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Design of the LBNF Beamline

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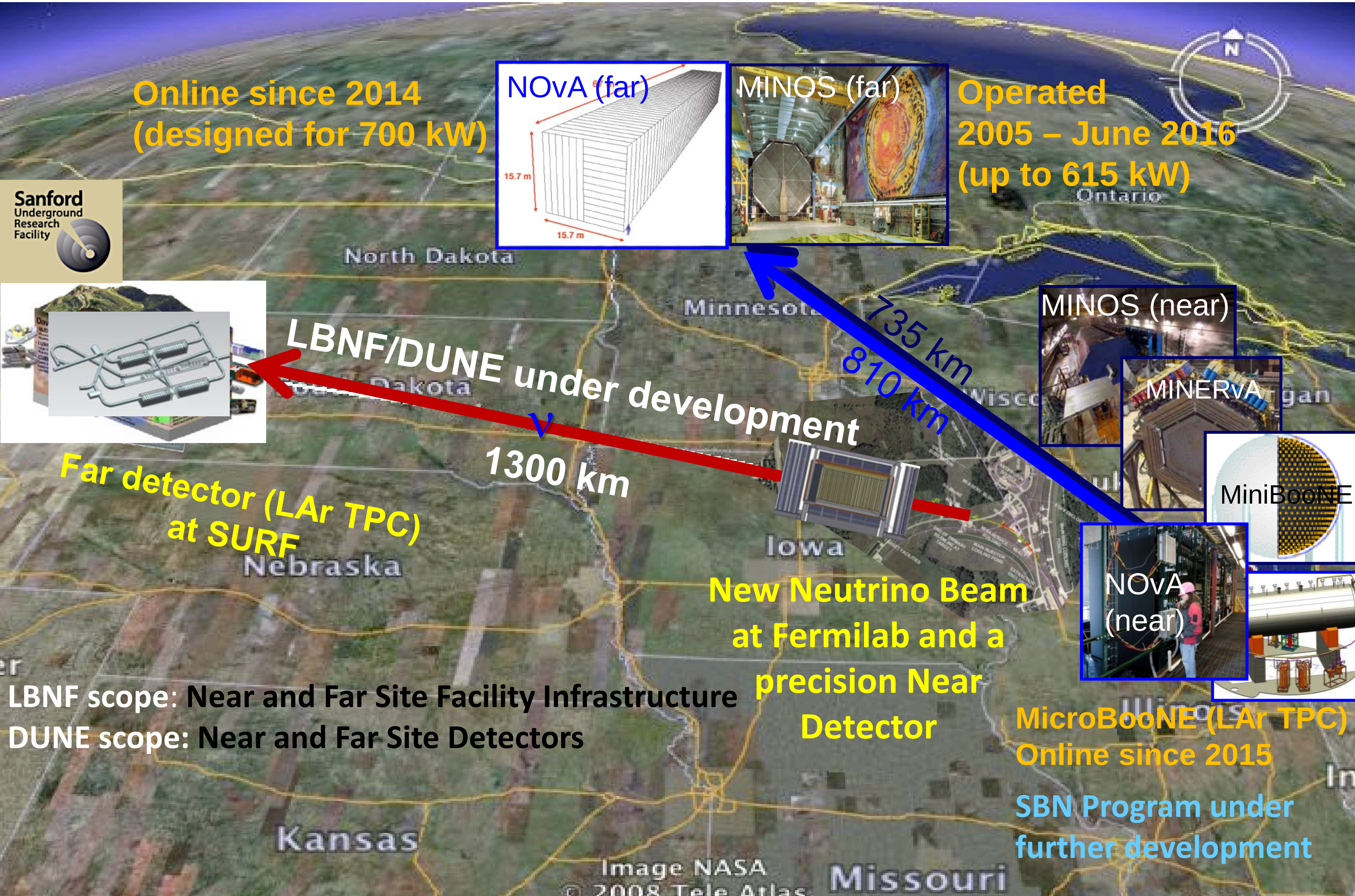
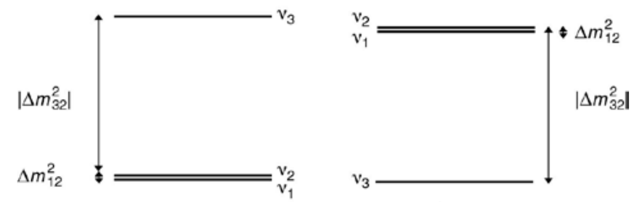
Outline

- LBNF/DUNE Science Goals
- The Fermilab Accelerator Complex
- Overview of the reference design of the LBNF Beamline
- Considered design upgrades
- LBNF/DUNE Milestones
- Conclusion

Neutrino Program at Fermilab



LBNF/DUNE Science Goals



In a single experiment

LBNF/DUNE is a comprehensive program to:

- Measure neutrino oscillations
  - Direct determination of CP violation in the leptonic sector
  - Measurement of the CP phase δ
  - Determination of the neutrino mass hierarchy
  - Determination of the θ_{23} octant and other precision measurements
  - Testing the 3-flavor mixing paradigm
  - Precision measurements of neutrino interactions with matter
  - Searching for new physics

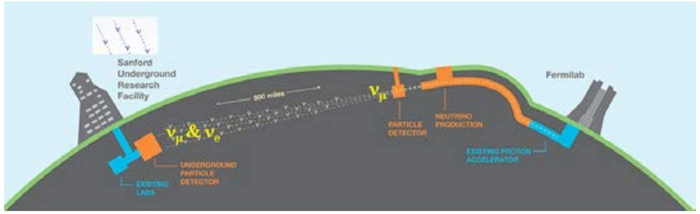
Start data taking ~ 2026

- Study other fundamental physics enabled by a massive, underground detector
  - Search for nucleon decays (e.g. targeting SUSY-favored modes)
  - Measurement of neutrinos from galactic core collapse supernovae
  - Measurements with atmospheric neutrinos

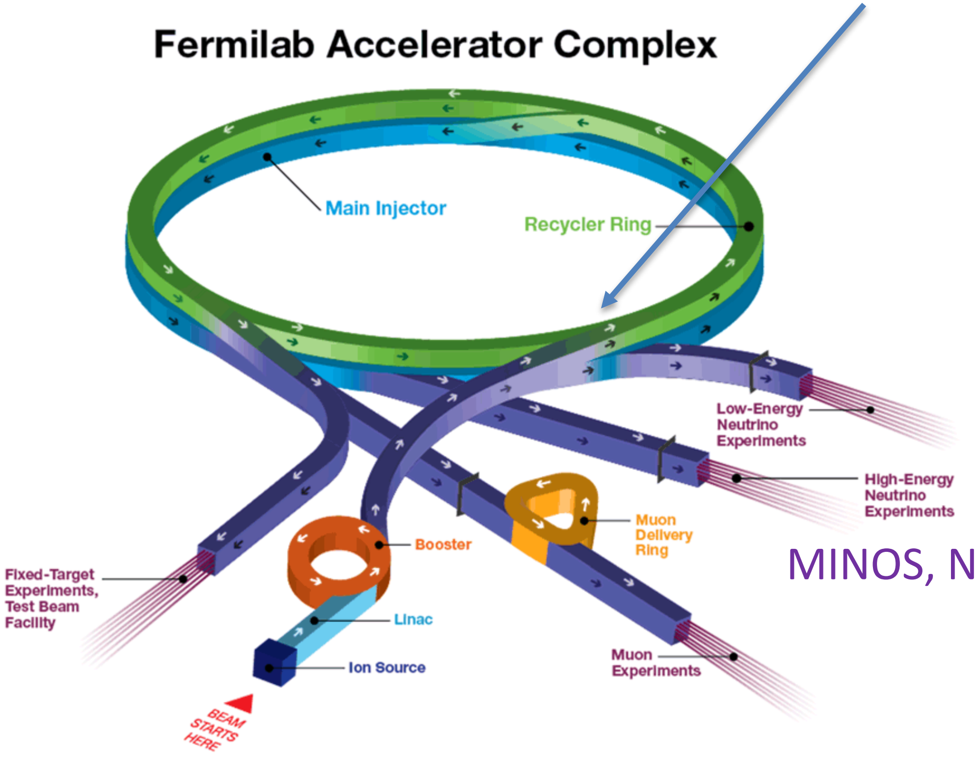
Start data taking ~ 2024

Fermilab Accelerator Complex

- H^- linac
  - 400 MeV
- Booster
  - h = 84
  - 15 Hz
  - 400 MeV -> 8 GeV
- Recycler
  - h = 588
  - Slip-stack 12 batches (double bunch intensity)
- Main Injector
  - 8 GeV -> 120 GeV



LBNF proton beam extracted from MI-10 straight section



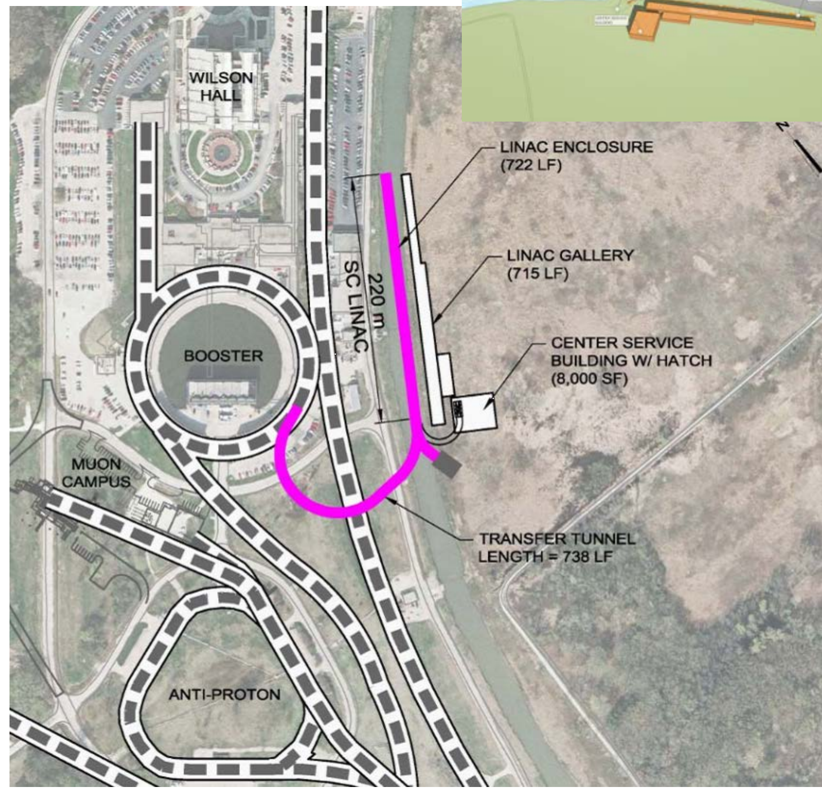
MINOS, NOvA

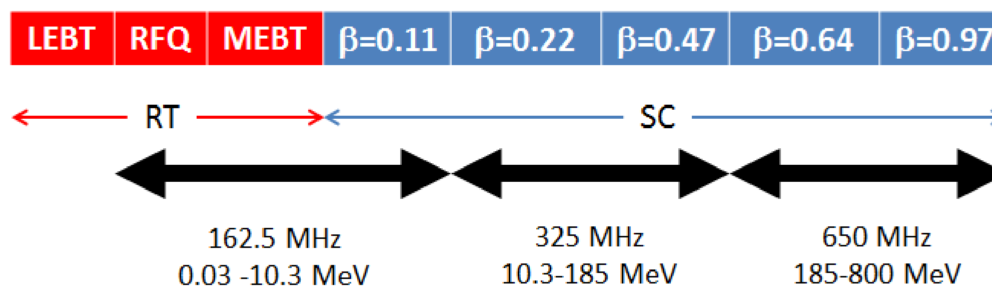
701 kW on the NuMI/NOvA target in one supercycle on June 13, 2016!!

Proton Improvement Plan (PIP)

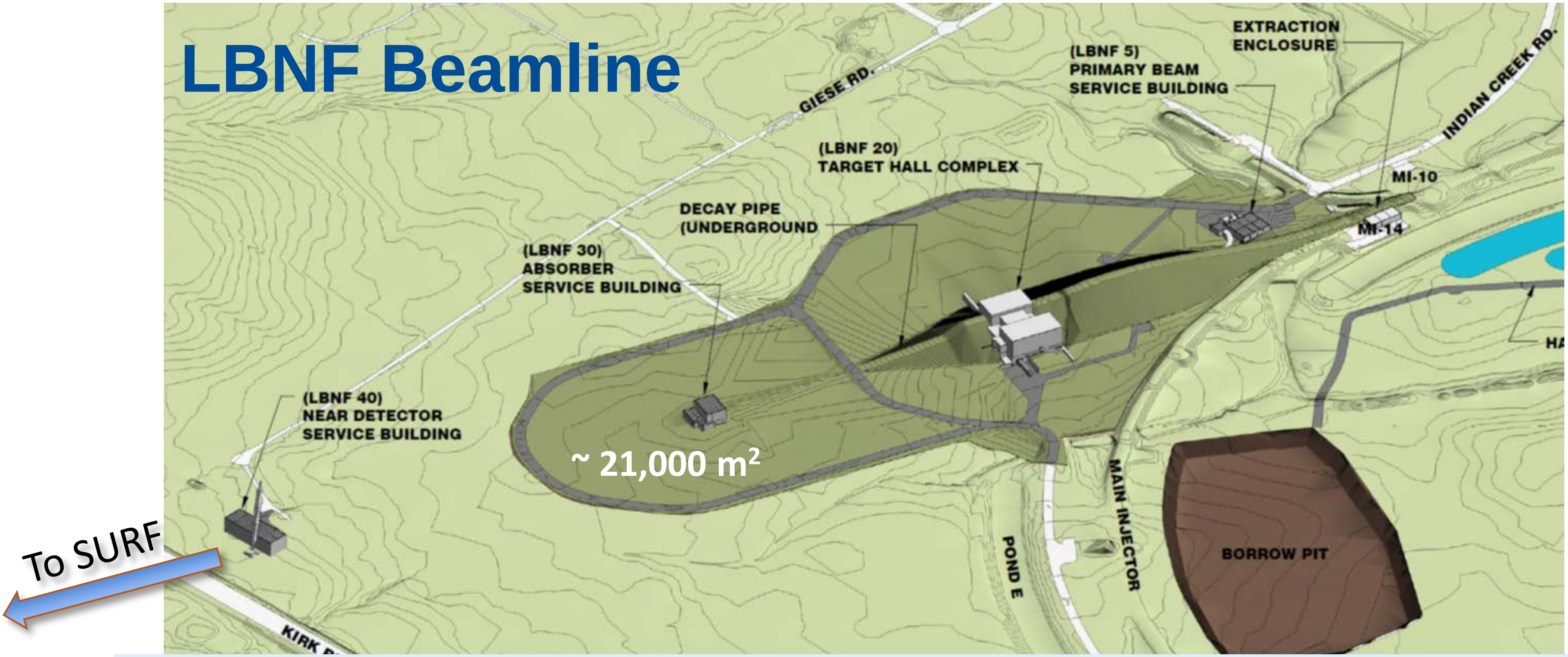
PIP-II (~2025)

- Key elements:
  - Replace existing 400 MeV linac with an 800 MeV linac capable of CW operation.
    - Higher energy + painting = more beam in Booster
  - Increase Booster rate to 20 Hz
  - “Modest” improvements to Recycler and MI
- Goals:
  - 1.2 MW @ 120 GeV
  - 100+ kW @ 800 MeV
    - Thanks to cryoplant from India

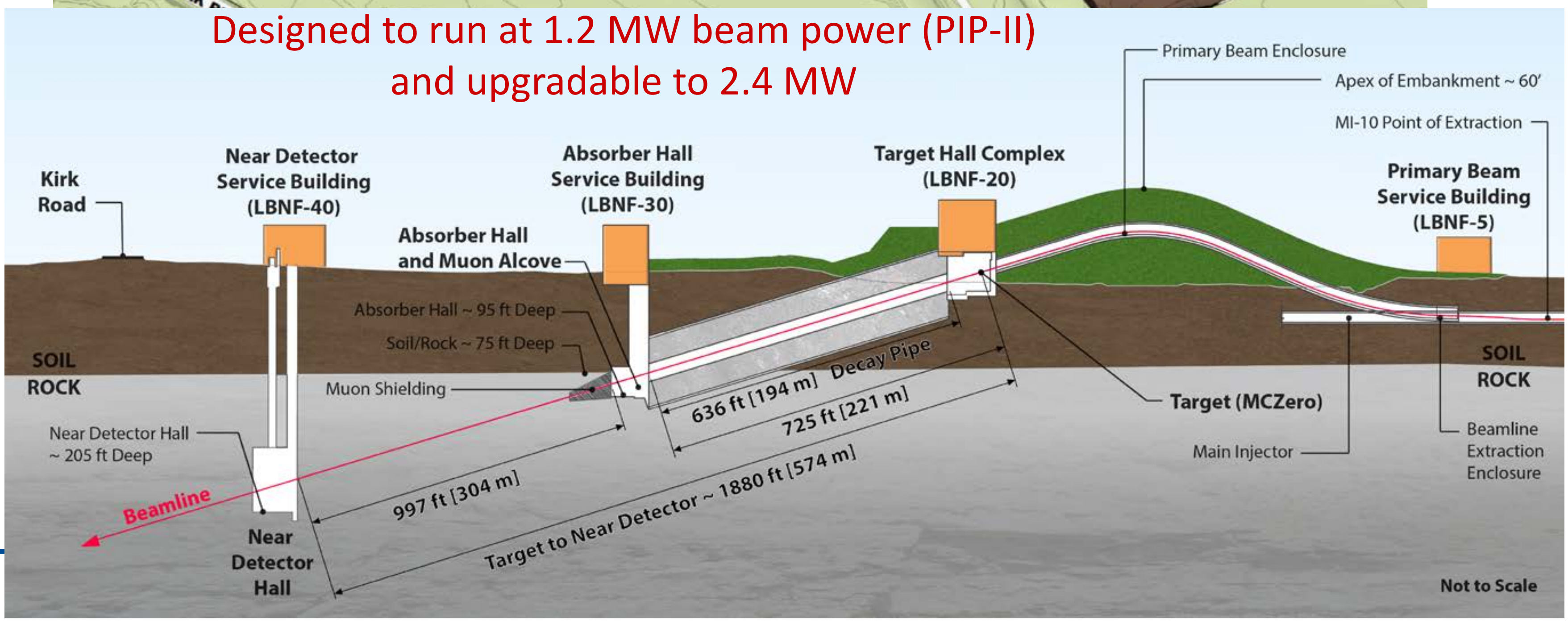




LBNF Beamline

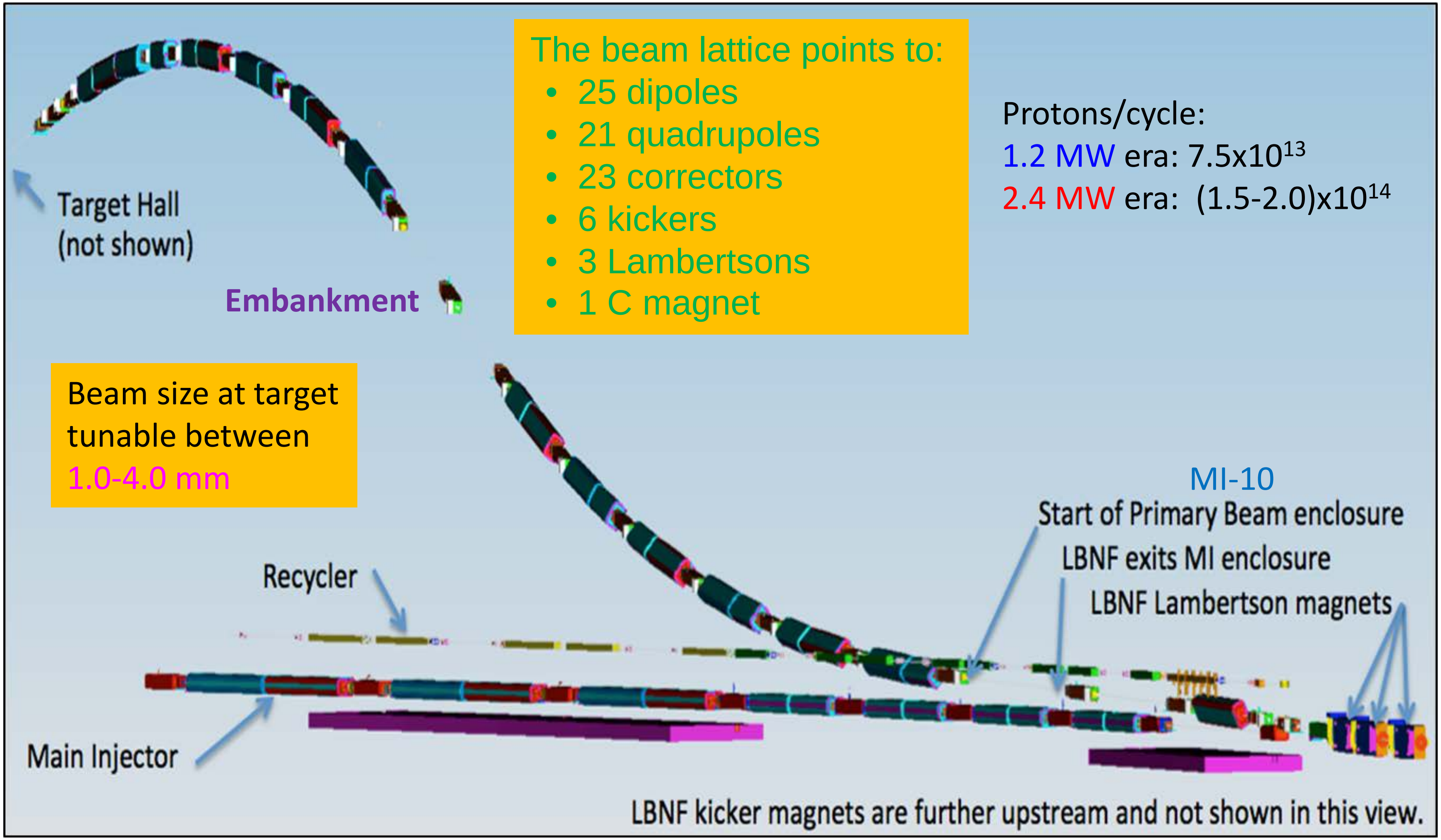


Designed to run at 1.2 MW beam power (PIP-II) and upgradable to 2.4 MW



Primary Beamline

The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNF target, with repetition rate of 0.7-1.2 sec, and 10 μs pulse duration



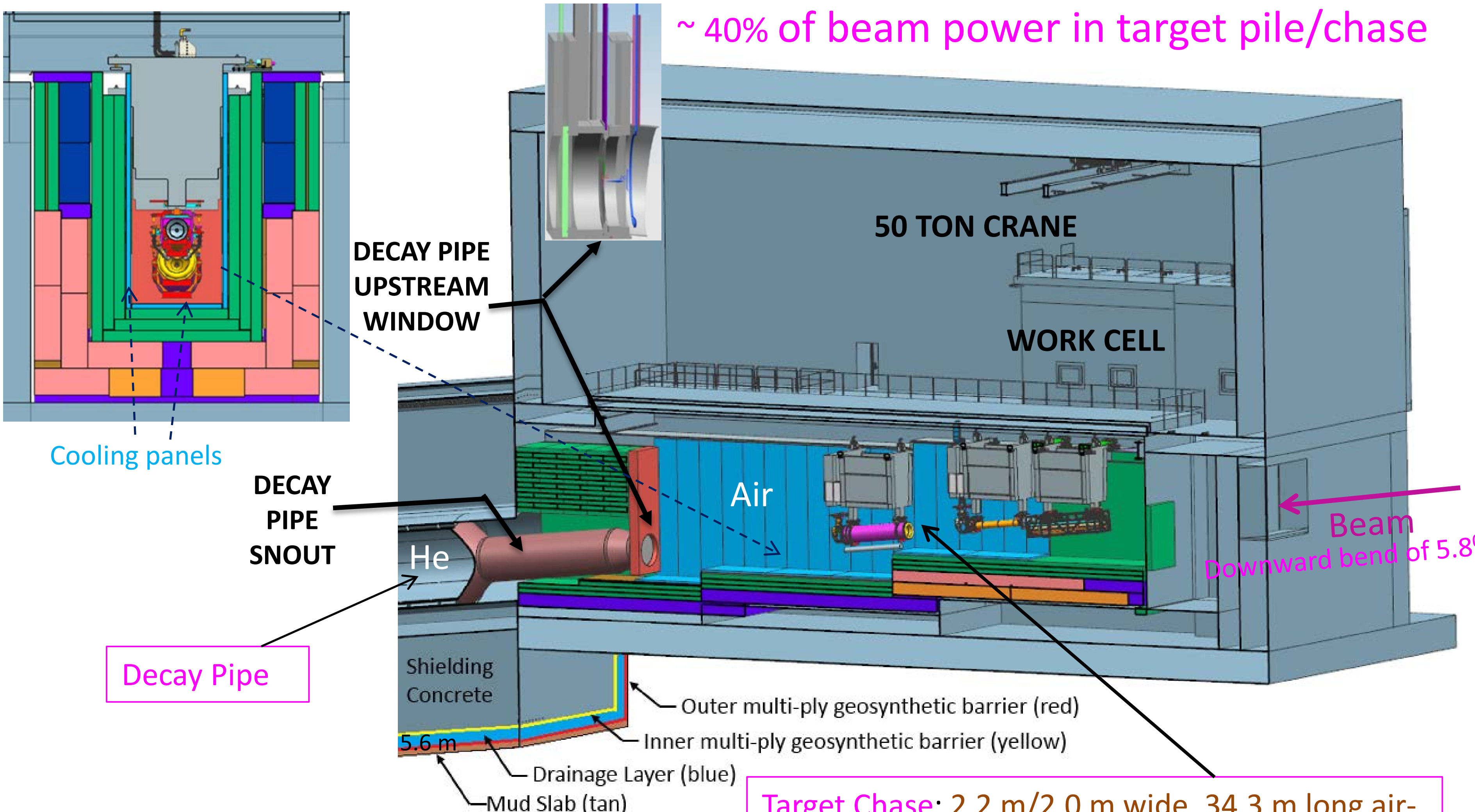
The beam lattice points to:

- 25 dipoles
- 21 quadrupoles
- 23 correctors
- 6 kickers
- 3 Lambertsons
- 1 C magnet

Protons/cycle:
1.2 MW era: 7.5×10^{13}
2.4 MW era: $(1.5\text{-}2.0) \times 10^{14}$

Beam size at target tunable between 1.0-4.0 mm

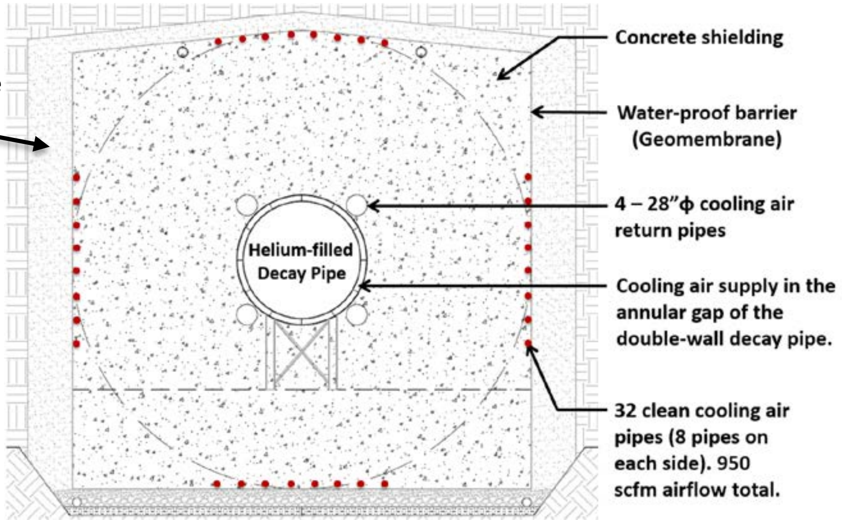
Target Hall Layout



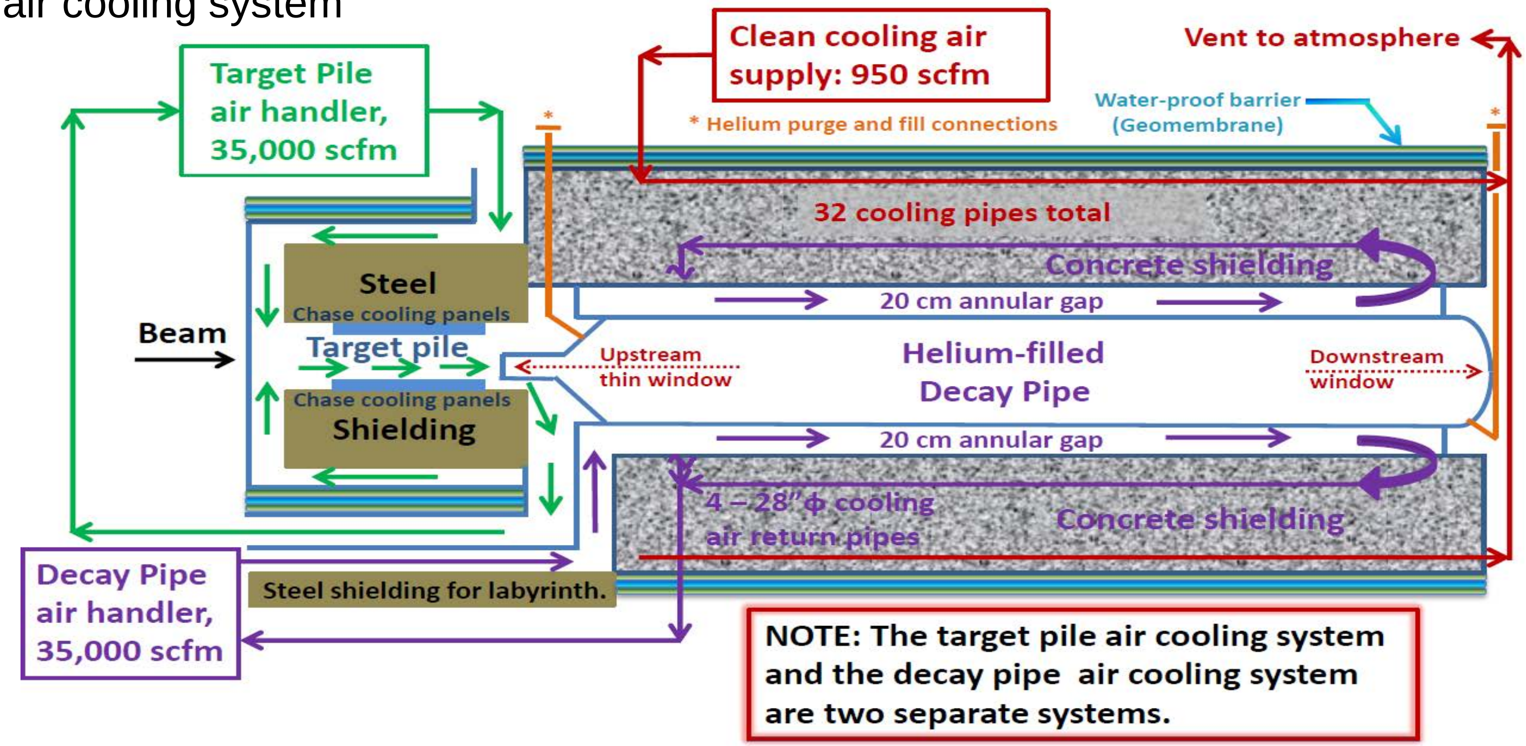
Main alternatives for Chase gas atmosphere: N_2 or He

Target Chase: 2.2 m/2.0 m wide, 34.3 m long air-filled and air & water-cooled (cooling panels). Sufficiently big to fit in alternative target/horns.

Decay Pipe Layout



- 194 m long, 4 m inside diameter
- Helium filled
- Double-wall, carbon steel decay pipe, with 20 cm annular gap
- 5.6 m thick concrete shielding
- It collects ~30% of the beam power, removed by an air cooling system



Hadron Absorber

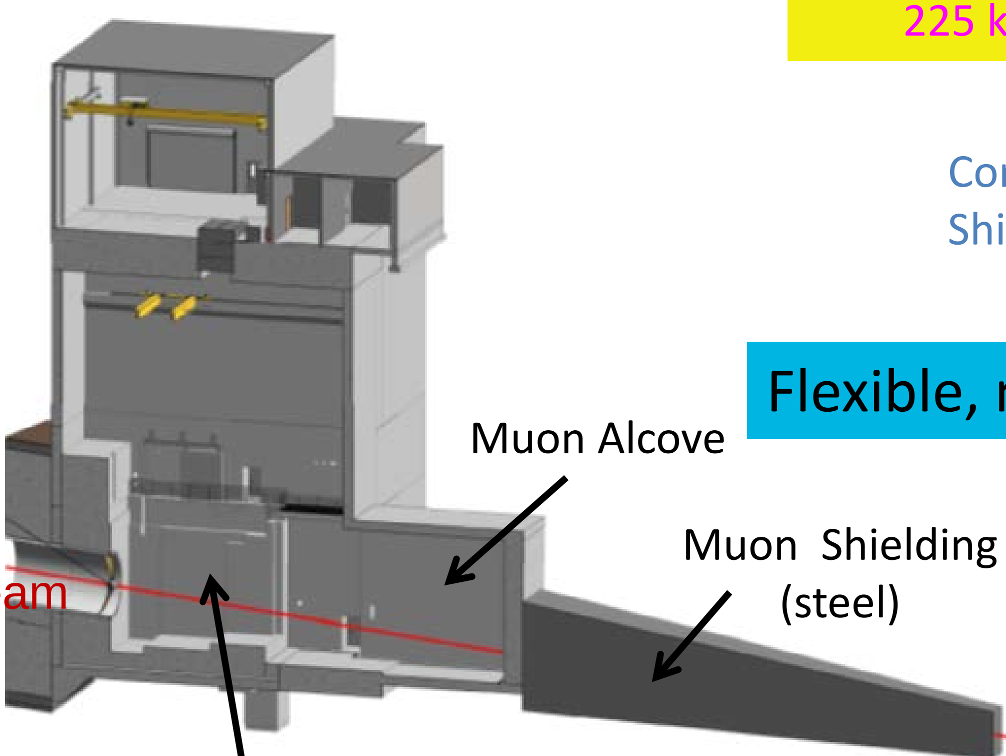
Absorber Hall and Service Building

The Absorber is designed for 2.4 MW
~ 30% of beam power in Absorber
515 kW in central core
225 kw in steel shielding

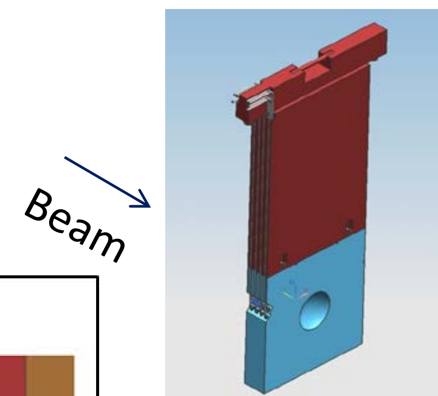
Absorber Cooling

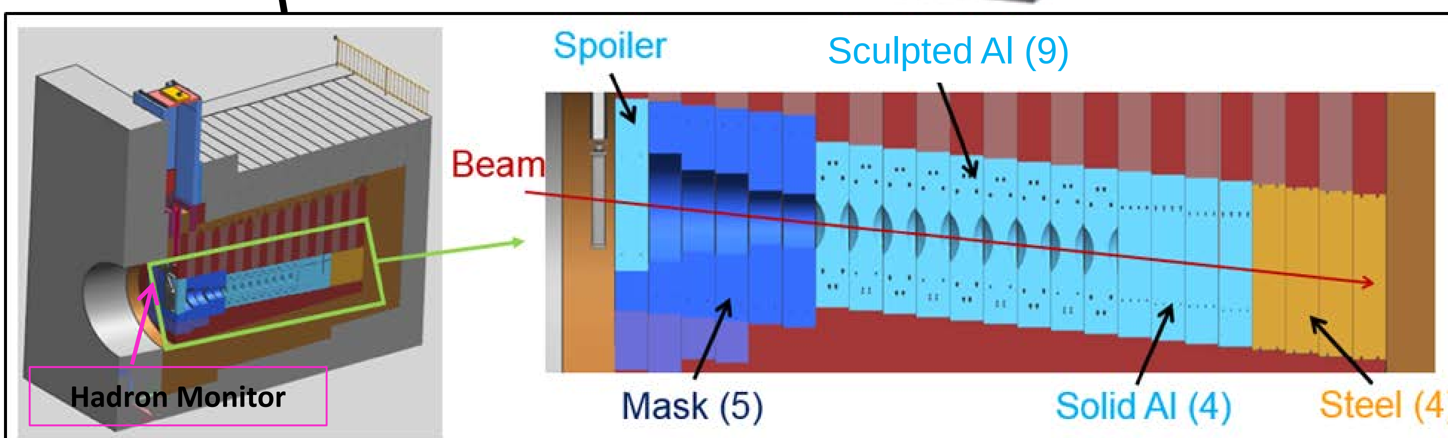
Core: water-cooled
Shielding: forced air-cooled

Flexible, modular design



Core blocks replaceable (each 1 ft thick)



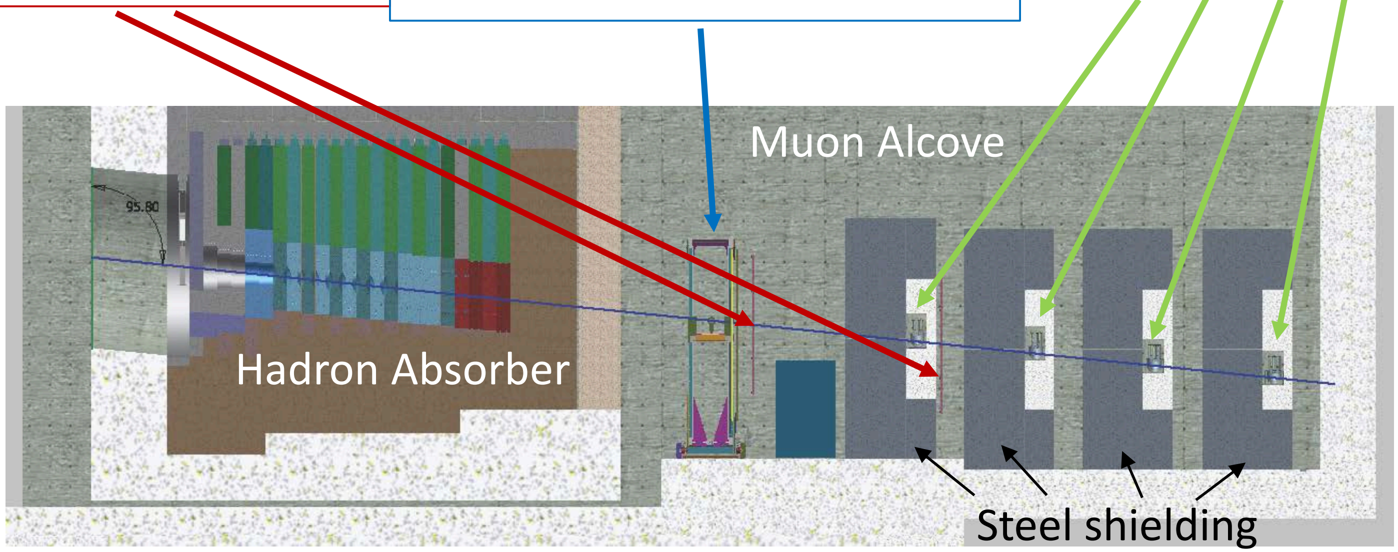


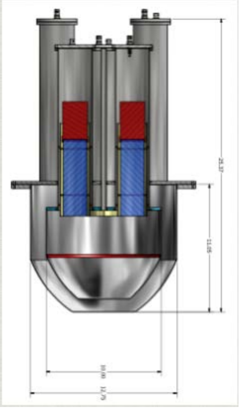
Overview of Beamline Muon Monitors

1. Array of Ionization Detectors that measure flux of all muons passing through (diamonds, Si)
   - Measure beam center and intensity
   - Spill by spill monitoring of beam

2. Threshold Gas Cherenkov Detector
   - Measure signal intensity at different gas pressures and detector orientations
   - Extract muon spectrum in alcove with the intention to constrain the neutrino flux

3. Stopped muon counters
   - Measure muon flux at several different energies
   - Robust measurement of beam flux and composition
   - Use to constrain neutrino flux





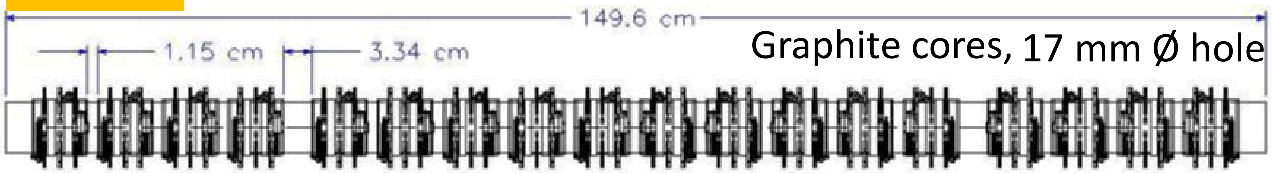
Testing prototypes at the NuMI beamline

Reference design baffle, target and horns - Viable for 1.2 MW

NuMI-like (low energy), with modest modifications

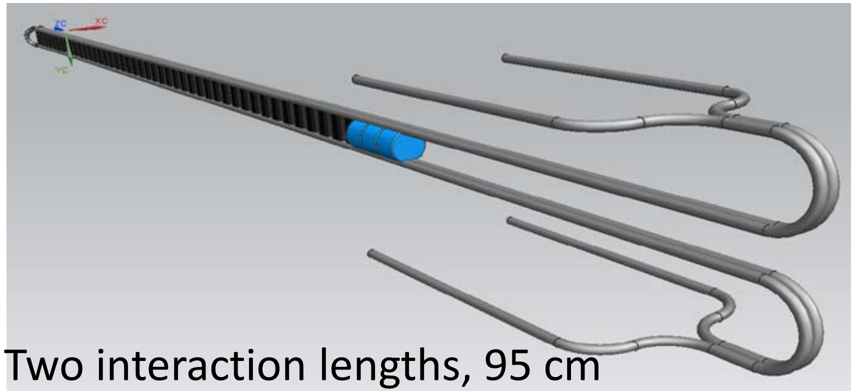
Baffle

Graphite cores, 17 mm Ø hole

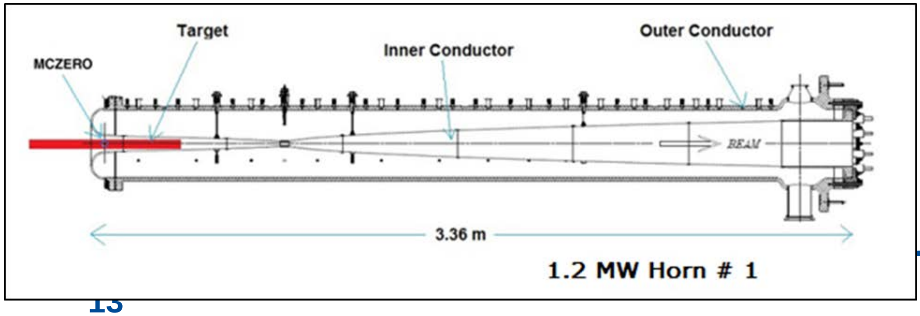


Protects target cooling structure and horns from errant beam pulses

47 graphite target segments, each 2 cm long and spaced 0.2 mm apart, 10 mm in width



Two interaction lengths, 95 cm

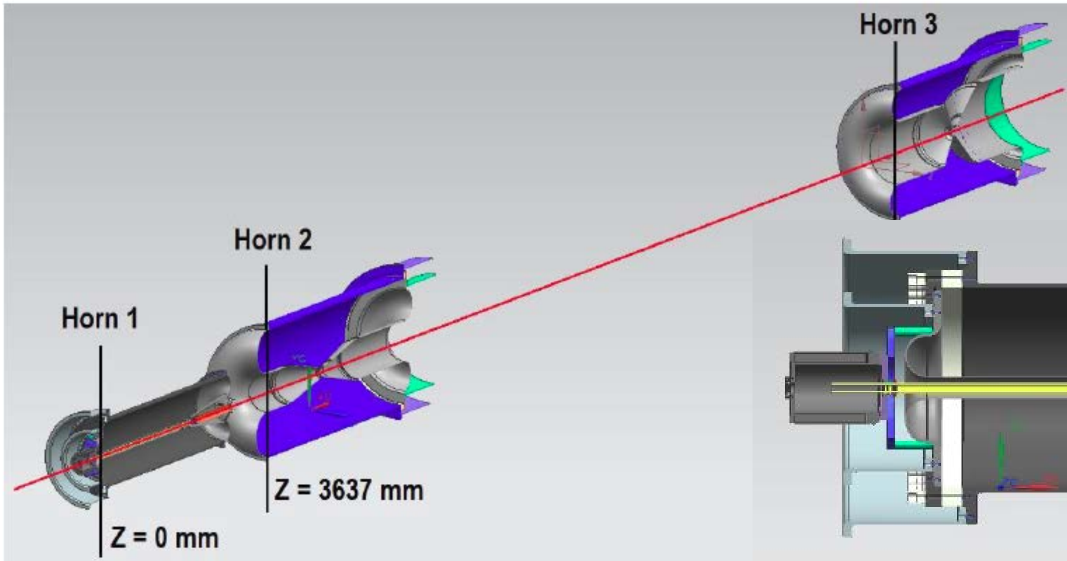


Strong target R&D program in place

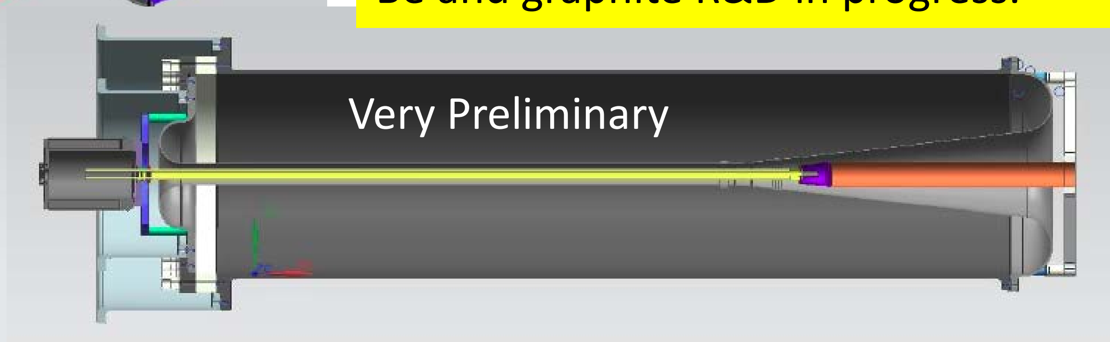
Inner Conductor of NuMI Horn

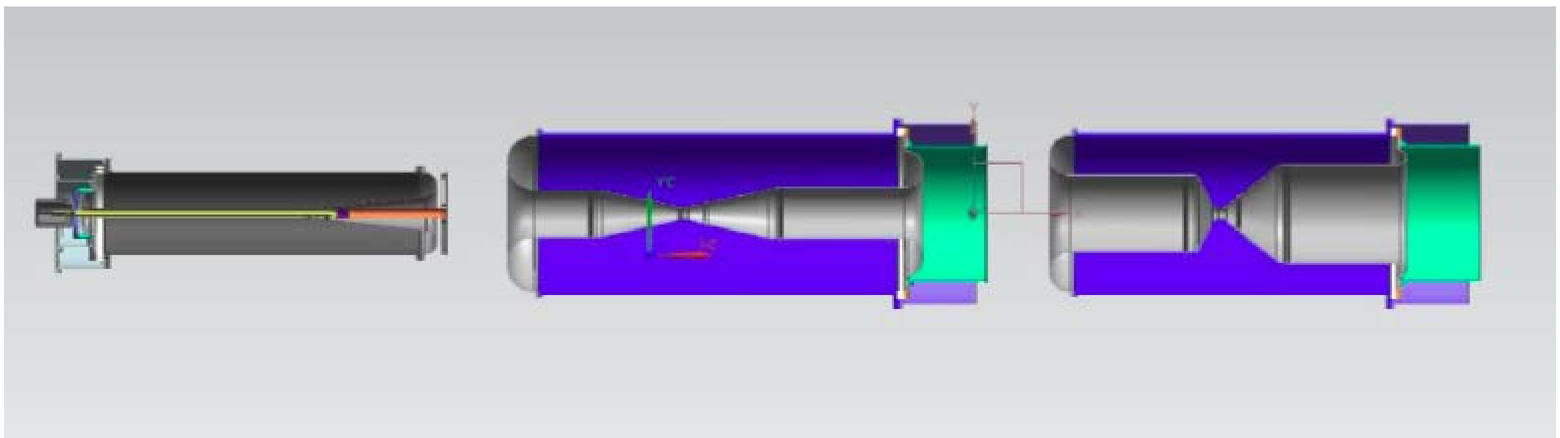
New Horn power supply needed to reduce the pulse width to 0.8 ms.

Mechanical model for optimized horns & target



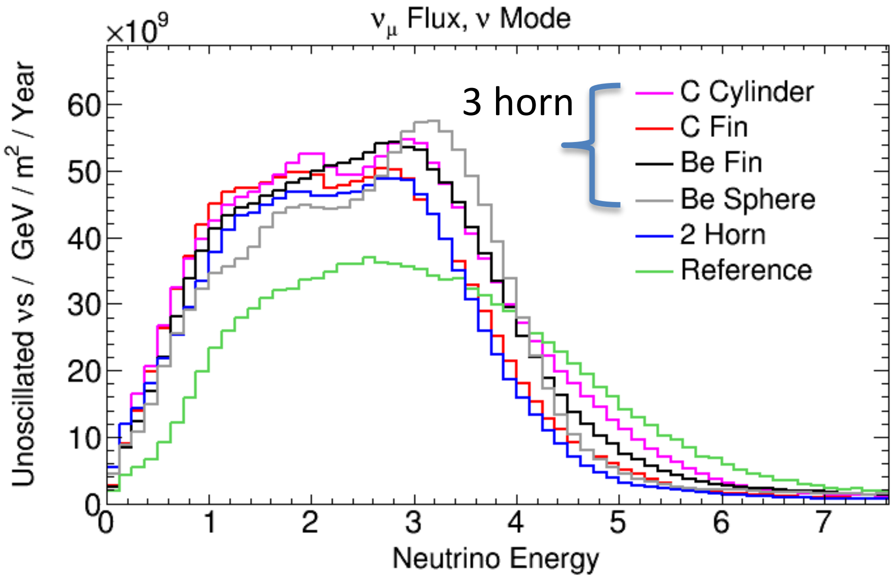
~ 2m long, graphite NuMI-style target for first iteration; cylindrical and spherical targets under R&D as well. Be and graphite R&D in progress.

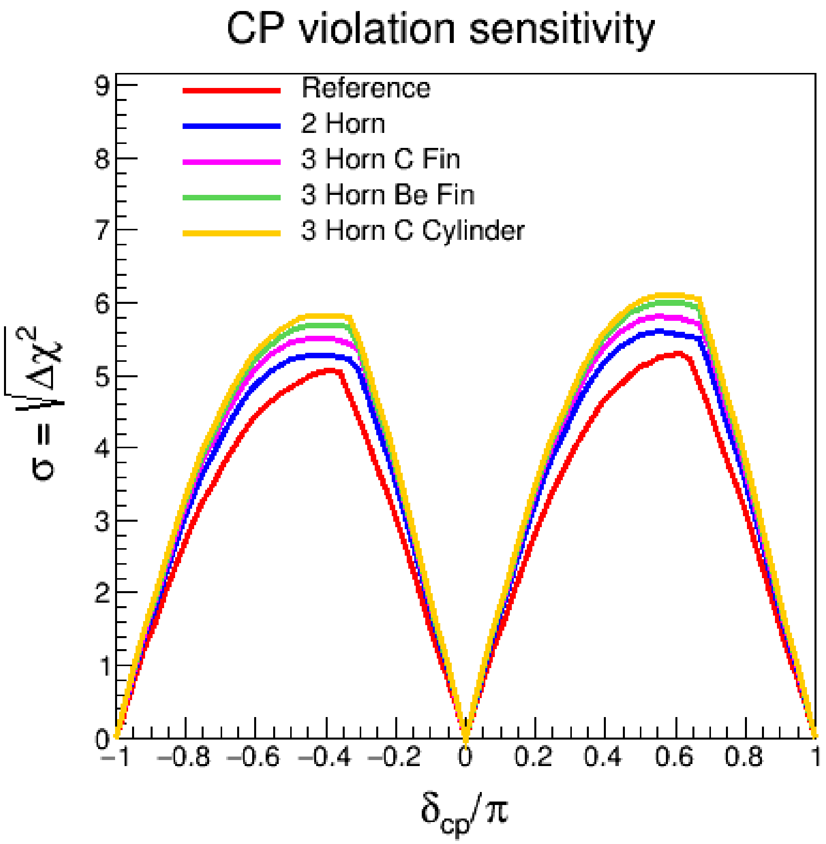




Horns constructed from 75% 6061-T6 aluminum forgings. Minimum fatigue life requirements of 100 million pulses for each design in the energy range from 60 – 120 GeV.

Preliminary optimization results





LBNF/DUNE Milestones

- Critical Decision-0 (CD-0) approved, January 8, 2010.
- CD-1 Refresh approved, November 5, 2015.
- CD-3a approval expected in December 2016 (far-site pre-excavation and excavation).
- Beamline optimization conceptual design ready for review, September 2017.
- CD-3b approval expected in April 2019 (near-site embankment placement).
- CD-2/CD-3c expected in March 2020 (baselining and start of construction).
- Beamline installation and checkout complete, August 2026.
- LBNF complete, December 2026.

Conclusions

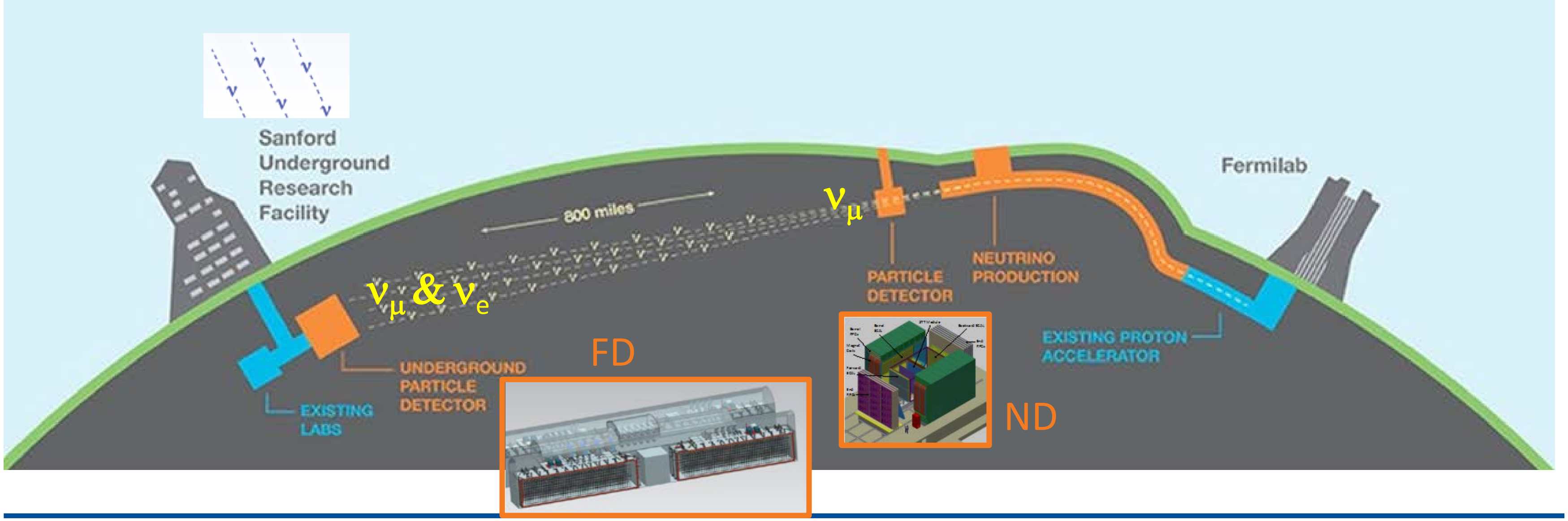
- Significant progress with preliminary design and beam optimization effort in all Beamline systems.
- Need to advance the conceptual design and take decisions on alternative/optimized options very soon since in October 2017 we need to start working on a definite preliminary design.
- Lots of opportunities for collaboration on the design of specific Beamline components as well as on beam simulations and R&D efforts.
- Now is the time to join the Beamline effort and make a substantial difference.
- We are excited and looking forward to design and build this Beamline working together with all our international partners!!

Backup

Fermilab Accelerator Complex

Facility and Experiment

- **LBNF**: provides facility infrastructure at two locations to support the experiment:
  - Near site: Fermilab, Batavia, IL – facilities and infrastructure to create neutrino beam and host the near DUNE detector
  - Far site: Sanford Underground Research Facility, Lead, SD – facilities to support the far DUNE detectors
- **DUNE**: Deep Underground Neutrino Experiment
  - Near and far site detectors



LBNF Beam Operating Parameters

Summary of key Beamline design parameters for $\leq$1.2 MW and $\leq$2.4 MW operation

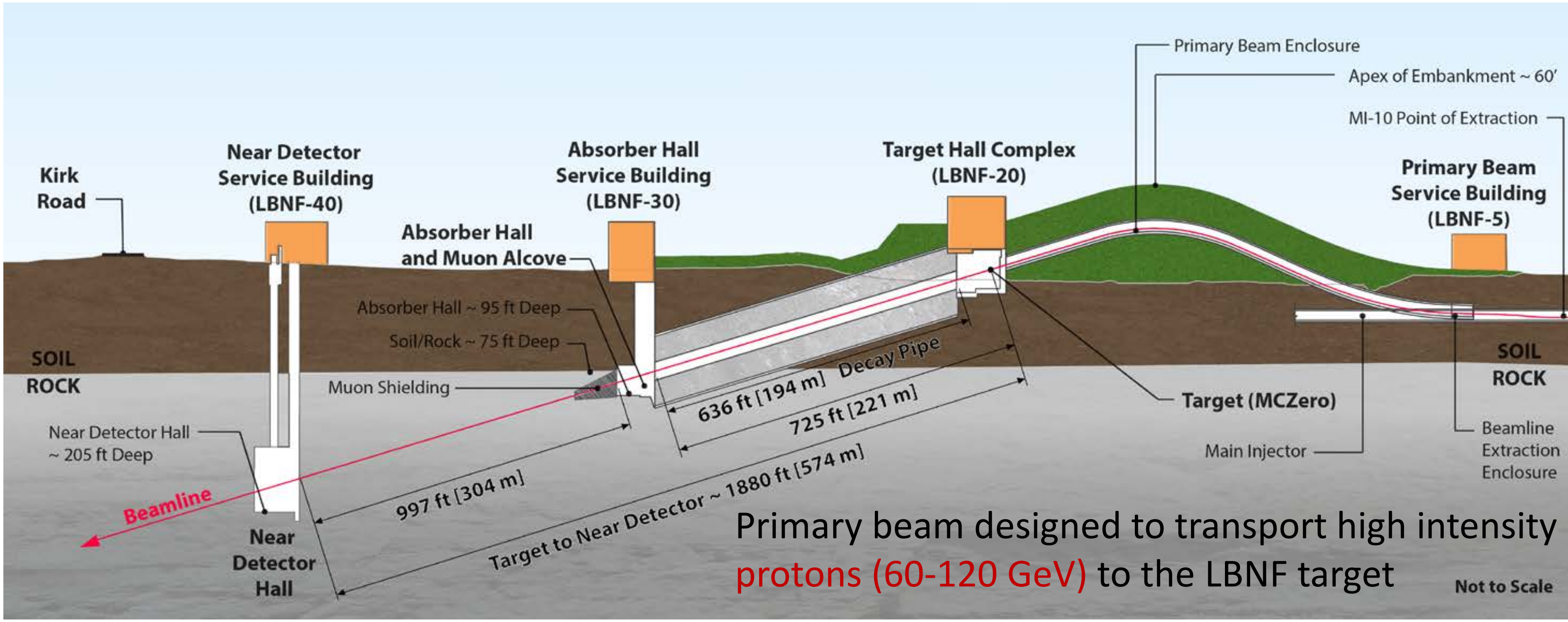
Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

(1.1 – 1.9)x10^{21} POT/yr

Pulse duration: 10 μs

Beamline for a new Long-Baseline Neutrino Facility
MI-10 Extraction, Shallow Beam

Beamline Facility contained within Fermilab property

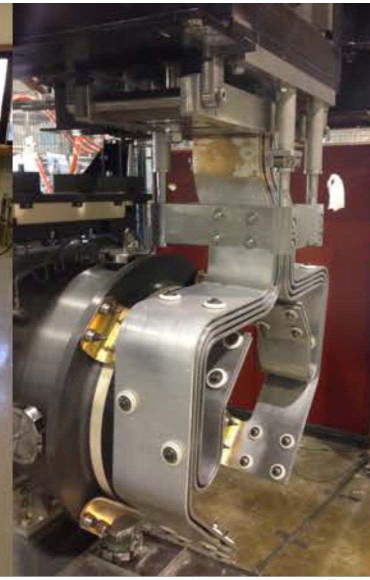


Constructed as Tunneled excavation

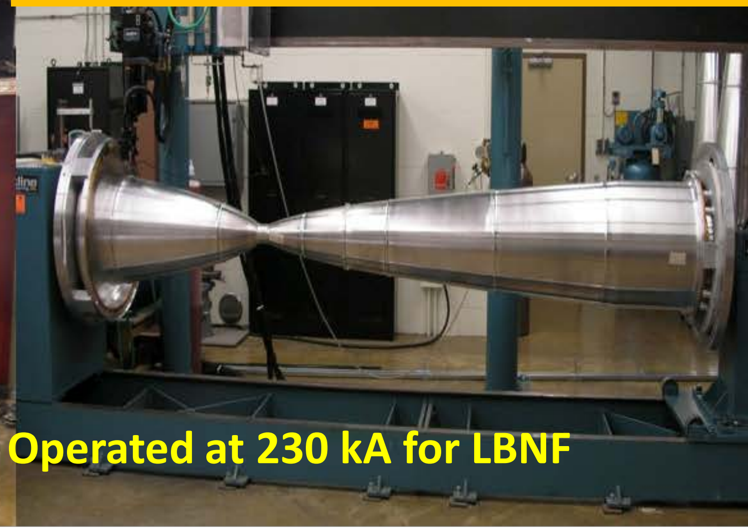
Constructed in Open Cut

All systems designed for 1.2 MW initial proton beam power (PIP-II).
Facility is upgradeable to 2.4 MW proton beam power.

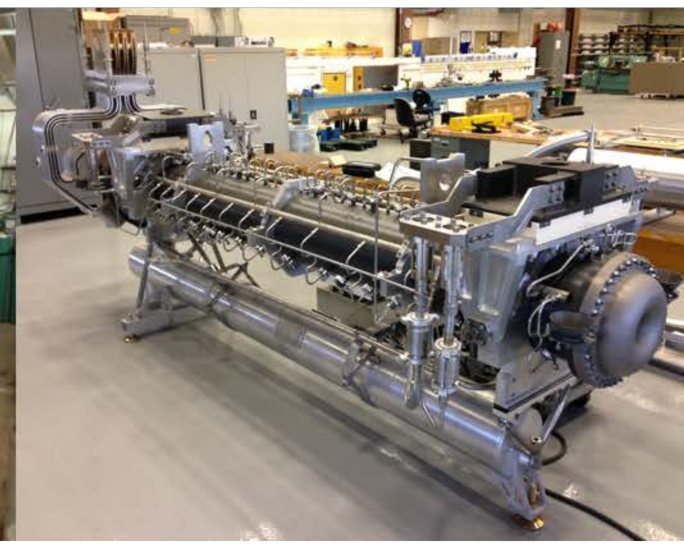
Pictures of NuMI Horns & Power Supplies

Inner Conductor of NuMI Horn

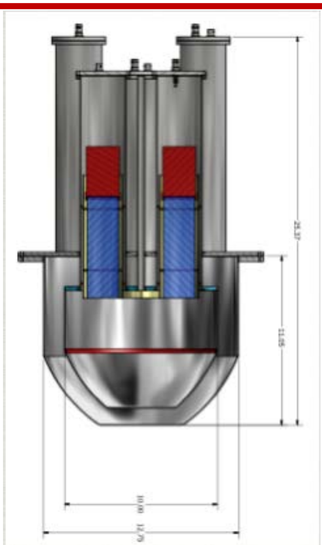






New Horn power supply needed for LBNF to reduce the pulse width to 0.8 ms.

Current Work on Muon Monitors

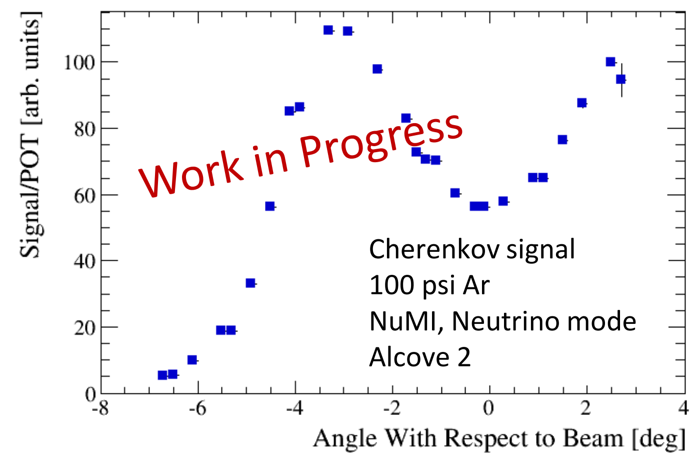


Stopped Muon Counter

- Small Cherenkov volume surrounded by scintillating veto
- Measure stopped μ decays downstream of the absorber after beam pulse ends

- Stopping muons have a fixed range: an array of detectors can measure a spectrum instead of just an integral above a threshold
- Muon lifetime fit allows for subtraction of any non-muon background
- Prototype production/testing underway at U. Colorado
- Will use custom PMT bases developed at Drexel to gate off PMTs during high-rate beam pulse, only operate tube after beam later, when muons are decaying

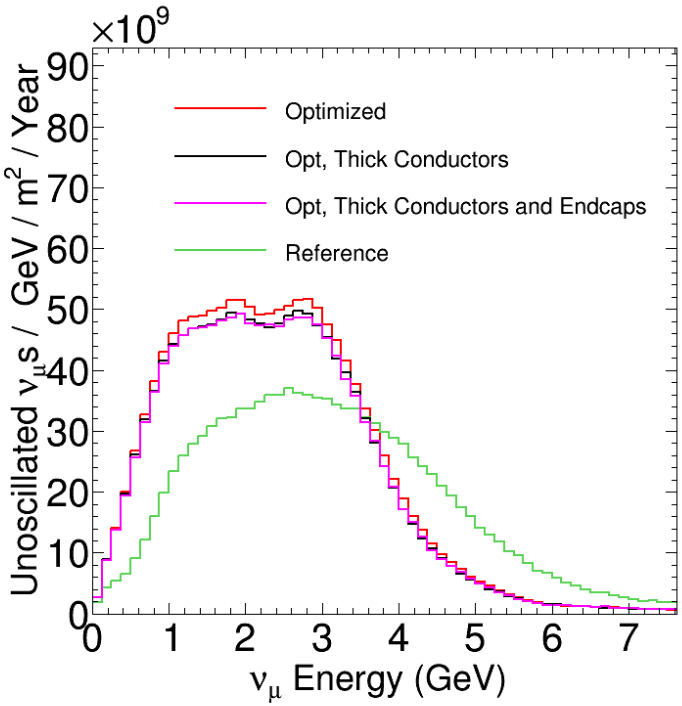
- Testing several possible technologies at the NuMI beamline
  - Diamond detectors, gas Cherenkov detector
- Studying detector operation and long-term stability
- Hope to measure muon flux using scans of Cherenkov detector angle and pressure

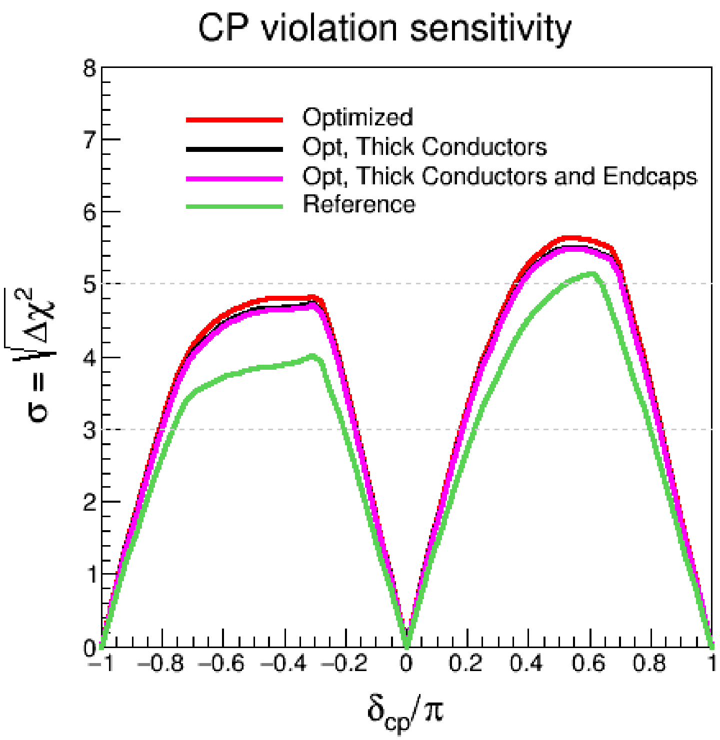


Scope of re-optimization

- Horns (long lead items)
- Target
- Integration/mounting of target into horn, baffle mounting, etc.
- Alternative option of gas in target chase
- Absorber
- Associated Modeling
- Associated Radiation Protection
- Horn support modules (three)
- Horn power supply (ies) (0.8 ms)
- Remote handling (casks, morgue capacity analysis, workcell,..)
- Associated Conventional Facilities

Preliminary optimization results

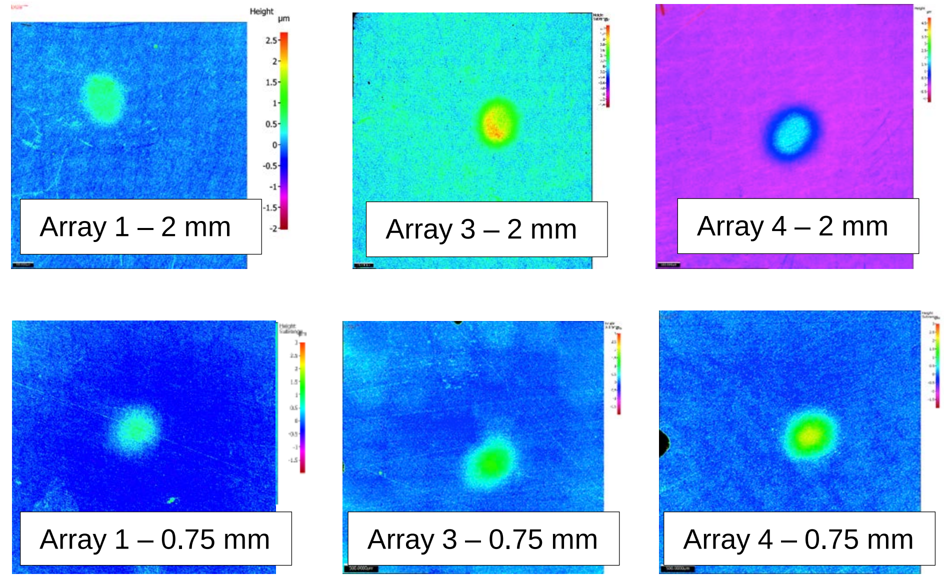




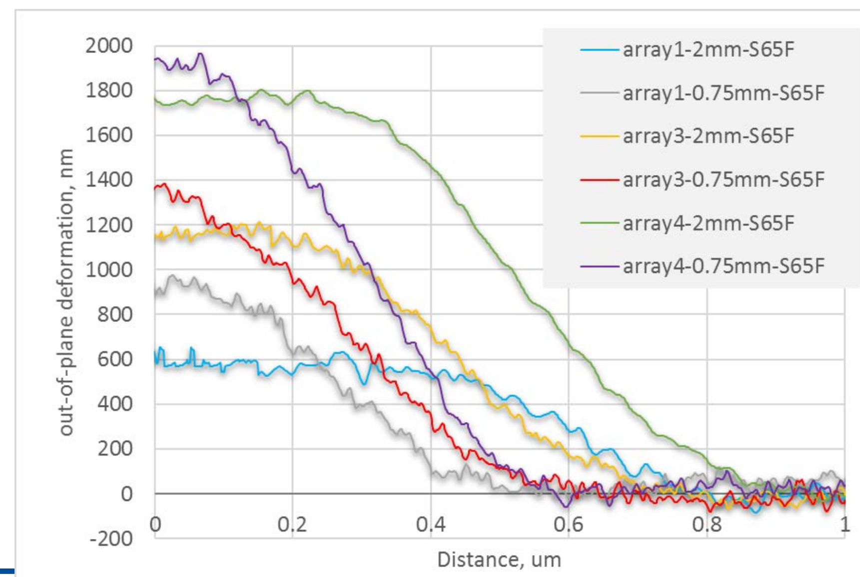
Beryllium R&D

K. Ammigan, C.Densham, P. Hurh et al.

- Be Strength Model Testing and Development at Southwest Research Institute
  - Testing complete
  - Strength model development on track to be complete in June
  - Will be used to benchmark with HiRadMat BeGrid results
- HiRadMat (CERN) BeGrid Experiment PIE
  - Profilometry of all exposed samples completed
  - Preliminary results indicate
    - less deformation than predicted with extrapolated strength model
    - One Be grade (S200FH) shows consistently less deformation than the others
    - Repeated pulses resulted in plastic strain ratcheting

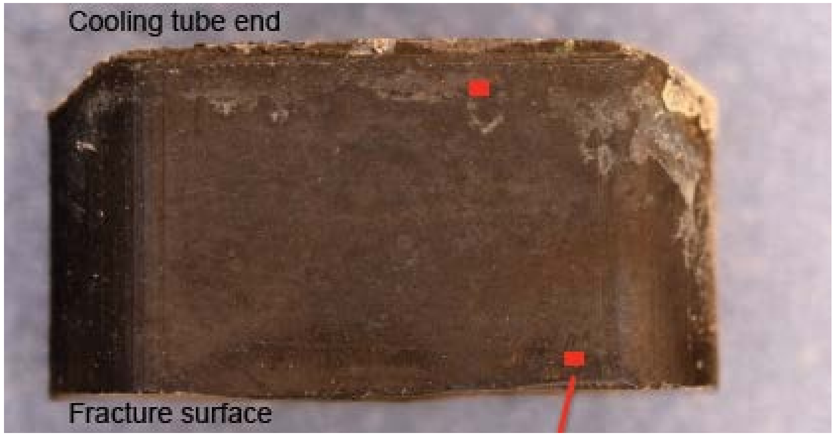


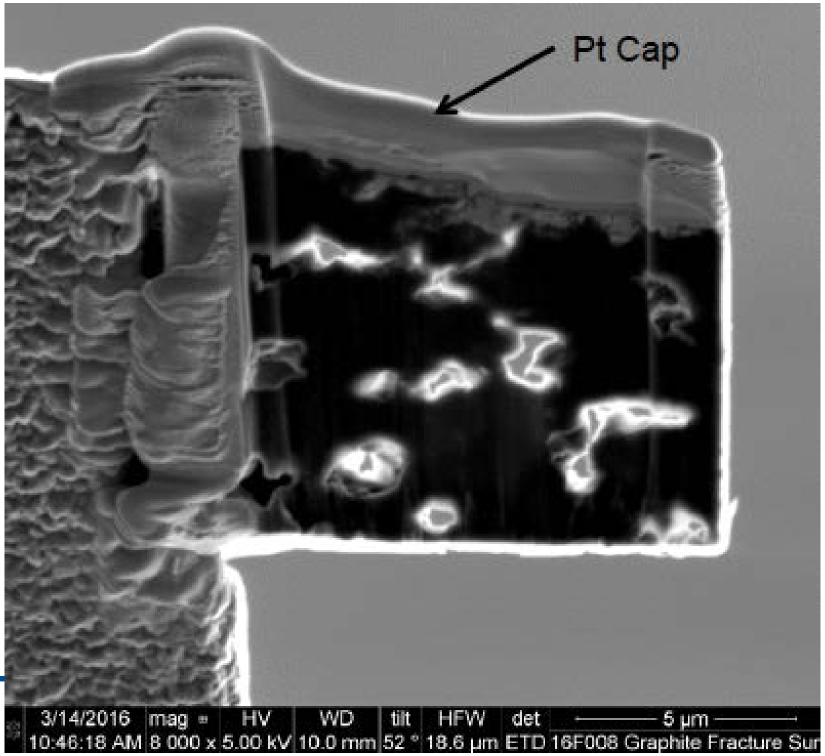
Major axis

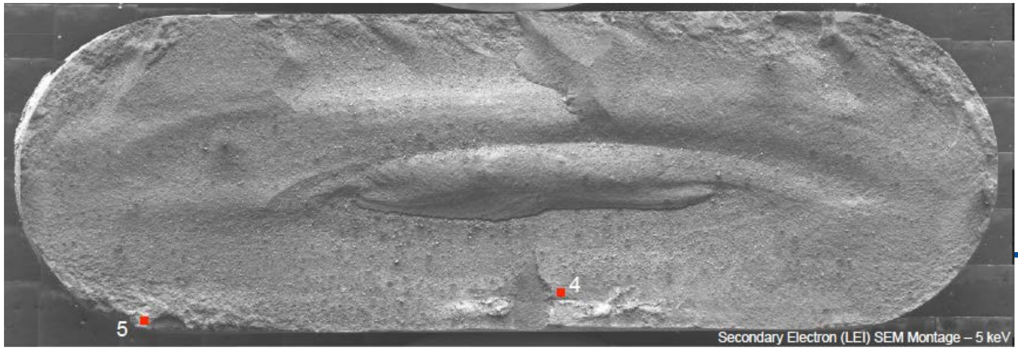


Graphite R&D

- NuMI Target (NT-02) graphite PIE at PNNL preliminary results:
  - Evidence of swelling in highly irradiated areas (2 - 5%)
  - Nature of impurities on fracture surface indicates cracking occurred during operation
  - Not much evidence of displacement damage in area away from beam
  - Currently examining area near beam center via TEM
  - Will use these results to bench-mark with other irradiations (lower energy, higher current)







Other ongoing HPT R&D Activities

- Continuation of studies on NuMI primary beam window at Oxford
- Preparation for RaDIATE irradiation run at BNL's BLIP facility
  - Hundreds of samples
  - Be, Graphite, Glassy Carbon, Ti alloys, Si, TZM, Ir
  - In collaboration with FRIB, J-PARC, BNL, CERN, ESS
- Preparation for LE ion irradiations
  - Possibly at Michigan, Surrey, and Notre Dame Universities