LBNF Neutrino Beam

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Outline

• Overview of LBNF/DUNE
• Current and expected capabilities of the Main Injector complex
• Reference design of the LBNF Neutrino Beam
• Optimizing the focusing system for greater physics reach
• Summary
Long-Baseline Neutrino Facility

A facility to enable a world-leading experimental program in neutrino physics, nucleon decay, and astroparticle physics. LBNF comprises:

- Underground and surface facilities at the Sanford Underground Research Facility capable of hosting a modular LAr TPC of fiducial mass $\geq 40$ kt ($\sim 70$ kt liquid mass)
- Cryostats, refrigeration and purification systems to operate the detectors
- A high-power, wide-band, tunable, $\nu$ beam at Fermilab
- Underground and surface facilities to host a highly-capable near detector at Fermilab … and potentially other non-oscillation neutrino experiments
LBNF/DUNE

- LBNF is a DOE/Fermilab hosted project with international participation.
- Major partners include CERN and SURF.
- DUNE Collaboration will build and operate the experiment* in LBNF.

*See DUNE talks:
DUNE Physics (WG1 Monday)
DUNE Near Detector (WG1-2 Tuesday)
DUNE Systematics (WG1-2-3 Thursday)
Fermilab Main Injector Capabilities

Routine operation >400 kW since March

Record beam power 520 kW just before summer shutdown.

Goal is 700 kW for NOvA by next spring
LBNF Beam Operating Parameters:
Main Injector Complex with PIP-II and PIP-III upgrades

Summary of key Beamline design parameters for ≤1.2 MW and ≤2.4 MW operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Protons per cycle</th>
<th>Cycle Time (sec)</th>
<th>Beam Power (MW)</th>
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<tbody>
<tr>
<td>≤ 1.2 MW Operation - Current Maximum Value for LBNF</td>
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<tr>
<td>Proton Beam Energy (GeV):</td>
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<tr>
<td>60</td>
<td>7.5E+13</td>
<td>0.7</td>
<td>1.03</td>
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<tr>
<td>80</td>
<td>7.5E+13</td>
<td>0.9</td>
<td>1.07</td>
</tr>
<tr>
<td>120</td>
<td>7.5E+13</td>
<td>1.2</td>
<td>1.20</td>
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PIP-II

(1.1 – 1.9)x10^{21} POT/yr

≤ 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            |

PIP-III

Pulse duration: 10 μs
Beam size at target: tunable 1.0-4.0 mm
LBNF Neutrino Beam

To SURF

Kirk Road

Near Detector Service Building (LBNF-40)

Absorber Hall Service Building (LBNF-30)

Target Hall Complex (LBNF-20)

Primary Beam Enclosure

Apex of Embankment ~ 60°

MI-10 Point of Extraction

Primary Beam Service Building (LBNF-5)

SOIL ROCK

Absorber Hall and Muon Alcove

Absorber Hall ~ 95 ft Deep

Soil/Rock ~ 75 ft Deep

Muon Shielding

Near Detector Hall ~ 205 ft Deep

Beamline

997 ft (304 m)

636 ft (194 m)

725 ft (221 m)

Target to Near Detector ~ 1880 ft (574 m)
Primary Beam and Lattice Functions

- The LBNF Primary Beam will transport 60 - 120 GeV protons from MI-10 to the LBNF target to create a neutrino beam. The beam lattice points to 79 conventional magnets (25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons and 1 C magnet).

Horizontal (solid) and vertical (dashed) lattice functions of the LBNF transfer line

Beam size at target tunable between 1.0-4.0 mm
Neutrino Beam Configuration

- Decay Pipe
- snout and window
- Water cooled panels
- Support modules for target/baffle carrier and horns
- Work cell
- Beam slopes down at 101 mrad towards the Far Detector 1300 km away
- Space reserved for more optimized horn system
- multi-ply geosynthetic barriers, separated by a drainage layer
Target Shield Pile

steel shielding surrounds the beamline components (baffle, target, Horn 1, Horn 2, and the decay pipe upstream window) installed in the target chase

Water-cooled chase panels

~40% of the beam energy deposited in the target chase

**Cooling**: combination of forced air & water-cooled panels
**Target and Focusing System – Reference Design**

**Protection Baffle**
Ten graphite cores, 17 mm Ø hole, enclosed by an aluminum tube.

**Target**
NuMI-style target: 47 graphite segments, each 2 cm long and spaced 0.2 mm apart, for a total target core length of 95 cm, $2 \lambda_I$. Viable for 1.2 MW beam power.

**Horns:** identical to NuMI, but operated at 230 kA current and subjected to a maximum beam power of 1.2 MW
- new Horn Power Supply necessary to reduce pulse width to 0.8 ms.

Target starting 45 cm upstream of MCZERO.
Initial Modifications for 1.2 MW

- Wider target material (still graphite): 7.4 → 10.0 mm
- Dual cooling pipes – greater surface area
- Slightly larger outer vessel diameter: 30 → 36 mm
(Move target upstream 10 cm from horn)

- 47 graphite segments, each 2 cm long

Graphite segment
Proton Beam

7.4 mm

BERYLLIUM
TITANIUM
WATER
GRAPHITE, 1.78 G/CC

700 kW design

mm

cm
Upstream Decay Pipe Window

- thin replaceable window
- 1.25 mm beryllium or beryllium-aluminum alloy foil welded to a heavier aluminum ring
- heavier ring includes a seal groove for an all metal seal
- viable design for 60-120 GeV/c protons, 1.03-1.20 MW beam power
Decay Pipe

- 194 m long, 4 m inside diameter
- Helium filled
- double-wall decay pipe, 20 cm annular gap
- 5.6 m thick concrete shielding
- It collects ~30% of the beam power, removed by an air cooling system
Combination of forced air & water cooling panels for Target Shield Pile
- Air-cooled Decay pipe
- 2 separate air systems for target Chase and Decay Pipe
- Possible need to replace air in the target chase with N2 or He under study
Absorber building

Absorber goes here

DECAY PIPE

BEAMLINE

MUON ALCOVE

MUON KERN STEEL SHIELDING

BEAM DIRECTION

ABSORBER SERVICE BUILDING

ABSORBER HALL
Beam Absorber Configuration

- ~30% of the beam energy deposited in the Absorber
- Core: replaceable water-cooled blocks, each 1 foot thick
- Outside of the core is forced-air cooled steel and concrete shielding
- Viable for 60-120 GeV/c protons, 2.06-2.4 MW beam power, including both steady-state operations and accident conditions
Remote Handling

- Remote Handling systems are integrated into the infrastructure of the Target complex, they must be designed to be sufficient for 2.4-MW beam power
  - Shield doors (will incorporate air seals)
  - Lifting fixtures, vision system
  - Morgue/Maintenance areas, Rail System
  - Hot Storage Rack and Work Cell

- Absorber Hall components and shielding allow future replacement
  - Low probability of complete failure, final design and construction of remote handling equipment not included in the LBNF project
  - No Work Cell needed in Absorber Hall
Beam Simulation

- Extensive MARS simulations for energy deposition and radiological studies as well as for Beamline configuration optimization studies.
  - ~40% of the beam power is deposited to the Target Hall Complex, 30% to the Decay Pipe region and 30% to the Absorber Hall complex.
- GEANT simulations for Beamline configuration optimization studies, neutrino fluxes, sensitivity and systematic studies.
What is being designed for 2.4 MW

- Designed for **2.4 MW**, since upgrading later would be prohibitively expensive and inconsistent with ALARA:
  - Size of enclosures (primary proton beamline, target chase, target hall, decay pipe, absorber hall)
  - Radiological shielding of enclosures (except from the roof of the target hall, that can be easily upgraded for 2.4 MW when needed)
  - Primary Beamline components
  - The water cooled target chase cooling panels
  - The decay pipe and its cooling and the decay pipe downstream window
  - beam absorber
  - remote handling equipment
  - radioactive water system piping
  - horn support structures are designed to last for the lifetime of the Facility
Neutrino Flux – Reference Configuration

Focusing positive particles ($\nu_\mu$ beam)

120 GeV protons
230 kA horn current

Focusing negative particles ($\bar{\nu}_\mu$ beam)
Studies for an optimal beam design - Physics

• **Proton energy** choice in the range 60-120 GeV (some programmatic consequences).

• **Horns**
  – **Shape/size**
  – **current** (power supply up to 300 kA, just completed new conceptual design)

• **Target** (currently two interaction lengths)
  – **Size/shape/position** with respect to Horn 1
  – **Material(s)** (higher longevity can increase up time - ongoing R&D)

• **Studied** **Decay Pipe length** and diameter. Current length 194 m (studied 170 m - 250 m). Current diameter 4 m (studied 2-6 m). *Recently fixed at 194 m long x 4 m diameter.*
Optimizing the focusing system for greater physics reach

Genetic algorithm, inspired by work done by LBNO Collaboration to optimize for CP Violation sensitivity

Genetic algorithm and new shape of Horn 1 Horn 2 is NuMI shape in this case but rescaled radially and longitudinally
Target chase allows for optimized focusing systems

Reference Design Target Chase indicating the positions of the reference design horns (in red) and the optimized horns (in blue)
Neutrino Flux of best configurations compared with Reference Design

**Enhanced:** thinner and shorter cylindrical Be target, 25 cm upstream of 1st horn
CPV and MH sensitivity improvement with optimized beam

50% CP Violation Sensitivity

30% less exposure req’d

40% less exposure req’d

5% ⊕ 1%

5% ⊕ 2%

5% ⊕ 3%
Further work required on optimized target-horn system

- Engineering needed to determine feasibility of horn designs selected by genetic algorithm
- Study effect of 2 -> 3 horn system

- Search phase-space of horn design more broadly, and consider other optimization criteria, e.g. for $\nu_\tau$ appearance.

- Alternate target designs and materials
- Target and horn R&D towards 2.4 MW operation
- Alternate ideas to “classical” horn focusing?

  => Ideas from new collaborators are needed!
Summary

• The Fermilab Main Injector is delivering the world’s highest beam power for neutrinos ... 0.5 MW now, 0.7 MW next year, 1.2 MW -> 2.4 MW with PIP-II and eventually PIP-III

• The LBNF beamline design is well developed, based on NuMI experience
  – All systems designed for 1.2 MW
  – All elements that cannot be replaced later are designed for 2.4 MW

• Further optimization can have a big impact on the physics reach of DUNE ... new ideas and new collaborators are needed now to realize this potential.