

DESIGN OF THE LBNF BEAMLINE*

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Abstract

The Long Baseline Neutrino Facility (LBNF) will utilize a beamline located at Fermilab to carry out a compelling research program in neutrino physics. The facility will aim a wide band neutrino beam toward underground detectors placed at the SURF Facility in South Dakota, about 1,300 km away. The main elements of the facility are a primary proton beamline and a neutrino beamline. The primary proton beam (60-120 GeV) will be extracted from the MI-10 section of Fermilab's Main Injector. Neutrinos are produced after the protons hit a solid target and produce mesons which are subsequently focused by magnetic horns into a 204 m long decay pipe where they decay into muons and neutrinos. The parameters of the facility were determined taking into account the physics goals, spacial and radiological constraints and the experience gained by operating the NuMI facility at Fermilab. The initial proton beam power is expected to be 1.2 MW, however the facility is designed to be upgradeable to 2.4 MW. We discuss here the design status and the associated challenges as well as plans for improvements before baselining the facility.

INTRODUCTION

The Beamline is a central component of LBNF and its driving physics considerations are the long baseline neutrino oscillation analyses. On January 8, 2010 the Department of Energy approved the "Mission Need" (CD-0) for the Long Baseline Neutrino Experiment (LBNE) and on December 10, 2012 the conceptual design (CD-1). As of January 2015, the LBNE experiment had evolved to the Deep Underground Neutrino Experiment (DUNE) which uses the LBNF Facility at the Fermilab and Sanford Underground Research Facility (SURF) sites. Because of the increased scope for LBNF/DUNE we are preparing for a "CD-1 refresh" review in July 2015. For the Beamline, the change of scope consists of being ready to accept beam power of 1.2 MW (instead of 700 kW) at day one of operations.

The beamline facility is expected to be fully contained within Fermilab property. The primary proton beam, in the energy range of 60-120 GeV, will be extracted from the Main Injector's (MI) [1] MI-10 section using "single-turn" extraction. For 120 GeV operation and with the MI upgrades implemented for the NOvA experiment [2] as well as with the expected implementation of the accelerator Proton Improvement Plan, phase II (PIP-II) [3], the fast, single turn extraction will deliver all the protons (7.5×10^{13}) in one MI machine cycle (1.2 sec) to the LBNF target in 10 μ s. The beam power is expected to be 1.03 to 1.20 MW in the energy range of 60 to 120 GeV

[3]. The charged mesons produced by the interaction of the protons with the target are sign selected and focused by two magnetic horns into the decay pipe towards the far detector. These mesons are short-lived and decay into muons and neutrinos. At the end of the decay region, an absorber pile is needed to remove the residual hadrons remaining at the end of the decay pipe. The neutrino beam is aimed 4850 ft underground at SURF in South Dakota, about 1300 km away.

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 initial operation of the facility will be at a beam power incident on the production target of 1.2 MW, however some of the initial implementation will have to be done in such a manner that operation at 2.4 MW can be achieved without retrofitting. Such a higher beam power is expected to become available in the future with additional improvements in the Fermilab accelerator complex [4]. In general, components of the LBNF beamline system which cannot be replaced or easily modified after substantial irradiation at 1.2 MW operation are being designed for 2.4 MW. Examples of such components are the shielding of the target chase and the decay pipe, and the hadron absorber.

The LBNF Beamline design has to implement as well stringent limits on the radiological protection of the environment, workers and members of the public. The relevant radiological concerns, prompt dose, residual dose, air activation and water activation have been extensively modeled and the results are incorporated in the system design. A most important aspect of modeling at the present design stage is the determination of the necessary shielding thickness and composition in order to protect the ground water and the public and to control air emissions.

This paper is a snapshot of the present status of the design, detailed in the 2012 Conceptual Design Report [5] and the more recently published LBNE science document [6].

STATUS OF THE DESIGN

Figure 1 shows a longitudinal section of the LBNF beamline facility. At MI-10 there is no existing extraction enclosure and we are minimizing the impact on the MI by introducing a 15.6 m long beam carrier pipe to transport the beam through the MI tunnel wall into the new LBNF enclosure. The extraction and transport components send the proton beam through a man-made embankment/hill

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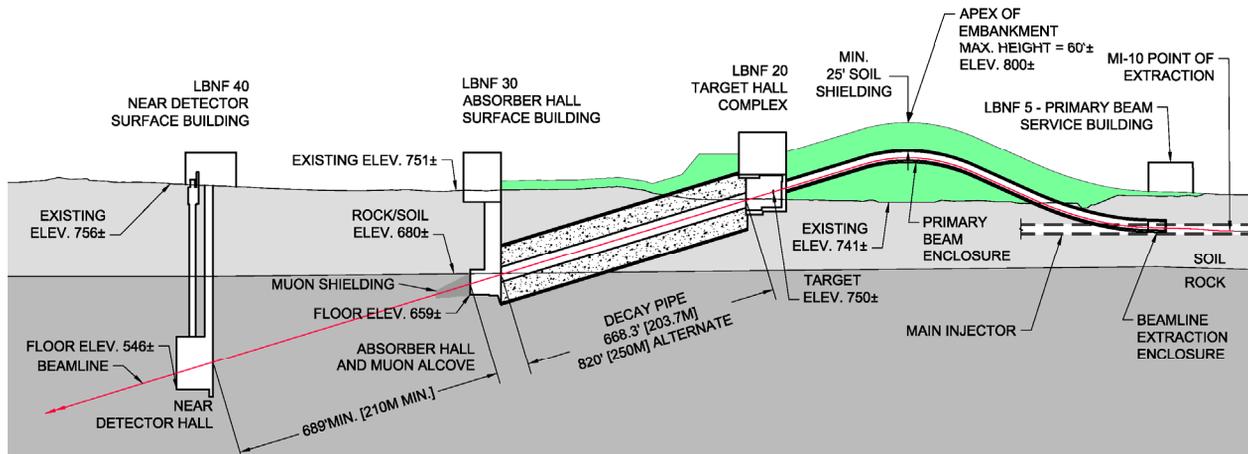


Figure 1: Longitudinal section of the LBNF beamline facility at Fermilab. The beam comes from the right, the protons being extracted from the MI-10 straight section of the MI.

whose apex is at 18.3 m from the ground and with a footprint of $\sim 21,370 \text{ m}^2$. The beam then will be bent downward toward a target located at grade level. The overall bend of the proton beam is 7.2° westward and 5.8° downward to establish the final trajectory toward the far detector.

In this shallow beamline design, because of the presence of a local aquifer at and near the top of the rock surface, an engineered geomembrane barrier and drainage system between the shielding and the environment prevents the contamination of groundwater from radionuclides. The decay pipe shielding thickness has been determined to be 5.6 m of concrete (see Fig. 2).

Beamline Scope

The LBNF Beamline scope includes a primary (proton) beamline, a neutrino beamline and associated conventional facilities. The primary beamline elements necessary for extraction and transport include vacuum pipes, dipole, quadrupole, corrector, kicker, lambertson and C magnets and beam monitoring equipment: Beam-Position Monitors, Beam-Loss Monitors, Beam-Profile Monitors and Beam-Intensity monitors. The magnets are conventional, MI design, and the magnet power supplies are a mixture of new, MI design power supplies and refurbished Tevatron power supplies. The beam optics accommodates a range of spot sizes on the target (1-4 mm) in the energy range of interest and for beam power up to 2.4 MW, and the beam transport is expected to take place with negligible losses.

The neutrino beamline includes in order of placement (1) a beryllium window that seals off and separates the evacuated primary beamline from the neutrino beamline, (2) a baffle collimator assembly to protect the target and the horns from mis-steered beam, (3) a target, (4) two magnetic horns. These elements are all located inside a heavily shielded, air-filled, air/water-cooled vault, called the target chase (see Fig. 2), that is isolated from the decay pipe at its downstream end by a replaceable, thin,

metallic window. A 204 m long, 4m in diameter helium-filled, air-cooled decay pipe follows in which pions and kaons decay to neutrinos. At its end is the hadron absorber (see Fig. 3) which must contain the energy of the particles that exit the decay pipe. The absorber core consists of replaceable, aluminum (cyan) and steel (orange) water-cooled blocks. Outside of the core we have steel and concrete shielding that is cooled by forced-air.

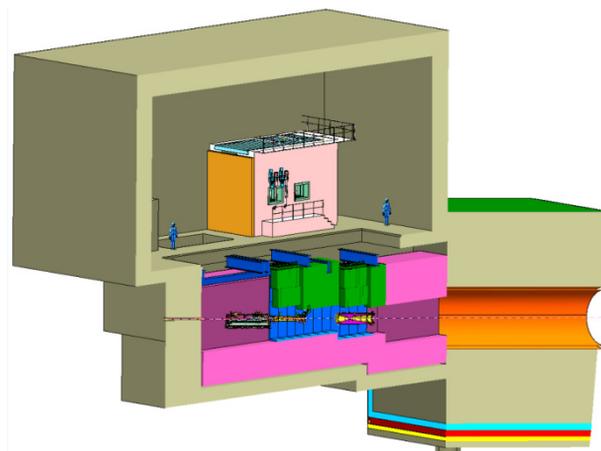


Figure 2: Schematic of the upstream portion of the LBNF neutrino beamline showing the major components of the neutrino beam. The target chase bulk steel shielding is shown in magenta. Inside the chase from left to right one can see the horn-protection baffle and the target mounted on a carrier, and the two focusing horns. The decay pipe follows (in orange). The beige areas indicate concrete shielding.

Radiation damage, cooling of elements, radionuclide mitigation, remote handling and storage of radioactive components are essential considerations for the conceptual design of the neutrino beamline.

Target and Horns and the 1.2 MW Challenge

One of the challenges for the LBNF Beamline is the recent requirement to be ready to accept 1.2 MW of beam power on day one of LBNF operations. Our approach has been to check if modest modifications to the CD-1 designs can achieve this. We attempted to reduce stress on the target by increasing the beam sigma from 1.3 to 1.7 mm.

The reference target design for LBNF is an upgraded version of the NuMI low-energy target that was used for ~eight years to deliver neutrino beam to the NuMI experiments. The target core is made of POCO ZXF-5Q graphite segmented into short rectangular segments oriented vertically, with the short direction transverse to the beam. The 95 cm long, two interaction length target consists of 47 20 mm long, 10 mm wide segments and it is water cooled. Also, in order to capture low energy pions and kaons from the target at large production angles, 50 cm of the target assembly is inserted into the first horn's magnetic lens. The horns are of NuMI design with their inner conductors having a double parabolic shape. Although they were designed for 200 kA we re-evaluated them and determined they can run at 230 kA. Thermal and stress analysis for horn 1 pointed to the need to round off the inner conductor's transition from parabola to neck and to move further upstream the upstream weld. FEA for the reference design 1.2 MW target and horns indicate acceptable to excellent safety factors in the proton energy range of 80 to 120 GeV. The plan is to power the LBNF horns by using a new design power supply with current pulse width of 0.8 ms and current up to 300 kA.

Physics Reach with the Reference Design and Alternative Options

Figure 4 shows the comparison of ν_μ fluxes from an 80 GeV proton beam for the reference design and various other studied modifications. The studies include a different target design consisting of a thinner and shorter cylindrical beryllium target that can be inserted further inside the first horn, a different decay pipe length or diameter, as well as an optimized horn focusing system configuration that increases the neutrino flux between the first and second oscillation maximum.

CONCLUSION

We described above the conceptual design of the LBNF beamline. We have addressed successfully the challenge of having the beamline ready to accept beam power of 1.2 MW at day one of LBNF operations and we are now in the process of advancing this design. In the mean time we are exploring some alternative options for the target and horn designs and for the size of the decay pipe that could possibly enhance the physics capabilities of DUNE. We will complete the evaluation of these alternatives before baselining.

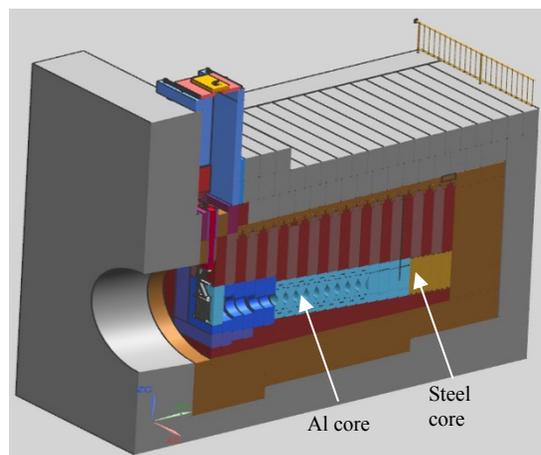


Figure 3: Cross section of absorber through beam axis. The concrete is indicated in gray color. The steel shielding in dark orange.

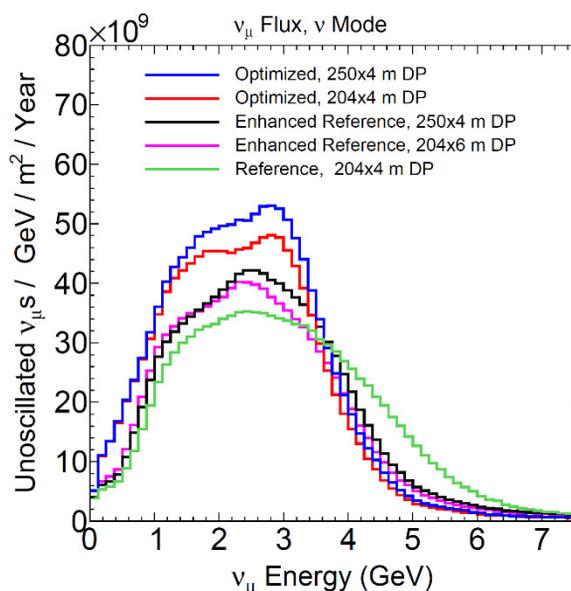


Figure 4: Neutrino mode muon neutrino fluxes as a function of neutrino energy for an 80 GeV proton beam and for several beam designs, including the reference design.

ACKNOWLEDGMENT

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