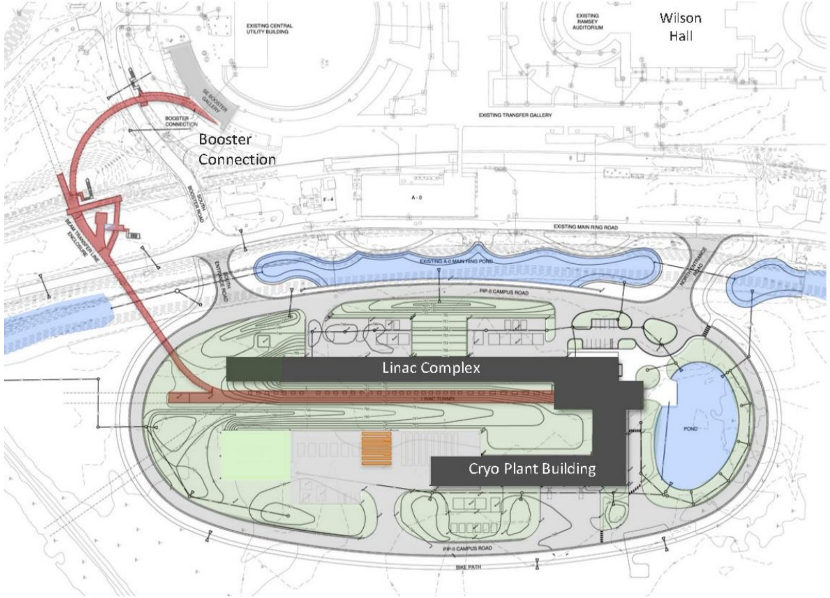
PIP-II Linac & Upgrades (1.2 MW power on target)



800 MeV H− linac
- Warm Front End
- SRF section

Linac-to-Booster transfer line
- 3-way beam split

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Conventional facilities
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

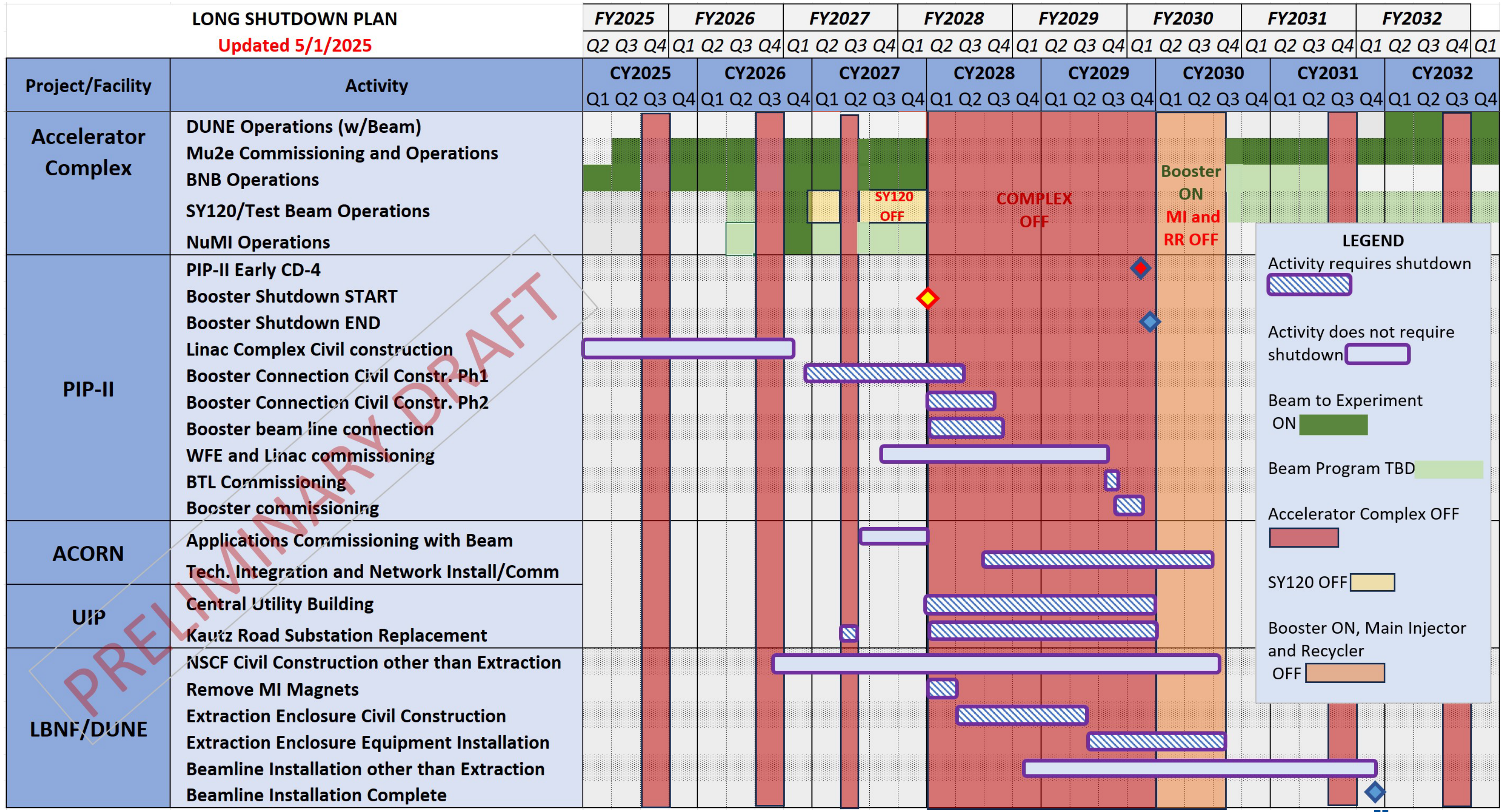
Project started in 2016 (CD-0)
First beam in Booster: 2029 (plan)
MI 1.2 MW beam on target: 2031 (plan)

PIP-II Project construction

- PIP-II received DOE CD-3 approval for start of construction/execution on April 18, 2023
  - Linac complex construction is actively underway
- Front end of PIP-II linac constructed and successfully tested with beam
- PIP-II cryoplant building complete
- Extensive in-kind and partner contributions arriving


PIP-II is the first particle accelerator built in the U.S. with significant international contributions

Mid-Term Accelerator Plans



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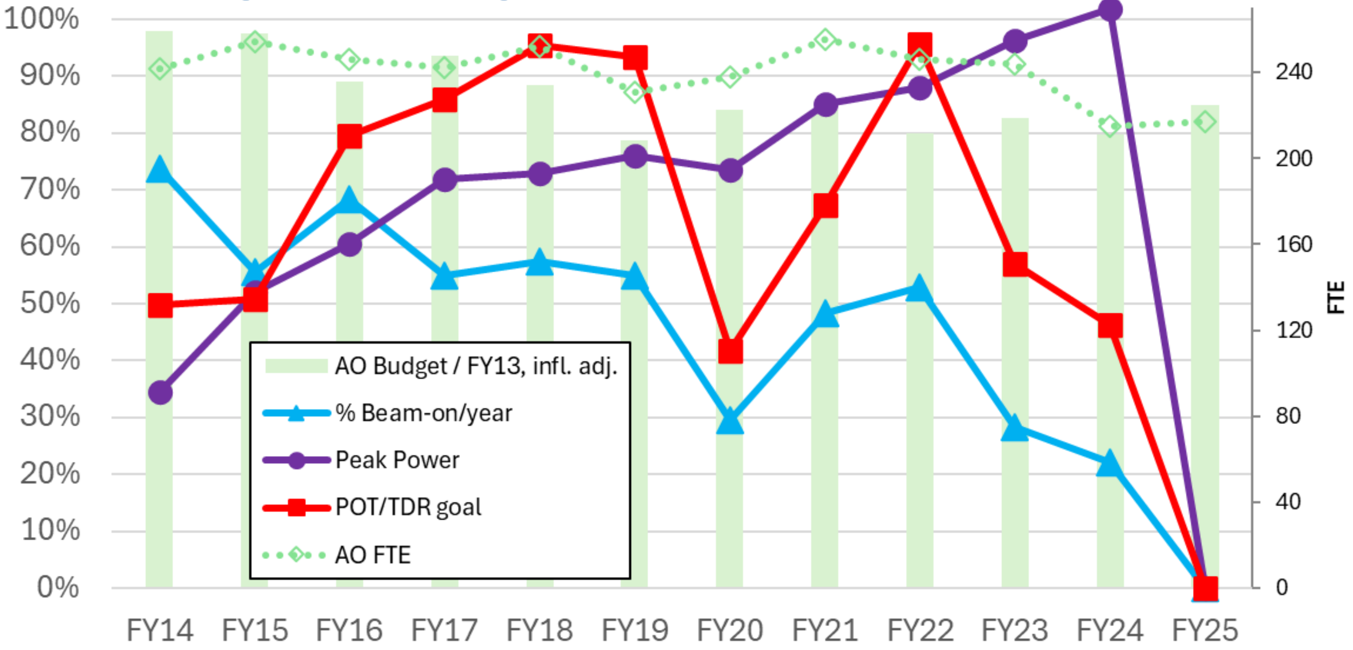
Lessons from long-term High-Power operations



- 2014-2019 investments in capability (PIP and operations investments) and strong Ops team enabled growth of peak power ×3 (0.3-1 MW)
- To realize full physics potential, sufficient run time allocation is essential
- Recent decrease in reliability is concerning

Physics output and Ops efficiency

Efficiency

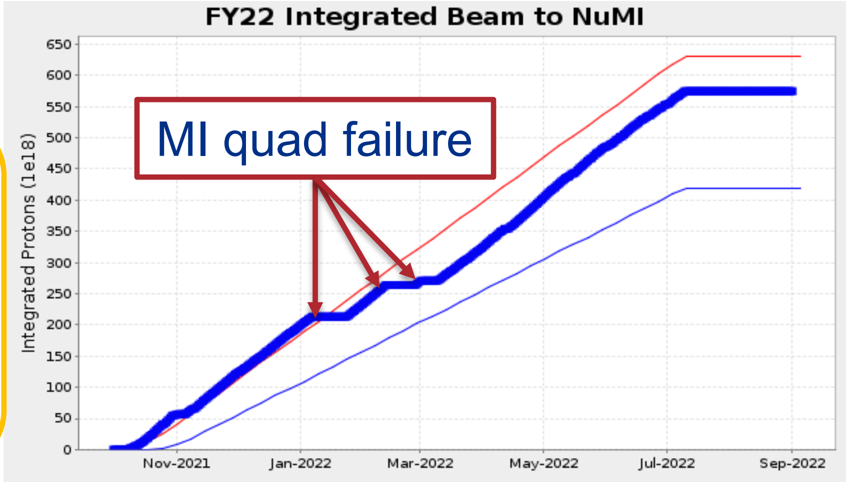
- Uptime = [run time]/[scheduled time]
  - FY22 69% ➜ 80% LBNF/DUNE
- Runtime = [scheduled time]/[CYear]
  - FY22 77% ➜ 80% LBNF/DUNE
- Sustained power fraction= <P>/Pmax
  - FY22 76% ➜ 90% LBNF/DUNE

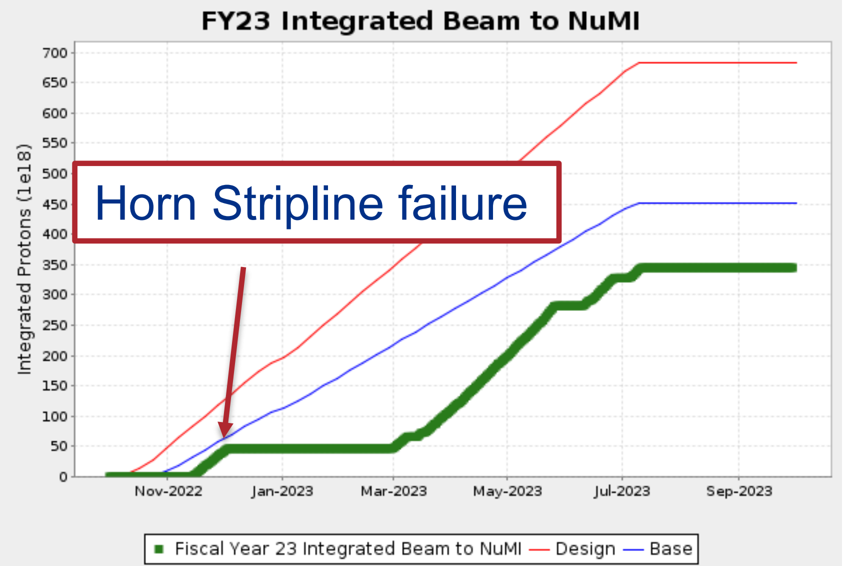
Capability

Machine capability Pmax

physics = **Pmax × Runtime × Uptime × Sustained power *f***

Investments in reliability and loss mitigation yield significant returns in physics, must be maintained over experiment run. **Present efficiency 40-45% ➜ >57% DUNE**





Accelerator Controls Operations Research Network (ACORN) Project

ACORN received CD-0 ESAAB approval Aug. 28, 2020. CD-1 expected in 2025.

- The Project will modernize the Fermilab's **accelerator control system** and replace end-of-life **accelerator power systems.**
- The control system and power systems are critical components needed to reliably accelerate beam from PIP-II through the entire accelerator chain and deliver it to LBNF/DUNE.
- The Fermilab Accelerator Advisory Committee summarized their findings in Dec. 2018:

> *The existing lab-wide accelerator control system has aging and heterogeneous front-end hardware, multiple different frameworks and network protocols, 1980s era network services and a collection of generic functionalities. The top level is a mix of high-level software some of which is using obsolete frameworks. Recent targeted modernization has included rather specific, targeted initiatives.*
>
> *Major issues include: lots of old hardware; lots of old software, and an aging and declining in strength work force (no software development related hires since 2001 for instance).*

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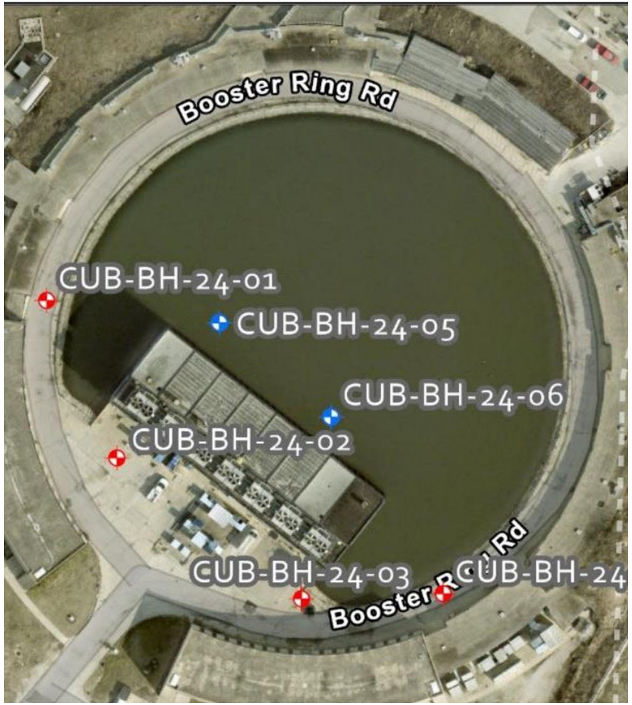
UIP: Utilities Infrastructure Project

- SLI Project
  - Science Laboratories Infrastructure
- Rebuild the Central Utilities Building
- Modernize the Kautz Road Substation
  - Master Substation was rebuilt ~ 10 years ago
- Addresses a subset infrastructure issues
- Expect CD-1 within the next few months
- To be completed during PIP-II / LBNF Shutdown

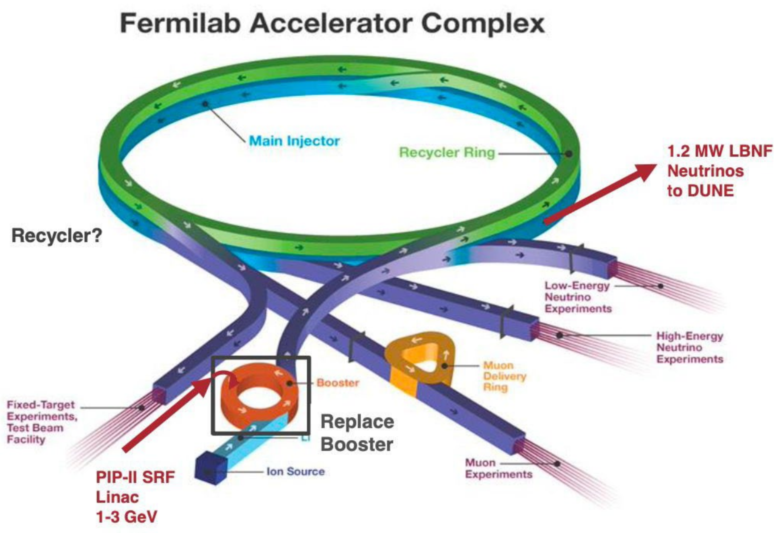


Replacing the Booster

- 2014 P5 Recommendation: Provide 2.4 MW to DUNE
  - Now ~ 0.9 MW max
  - With PIP-II can reach ~ 1.2 MW
  - Main bottleneck is the Booster synchrotron
  - Intensity can be improved but not enough to reach 2.4 MW

- Many studies, going back almost 25 years.

- 2023 P5 Recommendation: accelerate realization of 2+ MW with "MIRT"
  - Plan for future complex evolution, NOT replacing the Booster (at first)



In 2008, Project X: 8 GeV SRF Linac, directly into Main Injector.

In 2010, Project X ICD-2: 2 GeV Linac, New 2-8 GeV RCS.

In 2018, S. Nagaitsev and V. Lebedev: updated version of ICD-2.

In 2019, J. Eldred, V. Lebedev, A. Valishev: parametric study of RCS design.

In 2021, Committee for Fermilab Booster Upgrade an integrated design effort:

Science Working Group chaired by R. Harnik
"Physics Opportunities for the Fermilab Booster Replacement"

Accelerator Working Group chaired by M. Syphers
"An Upgrade Path for the Fermilab Accelerator Complex" (RCS Scenario)
"An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade"

ACE-MIRT scope to enable 2+ MW
Accelerator Complex Evolution

This component of ACE plan aims to develop the Fermilab accelerator complex capabilities beyond PIP-II, *without new accelerator construction.*

Overall efficiency and reliability of operations

- Implement improvements aiming to reduce losses, radioactive activation

Task 1) Improve MI reliability by replacing quadrupole magnets with robust design

Machine capability: Maximum proton flux produced by the accelerator

Task 2) Upgrade MI ramp power system to enable faster cycle time (1.2→0.6s)

Task 3) Upgrade MI RF acceleration system to allow for more beam flux

Ability of target station to convert protons to neutrinos

Task 4) Upgrade LBNF Target and Horns to reliable 2+ MW capability

Accelerator Complex Evolution (ACE) plan – beyond 1.2 MW

Our vision is centered on the ACE plan that has two components

2+ MW

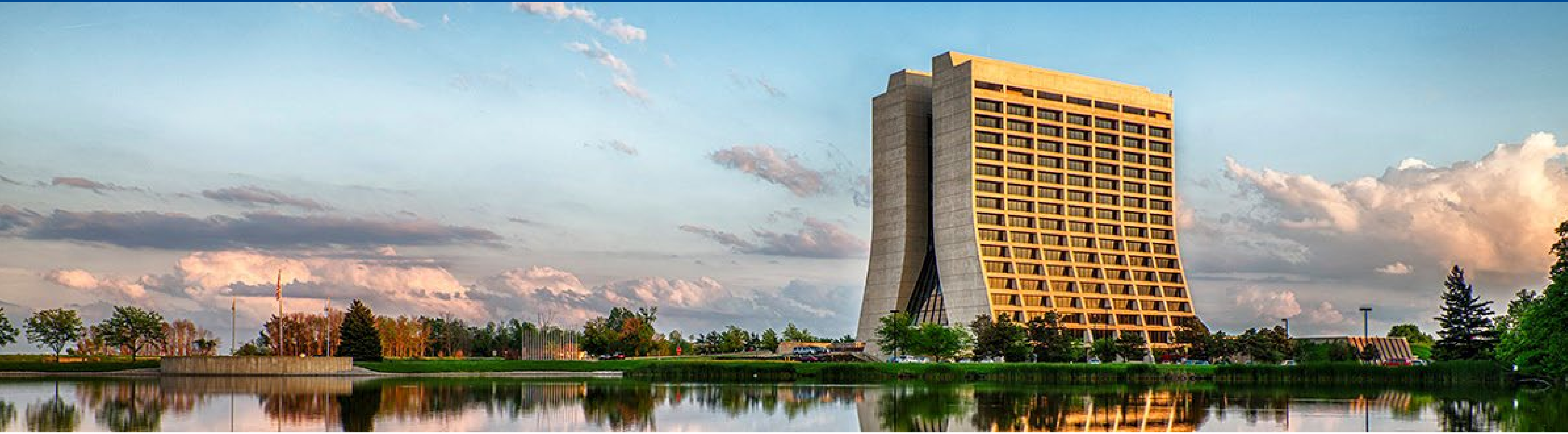
1. The Main Injector reliability improvements, cycle time shortening, and target systems upgrade to be carried out through the 2020's called **ACE-MIRT – without construction of new machines after PIP-II**
   - Will accelerate the achievement of the DUNE science goals with respect to the original PIP-II plan
   - Improve reliability and safety of the key machines for the future of accelerator complex

Multi-MW

2. Further, design a Next Accelerator Upgrade that builds upon the existing complex and enables Muon Collider R&D, and potentially a path to the collider
   - Enables the next set of experiments (beyond DUNE and Mu2e)
   - Capability of Muon Collider R&D, including a demonstrator facility
   - **Provide a robust and reliable platform for the future evolution of the Fermilab accelerator complex**

Summary

- Fermilab accelerator operations continues to enable the particle physics mission by delivering proton beams to science users
- The accelerator complex is transitioning from steady-state operations to integrating the PIP-II upgrade in preparation for the DUNE experiment
- Campaign of upgrades, modernization, and investments into for making the machines of accelerator complex compatible with PIP-II
  - Infrastructure projects, modernization (UIP, ACORN)
  - ACE-MIRT program
- Planning for future opportunities
  - New facilities and experiments with PIP-II
  - Continuing Accelerator Complex Evolution
  - Test Facilities and Demonstrators for future machines



The Fermilab Accelerator Complex

Robert Zwaska, Fermilab

Muon Collider Accelerator School, 2025

6 August 2025