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Neutrino Program at Fermilab - Enhancing proton beam power and accelerator infrastructure

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Neutrinos From Home

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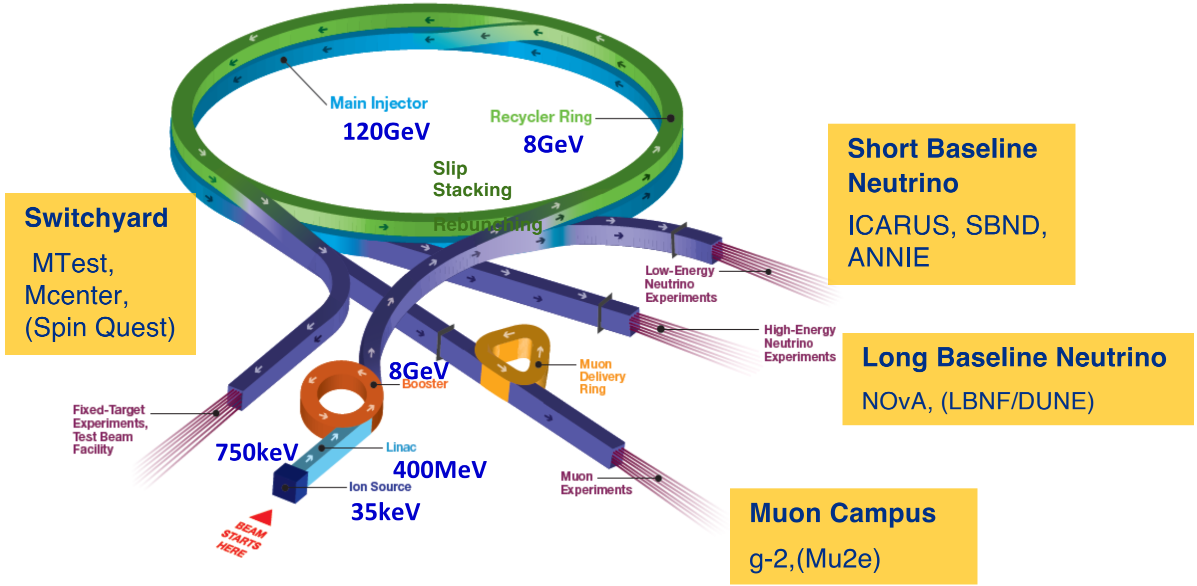
Content

- Current Accelerator Complex at Fermilab
- Fermilab Neutrino Program
- Megawatt upgrade
- LBNF/DUNE
- Accelerator Capabilities Enhancement (ACE) overview and opportunities
  - Main Injector Ramp & Targetry (MIRT)
- Neutrino Beam challenges
  - Targetry
  - Beam Instrumentation

Current Accelerator Complex at Fermilab

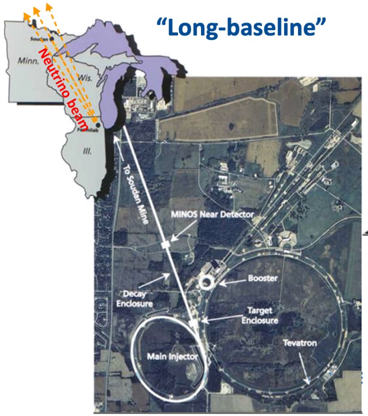


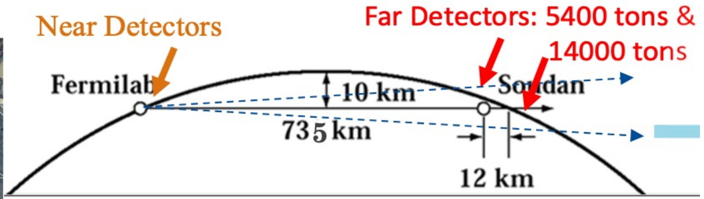
- **Fermilab operates largest particle accelerator complex in USA, 6,800 acres of federal land**
- **~1,900 staff with a yearly budget of ~ $600M**
- **Hosts facilities utilized by over 4,000 scientists from 50+ countries**
- **Continues its mission to unravel mysteries of matter, energy, space, and time for global benefit**

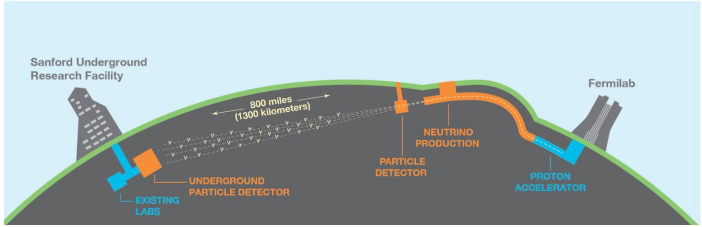
Fermilab Neutrino Program

- **Currently operating neutrino experiments**
  - NOvA
  - ICARUS
  - ANNIE
- **Designing & Building**
  - DUNE (LBNF)
  - Short-Baseline Neutrino Program (SBN)
    - SBND

"Long-baseline"



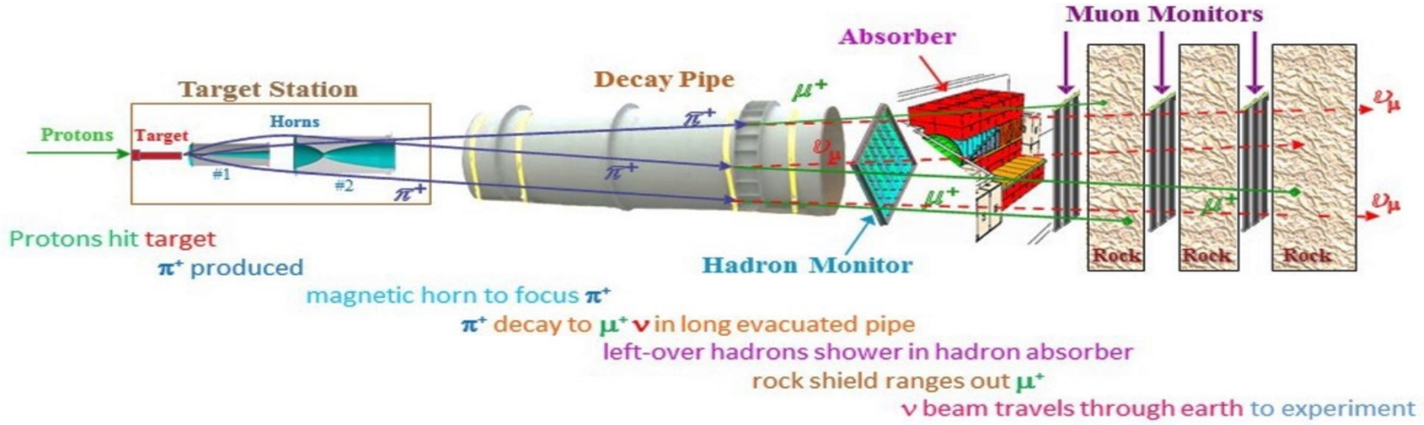




"Short-baseline"

- **Beamlines delivering beam to these experiments**
  - Long-baseline: NuMI/LBNF
  - Short-baseline: BNB

NuMI Beamline



- Intense beam of muon-neutrinos aimed towards Minnesota
- Main Injector provides 50–70 trillion 120GeV protons every 1.2 seconds
  - Originally designed for 400 kW
- Each pulse generates ~ 2x10^{14} ν_μ

  ~20 million pulses annually
- Commissioned in 2005, run until ~2027

NuMI Megawatt Upgrade

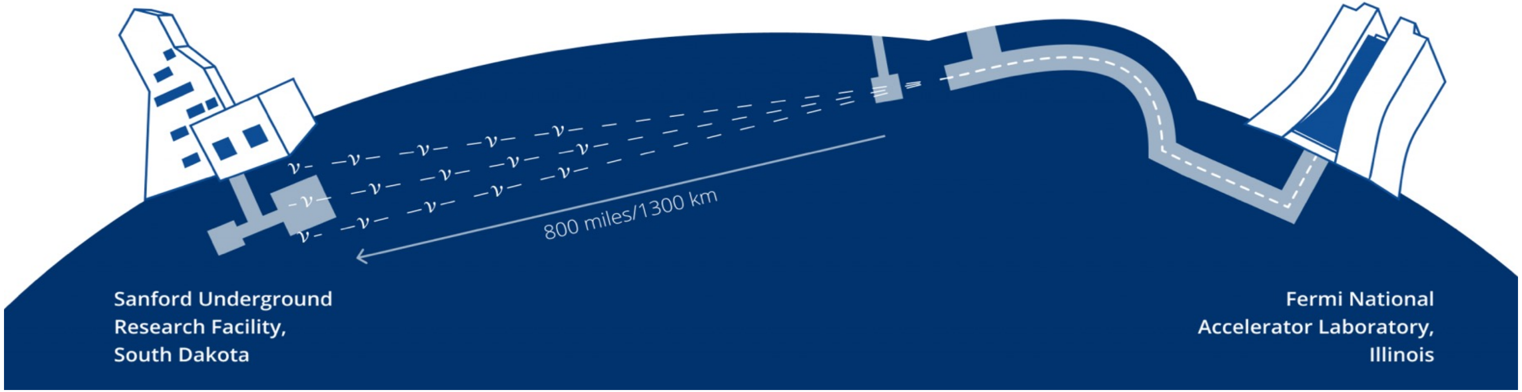
	NuMI Design	NOvA	1 MW upgrade
Proton beam energy	120 GeV		
Beam power (kW)	400	700	1 MW
Energy Spectrum	Low Energy	Medium Energy	
Cycle time (s)	1.87	1.33	1.2
Protons per spill	4.0 x 10^{13}	4.9 x 10^{13}	6.5 x 10^{13}
Spot Size (mm)	1.0	1.3	1.5
Beam pulse width	10 microsec		

R. Zwaska I Next-Gen Accelerators at Fermilab I NAPAC 2022

- **Enhanced Beam Power:**
  - Upgraded from 400 kW to 700 kW with NOvA /Accelerator & NuMI Upgrades (ANU)
  - NuMI Megawatt Accelerator Improvement Project (AIP): 2018-2021
- **Extended Capacity:** Modified to accept up to 1 MW beam power
  - Upgrade of target, horns, and supporting systems to be capable of accepting 1 MW beam power through 2025
- **Completion in 2021:** Finished upgrades after three annual shutdowns for component replacement
  - Various upgrade done, beam σ on target $= 1 - 1.5$ mm
- **Power Milestone:**
  - Set a record of nearly 959 kW in May 2023
  - Demonstrated capability with 1.133s MI cycle run

DUNE

World's most powerful neutrino experiment, powered by PIP-II & LBNF



Muon Neutrinos/Antineutrinos generated by high-power proton beam:

- **Proton Beam Power:**
  - 1.2 MW from inception
  - Scalable upgrade potential to 2.4 MW
- **Liquid Argon Time Projection Chambers (LArTPCs):**
  - Deployed in underground facilities
  - 4 x 17 kton fiducial mass of > 40 kton
- **Near Detector Functionality:**
  - Used for beam characterization
  - Records hundreds of millions of neutrino interactions

Science Goals

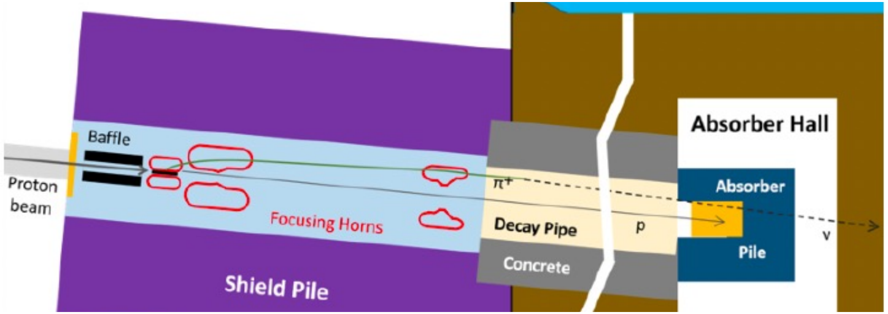
- Neutrino Oscillation Physics:
  - Search for CP Violation in neutrinos
  - Determine mass hierarchy
  - Precision oscillation physics
    - Testing 3-neutrino model, non-standard interactions…
- Supernova Burst Physics
- Nucleon Decay
- Other Topics: atmospheric neutrinos, sterile neutrinos, WIMPs, Lorentz invariance tests…..

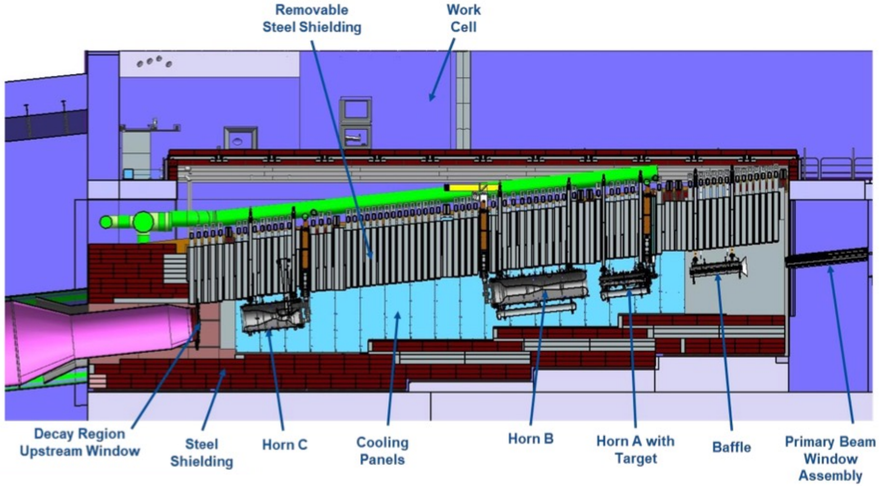
LBNF

LBNF/DUNE-US Project provides
- Up to 2.4 MW proton beamline
- 1.2 MW target systems
- Up to 2.4 MW of shielding and absorber

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





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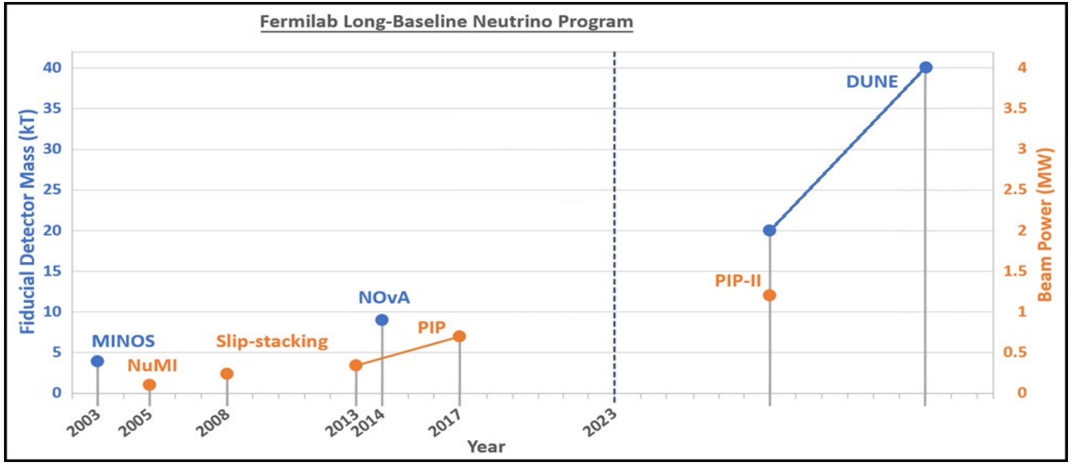
LBNF



From J. Eldred, JINST 2019

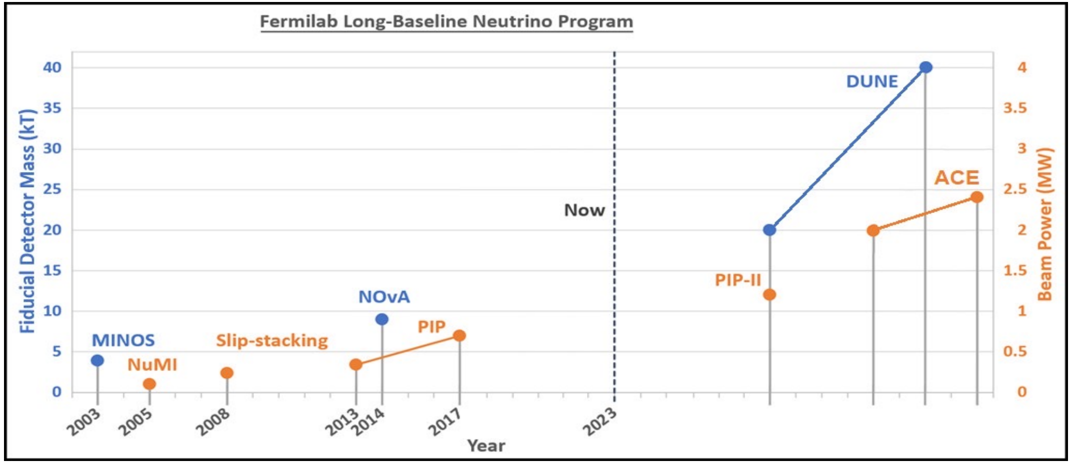
PIP-II upgrades will provide proton power of 1.2 MW (at max 1.35 MW)

LBNF/DUNE: Fermilab's highest priority

→ produce maximum neutrinos possible

→ increase proton flux, target station converts those protons to neutrinos

Accelerator Capabilities Enhancement (ACE) overview and opportunities



From J. Eldred, JINST 2019

PIP-II upgrades will provide proton power of 1.2 MW (at max 1.35 MW)

Set maximum energy (E) to 120 GeV; one option is to boost beam pulse intensity (N), requiring additional 8 GeV upgrades to beam intensity

Other option is to decrease MI ramp time

$$P = \frac{eNE}{T}$$

- ACE upgrade: accelerate beam delivery to LBNF/DUNE via MI cycle time reduction – faster way to 2+ MW
- ACE-MIRT upgrade: Main Injector Ramp & Targetry: MI cycle time + improvements of Target Systems capabilities

Accelerator Capabilities Enhancement (ACE) overview and opportunities

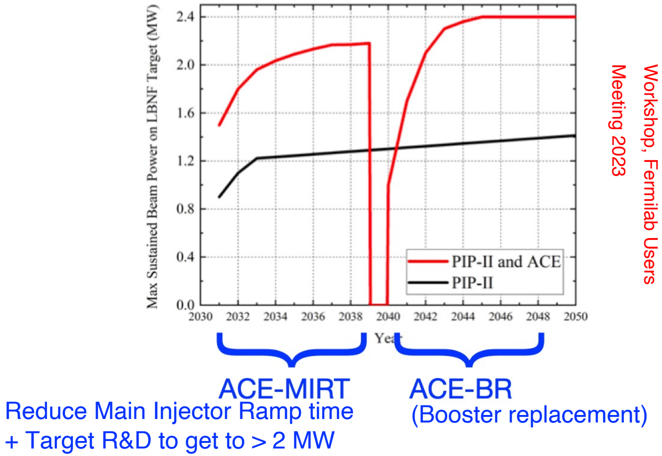
ACE-MIRT proposed to reduce Main Injector cycler to ~0.65s to increase beam power

		PIP-II Booster			
Operation scenario	**Nominal**	**PIP-II**	**A**	**B**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	s
Booster intensity	**4.5**			**6.5**	10^{12} p
Booster ramp rate	15			**20**	Hz
Number of batches	12		12		
MI power	0.75	**1.2**	1.7	**2.14**	MW
cycles for 8 GeV	6	12	6	2	
Available 8 GeV power	29	**83**	56	**24**	kW

From J. Eldred, Fermilab proton complex & muon collider planning, march, 2024

In ACE-MIRT period:

- Significant beams at 0.8 GeV
- Less at 8 GeV (because of MI cycle time, absolute minimum slip stacking time is 0.65s)
- More beam power with 120 GeV slow extraction



From N. Tran, ACE Science Workshop, Fermilab Users Meeting 2023

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Neutrino Beam Challenges

Many challenges to conventional neutrino beams:

Proton beams

- Targets
- Horns / focusing
- Precision
- Instrumentation
- Hadroproduction Modeling & Experiments
- Radiation Protection
- Radionuclide handling

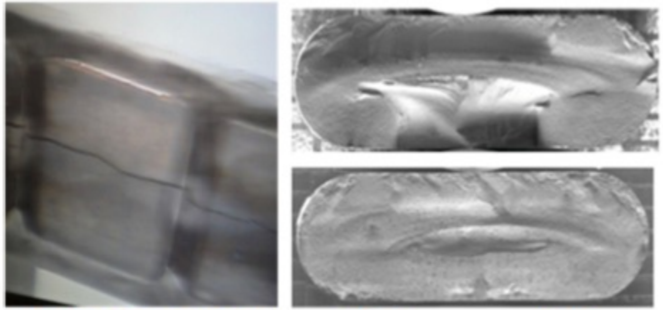
For ACE 2+ MW operation:

- Staged approach in Targetry needed for next-gen targets to maximize POT from accelerator complex
- Higher thermal load from beam – affects horn inner conductor due to higher heat and thermal stress
- Increased pulse rate – affects horn strip line due to fatigue
- To Maximize physics
  - Reliability, availability, stability over max power
  - Reduce shutdown duration

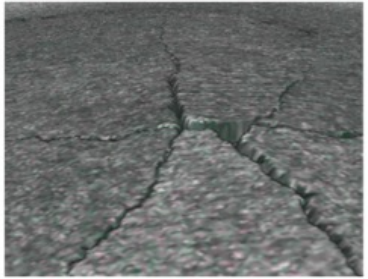
Neutrino Beam Challenges

Targetry R&D

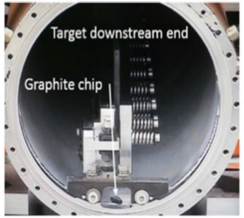
- Major facilities experience limitations in beam power
- Limitations often due to target survivability concerns rather than accelerator capabilities
- Successful HPT R&D enables facilities to operate at higher beam powers
- If 2+ MW upgrade is accelerated, long R&D cycle (~5 years), current data, results should be evaluated now to indicate expected lifetimes
- Need of new facilities: irradiation stations, Post-Irradiation Examination (PIE) facilities),development of modeling



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



Be window embrittlement (FNAL)



NOvA MET-01 target fin fracture (FNAL)

Neutrino Beam Challenges

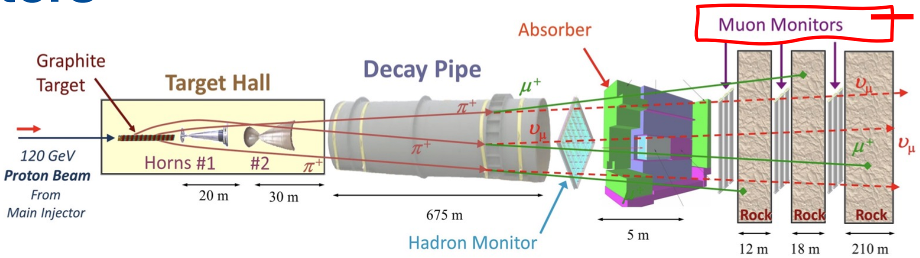
Beam Instrumentation

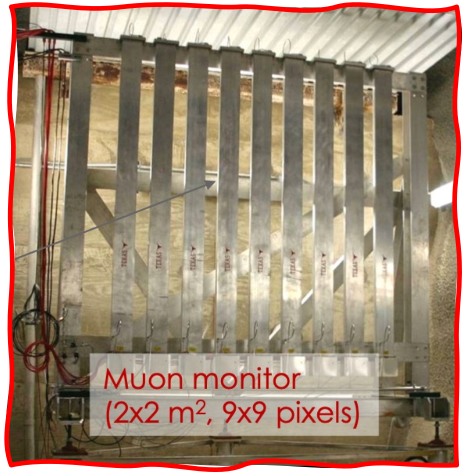
- Essential for smooth operation of accelerator complexes
- Impacted by immediate/cumulative radiation exposure, ambient temperature, humidity etc.
  e.g. NuMI Muon monitor1 damaged by radiation
- Affects range of operational beam parameters, e.g. highest possible beam power
- Essential for reliable and efficient operations at higher beam power for future multi-MW facilities
- Fermilab, KEK/J-PARC collaborating on a global R&D efforts to enhance beam instrumentation

Ideas for radiation hardened beam instrumentations

Facility	Beam Energy	Beam Power	Instruments
LBNF	60 - 120 GeV	1.2 MW - 2.4 MW (50-70e12 protons per spill, 0.6-1.2 sec repetition time)	1. Target Health Monitor. (non-contact sensor) 2. More radiation hardened Beam Loss Monitors (BLMs). 3. More radiation hardened Hadron Monitor. 4. Pico-second muon monitor. 5. Primary Proton Beam monitor.
Mu2e	8 GeV	8 kW (slow extraction beam, 1e9 protons per spill)	1. Target health monitor. (non-contact sensor) 2. Use same radiation hardened hadron monitor technology as production target monitor. 3. Primary Proton Beam Monitor.
Mu2e-II	0.8 GeV	100 kW	1. Target health monitor. 2. Primary Proton Beam Monitor.

Muon Monitors





Beam monitor

•Real-time detector for multi-MW target system
•Ensures quality spill-by-spill
•Requires high reliability, long lifetime and radiation-hardened design essential

Muon monitors

•Multi-pixel ionization chambers
•Located downstream of decay pipe
•Monitor secondary/tertiary particle profiles
•Ensure target system health
•High-power proton beam increases muon flux
•Space charge effect impacts monitor performance
•Decreased sensitivity due to radiation damage

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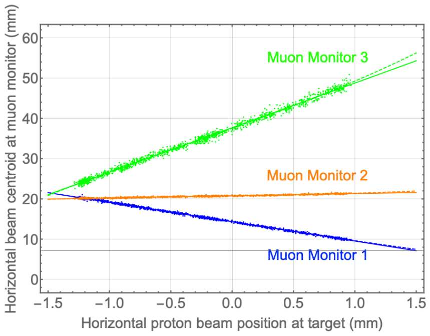
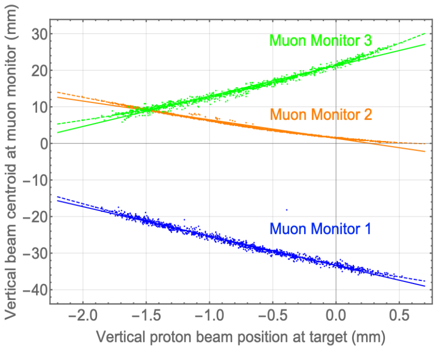
Muon Monitors

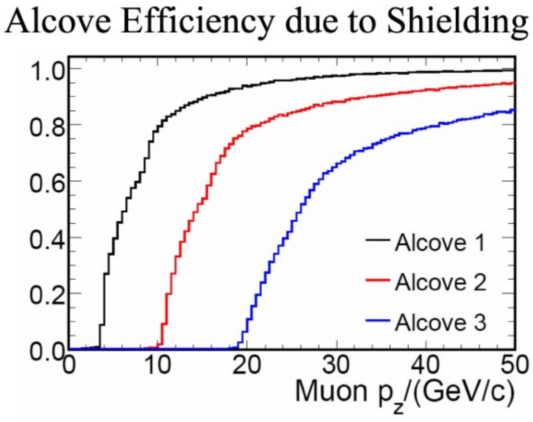
- Strong linear correlation between primary proton and muon beam on Muon Monitors
- MM2 exhibits opposite slope compared to MM1
- Aberration of horns causes this difference

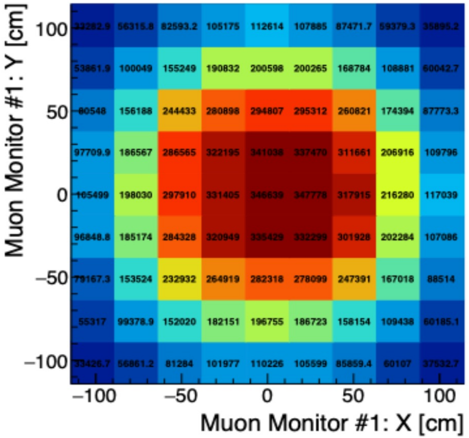




https://arxiv.org/pdf/2305.08695.pdf

Three monitor receive different energy muons





Muon Monitor 1 signal

https://arxiv.org/pdf/2309.08029.pdf

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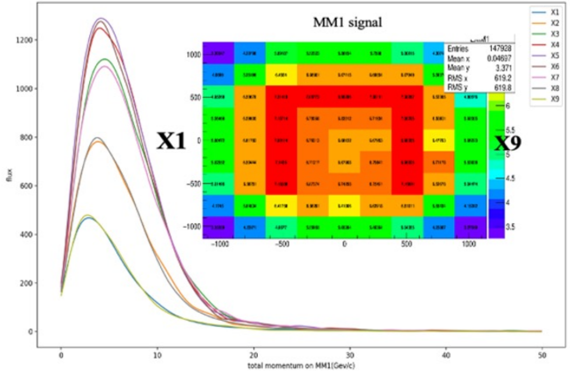
New Instrumentation Ideas

- Large Area Picosecond Photodetector (LAPPD)

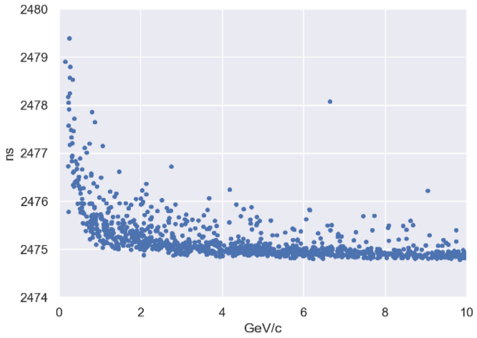
- use LAPPD as muon monitors, provides muon TOF measurement in alcoves across transverse plane
- allows application of precision timing in neutrino experiments

- LAPPDs already offer a space resolution of 1x1 mm and a time resolution of ~55 ps or better

Simulated momentum spectra on central row of MM1



Simulated time-of-flight vs muon momentum at MM1



- Individual pixel sees different muon spectrum
- X1 & X9, X2 & X8, X3 & X7, X4 & X6 shows similar shape

- Observed time distribution will be different at different pixel position

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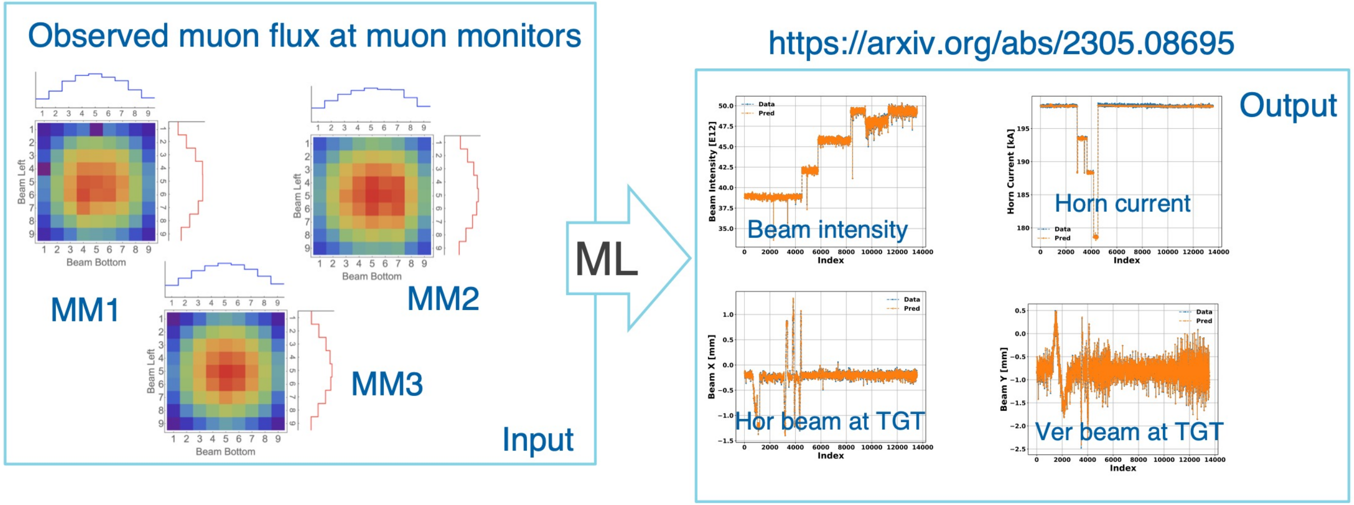
New Instrumentation Ideas

Machine Learning for Beam Quality Assessment in NuMI:

•NuMI horn's linear beam optics implies linear response to beam changes.
•ML algorithm with ANN predicts target beam positions.
•Based on 241 observed values, accuracy: ±0.018 mm horizontally, ±0.013 mm vertically observed
•ML matches traditional instrumentation accuracy



> 1,000 flux images are required for training ML

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Summary

ACE-MIRT plans to upgrade Main Injector to reduce ramp time and deliver more beam power to DUNE (max ~ 2.1 MW) as soon as possible

requires target R&D to ensure that DUNE can handle up to 2.4 MW of beam power

requires

Need significant R&D efforts focused on radiation-hard beam instrumentation

Fermilab and KEK/J-PARC accelerator and beamline groups have joined forces – plan to expand