# Next-Generation Accelerator Facilities at Fermilab: Megawatt Upgrade of the NuMI Neutrino Beam

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# Outline

- Fermilab Science Overview
- Accelerator Complex
- NuMI Beam & Experiments (400 kW)
- ANU Upgrade (700 kW)
- PIP Upgrade (700+ kW)
- Megawatt Upgrade (1 MW)
- LBNF/DUNE (1.2 – 2.4 MW)
- PIP-II (1.2 MW + 1.6 MW)
- Proton Intensity Upgrade (PIU) Planning (xxx MW in several “spigots”)
    - Options
    - Emerging Themes
    - R&D
    - Hooks into far-future Program
- Process going forward

# 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

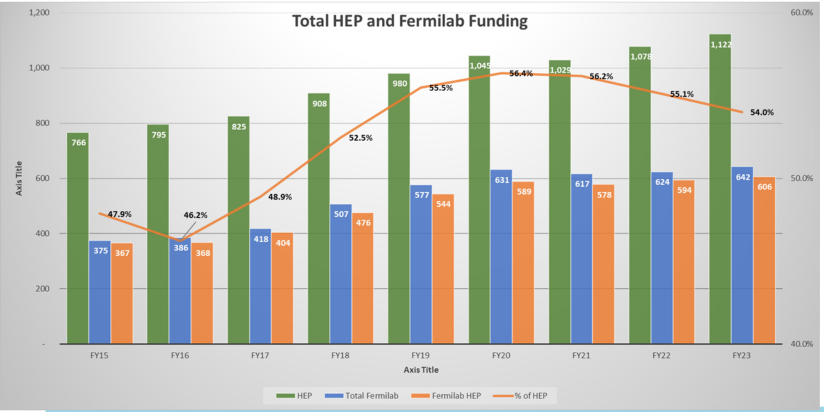
As Fermilab moves into its second 50 years, its vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

# 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 is following the P5 strategy

- The flagship projects LBNF/DUNE/PIP-II, HL-LHC anchor the program but 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
- Fermilab projects drive funding growth for HEP

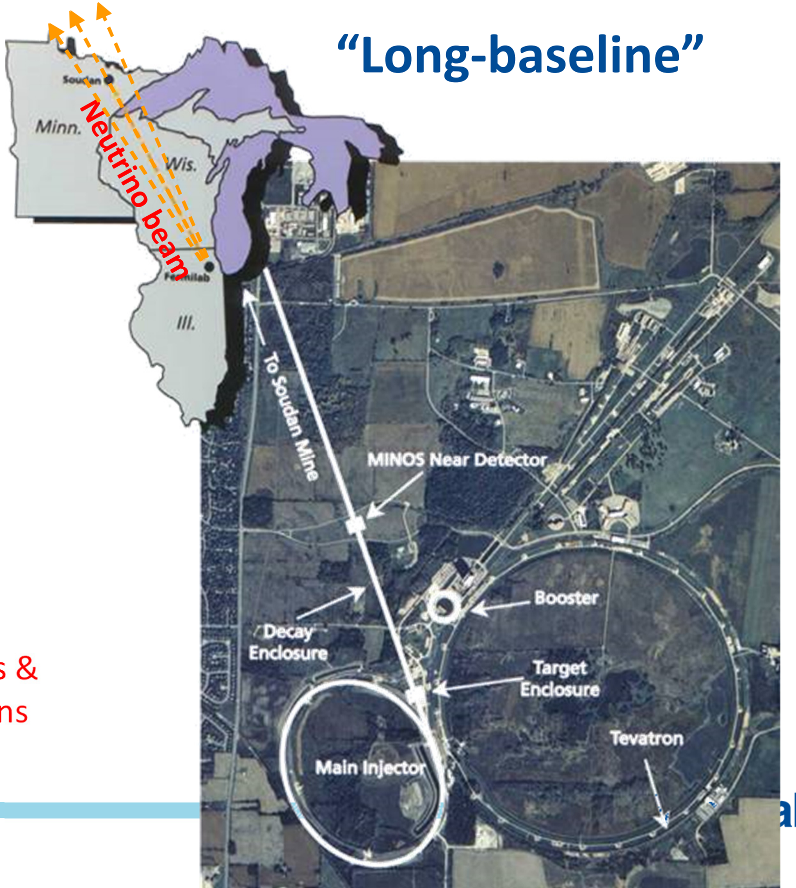



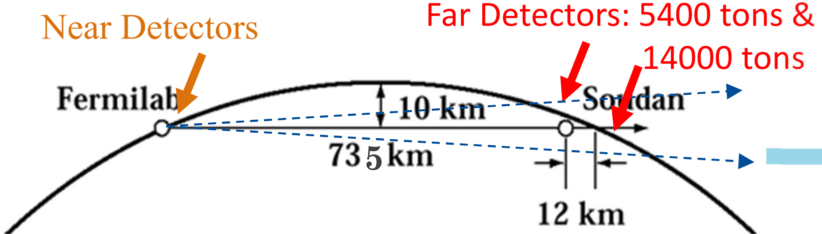

# Fermilab Accelerator Complex

# 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
- Each pulse produces about $2 \times 10^{14}$ $\nu_{\mu}$
  - ~ 20,000,000 Pulses per year
  - Direct beam 3° down
- Commissioned in 2005, expect to run to ~ 2027

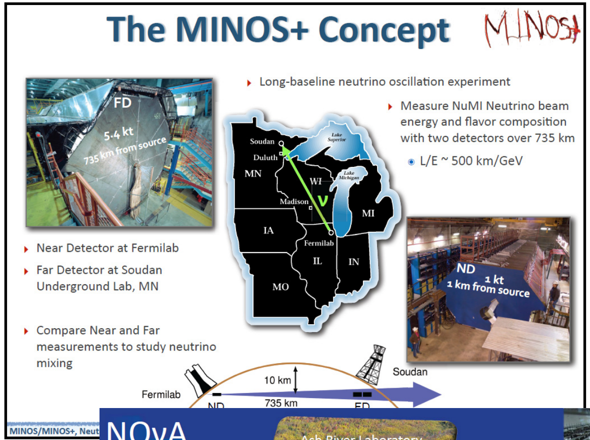
"Long-baseline"



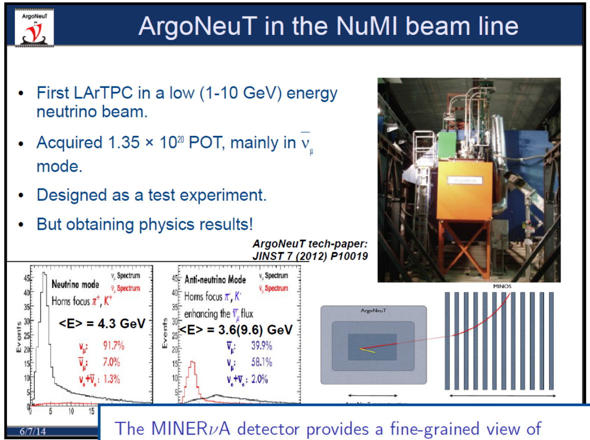
# Multiple Experiments in the NuMI Beam

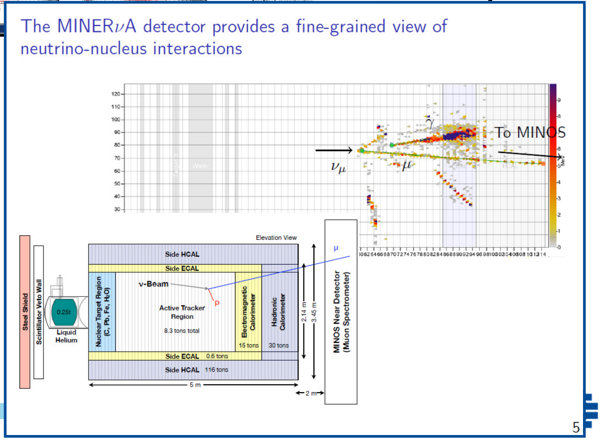
## Long-baseline oscillation experiments





## Neutrino scattering experiments

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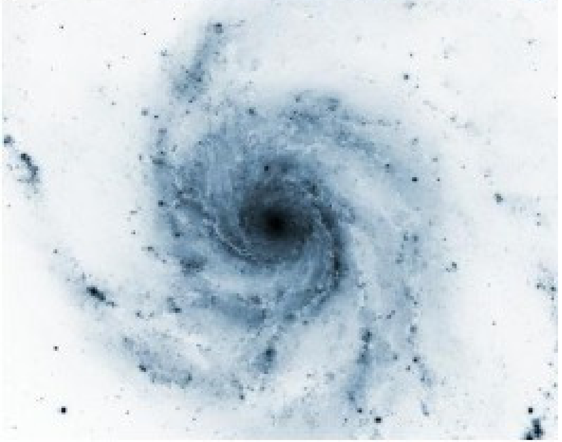
# Neutrino oscillations: Big picture questions

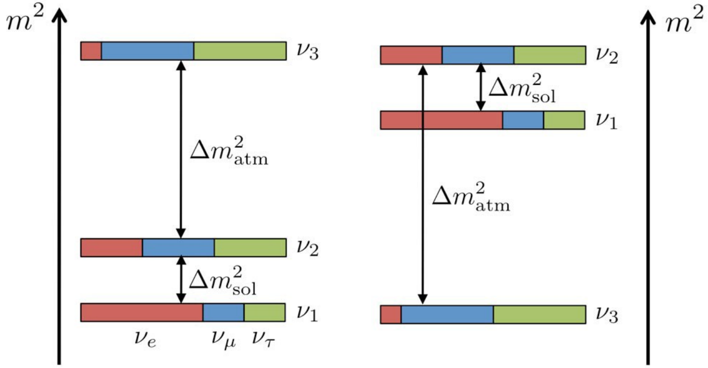
- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?
- How must the Standard Model be modified for neutrinos? Is the νSM complete? Are there additional neutrinos?



# Neutrino oscillations: current status

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Measure neutrino oscillations precisely, including $\nu_\mu \rightarrow \nu_e$ that is sensitive to CP violation
- Test the three-flavor paradigm → overconstrain the system




- Current precision:
  - $\theta_{13} \sim 2.7\%$ (reactor $\bar{\nu}_e$ disappearance)
  - $|\Delta m^2_{32}| \sim 3\%$ (reactor $\bar{\nu}_e$ disappearance and accelerator $\nu_\mu$ disappearance), mass ordering unknown
  - $\sin^2\theta_{23} \sim 0.5 \pm 0.1$ (atmospheric and accelerator $\nu_\mu$ disappearance + $\nu_e$ appearance)
  - $\delta_{CP}$ unknown

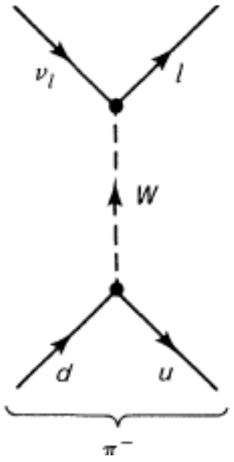
# Why a Beam? – Controlled Laboratory Experiment

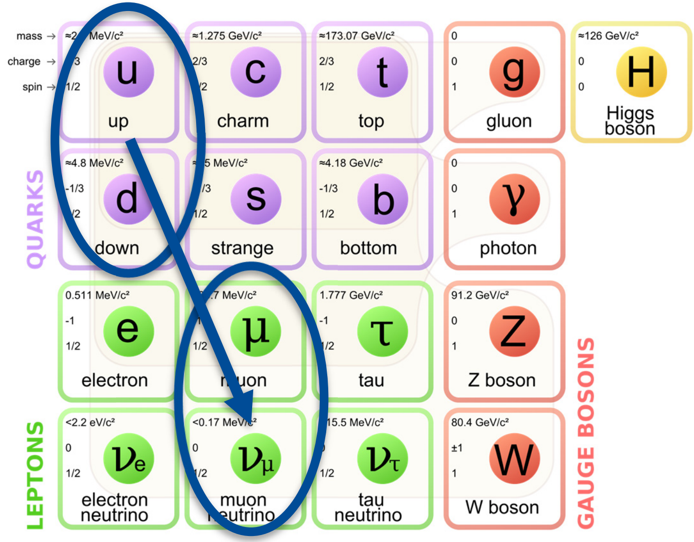
- Natural sources exist – but they are very weak and not necessarily well understood
  - Solar and atmospheric neutrinos were only understood once oscillations were established and well measured
    - Moving from observation to experiment
  - Supernovae are hard to come by
- Artificial beams are controlled and intense ⇨ Precision!
  - Decide when, where, and how the beam is generated
  - Detectors are placed strategically
  - Beams can be controlled with precision – vital as measurements approach 1%
- Applications:
  - Today neutrino oscillation is the first focus
  - Probe of nuclear structure
  - Observation of the neutral current
  - Demonstration of neutrino flavor (muon, tau)
  - Measurement of weak mixing angle

# Pion Decay!

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

- Most all of our neutrinos come from pion decays
  - Convert the kinetic energy of the accelerator beam into new massive particles (pions), which decay to neutrin0s
- Two quarks, bound together by gluons, convert into a neutrino and muon




- A “simple” decay (at first)
  - Pion mass ~ 140 MeV/$c^2$, Muon mass ~ 105 MeV/$c^2$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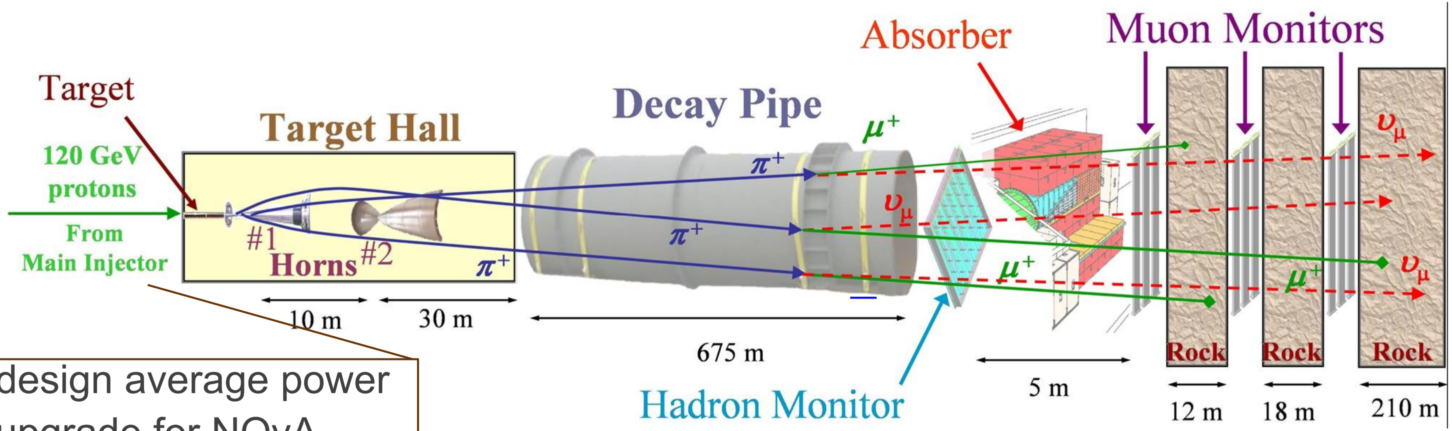
# Neutrino Beam in a Nutshell (NuMI)




- 400 kW design average power
- 700 kW upgrade for NOvA
- 1 MW upgrade just complete
- $\sigma \sim$ 1-1.5 mm



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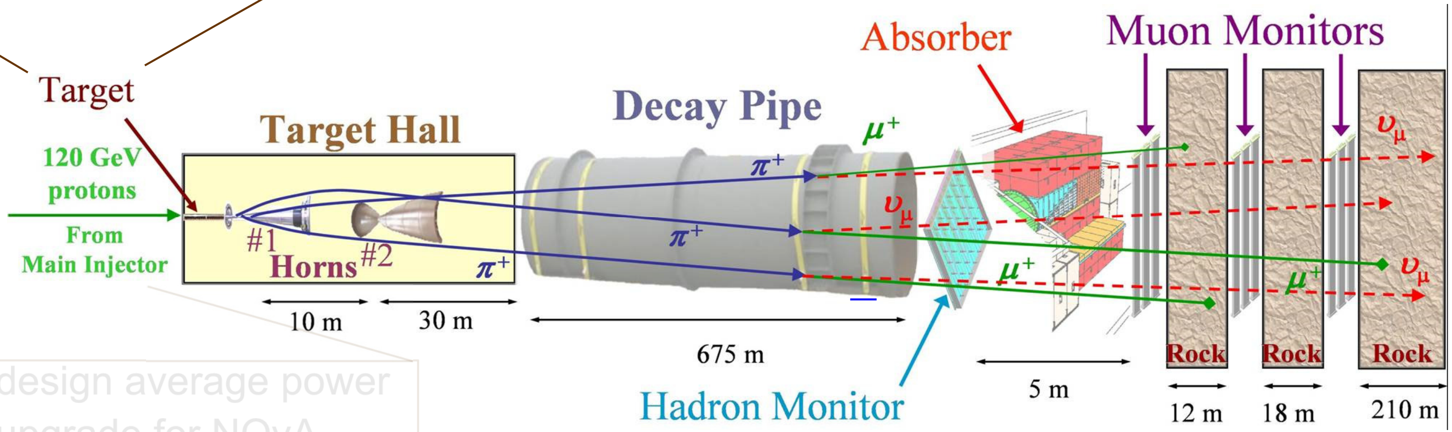
- 2 interaction length, C target
- Produces $\pi^+$, $K^+$ mesons

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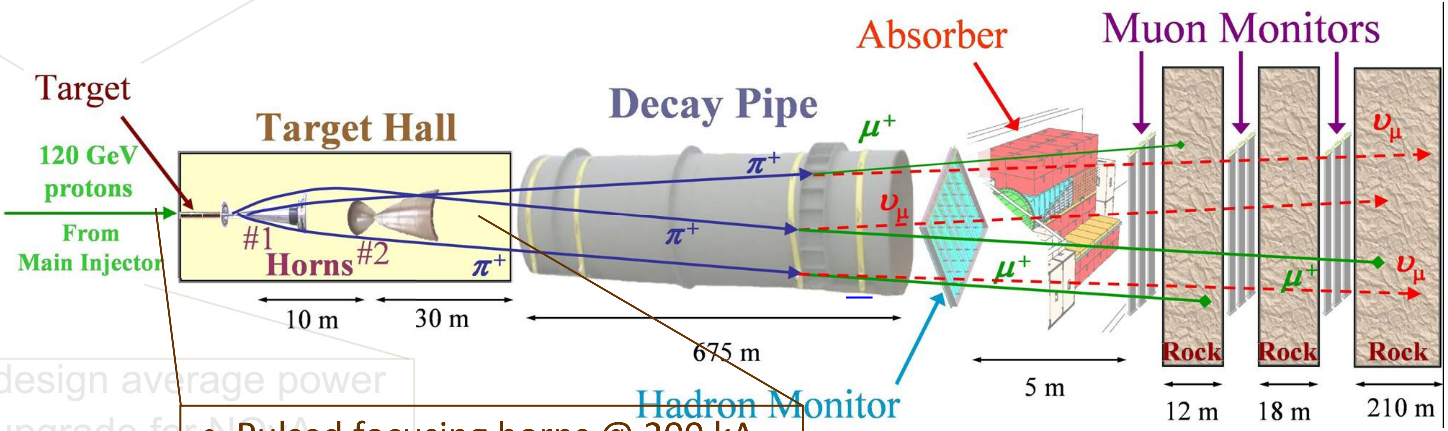


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- Pulsed focusing horns @ 200 kA
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

# Neutrino Beam in a Nutshell (NuMI)

- 2 m diameter
- Roughly decay length for 10 GeV $\pi^+$
- He-filled

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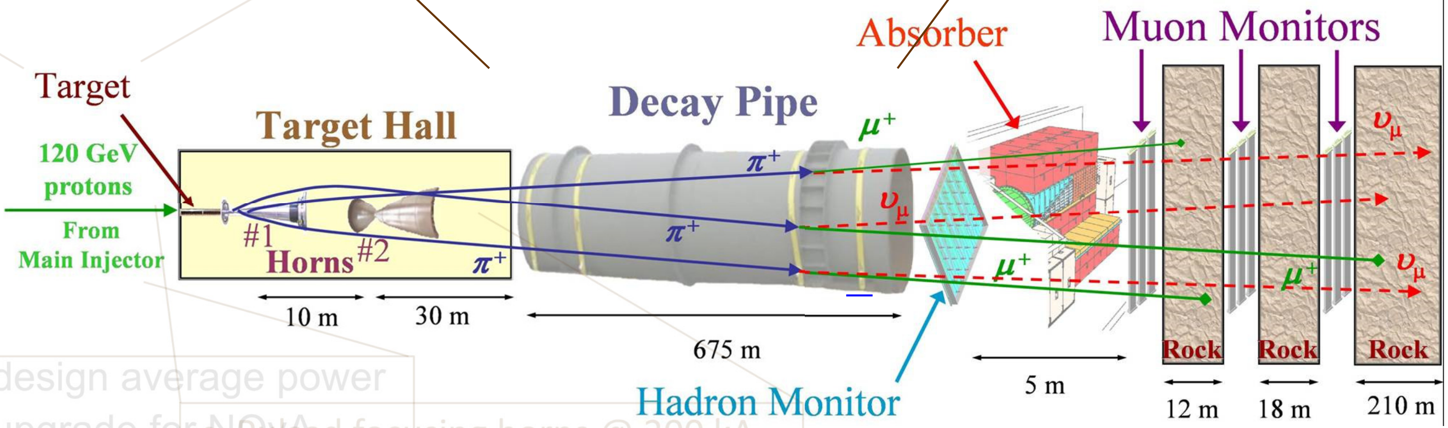


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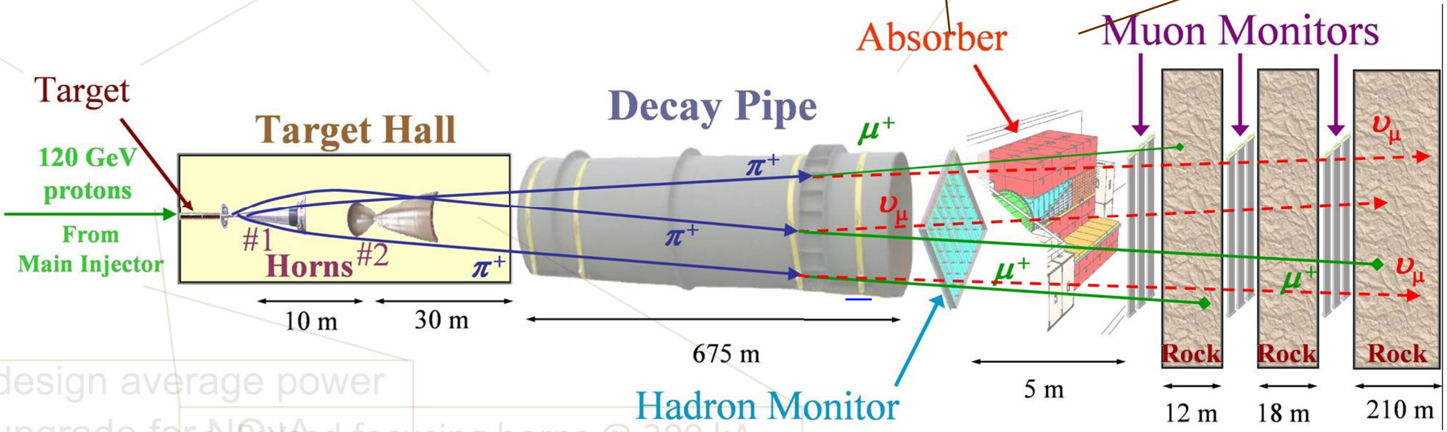
- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate

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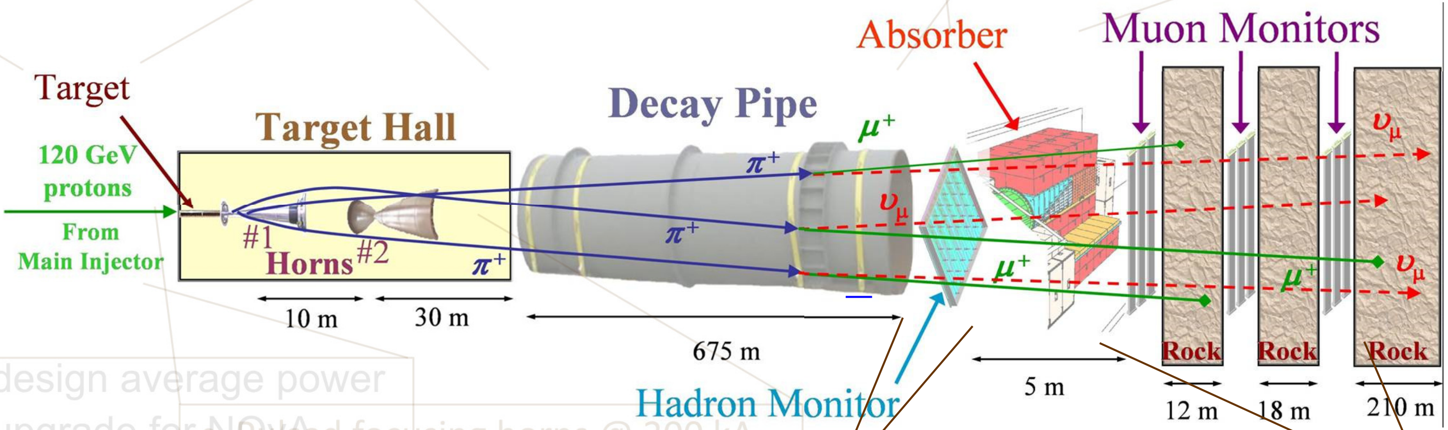


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- Measure hadron & muon fluxes
- Arrays measure distributions

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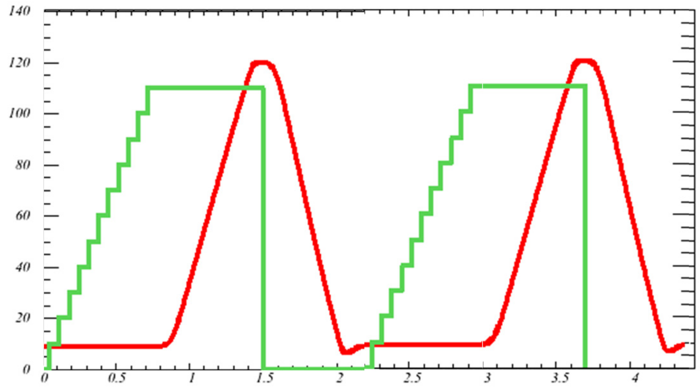
# Defining Characteristics of Long Baseline Beams

- Proton Beams: synchrotron based, ~ 1 MW
  - High Stored Energy: ~ 1 MJ
  - Small Beam Spot: 1 – few mm
  - High Proton Energy: 30-120 GeV
  - Single-turn extraction, long cycle time: 1 – few seconds
- Pion Focusing: Pulsed horns
  - Horns more efficient than quads
  - High currents: few hundred kA
- Large Decay volume
  - Meters in cross-section
  - 100s of meters in length
- Beam radiation dispersed over extended area

  Tritium, activation, corrosion, cooling

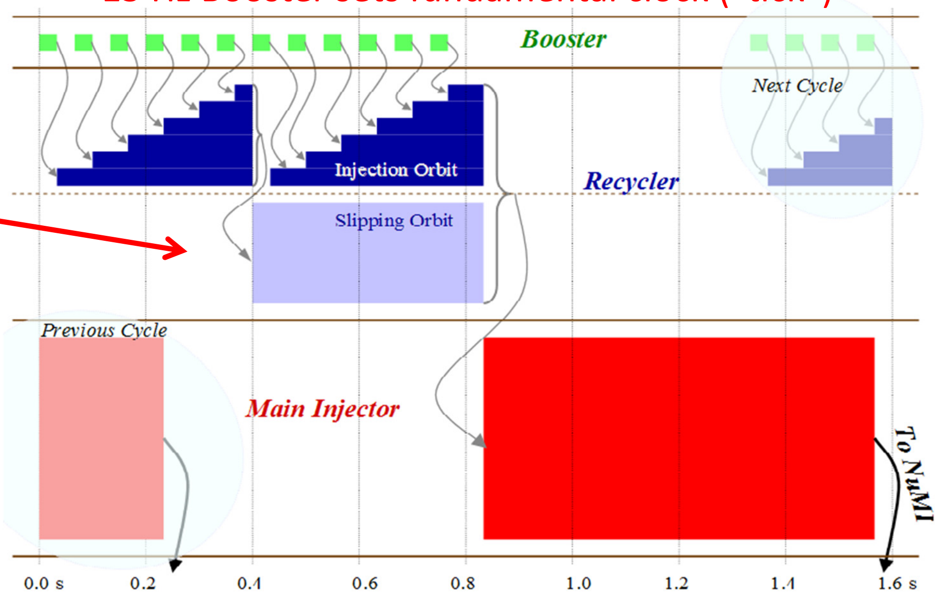
# NOvA Accelerator & NuMI Upgrades (ANU): the 700 kW Upgrade

- Previous Stacking operation (~ 380 kW in 2011):
  - $H^-$ linac at ~35 mA
  - $H^-$ stripping into Booster 10-11 turns:  4.3e12 protond
  - 11 pulses (at 15 Hz) into Main Injector with RF slip stacking
  - Ramp to 120 GeV at 204 GeV/s and extract to NuMI target



# Increasing Beam Power to 700 kW

“slip-stacking” cleverly gets around limits on Booster batch size




- Employ Recycler ring to load 12 slip-stacked Booster batches *while* the Main Injector was ramping

The installation of a direct injection line from the Booster to the Recycler to eliminate Main Injector loading time was the key component of the “ANU” improvement campaign for NOvA (400 kW->700 kW) available by 2015

# Goals for the Proton Improvement Plan (2011-2018)

- The ***Proton Improvement Plan*** should enable Linac/Booster operation capable of
  - Delivering 2.3E17 protons/hour (at 15 Hz) ***x2 previous***

  ***while***
  - Maintaining Linac/Booster availability > 85%, and
  - Maintaining residual activation at acceptable levels

  and also ensuring a useful operating life of the linac through 2023, and Booster through 2030 or later

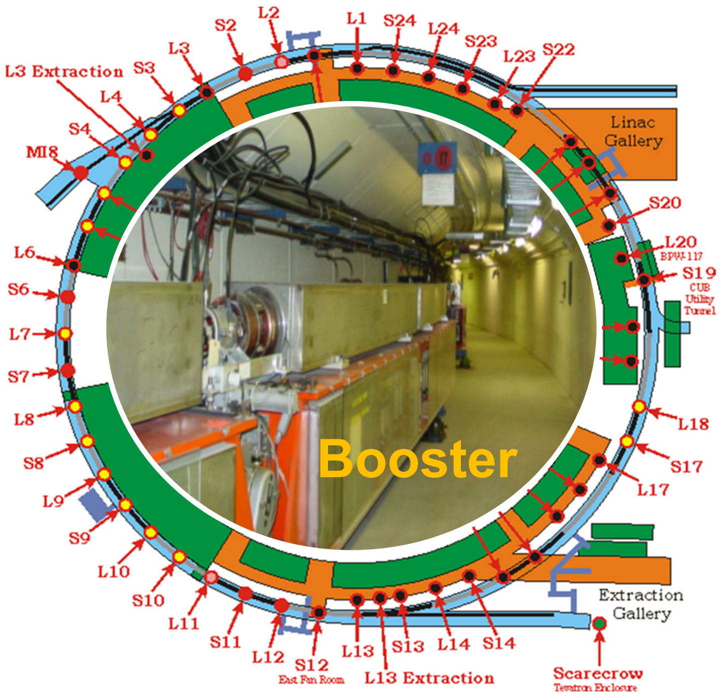
The scope of the ***Proton Improvement Plan*** included
  - Upgrading (or replacing) components to increase the Booster repetition rate
  - Replacing components that have (or will have) poor reliability
  - Replacing components that are (or will soon become) obsolete
  - Studying beam dynamics to diagnose performance limitations
  - Implementing operational changes to reduce beam loss

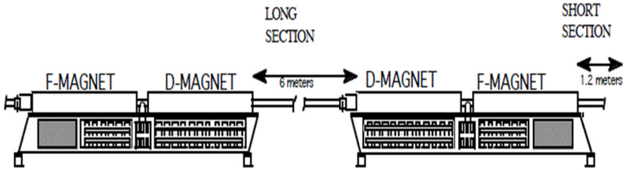
# Booster Overview

- H$^-$ ions are 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
No failures after initial phase…
but 8 spares have been refurbished as part of PIP…





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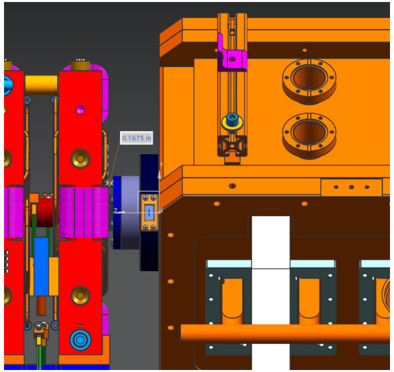
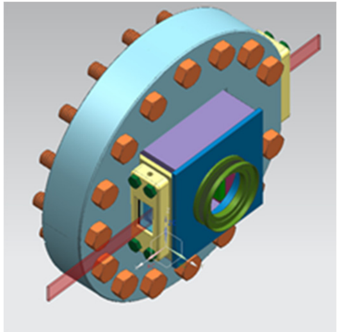
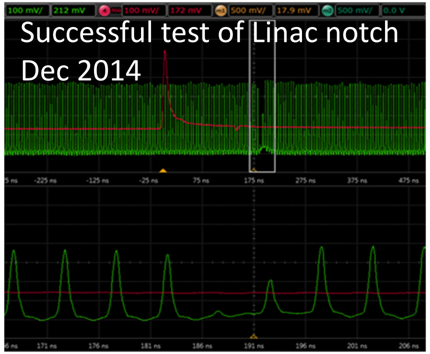
# Booster loss and Linac laser notch

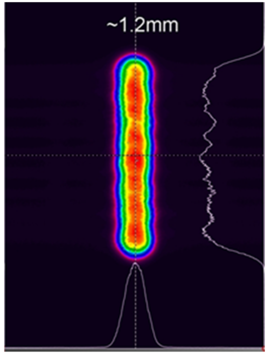
- Doubling the beam repetition rate requires cutting the losses per Booster cycle in half
- Addressing each of the three main areas of Booster beam loss:
  - Injection
  - Notching the beam to create a gap for extraction kickers to fire
  - Transition, related to RF during acceleration
- Phased improvements to notch creation
  - New cogging system which allowed notching at 400 MeV instead of 700 MeV $\rightarrow$ lower energy losses into an absorber
- Final phase was a laser notcher in Linac MEBT
  - Laser Neutralization of $H^-$ with zero space
  - Unique laser with micro, meso, and macro timescales, and vertical spatial profile





Optical cavity
(attached end of RFQ)



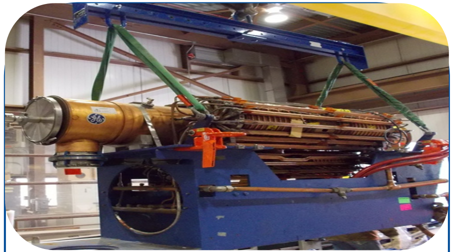




Laser profile

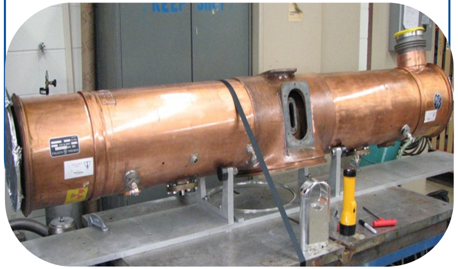
# Booster PIP - Refurbishment of 40 year old cavities

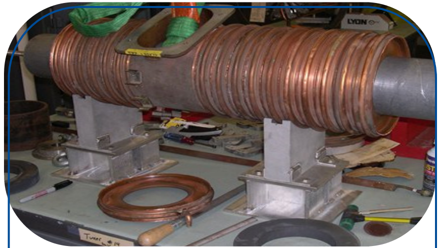
(Weeks)

Cool-down
Remove Tuners
Cavity Removal
Rebuild - Cones & Tuners
Rebuild Stems/Flanges
Re-Assemble
Testing

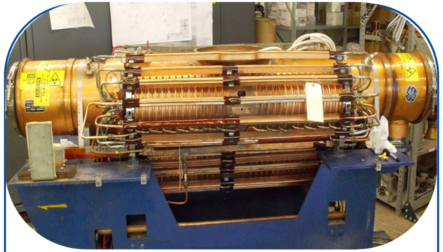


Cavity Removal - Stripping

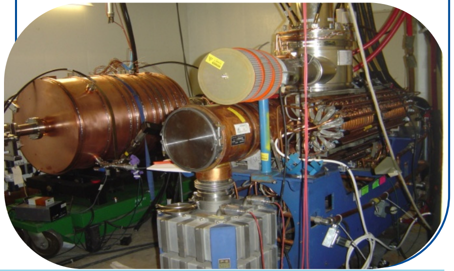




Tuners Rebuild



Rebuild and Test





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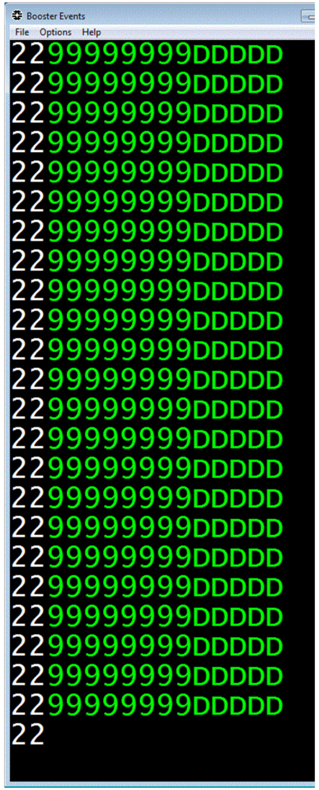
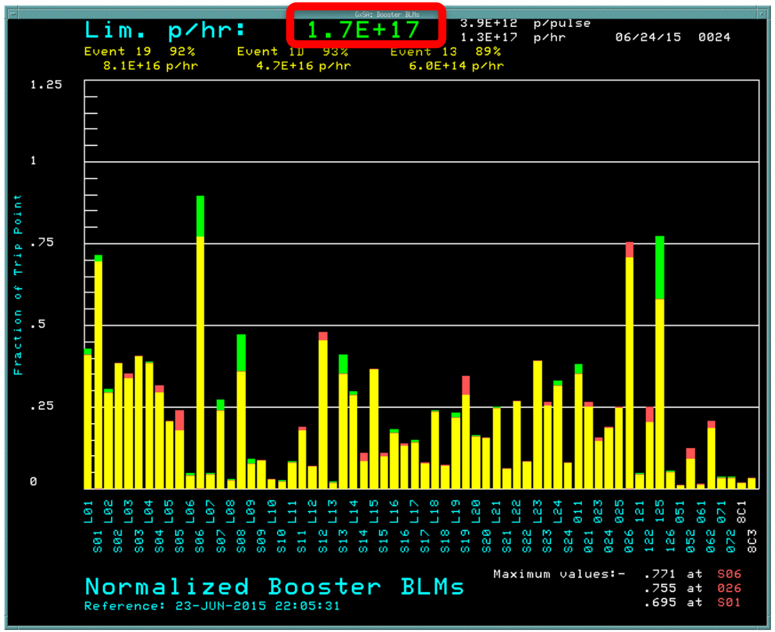
# Booster 15 Hz – A significant achievement for PIP/FNAL




TLG with 13 (fixed target event) beam events & 2 pre-pulses, $17 (Booster event) then replaced the pre-pulses for full **15** Hz beam operation – record intensity **>2.1E17/hr** !

$19 (NoVA event) or $1D Boone Event) cycles at reduced intensity allowed for 15 Hz beam and some overhead




PIPs success led to the possibility to increase Main Injector beam to close to 1 MW with modest upgrades in other parts of the accelerator chain



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# 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
  - Record 893 kW beam power achieved in April 2022

| | 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 | $4.0 \times 10^{13}$ | $4.9 \times 10^{13}$ | $6.5 \times 10^{13}$ |
| Spot Size (mm) | 1.0 | 1.3 | 1.5 |
| Beam pulse width | 10 microsec | | |



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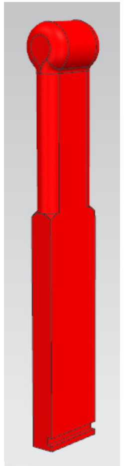
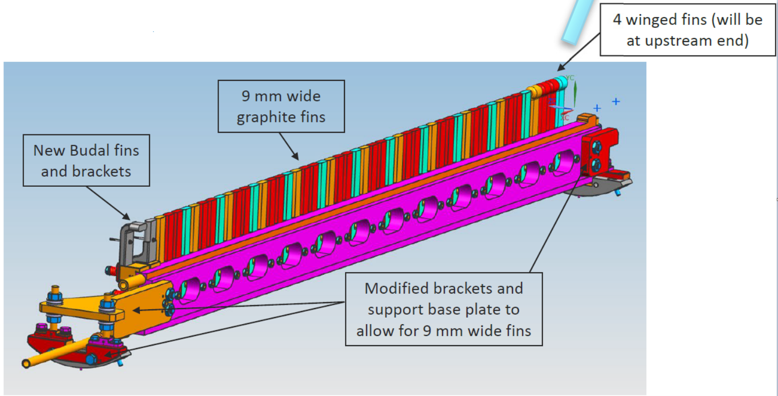
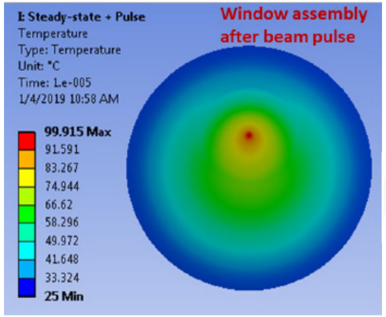
# NuMI AIP – 1 MW Target Upgrade

- Core redesigned for increased beam spot size from original 1.3 mm to 1.5 mm
  - Graphite fins width increased from 7.4 mm to 9 mm
  - Winged fins added upstream in case of beam mis-steering
- Cooling loop added on downstream Beryllium window

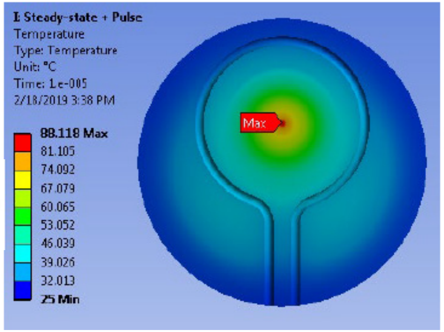
| | $T_{grahite,max}$ |
|---|---|
| 700 kW design | 913 ℃ |
| 1 MW design | 890 ℃ |





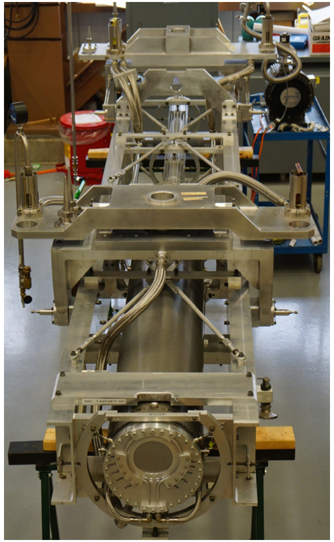

*Former Be window design temperature immediately after beam spill*




*1 MW Be window design with cooling loop temperature immediately after beam spill*

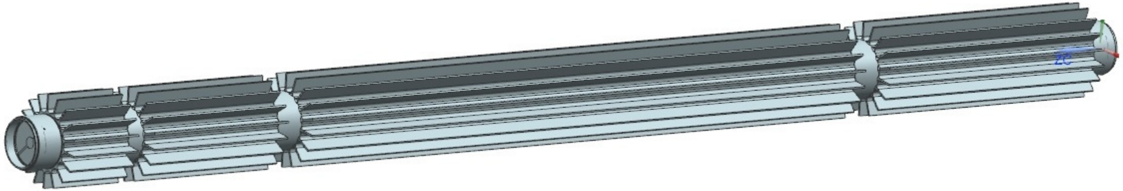
# NuMI AIP – 1 MW Target Upgrade

- Baffle core increased bore size from 13 mm to 15 mm
  - Integrated in target carrier
- 1 MW target successfully installed during 2019 accelerator summer shutdown



*1 MW target completed*

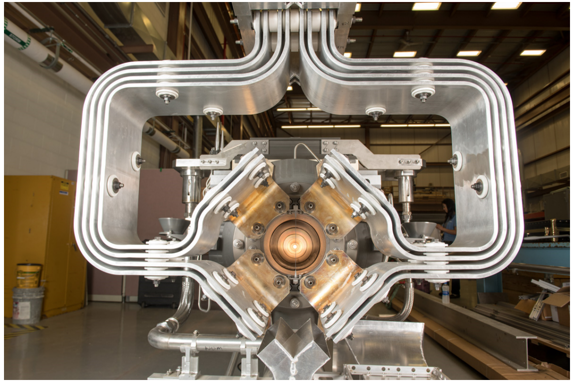
*1 MW target lifted during installation*



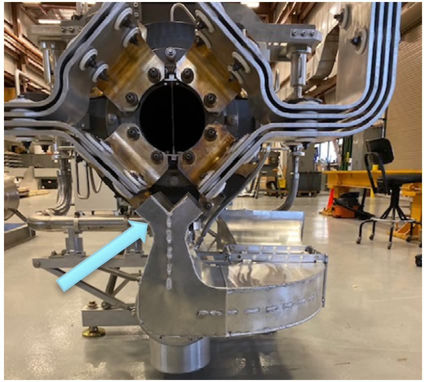
*1 MW target baffle*

# NuMI AIP – 1 MW Horn Upgrade

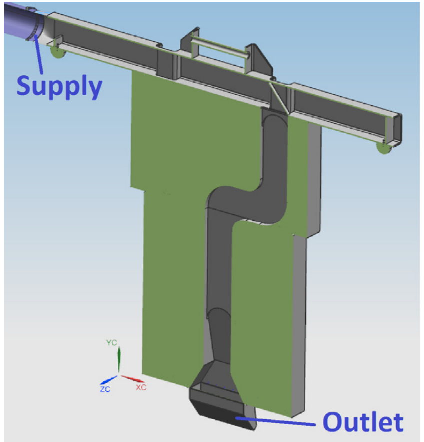
- Design changes to increase cooling to keep stripline < 100 ℃
  - Re-design of air diverter at base of stripline for improved air flow
  - T-Block air cooling
- Stripline modified for 1 MW
  - Changed material from Al 6101-T61 to 6013-T651 in key sections
  - Higher yield strength and increased fatigue life



*NuMI 1 MW horn stripline*



*Horn stripline air diverter*

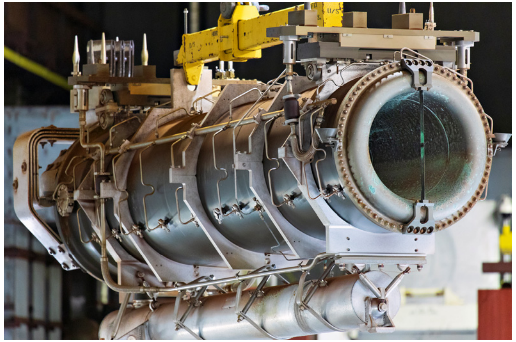



*T-block air diverter*

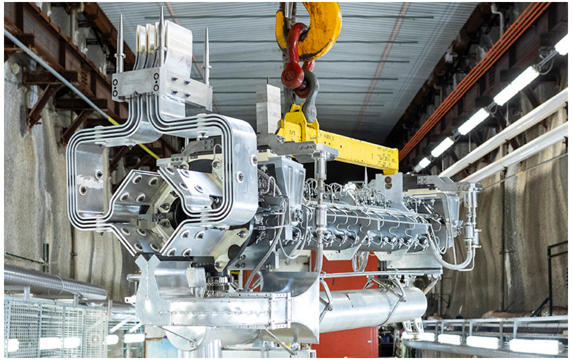
# NuMI AIP – 1 MW Horn Upgrade

- Upgraded Horn 1 installed during 2020 summer shutdown
- Horn 2 also replaced due to water leak
  - 12 year/100 million pulses lifetime
- Accompanying Horn 1 module rebuilt and replaced
  - Drive mechanisms for horn positioning no longer functional

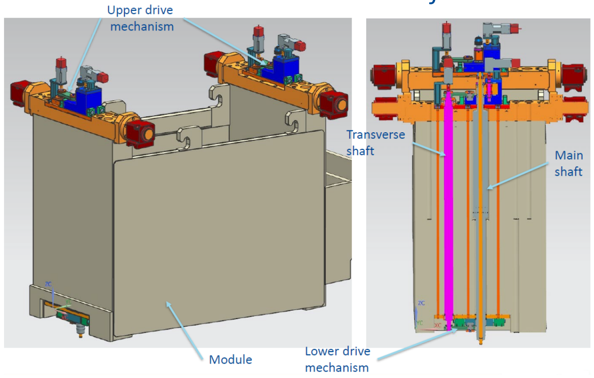
*Horn 1 and module test fitment*



*PH2-02 removed after 12 years of service*



*1 MW PH1-05 being installed*




*Horn 1 module mechanisms replaced*

# 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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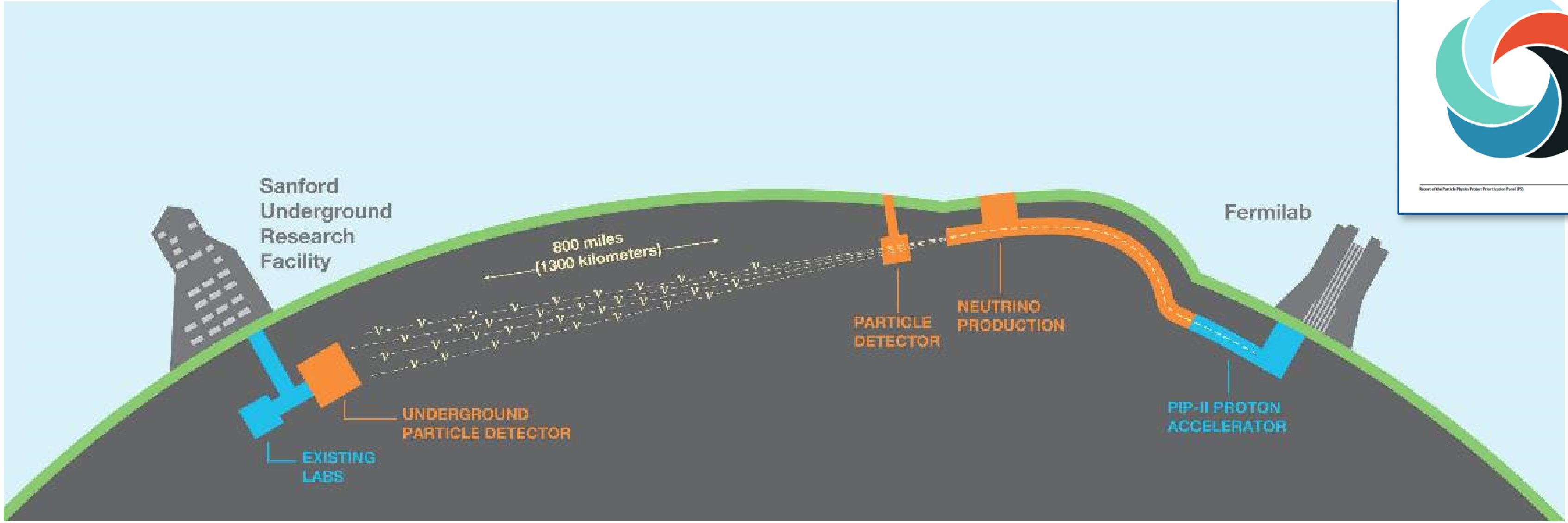
# Science Objectives


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

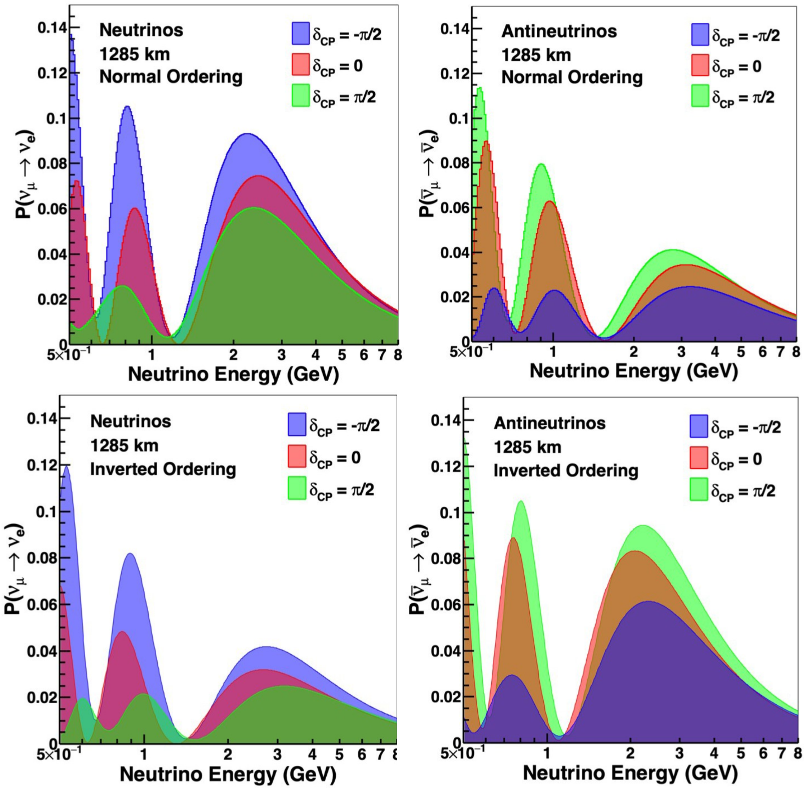
**Neutron star and black hole formation.** Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.

**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***

# Exquisite Measurement Possibilities with Long Baseline and Broad Beam

- DUNE is designed to resolve degeneracies by measuring flavor transitions as a function of energy over more than a full oscillation period
- DUNE will determine the mass ordering and measure δCP, regardless of the true values
- Expect the unexpected: DUNE is robust against systematic effects and for resolving deviations from νSM



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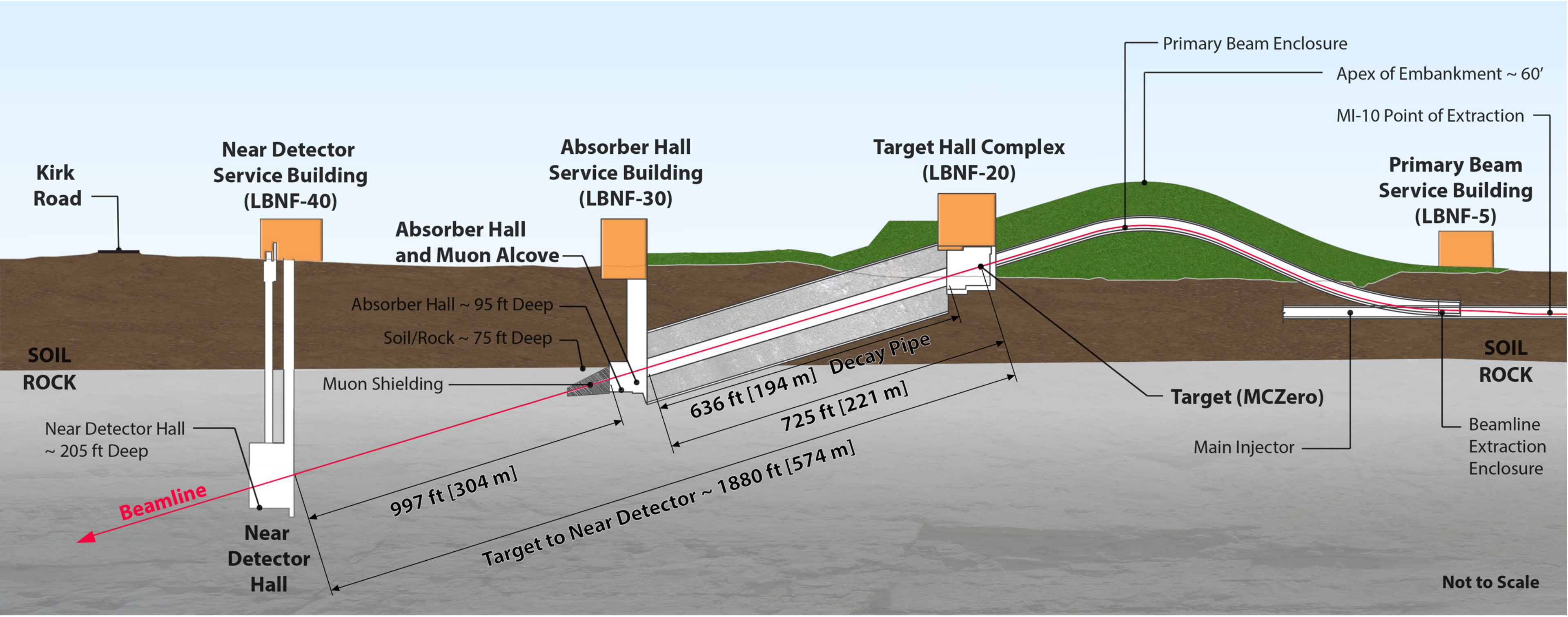
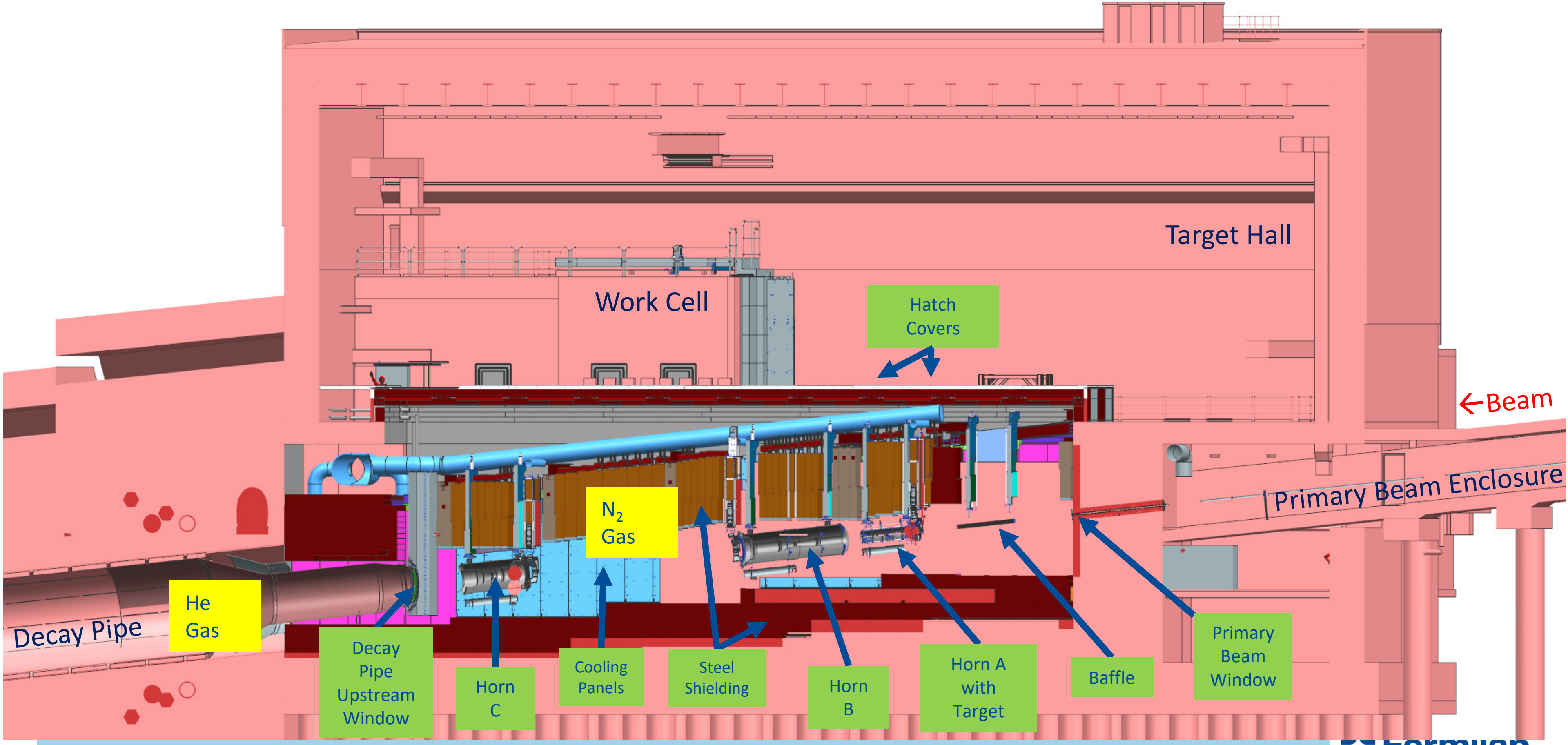
# The LBNF Beam




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

# Section View of Target Complex – Target Hall



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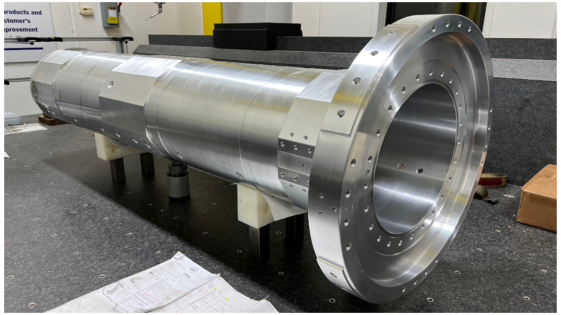
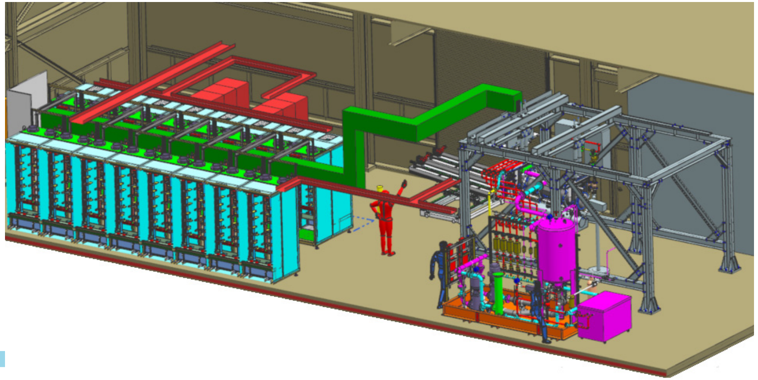
# LBNF Development in AD

- Prototype Horn has been welded and assembly started in 2022
- Major procurements for horns to begin in 2022
- UKRI RAL developing target – prototypes to be integrated at Fermilab
- Major new horn teststand to be bult 2022-2024 in existing technical space (MI-8)
- Numerous persons working on the project
  - Design
  - Radiation Modelling
  - Prototyping
  - Project Management





# Definition of LBNF/DUNE Phases

- Originally described in the 2014 P5 plan
- **Phase I**
  - Accomplished with PIP-II, LBNF/DUNE-US, and DUNE International Partners
  - Meets P5 minimum requirements to proceed by 2035 timeframe
  - **Same project scope as proposed at CD-1R in July 2015**
- **Phase II**
  - Increased mass at Far Detector
  - More Capable Near Detector (MCND)
  - Increased beam power by Booster replacement

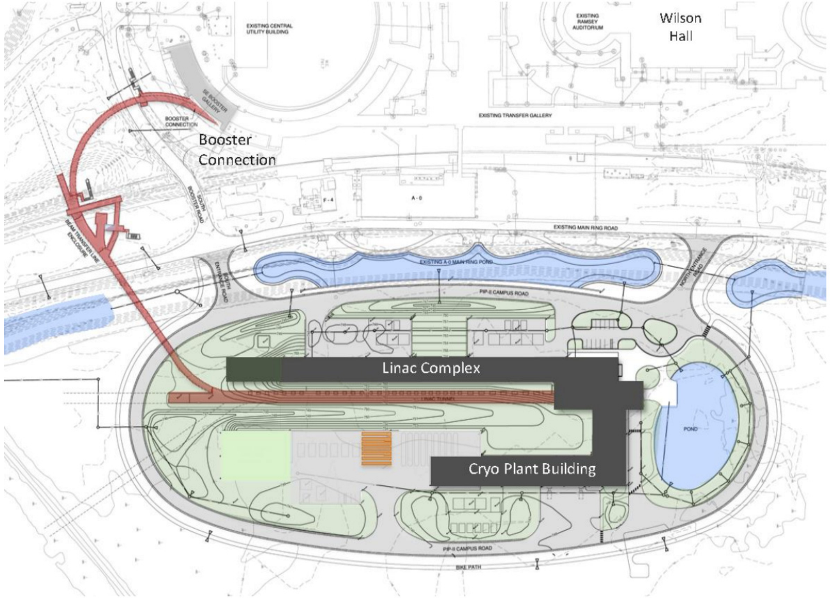
| Capability Description | Phase I (LBNF/DUNE-US Project + DUNE Int'l Project) | Phase II |
|---|---|---|
| **Beamline** | | |
| 1.2MW (includes 2.4MW infrastructure) | X | |
| 2.4MW | | X[1] |
| **Far Detectors** | | |
| FD1 – 17 kton | X | |
| FD2 – 17 kton | X | |
| FD3 | | X |
| FD4 | | X |
| **Near Detectors**[2] | | |
| ND Lar | X | |
| TMS | X | |
| SAND | X | |
| MCND (ND GAr) | | X |

**Note 1**: requires upgrades to LBNF neutrino target and upgrades to Fermilab accelerator complex. The LBNF facility is built to support 2.4MW in Phase I.
**Note 2:** Near Detector Subproject threshold scope provides "day 1" requirements to start the DUNE experiment

# 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)




**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 (CD0)
First beam in Booster: 2028 (plan)
MI 1.2 MW beam on target: 2031 (projection)

# Critical Issue: Space Charge Limit

- Injected intensity is limited by the space charge tune-shift, which can drive harmonic instabilities.

total protons

"Bunch factor" = $I_{peak}/I_{ave}$
(Reduce with higher RF harmonics)

$$\Delta\nu \approx \frac{N r_0}{2\pi \epsilon_N \beta\gamma^2} FB \lesssim .2$$

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

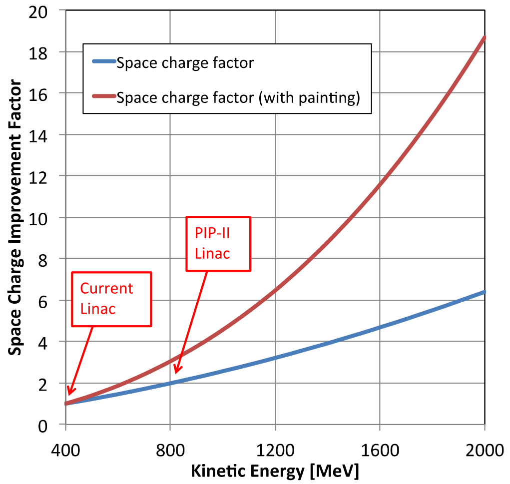
normalized emittance

$\epsilon_N = \epsilon\beta\gamma = \text{constant}$

- Thus, the maximum injected charge grows rapidly with increasing energy

$$N_{max} \propto \beta\gamma^2 \quad \text{without painting}$$
$$\propto \beta^2\gamma^3 \quad \text{painted to fill physical aperture}$$

doesn't include improvement of going to uniform distribution with painting





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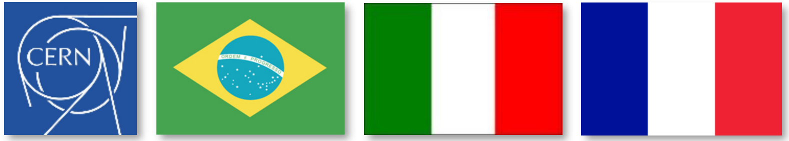
# PIP-II Project construction begins!

- PIP-II received DOE CD-3 approval for start of construction/execution on April 18
  - Linac complex RFP issued
- Front end of PIP-II linac constructed and successfully tested with beam
- PIP-II cryoplant building 98% complete
- HB650 prototype cryomodule in assembly – first of its kind

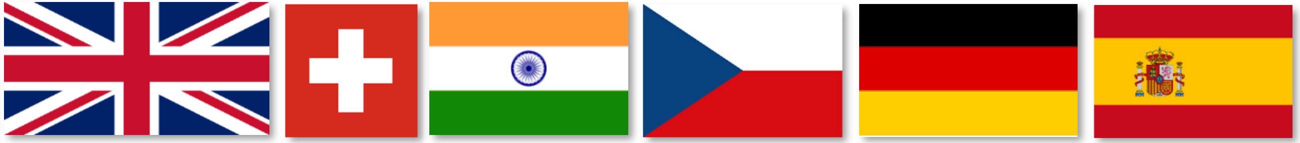

***PIP-II is the first particle accelerator built in the U.S. with significant international contributions***

# LBNF/DUNE/PIP-II in-kind contributions $1.1B with growth potential

- LBNF/DUNE-US
  - $262M in-kind contributions to LBNF (does not include private @ $70M or State of SD @ $93M to support SURF)
  - $310M in contributions to DUNE detectors
  - $84M in CERN contributions to protoDUNE efforts (does not include French contributions to protoDUNE R&D)
- Additionally, LBNF powered by PIP-II, which has secured $310M in international contributions




- All in-kind contributions are expressed in DOE TPC units
- Numbers do not include other IKCs received in support of Fermilab's short-baseline neutrino program

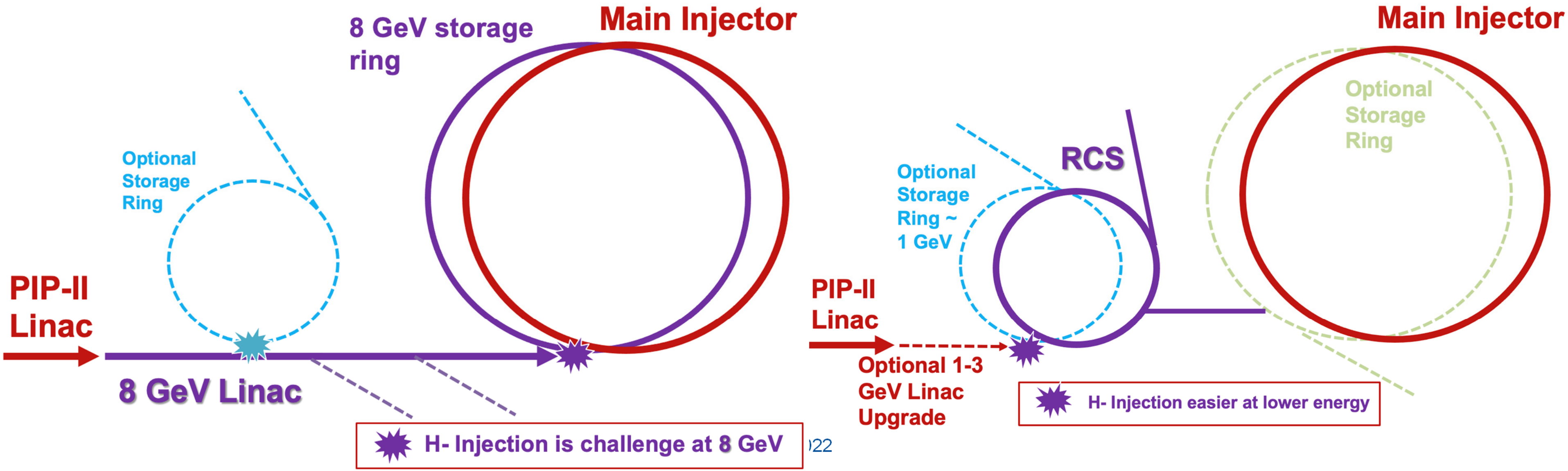


*In-kind contributions supported by 10 Government-to-Government agreements and 17 I-CRADAS*

# Booster Replacement / Proton Intensity Upgrade (PIU)

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

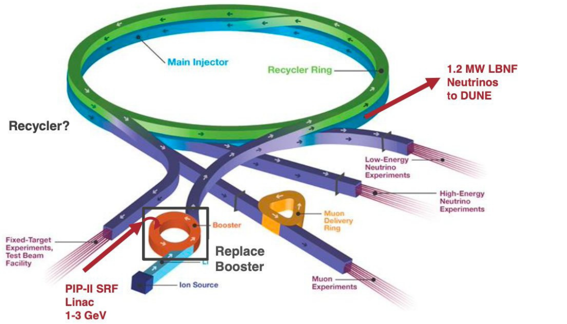
- Cost-effective and fastest path to increased power to 2.4MW for LBNF.
- Capture options for additional medium and small-scale experiments.
- Enable long-term vision.



# Why Replace 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
- A lot of work has been done already
  - Luciano Ristori presentation to PAC June 2021
  - White Papers for Snowmass describe design options and potential for rich low energy science program
  - Users meeting “Future Accelerators for Fermilab Proton Complex” June 2022 Jeff Eldred

Fermilab Accelerator Complex




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”**



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# Experiment/Physics Possibilities

Range of experiments could be performed with different iterations of the PIU

Experiments grouped into physics categories that they service (multiply)

(electrons)

| Experiment | Dark Sectors | ν Physics | CLFV | Precision tests | R&D |
|---|---|---|---|---|---|
| Lepton flavor violation: μ-to-e conversion | | | | | |
| Lepton flavor violation: μ decay | | | | | |
| PIP2-BD: ~GeV Proton beam dump | | | | | |
| SBN-BD: ~10 GeV Proton beam dump | | | | | |
| High energy proton fixed target | | | | | |
| Electron missing momentum | | | | | |
| Nucleon form factor w/ lepton scattering | | | | | |
| Electron beam dumps | | | | | |
| Muon Missing Momentum | | | | | |
| Muon beam dump | | | | | |
| Physics with muonium | | | | | |
| Muon collider R&D and neutrino factory | | | | | |
| Rare decays of light mesons | | | | | |
| Ultra-cold neutrons | | | | | |
| Proton storage ring for EDM and axions | | | | | |
| Tau neutrinos | | | | | |
| Proton irradiation facility | | | | | |
| Test-beam facility | | | | | |

Physics Opportunities for the Fermilab Booster Replacement, 2021

# Booster Replacement Era Proposed Experiments (SM whitepapers)

| Experiment | Experiment type | Primary beam particle | Beam Energy [GeV] | Beam power [kW] | Beam time structure | Uses existing or under construction beamline? |
|---|---|---|---|---|---|---|
| Proton Storage Ring: EDM and Axion Searches | Precision tests, Dark Matter | proton | 0.7 GeV/c beam momentum | 1e11 polarized protons per fill | Fill the ring every 1000s | no |
| Physics with Muonium | Precision tests | proton (producing surface muons) | 0.8 GeV | 1e13pm1 POT per second | CW | no |
| Nucleon Electromagnetic Form Factors from Lepton Scattering | Neutrino | electron or proton (producing muons) | 0.85 GeV to 2 GeV | 1 nA to 10 microA for electrons, 10^7 to 10^8 per second for muons | A continuous or pulsed structure (ideally with a duty factor of 1% or larger) should be sufficient | no |
| Rare Decays of Light Mesons (REDTOP) | Precision tests | proton | 1.8-2.2 GeV (Run I), 0.8-0.92 (Run II), 1.7 (Run III) | 0.03-0.05 (Run I), 200 (Runs II and III) | CW, slow extraction for Run I | no |
| Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations | Precision tests | proton | 0.8-2 | 1,000 | quasi-continuous | no |
| CLFV with Muon Decays | CLFV | proton | Not critical 0.8 to a few GeV | 100 or more | continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better | Muon Campus |
| Mu2e II | CLFV | proton | 1 to 3 | 100 | pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation | no |
| Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump | Dark Sector, Neutrino | proton | 0.8 to 1.5 GeV | 100 or more | <O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^(-5) or better duty factor | no |
| PRISM-like Charged Lepton Flavor Violation | CLFV | proton | 1-3 GeV | up to 2 MW | 15ns pulses at a rep rate of about 1 kHz | no |
| Electron Missing Momentum (LDMX) | Dark Sector | electron | ~3 GeV to ~20 GeV | O(1 electron per RF bucket at 53 MHz) | CWish | no |
| Electron Beam Dumps | Dark Sector | electron | few GeV | 10^(20) electrons on target over the experiment al runtime | Pulsed beam (duty factor not specified) | no |
| Proton Irradiation Facility | R&D | proton | Energy is not very important | 1e18 protons in a few hours | Pulsed beam (duty factor not specified) | no |
| SBN | Neutrino | proton | 8 | 32 | 20Hz | BNB |
| Mu2e | CLFV | proton | 8 | 8 | <10^(-10) extinction | Muon Campus |
| Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump | Dark Sector, Neutrino | proton | 8 | up to 115 | Beam spills less than a few microsec with separation between spills greater than 50 microsec | BNB |
| Muon beam dump | Dark Sector | proton (producing muons) | 3 GeV muons | 3e14 muons in total on target for the whole run | CW | Muon Campus |
| Muon Collider R&D and Neutrino Factory | R&D | proton | 5 - 30GeV | 1e12 to 1e13 protons per bunch | 10 - 50 Hz rep rate and bunch length 1-3 ns | no |
| Muon Missing Momentum | Dark Sector | proton (producing muons) | few 10s of GeV | 10^(10) muons per experimental runtime | Pulsed beam (duty factor not specified) | no |
| High Energy Proton Fixed Target | Dark Sector, Neutrino | proton | O(100 GeV) | 1e12 POT/s therefore ~20 kW | CW via resonant extraction. "IF we could up the duty factor that woul dbe even better"(?) | Switchyard |
| Test-Beam Facility | R&D | proton | 120, lower energies would also be beneficial | 10 to 100 kHz on the testing apparatus | Pulsed beam (duty factor not specified) | no |
| Tau Neutrinos | Neutrino | proton | 120 | 1200 or higher | MI time structure | LBNF |

Electron beam

~2 GeV CW-capable beam

~2 GeV pulsed beam from storage ring ~1MW

~8 GeV pulsed beam ~1MW

120 GeV Slow extraction or LBNF beam

Adapted from Jeff Eldred's 2022 Fermilab Users Meeting Talk

# 8-GeV Linac Program (MI program)

| Performance Parameter | PIP | PIP-II | BRL | Unit |
|---|---|---|---|---|
| Linac Beam Energy | 400 | 800 | 8000 | MeV |
| Linac Beam Current (chopped) | 25 | 2 | 2 | mA |
| Linac Pulse Length | 0.03 | 0.54 | 2.2 | ms |
| Linac Pulse Repetition Rate | 15 | 20 | 20 | Hz |
| Linac Upgrade Potential | N/A | CW | CW | |
| 8 GeV Protons per Pulse (extracted) | 4.2 | 6.5 | 27.5 | $10^{12}$ |
| 8 GeV Pulse Repetition Rate | 15 | 20 | 20 | Hz |
| Beam Power @ 8 GeV | 80 | 166 | 700 | kW |
| 8 GeV Beam Power to MI | 50 | 83-142* | 176-300 | kW |
| Beam Power to 8 GeV Program (pulsed mode) | 30 | 83-24* | 500-375 | kW |
| Main Injector Protons per Pulse (extracted) | 4.9 | 7.5 | 15.6 | $10^{13}$ |
| Main Injector Cycle Time @ 120 GeV | 1.33 | 1.2 | 1.2 | s |
| Main Injector Cycle Time @ 60 GeV | N/A | 0.7 | 0.7 | s |
| Beam Power @ 60 GeV | N/A | 1 | 2.15 | MW |
| Beam Power @ 120 GeV | 0.7 | 1.2 | 2.5 | MW |

*Total PIP-II with Booster 8 GeV power is 166 kW.

Injects at 20Hz into MI over six 2.2ms pulses

| Section | Length | Bending field or RF frequency | Total bending angle or Linac mode | Cavities/magnets/ cryomodules | Cryomodule length |
|---|---|---|---|---|---|
| 1 GeV transport | 40 m | 0.277 T | -45° | | |
| 1 → 3 GeV Linac | 240 m | 650 MHz | CW | 120/20/20 | 9.92 m |
| 3 GeV bend | 200 m | 0.13 T | 105° | | |
| 3 → 8 GeV Linac | 390 m | 1300 MHz | Pulsed, 10 Hz | 224/28/28 | 12.5 m |
| 8 GeV injection | | 0.055 T | | | |



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# 8-GeV Linac Program (8-GeV program)

| Performance Parameter | PIP | PIP-II | BRL | Unit |
|---|---|---|---|---|
| Linac Beam Energy | 400 | 800 | 8000 | MeV |
| Linac Beam Current (chopped) | 25 | 2 | 2 | mA |
| Linac Pulse Length | 0.03 | 0.54 | 2.2 | ms |
| Linac Pulse Repetition Rate | 15 | 20 | 20 | Hz |
| Linac Upgrade Potential | N/A | CW | CW | |
| 8 GeV Protons per Pulse (extracted) | 4.2 | 6.5 | 27.5 | $10^{12}$ |
| 8 GeV Pulse Repetition Rate | 15 | 20 | 20 | Hz |
| Beam Power @ 8 GeV | 80 | 166 | 700 | kW |
| 8 GeV Beam Power to MI | 50 | 83-142* | 176-300 | kW |
| Beam Power to 8 GeV Program (pulsed mode) | 30 | 83-24* | 500-375 | kW |
| Main Injector Protons per Pulse (extracted) | 4.9 | 7.5 | 15.6 | $10^{13}$ |
| Main Injector Cycle Time @ 120 GeV | 1.33 | 1.2 | 1.2 | s |
| Main Injector Cycle Time @ 60 GeV | N/A | 0.7 | 0.7 | s |
| Beam Power @ 60 GeV | N/A | 1 | 2.15 | MW |
| Beam Power @ 120 GeV | 0.7 | 1.2 | 2.5 | MW |

*Total PIP-II with Booster 8 GeV power is 166 kW.

8-GeV pulsed
2µs -> 2ms

| Section | Length | Bending field or RF frequency | Total bending angle or Linac mode | Cavities/magnets/ cryomodules | Cryomodule length |
|---|---|---|---|---|---|
| 1 GeV transport | 40 m | 0.277 T | -45° | | |
| 1 → 3 GeV Linac | 240 m | 650 MHz | CW | 120/20/20 | 9.92 m |
| 3 GeV bend | 200 m | 0.13 T | 105° | | |
| 3 → 8 GeV Linac | 390 m | 1300 MHz | Pulsed, 10 Hz | 224/28/28 | 12.5 m |
| 8 GeV injection | | 0.055 T | | | |

# RCS Scenarios

**"Design Considerations for Fermilab Multi-MW Proton Facility"** white paper

| Parameter | PIP-II Booster | ICD-2 | BSR |
|---|---|---|---|
| Linac Energy | 0.8 GeV | 2 GeV | 2 GeV |
| Minimum Linac Current | 2 mA | 2 mA | 2 mA |
| GeV-scale Accumulator Ring | Optional | Optional | Required |
| RCS Energy | 8 GeV | 8 GeV | 8 GeV |
| RCS Intensity | 6.5 e12 | 26 e12 | 37 e12 |
| RCS Circumference | 474.2 m | 553.2 m | 570 m |
| RCS Rep. Rate | 20 Hz | 10 Hz | 20 Hz |
| Number of Batches | 12 | 6 | 5 |
| Accumulation Technique | Slip-stacking | Conventional | Conventional |
| 8 GeV Accumulation | Recycler | Recycler | Main Injector |
| Available RCS Power | 80 kW | 170 kW | 750 kW |
| Main Injector Intensity | 80 e12 | 156 e12 | 185 e12 |
| Main Injector Cycle Time | 1.2 s | 1.2 s | 1.4 s |
| Main Injector Power (120 GeV) | 1.2 MW | 2.4 MW | 2.4 MW |
| Upgraded Main Injector Power | | 3.3 MW | 4.0 MW |

# RCS Scenarios (ramp rate and 8 GeV program)

**"Design Considerations for Fermilab Multi-MW Proton Facility"** **white paper**

| Parameter | PIP-II Booster | ICD-2 | BSR |
|---|---|---|---|
| Linac Energy | 0.8 GeV | 2 GeV | 2 GeV |
| Minimum Linac Current | 2 mA | 2 mA | 2 mA |
| GeV-scale Accumulator Ring | Optional | Optional | Required |
| RCS Energy | 8 GeV | 8 GeV | 8 GeV |
| RCS Intensity | 6.5 e12 | 26 e12 | 37 e12 |
| RCS Circumference | 474.2 m | 553.2 m | 570 m |
| RCS Rep. Rate | 20 Hz | 10 Hz | 20 Hz |
| Number of Batches | 12 | 6 | 5 |
| Accumulation Technique | Slip-stacking | Conventional | Conventional |
| 8 GeV Accumulation | Recycler | Recycler | Main Injector |
| Available RCS Power | 80 kW | 170 kW | 750 kW |
| Main Injector Intensity | 80 e12 | 156 e12 | 185 e12 |
| Main Injector Cycle Time | 1.2 s | 1.2 s | 1.4 s |
| Main Injector Power (120 GeV) | 1.2 MW | 2.4 MW | 2.4 MW |
| Upgraded Main Injector Power | | 3.3 MW | 4.0 MW |

ICD-2 RCS is more cost-effective, BSR is more ambitious

BSR delivers more for 8 GeV, compatible with a second LBNF target station

# RCS Scenarios (required rings)

**"Design Considerations for Fermilab Multi-MW Proton Facility"** **white paper**

| Parameter | PIP-II Booster | ICD-2 | BSR |
|---|---|---|---|
| Linac Energy | 0.8 GeV | 2 GeV | 2 GeV |
| Minimum Linac Current | 2 mA | 2 mA | 2 mA |
| GeV-scale Accumulator Ring | Optional | Optional | Required |
| RCS Energy | 8 GeV | 8 GeV | 8 GeV |
| RCS Intensity | 6.5 e12 | 26 e12 | 37 e12 |
| RCS Circumference | 474.2 m | 553.2 m | 570 m |
| RCS Rep. Rate | 20 Hz | 10 Hz | 20 Hz |
| Number of Batches | 12 | 6 | 5 |
| Accumulation Technique | Slip-stacking | Conventional | Conventional |
| 8 GeV Accumulation | Recycler | Recycler | Main Injector |
| Available RCS Power | 80 kW | 170 kW | 750 kW |
| Main Injector Intensity | 80 e12 | 156 e12 | 185 e12 |
| Main Injector Cycle Time | 1.2 s | 1.2 s | 1.4 s |
| Main Injector Power (120 GeV) | 1.2 MW | 2.4 MW | 2.4 MW |
| Upgraded Main Injector Power | | 3.3 MW | 4.0 MW |

ICD-2 scenario require Recycler (or similar), maintains RR experimental program.

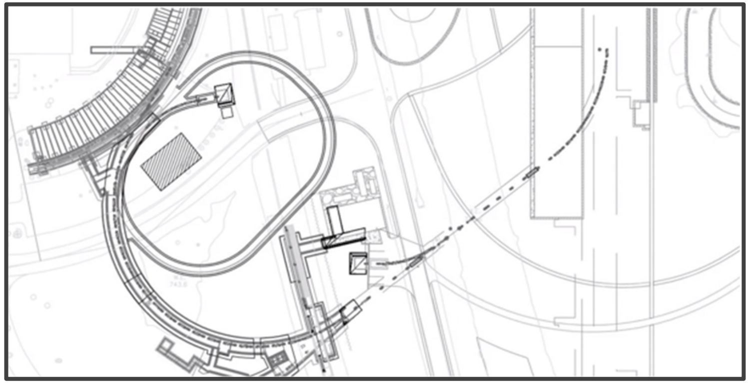
BSR scenario requires either an Accumulator Ring or 5 mA linac upgrade.

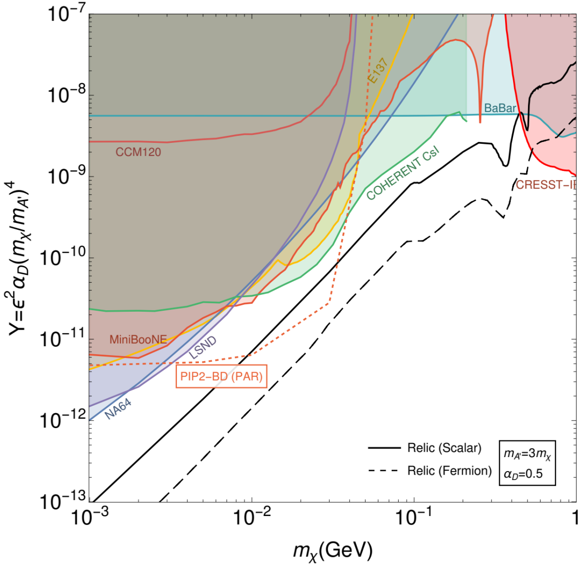
# Proposed PIP-II Accumulator Ring (PAR)

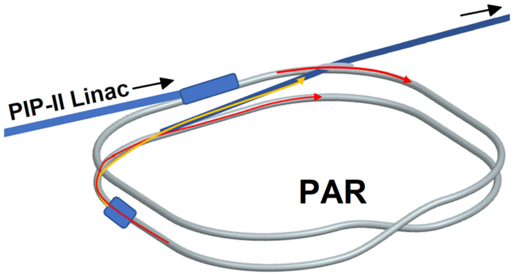
**Features:**
- Proposed 0.8-1.0 GeV proton storage ring.
- 474m in the form of a folded figure 8.
- Does not interfere with PIP-II commissioning.

**Benefits:**
- 100 kW Dark Sector Program.
- Enables 1 GeV upgrade of Booster injection.

**Snowmass white papers PAR, PIP2-BD**





# Emerging Themes for PIU / Design Options / R&D

- At least one ring will certainly be necessary
  - Accumulator, compressor, and/or RCS
  - Many experiments require short bunches. The CW beam must be extensively reformatted to be useful.
  - Muon Collider future compatibility requires the compression of ~ $10^7$ linac microbunches into a single 1-2 ns bunch
  - Need to develop beam dynamics, RF Gymnastics, and other issues
- H- Stripping becomes a challenge at high rate (and low linac current)
  - Motivates Laser Stripping, foil development
- Linac Current increase is potentially very useful
  - Stripping, injection, experiments
- MI Cycle Time could be further reduced for conceivably 4+ MW
- Energy Consumption / Sustainability must be considered
- Higher energy injection into the MI could allow higher emittance beams, avoiding transition

# Path Forward for Upgrades

- PIP-II is in construction – complete ~ 2028
- LBNF has started construction – complete ~ 2031
- Planning for Booster Replacement / Proton Intensity Upgrade (PIU)
  - **Snowmass Process** 2020-22 (fall) – Catalog many of the community proposals for all particle physics, including accelerators
  - **P5 Process** 2022-23 HEPAP (DOE & NSF) panel prioritizes particle physics projects
  - Follow-on panels to P5 (e.g. NAS, AARD) 2023-24
  - **DOE issues CD-0** within the above process, and formal design begins
  - Alternatives chosen at CD-1
  - Ideally operational in the middle of the 2030s
- In parallel, a possible instrumentation build-out of PIP-II:
  - Individual experiments, accumulator rings, beam delivery, targets stations, …

# Timeline of High-Power Target Stations

| Station | Design Power | Period | Comments |
|---|---|---|---|
| BNB | 30 kW | 2002 – 2027 (?) | |
| NuMI | 700 kW – 1 MW | 2004 – 2027 (?) | Megawatt Upgrade Complete. |
| AP-0 / Muon g-2 | 20 kW | 2017 – 2023 (?) | Using legacy targets & lenses from Antiproton Source. |
| Mu2e | 8 kW | 2025 (?) - | Very challenging high-Z, radiatively cooled target, even with low power. |
| LBNF/DUNE | 1.2 MW | 2029 (?) - | Challenging, but achievable devices. Production may be greatest challenge. |

- Three operating stations, two in various stages of design & construction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# Timeline of High-Power Target Stations with PIP-II and Successor

| Station | Design Power | Period | Comments |
|---|---|---|---|
| BNB | 30 kW | 2002 – 2027 (?) | |
| NuMI | 700 kW – 1 MW | 2004 – 2027 (?) | Megawatt Upgrade in progress. |
| AP-0 / Muon g-2 | 20 kW | 2017 – 2023 (?) | Using legacy targets & lenses from Antiproton Source. |
| Mu2e | 8 kW | 2025 - | Very challenging high-Z, radiatively cooled target, even with low power. |
| Mu2e-II | 100 kW | 2033 (?) - | Much more challenging than Mu2e |
| LBNF/DUNE | 1.2 MW | 2029 (?) - | Challenging, but achievable devices. Rate of production may be greatest challenge. |
| LBNF2 | 2.5 MW | 2035 (?) - | Challenging, Enabled by PIU |
| **800 MeV Exp't(s)** | **1.6 MW** | **2029 (?) -** | Enabled by PIP-II |
| **2 GeV Exp't(s)** | **4 MW (?)** | **2035 (?) -** | Enabled by PIU |
| **8 GeV Exp't(s)** | **0.8 – 16 MW (?)** | **2035 (?) -** | Enabled by PIU |

The Multi-Megawatt Frontier

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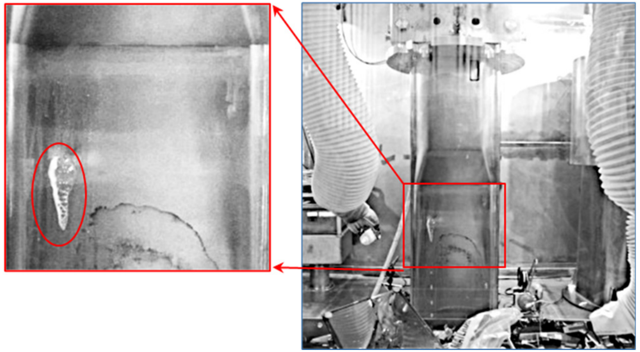
# High Power Targetry (HPT) R&D is Vital to Delivering Performance at Major Facilities

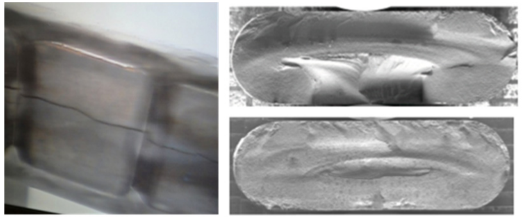
Recently, major accelerator facilities have been limited in beam power not by their accelerators, but by target survivability concerns

- NuMI-MINOS, FNAL (2010-11)
  - Reduced beam power (-10% to -40%)
  - Target failures attributed to faulty welds
- MLF, J-PARC (2015-16)
  - Early replacement of target
  - Limited to 200 kW when resuming ops
- SNS, ORNL
  - Reduced beam power (-15%) frequently in 2013-14
  - Target vessel failures attributed to faulty welds and dynamic stresses

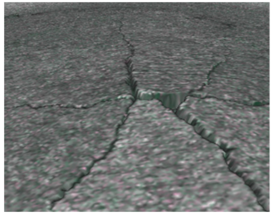
MINOS NT-01 target (FNAL)



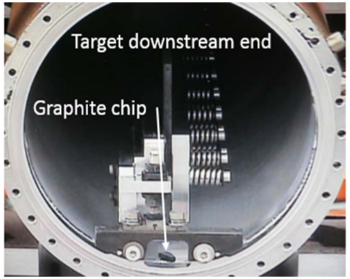
SNS target vessel (ORNL)



MINOS NT-02 target failure: radiation-induced swelling (FNAL)



Be window embrittlement (FNAL)




NOvA MET-01 target fin fracture (FNAL)

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# Summary

- Fermilab has successfully delivered several modest projects to significantly increase beam power:
  - NOvA/ANU -> 700kW
  - PIP -> 700+ kW and better throughput / reliability
  - NuMI Megawatt AIP -> 1 MW capability
- Major Projects are underway
  - LBNF 1.2 – 2.4 MW capability
  - PIP-II -> 1.2 MW + 1.6 MW

- Planning has begun for a successor project to PIP-II: Booster Replacement or PIU
  - Fixed purpose is providing 2.4 MW to LBNF/DUNE
  - Alternatives of Linac Extension + RCS or 8 GeV Linac
  - Many potential experimental users of 1, 2, 8, 120 GeV megawatt-class beams

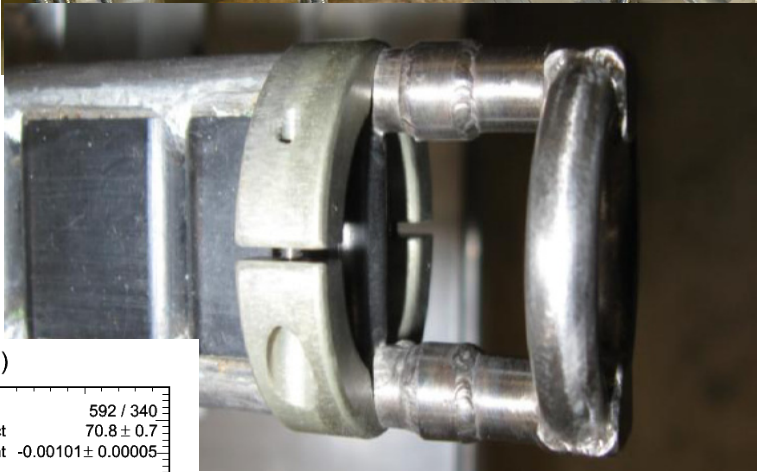
# Next-Generation Accelerator Facilities at Fermilab: Megawatt Upgrade of the NuMI Neutrino Beam

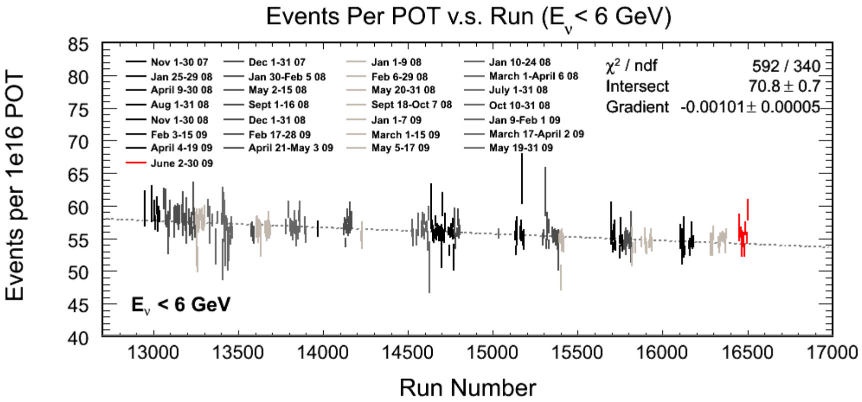
Robert Zwaska

10 August 2022

# Target Issues

- Common failure mode was water cooling
  - Also, an issue for horns
  - Many lessons were learned in design and in quality control
- NOvA target is more robust in its design
  - Made possible by being outside of the horn.
  - LBNF Design returns to inside the horn
- Graphite degradation was observed on one target
  - May ultimately limit the performance of the target





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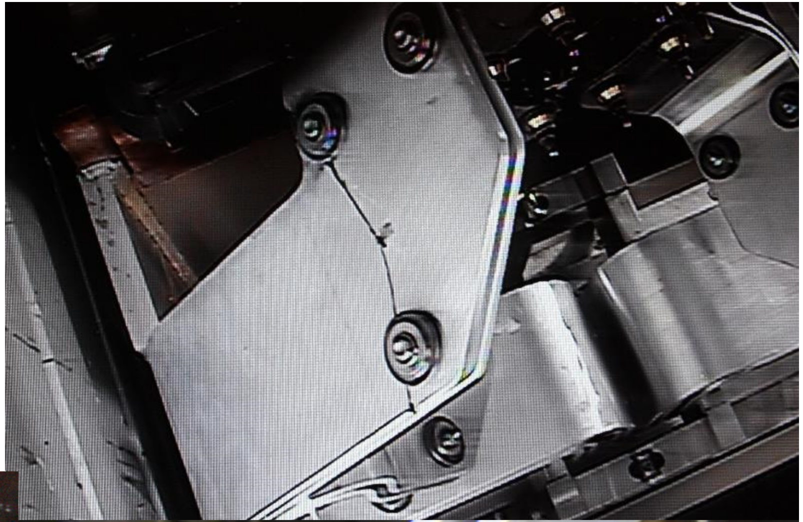
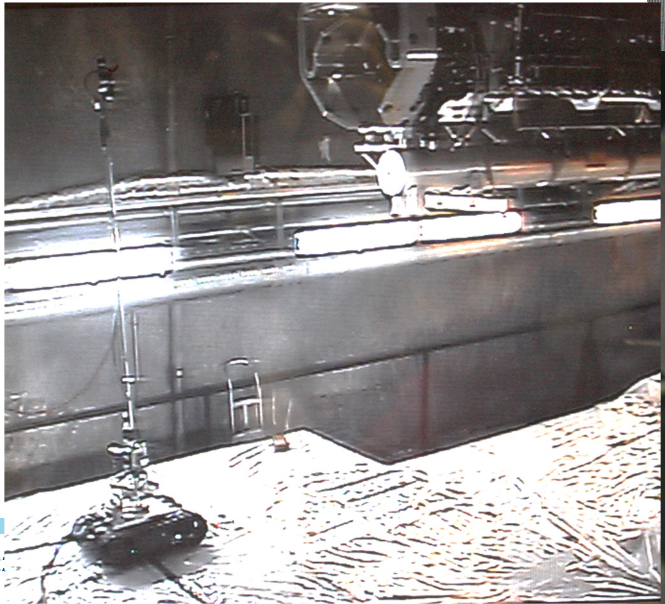
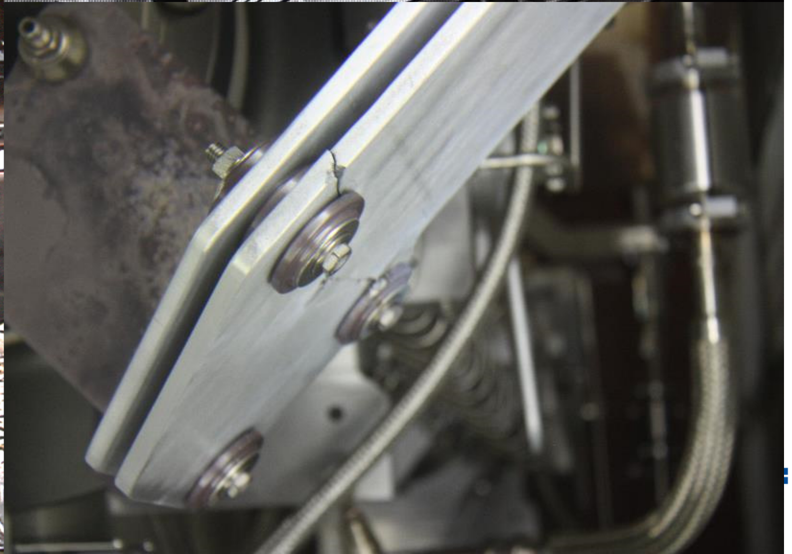
# Challenging Environments

- Replaced NuMI Horn summer 2015 due to failed stripline
  - First 700 kW capable horn, in service since Sept. 2013, accumulated ~ 27 million pulses
- Failure was due to fatigue, likely enhance by vibrations

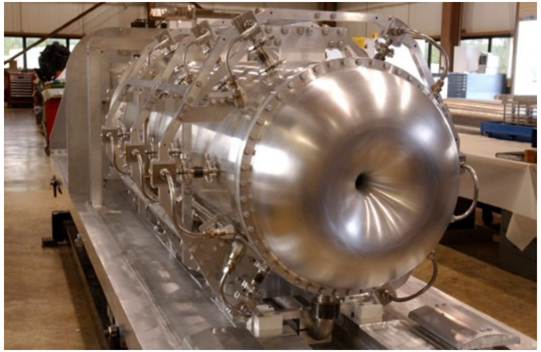






# Booster Neutrino Beam (BNB)

- 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



# High Power Targetry: Materials R&D

***Multi-MW*** Neutrino Targets & Beam Windows Materials:

- Graphite (target core material) studies:
  - Swelling/fracture studies
  - Preparing for HE proton irradiation at BLIP (2020) to confirm elevated temperature annealing
- Beryllium (beam window material) studies:
  - Examination of BLIP irradiated Be specimens underway
  - Helium implantation studies show bubble formation at irradiation temperatures above 360 ˚C
- Titanium Alloys (beam window material) studies:
  - Examination of BLIP irradiated specimens underway
  - World first high cycle fatigue testing of irradiated titanium underway at FNAL

RaDIATE

Benefits to multi-MW targets e.g. LBNF):

- alloy/grade choice
- cooling system design
- tolerable beam intensities
- expected lifetimes

In-beam thermal shock testing of *BLIP irradiated* Be and Ti alloys at CERN

# RaDIATE Collaboration

***Radiation Damage In Accelerator Target Environments***

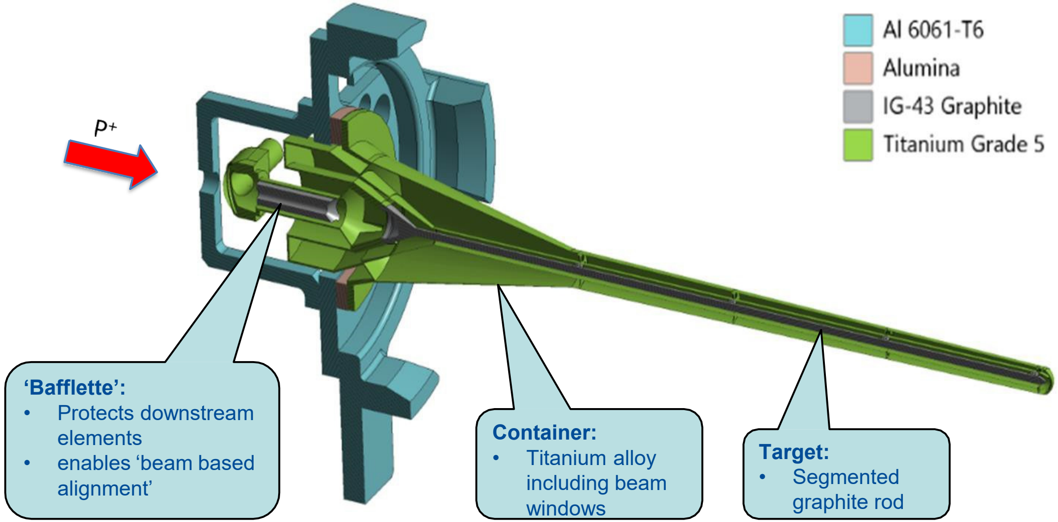
Broad aims are threefold:

www-radiate.fnal.gov

- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

Fermilab | University of Oxford | Brookhaven National Laboratory | European Spallation Source | Argonne National Laboratory | Science & Technology Facilities Council | CERN | Oak Ridge National Laboratory | Los Alamos National Laboratory EST. 1943 | Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas | FRIB | Pacific Northwest National Laboratory

# LBNF Target Design




- Target core: segmented graphite rod 16 mm diameter 1.5 m long
- 24 kW beam heat removed by high velocity helium gas
- Titanium target containment vessel with up-stream and down-stream beam windows

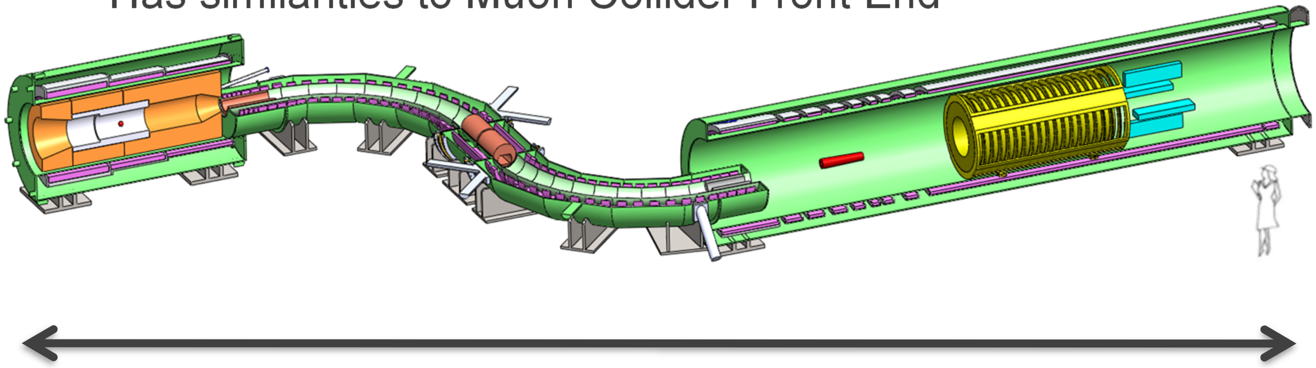
- 1.2 MW Design is evolved from T2K target: longer, higher power, sits within horn, more protection, more precision
- 2.4 MW Design has not been seriously pursued yet, helium cooling may be at its limit
- Prototyping has begun

# MINOS / NOVA / LBNF Targets

| | NuMI / MINOS | NuMI / NOvA | NuMI / NOvA 1 MW | LBNF |
|---|---|---|---|---|
| Distance to far detector | 735 km | 810 km | 810 km | 1300 km |
| Desired ν energy | 1 to 15 GeV | 2 GeV | 2 GeV | 0.8 & 2.7 GeV |
| Detector Off-beam-axis angle | 0 | 14 mrad | 14 mrad | 0 |
| Design beam power | 400 kW | 700 kW | 1 MW | 1.2 MW initial |
| Energy per proton | 120 GeV | 120 GeV | 120 GeV | 80-120 GeV |
| Number of horns | 2 | 2 | 2 | 3 |
| | | | | |
| Target length | 0.95 m | 1.2 m | 1.2 m | 1.5-2.2 m |
| Distance between target downstream end and horn | 1.6 m to -0.6 m (Variable) | 0.2 m (Not in horn) | 0.2 m (Not in horn) | -1.5 m (In horn) |
| | | | | |
| Protons/spill | 4.4 E13 | 4.9 E13 | 6.25 E13 | 7.6 E13 |
| Repetition rate | 2.2 sec | 1.33 sec | 1.2 sec | 1.2 sec |

# Mu2eTarget Station

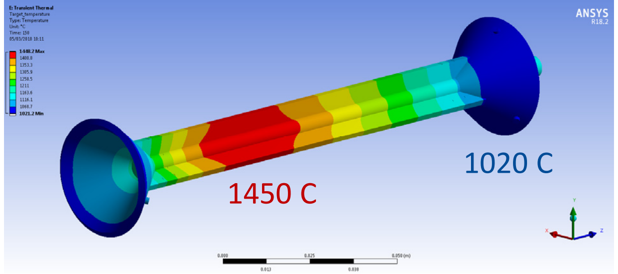
- 8 GeV Protons from Delivery Ring @ 8 kW
  - 8 Slow Spill bunches to Mu2e each 43 msec long for 380 ms.
  - Then, 1020 msec of no beam
  - Operate for 1 year (2 x $10^7$ seconds ~ 5555 hrs ~ 33 weeks)
- Target operates within a superconducting solenoid (2-5 T) and a vacuum
  - Has similarities to Muon Collider Front End

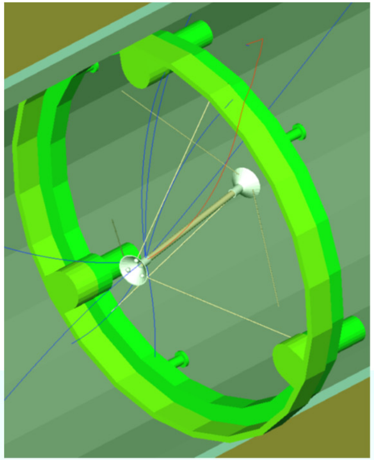


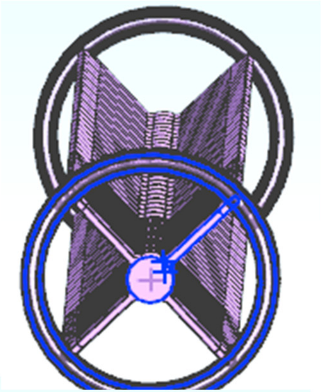
about 75 feet end-to-end

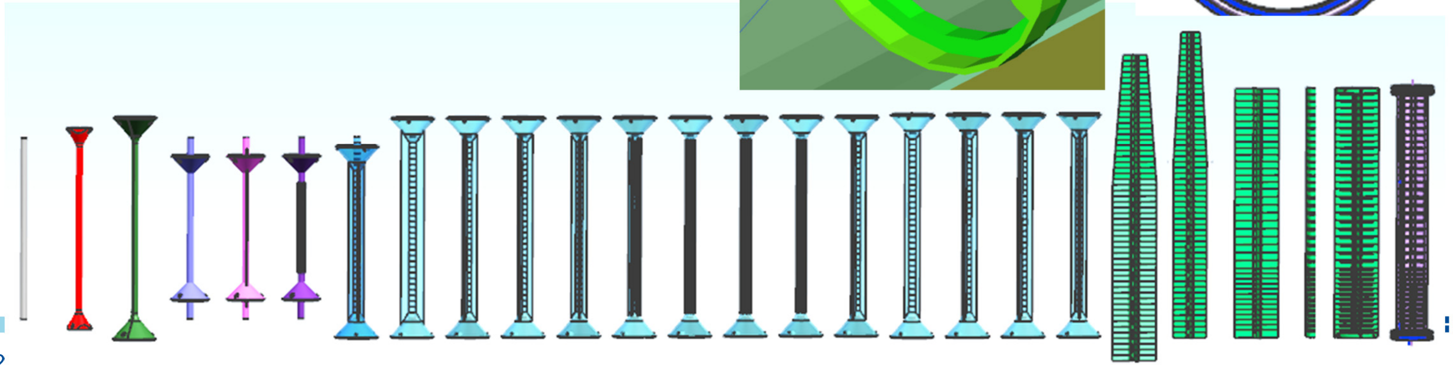
# Mu2e Target Evolution

- Simplicity: Radiatively-cooled, high-density target - Tungsten
  - 8 kW is at the edge of possibility for this target
- Refractory metals can go to very high temperatures, but tend to crystallize in a form that is very brittle
  - Tungsten must be kept < 1200 C
- Helium- or water-cooled target as an alternative or upgrade







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# A few notes for Muon Collider Targets

- Most comparable configuration is Mu2e – challenging at 8 kW @ 8 GeV.
  - Extrapolation to Mu2e-II (100 kW @ 1 GeV) has no present solution
  - Cannot Extrapolate to historical Muon Collider (4 MW @ few GeV)

- Higher proton beam energy is better for the target (less power deposited in target for the same beam power)

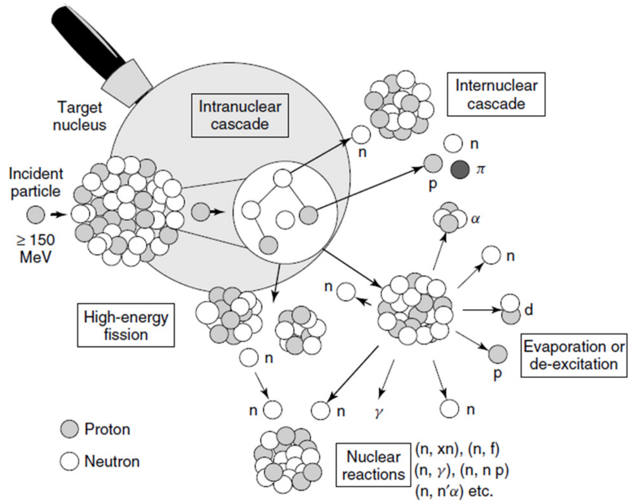
- Separating target from optics is very beneficial
  - Has the capacity to allow rotation and more robust support systems
  - Can more forward production from higher-energy protons be used?

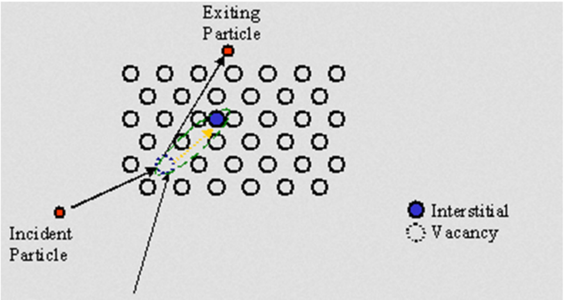
- Muon collider requirements on precision may be less strict

- Machine Protection is vitally important at high power. Targets and facilities must have this built in from the beginning.

- Attempt to avoid liquid targets. Enormous investment and R&D, many risks. SNS, ESS, J-PARC have all decided against liquid targets for new target stations

# Radiation Damage Disorders Microstructure

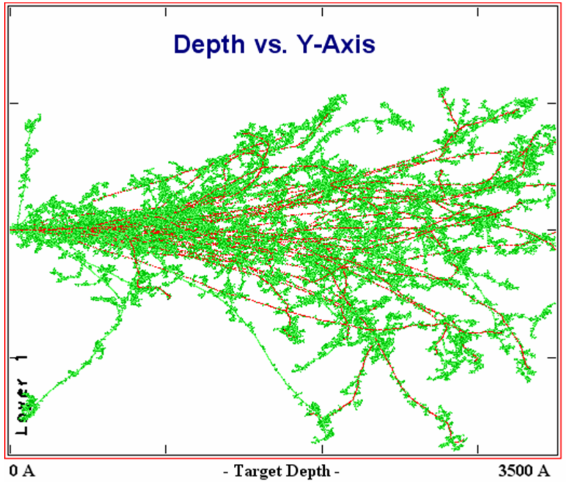


A Frenkel pair consists of a vacancy and an interstitial atom.

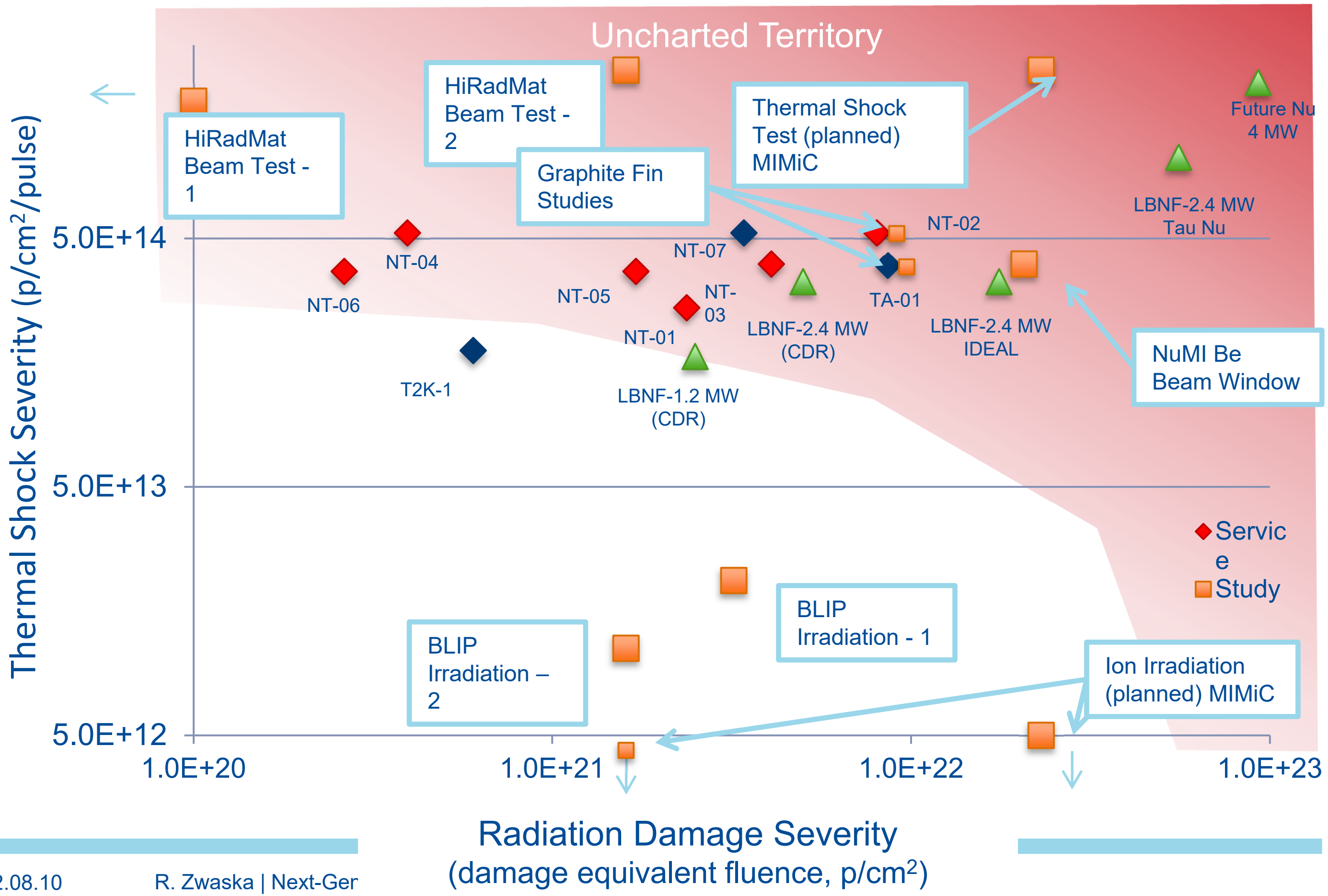
**Microstructural response:**

- *creation of transmutation products;*
- *atomic displacements (cascades)*
  - *average number of stable interstitial/vacancy pairs created = DPA (Displacements Per Atom)*
- *Gas production (hydrogen / helium)*




Slide prepared by V. Kuksenko (Oxford)

# Nu HPT R&D Materials Exploratory Map



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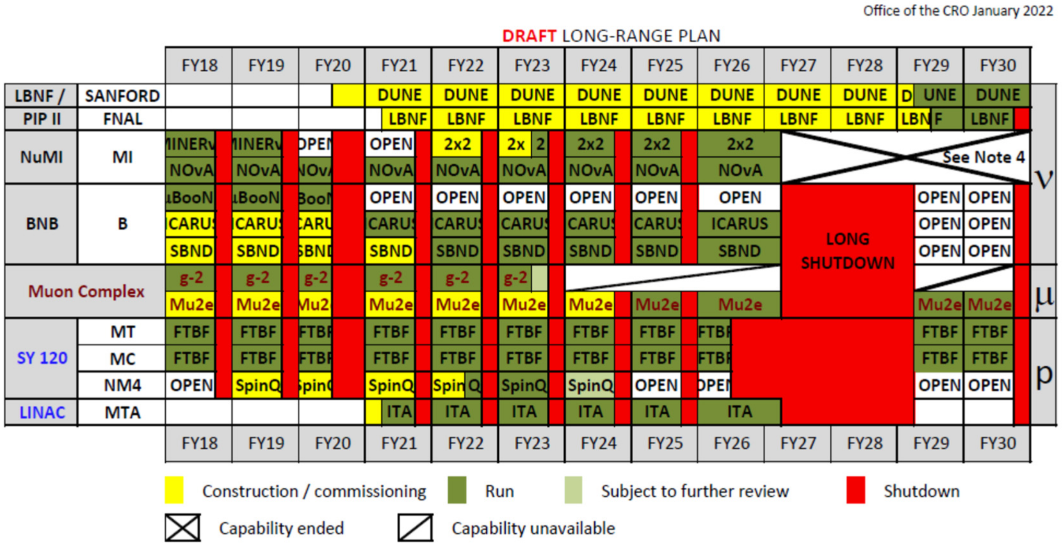
# Fermilab Experiments’ Run Schedule




**NOTES**

1. This draft long-range plan is updated bi-annually, typically following PAC meetings.
2. The timing and length of the Long Shutdown associated with the major construction activities at the lab will become clearer as the projects are baselined. Optimized commissioning and physics startup plans will be developed. Summer shutdowns will typically last about 4 months during the construction of LBNF/DUNE and PIP-II.
3. There will be no SY120 running from 6/2026 through the end of the long shutdown.
4. NOvA will run at least until the beginning of the Long Shutdown. A decision on whether to run after the Long Shutdown using PIP-II will be made before the Long Shutdown begins. The NOvA experiment will continue to alternate between neutrino and anti-neutrino running.
5. SpinQuest is expected to finish commissioning and start running late in FY22. Running beyond FY23 is subject to further review.
6. The MTA beamline and the Irradiation Test Area (ITA) began operations in FY21. It will not return in FY29.
7. The optimal timing of the Muon Complex switch from Muon g-2 to Mu2e commisioning and data running will continue to be monitored as Mu2e construction and g-2 data collection progress.



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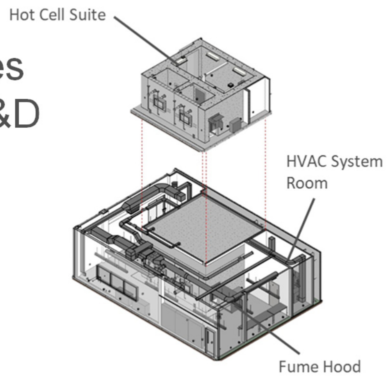
# High Power Target Materials R&D [1]

## Examine targets and beam window materials behavior under prototypic multi-MW proton beam conditions

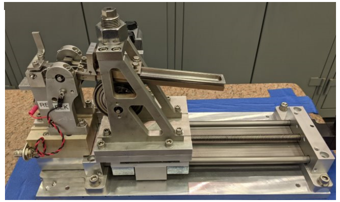
- Graphite (target core) studies:
  - Beam-induced swelling and fracture studies
  - High-dose ion irradiation of graphite
- Beryllium (beam window) studies:
  - NuMI beam window analysis & Helium ion implantation
  - Post-irradiation examination of BLIP-irradiated specimens
  - In-beam thermal shock testing at CERN's HiRadMat facility
- Titanium (beam window) studies:
  - Tensile testing of BLIP-irradiated specimens
  - Low-energy ion irradiation and nano-indentation
  - World first high-cycle fatigue testing of irradiated titanium at FNAL
- Novel materials studies:
  - Electro-spun nanofibers, high-entropy alloys, metal foams, MoGr, highly-ductile TFGR tungsten

# High Power Target Materials R&D [2]

- Bulk material properties change as a result of radiation damage in highly irradiated materials.
- Very limited engineering data (physical properties) exists for high energy proton irradiated materials
  - Need to collect relevant data to support target design and material choice
  - High energy proton irradiation
    - Highly activated material ⇨ need hot cells and specific characterization equipment
    - High energy ⇨ Low dpa rate ⇨ long irradiation time (order of months) ⇨ Expensive
  - Future needs
    - Develop dedicated tools for irradiated material studies
    - Develop new capabilities on-site to better support R&D
      - HPT laboratory with cold area and hot lab
    - Develop alternatives to
      - Radiation damage methods
      - Thermal shock and thermal fatigue



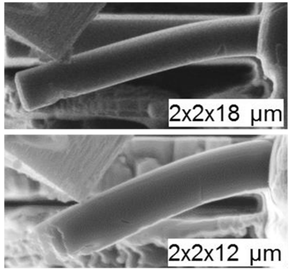

Hot lab of the future High Power Targetry (HPT) Lab

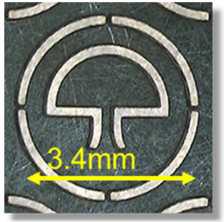


FNAL Fatigue test machine for irradiated samples

# Alternative to High Energy Proton Beam

- Alternative radiation damage method
  - Low-energy ion irradiation
    - Lower cost, high dose rate without activating the specimen
    - Narrow penetration depth
      - Micro-mechanics and meso-scale testing
    - Doesn't reproduce the gas (H and He) production
      - He implantation in Graphite at Michigan Ion Beam Lab
  - Very few heavy ion irradiation facilities around the world ⇨ Need more development of such facilities
- Alternative thermal shock method
  - Use of electron beams, lasers, or other techniques could reduce the cost and length of R&D cycles compared to proton beam-line tests
- Ab initio and MD modeling could help to guide the development of alternative techniques

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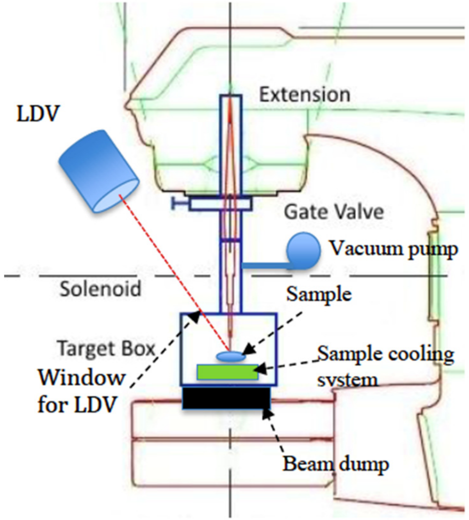




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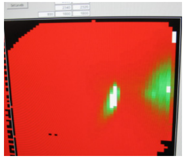
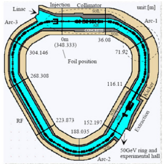
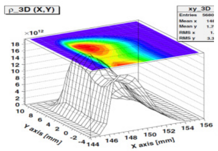
# Making Predictions is Hard, Especially about the Future: We will need targets

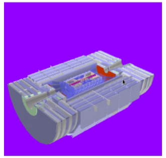
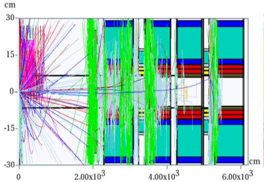
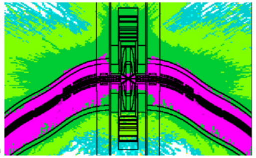
- **We know:**
  - LBNF is to run at 1.2, then 2.4 MW
  - PIP-II will be capable of 1.6 MW @ 800MeV
  - A Mu2e follow-on experiment will be desired

- **We don't know:**
  - Which experiments want 800 MeV beam (or 2 GeV or 8 GeV)
  - If future upgrades, will be linacs, synchrotrons, or accumulators
  - Whether the linac portion will be full CW capable
  - Whether the exiting target stations will continue to run

- **What else do we not know we don't know?**

The Bottom Line is that we need to develop our expertise in targets and target stations to execute the HEP program.

**Particle yields:**
**p, n, π, K, μ, Σ, HI**

**Nuclide inventory**

**Radiation damage:**
**DPA, dose, H/He,**
**soft errors (SEE)**


**Detector background suppression**

**Beamline optimization, beam loss, particle capture and collimation, SC magnet quench**

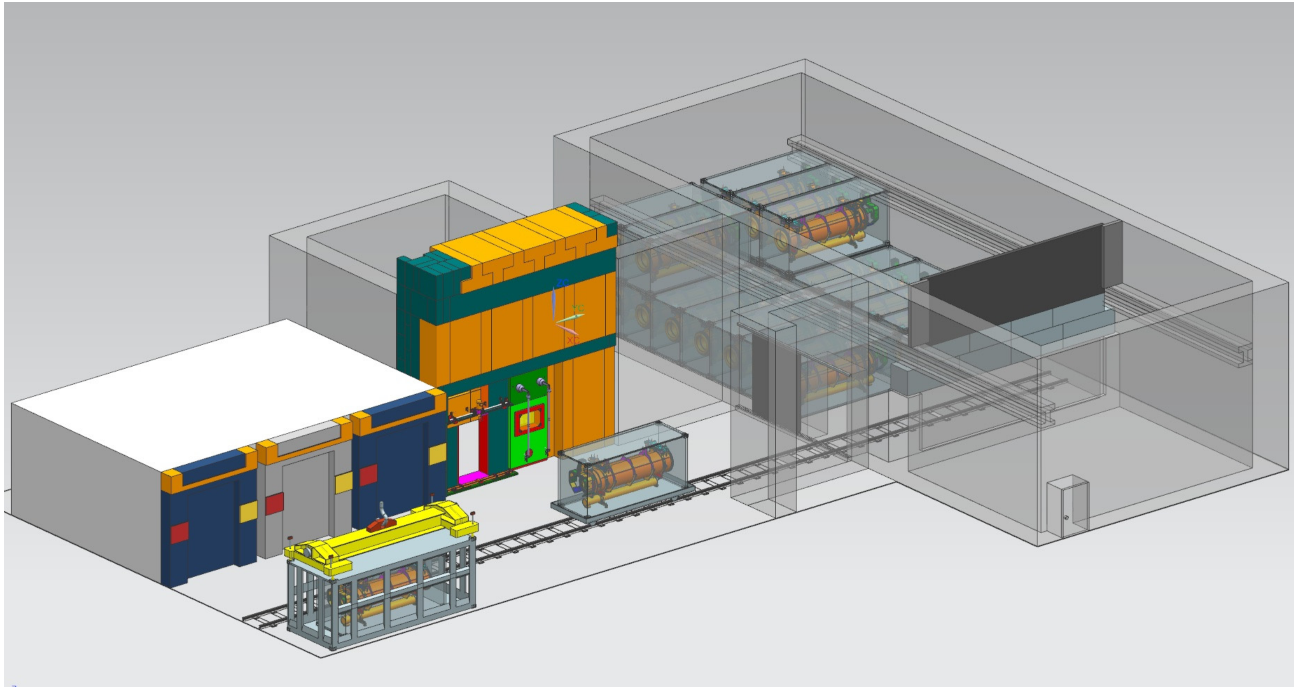
**Prompt and residual radiation, shielding, impact on environment**

**Targetry: power dissipation, integrity (shock & buildup), magnetohydrodynamics**

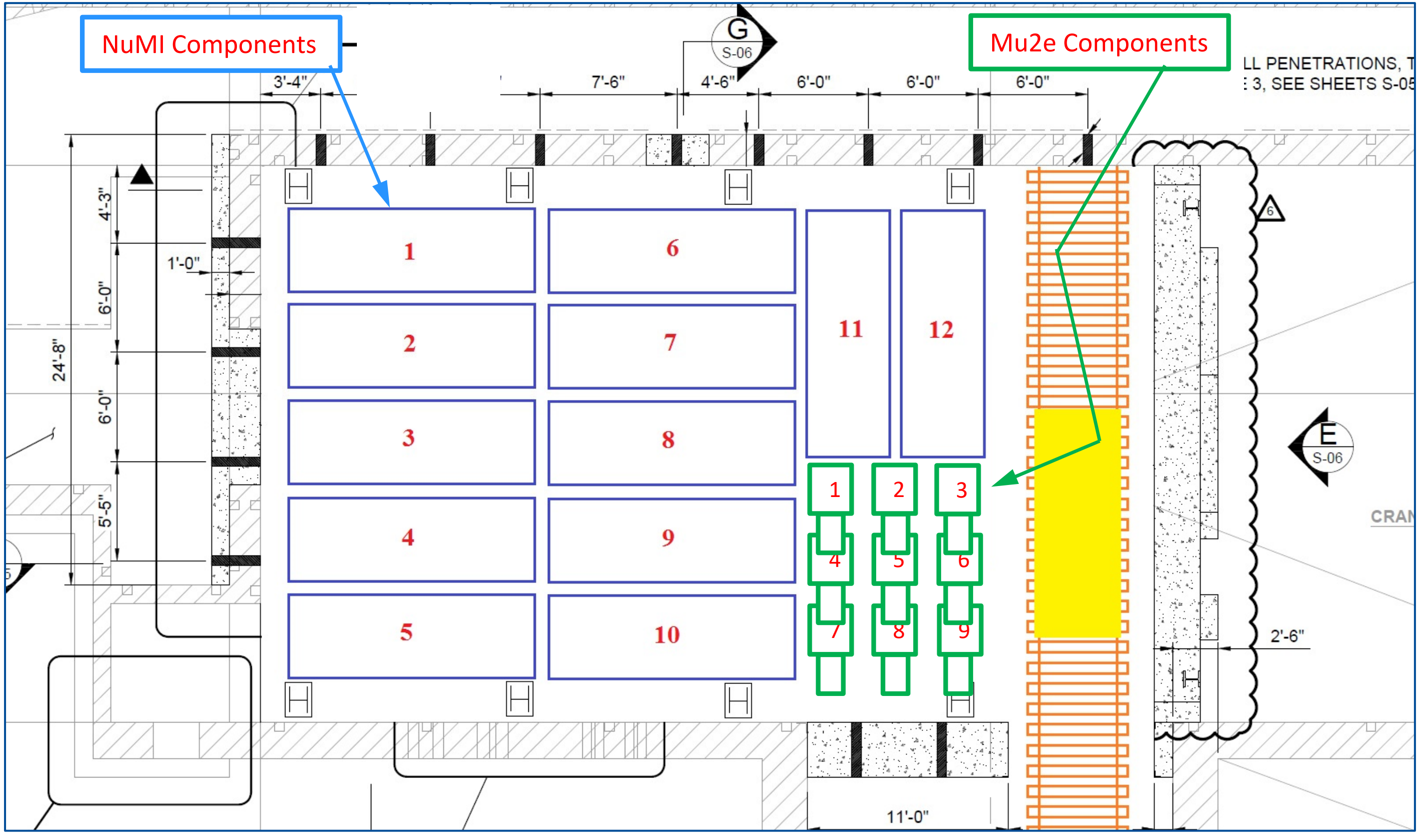
# Czero Long Term Storage and Remote Handling Facility

- Long-term storage for spent beam devices
- Handling facilities for investigations

- Three Medium-term storage bays
- Large, long-term storage hall
- One hot-cell with telemanipulators



# Storage Hall Layout



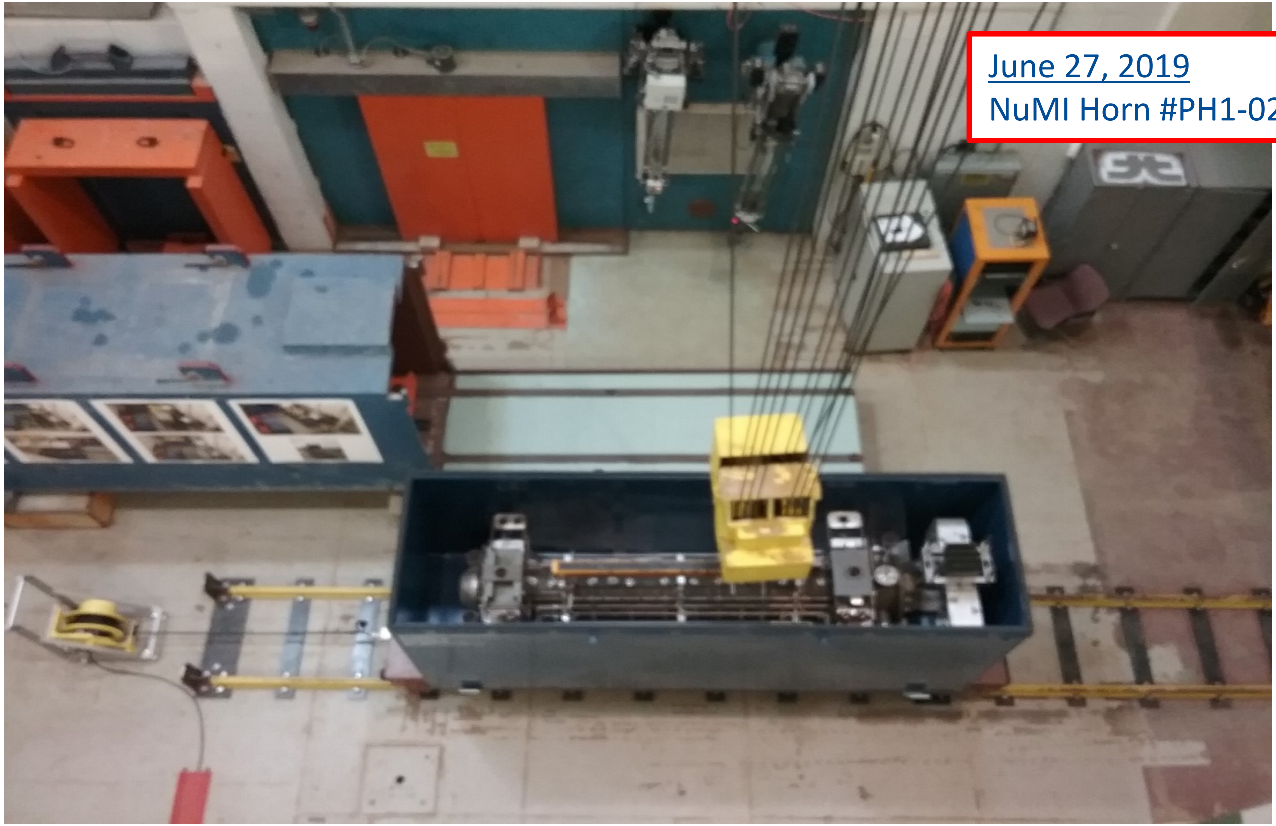


Fermilab

# Storage Hall

Fermilab

# Moving In First Hot Component



June 27, 2019
NuMI Horn #PH1-02



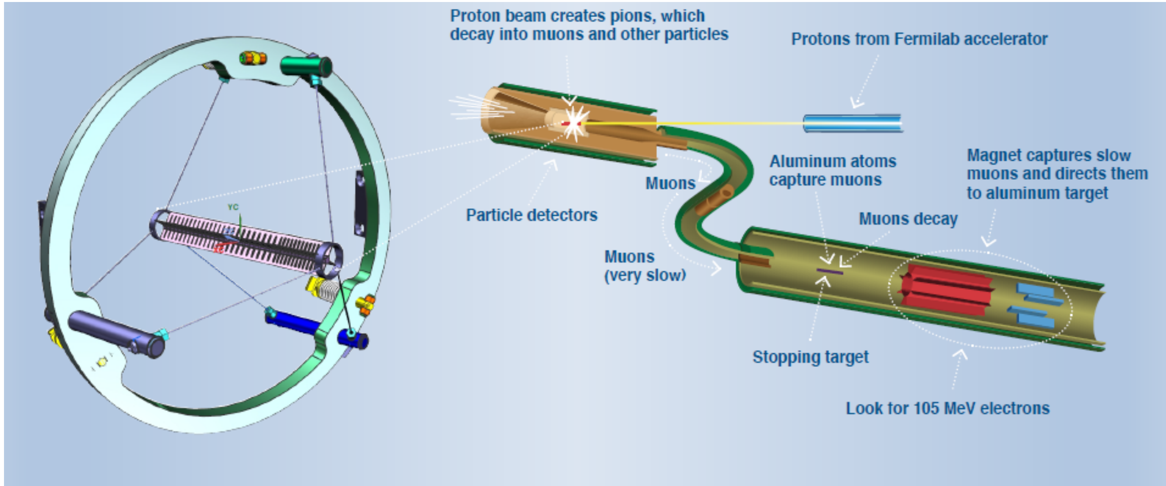
Fermilab

# PH1-02 in place in storage hall

- Will be ready for permanent disposal in 3-6 years
- Have a lot of space
- Remote Handling is for moving casks only

# Mu2e Target

- Radiatively-cooled Tungsten target, suspended in solenoid vacuum
  - Finned shape for expansion and thermal radiation
  - Unmeasured behavior of tungsten with this intense beam exposure
- Design power is only 8 kW beam, ~ 4 kW deposited in target
  - Still, the target design is very challenging within the experimental constraints – expect continuous development
- Mu2e team has recently been augmented with the hiring of a lead engineer and a lead physicist
- Expecting beam operations in ~ 2025

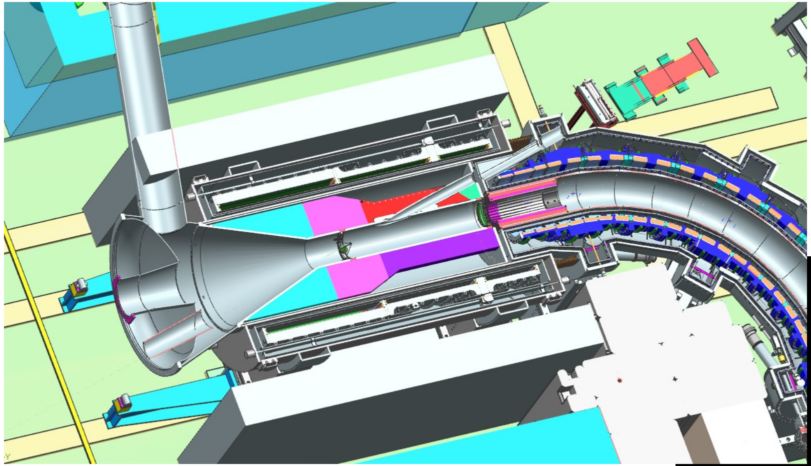



## Mu2e-II Target !!

- Proposed upgrade of Mu2e to use PIP-II 800 MeV beam at 100 kW
- Target considerations are more directly related to the number of protons
  - ***120x More Challenging!***
    - 12x from power
    - 10x from energy
- Mu2e-II target will be completely distinct from Mu2e, and possibly major portions of the experiment need to be rebuilt
  - Developing a concept for a target would enable the start of materials R&D

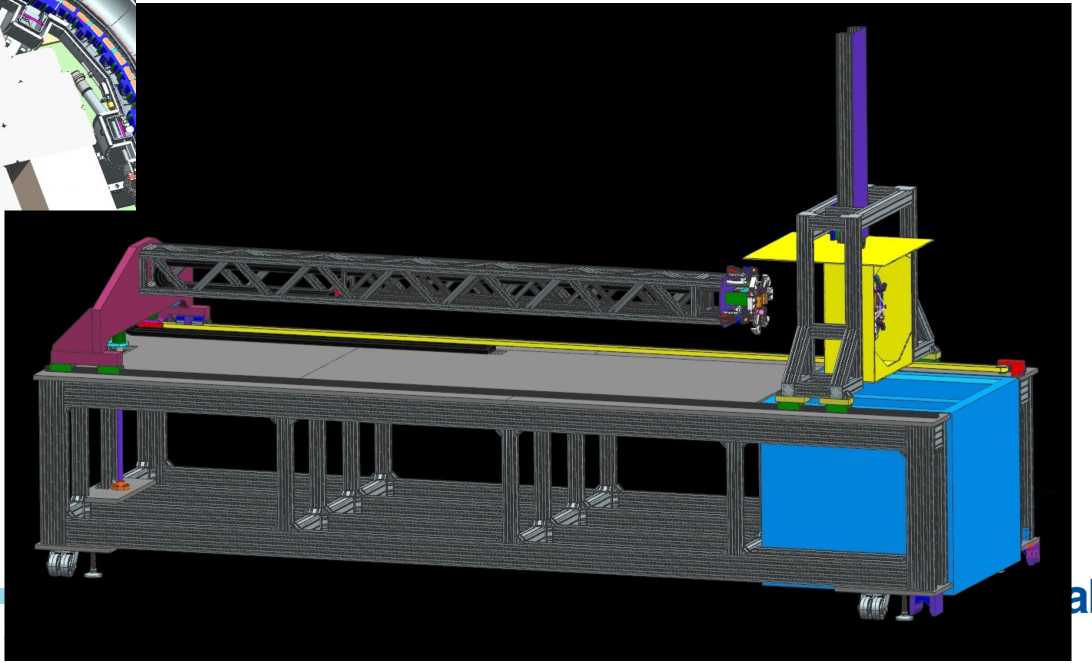
| | |
|---|---|
| Kinetic Enegy [MeV] | 800 |
| Instantanous Current [mA] | 10 |
| Instantaneous Power [kW] | 8000 |
| Average available Power [kW] | 100 |
| f {MHz] | 162.5 |
| Bunch spacing [ns] | 6.2 |
| Bulse length [ps] | 4.0 |
| protons/bunch | 3.8E+08 |

# Mu2e Remote Handling



- Procedurally controlled robotic replacement system
  - Has some minimal feedback loops
  - A new approach for Fermilab in remote handling
  - Likely to be used yearly

- Prototype system has been built and is being tested and developed as part of the project



- Expect to develop this system as operations begins
  - Build Body of knowledge for Mu2e-II