Status of Fermilab's Neutrino Facilities

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Abstract

Fermilab is the only laboratory in the world that operates two accelerator-based neutrino beams simultaneously. These intense neutrino sources enable an important collection of experiments that are studying neutrinos over both short and long distances, allowing the experiments to address questions such as the neutrino mass ordering, whether additional (sterile) neutrinos exist, and whether neutrinos violate matter-antimatter (CP) symmetry. The 8 GeV protons from the Booster are supplied to the Booster Neutrino Beam (BNB), which serves ANNIE, MicroBooNE and MiniBooNE and will soon serve ICARUS and SBND. The 120 GeV proton beam from the Main Injector supports neutrino experiments at NuMI (MINERvA and NOvA) and will support the Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) in the future.

The NOvA experiment explores the details of neutrino flavor transformation. DUNE will push beyond the precision achievable by NOvA in a new beamline created as part of the LBNF and powered by the Proton Improvement Plan II (PIP-II) accelerator upgrades. MINERvA, scheduled to cease data taking in 2019, enables these measurements with precision measurements of neutrino interactions with various nuclear targets. The Short Baseline Neutrino (SBN) Program on the low-energy BNB is designed to definitively address the question of sterile neutrinos through a suite of three experiments: MicroBooNE, that began operating with beam in 2015; ICARUS, that will begin operating in 2019; and SBND, the Short-Baseline Near Detector that will follow in 2020. Experience with these liquid argon detectors will also inform the future flagship international LBNF/DUNE program.

1 Current Long-Baseline Facilities

NOvA is the current flagship operating experiment at Fermilab. As it is expected to run until the start of the long shutdown planned for beamline construction of LBNF, it will be producing new neutrino oscillation results past the middle of the coming decade. It uses the NuMI beam of 120 GeV protons, which since 2017, has routinely operated at 700 kW, and for which there are plans to further increase the beam power. The NOvA experiment is in the midst of its multi-year program to study some of the most important remaining questions related to the physics of neutrino mass and flavor by studying neutrino oscillations over a baseline of 810 km, using two detectors and an intense, narrow-band off-axis beam of predominantly muon neutrinos or antineutrinos peaked near 2 GeV in energy. The NOvA Far Detector, located in Ash River, MN, is a 14 kton liquid scintillator tracking calorimeter. The NOvA Near Detector is a 300 ton functionally identical version of the

Far Detector, with the addition of a muon range stack at the downstream end. It is located at Fermilab in Batavia, IL, 1 km from the NuMI target and 100 m underground.

Measurements by NOvA can resolve the neutrino mass ordering, the relative contribution of tau and muon flavor to the third neutrino mass state (parameterized by θ_{23}), shed light on whether CP-symmetry is violated in the lepton sector, and search for phenomena not explicable within a 3-flavor neutrino mixing framework. In addition, to neutrino oscillation physics, the high intensity, narrow energy spectrum, and high flavor purity of the beam at the near detector presents unique neutrino cross section measurement opportunities, and both detectors present unique opportunities for searches for exotic phenomena.

Several factors are anticipated to extend the reach of NOvA well beyond the projections of the NOvA Technical Design Report [1]. Opportunities exist to increase the power available to the NuMI beam from above 700 kW in 2019 to 900 kW by 2021. Fermilab accelerator operations team is currently considering a campaign aimed at increasing the NuMI beam power to the 0.9-1 MW level without major changes to the existing accelerator complex. The campaign will be finished prior to the construction of the Proton Improvement Plan-II linear accelerator [2] and includes upgrades of the NuMI target station to be robust up to 1 MW, a series of improvements to reduce losses in the Booster increasing the number of protons per pulse by 30%, increasing the Booster rate from 15 Hz to 20 Hz, and corresponding Main Injector modifications to allow a faster 1.1 s cycle [2].

With the current NuMI beam performance and analysis techniques, and for favorable parameters consistent with current results, NOvA expects to have sensitivity to the mass hierarchy at 3σ as early as 2020 in the most favorable physics scenario, and 3σ sensitivity over 30-50% of the δ_{CP} range by 2024. With the planned P.O.T. improvements NOvA can achieve greater than 5σ for favorable cases.

Although NOvA is a mature collaboration, it continues to build on its successes with ongoing improvements to both operations and analysis aimed at enhancing its ultimate sensitivity. Effort from additional European groups in NOvA operations, analysis support, and physics analysis, would help ensure timely delivery of the highest quality physics results and would be welcome. The experiment also provides an excellent opportunity for European groups to develop experience with operations and analysis on a running long-baseline oscillation experiment, that will be directly transferable to DUNE.

2 Future Long-Baseline Program

The Long Baseline Neutrino Experiment (LBNF) collaboration includes two main parts: LBNF and DUNE [3], following the model of the detectors at the LHC. LBNF is a U.S.-led project, hosted by Fermilab, with international partners; it encompasses the beam and the conventional facilities at the Near and Far detector sites, including construction and operation. DUNE is an international collaboration that will build the neutrino detectors sited both at Fermilab and at SURF. DUNE will be the flagship domestic experiment of the U.S. High Energy Physics program in the next decade and is a top Particle Physics Project Prioritization Panel (P5) priority. DUNE will measure the extent to which CP is violated in the neutrino sector, make a comprehensive investigation of the three-neutrino mixing scheme, search for proton decay, as well as, for neutrinos from supernovae.

The DUNE experiment will consist of two detectors, a Far Detector located in the Sanford Underground Research Facility (SURF) near Lead, South Dakota, 1300 km away from Fermilab, and a Near Detector complex located on site at Fermilab, Batavia, IL. The experiment will use a wide-band neutrino beam from Fermilab, constructed as part of the LBNF. This LBNF wide-band beam requires a series of undertaken and planned upgrades of the FNAL accelerator complex. These upgrades, the PIP-II project, will achieve multi-MW proton beam power. It requires replacing the existing 400 MeV Linac with a modern 800 MeV superconducting RF Linac. The initial beam power will be 1.2 MW of 120 GeV protons, based upon the existing performance of the Fermilab accelerators, and anticipated intensity improvements from the PIP-II Project.

The energy of the proton beam can be reduced, if physics optimization requires, but beam power suffers. For 80 GeV protons, the beam power is about 10% less, and for 60 GeV protons the beam power is about 15% reduced. Below 60 GeV the beam power is approximately linear with beam energy. Future upgrades of the Fermilab accelerator complex, PIP-III, are under study with a central goal of being able to deliver in excess of 2 MW of protons to the LBNF beamline in the early-mid 2030s. PIP-III project requires replacing the existing 8 GeV Booster [2]. The LBNF facility will be built to accommodate this higher beam power, but several in-beam devices may need to be replaced at the time of the upgrade, such as the windows, target, or horns.

The DUNE Far Detector will consist of four similar liquid argon (LAr) TPC 10-kiloton fiducial-mass modules placed 4850 ft underground in the Homestake Mine, SD, as depicted in Figure 1. The underground location for the Far Detector will enable a suite of non-accelerator-based measurements using atmospheric neutrinos, searches for neutrinos from supernovae, and searches for proton decay. The use of the LArTPC technology provides many advantages, it enables excellent tracking and calorimetry. The first module is assumed to use Single-Phase technology and the second Dual-Phase technology [4]. The Far Detector complex is being constructed to contain space and support for additional third and fourth modules which provide opportunities for novel detector ideas to be implemented and for new collaboration. Collaboration from European groups on these modules will provide opportunities for new ideas to maximize the physics output of DUNE. The milestones, as stated in the Interim Design Report [4], are to start the main cavern excavation in South Dakota in 2019, to start the installation of the first Far Detector module in 2022, and to have the beam operational with two Far Detector modules in 2026. It is expected for the first of the two detectors to be operational before beam, with the second and third modules completed one and two years later, respectively. The Technical Design Report is currently being written and is scheduled to be released in 2019.

The DUNE Near Detector complex, situated at approximately 575 m from the neutrino production target, will be home to a suite of detectors that are critical to fulfilling the physics goals of DUNE. The Near Detectors are responsible for characterizing the muon neutrino beam at the production site by measuring the rates and types of interactions occurring before any of the neutrinos have oscillated. The Near Detector suite is currently planned to consist of a modular liquid argon time projection chamber as the most upstream component, followed by a multi-purpose detector (MPD) made up of a high-pressure gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL), both within a magnetic field to provide charge-sign discrimination of tracks exiting the LArTPC. In addition, a magnetized 3-dimensional scintillator tracker (3DST) will supplement the MPD, providing both high-statistics measurements of the neutrino flux, and a bridge to compare neutrino cross section measurements on carbon and argon. The DUNE Near Detector suite is designed with a novel capability, the DUNE-Prism concept, which will enable measurements of the near site neutrino flux at different off-axis angles by moving the detectors location in the hall.

The Near Detector hall and conventional facilities are designed with the DUNE-Prism concept in mind. The detector hall will extend in a direction transverse to the beam, allowing the Near

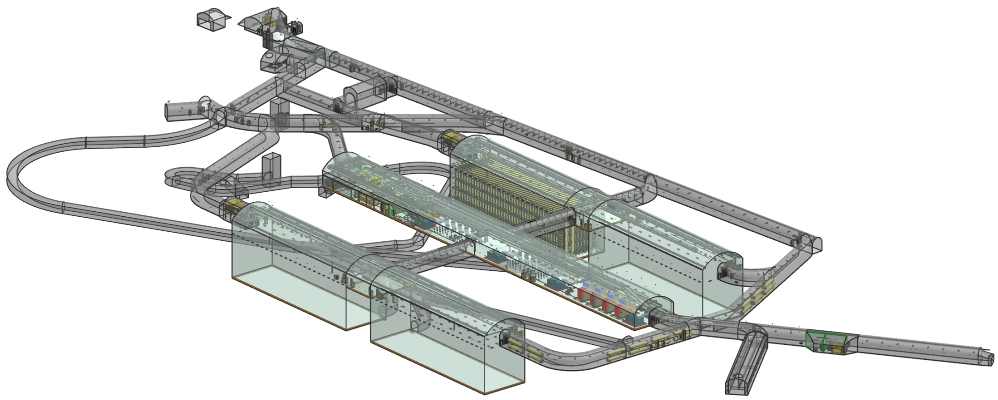

Figure 1: Schematic of the four caverns and cryogenic systems for the four DUNE Far Detector Modules, at SURF.

Detector to be moved within the hall. The full designs of the hall and the detectors are in progress. A conceptual design report (CDR) for the Near Detector suite will be completed in 2019, with a technical design report planned for the following year. The Near Detector hall and detectors are planned to be completed by 2026, when the DUNE/LBNF neutrino beam will be operational. A schematic of the proposed location of the DUNE Near Detector and beamline is shown in Figure 2. The details of DUNE Near Detector complex and the halls it will be location in are still being discussed enabling opportunities for additional and future collaboration on the currently planned detectors or additional detectors.

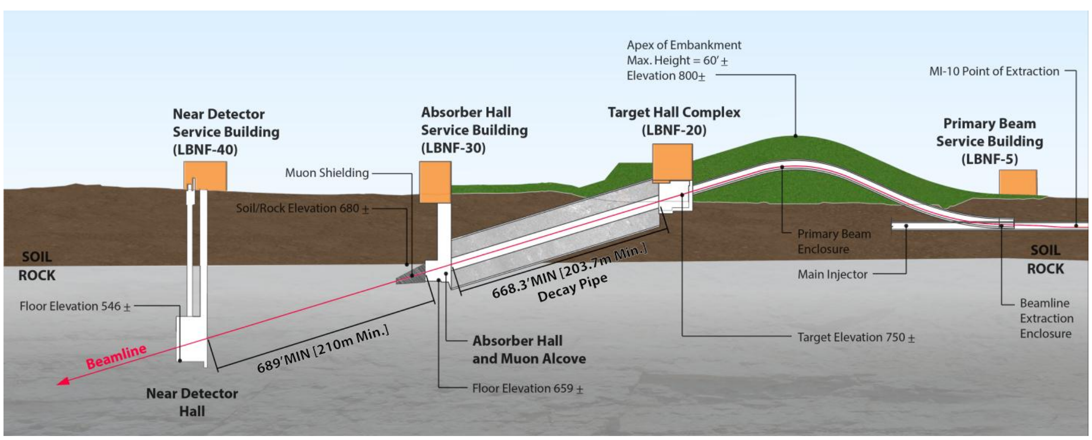

Figure 2: Schematic of the proposed location of the DUNE Near Detector complex and beamline. Showing the location of the target and absorber halls and the primary beam building.

Current sensitivity predictions are that DUNE will provide a 5σ measurement of 50% of δ_{cp} values after 9 years of data taking and complete coverage of the mass hierarchy at 5σ after 6 years. DUNE will also provide the most stringent test of the PMNS oscillation matrix formalism to date. Along with these neutrino measurements, DUNE will also serve as an important platform for supernova observation and nucleon decay measurements.

3 Current Short-Baseline Facilities

The 8 GeV protons from the Booster are supplied to the BNB, which serves ANNIE, MITPC, MicroBooNE and MiniBooNE and will soon serve ICARUS and SBND. The BNB produces neutrinos with $\langle E_\nu \rangle \approx 700$ MeV, with standard operations significantly higher than 60×10^{15} protons/hour. The BNB serves a wide range of experiments and there is opportunities for additional experiments to utilize this beam.

The SBN Program is the primary users of the BNB and has the primary goal to address the question of whether sterile neutrinos at the eV mass-scale exist, and if they do, to measure their oscillation parameters. The P5 specifically recommended a near-term, world-leading short-baseline experimental neutrino program. Full details on the SBN are available in [5].

The three-LArTPCs, MicroBooNE, ICARUS and SBND, make up the SBN Program and operate at different baselines in the BNB: SBND, with its 112-ton active mass, is the nearest to the neutrino production target at 110 m, followed by MicroBooNE (87-ton active mass) at 470 m, and ICARUS (476-ton active mass) at 600 m. The flagship analysis of the SBN Program is the search for neutrino oscillations at high $\Delta m^2 \approx 1$ eV^2 , both in $\nu_\mu \rightarrow \nu_e$ appearance and in $\nu_\mu \rightarrow \nu_x$ disappearance channels. The SBN Program will also measure neutrino-argon cross sections, using the well-characterized neutrino fluxes of the BNB, especially with the millions of interactions expected in SBND. The ICARUS and MircoBooNE detectors will also record events from the off-axis flux of the NuMI neutrino beam, with higher electron neutrino content and in a energy range of direct relevence for DUNE. Finally, the SBN Program is an excellent opportunity to further develop the LArTPC technology for the future DUNE long-baseline neutrino program.

MicroBooNE began data taking in 2015, collecting 1×10^{21} P.O.T., and has been approved to continue data taking until it has collected 1.32×10^{21} P.O.T. of neutrino-mode data. ICARUS, will begin operating in 2019; and SBND, will follow in 2020. Both experiments are approved to take data until SBND has collected 6.6×10^{20} P.O.T. of neutrino-mode data.

4 Liquid Argon R&D Facilities

The suite of LAr cryostats hosted at Fermilab's Noble Liquid Detector Development Facility (called PAB for historical reasons), has created the opportunity and environment for Fermilab scientists and colleagues from other institutions to coordinate the further developments of LAr detectors, sharing ideas and results, and avoiding redundant efforts. This LAr R&D program will continue to support near- and longer-term LAr experiments looking forward, and the goal is to maintain the flexible nature of the facility to adapt to R&D needs as they arise. This includes both the ongoing efforts and the opportunity for new collaboration researching LAr properties and in test beam experiments.

The new Integrated Engineering Research Center (IERC) is planned to be completed by 2022, providing additional space for LAr R&D activities and expanding the opportunities for European collaboration. Another dedicated lab space in IERC will be used for testing and assembly of the sub-detectors that will make up the DUNE Near Detector. The current R&D is aimed towards optimizing DUNE with the goal of finalizing and improving the LArTPC technology planned to be used in both the Near and the Far Detectors, as well as developing or optimizing additional technologies for the Near Detector. For the Near Detector, in addition to the LArTPC work, R&D is ongoing in a magnetized high-pressure gas TPC with a 3D scintillating tracker. The R&D aimed towards optimizing DUNE is a global effort and additional European collaboration on the facilities available at Fermilab is welcome and to develop European partnerships to enable collaboration/coordination with the CERN neutrino platform.

5 Fermilab Neutrino Facilities Possibilities Beyond 2026

5.1 Alternative LBNF Beamline Configurations

The DUNE experiment can be used to look for tau neutrino appearance. The neutrino flux has been optimized below 5 eV for the CP-phase measurement, for the tau neutrino appearance search the higher energy part of the spectrum is important, as the cross section for tau neutrino charged current interactions becomes significant above 5 GeV. After its planned run, the LBNF beamline could be modified to produce a higher energy spectrum by modifying the relative position of the target and horns, and using NuMI style parabolic horns. This alternative configuration has been shown to provide a significant increase in expected tau neutrino interactions and better sensitivity to tau neutrino appearance. Studies into modified and re-optimized beams are ongoing, enabling opportunities for additional and expanded collaboration, both in studies in future optimization and in areas such as target design and material radiation damage.

5.2 Expanding LArTPC Capabilities

The LAr R&D program at Fermilab is working to enhance the LArTPC technology beyond current technological limitations. The Fermilab provided LAr R&D facilities are currently used by collaborators from 50 labs and institutions, including 10 European institutions and labs. The current and ongoing work has concentrated on several areas including: high voltage instabilities, improvement of scintillation light collection systems, enhancement of charge readout, bringing all electronic stages into the cold volume, and optimization and simplification of the LAr purification system. Such a program should enable these detectors to push towards lowering the energy threshold of existing detectors for searches of supernovae neutrinos, solar neutrinos, coherent neutrino scattering processes, or searches for non-standard interactions.

This program enables many ongoing and future opportunities for European institutions to utilize the facilities or test beams at Fermilab to study and develop future LArTPC R&D enhancements and we welcome additional collaboration from the European community especially given the substantial expertise in many areas including: dual-phase LArTPC technology, pixel readout, laser calibrations, and cryostat construction.

5.3 Future Sterile Neutrino Exploration

With the possibility of discovery of sterile neutrino, Fermilab has a unique set of neutrino beams providing opportunities to explore this new landscape with existing or new facilities. New possible research directions are very flexible if the SBN program observes a signal, this would enable excellent opportunities for European groups to develop proposals for subsequent experiments to precisely map out the sterile sector.

6 Summary and Conclusions

Fermilab currently operates two accelerator-based neutrino beams simultaneously. The 8 GeV Booster Neutrino Beam which serves ANNIE, MicroBooNE, and MiniBooNE and will soon serve ICARUS and SBND, and the 120 GeV proton beam from the Main Injector which supports neutrino experiments at NuMI (MINERvA and NOvA) and will support LBNF/DUNE in the future. The NuMI beam power, which since 2017 has been routine at 700 kW, has opportunities to be increased above 700 kW in 2019 to 900 kW or beyond by 2021. The future LBNF beam is designed to achieve 1.2 MW proton beam power, through the PIP-II accelerator upgrade project. There is also the opportunity for further upgrades, PIP-III, to double the beam power to 2.4 MW. In addition to the current short- and long-baseline facilities at Fermilab, the LBNF project will construct conventional facilities at the Near and Far detector sites to support the DUNE near and far detectors.

These programs all have opportunities for new or expanded European collaboration and/or partnership. For the current program these include but are not limited too: the third and forth DUNE modules; efforts on NOvA operations, analysis support, and physics analysis which in turn provide a opportunity to develop experience on a long-baseline oscillation experiment, that will be directly transferable to DUNE; efforts on LAr R&D and future test beam experiments; opportunities on the SBN Program and using the BNB facilities; efforts on the LBNF beam and its upgrades and optimization. In addition, there are opportunities for future experiments using the Fermilab facilities, for example, in the case that a light sterile neutrino is discovered, proposals for subsequent experiments to precisely map out the sterile sector.

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