LBNF Neutrino Beam*

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Abstract

The Long-Baseline Neutrino Facility will provide a high-power, broad band, tuneable neutrino beam at Fermilab to illuminate the Deep Underground Neutrino Experiment's liquid argon detector at the Sanford Underground Research Facility 1,300 km from Fermilab and near detector on the Fermilab site. The reference design uses a NuMI-type target-horn system, and a 194 m long, 4 m diameter, helium-filled decay pipe. The system is designed to accommodate a 1.2 MW beam from the Fermilab Main Injector, and all components which cannot be replaced later are designed for 2.4 MW. Studies are under way which hold the promise to improve the neutrino flux spectrum and substantially increase the reach for determination of CP violation and the neutrino mass ordering.

INTRODUCTION

The Long-Baseline Neutrino Facility (LBNF) will enable a world-leading experimental program[1, 2] in neutrino physics, nucleon decay and astroparticle physics to be carried out by the DUNE Collaboration[3]. LBNF[4] comprises: 1) Underground and surface facilities at the Sanford Underground Research Facility (SURF) capable of hosting a modular LAr TPC of fiducial mass $\geq$40 kt ($\sim$70 kt liquid mass)[5], to be built and operated by the DUNE Collaboration; 2) Cryostats, refrigeration and purification systems to operate the detectors; 3) A high-power, broad-band, tunable, sign-selected neutrino beam at Fermilab; and 4) Underground and surface facilities to host the DUNE near detector[5]. LBNF is a DOE/Fermilab hosted project with international participation. DUNE is a fully-international collaboration with members from 26 countries on five continents.

The LBNF neutrino beam will be driven by the proton beam from the Fermilab Main Injector. In parallel with the construction of LBNF, the PIP-II upgrade[6] of the Fermilab accelerator complex will increase the proton beam power for neutrinos up to 1.2 MW, and allow >1 MW operation for proton beam energies between 60 and 120 GeV. The LBNF beamline is designed to accommodate potential future upgrades to 2.4 MW. Figure 1 summarizes the beam-power parameters to which LBNF is designed.

Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 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

FIG. 1: Main Injector beam-power related parameters with the PIP-II upgrade (top half) and a possible doubling of beam power beyond PIP-II (bottom half).

THE LBNF BEAM DESIGN

The LBNF neutrino beam is driven by protons from the Fermilab Main Injector (MI). Figure 2 shows the layout of the beamline on the Fermilab site. The proton beam is extracted at MI-10, directed up and over a man-made embankment, and then directed downward at a 10% slope towards SURF. The proton beam strikes a target, which produces a shower of secondary particle which are focused by a two-horn system. The secondary particles enter a 194 m long, 4 m diameter decay pipe in which pions and kaons decay to produce the neutrino beam. An absorber at the end of the decay pipe removes un-decayed mesons and protons that are transmitted by the target. Muons range out in the rock downstream of the absorber. With the primary beamline on an embankment, the target hall complex is placed at grade level, easing access and situating this high-radiation environment well above the aquifer. The decay pipe is mainly in glacial till and enters bedrock only at the downstream end, making for more economical construction than in a deeper design.

The target hall complex, including the target-horn system and upstream end of the decay pipe is shown in Fig. 3. The reference beam design uses NuMI-type horns and a NuMI-like target and baffle system[7]. The target chase is longer and wider than is necessary to accommodate the reference design shown, to allow for more advanced target-horn systems which can increase the neutrino flux substantially, as discussed below.

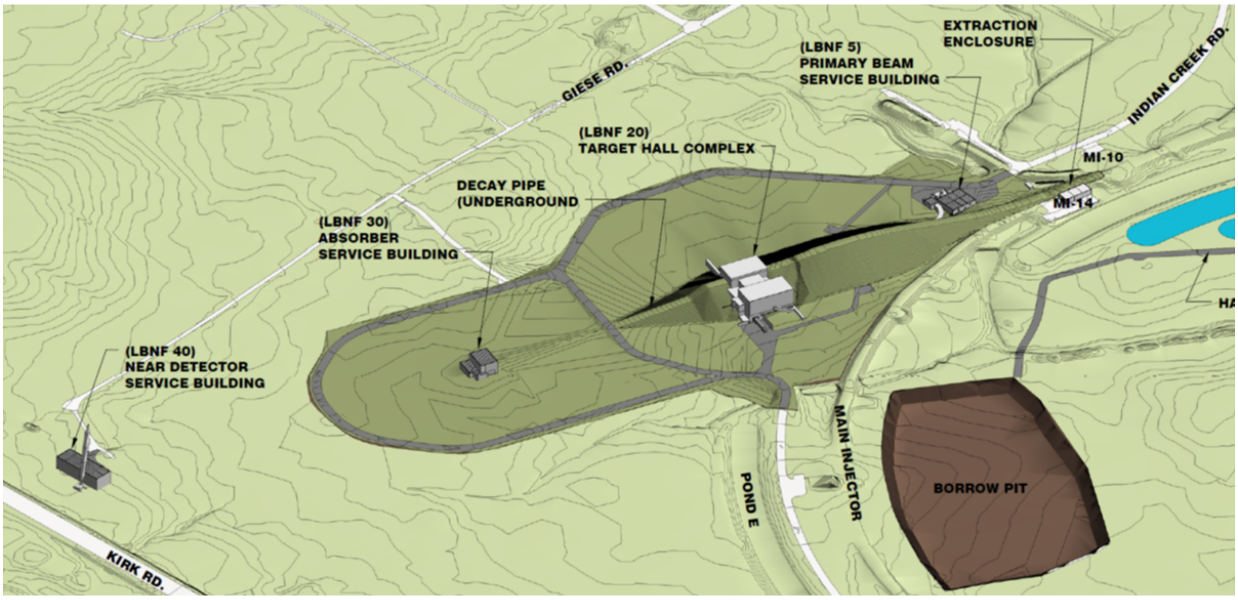

FIG. 2: Overview of the LBNF beamline on the Fermilab site.

The LBNF beamline utilizes a segmented graphite target, very similar to the NuMI design. However, the width of the rectangular target has been increased from 7.4 mm to 10 mm to accommodate the larger beam size that is necessary to allow the target to survive the higher power 1.2 MW beam and the number of cooling tubes has been doubled. A transverse section of the LBNF Target is shown in Fig. 4.

Figure 5 is a longitudinal section of the first horn, showing the placement of the target. The LBNF horn conductors are identical to the NuMI design, but they will be operated at a higher current of 230 kA to increase the neutrino flux. A new power supply is required to generate a narrower 0.8 ms pulse to compensate for the greater beam heating and higher peak current. The spacing between the two horns is 6.6 m from the upstream end of horn 1 to that of horn 2 (see Fig 3), which is set to maximize the flux at the first oscillation maximum ($\sim$2.4 GeV) and to the extent possible at the second maximum.

The target chase is air filled and cooled by a combination of air and water. The decay pipe is helium filled, requiring a thin window between the two environments. This window is mounted on the upstream end of a reduced-diameter "snout" at the upstream end of the decay pipe, as shown in Fig. 3, and is designed to be replaceable using remote handling techniques. The decay pipe is a closed, helium-filled volume which is cooled by air flowing through an annular gap between an inner and outer pipe, as shown in Fig. 6. The cooling air is returned in a closed loop through four smaller pipes placed just outside the decay pipe

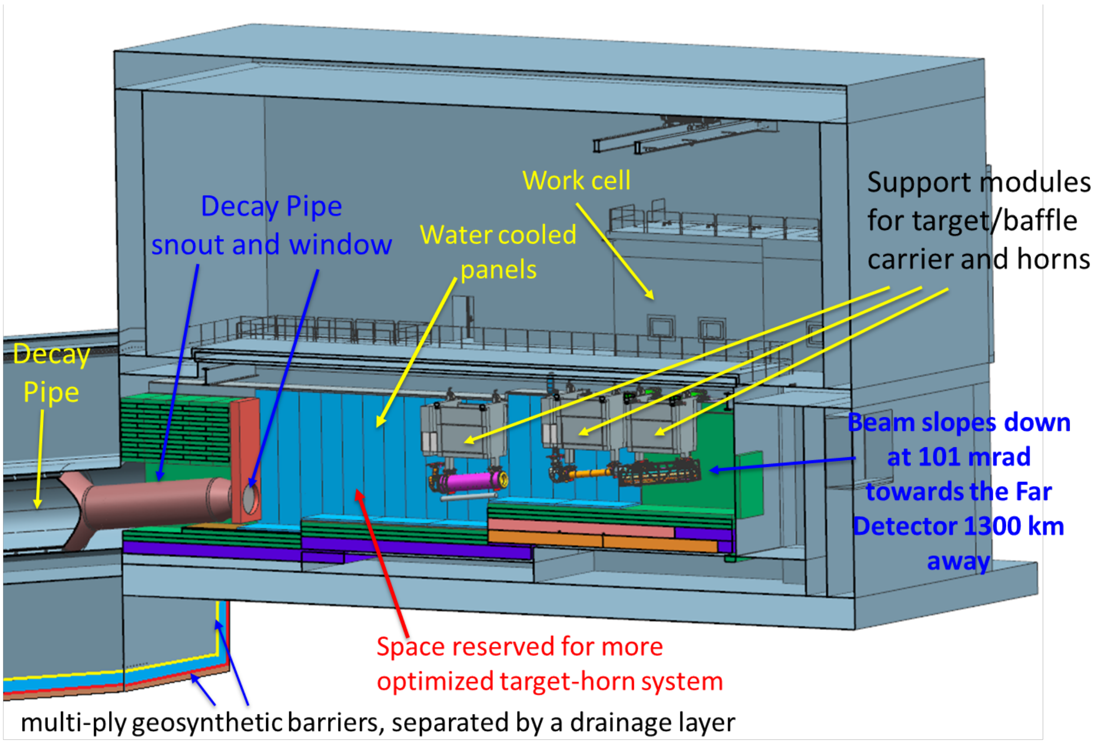

FIG. 3: The LBNF neutrino beamline target hall and upstream end of the decay pipe.

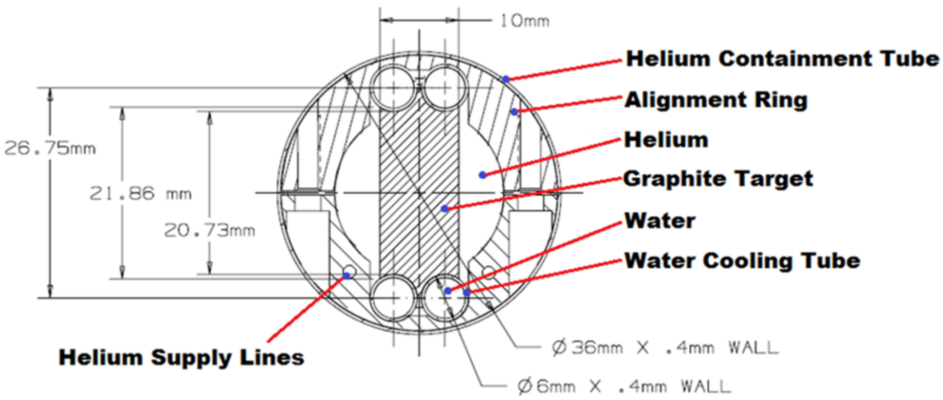

FIG. 4: Cross-section of the LBNF target.

itself. The decay pipe is surrounded by massive concrete shielding with a minimum radial thickness of 5.6 m, to accommodate up to a 2.4 MW beam. The shielding is surrounded by a water-proof geomembrane system to keep the concrete dry and separated from ground water. Beam heat is intercepted by a set of air cooling tubes, as indicated in Fig. 6, to maintain the geomembrane at an acceptable temperature even with a 2.4 MW beam.

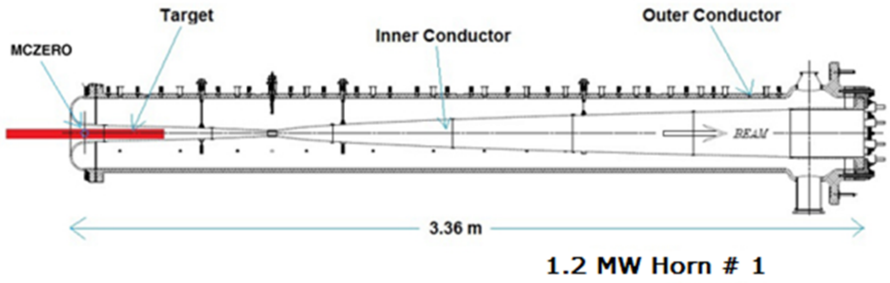

FIG. 5: The reference design horn 1 and target.

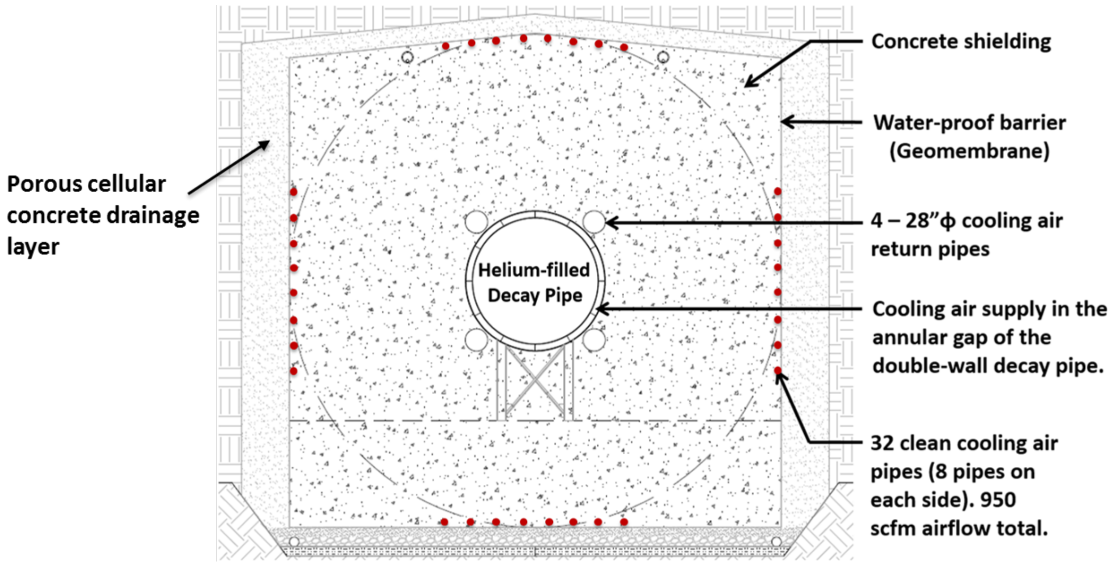

FIG. 6: Cross-section of the LBNF decay pipe.

Almost one-third of the proton beam power is deposited in the absorber. In addition, the absorber must be able to handle an accident condition in which two pulses of the full proton beam hit it. The absorber is made with a core of replaceable water-cooled aluminum blocks, surrounded by forced-air cooled steel and concrete shielding. A "spoiler" and sculpted aluminum blocks in the upstream part of the absorber serve to lower the average density and spread the showers transversely to reduce the peak average power density and peak energy density in an accident. Extensive MARS modeling has been done to validate the design. This modeling revealed that the muon plume downstream of the absorber is sufficiently intense at high beam power as to be a concern for groundwater activation. To protect the groundwater, a 30 m long steel absorber ("kern") is placed downstream of the absorber hall. It, together with the absorber hall itself, are surrounded by the same geomembrane system

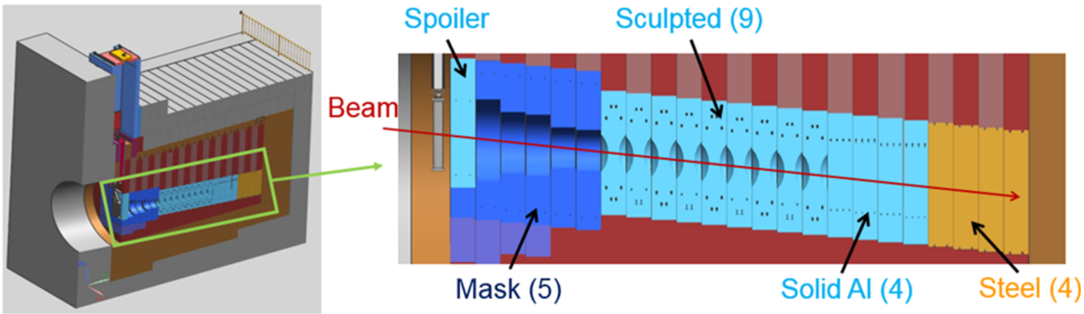

FIG. 7: The LBNF beam absorber.

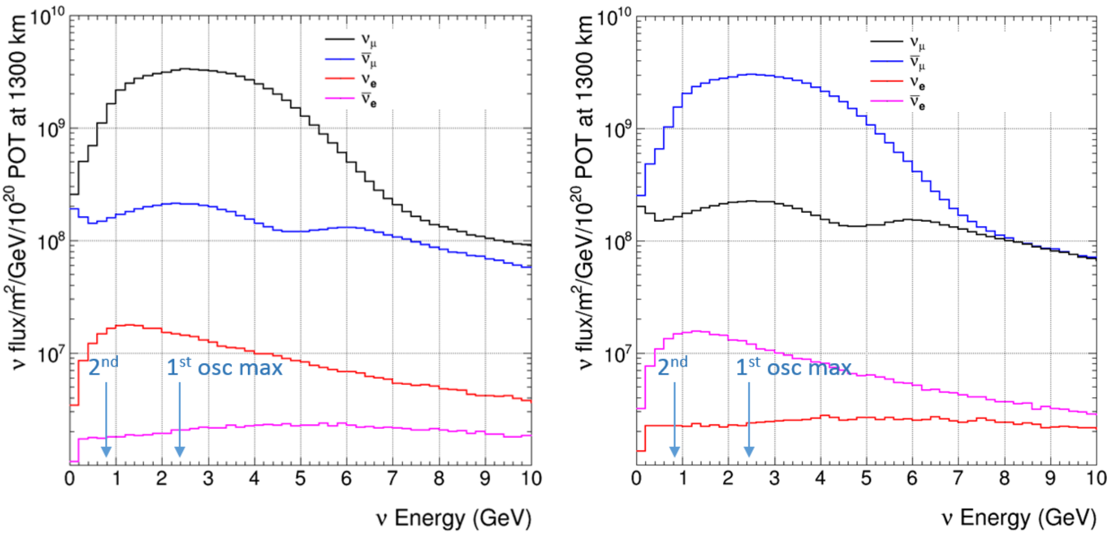

FIG. 8: Neutrino spectra for the reference beam design for positive horn current (left) and negative horn current (right).

used to separate the decay pipe from the groundwater.

All components of the neutrino beamline are designed to accommodate a 1.2 MW beam at 120 GeV. Those parts which cannot practically be changed later are designed for 2.4 MW. These include: the sizes and the shielding of all enclosures; the primary beamline components; the decay pipe shielding, cooling system and downstream window; the beam absorber; remote handling equipment; and the radioactive water system piping.

The neutrino spectra generated by the reference beam configuration are shown in Fig. 8. The ν_μ spectrum peaks near the first oscillation maximum. At the second maximum, the flux is about 1/3 that at the peak and coupled with the lower cross-section at lower energy, the event rate at the second maximum is expected to be about 10% that at the first maximum.

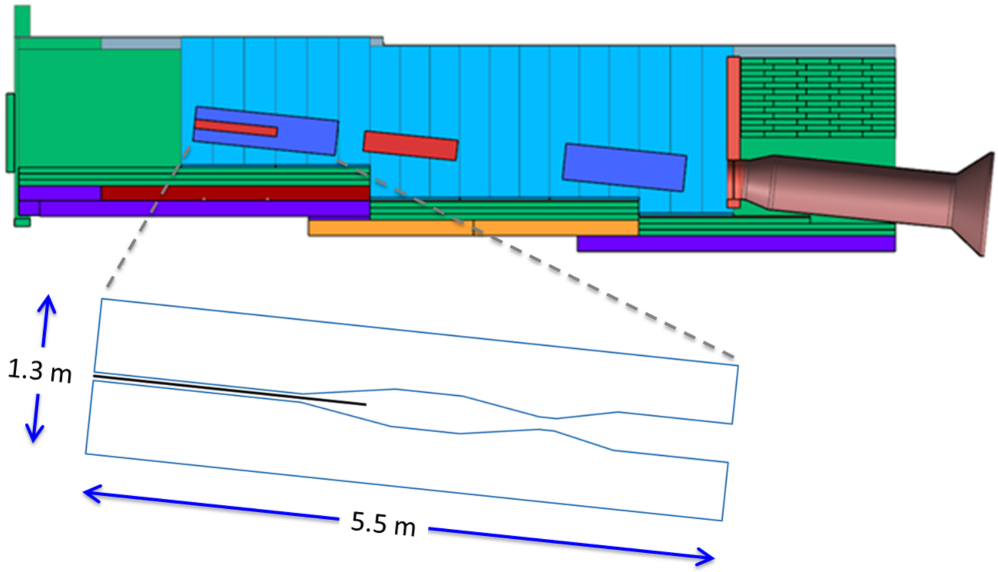

FIG. 9: The optimized target-horn system in the LBNF target chase. The red rectangles indicate the size and positions of the two reference design horns; the blue rectangles show the optimized horn system. The shape and size of the first horn is indicated in the lower part of the figure.

OPTIMIZATION OF THE BEAM DESIGN

A number of studies have been done to improve the spectrum to increase CP violation and mass hierarchy sensitivity. These include varying the proton beam energy, the horn currents, the decay pipe dimensions, and the target material, dimensions and position. Following work done in the LAGUNA-LBNO Design Study[8], a genetic algorithm has been used to optimize the dimensions of a horn 1 with a new shape and a horn 2 of the NuMI shape but with the length and radial dimensions independently varied. The spacing between the horns and the target position, length and diameter were also varied. The algorithm optimized the system parameters to maximize the minimum significance for CP violation determination ($\sqrt{\Delta\chi^2}$) over 75% of the range of δ_{CP}. This optimization favors a more complex shape for horn 1, substantially longer and larger diameter horns (e.g. horn 1 goes from 3.4 m to 5.5 m long), and a longer target ($2\lambda \rightarrow 5\lambda$), as shown in Fig. 9.

The ν_μ spectrum generated by this beam design is compared with the reference design as well as several other configurations in Fig. 10. The "Enhanced Reference" design uses the reference design (NuMI) horns, but with a thinner, shorter cylindrical beryllium target placed 25 cm upstream of horn 1. The effect of varying the decay pipe length and diameter

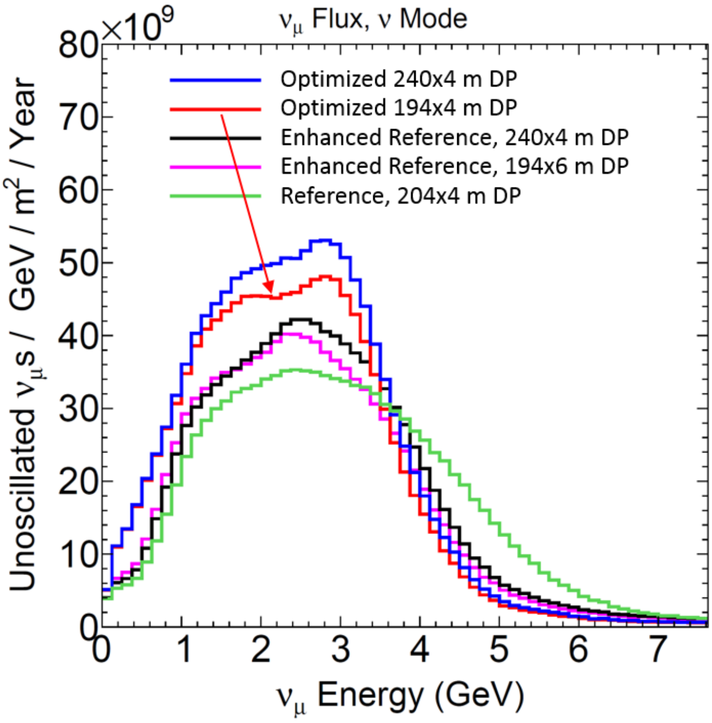

FIG. 10: Comparison of the optimized neutrino flux spectrum with the reference design and several other configurations.

are also shown. An 80 GeV proton beam is assumed in all cases. The optimized design utilizing the reference decay pipe dimensions gives about 30% more flux at the first oscillation maximum and almost 100% more flux at the second maximum. It also reduces the high-energy tail, which contributes little to the ν_e appearance signal but does contribute to the background from neutral current and ν_τ appearance events. The optimized beam reduces the time necessary to achieve a given sensitivity for CP violation or mass hierarchy determination by 30-40% as presented in [9].

Further work is required on optimization of the target-horn system. Engineering is needed to determine the feasibility of the horn designs chosen by the genetic algorithm. The physics impact of splitting the complex horn 1 design from the genetic algorithm into two closely-spaced horns is being evaluated. The phase space for horn design should be more broadly considered, including other evaluation criteria, e.g. ν_τ appearance. Alternate designs and materials for the target could be explored. R&D is required to develop designs that will work at 2.4 MW.

SUMMARY

The LBNF neutrino beam design is well developed and is based on designs and experience with the NuMI neutrino beam. All systems are designed for up to 1.2 MW operation with proton beam energy between 60 and 120 GeV, and systems that cannot be replaced later are designed for 2.4 MW. Initial studies show that a more optimized target-horn system can have a big impact on the physics reach of DUNE, and there may be room for further improvement.

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