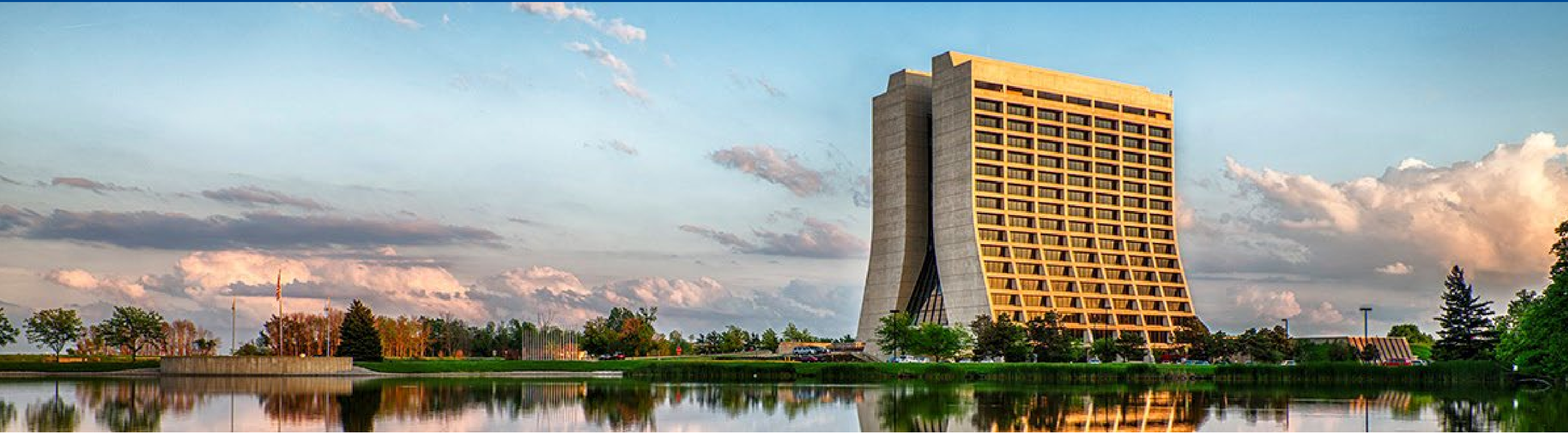


Fermilab Accelerator Plans and Schedule

Robert Zwaska, for the Fermilab Accelerator Directorate
NuFact 2024
18 September 2024

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

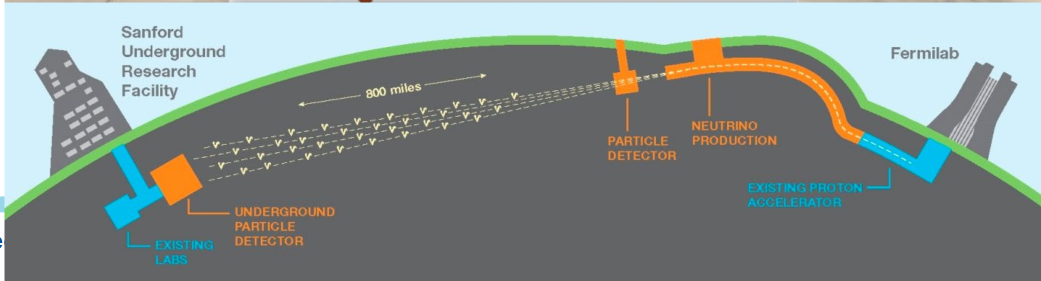
- Until 2027:
  - Continue to deliver to present and new experiments
    - NOvA, SBND, ICARUS, 2x2, ANNIE, Mu2e, Spinquest, MTA/ITA, FTBF, …

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

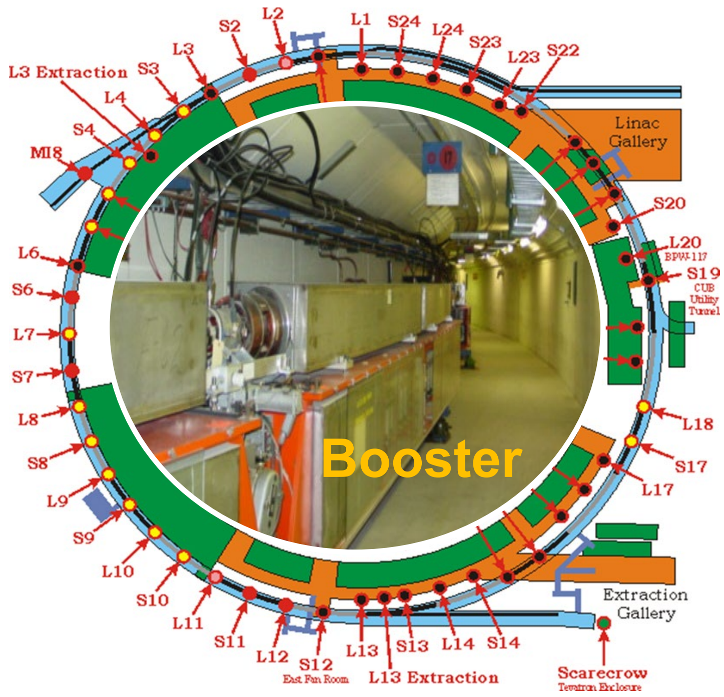
The Fermilab Linac

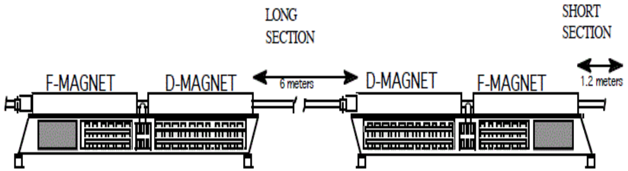
- Linear (copper) Accelerator
- Accelerates H^- ions
  - 750 keV → 400 MeV
    - Thousands to millions of volts
- Beam bunched at 200 MHz
  - ~ 1.5 Billion ions / bunch
- RF of 200 & 800 MHz
  - Distance between drift tubes changes with beam velocity
- Pulse length of ~ 80 μs
  - Many particles for short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

Fermilab

Main Injector & Recycler

Main Injector: 120 GeV Fast-cycling synchrotron

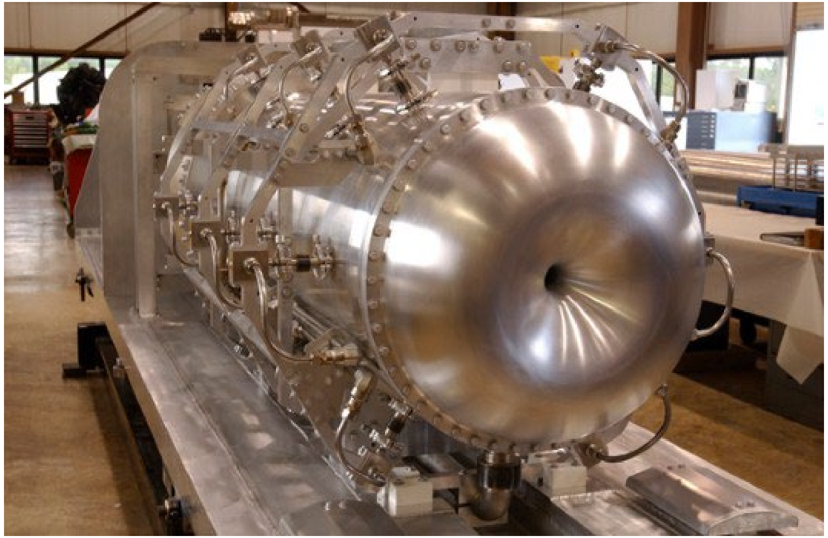
- 360 main dipole magnets
- 200 main quadrupole magnets
- 108 sextupoles, 66 octupoles, corrector dipoles/ qua extraction magnets
- Twenty 53-MHz RF cavities to accelerate beam
- 170 DC and 360 ramped magnet supplies with total pulsed magnet supplies

Recycler: 8 GeV Storage Ring

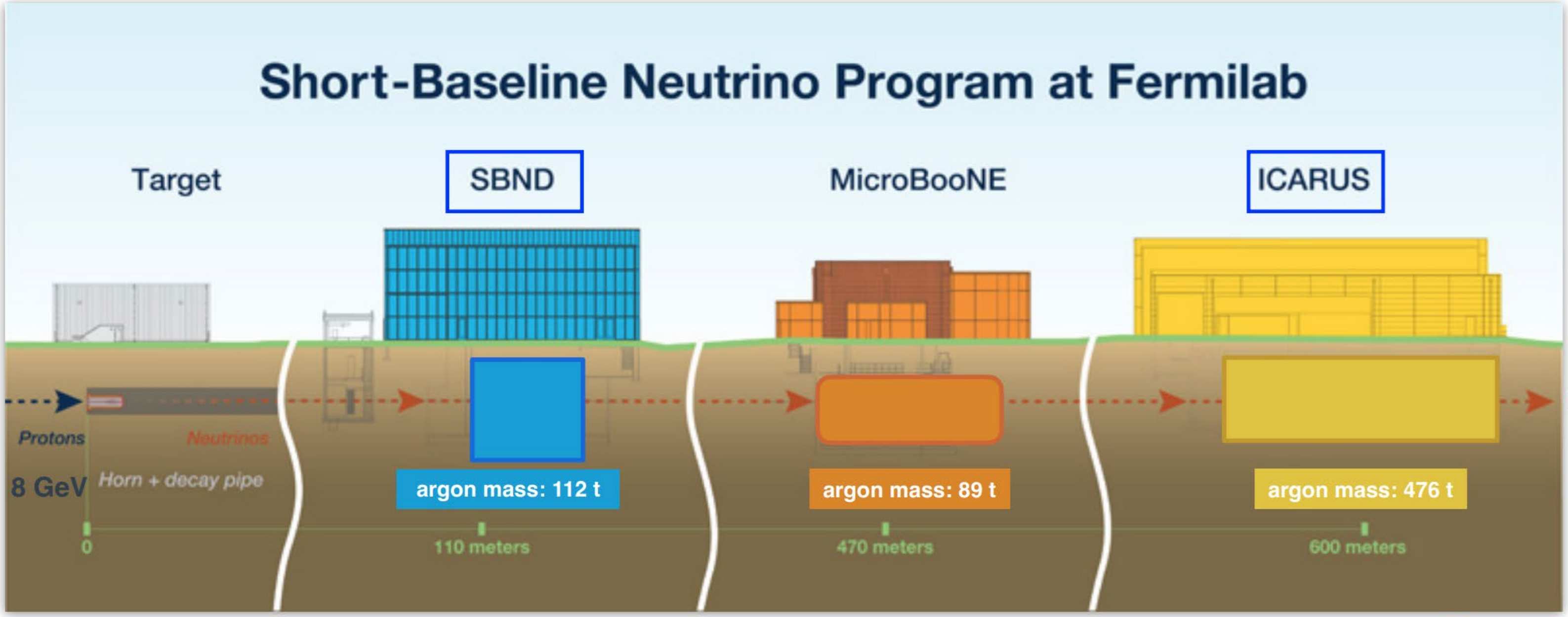
- Originally built for antiproton storage, repurposed for
- Combined function, permanent magnets
- RF cavities for stacking proton beams

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



SBN Program



Booster Neutrino Beam (BNB)

2015-2021
Large production of scientific results

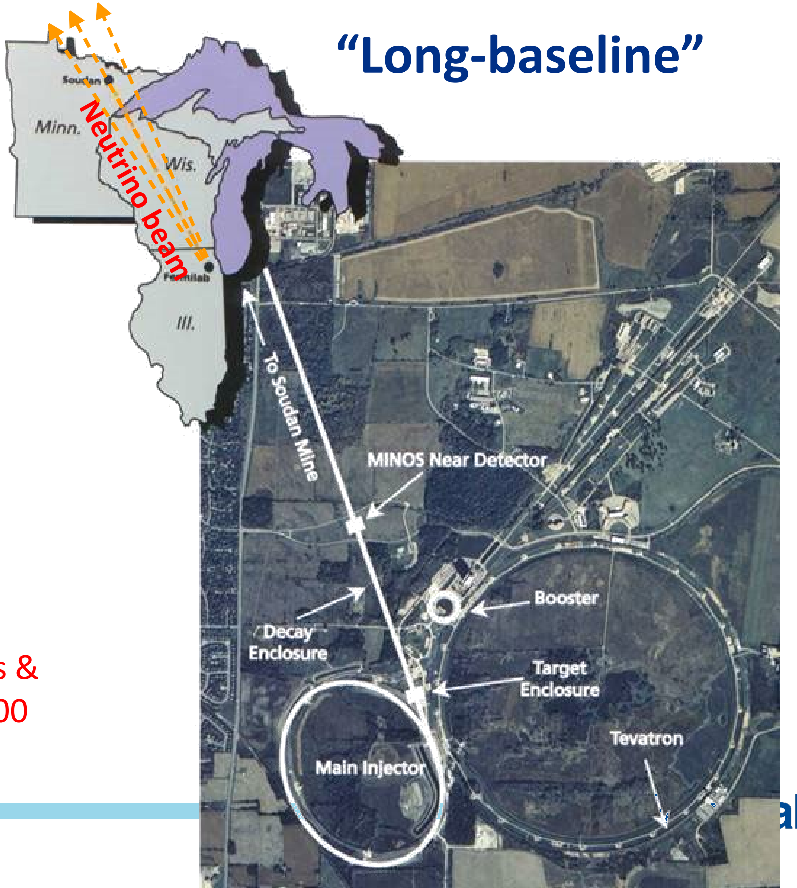
Beam composition:
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.9%)
$\nu_e+\bar{\nu}_e$ (0.5%)

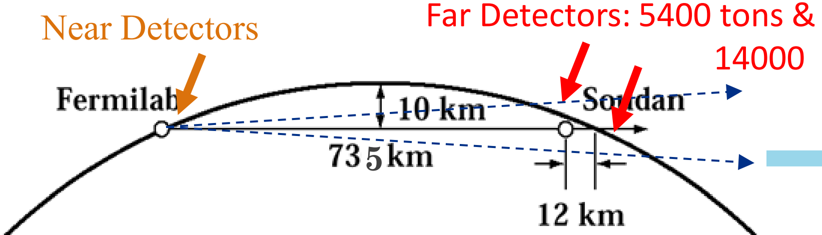
Mean ν_μ energy: ~0.8 GeV

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 $2x10^{14}$ ν_{μ}
  - ~ 20,000,000 Pulses per year
  - Direct beam 3° down
- Commissioned in 2005, expect to run to ~ 2027

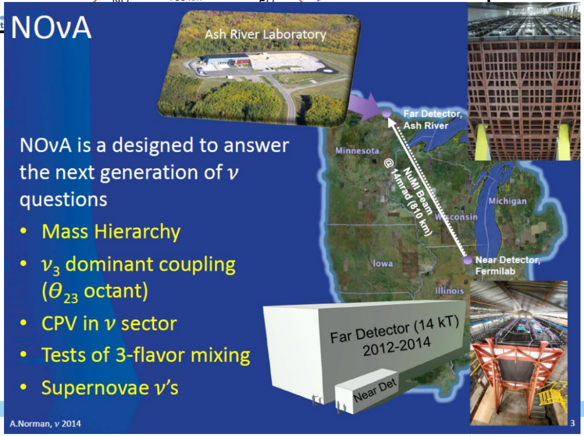
"Long-baseline"



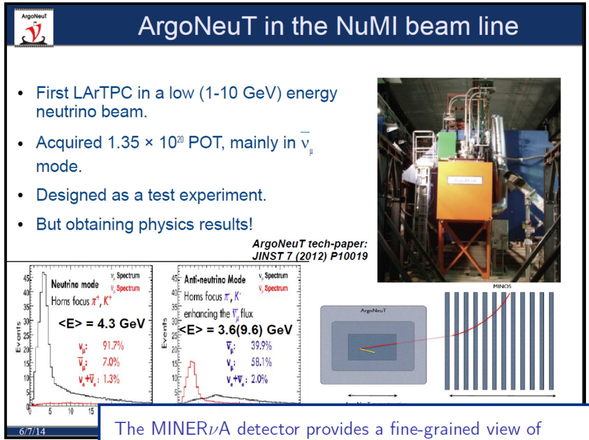


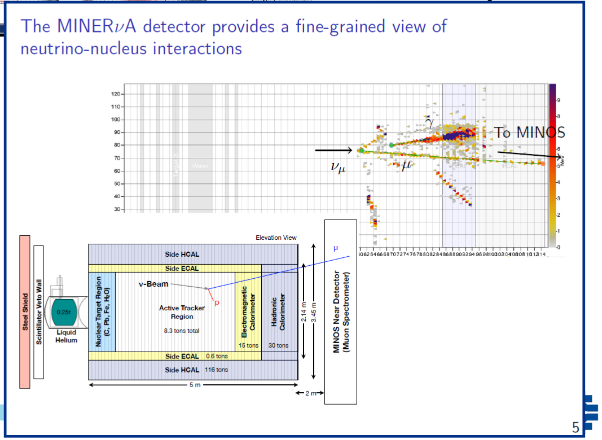
Multiple Experiments Simultaneously in the NuMI Beam

Long-baseline oscillation experiments



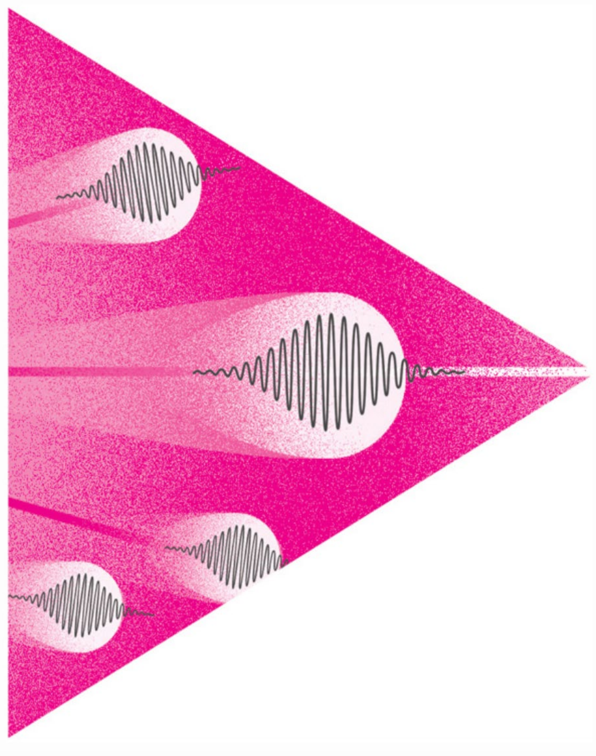
Neutrino scattering experiments





Neutrino oscillations: Big picture questions

- What are the masses of neutrinos?
- What is the mass ordering of neutrinos? If inverted, might a new symmetry be needed to account for two heavier neutrinos having similar masses?
- Are neutrinos their own antiparticles? Can this help us explain the matter-dominated universe we are in?
- Do antineutrinos oscillate differently than neutrinos? (Is CP symmetry violated?) Can this explain the matter-dominated universe we are in?
- What astrophysical phenomena can neutrinos open to us?



Fermilab

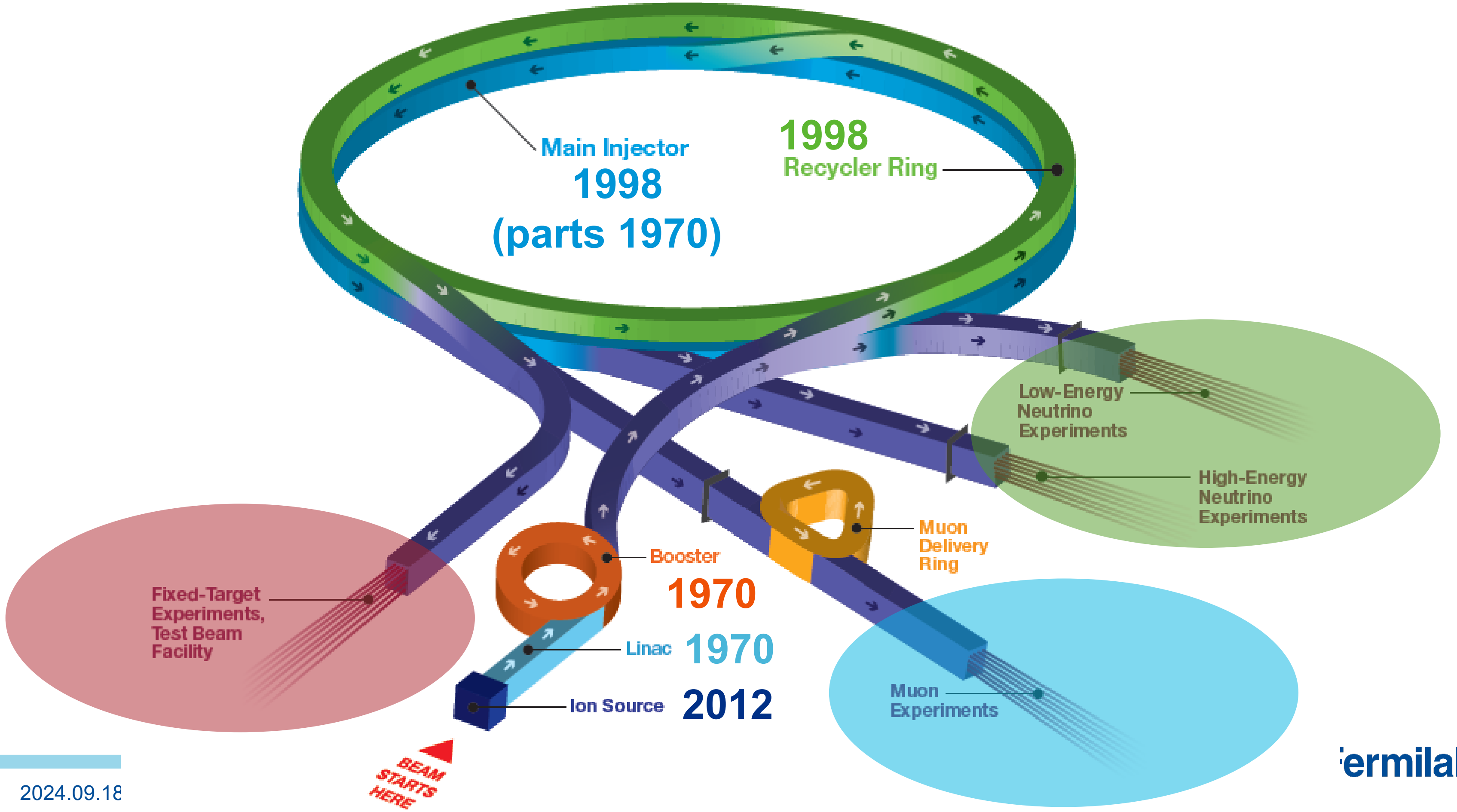
AD Vision and Mission

Accelerator Directorate’s vision is to develop and operate Fermilab’s accelerator facilities delivering particle beams that enable the high energy physics mission while also leading in innovating and realizing future accelerators for scientific discoveries.

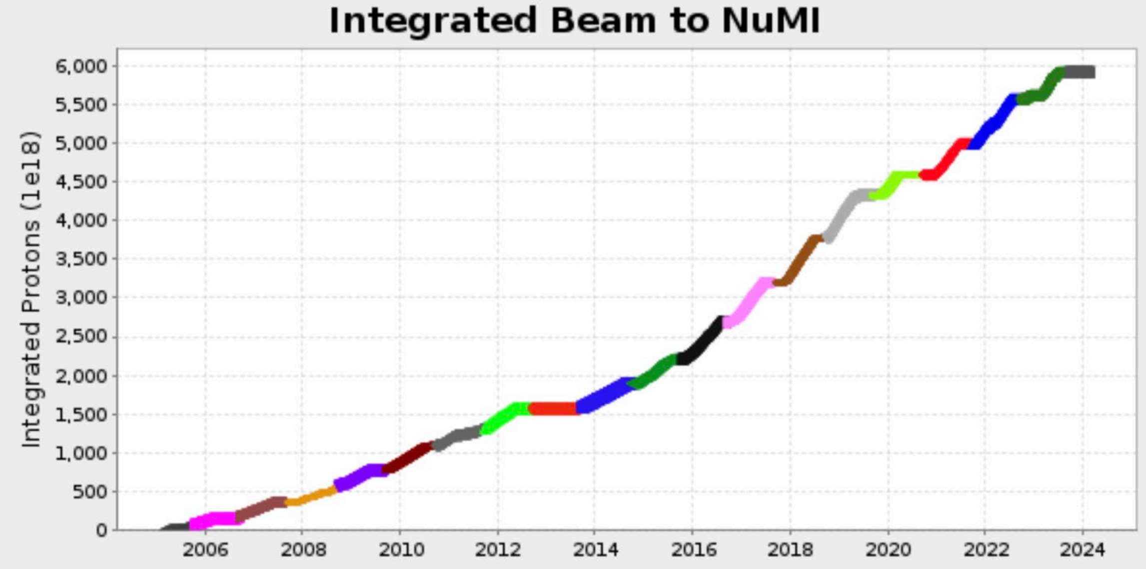
Our mission is to drive scientific discovery by:

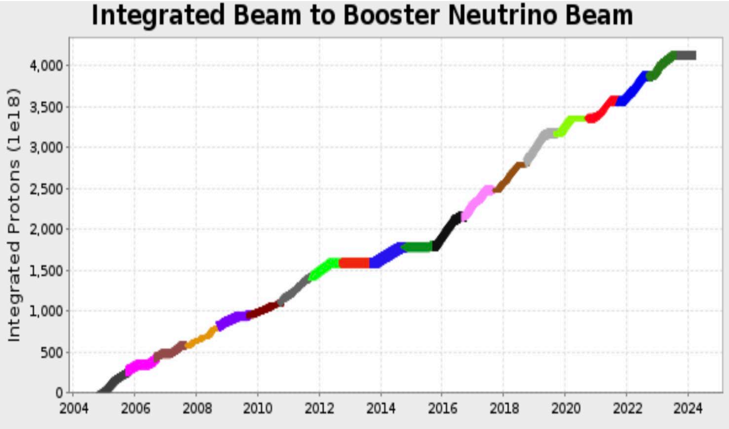
- **Reliable delivery of megawatt class particle beams** for scientific research;
- Advancing **accelerator physics research** to enable future accelerators;
- **Designing and building accelerator systems** and support installations to extend the scientific reach of existing facilities;
- Engaging in national and international collaborations and supporting training programs to develop and maintain a **world-class accelerator workforce**.

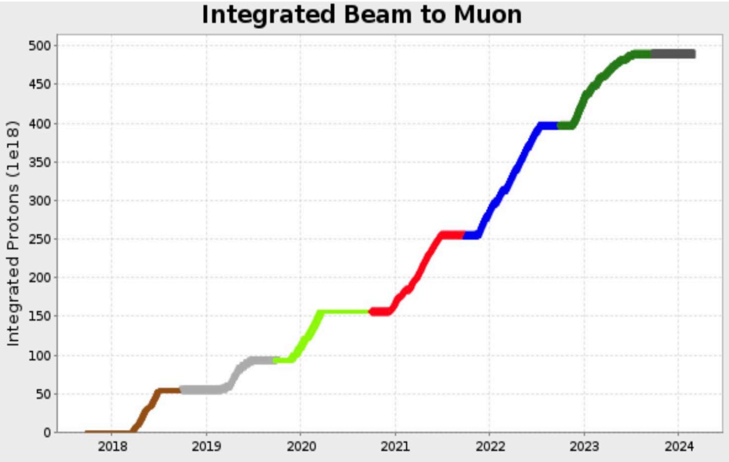
Fermilab Accelerator Complex – National Users Facility



Accelerator Complex function - beam delivery to science users

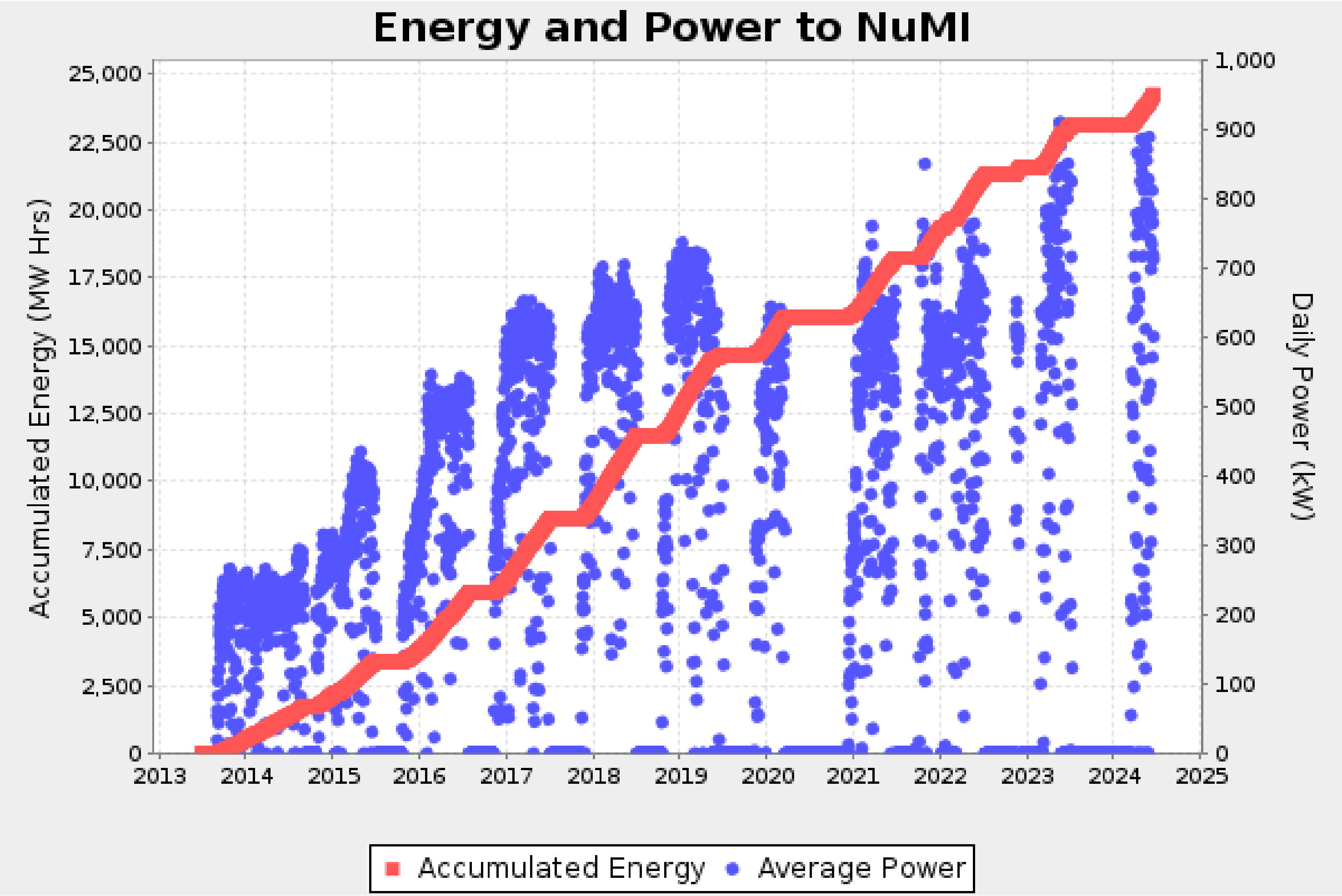






Protons-On-Target ∝ Power × Runtime × Uptime

Multiple experiments operate concurrently


Energy and Power to NuMI
Accumulated Energy (MW Hrs)
Daily Power (kW)
25,000
22,500
20,000
17,500
15,000
12,500
10,000
7,500
5,000
2,500
0
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

Fermilab

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

Fermilab

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 x 10^{13}	4.9 x 10^{13}	6.5 x 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

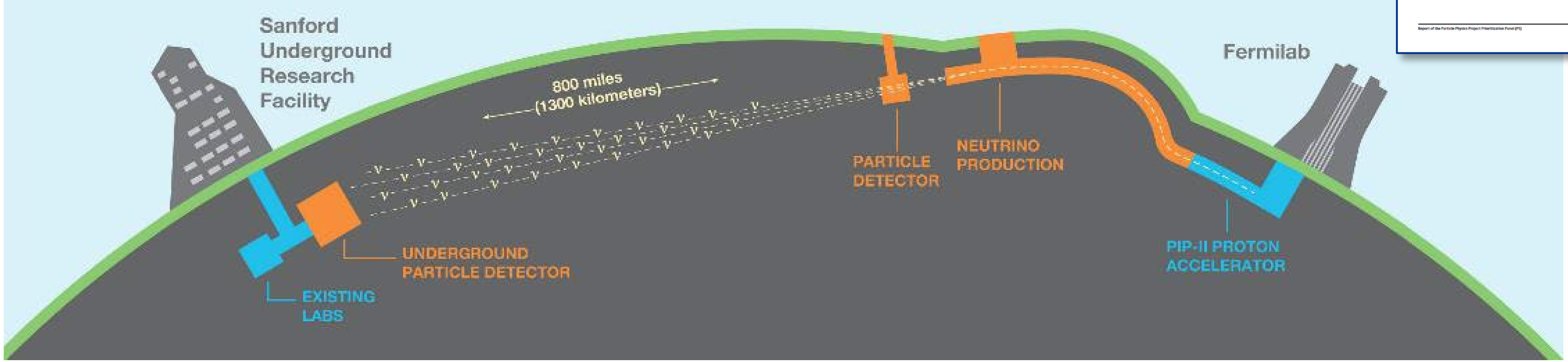

1-MW Horn-1 Installation

Fermilab

Mu2e: Muon to Electron Conversion Experiment

- Two transport solenoids were installed into the Mu2e experimental hall
  - Looking forward to production and detector solenoids
- Beamline has been commissioning
  - Electrostatic septa built & installed
  - Goals for 2025 & 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

Deep Underground Neutrino Experiment



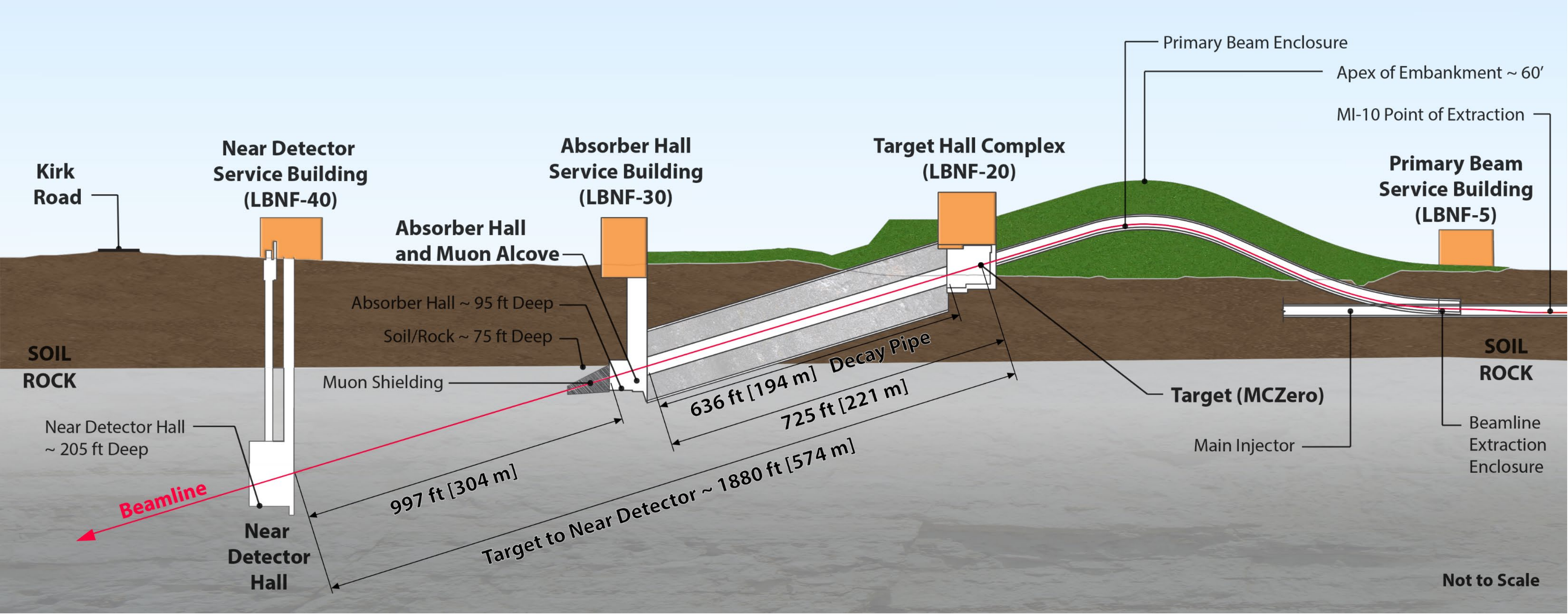
Origin of matter. Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?

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.

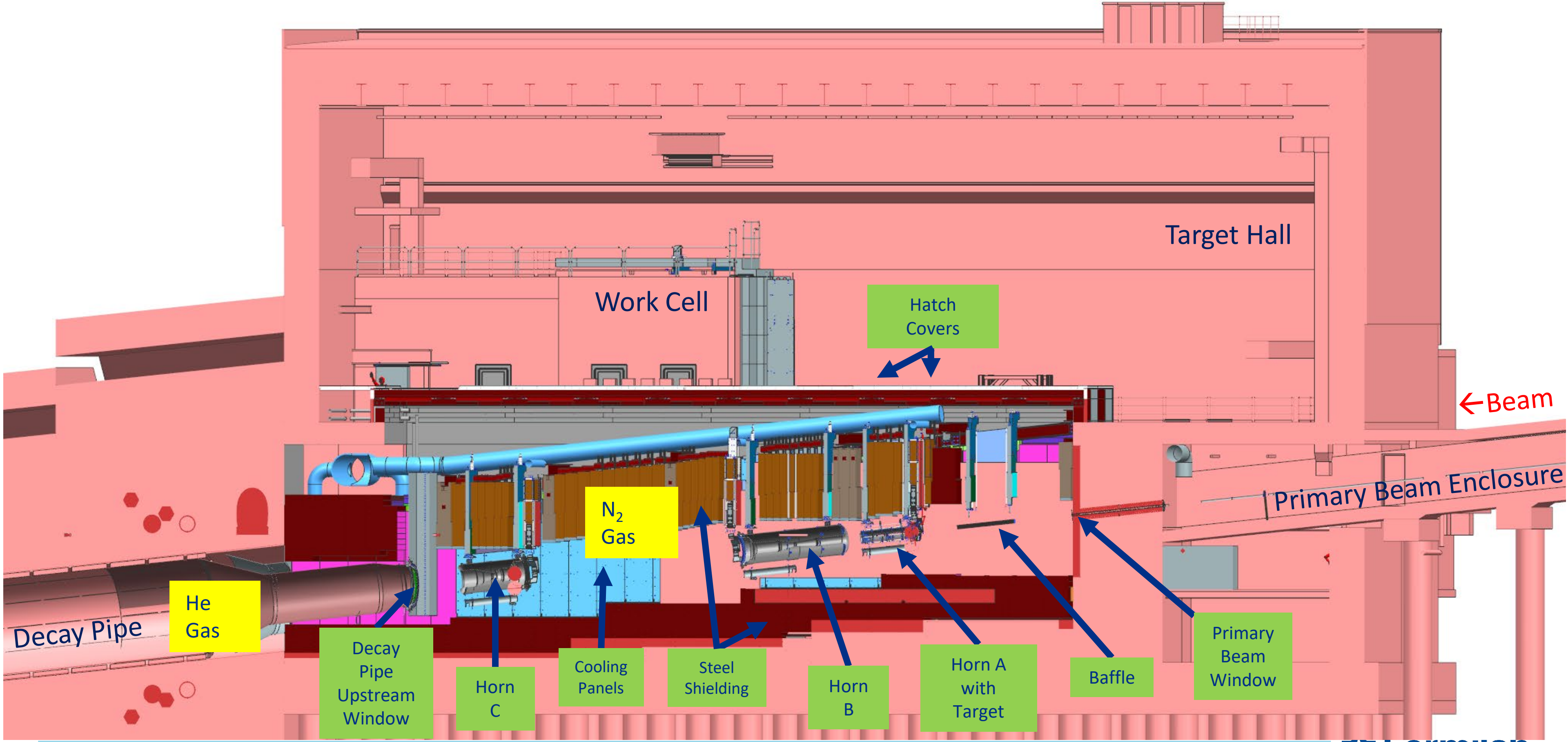
The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

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

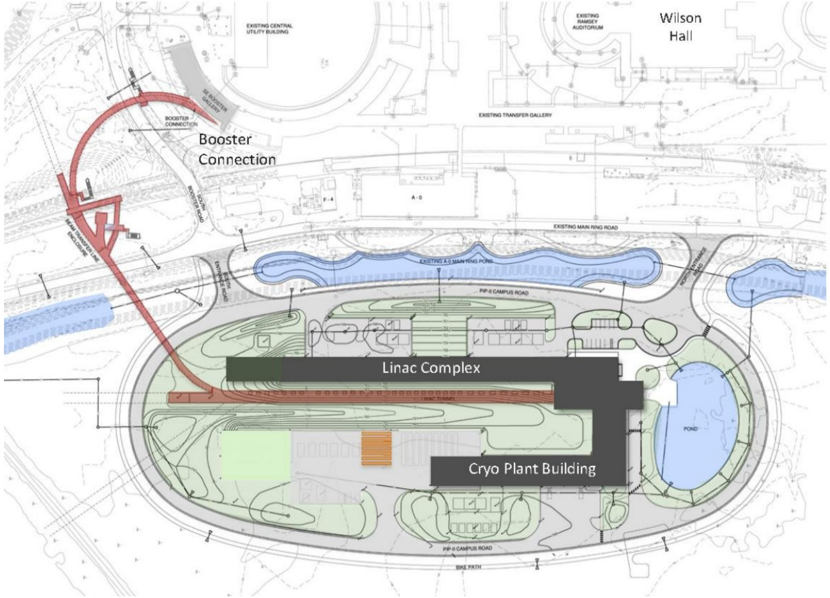


Proton Improvement Plan II (PIP-II)

- 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

Fermilab

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

E. Pozdeyev, SpaceCharge19

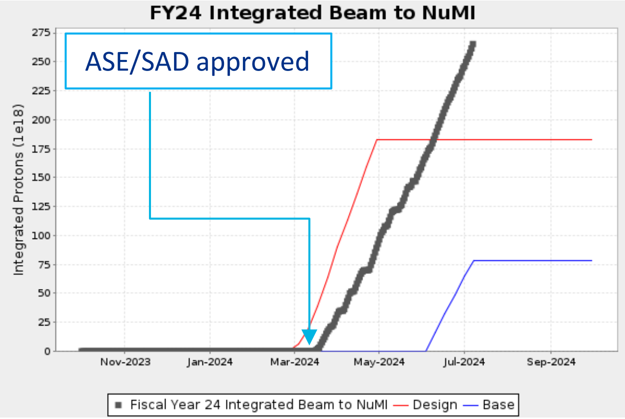
Project started in 2016 (CD-0)
First beam in Booster: 2029 (plan)
MI 1.2 MW beam on target: 2031 (plan)

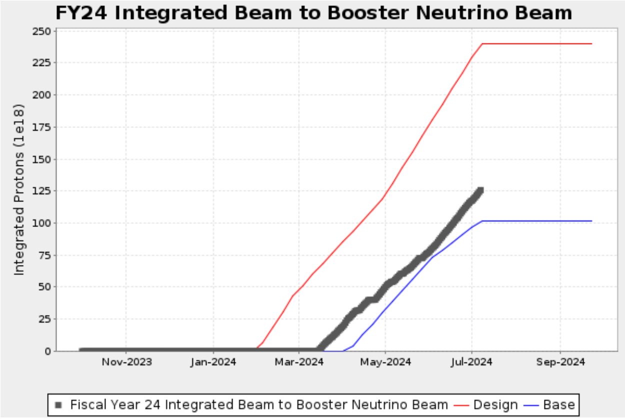
PIP-II Project construction

- 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

FY24 accelerator run – accomplishments





Machine	Review	Approval to run beam
Linac / MTA	SAD/ASE review Nov 29-Dec 1 ✓	Jan 2024 ✓
Booster/MI8/BNB/MI/NuMI	SAD/ASE review Jan 9-11 ✓	March 2024 ✓
Muon/SY120/ Meson	SAD/ASE review Jan 23-25	March 2024 ✓
NM/SpinQuest	SAD/ASE review Jan 23-25 ARR Feb 13-15	March 2024 ✓
Accelerator Complex	ARR Feb 13-15	validate compliance ✓

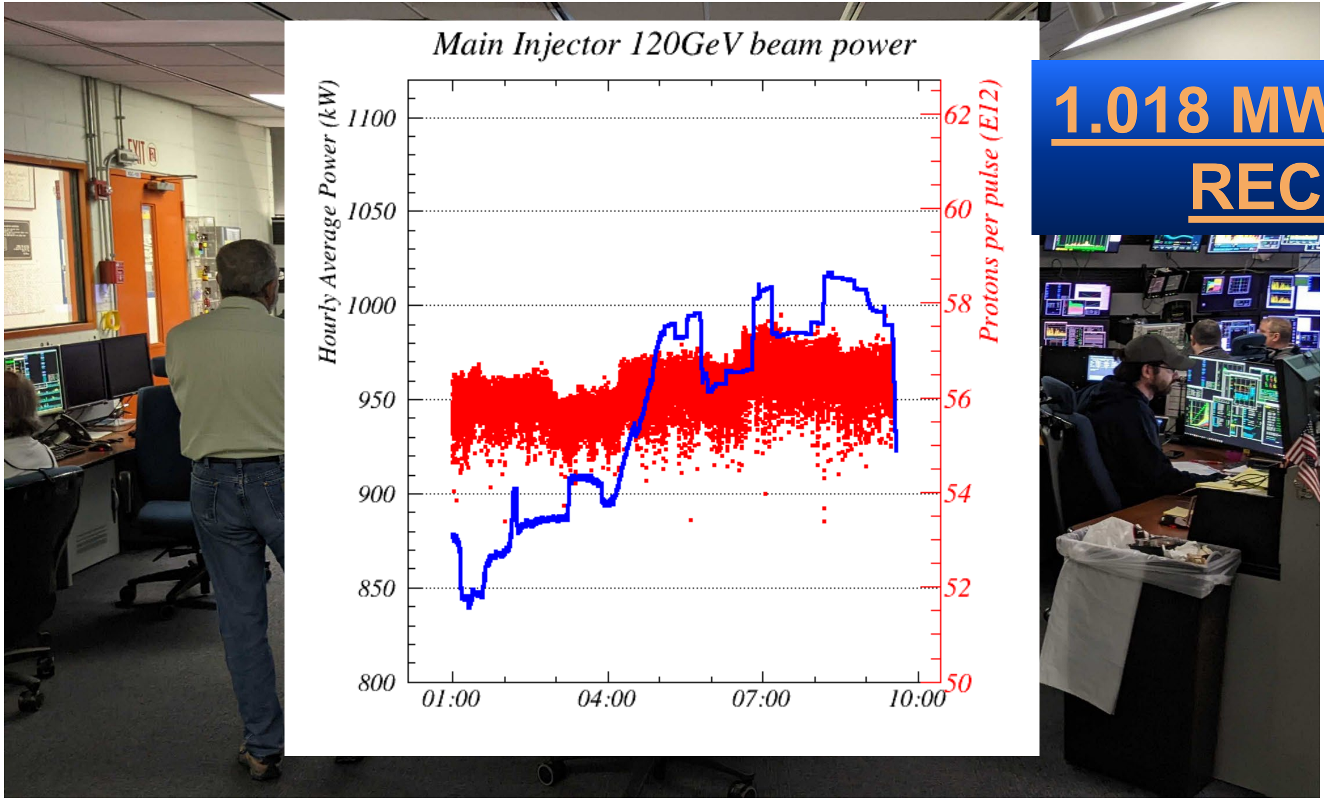
- **Accelerator Safety Documentation** [Safety Assessment Document (SAD) and Accelerator Safety Envelope (ASE)] to comply with updated DOE Order 420.2D for Accelerator Complex **updated and approved**
- **Beam delivery to users started on 3/8/24**
- **Upgraded Main Injector to 1.067 s cycle operation** – Achieved 1 MW

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

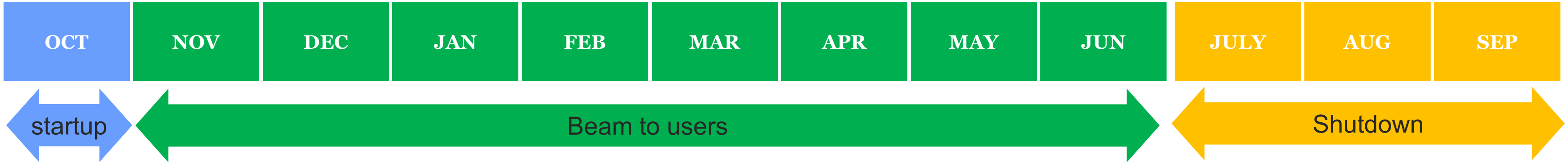
1.018 MW



1.018 MW POWER RECORD

Fermilab

FY25 plan



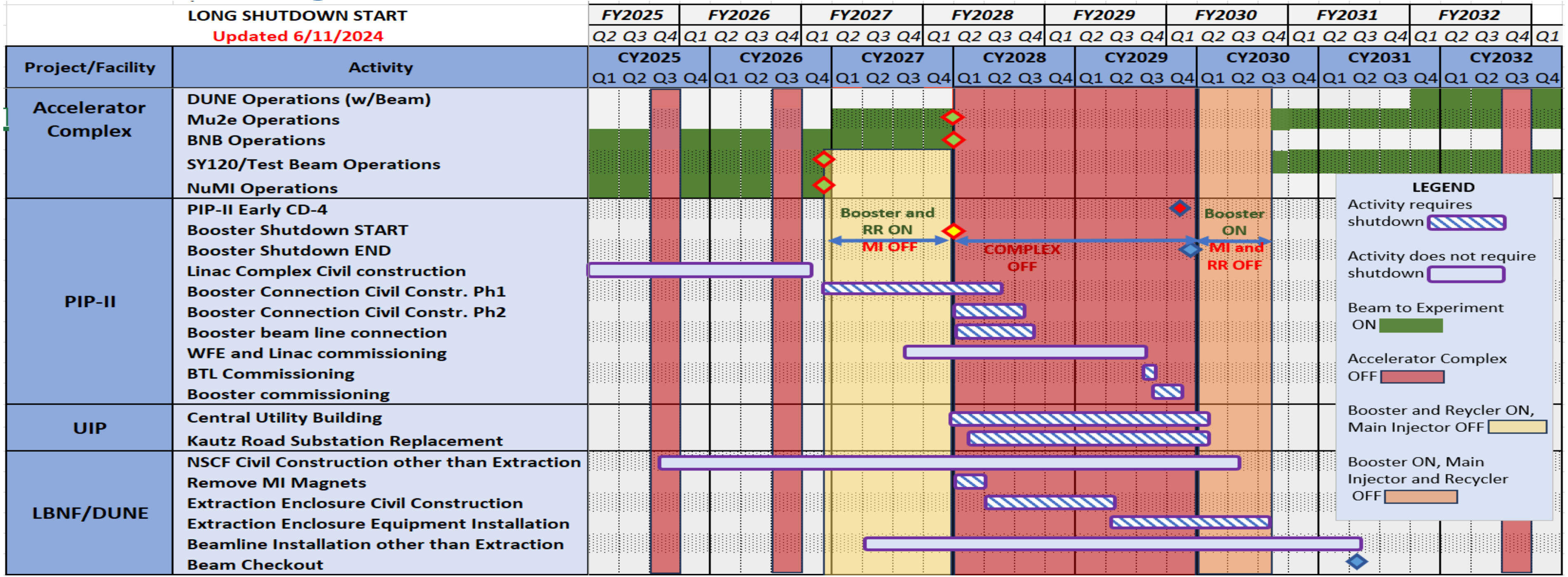
- **Optimal Operations of the present experimental program**
  - Prioritize BNB (beam to ICARUS and SBND): maximum 40 BNB weeks
  - Operation of Main Injector up to 40 weeks
    - Operate Switchyard 120 GeV (Test Beam, SpinQuest)
    - Continue to deliver beam to NOvA in the NuMI line
  - Operate MeV Test Area (MTA)/ Irradiation Test Area (ITA)
  - Commissioning of resonant extraction for Mu2e beam and transition to operations
  - *Optimal Operations contingent on sufficient funding (CR) and fixing technical issues*
- **Modernization of the accelerator systems and infrastructure to integrate PIP-II and to enable efficient beam delivery at high power in the PIP-II/LBNF era**
  - Continue execution of MI-8 Instrumentation AIP to make systems compatible with 20Hz Booster operations
  - Start targeted R&D for ACE-MIRT

Fermilab

FY26 priorities

- Operating current accelerator to deliver beam to science users
  - As allowed by power budget and personnel availability
- Mu2e transition to operations
- PIP-II Transition to Operations begins
  - Systems and buildings are being handed off to Operations: Cryogenic Plant
  - Additional electric power
- Critical investments to modernization for PIP-II/LBNF operations
  - Prioritize Instrumentation AIPs
  - ACE-MIRT design work
- Production of spare parts for operations
- Maintenance of systems

Updated long-term Accelerator Operations plan – 2028 shutdown



- Allows 12 months of Mu2e data taking
- Additional year of BNB operations to provide more data to SBND
- Main Injector shutdown as planned earlier in CY27 for cost savings and access for ACE-MIRT execution

Fermilab

Relevant P5 recommendations

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science

b. The first phase of DUNE and PIP-II to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science

continued support for the following ongoing experiments at the medium scale

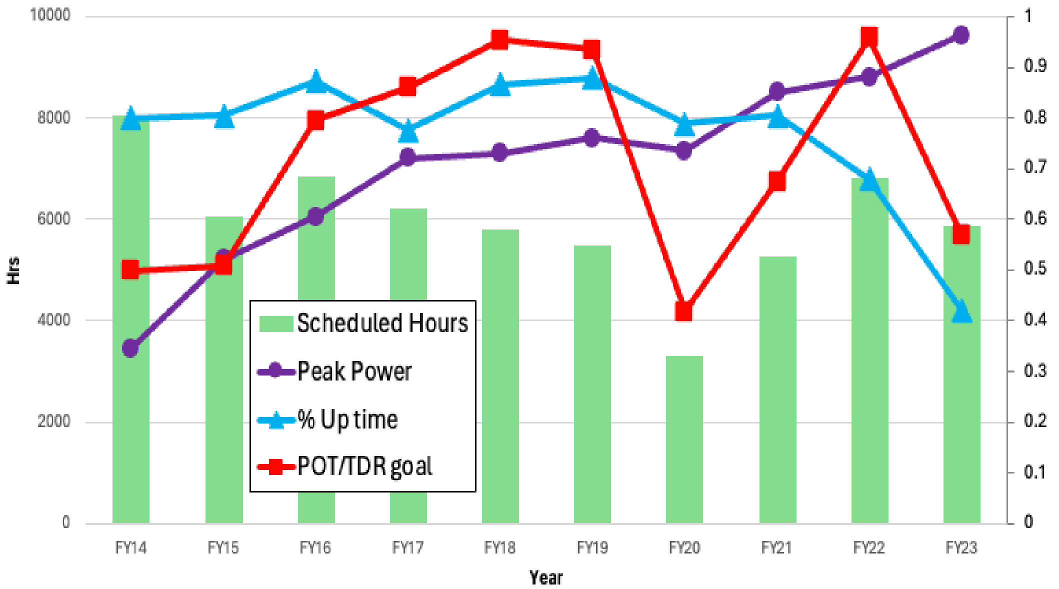
d. NOvA, SBN; g. Mu2e

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future

b. Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT

Area Recommendation 13: Assess the Booster synchrotron and related systems for reliability risks through the first decade of DUNE operation, and take measures to preemptively address these risks.

Lessons from long-term NuMI operations



- 2014-2019 investments in capability (PIP-I 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

Fermilab

Physics output and Ops efficiency

Efficiency

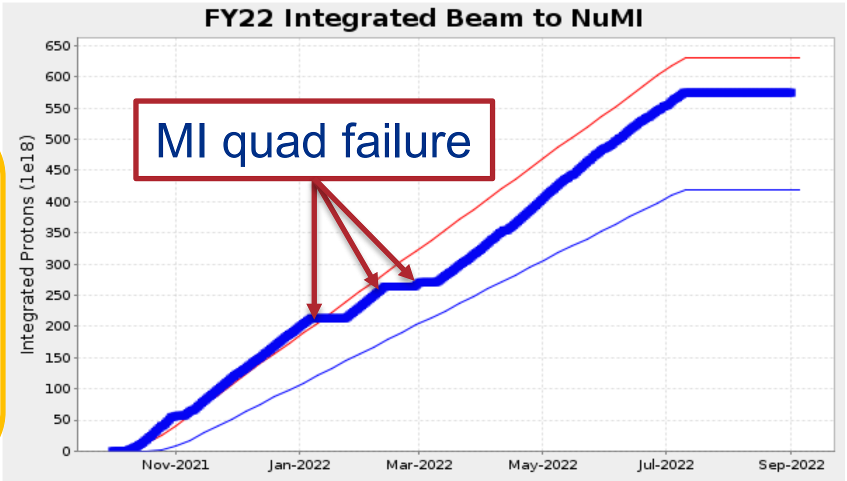
- Uptime = [run time]/[scheduled time]
  – FY22 69% ➜ 80% LBNF/DUNE
- Runtime = [scheduled time]/[CYear]
  – FY22 77% ➜ 80% LBNF/DUNE
- Sustained power fraction= <P>/Pmax
  – FY22 76% ➜ 90% LBNF/DUNE

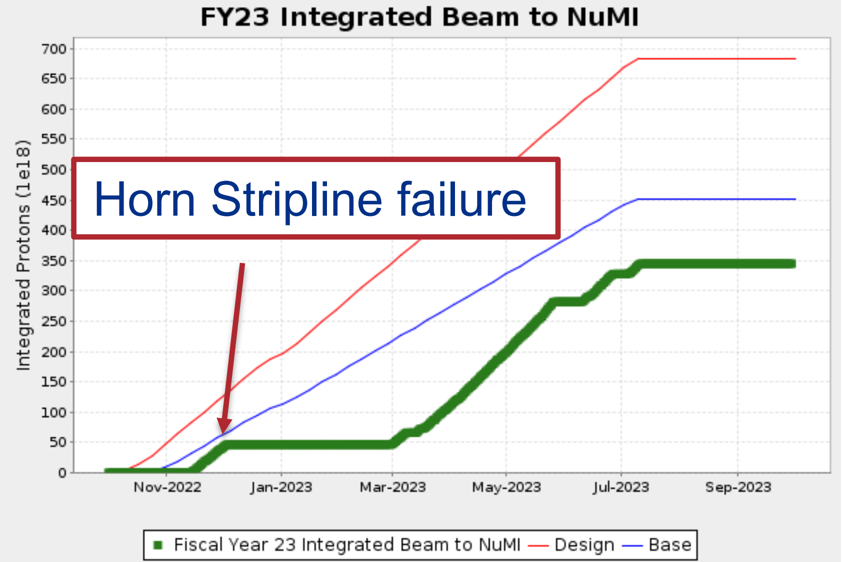
Capability

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

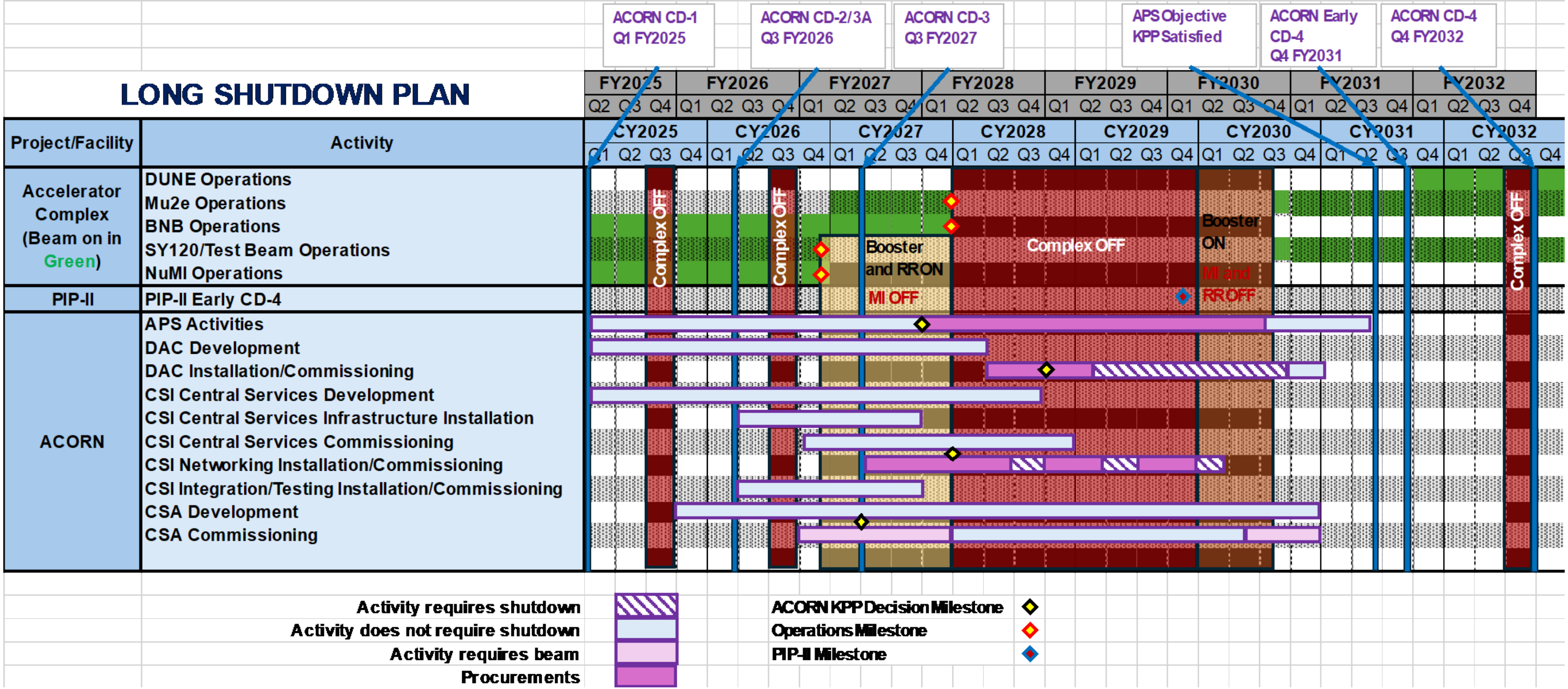
ACORN received CD-0 ESAAB approval Aug. 28, 2020. CD-1 expected in 2025.

- 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).*

ACORN Project Timeline and Integration Plan



Fermilab

Electrical Infrastructure: Kautz Rd Substation Transformer

- 345 kV Electrical Transformer Deflagration
  - T88 @ KRS w/ high-voltage (HV) bushing failure on 8/3/24.
  - T81 @ MSS of the same vintage as T88. Hotspot was found on same HV bushing, was taken OOS 8/23/24
  - T84/MSS and T87/KRS OOS due to an advisory bulletin (compromised bushings)

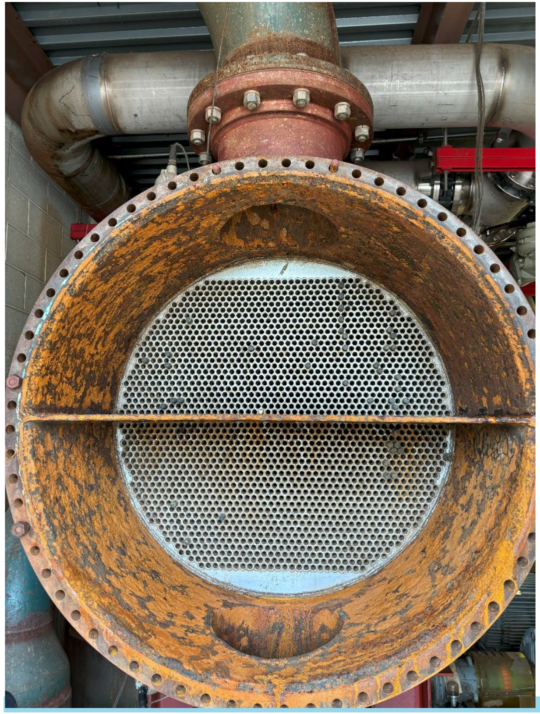
- Plan To Energize in the near future
  - Having two transformers available in each substation i.e. T82 and T83 @ MSS, T85 & T86 @ KRS
  - T86 oil sample w/ moisture content. Oil will have to be reprocessed before we energize T86
  - MSS having preventive maintenance. Running complex off T85 @ KRS

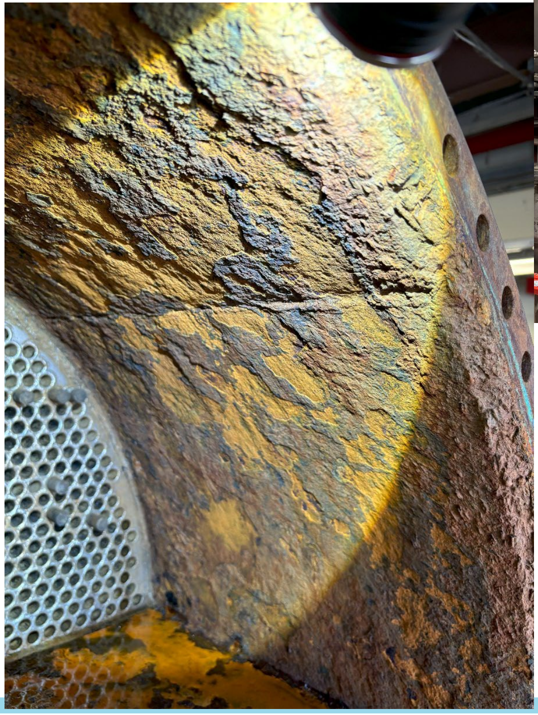
- Proposed KRS Reconfiguration for FY2025
  - Reduced number of transformers requires alternate configuration of switches and feeders
  - Power quality monitors to track power quality of this "unconventional" configuration
  - Likely reduced power to NuMI this run - TBD

PIC 4
T-88 FAILED BUSHING - PIC 2

Cooling Infrastructure: MI Heat Exchanger Corrosion

- Main Injector heat exchangers interiors are experiencing severe corrosion.



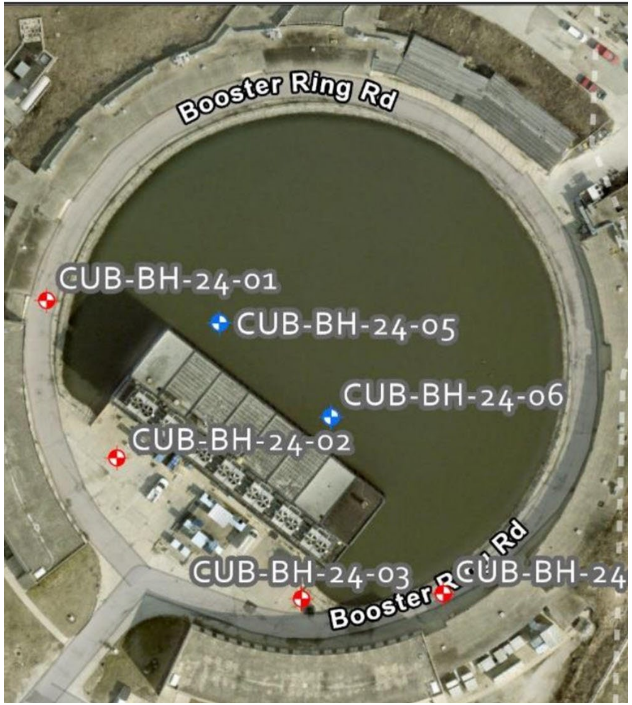


- Inspections underway to determine condition
- Repair / mitigation plans being formulated
- Possibility of reduced cooling capacity in FY25

Fermilab

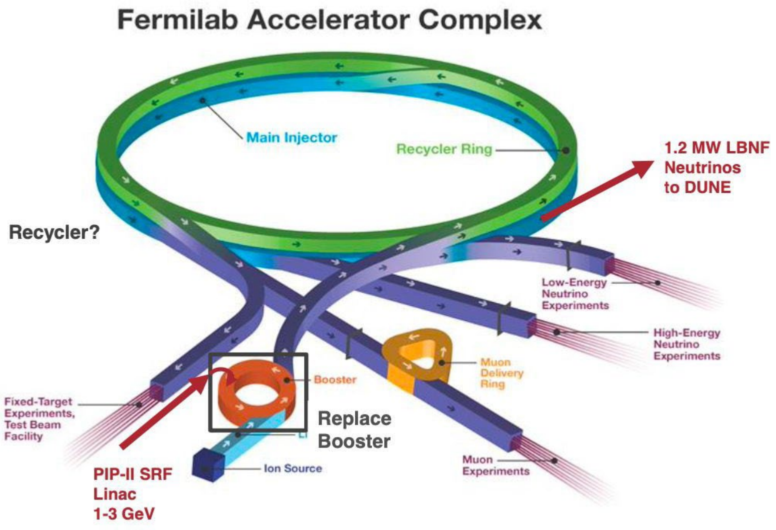
UIP: Utilities Infrastructure Project

- 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.
  - Luciano Ristori presentation to PAC June 2021
  - White Papers for Snowmass describe design options and potential for rich low energy science program
  - Recent PIU and ACE studies
- 2023 P5 Recommendation: accelerate realization of 2+ MW with "MIRT"
  - Plan for future complex evolution



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"

Fermilab

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

2.4 MW

2. Further, a Project would be established to build Booster Replacement. The implementation of **ACE-BR** would
   - **Reliably deliver even more beam power to LBNF** to ensure CP Violation measurement in DUNE Phase II
   - **Considerably enhance beam capabilities for a broader physics program**
   - **Provide a robust and reliable platform for the future evolution of the Fermilab accelerator complex**, possibly including a proton source for multi-TeV accelerator research

ACE-MIRT plan is motivated by faster delivery of DUNE science

For instance, allows to achieve 5 σ mass ordering sensitivity for 100% of δ_{cp} values in 3.5 years instead of 5 years

Fermilab and AD have a strong record of extracting maximum physics out of facilities by implementing clever improvements: Tevatron fixed target→collider, recycler with electron cooling, neutrino program, etc.

Physics data for accelerator HEP experiment is determined by capability, capacity, and reliability

1. Accelerator capability enhancement
   a) Implement LBNF target capable of 2.1 MW
   b) Upgrade Main Injector to allow for cycle time of 0.65 s (~2 × faster than design)
2. Capacity
   - The plan enables capability of using all 8 GeV beam capacity
   - As such, maximum LBNF power is in tension with any 8 GeV program and Test Beam or SpinQuest operations
3. Reliability enhancements

ACE-MIRT scope to enable >2MW

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

Proposed components offer independent (*) and incremental benefits

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 (*)

Fermilab

Accelerator Complex Evolution Task Force – Main Injector Ramp and Targetry (ACE-MIRT)

- Increase protons on target to DUNE by
  - Shortening Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the accelerator complex

- Team:
  Mary Convery (interim manager)
  Bill Pellico (engineering lead)
  Srinivas Krishnagopal (physics lead)
  Kevin Lynch (targets)
  Dan Broemmelsiek (rad safety)

- Charge to team:
  1. Develop an integrated schedule taking into consideration interfaces with the operation of ongoing science program, major projects (PIP-II, LBNF, ACORN, UIP), infrastructure needs, and future experiments. This should include a funding profile.
  2. Evaluate risks for reliable long-term operation of the Booster in the PIP-II/LBNF era and identify the necessary R&D, upgrade needs and path forward.
  3. Evaluate the implications of operating the accelerator complex at the power of 2.1MW in the context of DOE O420.2d ‘Safety of Accelerators’.

Preparing for CD-0

Strategy for ACE-MIRT

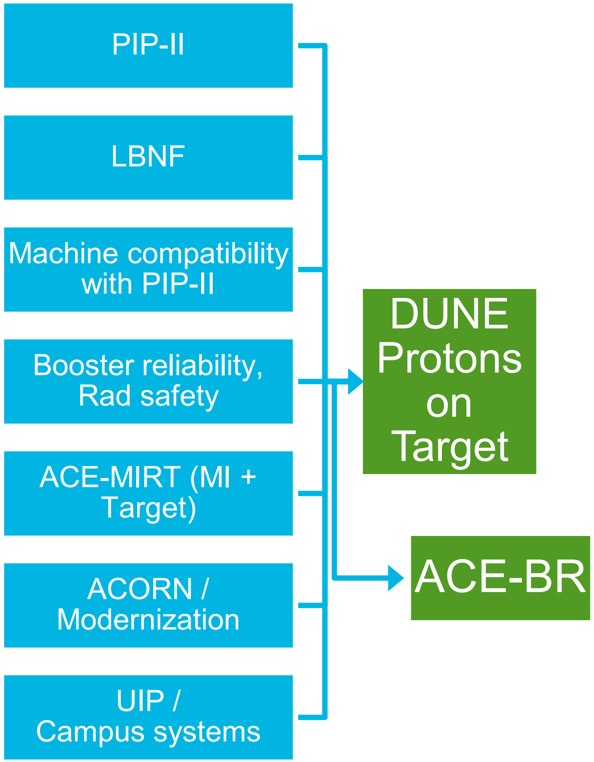
- Main Injector
  - Power supplies ~$100M (DOE O413.3b project), needs alternatives analysis
  - RF ~$140M (DOE O413.3b project), needs alternatives analysis
  - Abort line upgrade Accelerator Improvement Project (AIP)
  - Provide power supplies for LBNF beamline which need different specifications for fast cycle time
- Targetry
  - Target materials R&D
  - Staged target development for higher beam power
  - Horn analysis and design modification
- Reliability
  - Complete instrumentation AIPs for 20-Hz operations
  - MI magnet testing at faster cycle time, produce spare quadrupoles to install as needed
  - Increment in ops funding eg $5M/y for modernization, $0.5M/y for SPS

PIP-II/LBNF beam power in numbers – ACE-MIRT

		PIP-II Booster			
Operation scenario	**Present**	**PIP-II**	**ACE (a)**	**ACE (b)**	**units**
MI 120 GeV cycle time	**1.06**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.7**	**6.5**			10^{12} p
Booster ramp rate	15	**20**			Hz
Number of batches	12	12			
MI power	**1.0**	**1.2**	**1.7**	**2.1**	MW
cycles for 8 GeV	**4**	**12**	**6**	**2**	
Available 8 GeV power	23	83	56	24	kW

Legend: **enabled by PIP-II** **enabled by ACE-MIRT**

ACE-MIRT as part of the overall strategy

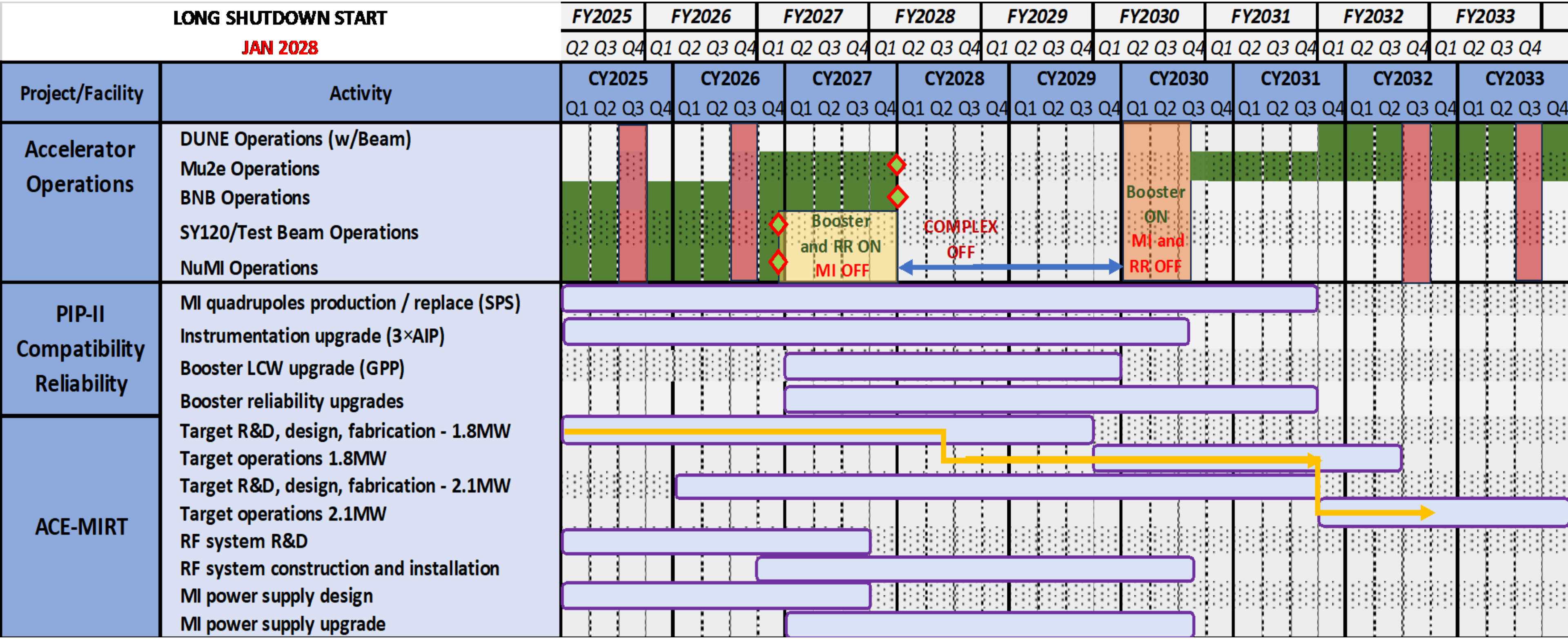


Management and integration team tasked to implement plan

- Mary Convery (interim manager at program start)
- Bill Pellico (engineering lead)
- Srinivas Krishnagopal (physics lead)
- Kevin Lynch (targets)

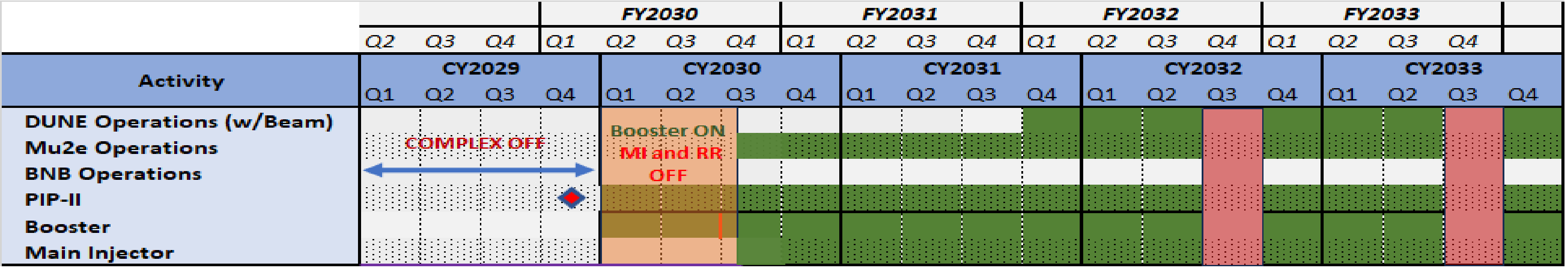
1. Develop an integrated schedule taking into consideration interfaces with the operation of ongoing science program, major projects (PIP-II, LBNF, ACORN, UIP), infrastructure needs, and future experiments.
2. Evaluate risks for reliable long-term operation of the Booster in the PIP-II/LBNF era and identify the necessary R&D, upgrade needs and path forward.
3. Evaluate the implications of operating the accelerator complex at the power of 2.1MW in the context of DOE O420.2d ‘Safety of Accelerators’.

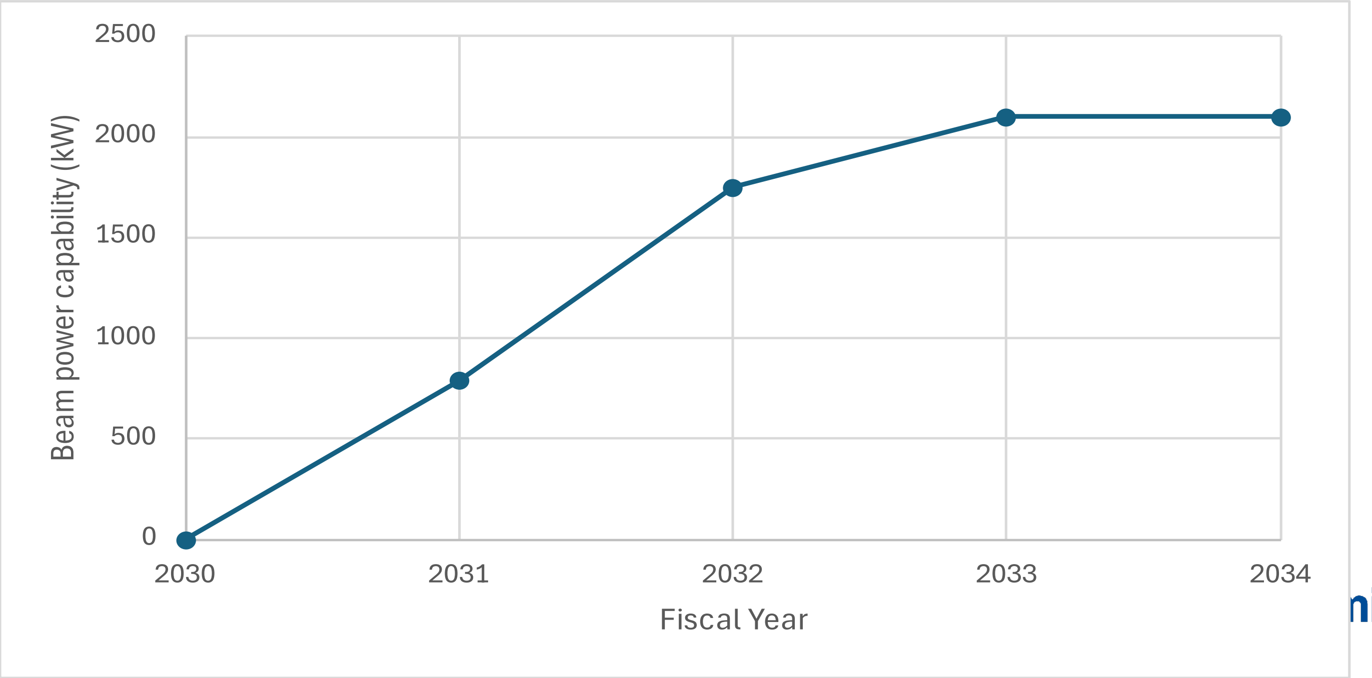
ACE-MIRT technically limited schedule



Fermilab

LBNF/DUNE technically limited beam power projection





P5 Recommendations for the future: ACE-BR etc.

Rec 2b Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam (MIRT), a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

Rec 4g Develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of this report including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

Rec 6 Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program …

Area Rec 12 Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.

Area Rec 13 Assess the Booster synchrotron and related systems for reliability risks through the first decade of DUNE operation, and take measures to preemptively address these risks.

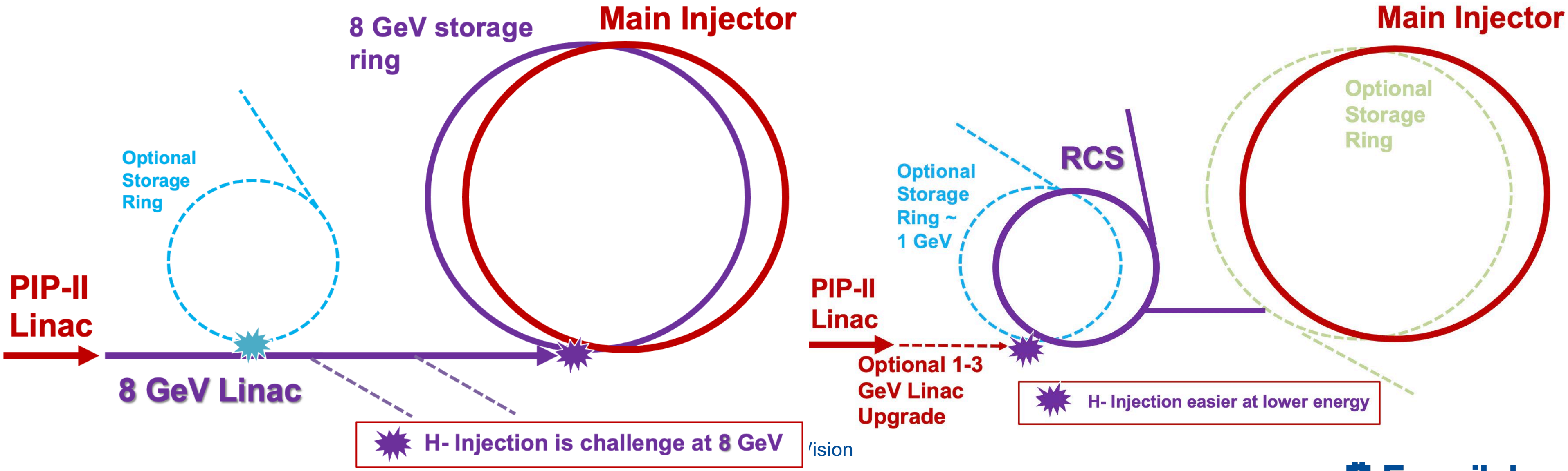
- Strong support for an expedited implementation of MIRT
  - Focus on reliability and delivery
  - AD Workshop: https://indico.fnal.gov/event/63152/

- Support for R&D & planning for a reformulation of ACE's future stage(s)
  - The focus of the post-MIRT ACE is *not* necessarily LBNF

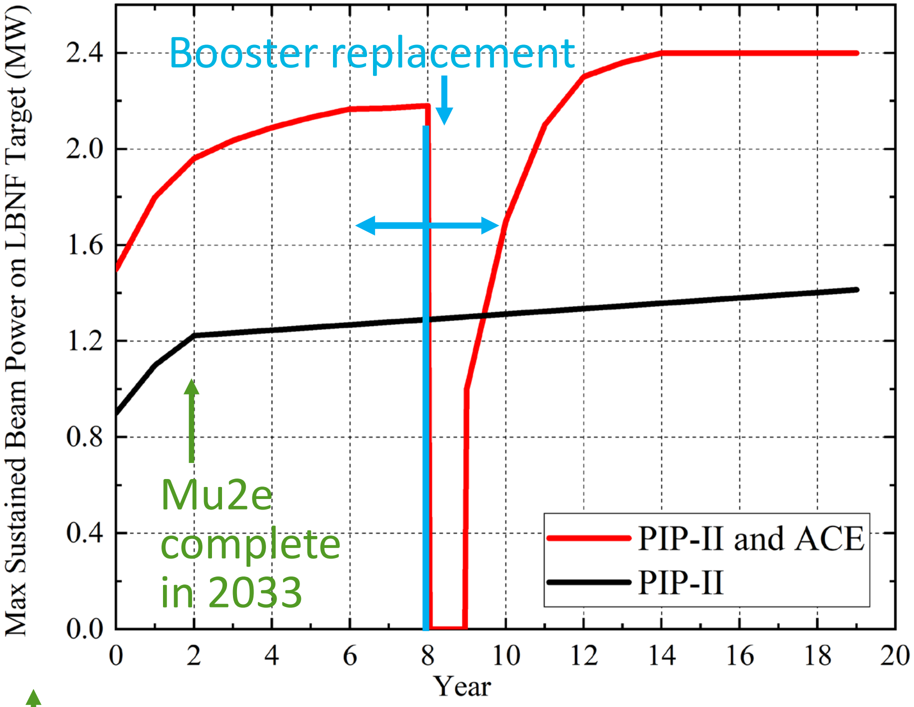
ACE-BR: Booster Replacement

Booster replacement scenarios were developed informed by studies from the past and input to Snowmass/P5

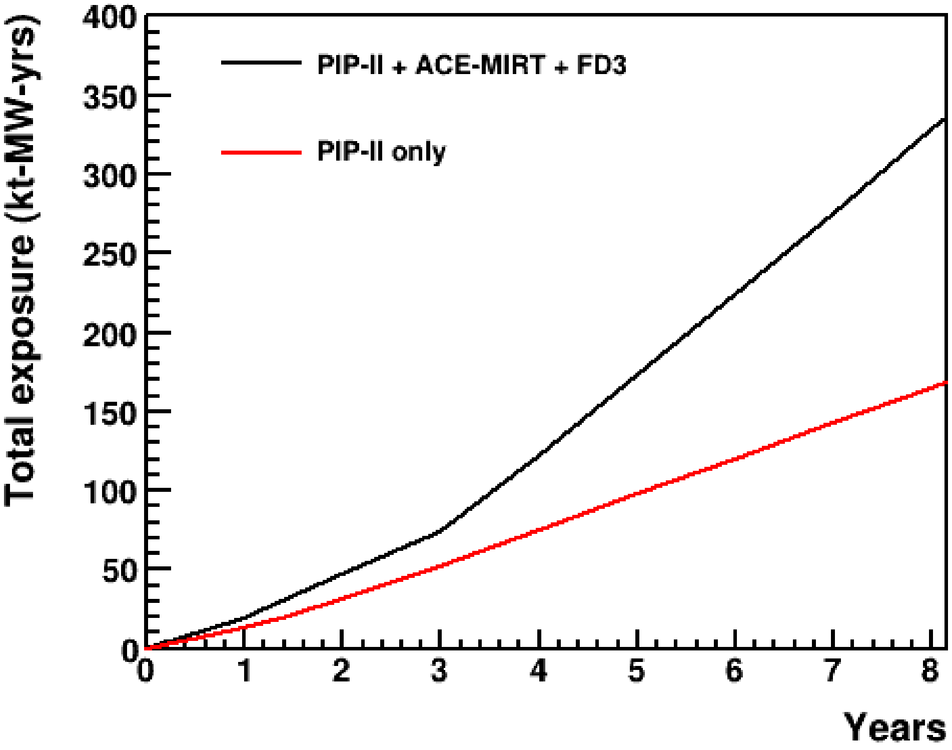
- Robust and capable 2.4MW accelerator complex for LBNF.
- Capture options for additional experiments at 1, 2, 8 GeV
- Provide a platform for accelerator test facilities and demonstrators for future accelerators and colliders



DUNE power with a Booster Replacement

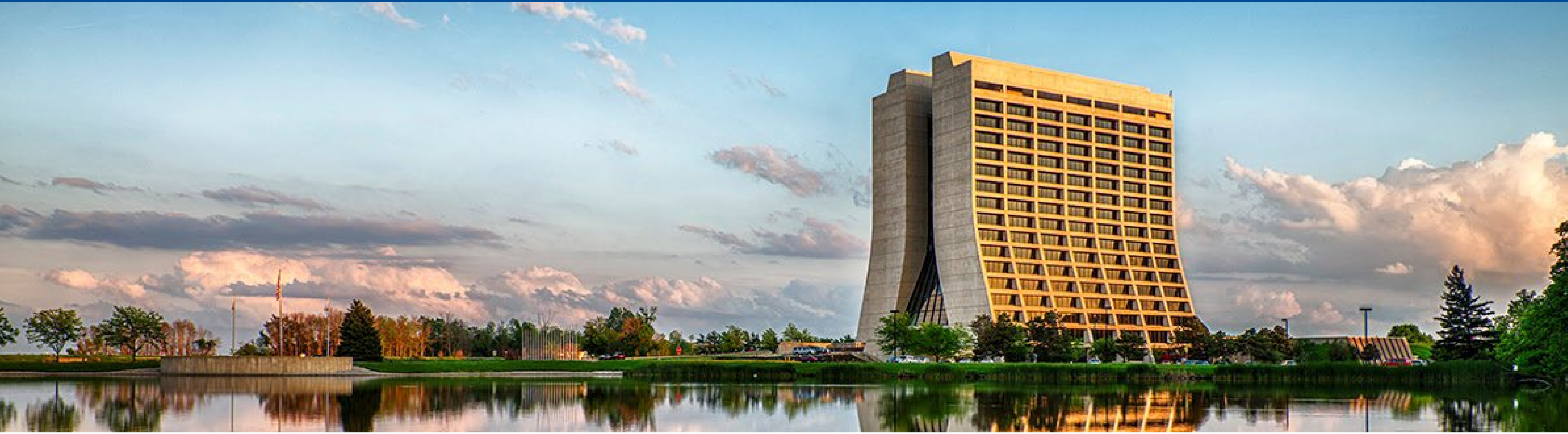


(Mu2e restarts 2029)



Summary

- Fermilab accelerator operations continues to enable the particle physics mission by delivering proton beams to science users
- The FY24 accomplishments include the update of accelerator safety documentation and implementation of a shorter, 1.067 s cycle time in the Main Injector, achieving 1.018 MW proton power
- The accelerator complex is transitioning from steady-state operations to integrating the PIP-II upgrade in preparation for the DUNE experiment
  - With constrained budget, our approach is to prioritize PIP-II/LBNF integration, upgrades and modernization at the expense of operating current user program
- Campaign of upgrades, modernization, and investments into spare parts AIPs for making 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
  - ACE Booster Replacement to enable future experiments
  - Test Facilities and Demonstrators for future machines



Fermilab Accelerator Plans and Schedule

Robert Zwaska, for the Fermilab Accelerator Directorate

NuFact 2024

18 September 2024

MIRT: Evaluate risks for reliable long-term operation of the Booster in the PIP-II/LBNF era and identify the necessary R&D, upgrade needs and path forward

- Accelerator Complex Studies Task Force led by CY Tan has identified needs for the Booster and Booster Transfer Line (BTL) to operate reliably at 20Hz with beam from the PIP-II Linac
  - Reports: FY23, FY22, FY21, FY20
- Upgrades specific to the Main Injector (MI) needed to support reliable beam to LBNF in the PIP-II era, and LBNF Target Systems for >1.2MW were explored in an ACE workshop
  - https://indico.fnal.gov/event/57326/ January 30, 2023
- The AD Preparation for DUNE-PIPII Era Workshop looked more broadly at needs for the complex in the PIP-II/LBNF era
  - https://indico.fnal.gov/event/63152/ March 5-7, 2024
  - Workshop summary