FERMILAB-CONF-18-169-AD

DESIGN STATUS OF THE LBNF/DUNE BEAMLINE*

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Abstract

The Long Baseline Neutrino Facility (LBNF) will utilize a beamline located at Fermilab to provide and aim a wide band beam of neutrinos of sufficient intensity and appropriate energy toward DUNE detectors, placed 4850 feet underground at SURF in South Dakota, about 1,300 km away. 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 four-interaction length solid target and produce mesons which are subsequently focused by a set of three magnetic horns into a 194 m long helium-filled decay pipe where they decay into muons and neutrinos. The parameters of the facility were determined taking into account the physics goals, spatial and radiological constraints, extensive simulations and the experience gained by operating the NuMI facility at Fermilab. The Beamline facility is designed for initial operation at a proton-beam power of 1.2 MW, with the capability to support an upgrade to about 2.4 MW. LBNF/DUNE obtained CD-1 approval in November 2015 and CD-3a approval in September 2016. We discuss here the Beamline design status and the associated challenges.

INTRODUCTION

The Beamline is a central component of LBNF and it is expected to produce the highest power neutrino beam in the world. Its driving physics consideration is the study of long baseline neutrino oscillations. This study will take place through the Deep Underground Neutrino Experiment (DUNE) which has detectors located both at the Fermilab site and at the Sanford Underground Research Facility (SURF), about 1300 km away. LBNF/DUNE achieved the CD-1 conceptual design milestone in November 2015. Approval for the start of construction of the conventional facilities at SURF (CD-3a) was granted in September 2016.

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. With the MI upgrades already 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 7.5 x 10^{13} protons in one MI machine cycle (0.7 sec/60GeV - 1.2 sec/120GeV) to the LBNF target in 10 μs. The beam power is expected to be between 1.03 and 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 three 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 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.

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 thus we are 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 of 1.2 MW on the production target, 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 major 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 hadron absorber and the shielding of the target station and decay pipe.

The LBNF Beamline design has to implement a stringent radiological protection program for the environment, workers and members of the public. The relevant radiological concerns: prompt dose, residual dose, air activation and water activation have been extensively modelled and the results are incorporated in the system design. A most important aspect of modelling 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 2015 Conceptual Design Report [5, 6] and in the 2017 Optimized Neutrino Beamline Conceptual Design Report [7].

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

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This document was prepared by [DUNE Collaboration] using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

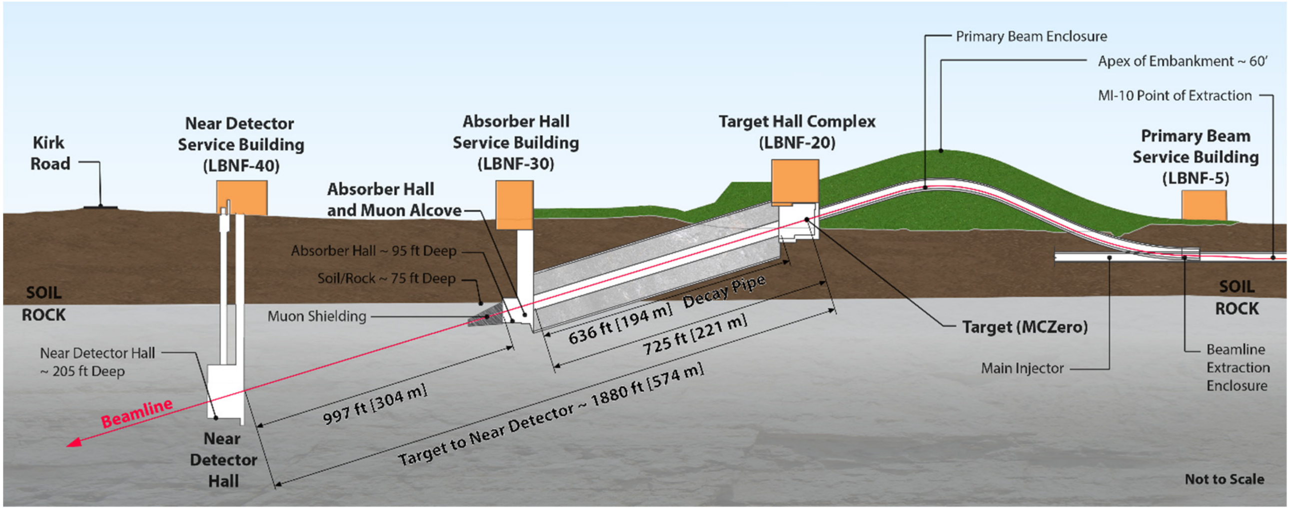

Figure 1: Longitudinal section of the LBNF beamline facility at Fermilab. The beam comes from the right, the protons being extracted from the MI-10 straight section of the MI.

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 over a man-made embankment/hill whose apex is at 18.3 m above ground and with a footprint of ~21,400 m^2. At the top of the hill the beam then will be bent downward toward a target located at grade level. The overall bend of the proton beam is 5.8^o 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. 1).

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 kicker, Lambertson, C, dipole, quadrupole and corrector magnets (see Fig. 2).

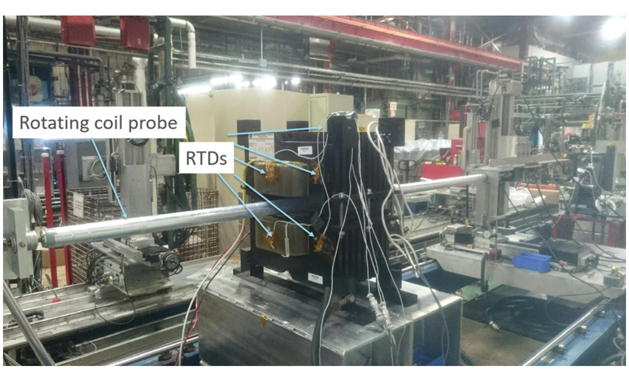

Figure 2: The LBNF corrector magnet prototype, manufactured at IHEP/China, on a test stand at Fermilab.

The primary beamline elements are connected by vacuum pipes and beam monitoring equipment (Beam-Position Monitors, Beam-Loss Monitors, Beam-Profile Monitors, and Beam-Intensity Monitors). The magnets (79 in total) are conventional electromagnets using existing or similar to existing designs. The magnet power supplies are a mixture of new power supplies of existing design and refurbished Tevatron power supplies. The beam optics accommodates a range of spot sizes on the target (1-4 mm RMS) 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) three magnetic horns. The LBNF horns operate at higher current and lower pulse width compared to NuMI [2]. These elements are all located inside a heavily shielded, nitrogen-filled, nitrogen/water-cooled vault, called the target chase (see Fig. 3), that is isolated from the decay pipe at its downstream end by a replaceable, thin, metallic window. A 194 m long, 4 m in diameter helium-filled, nitrogen-cooled decay pipe follows the chase and within it pions and kaons decay to neutrinos. The nitrogen cooling lines are visible in Fig. 3. Downstream of the decay pipe is the hadron absorber which must contain the energy of the particles that exit the decay pipe. The absorber core consists of replaceable aluminium and steel water-cooled blocks. Outside of the core we have steel and concrete shielding that is cooled by forced-air. Approximately 52% of the beam power is deposited in the target chase components and surrounding shielding, 23% in the decay pipe, and 17% in the absorber.

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.

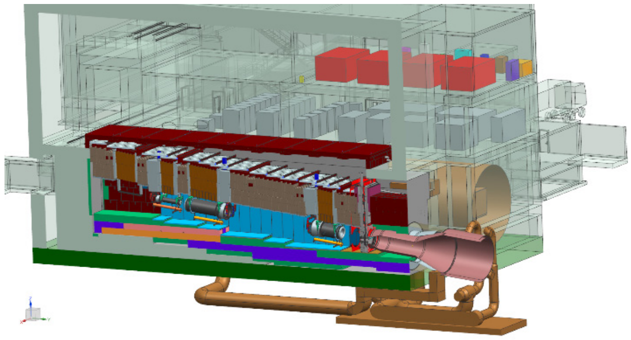

Figure 3: Schematic of the upstream portion of the LBNF neutrino beamline showing its major components. Inside the chase, from left to right, one can see the horn-protection baffle, the target, fully inserted into the first horn, and the three focusing horns. The decay pipe follows. The beam comes from the left.

The Optimized LBNF Target and Horns

Efforts to increase the physics reach of DUNE by optimizing the target and horn designs for maximal CP violation sensitivity were recently completed, resulting on a four-interaction length target and three focusing magnetic horns in series. The optimized LBNF target is a 2.2 m long graphite cylinder, approximately four interaction lengths, and 16 mm in diameter. It is fully inserted into the first horn's inner conductor and it is fully helium cooled (see Fig. 4). Containment of the target core material is provided by a fully welded structure comprising a titanium manifold, titanium alloy upstream and downstream beam windows and a titanium outer containment tube. Given the length of the target, it has to be supported at the downstream end and at the same time actively cooled. The horns' inner conductors consist of cylindrical and conical shape sections and can be operated at 300 kA. The conductor lengths are 2.2 m, 3.9 m and 2.2 m for horns A, B and C respectively. The horns are water cooled and the diameters of their outer conductors vary between 0.44 and 1.3 m. The LBNF horn power supply current pulse width will be 0.8 ms.

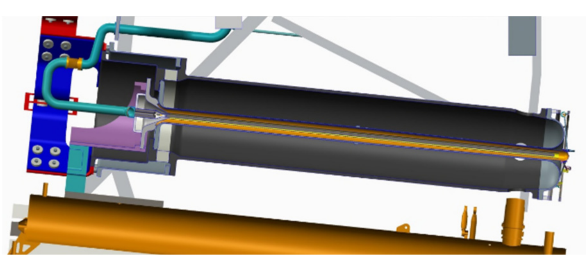

Figure 4: The optimized LBNF target mounted into the first horn. The proton beam comes from the left. The helium supply line is shown in light blue.

Assuming 120 GeV protons, Fig. 5 shows the un-oscillated ν_μ flux for the recently optimized beam design which is now the LBNF default design. We note that with the optimized configuration the neutrino flux is increased by 36% near the first oscillation maximum and by a factor of two near the second oscillation maximum in comparison with the CD-1 design.

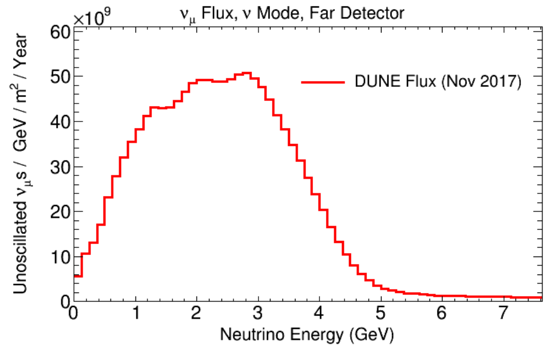

Figure 5: Neutrino mode flux of muon neutrinos as a function of neutrino energy for the recently optimized beam design.

CONCLUSION

We described above the conceptual design of the LBNF/DUNE beamline, optimized recently further for the physics. We are now in the process of advancing this design toward baselining (CD-2) which is expected by the end of 2019.

ACKNOWLEDGMENTS

We would like to thank all the members of the LBNF beamline team for their numerous contributions towards developing and costing the beamline conceptual design and advancing it in all areas towards baselining. We also thank the LBNF beam simulation and physics groups for detailed studies on the neutrino fluxes.

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