Design of the LBNF Beamline

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38th International Conference on High Energy Physics

August 3-10, 2016

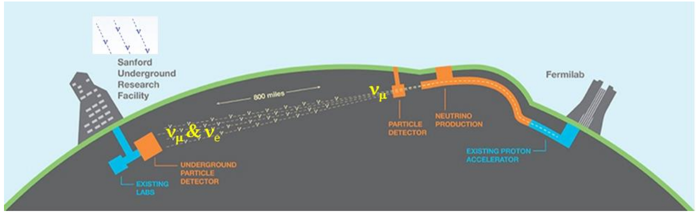
Outline

- The Fermilab Accelerator Complex
- Overview of the reference design of the LBNF Beamline
- Considered design upgrades
- Conclusion

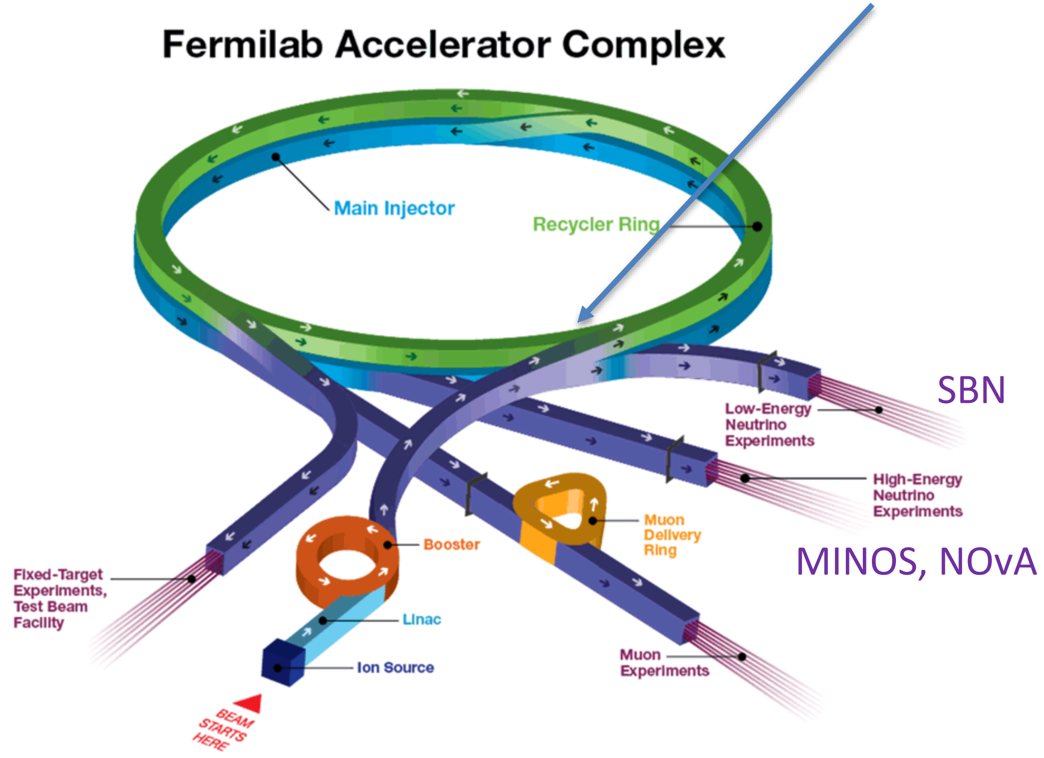
Neutrino Program at Fermilab

Fermilab Accelerator Complex

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



LBNF proton beam extracted from MI-10 straight section



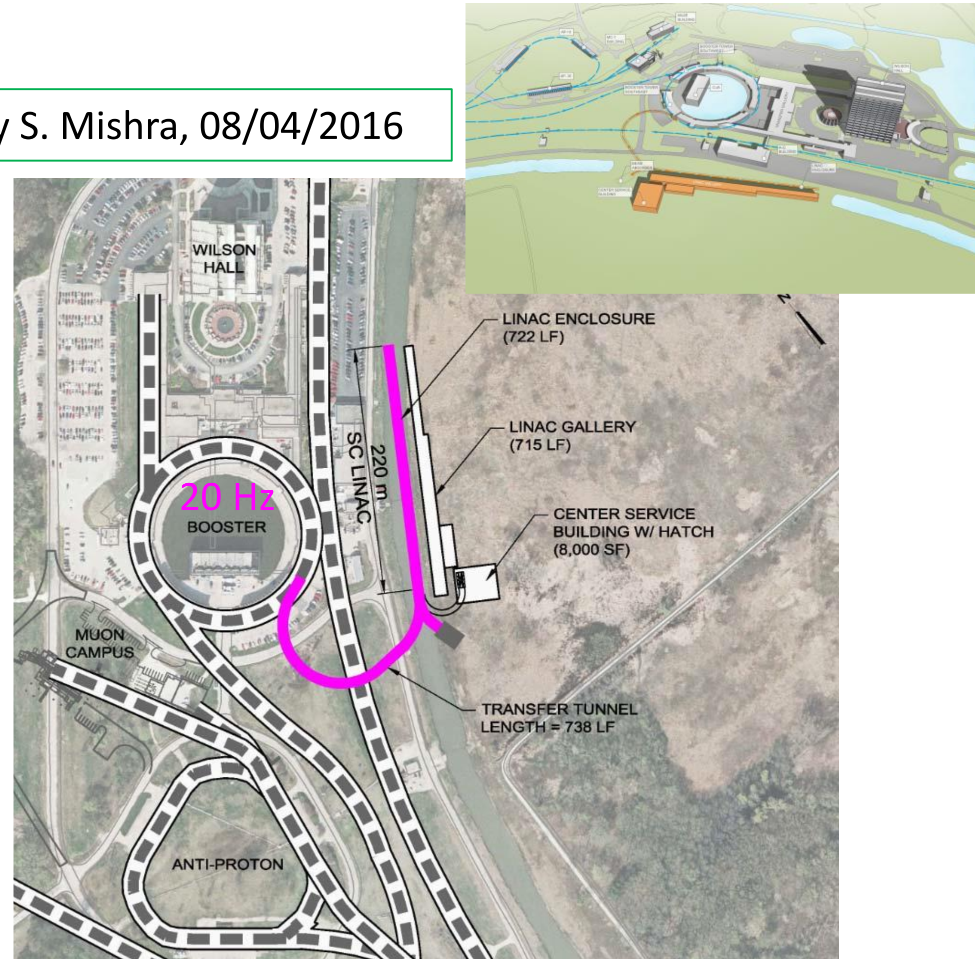
701 kW on the NuMI/NOvA target in one supercycle on June 13, 2016!!

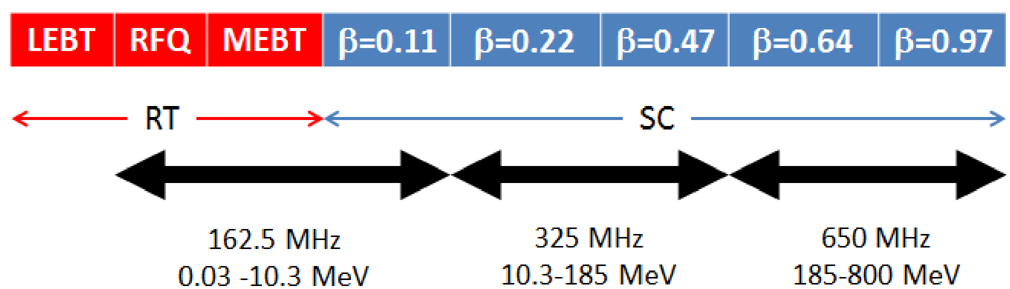
Proton Improvement Plan (PIP)

PIP-II (~2025)

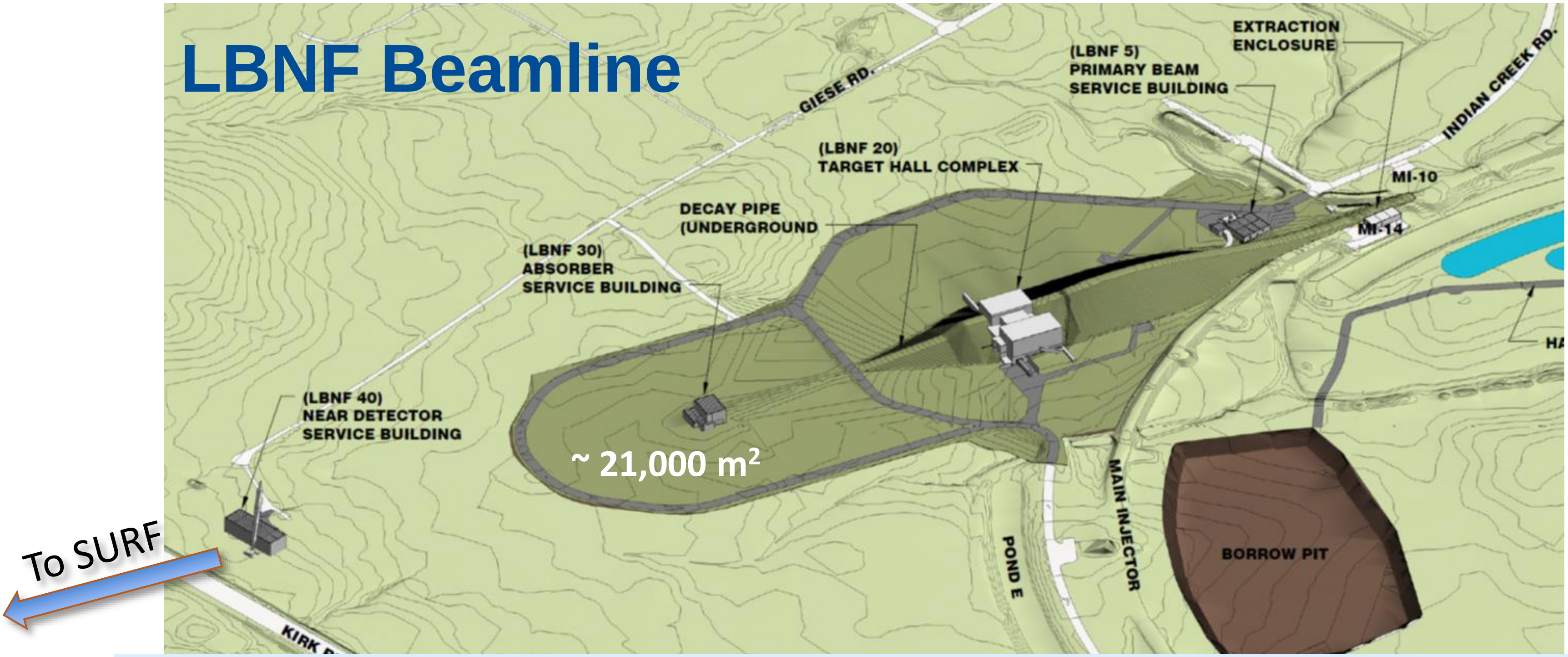
See talk by S. Mishra, 08/04/2016

- 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

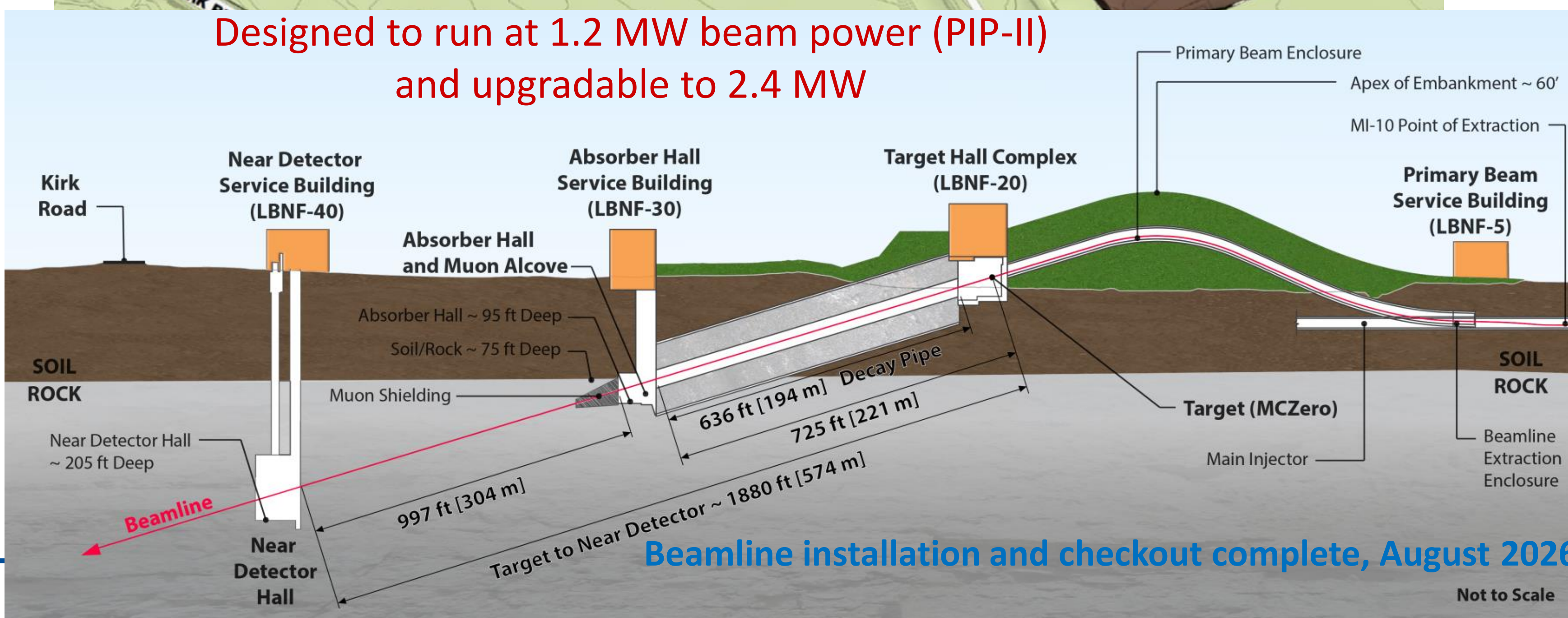




LBNF Beamline



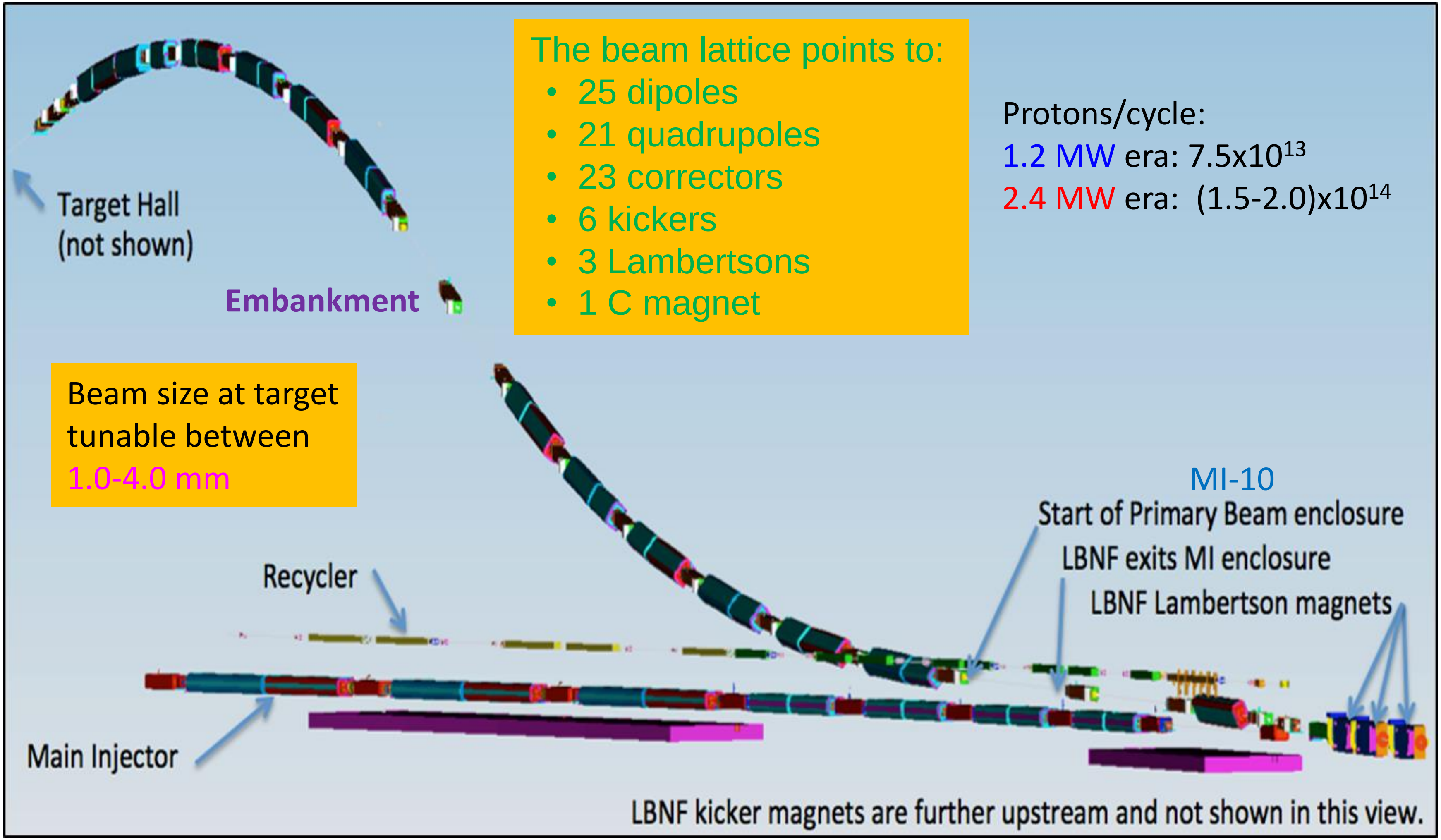
Designed to run at 1.2 MW beam power (PIP-II) and upgradable to 2.4 MW



Beamline installation and checkout complete, August 2026

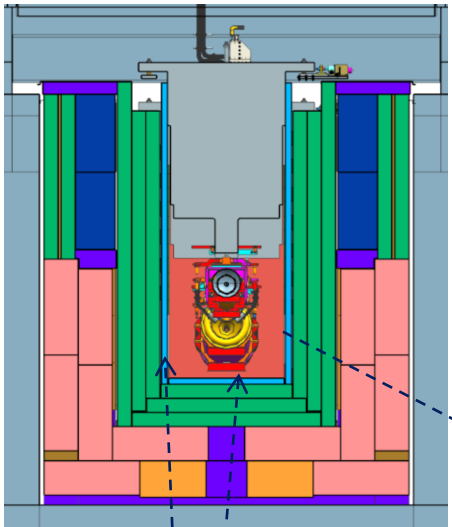
Primary Beamline

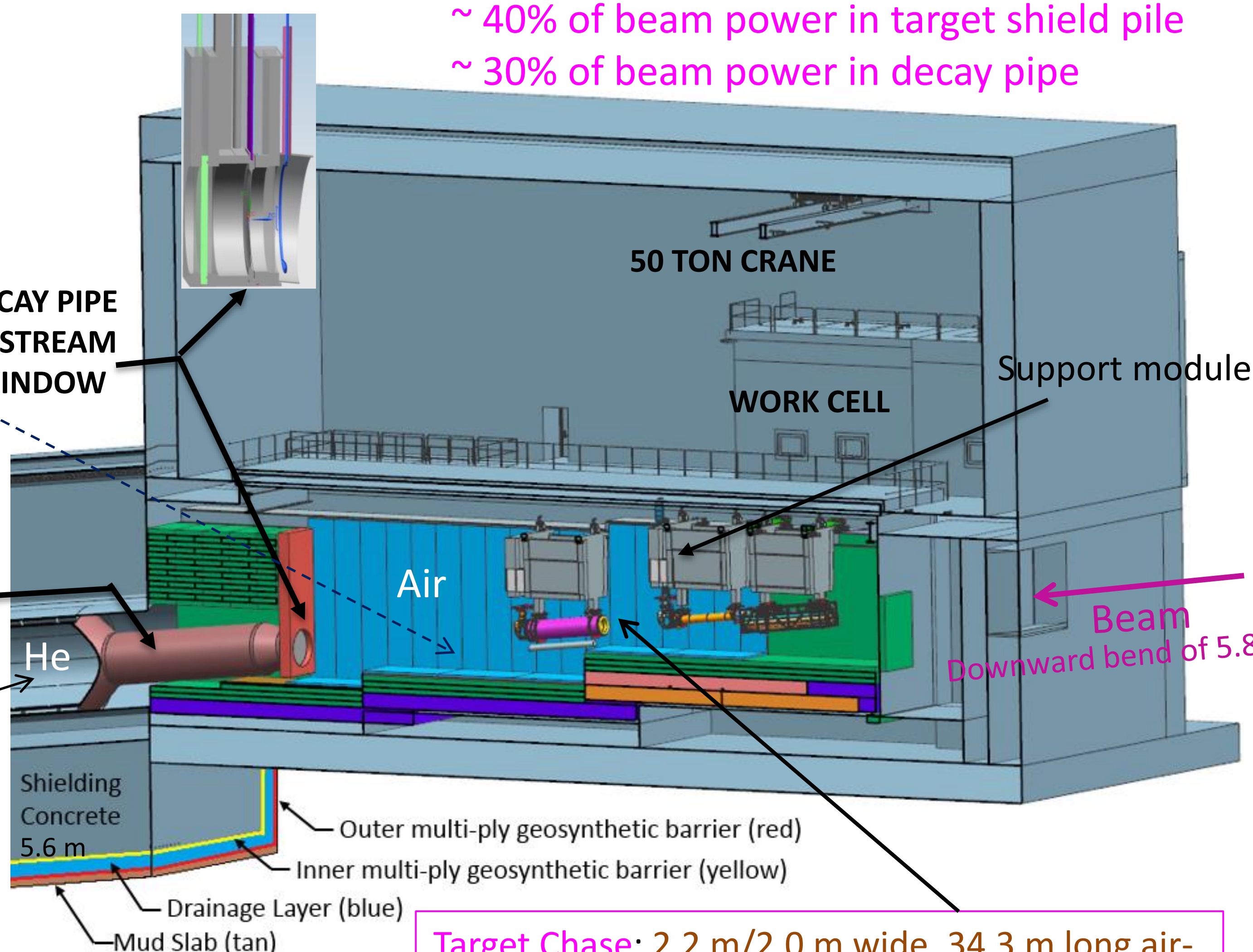
The primary beam designed to transport high intensity protons in the energy range of 60 -120 GeV to the LBNF target, with repetition rate of 0.7-1.2 sec, and 10 μs pulse duration



Target Hall and Decay Pipe Layout

~ 40% of beam power in target shield pile
~ 30% of beam power in decay pipe





Decay Pipe: 194 m long, 4 m in diameter, double – wall carbon steel, helium filled, air-cooled.

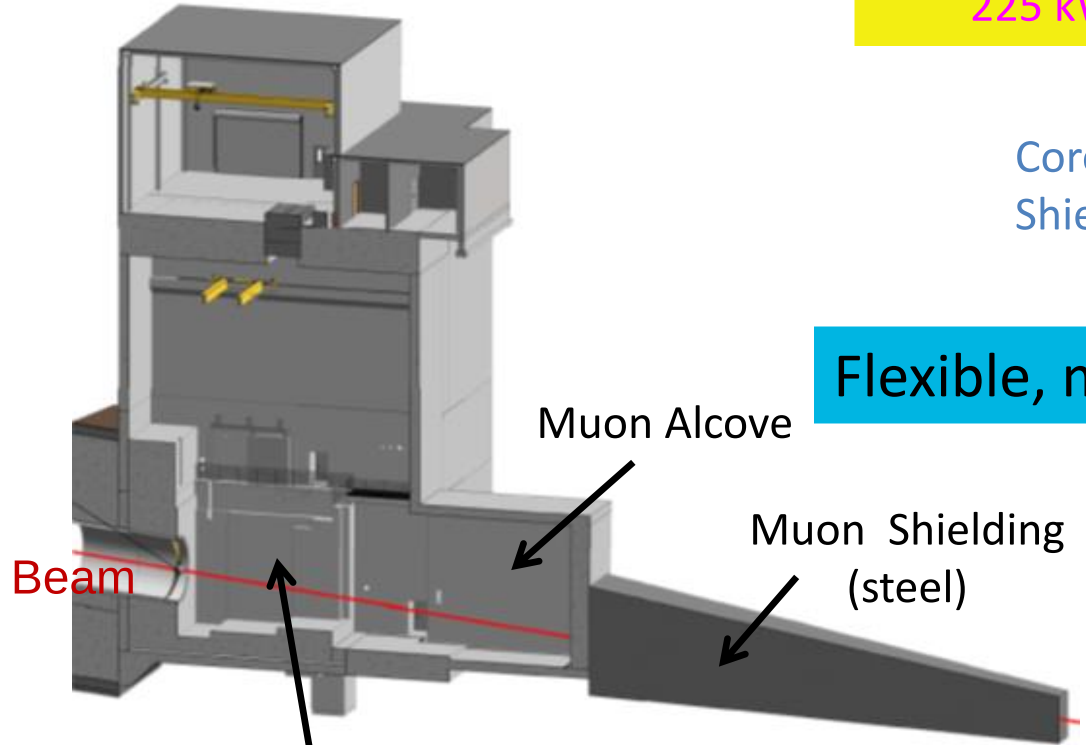
Main alternatives for Chase gas atmosphere: N_2 or He

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.

Hadron Absorber

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 Hall and Service Building



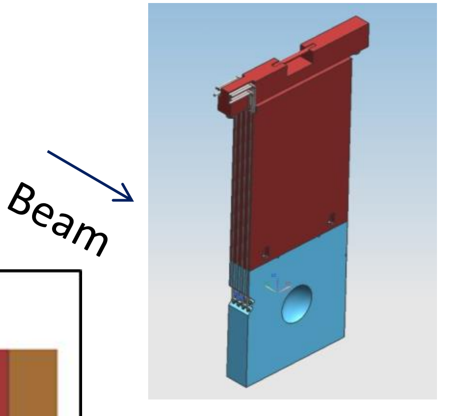
Absorber Cooling

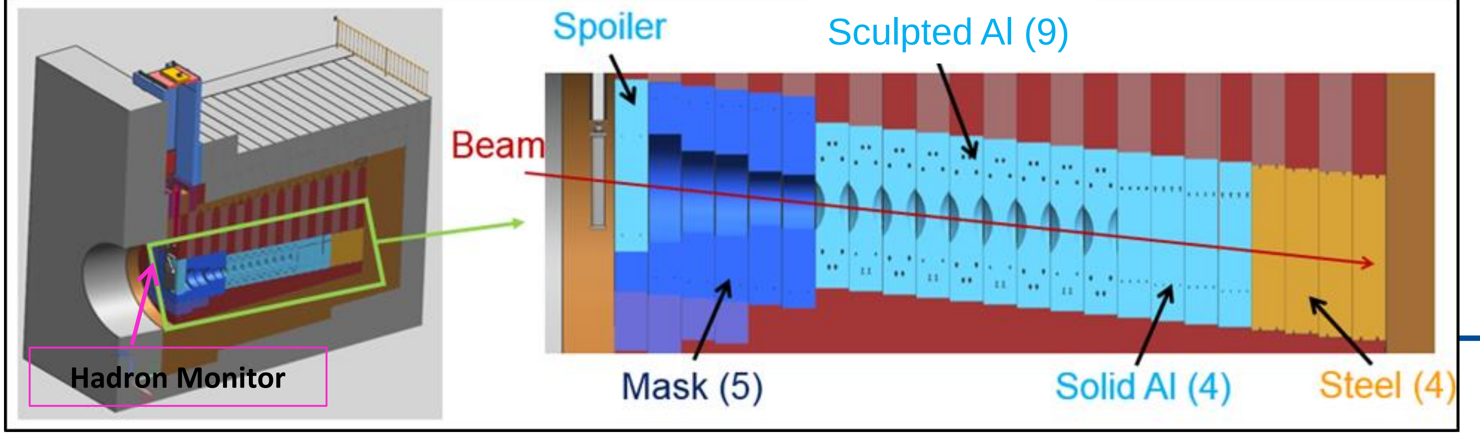
Core: water-cooled

Shielding: forced air-cooled

Flexible, modular design

Core blocks replaceable
(each 1 ft thick)



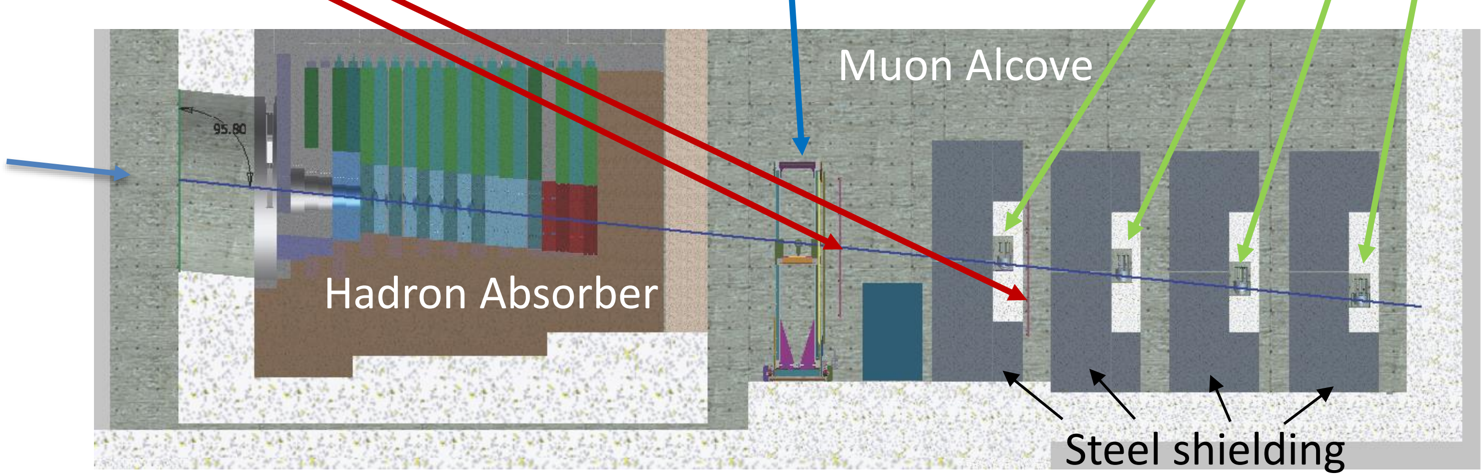


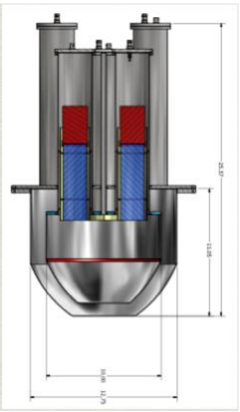
Overview of Beamline Muon Monitors

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



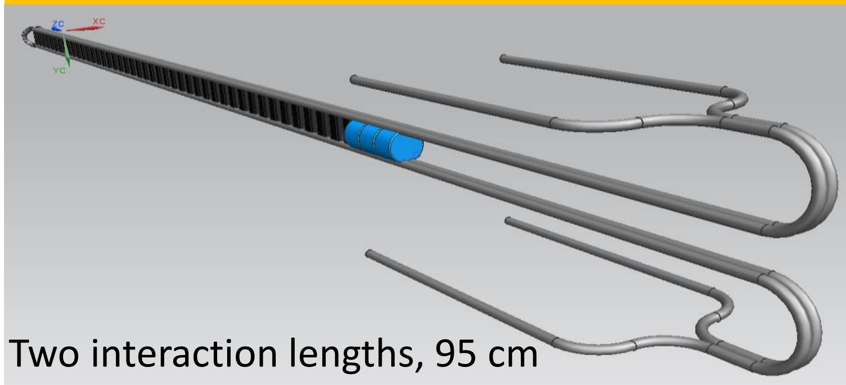


Testing prototypes at the NuMI beamline

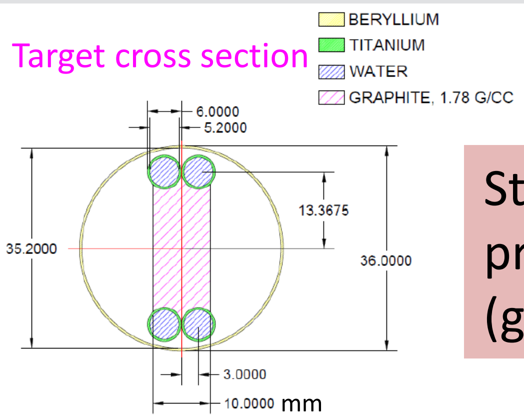
Reference design for target and horns - Viable for 1.2 MW

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

NuMI-like (low energy), with modest modifications



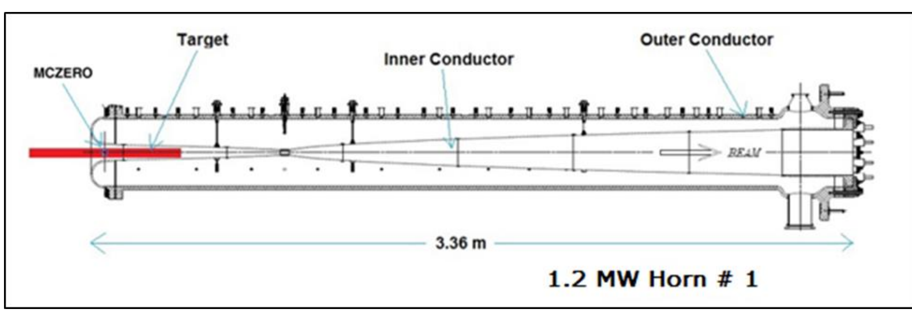
Target cross section



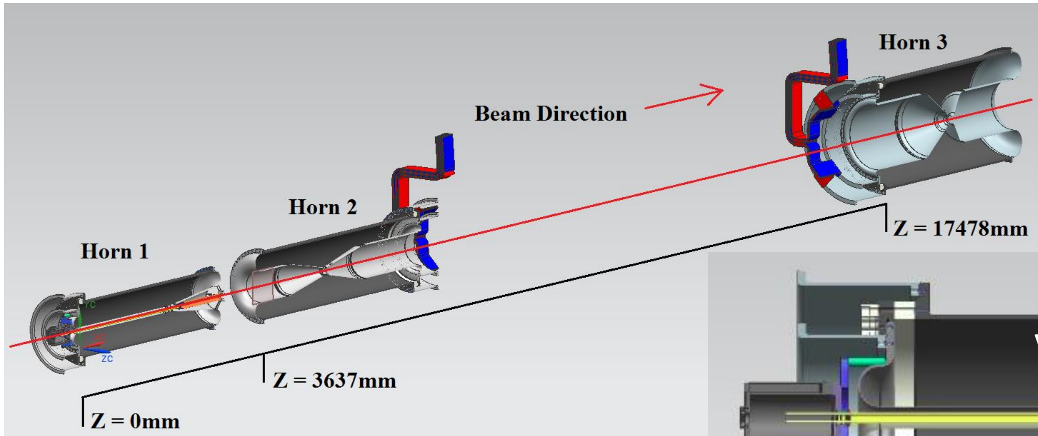
Strong target R&D program in place (graphite, Be, etc.)

Inner Conductor of NuMI Horn

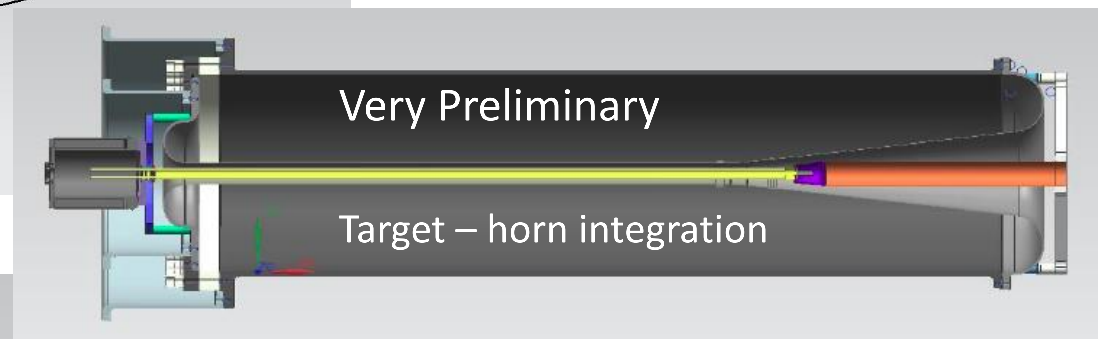
New Horn power supply needed to reduce the pulse width to 0.8 ms.

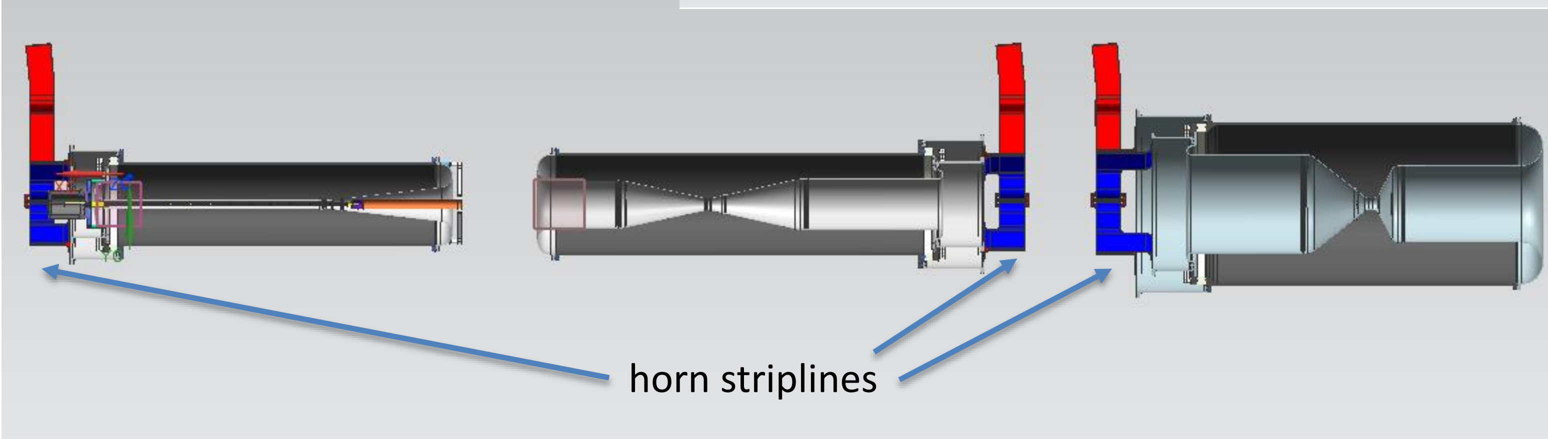


Mechanical model for optimized horns & target



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

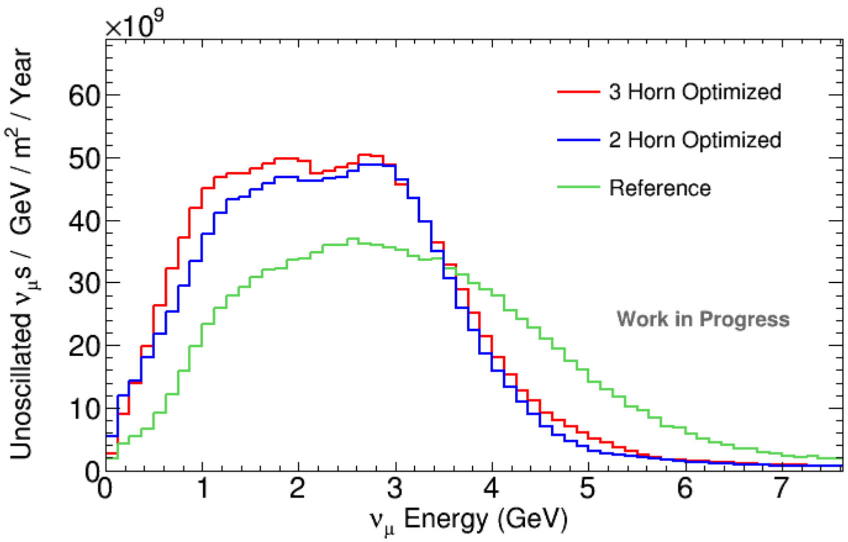


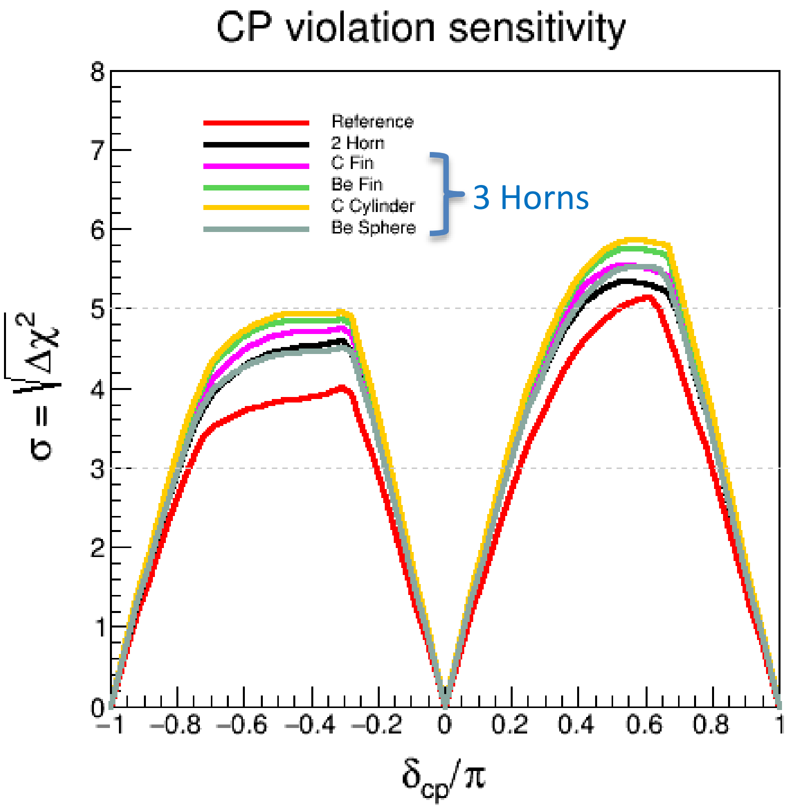


Review by August 2017

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

Preliminary beam optimization results





Long first optimized horn split into two horns for increased engineering feasibility. Yields slightly better flux as well.

3.5 yr ν_μ + 3.5 yr $\bar{\nu}_\mu$
40 kt detector,
PIP-II beam power(1.03-1.2 MW)

See also: E. Worcester's talk on the "DUNE physics program" & L. Fields poster on the "Optimization of the LBNF Neutrino Beam", 08/04/2016.

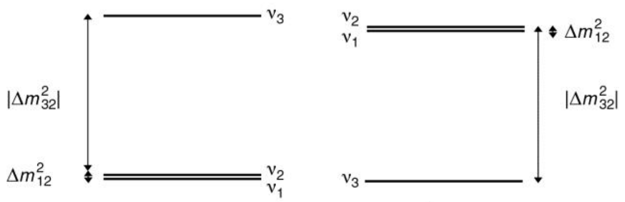
Conclusions

- Significant progress with reference design and beam optimization effort for all Beamline systems.
- Need to advance the conceptual design of optimized beamline and take decisions on alternative/optimized options very soon, since in October 2017 we need to start working on the 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

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

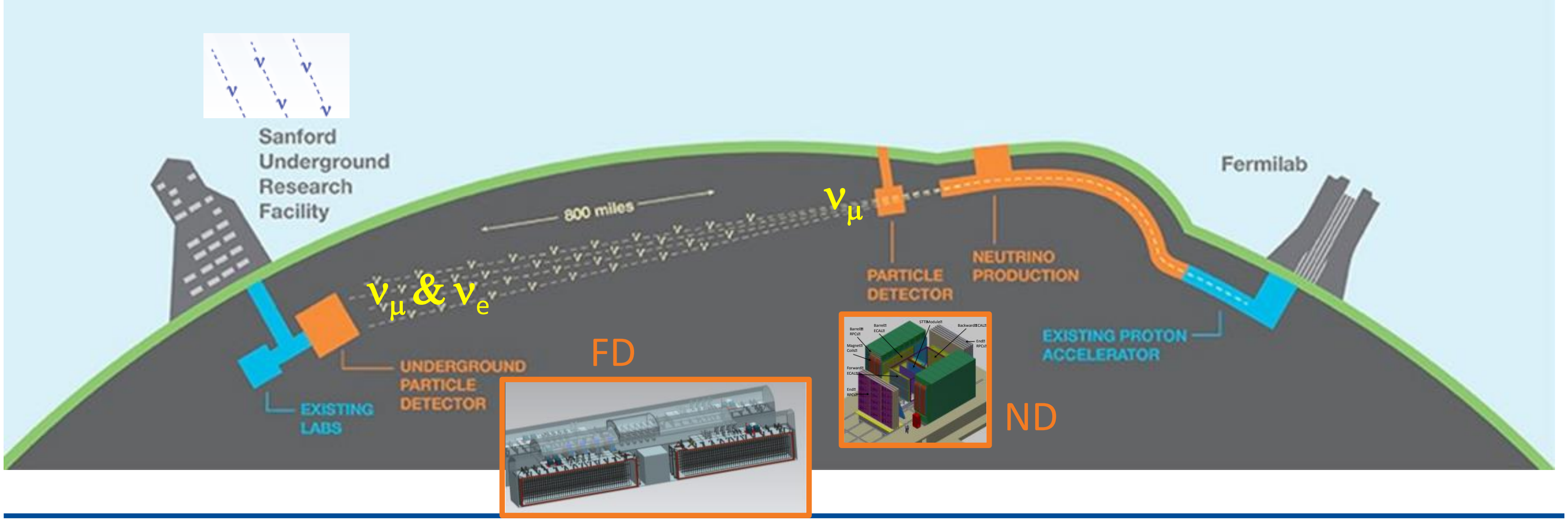
- Study other fundamental physics enabled by a massive, underground detector
  - Search for nucleon decays (e.g. targeting SUSY-favored modes)
  - Measurement of neutrinos from galactic core collapse supernovae
  - Measurements with atmospheric neutrinos

Start data taking ~ 2025

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

Pulse duration: 10 μs

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**

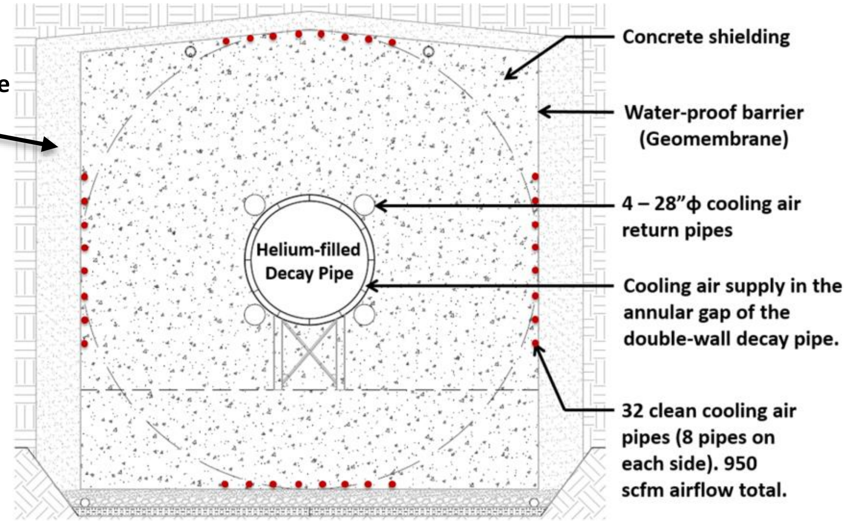
Assuming a superconducting 800 MeV Linac (PIP-II)

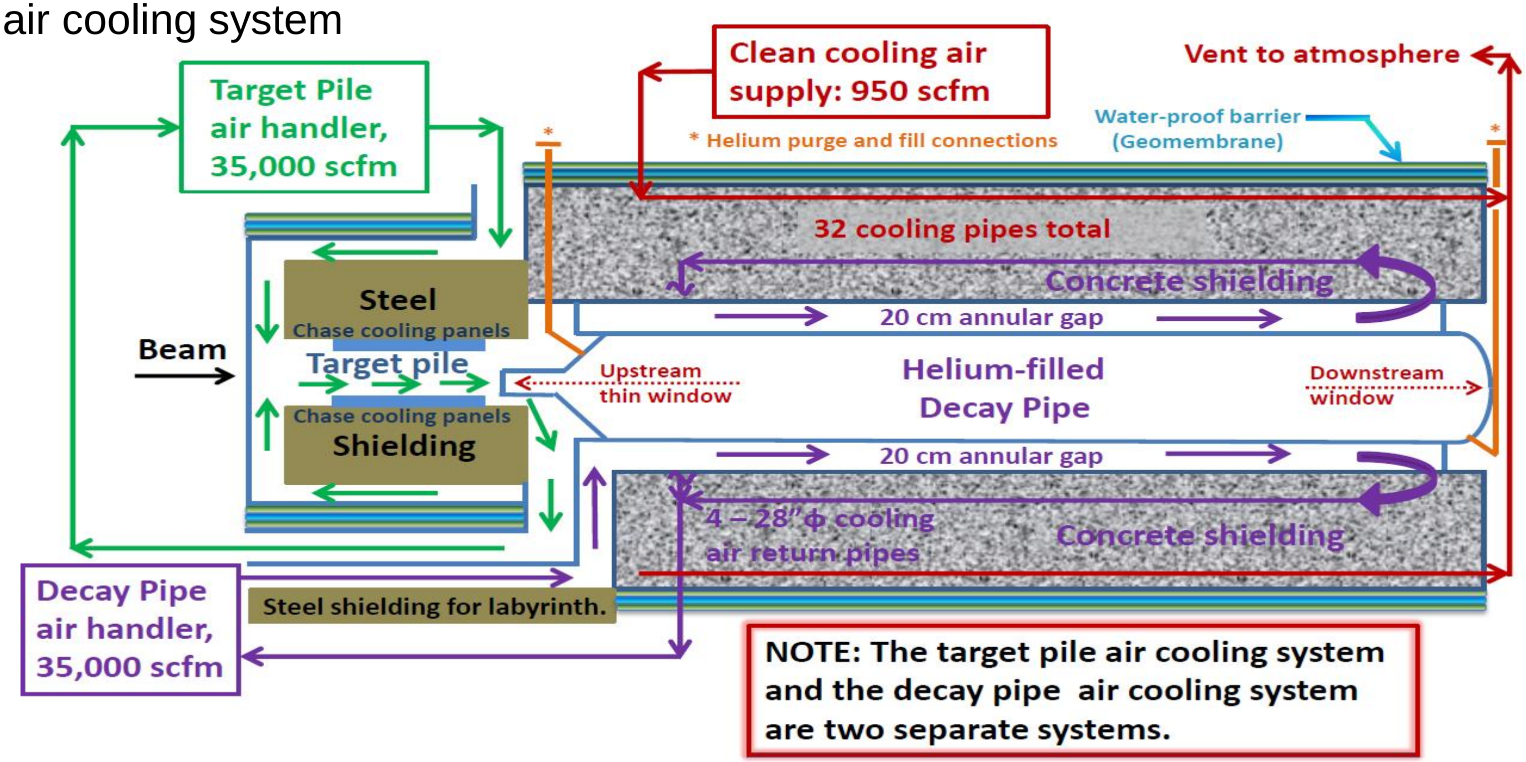
$(1.1 – 1.9)\text{x}10^{21}$ POT/yr

Assuming a Linac extension to the PIP-II Linac

Decay Pipe Layout

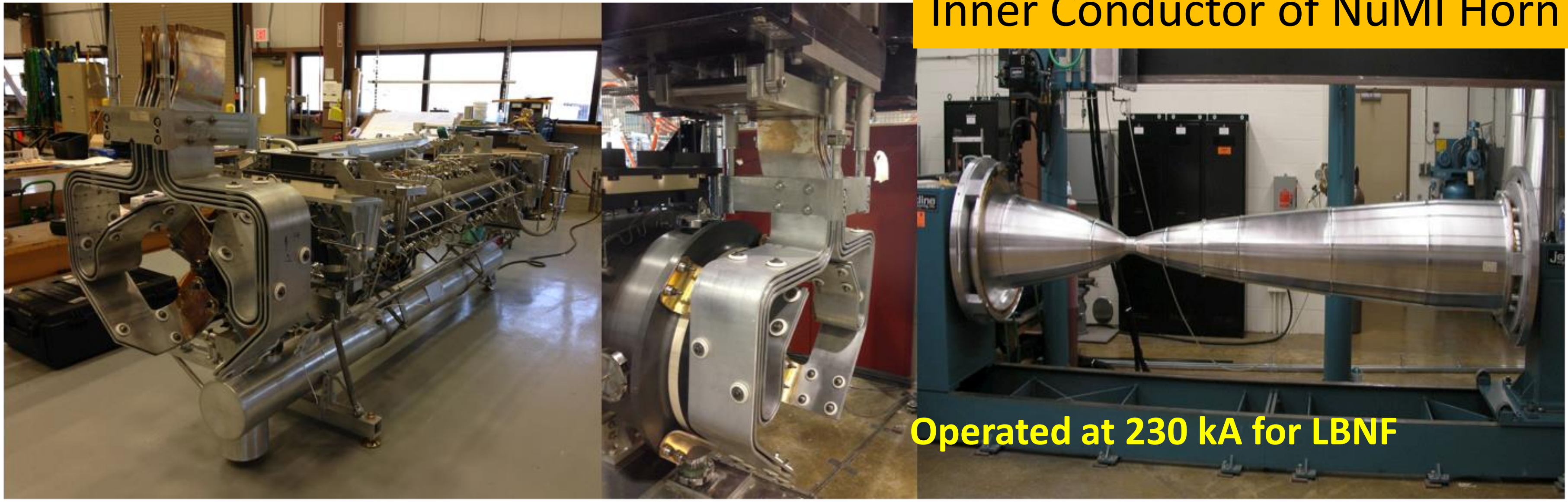
- 194 m long, 4 m inside diameter
- Helium filled
- Double-wall, carbon steel decay pipe, with 20 cm annular gap
- 5.6 m thick concrete shielding
- It collects ~30% of the beam power, removed by an air cooling system



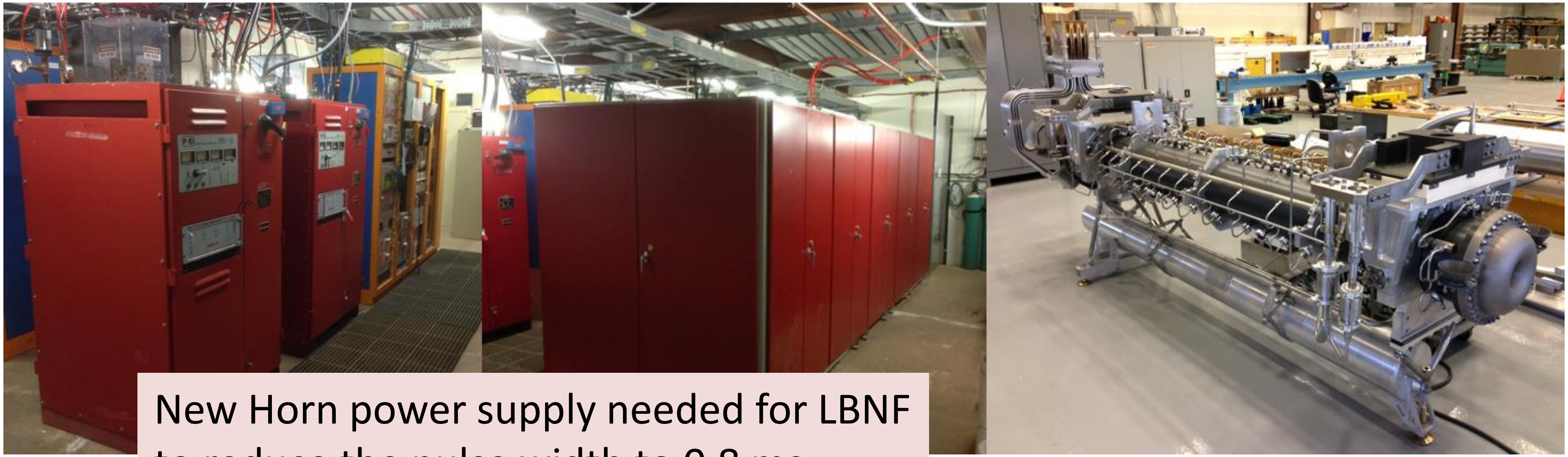


Pictures of NuMI Horns & Power Supplies

Inner Conductor of NuMI Horn



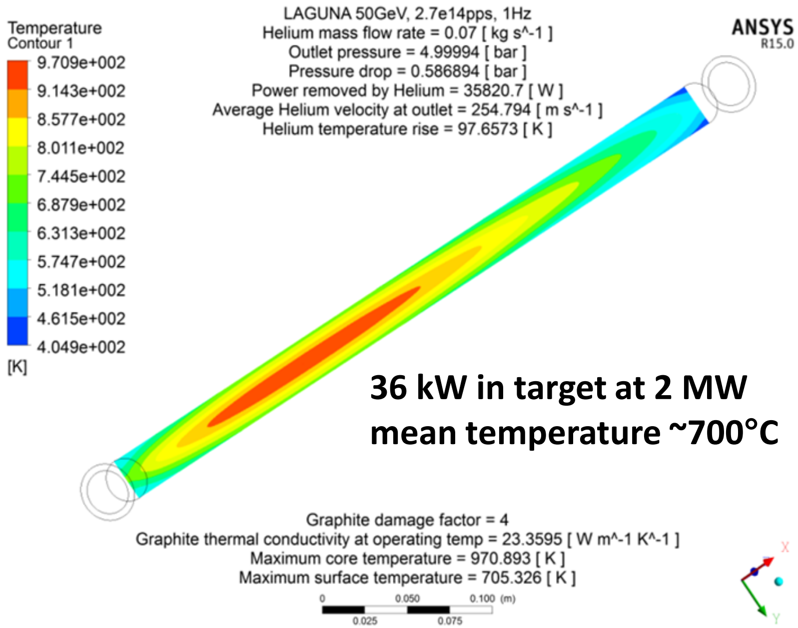
Operated at 230 kA for LBNF



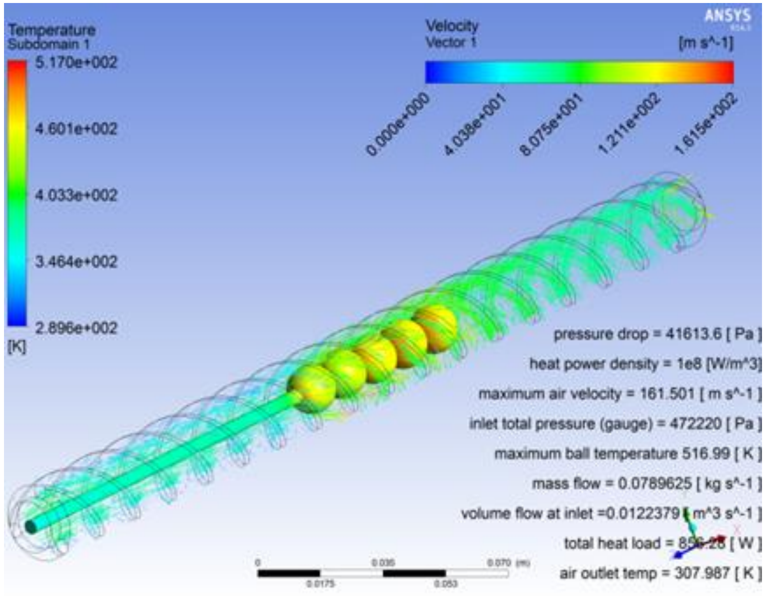
New Horn power supply needed for LBNF to reduce the pulse width to 0.8 ms.

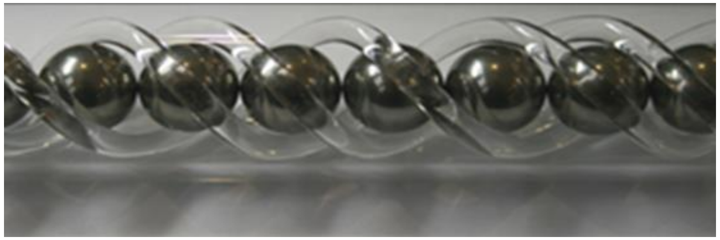
Target developments

Helium-cooled graphite rod

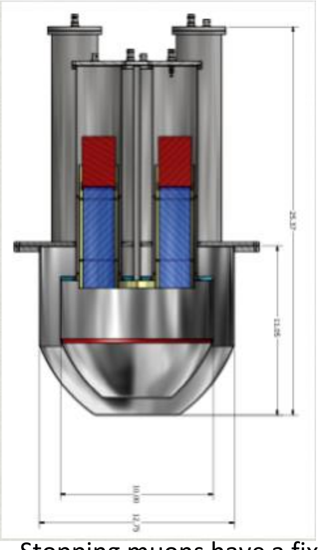


Helium-cooled spherical array target
Be or graphite





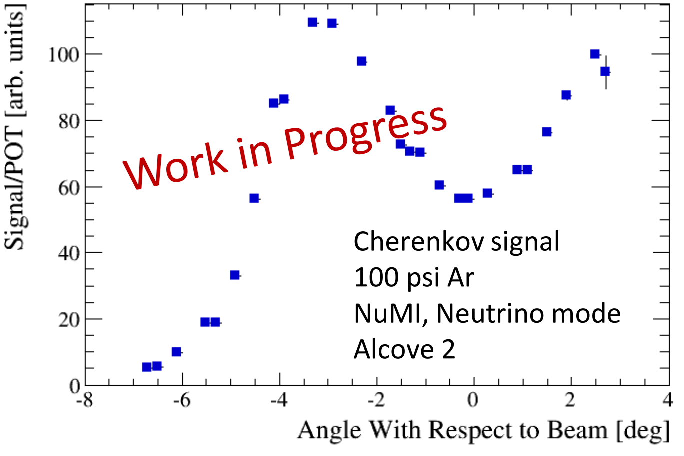
Current Work on Muon Monitors



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 U. 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
- Expect to measure muon flux using scans of Cherenkov detector angle and pressure

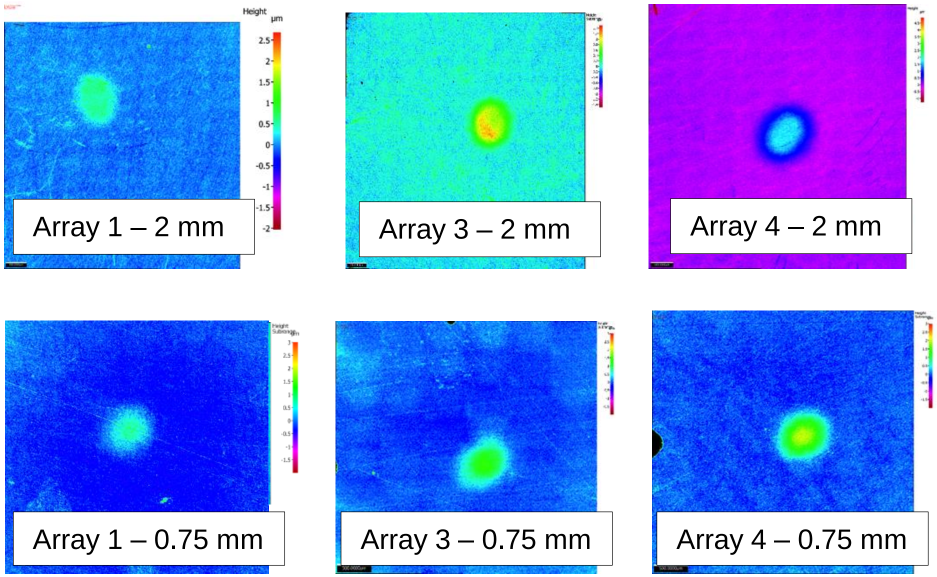


Scope of Beamline re-optimization

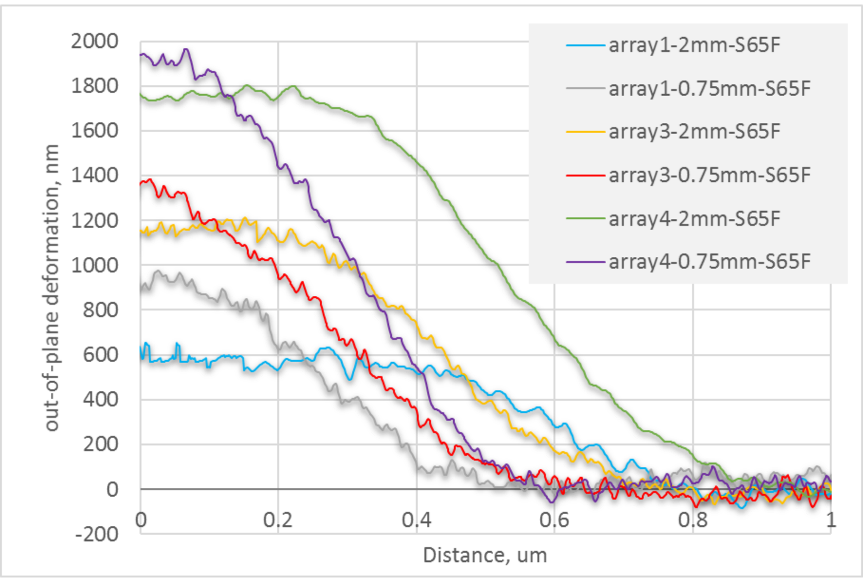
- Horns (three)
- Target
- Integration/mounting of target into horn, baffle mounting, etc.
- Alternative option of inert gas in target chase
- Absorber
- Associated Modeling
- Associated Radiation Protection
- Horn support modules (three)
- Horn power supply (ies) (0.8 ms)
- Remote handling (casks, morgue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

Beryllium R&D

- 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

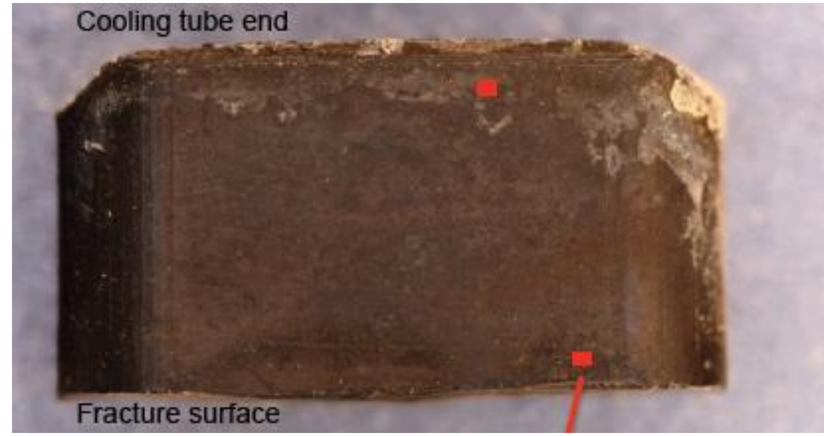


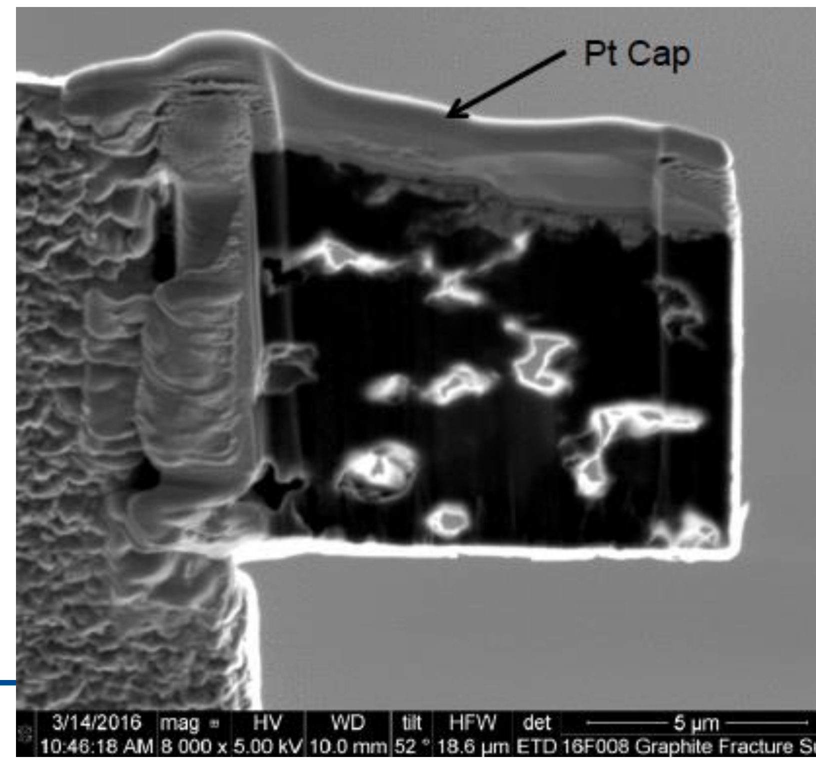
Major axis

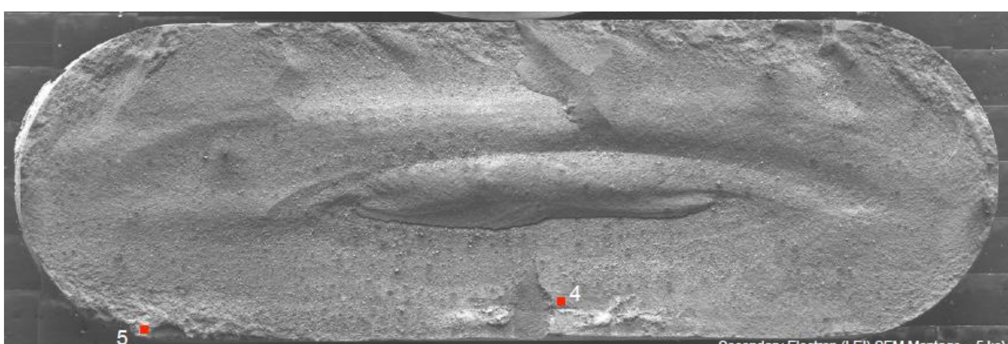


Graphite R&D

- 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)

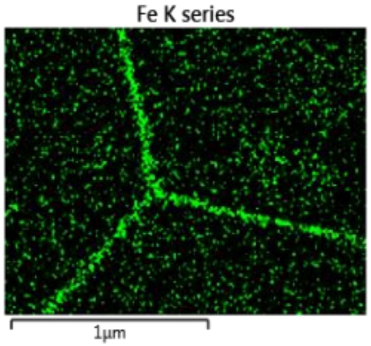


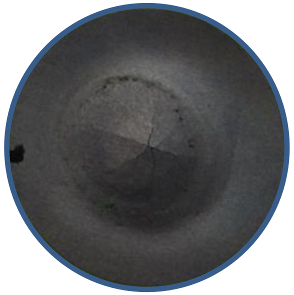


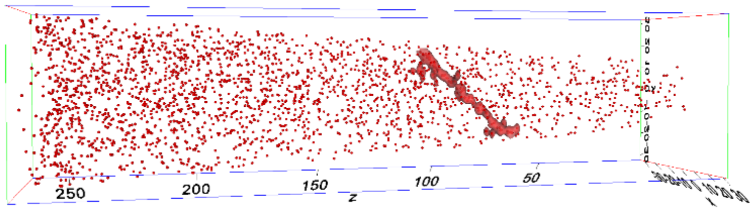


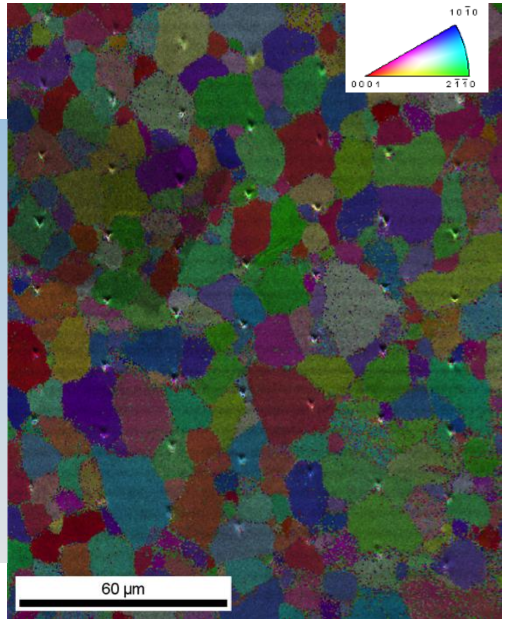
Other ongoing HPT R&D Activities

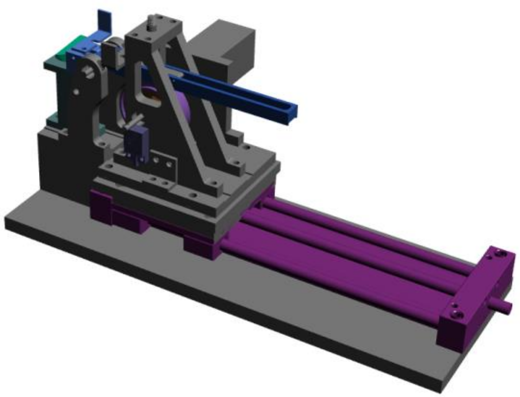
- Continuation of studies on NuMI primary beam window at Oxford
- Preparation for RaDIATE irradiation run at BNL's BLIP facility
  - Hundreds of samples
  - Be, Graphite, Glassy Carbon, Ti alloys, Si, TZM, Ir
  - In collaboration with FRIB, J-PARC, BNL, CERN, ESS
- Preparation for LE ion irradiations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

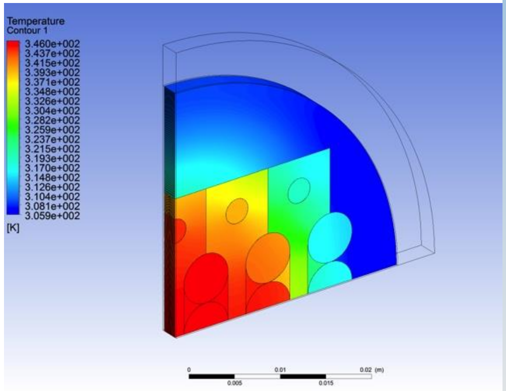


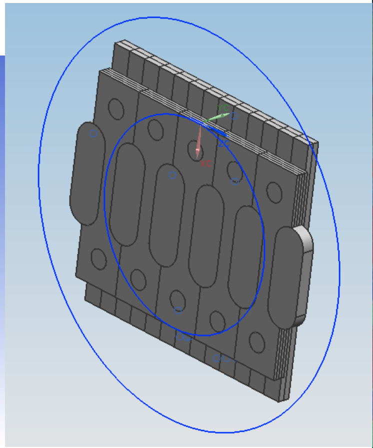






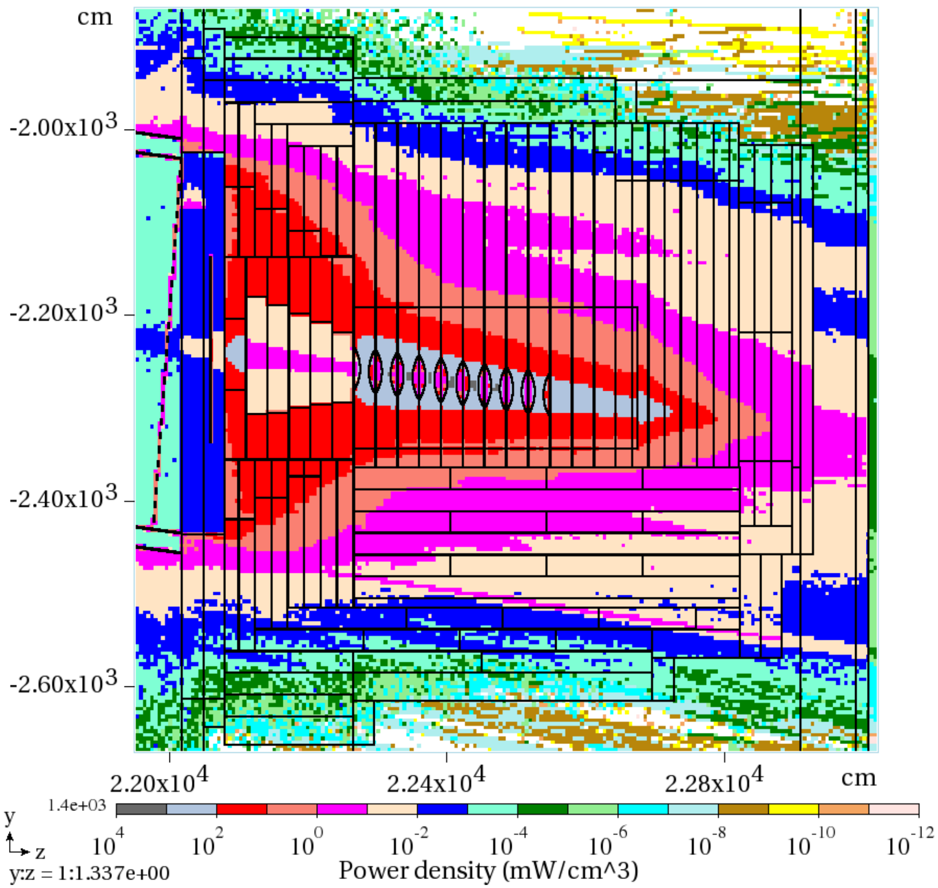




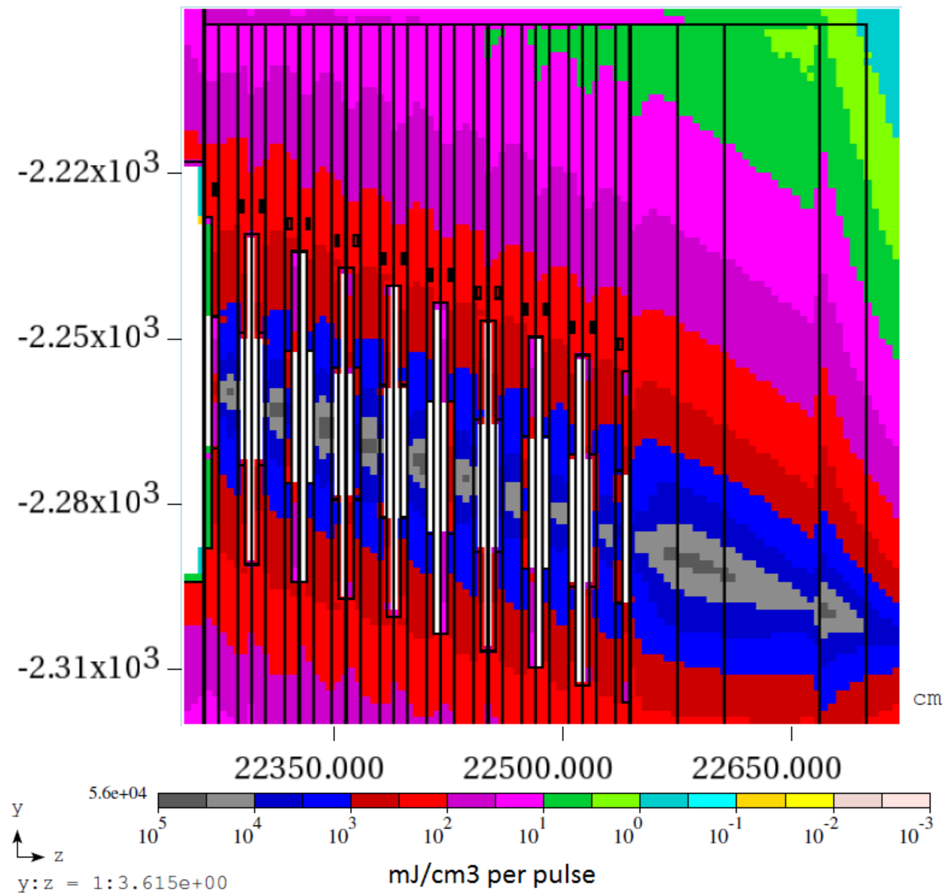


Energy Deposition (mW/cm^3) y-z Profiles

Normal, 120 GeV



On-axis accident, 120 GeV



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.