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Fermilab Accelerators and Demonstrator Concept

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** Thanks to Diktys Stratakis for Demonstrator Slides*



U.S. DEPARTMENT
of **ENERGY**

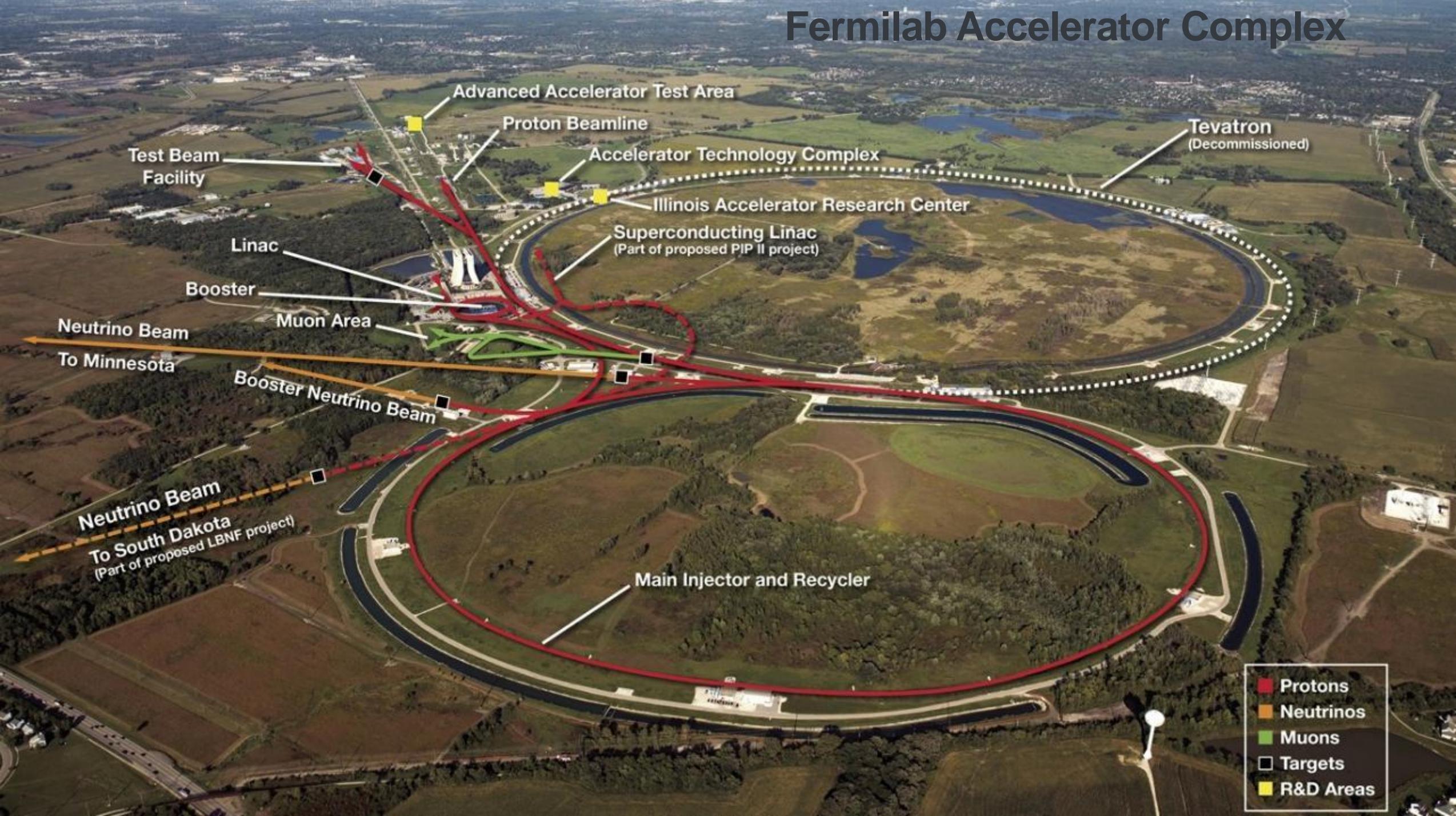
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Summary

- Fermilab operates an accelerator complex providing up to 1 MW of proton beam for neutrino and muon experiments
 - A continuous campaign of improvements has pushed beam power and reliability
 - Ageing infrastructure has impacted beam delivery
 - Upgrades are underway for DUNE and future accelerator-based experiments
- A Muon Collider Demonstrator Facility is desired
 - The Muon Collider is very ambitious in several ways
 - A concept for a cooling demonstrator is being studied for Fermilab

Fermilab Accelerator Complex



Advanced Accelerator Test Area

Proton Beamline

Accelerator Technology Complex

Tevatron
(Decommissioned)

Test Beam
Facility

Illinois Accelerator Research Center

Superconducting Linac
(Part of proposed PIP II project)

Linac

Booster

Muon Area

Neutrino Beam
To Minnesota

Booster Neutrino Beam

Neutrino Beam
To South Dakota
(Part of proposed LBNF project)

Main Injector and Recycler

- Protons
- Neutrinos
- Muons
- Targets
- R&D Areas

The Fermilab Linac

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

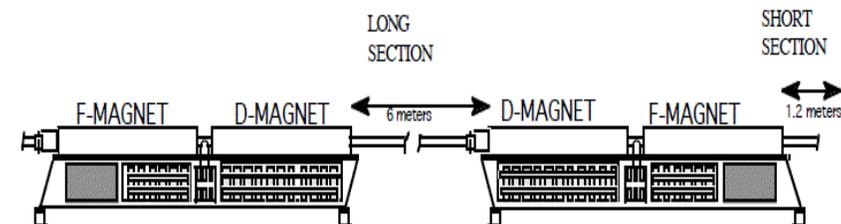
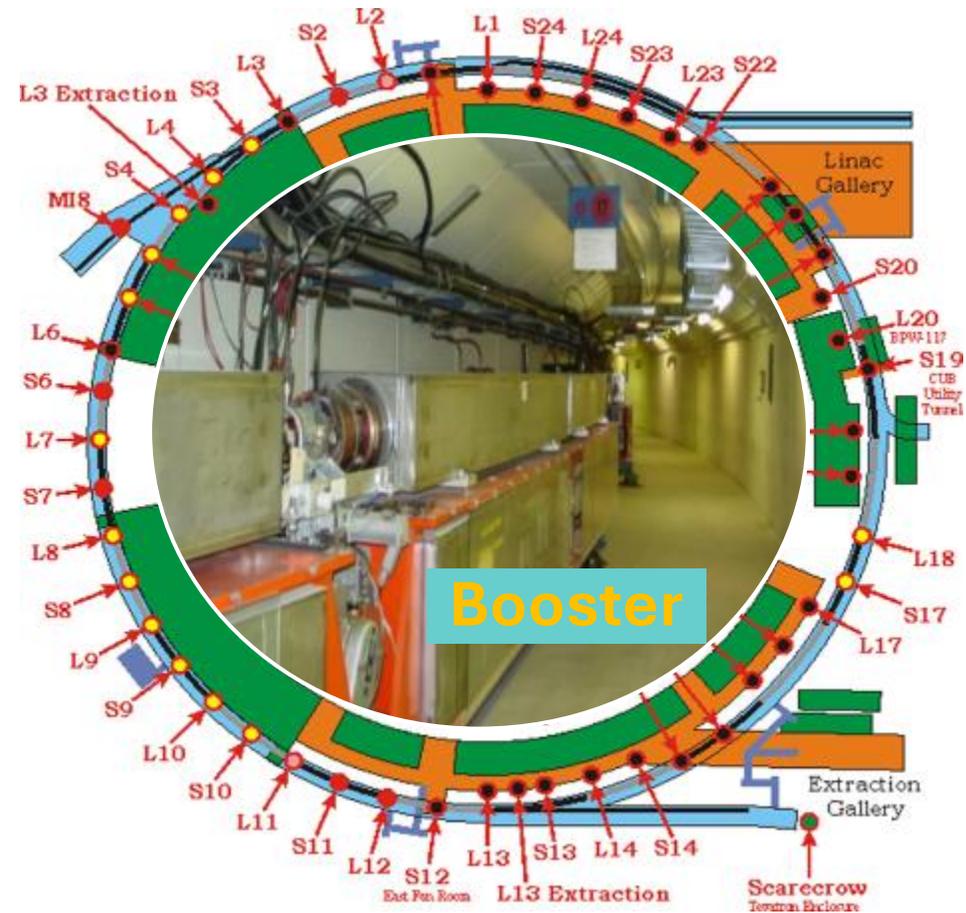


Booster Overview

- 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 systems upgraded over the decades

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



Main Injector & Recycler

Main Injector: 120 GeV Fast-cycling synchrotron

- 360 main dipole magnets
- 200 main quadrupole magnets
- 108 sextupoles, 66 octupoles, corrector dipoles/ quads, specialty injection and extraction magnets
- Twenty 53-MHz RF cavities to accelerate beam
- 170 DC and 360 ramped magnet supplies with total of 140 MVA, 40 specialty pulsed magnet supplies

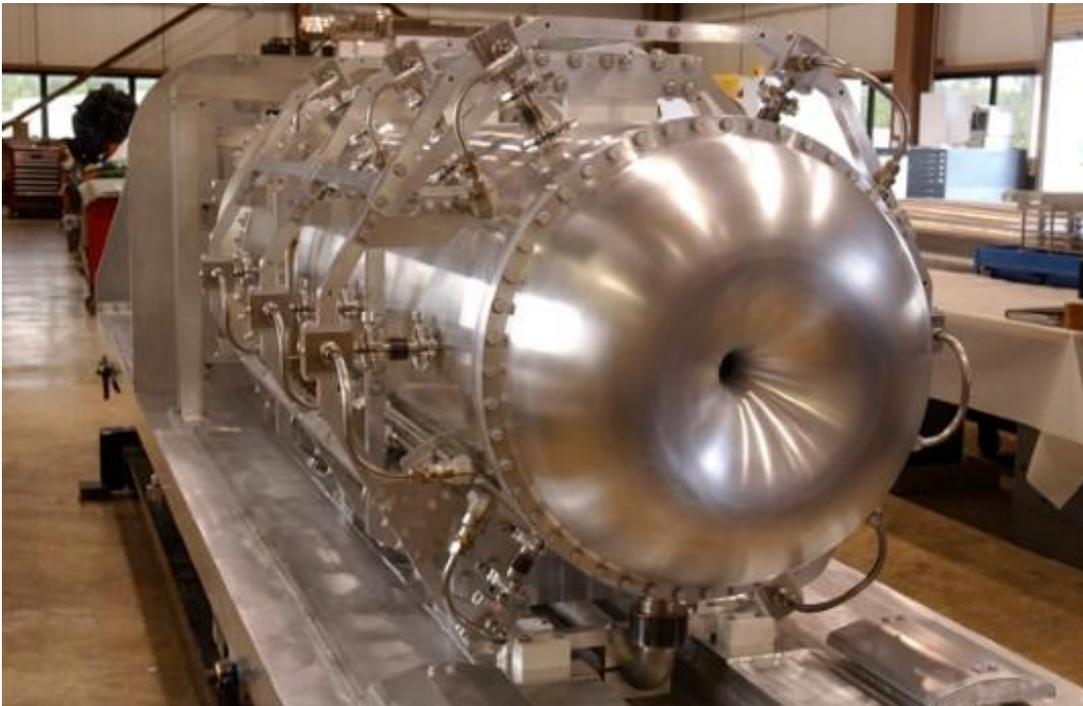
Recycler: 8 GeV Storage Ring

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

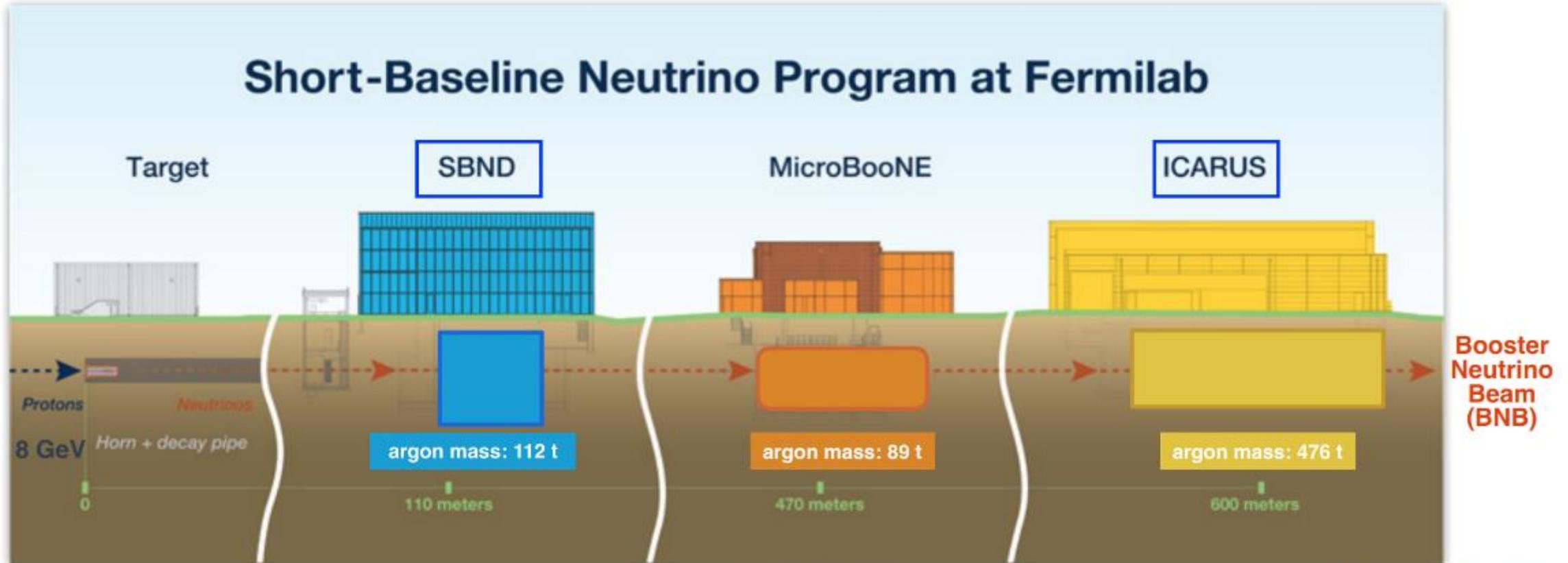


Booster Neutrino Beam (BNB)

- 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



2015-2021
Large production of
scientific results

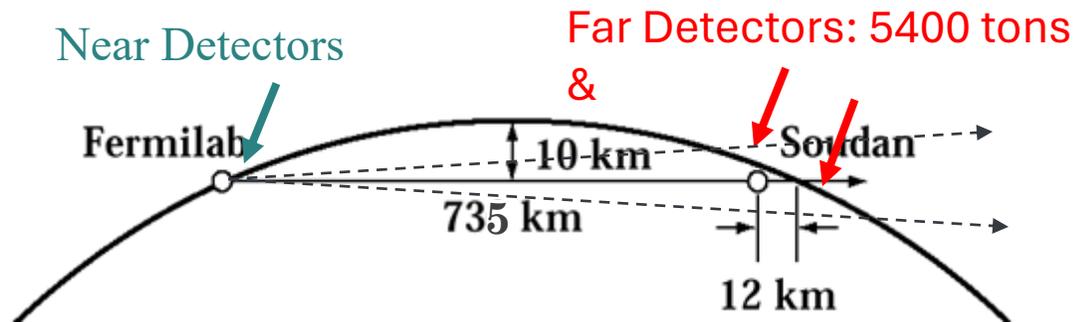
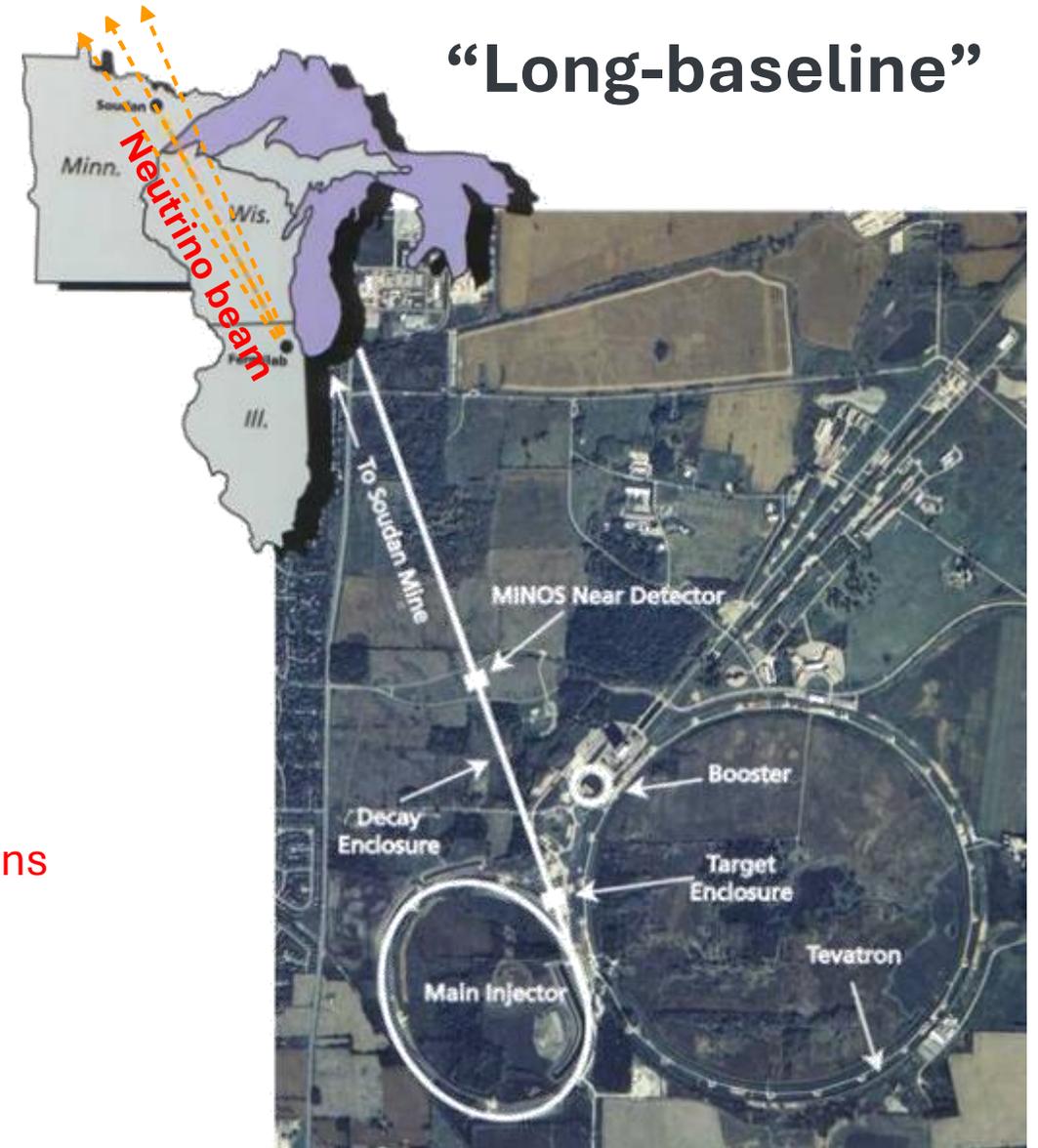
Beam composition:

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

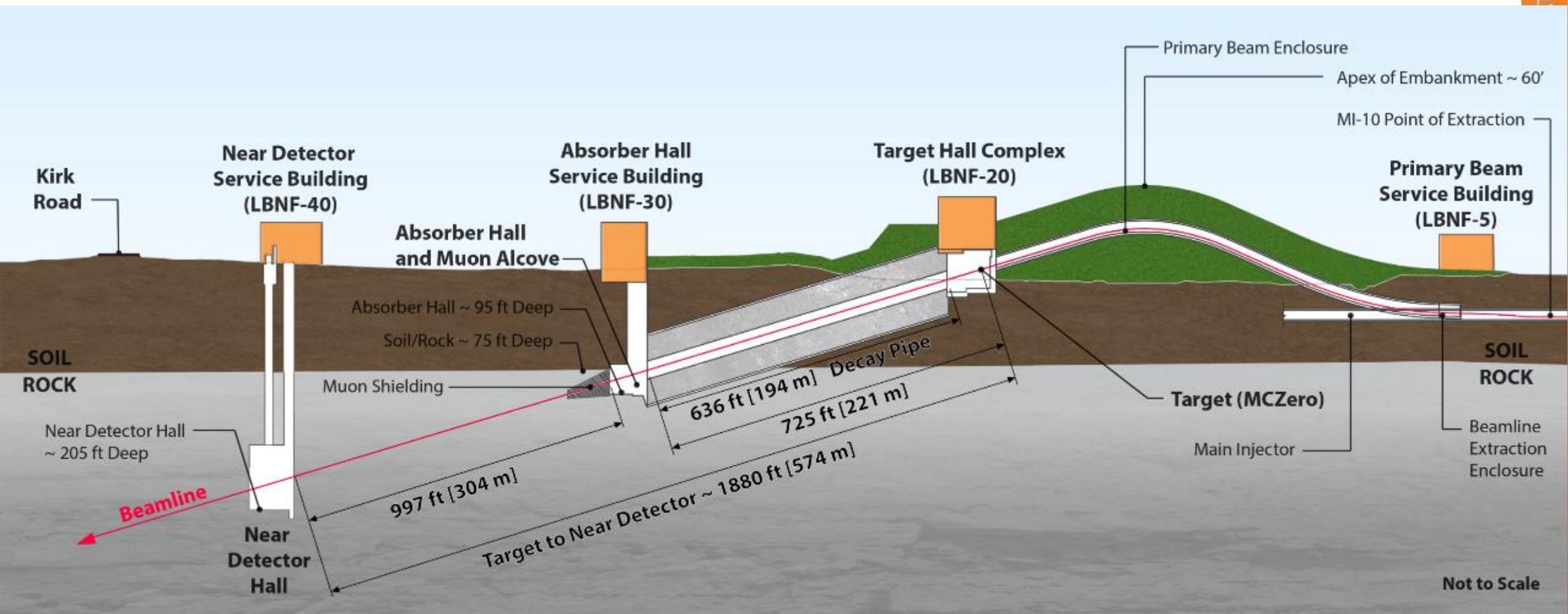
Mean ν_μ energy:
~0.8 GeV

The NuMI Facility: “Neutrinos ($\nu \rightarrow \text{Nu}$) at the Main Injector”

- Intense muon-neutrino beam directed towards Minnesota
- Main Injector supplies $50\text{--}70 \times 10^{12}$ 120 GeV 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

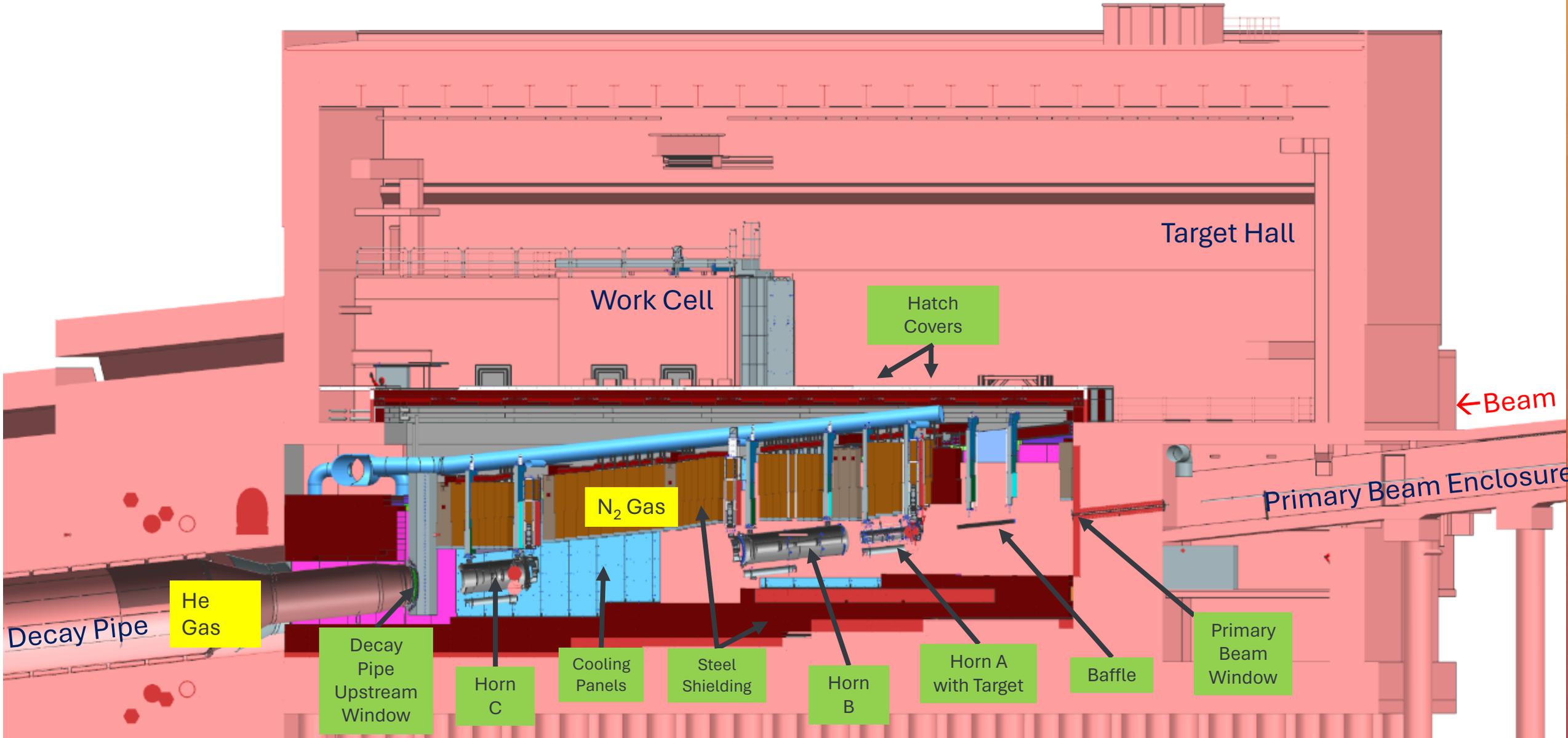


The LBNF Beam

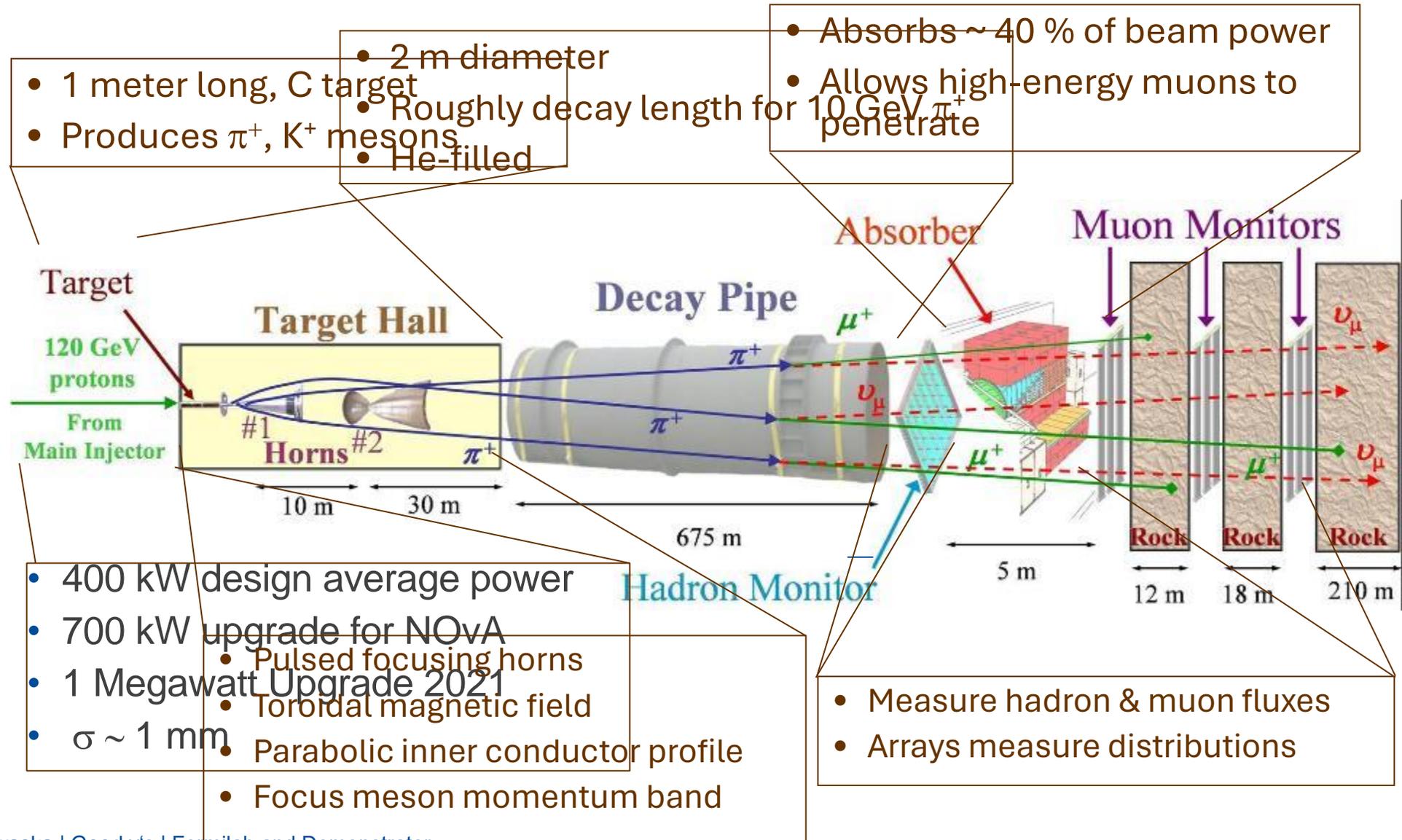


Facility designed for initial beam power of 1.2 MW, upgradeable to 2.4 MW

Section View of Target Complex – Target Hall



The NuMI Beam “Neutrinos at the Main Injector”



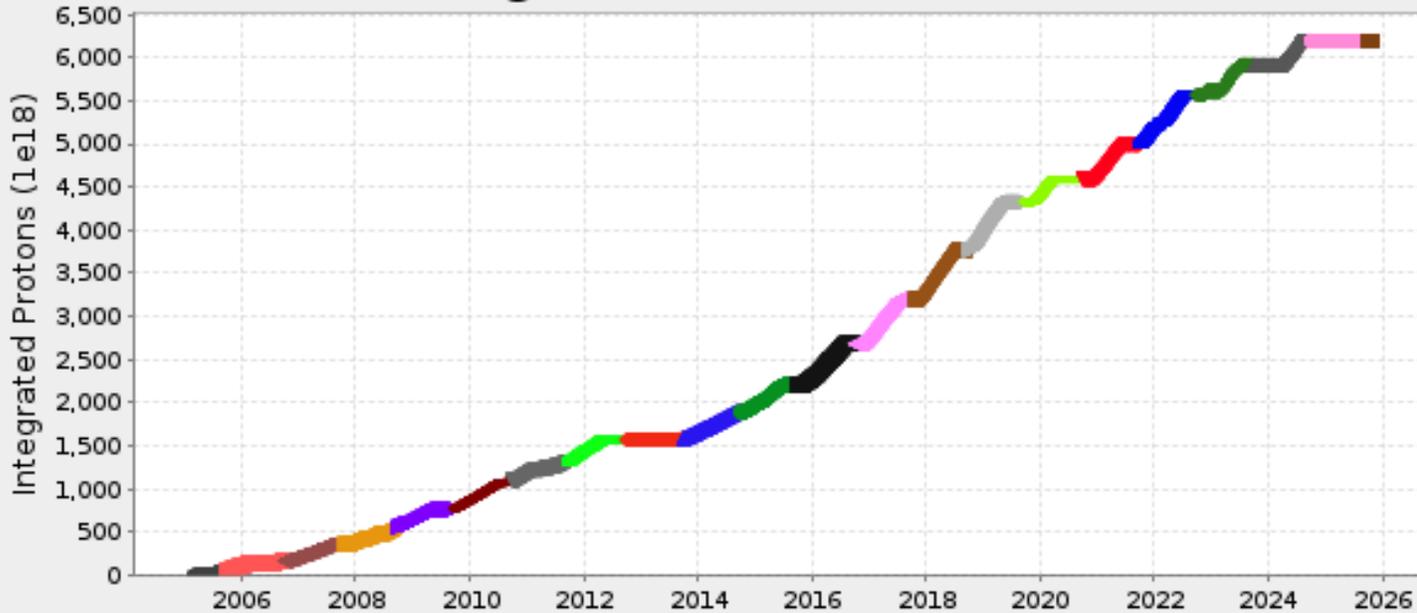
Mu2e: Muon to Electron Conversion Experiment

- Two transport solenoids and production solenoid were installed into the Mu2e experimental hall
 - Looking forward to detector solenoid
- Detectors components starting to install
- Beamline has been commissioning
 - Electrostatic septa operated for slow extraction
 - AC Dipoles being installed for extinction
- Plan to have a 4 month physics run before the long shutdown

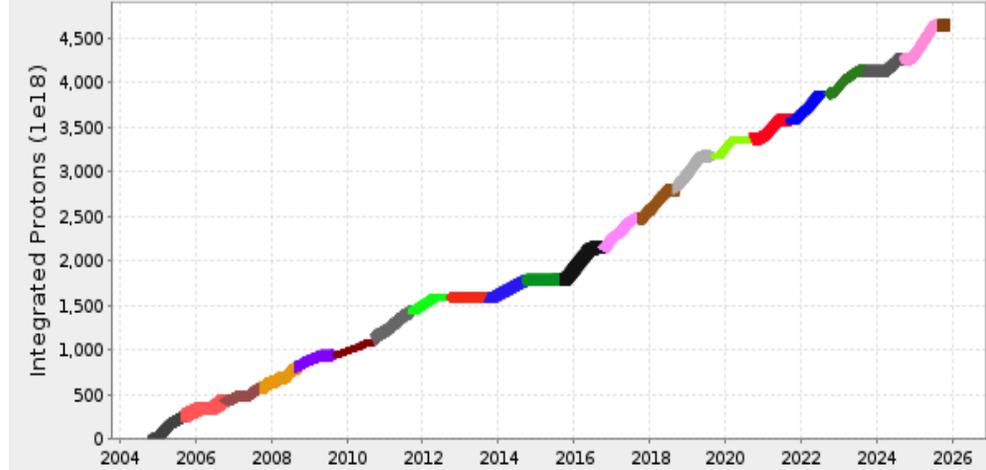


Accelerator Complex function - beam delivery to science users

Integrated Beam to NuMI



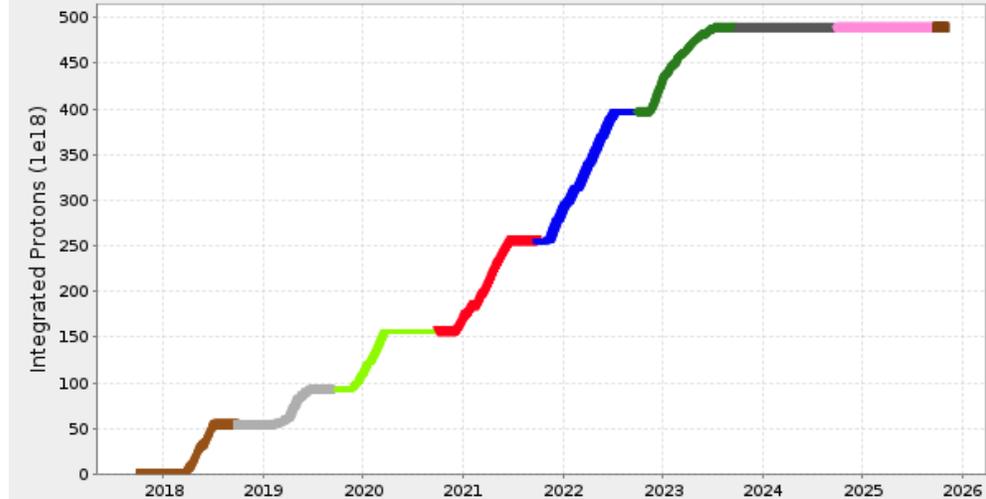
Integrated Beam to Booster Neutrino Beam



Protons-On-Target \propto Power \times Runtime \times Uptime

Multiple experiments operate concurrently

Integrated Beam to Muon

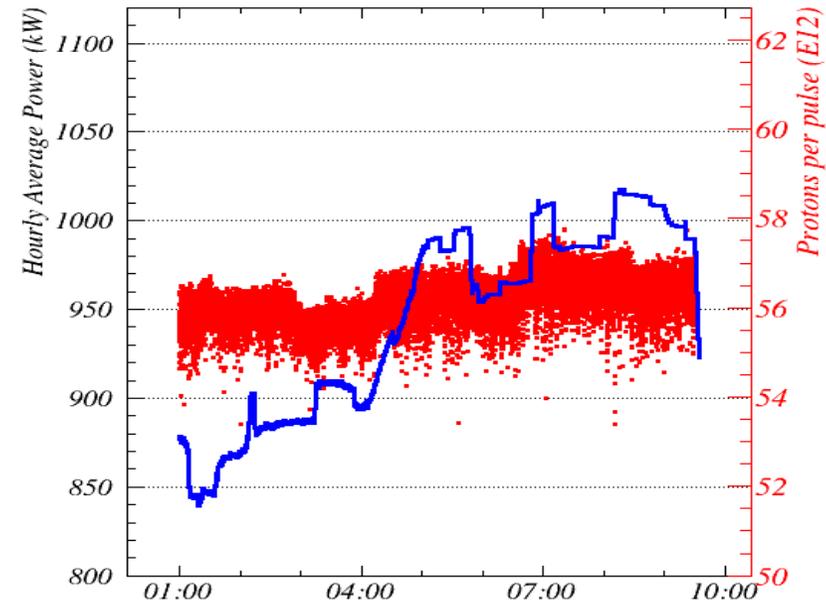


1 MW Test Run: June 26, 2024

- 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
- 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
- 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.



Main Injector 120GeV beam power





Major Issues Impacting Beam Operations



Kautz Road transform failure
August of 2024



Master/Kautz Rd
bushing
recall/failure



Main Injector heat
exchanger corrosion issue



Main Interconnecting duct bank between
Master Sub Station and Kautz Rd.

MI Heat Exchanger Corrosion



- At the end of the 2024 Summer Shutdown, the corrosion issue was found.
- Solution was to replace the end channels on the impacted heat exchangers.
- All heat exchangers have been repaired/replaced as of September 2025.

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



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



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

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
- Cryopant Building
- Linac Complex
- Booster Connection

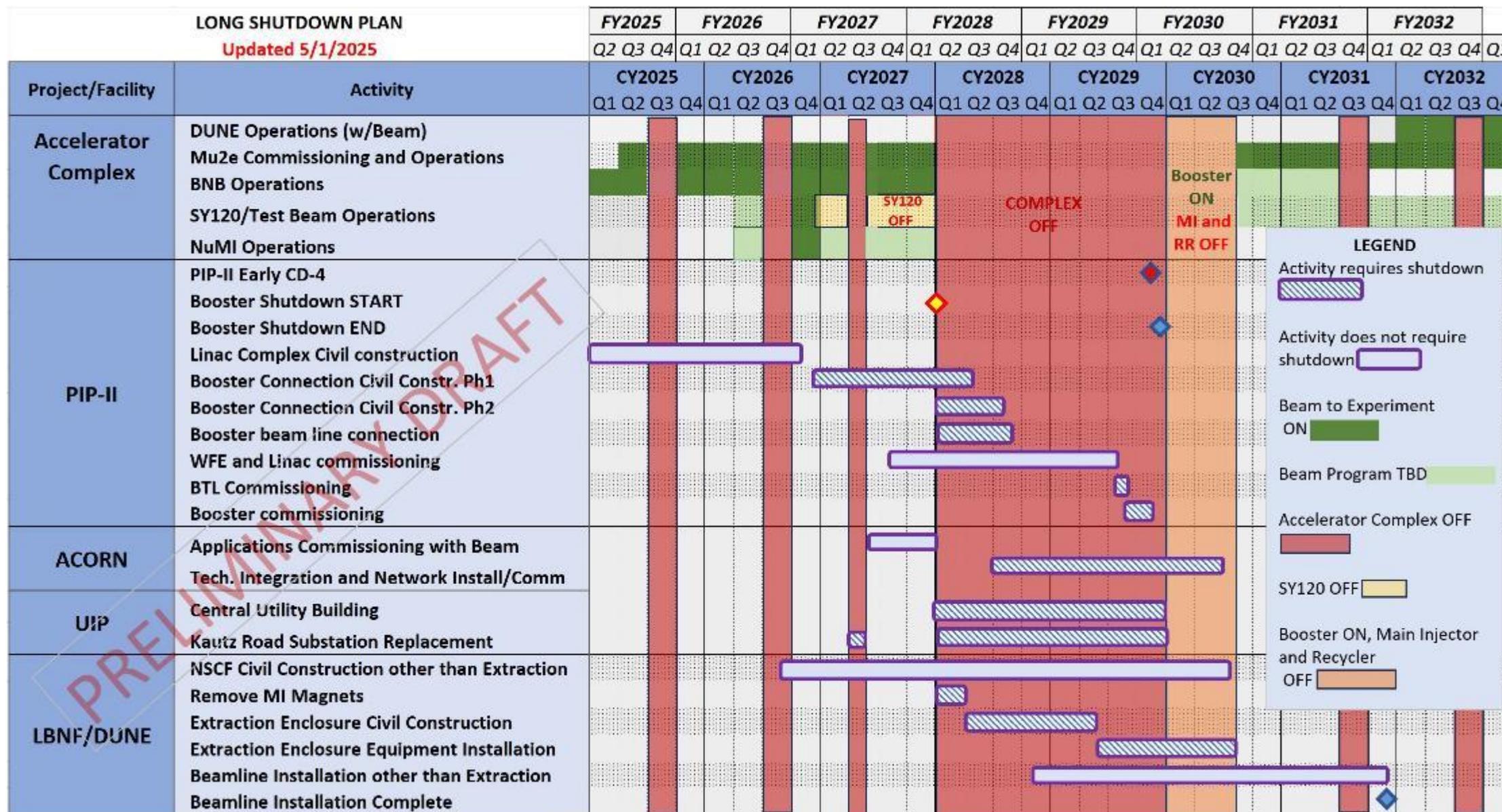
PIP-II Project construction

- 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



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 started in 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**

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

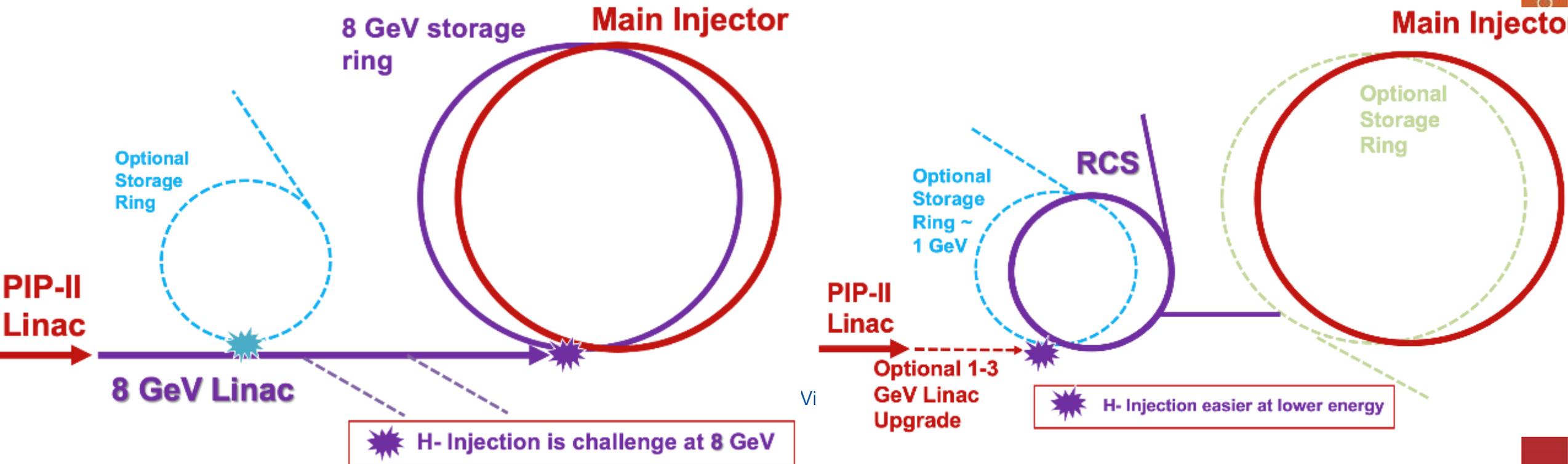
Task 4) Upgrade LBNF Target and Horns to reliable 2+ MW capability

Numerous concepts for future proton accelerators

Scenarios were developed informed by studies from the past and input to Snowmass/P5

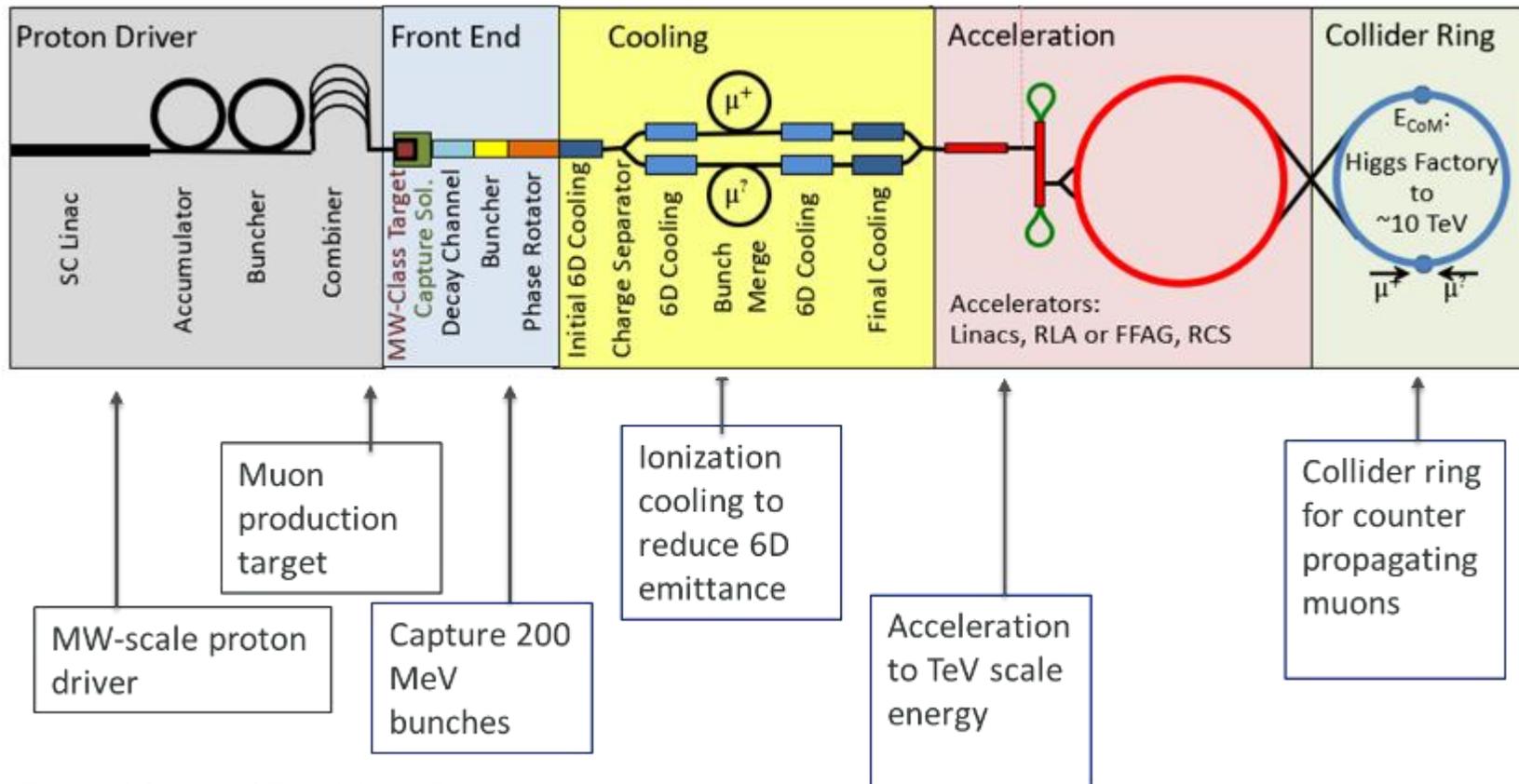
- Robust and capable 2.4MW accelerator complex for LBNF.
- Opportunities for high-power experiments at 1, 2, 8 GeV
- A platform for accelerator test facilities and demonstrators for future accelerators and colliders

Community engagement and design studies will continue

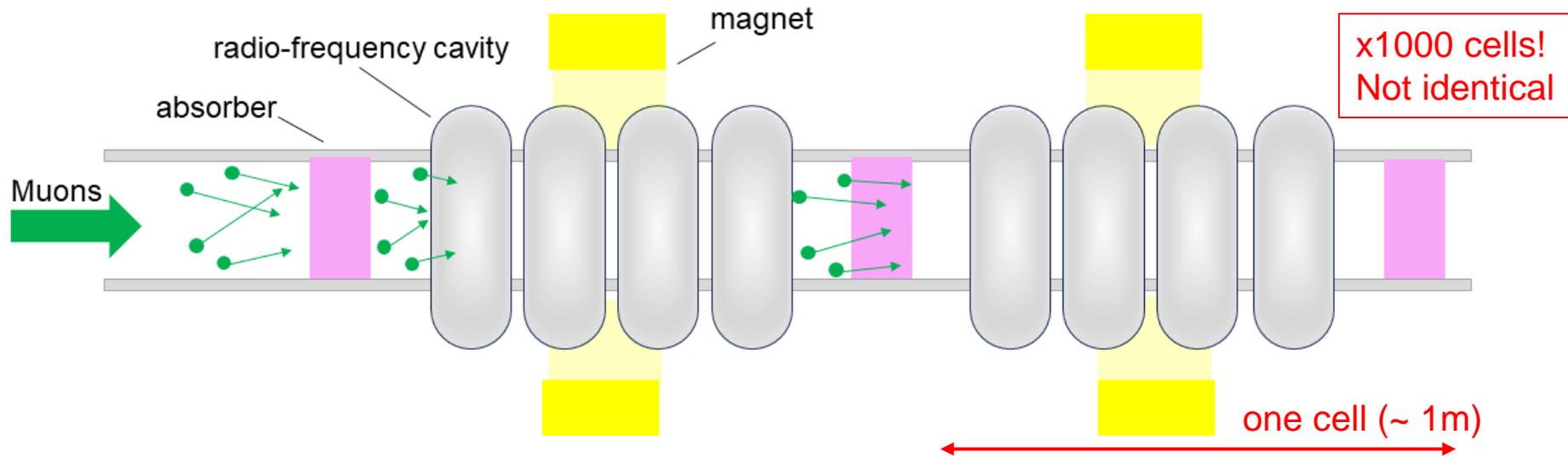


Muon Collider Demonstrator

- Many challenges throughout the proposed complex
 - Numerous technologies to be demonstrated
- Ionization cooling is one of the more novel approaches, and requires a great deal of integration



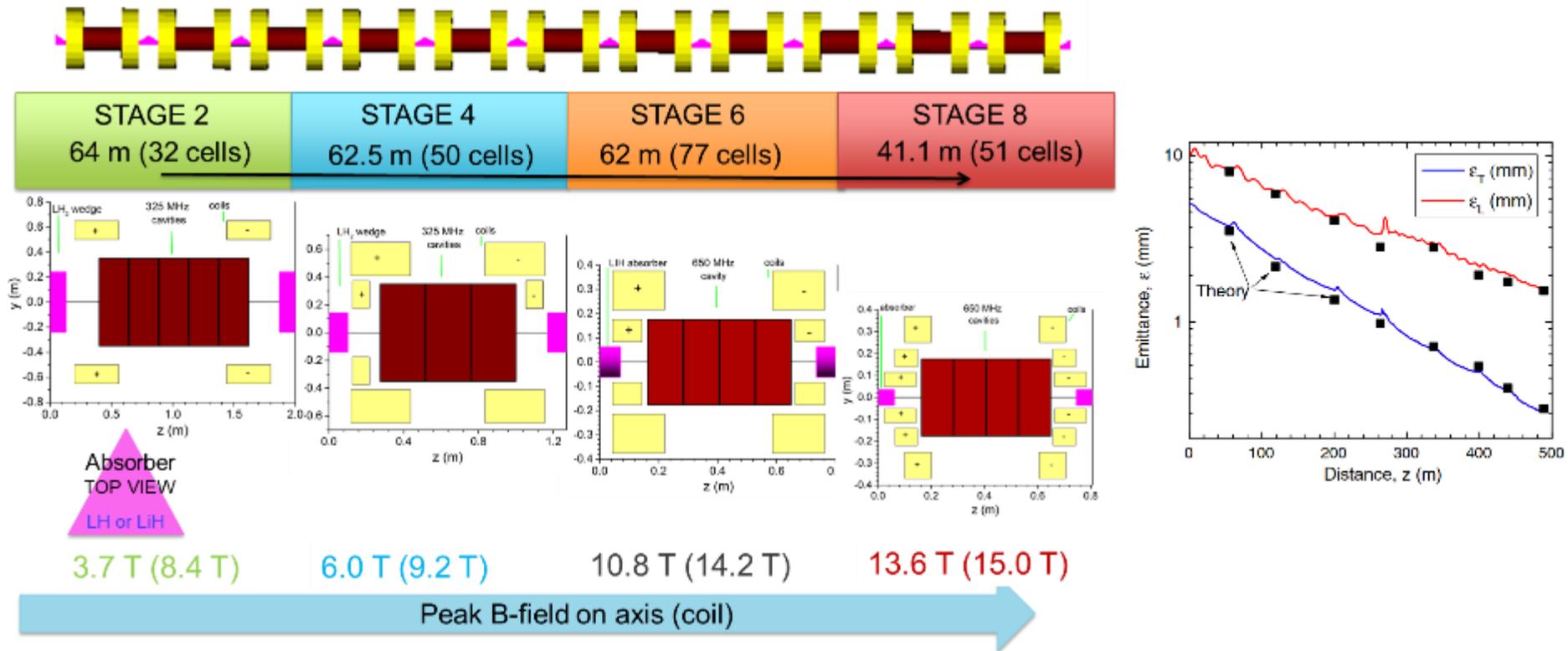
Concept of ionization cooling



- Considerations for MuC cooling:
 - Beam size must be small at the absorber to reduce scattering
 - Absorbers with low Z and large energy loss must be selected
 - Magnetic field has to increase in strength over distance to keep cooling
 - The magnetic field, makes normal conducting (NC) cavities the only option

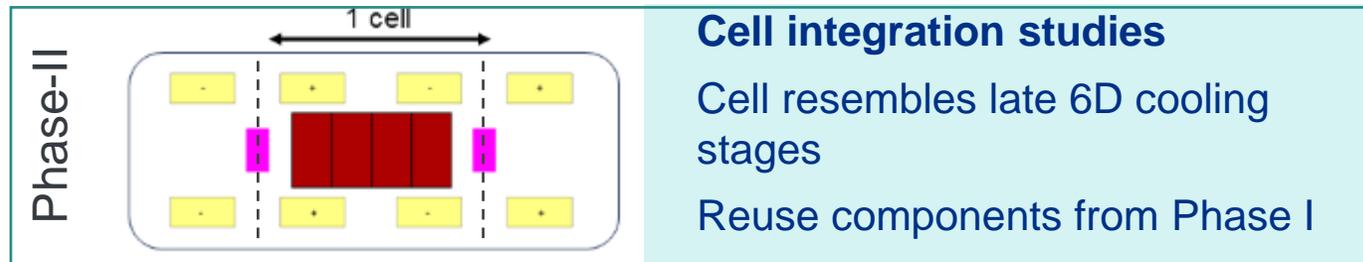
Design & simulation studies for cooling

- During the MAP-era a complete design of a Muon Collider cooling system was developed; further improved by the IMCC
- Simulation findings look promising but more R&D is needed to benchmark assumptions



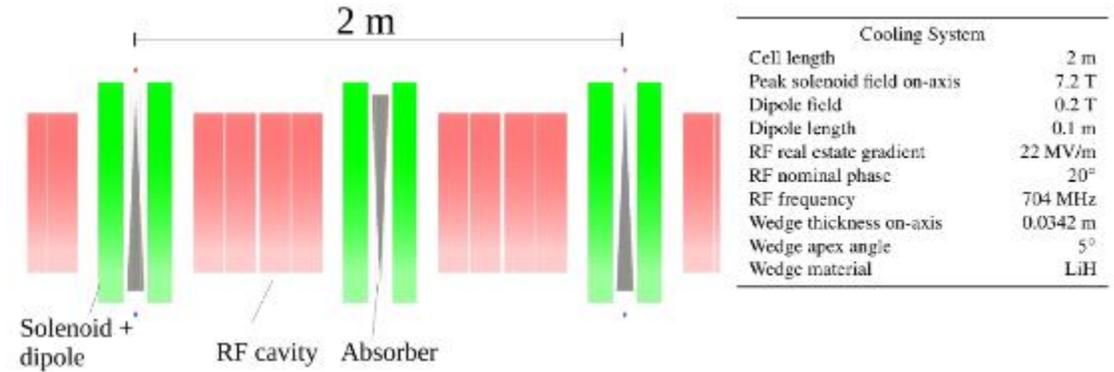
Muon demonstrator staging

- Detailed parameters will depend on available funding and resources

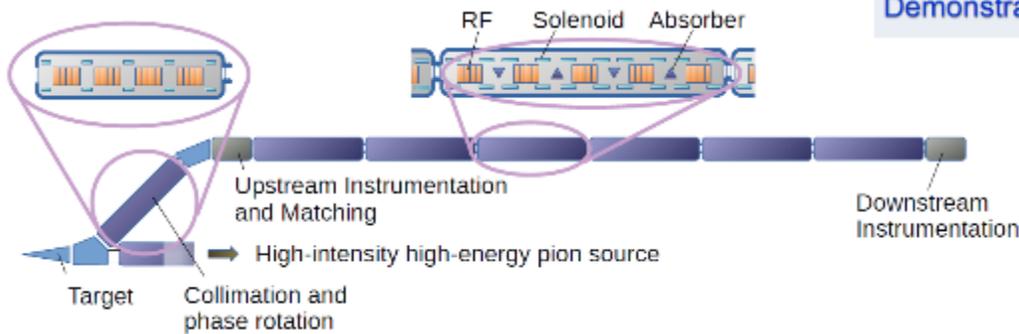


Full demonstrator with beam

- Design in progress
 - Muon source, target and transport
 - Beam transport
 - Cooling channel
- Investing commonalities with other applications



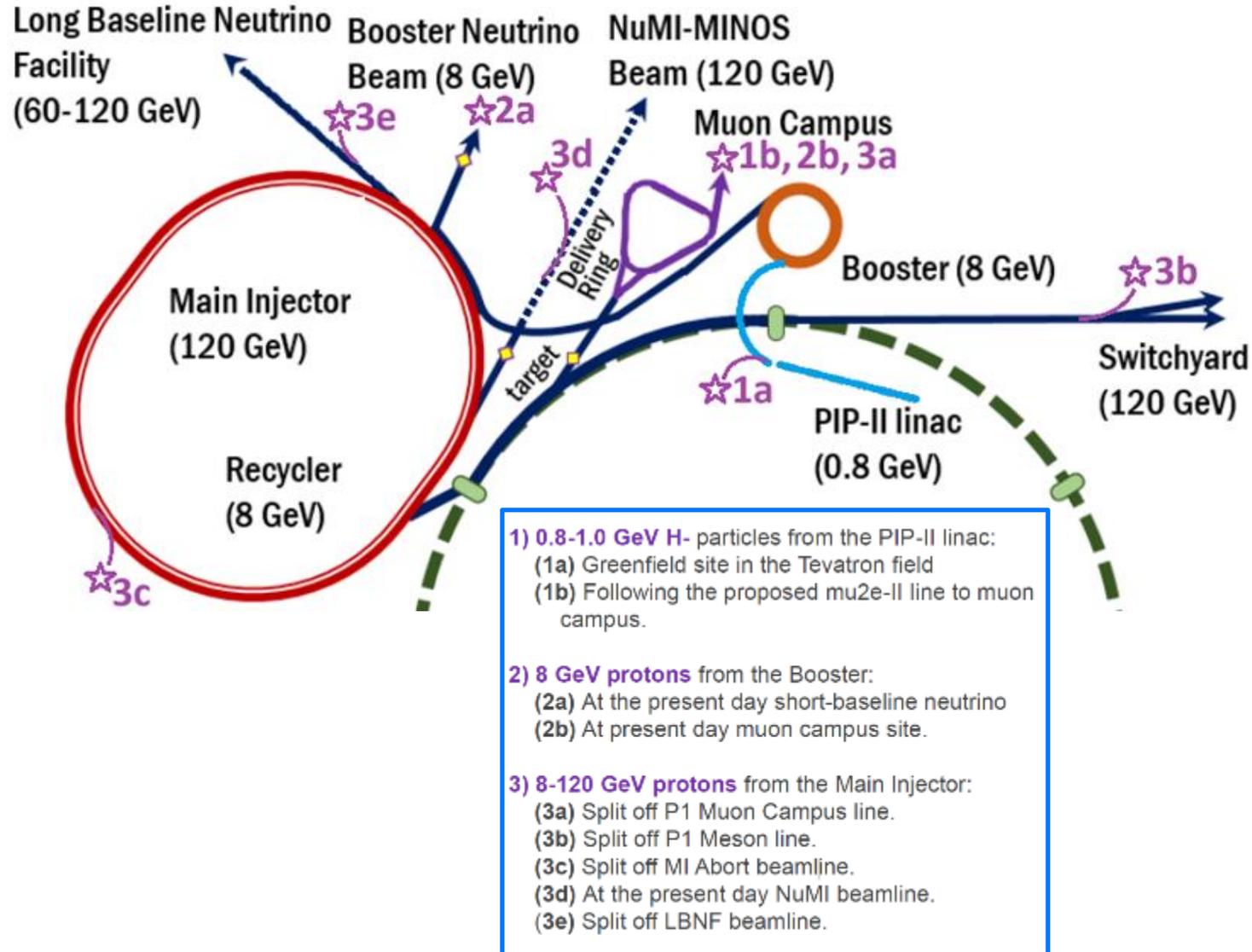
	Muon energy, MeV	Total length, m	Total # of cells	B_max, T	6D emm. reduction	Beam loss, %
Full scale MC	200	~980	~820	2-14	$\times 1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	$\times 1/2$	4-6%



C. Rogers, Phys. Sci. Forum **2023**, 8(1), 37

Fermilab with access to high-power proton beams and technological expertise, is a good candidate for a Cooling Demonstrator

Candidate locations at Fermilab





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Thank you!



Fermi *FORWARD*



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