Long Base Neutrino Facility (LBNF) Conceptual Design Report

 **Volume 3—Copy**

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# CHANGE LOG

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# Overview

## Introduction

The global neutrino physics community is coming together to develop a leading-edge, dual-site experiment for neutrino science and proton decay studiesthe Deep Underground Neutrino Experiment (DUNE), hosted at Fermilab in Batavia, IL. The facility required for this experiment, the Long-Baseline Neutrino Facility (LBNF), will be an internationally designed, coordinated and funded program, comprising the world's highest-intensity neutrino beam at Fermilab and the infrastructure necessary to support DUNE's massive, cryogenic far detectors installed deep underground at the Sanford Underground Research Facility (SURF), 800 miles (1,300 km) downstream, in Lead, SD. LBNF will also provide the facilities to house the experiment's near detectors on the Fermilab site. LBNF and DUNE will be tightly coordinated as DUNE collaborators design the detectors that will carry out its experimental program.

The LBNF scope includes the following items:

* an intense neutrino beam aimed at a far site
* conventional facilities at both the near and far sites
* cryogenics infrastructure at the far site to support the DUNE liquid argon time-projection chamber (LArTPC) detector

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# Beamline

## Overview

The LBNF beamline at Fermilab is being designed to provide a neutrino beam of sufficient intensity and appropriate energy range to meet the goals of the DUNE experiment with respect to long-baseline neutrino-oscillation physics. It aims at a wide band neutrino beam about 1,300 km away, toward detectors 4850 ft underground, placed at the SURF Facility in South Dakota. The design is a conventional beamline, with horn-focused, sign selected neutrino beam. The components of the beamline are being designed to extract a proton beam from the Fermilab Main Injector (MI) and transport it to a target area where the collisions generate a beam of charged particles. This secondary beam, aimed toward the Far Detector, is followed by a decay-pipe where the particles of the secondary beam decay to generate the neutrino beam. At the end of the decay pipe, an absorber pile removes the residual hadrons. (see Fig. 2-1).



Figure ‑: Longitudinal section of the LBNF beamline facility at Fermilab. The beam comes from the right, the protons being extracted from the MI-10 straight section of the MI.

In the reference design, the extraction of the proton beam (60 – 120 GeV) occurs at MI-10, a new installation. The extraction and transport components send the proton beam through a man-made embankment/hill whose apex is at 18.3 m from the ground and with a footprint of ~21,370 m2. The beam then will be bent downward towards a target located at grade level. The overall bend of the proton beam is 7.2o westward and 5.8o downward to establish the final trajectory towards the far detector.

The general primary-beam specifications and beam characteristics are listed in Tables 2-New-1 and 2-New-2.

 Table 2‑1: Summary of Principal Beam Design Parameters

| **Parameter**  | **Value**  |
| --- | --- |
| Protons per cycle  | 7.5×1013  |
| Spill duration  | 1.0×10-5 sec  |
| Energy  | 60 to 120 GeV  |
| Protons on target per year  | 1.9 x 1021 to 1.1×1021  |
| Beam/batch (84 bunches)  | 8×1012 nominal; (3×1011 commissioning)  |
| Cycle time  | 0.7 to 1.2 sec  |
| Beam Power | 1.03 to 1.20 MW |

 **Table New-1: Beam Characteristics**

| **Parameter**  | **Value**  |
| --- | --- |
| Beam size at target  |  1.5 to 1.7 mm  |
| Δp/p | 11×10-4 99% (28×10-4 100%) |
| Transverse emittance | 30π μm 99% (360π μm 100%)  |
| Beam divergence (x,y) | 17 to 15 μrad  |

Neutrinos are produced after the protons hit a solid target and produce mesons that are subsequently focused by magnetic horns into a 204m long decay pipe where they decay into muons and neutrinos. A wide band neutrino beam is needed to cover the first and second neutrino oscillation maxima, which for a 1300 km baseline are expected to be approximately at 2.4 and 0.8 GeV. The beam must provide a high neutrino flux at the energies bounded by the oscillation peaks and we are therefore optimizing the beamline design for neutrino energies between 0.5 and 5 GeV.

The facility is designed for initial operation at proton beam power of 1.2 MW with the capability to support an upgrade to 2.4 MW. The Beamline systems that are designed from the beginning for 2.4 MW operation include:

* The size of the enclosures (primary proton beamline, target chase, target hall, decay pipe, absorber hall)
* The radiological shielding of the enclosures, the only exception being the roof of the target hall that can be easily upgraded later for 2.4 MW
* The primary proton beamline components
* The water cooled target chase shielding panels
* The decay-pipe and its cooling and the decay pipe downstream window
* The beam absorber
* The remote handling equipment
* The RAdioactive Water (RAW) system piping

None of these can be upgraded after exposure to a high-intensity beam.
**Note:** According to detailed MARS simulations, 39% of the beam power is deposited to the Target Hall complex, 30% to the decay pipe region and 31% to the Absorber Hall complex.

The LBNF Beamline is being designed for twenty years of operation, while the Beamline Facility, including the shielding are planned for its entire lifetime of 30 years. A conservative stance is that for the first five years, the Beamline will operate at 1.2 MW of beam power and for the remaining fifteen years at 2.4 MW.

### Scope

For organizational purposes, the LBNF beamline is broken into four principal systems:

* **Beamline Management:** Management and oversight, modeling effort, radiation physics and radiation protection activities
* **Primary Beam:** Components required for the initial, high-intensity proton beam
* **Neutrino Beam:** Components used to create a high-intensity neutrino beam from the initial proton beam.
* **System Integration**

### Physics Reach with the Reference Design

The goal for accumulating 120-GeV protons at the neutrino target with beam power of 1.2 MW is 1.1×1021 protons-on-target (POT) per year. This assumes 7.5×1013 protons per MI cycle of 1.2 sec [1-POT-new] and the total LBNF efficiency of 0.56. The total LBNF efficiency used in the POT calculation and discussed below includes the total expected efficiency and up-time of the accelerator complex as well as the expected up-time of the LBNF Beamline.

The neutrino flux at the Far Detector site is shown in Figures 2-2 and 2-3, calculated for a 120 GeV proton beam, the NuMI horns at 230 kA and 6.6 m apart, and a decay distance (between horn 1 and the decay pipe) of 17.3 m. The decay pipe is 203.7 m long and 4 m in diameter.



**Figure 2-2: Neutrino Fluxes at the Far Detector as a function of energy in the absence of oscillations with the horns focusing positive particles. In addition to the dominant *νμ* flux, the minor components are also shown.**



Figure 2-3: Antineutrino Fluxes at the Far Detector as a function of energy in the absence of oscillations with the horns focusing negative particles. In addition to the dominant anti-ν flux, the minor components are also shown. Note the logarithmic scale.

### Reference

For detailed information on Beamline, refer to the Annex document.

## System Integration (WBS 130.02.04)

### Introduction

This section covers the System Integration activity of the LBNF Beamline L2 Project. The System Integration team’s responsibilities can be broken into two major areas: first, the oversight of systems for Controls, Alignment and Interlocks, and Installation Coordination. Second, there is the task of ensuring that the interfaces between each of the subsystems of the Beamline L2 Project are complete. The Controls, Alignment, Interlocks and Installation Coordination span the entire Beamline project and must therefore be properly supported by all the interfaces in addition to the relevant components. Interface coordination involves both achieving consensus as to the location and nature of each interface and the party responsible for it. The coordination activity must also ensure proper distribution of requirements and specifications so that all the needed components are accounted for, and that they will be constructed such that they will fit together properly during installation and operate successfully.

System Integration thus has the primary responsibility of facilitating good communication throughout the L2 project to prevent deficiencies and scope-related problems, and for any that are introduced?, to spot them early on and make sure they get corrected.

### Controls (WBS 130.02.04.02)

### Radiation-Safety Interlock Systems (WBS 130.02.04.03)

####  Introduction

This section describes the philosophy, policies, procedures, design, fabrication, installation, checkout and commissioning for the Electrical Safety interlock System (ESS), Radiation Safety Interlock Systems (RSS), Radiation Monitors, Radiation Air Monitors, and Radiation Frisker Stations. Underlying all safety-system designs is a commitment to providing the necessary hardware, procedures, and knowledge to personnel to ensure their well-being. Inherent in each of these systems is the concept of redundancy.

### Alignment (WBS 130.02.04.04)

#### Overview

This section summarizes the concepts, methodology, implementation and commissioning of the geodetic surveying (global positioning) efforts for determining the absolute positions of the LBNF beamline components at Fermilab and the location for the Far Detector at SURF. This information is critical to achieving proper aim of the neutrino beam. From this information, the beam orientation parameters are computed, as well as the alignment of the LBNF beamline.

### Installation Coordination

This activity provides the management oversight of the day-to-day activities taking place in the installation areas and the framework for sequencing and scheduling the installation tasks. The scope of this role is driven by the need to balance the resources required in four distinct installation sub-projects. In addition, there is a need to ensure that all activities are conducted with a consistent level of safety and quality assurance throughout the project. The role of Installation Coordination is distinct from the actual task of installation. Its role is primarily the coordination of installation activities and will be led by an Installation Coordinator. The responsibility for the design, fabrication and installation of each element of the Beamline L2 Project resides in its appropriate subsystem.

Installation Coordination will draw on the experiences of previous installations such as NuMI, and the lessons learned from more recent installation projects such as ANU. In addition, the team will be organized in a manner that advantageously uses the project management tools being implemented throughout the laboratory. The implementation of Installation Coordination will begin with the managerial role of sequencing and controlling the activities in each of the areas (as illustrated below). Each area (e.g., Main Injector, Primary Beamline, Target Complex, and Absorber Hall) will be under the supervision of either an Operations Specialist or a Floor Manager whose job it is to oversee the overall installation activity taking place in the area and to supervise the daily activities of task managers who are leading the work crews in each area. Floor Managers will report directly to the Installation Coordinator.

## Alternative Beamline Options

As discussed earlier in this CDR, the LBNF Beamline Facility is being designed for twenty years of operation with thirty years of actual lifetime. During this time period, the beam power is expected to increase from 1.2 MW to 2.4 MW and the facility must accommodate upgraded targets and horns in different configurations to maximize the neutrino flux in the appropriate energy range and to enable tunability in the neutrino energy spectrum. To allow for some flexibility and for improved capabilities in the future, the LBNF Beamline Team is investigating and considering a few alternative design options. Three of those changes affect physics and one is a technical alternative in case the current default design proves insufficient after more detailed design work. The considered alternatives are:

* A further optimized target-horn system
* A larger target chase to accommodate longer or different shape targets, and longer/wider horns possibly at a larger distance among themselves than in the current reference design
* A longer or wider decay pipe
* A gas different than air in the target chase (e.g. nitrogen or helium)

and their expected cost impacts are included in the LBNF cost range.

The reference Beamline design uses a NuMI-like target and NuMI-style horns appropriately modified for the 1.2 MW operation. Further optimization of the target-horn system has the potential to substantially increase the neutrino flux at the first and especially second oscillation maxima as well as the area in between the two maxima and reduce wrong-sign neutrino background, thereby increasing the sensitivity to CP violation and mass hierarchy determination (see discussion in Volume 2). Target R&D and target-horn optimization work is on-going and may yield further improvements beyond those currently achieved. Engineering studies of the proposed target and horn designs and methods of integrating the target into the first horn must be performed to turn these concepts into real buildable and reliable structures. These studies will be carried out between CD­‑1 and CD-2 to determine the baseline design for the LBNF target-horn system. In addition, since targets and horns are consumables, more advanced ones could very well be designed in the future as 2nd generation components.

The more advanced target and focusing system described in Volume 2 utilizes two horns that are longer, of larger diameter and that are spaced farther apart than in the reference design. The first horn in particular is ~ 5.5 m long and ~ 1.3 m in diameter and functions effectively as two two horns in one structure. The second horn, is NuMI-style but wider and longer, and is 7.8m farther downstream than that of the reference design. This would require a target chase approximately 9m longer and 0.6m wider than the reference design. Taking into account that the target chase cannot be expanded after construction and to sustain at 2.4 MW operation, a longer baffle and the ability to maintain a 2.5m motion flexibility for the target are essential in and out of the first horn. Additionally, the size of the target chase between CD-1 and CD-2 must be reconsidered after the target-horn optimization is complete.

The length and diameter of the decay pipe also affect the neutrino flux spectrum. A longer decay pipe increases the total neutrino flux with a larger flux increase at higher energies, while a larger diameter allows the capture and decay of lower-energy pions, increasing the neutrino flux at lower energies. The dimensions of the pipe affect some of the backgrounds. Taking into account that the decay pipe cannot be modified after the facility is built, makes the choice of geometry particularly important. The reference design values of 204 m length and 4m diameter appear well matched to the physics of LBNF [BLundberg-5024], but studies to determine the optimal dimensions will continue between CD1 and CD2. These studies will be coordinated as well with the optimization of the target and horn systems described above.

As described earlier in this CDR, the target chase is air filled and together with the surrounding target pile it is cooled by air. There are two studies in progress that could eventually determine gas selection for use in the target chase/pile cooling system: (1) the LBNF Corrosion Task Force studies that includes both measurements at NuMI and associated modeling, and (2) LBNF studies of Air Releases to the Atmosphere. The conclusion from either one or both of these studies could require that the oxygen and argon concentrations in the target pile cooling system be minimized to mitigate the possible problems of (1) corrosion due to ozone production, and/or (2) radionuclide emission to the Atmosphere. As discussed in the Neutrino Beam section of the CDR, compliance with a requirement to minimize the oxygen concentration will be accomplished by changing the cooling gas from air to nitrogen gas or possibly to helium. The conclusion of the “LBNF Beamline Air-Releases Design Review” [Air-Releases-Review] that took place in April 2015 indicates that the reference design scheme to keep air-releases under control is reasonable and with sufficient safety factor. We will need to revisit the air-releases calculations between CD-1 and CD-2 after we finalize the volumes of the target chase and decay pipe.