Design of the LBNF Neutrino Beamline

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Outline

• LBNF/DUNE scientific goals
• LBNF Beamline Overview
• Recent engineering progress in various areas of the Beamline work
  • Progress on the optimization effort
    • Horns
    • Target
    • Impacted systems
  • Progress in other areas
    • Target chase atmosphere (air releases, inert gas)
    • Beam windows
• Schedule and milestones
• Conclusion
LBNF/DUNE Science Goals

LBNF/DUNE is a comprehensive program to:

- **Measure neutrino oscillations**
  - Direct determination of CP violation in the leptonic sector
  - Measurement of the CP phase $\delta$
  - Determination of the neutrino mass hierarchy
  - Determination of the $\theta_{23}$ 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
LBNF/DUNE Science Goals

LBNF/DUNE is a comprehensive program to:

• **Study other fundamental physics enabled by a massive, underground detector**
  
  – Search for nucleon decays (reveal a relation between the stability of matter and the Grand Unification of forces?)
  
  – Measurement of neutrinos from galactic core collapse supernovae (peer inside newly-formed neutron stars and potentially witness the birth of a black hole?)
  
  – Measurements with atmospheric neutrinos

Start data taking ~ 2024
701 kW on the NuMI/NOvA target in one supercycle on June 13, 2016!!

Proton Improvement Plan (PIP)

After Nov. 2016 expect to run at ~ 700 kW on a continuous basis

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LBNF Beamline

~ 21,000 m²

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

60-120 GeV proton beam

Constructed in Open Cut

Tunneled excavation
Primary Beamline

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

Beam size at target tunable between 1.0-4.0 mm

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

In the process of prototyping corrector and kicker magnets

LBNF kicker magnets are further upstream and not shown in this view.
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:
N₂ 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
1.2 MW reference design target and horns

- 47 graphite target segments, each 2 cm long
- 0.2 mm spacing in between
- Two interaction lengths, 95 cm
- First few fins have “wings”, 26 mm disks

NuMI-like (low energy) with modest modifications target and (two) horns

Target cross section

Operated at 230 kA for LBNF

New Horn power supply needed - reduced pulse width of 0.8 ms.
Upstream Beam Window Concepts

Autoclave with rotating ring

Pressured slabs

Bolted Flange Connection

Remotely operated Hydraulic Wrench

Consider Use of a flange with multiple bolts to apply load to the seal and restrain the force from the pressure over the window area.
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)
Optimizing target and horns

- Optimizing target and horns for better physics.
- Optimizing on the basis of sensitivity to CP violation.
- Encouragement by the CD-1 Refresh Review Committee to continue along these lines.
- The optimization leads to significantly more flux, a flatter spectrum in the energy range of interest and reduced high energy tail.
Horns constructed from 6061-T6 aluminum forgings. Minimum fatigue life requirements of 100 million pulses in the proton energy range from 60 – 120 GeV.
Mechanical model for optimized horn A and target integration – 1\textsuperscript{st} iteration

2m long (4 interaction lengths) NuMI style target for first iteration of MARS simulations; cylindrical and spherical targets under R&D as well.
Finite Element Analysis for Horn A

- First iteration thermal/stress FEA for optimized horn A.

Preliminary FEA for Horn A shows:
- Acceptable inner and outer conductor temperatures and stresses.
- Support of target at DS end too hot (> 1,000°C); needs redesign.
- Tentative design philosophy is to extend target containment tube till end of Horn A and support through helium-cooled titanium tubes.

Stress after beam pulse with both thermal and magnetic load

Maximum current: 300 kA
Current pulse width: 0.8 ms
Finite Element Analysis for Horn B

Maximum current: 300 kA
Current pulse width: 0.8 ms

Preliminary FEA for Horn B shows:

- Acceptable conductor temps
- Inner conductor neck wall can be thinned out (from 4 mm to 3 mm)
- Hot equalization sections. Must be modified. We know how to address.
Cylindrical Horn A / integrated target

- Shorter cylindrical horn A (2.2m), longer (3.9 m) horn B
- Shorter, cylindrical horn A easier to build; easier to support and cool target that way

- Target fins cooled by two water tubes; horn inner conductor cooled by water spray and air flow
- Helium exhaust tubes act as support for D.S. end of target
- Horn A and target to be exchanged as one unit
Tapered Horn A

- On September 22, 2016 we decided to move forward with a “tapered” Horn A because it provided improved neutrino flux and CP sensitivity.

- Working on mechanical designs of horns B and C and on implementing all horns in 2nd MARS iteration
- FEA will follow
- NuMI-style target, 2 m long for now
- Collaboration with RAL on target conceptual design and mounting to horn
- A mounting design that allows for a separately replaceable target is desirable
Target developments

Can we build a target lasting over a year?

Helium-cooled graphite rod

Helium-cooled spherical array target

Be or graphite

36 kW in target at 2 MW mean temperature ~700°C
Optimizing target and horns

- Optimizing target and horns for better physics.
- Optimizing on the basis of sensitivity to CP violation.
Tau appearance optimization

- Studies indicate that more than 700 events per year is possible.
- Using NuMI like target and horns

\[ \nu_\tau \text{ cc events over target and horns distance} \]
Impacts on other systems

Re-assess:
• Horn support modules
• Horn power supply
• Target shielding/cooling
• Decay pipe shielding/cooling
• Decay pipe upstream window and snout
• Remote handling (casks, morgue capacity analysis, work-cell,..)
• Hadron absorber
• Muon shielding in the end of the hadron absorber
• Conventional Facilities
Horn Support Modules preliminary FEA

- Life-of-facility components, adjustable and serviceable by remote control
- Modules analyzed at beam energies 60-120 GeV
- Max temperature found was ~ 84°C for Horn A which is well within limits for mainframe
Gas in the target chase

• Issues to be further understood with the reference design that has air in the target chase:
  • Repeating air-releases calculations with bigger chase, shorter decay pipe (Preliminary results just became available from three independent analyses)
  • Corrosion (work in progress; on the basis of NuMI measurements, 20-60 ppm of Ozone expected in LBNF at 2.4 MW operation with only minimal amounts of nitric acid generation.
• Developing alternative design with Nitrogen in the target chase (CDR follow-up)
Air in the target chase – Activated Air emissions

LBNF goal < 30 µrem (100 µrem Lab budget)

Ar$^{41}$ in test sample at NuMI is a factor of a few lower than calculations but too close to the limit

<table>
<thead>
<tr>
<th>Decay Volume used</th>
<th>$T_{\text{transit}}$ (min)</th>
<th>Release (Ci/yr)</th>
<th>Ar-41 fraction</th>
<th>MEOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>out of LBNF (TH)</td>
<td>0</td>
<td>1526</td>
<td>34.7%</td>
<td>670</td>
</tr>
<tr>
<td>LBNF (PT)</td>
<td>33</td>
<td>754</td>
<td>57.1%</td>
<td>331</td>
</tr>
<tr>
<td>pipe (LBNF to NuMI)</td>
<td>3</td>
<td>1419</td>
<td>36.6%</td>
<td>623</td>
</tr>
<tr>
<td>pipe + NuMI (TH)</td>
<td>56</td>
<td>520</td>
<td>71.5%</td>
<td>228</td>
</tr>
<tr>
<td>pipe + NuMI (PT)</td>
<td>28</td>
<td>827</td>
<td>53.6%</td>
<td>363</td>
</tr>
<tr>
<td>pipe + NuMI (TH+PT)</td>
<td>81</td>
<td>381</td>
<td>83.4%</td>
<td>167</td>
</tr>
<tr>
<td>pipe + NuMI (TH+PT+Carrier pipe)</td>
<td>137</td>
<td>232</td>
<td>95.9%</td>
<td>102</td>
</tr>
</tbody>
</table>

If we use inert gas in target chase do we still need NuMI for cooldown?
Nitrogen in the target chase

• Requires robust leak-tight seals at all openings and feedthroughs, plus leak tight seal at decay pipe & and window interfaces.
• Need minimal leak rate ~6 cfm or about 2 orders magnitude less than that for air – due to ODH and nitrogen cost considerations.
• Requires containment vessel (not accessible for repair) within concrete tub that might affect thermal stability of the concrete which is currently directly cooled with air flow (alignment considerations).
• Hatch covers need to be removable including the supporting crossmembers (modular design) since we don’t know the exact position, dimensions, etc. of all components and need to accommodate different component configurations in future. Sealing at the seams and cross-beam interfaces is especially challenging.
• Requires a nitrogen fill and monitoring system plus ODH considerations.
• System will need to operate at positive pressure to prevent air/oxygen coming in and accommodate barometric pressure changes due to weather.
• The **concrete walls** support the chase components (target and horns) and therefore need to see a minimal thermal variation ($\Delta T \leq 4 ^\circ C$) in order to maintain component alignment.

• The interior of the concrete walls have a stainless-steel liner (for gas containment) and a small air gap is assumed between the liner and concrete wall. The surfaces of the liner are actively cooled by the gas.

• By applying a free-convection boundary condition at the outer wall surfaces, an acceptable temperature rise is achieved, with a maximum vertical wall displacement of 4mm (alignment tolerance is ~ 8mm).

• Investigating forced air circulation.
Nitrogen in the target chase – Hatch Cover Assembly

10 Hatch Covers (some stacked for target replacement)

Hatch cover removed (~40 tons each)

Hatch Cover Seams with supporting cross beams underneath

Battlement
Cut-out in battlement for cross-member placement
LBNF/DUNE Milestones

• Critical Decision-0 (CD-0) approved, January 8, 2010.
• CD-1 Refresh approved, November 5, 2015 (Conceptual Design)
• CD-3a approved, September 1, 2016 (far-site pre-excavation and excavation)
• Complete Sanford Laboratory reliability projects in FY2018
• CD-2 for the entire project expected in December 2019 (baselining)
• Complete first cryostat and cryo systems construction to enable detector installation to begin in 2021
• Commission first 10 kTon far detector in 2024
• Add a second 10 kTon far detector and the near detector by 2026
• Produce neutrino beam in 2026
Conclusion

• Reference conceptual design for the LBNF Beamline already available and approved by DOE.

• Considerable effort and satisfactory progress on beam optimization and design improvement areas.

• Need to take decisions on alternative/optimized options by October 2017 so that we can start the next phase of the design with the new fiscal year.
Beamline Requirements and LBNF/DUNE neutrino beam spectra

Normal mass hierarchy

CP effects

1\text{st} \ & \ 2\text{nd} \ max

Mass hierarchy

1\text{st} \ max

0.8 \ GeV

2.4 \ GeV

➢ Need a wide band beam to cover the 1\text{st} \ and \ 2\text{nd} \ oscillation maxima

3.5 \ yr \ \nu_\mu + 3.5 \ yr \ \overline{\nu}_\mu

40 \ kt \ detector,

PIP-II beam power(1.03-1.2 \ MW)
Facility and Experiment

• **LBNF:**
  • **Near site:** Fermilab, Batavia, IL – facilities and infrastructure to:
    • create a broad band, sign selected neutrino beam
    • host the near DUNE detector
  • **Far site:** Sanford Underground Research Facility, Lead, SD – facilities to support the far DUNE detectors (4850 L)

• **DUNE:**
  • Near site detector and Far site detectors
Fermilab design, double-checked by IHEP colleagues. Large aperture, air-cooled, relatively high field, large good field region, sufficiently flexible design.

IHEP finished with final drawings and technical files of tooling needed and began fabrication of tooling early October, 2016 (punching die, stacking fixture, winding former and potting mold).

Fittings of coil and room temperature cure epoxy from Fermilab.

Prototype complete – February 2017.

SOW in review stage, covering additional 24 production corrector magnets.
Near Detector Hall and Detector

Near Neutrino Detector Hall and LBNF 40 Service Building

Three types of Near Detector considered:
- Fine-Grained Tracker (reference)
- High-Pressure Gaseous Argon TPC
- Lar-TPC