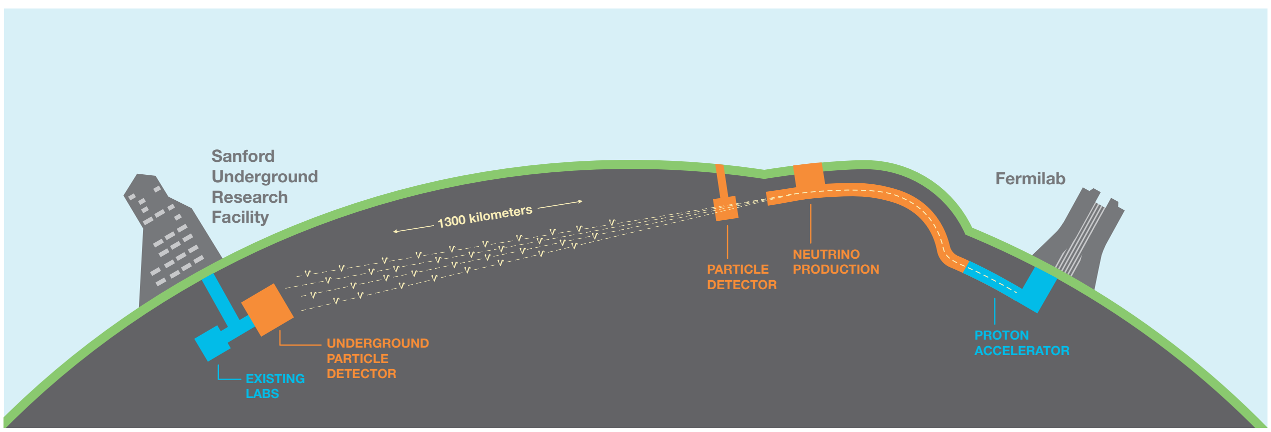
Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)

Conceptual Design Report

Volume 1: The LBNF and DUNE Projects



August 14, 2015

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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Chapter 1

Introduction to LBNF and DUNE

1.1 International Convergence

During the last decade, several independent worldwide efforts have attempted to develop paths towards a next-generation long-baseline neutrino experiment, including in the U.S. with LBNE, in Europe with LBNO and in Japan with Hyper-Kamiokande. The community has generally recognized that putting in place the conditions necessary to execute this challenging science program in a comprehensive way requires previously independent efforts to converge.

In this context, the Deep Underground Neutrino Experiment (DUNE) represents the convergence of a substantial fraction of the worldwide neutrino-physics community around the opportunity provided by the large investment planned by the U.S. Department of Energy (DOE) to support a significant expansion of the underground infrastructure at the Sanford Underground Research Facility (SURF) in South Dakota, 1300 km from Fermilab, and to create a megawatt neutrino-beam facility at Fermilab by 2026. The PIP-II accelerator upgrade [?] at Fermilab will drive the new neutrino beamline at Fermilab with a beam power[1] of up to 1.2 MW, with a planned upgrade of the accelerator complex to enable it to provide up to 2.4 MW of beam power by 2030.

This document presents the Conceptual Design Report (CDR) put forward by an international neutrino community to pursue the Deep Underground Neutrino Experiment at the Long-Baseline Neutrino Facility (LBNF/DUNE), a groundbreaking science experiment for long-baseline neutrino oscillation studies and for neutrino astrophysics and nucleon decay searches. The DUNE far detector will be a very large modular liquid argon time-projection chamber (LArTPC) located deep underground, coupled to the LBNF multi-megawatt wide-band neutrino beam. DUNE will also have a high-resolution and high-precision near detector.

The physics case for the LBNF neutrino facility was highlighted as a strategic priority in the 2014 P5 report [?]. P5 identified the following minimum requirements for LBNF to proceed: the

[1] assuming a 120 GeV primary proton beam. For a 80 GeV primary proton beam, the corresponding beam power is 1.07 MW.

identified capability to reach an exposure of at least 120 kt · MW · year [2] by the 2035 timeframe; the far detector situated underground with cavern space for expansion to at least 40-kt LAr fiducial; 1.2-MW beam power upgradable to multi-megawatt power; demonstrated capability to search for supernova bursts; and a demonstrated capability to search for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime. Furthermore, P5 identified the *goal* of a sensitivity to CP violation of better than 3σ over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. The strategy presented in this CDR meets all of these requirements.

1.2 The LBNF/DUNE Conceptual Design Report Volumes

1.2.1 A Roadmap of the CDR

The LBNF/DUNE CDR describes the proposed physics program and conceptual technical designs of the facility and detectors. At this stage, the design is still undergoing development and the CDR therefore presents a *reference design* for each element as well as any *alternative designs* that are under consideration.

The CDR is composed of four volumes and is supplemented by several annexes that provide details of the physics program and technical designs. The volumes are as follows

- Volume 1: *The LBNF and DUNE Projects* — provides an executive summary of and strategy for the experimental program and of the CDR as a whole.

- Volume 2: *The Physics Program for DUNE at LBNF* — outlines the scientific objectives and describes the physics studies that the DUNE Collaboration will undertake to address them.

- Volume 3: *The Long-Baseline Neutrino Facility for DUNE* — describes the LBNF Project, which includes design and construction of the beamline at Fermilab, the conventional facilities at both Fermilab and SURF, and the cryostat and cryogenics infrastructure required for the DUNE far detector.

- Volume 4: *The DUNE Detectors at LBNF* — describes the DUNE Project, which includes the design, construction and commissioning of the near and far detectors.

More detailed information for each of these volumes is provided in a set of annexes listed on the review website.

[2] An exposure of 1 MW.year corresponds to 1×10^{21} protons-on-target per year at 120 GeV. This includes the LBNF beamline efficiency which is estimated to be 56%.

1.2.2 About this Volume

This introductory volume of the LBNF/DUNE Conceptual Design Report provides an overview of LBNF and DUNE (Chapter **??**), including the strategy that is being developed to construct, install and commission the technical and conventional facilities in accordance with the requirements set out by the P5 report of 2014 [**?**], which, in turn, is in line with the CERN European Strategy for Particle Physics (ESPP) of 2013 [**?**]. This volume also introduces the DUNE science program (Chapter 2) and the technical designs of the facilities and the detectors (Chapter 3). It concludes with a description of the LBNF and DUNE organization and management structures (Chapter 4).

1.3 A Compelling Scientific Program

The study of the properties of neutrinos has produced many surprises, including the evidence for physics beyond the Standard Model of elementary particles and interactions. The phenomenon of neutrino flavor oscillations, whereby neutrinos can transform into a different flavor after traveling a distance, is now well established. Important conclusions that follow from these discoveries include that neutrinos have mass and that their mass eigenstates are mixtures of their flavor eigenstates.

Speculations on the origin of neutrino masses and mixings are wide-ranging. Solving the puzzle will require more precise and detailed experimental information with neutrinos and antineutrinos and with sensitivity to matter effects. With the exception of a few anomalous results, the current data can be described in terms of the three-neutrino paradigm, in which the quantum-mechanical mixing of the three mass eigenstates produces the three known neutrino-flavor states. The mixings are described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, a parameterization that includes a CP-violating phase.

The primary science objectives of DUNE are to carry out a comprehensive investigation of neutrino oscillations to test CP violation in the lepton sector, determine the ordering of the neutrino masses, and to test the three-neutrino paradigm. By measuring *independently* the propagation of neutrinos and antineutrinos through matter, DUNE will be able to observe neutrino transitions with the precision required to determine the CP-violating phase and the neutrino mass hierarchy.

The construction of LBNF and DUNE will also enable a high-priority ancillary science program, such as very precise measurements of neutrino interactions and cross-sections, studies of nuclear effects in such interactions, measurements of the structure of nucleons, as well as precise tests of the electroweak theory. These measurements of the properties of neutrino interactions are also necessary to achieve the best sensitivities in the long-baseline neutrino oscillation program.

The DUNE far detector, consisting of four LArTPC modules located deep underground, each with a mass forty times larger than ever before built, will offer unique capabilities for addressing non-accelerator physics topics. These include measuring atmospheric neutrinos, searching for nucleon decay, and measuring astrophysical neutrinos — possibly even the neutrino burst from a core-collapse supernova. Observations of these kinds will bring new insight into these fascinating natural phenomena.

An intriguing conjecture is that of neutrino masses being related to an ultra-high-energy scale that may be associated with the unification of matter and forces. Such theories are able to describe the absence of antimatter in the universe in terms of the properties of ultra-heavy particles; they also offer an explanation of cosmological inflation in terms of the phase transitions associated with the breaking of symmetries at this ultra-high-energy scale. DUNE's capability to detect and study rare events such as nucleon decays in an unbiased and unprecedented way will allow it to probe these very high-energy scales.

Finally, further developments of LArTPC technology during the course of the DUNE far detector construction may open up the opportunity to observe very low-energy phenomena such as solar neutrinos or even the diffuse supernova neutrino flux.

1.4 Overall LBNF/DUNE Project Strategy

The LBNF/DUNE Project (the "Project") strategy presented in this CDR has been developed to meet the requirements set out in the P5 report and takes into account the recommendations of the CERN European Strategy for Particle Physics (ESPP) of 2013, which classified the long-baseline neutrino program as one of the four scientific objectives with required international infrastructure.

The Report of the Particle Physics Project Prioritization Panel (P5) states that for a long-baseline neutrino oscillation experiment, "The minimum requirements to proceed are the identified capability to reach an exposure of 120 kt $\cdot$ MW $\cdot$ year by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime." Based on the resource-loaded schedules for the reference designs of the facility (Volume 3: *The Long-Baseline Neutrino Facility for DUNE*) and the detectors (Volume 4: *The DUNE Detectors at LBNF*), the strategy presented here meets these criteria.

With the availability of space for expansion and improved access at SURF, the international DUNE Collaboration proposes to construct a deep-underground neutrino observatory based on four independent 10-kt LArTPCs at this site. The goal is the deployment of two 10-kt fiducial mass detectors in a relatively short timeframe, followed by future expansion to the full detector size as soon thereafter as possible.

Several LArTPC designs are under development by different groups worldwide, involving both single- and dual-phase readout technology. The DUNE Collaboration has the necessary scientific and technical expertise, and international participation to design and implement this exciting discovery experiment.

The Long-Baseline Neutrino Facility (LBNF) provides

- the technical and conventional facilities for a powerful 1.2-MW neutrino beam utilizing the

PIP-II upgrade of the Fermilab accelerator complex, to become operational by 2025 at the latest, and to be upgradable to 2.4 MW with the proposed PIP-III upgrade

- the civil construction (conventional facilities or CF) for the near detector systems at Fermilab
- the excavation of four underground caverns at SURF, planned to be completed by 2021 under a single contract; each cavern to be capable of housing a cryostat for a minimum 10-kt fiducial mass LArTPC
- surface, shaft, and underground infrastructure to support the outfitting of the caverns with four free-standing, steel-supported cryostats and the required cryogenics systems. The first cryostat will be available for filling, after installation of the detector components, by 2023, enabling a rapid deployment of the first two 10-kt far detector modules. The intention is to install the third and fourth cryostats as rapidly as funding will allow.

The Deep Underground Neutrino Experiment (DUNE) provides

- four massive LArTPCs, each with a fiducial mass of at least 10 kt. The division of the far detector into four equal-mass detectors provides the Project flexibility in the installation and funding (DOE vs. non-DOE); this division also mitigates risks and allows for an early and graded science return.
- the near detector systems, consisting of a high-resolution neutrino detector and the muon monitoring system that will enable the precision needed to fully exploit the statistical power of the far detector coupled to the MW-class neutrino beam

Based on the reference design described below and in Volumes 2, 3 and 4 of this CDR, the resource-loaded schedule plans for the first two 10-kt far detector modules to be operational by 2025, with first beam shortly afterward. At that time, the cavern space for all four 10-kt far detector modules will be available, allowing for an accelerated installation schedule if sufficient funding sources for the experiment can be established on an accelerated timescale.

The Project strategy described above meets the experiment's scientific objectives, reaching an exposure of 120 kt · MW · year by 2032, and potentially earlier if additional resources are identified. The P5 recommendation of sensitivity to CP violation of 3σ for 75% of $\delta_{\rm CP}$ values can be reached with an exposure of 850 kt · MW · year with an optimized beam.

1.5 The International Organization and Responsibilities

The model used by CERN for managing the construction and exploitation of the LHC and its experiments was used as a starting point for the joint management of LBNF and the experimental program. Fermilab, as the host laboratory, has the responsibility for the facilities and their operations and oversight of the experiment and its operations. Mechanisms to ensure input from and coordination among all of the funding agencies supporting the Collaboration, modelled on the

CERN Resource Review Board, have been adopted. A similar structure is employed to coordinate among funding agencies supporting the LBNF construction and operation.

The LBNF/DUNE Project will be organized as two distinct entities. The LBNF portion is funded primarily by the U.S. DOE acting on behalf of the hosting country. CERN provides in-kind contributions to the LBNF infrastructure needed for the DUNE experiment. The DUNE portion is organized as an international collaboration; it is adopting a model in which the DOE and international funding agencies share costs for the DUNE detectors.

The DUNE Collaboration is responsible for

- the definition of the scientific goals and corresponding scientific and technical requirements on the detector systems and neutrino beamline
- the design, construction, commissioning and operation of the detectors
- the scientific research program conducted with the DUNE detectors

The high-intensity proton source at Fermilab that will drive the long-baseline neutrino beam utilizes the existing Main Injector with upgraded injectors (PIP-II). PIP-II is also being planned with significant international collaboration. Fermilab, working with the participation and support of international partners, is responsible for LBNF, including

- design, construction and operation of the LBNF beamline, including the primary proton beamline and the neutrino beamline including target, focusing structure (horns), decay pipe, absorber, and corresponding beam instrumentation
- design, construction and operation of the CF and experiment infrastructure on the Fermilab site required for the near detector system
- design, construction and operation of the CF and experiment infrastructure at SURF, including the cryostats and cryogenics systems, required for the far detector

1.6 A Two-Pronged Schedule

The schedule for the design and construction work for LBNF and DUNE has two critical parallel paths: one for the far site (SURF) and another for the near site (Fermilab). The schedule for the initial work is driven by the CF design and construction at each site. A summary of the schedule is shown in Figure fig:summary-sched **??**.

Within the anticipated DOE funding profile, in particular during the initial phase of the Project, the far site conventional facilities are advanced first; their final design starts in fall 2015. Early site preparation is timed to be completed in time to start excavation when the Ross Shaft rehabilitation work finishes in late 2017. As each detector cavern is excavated and sufficient utilities are installed,

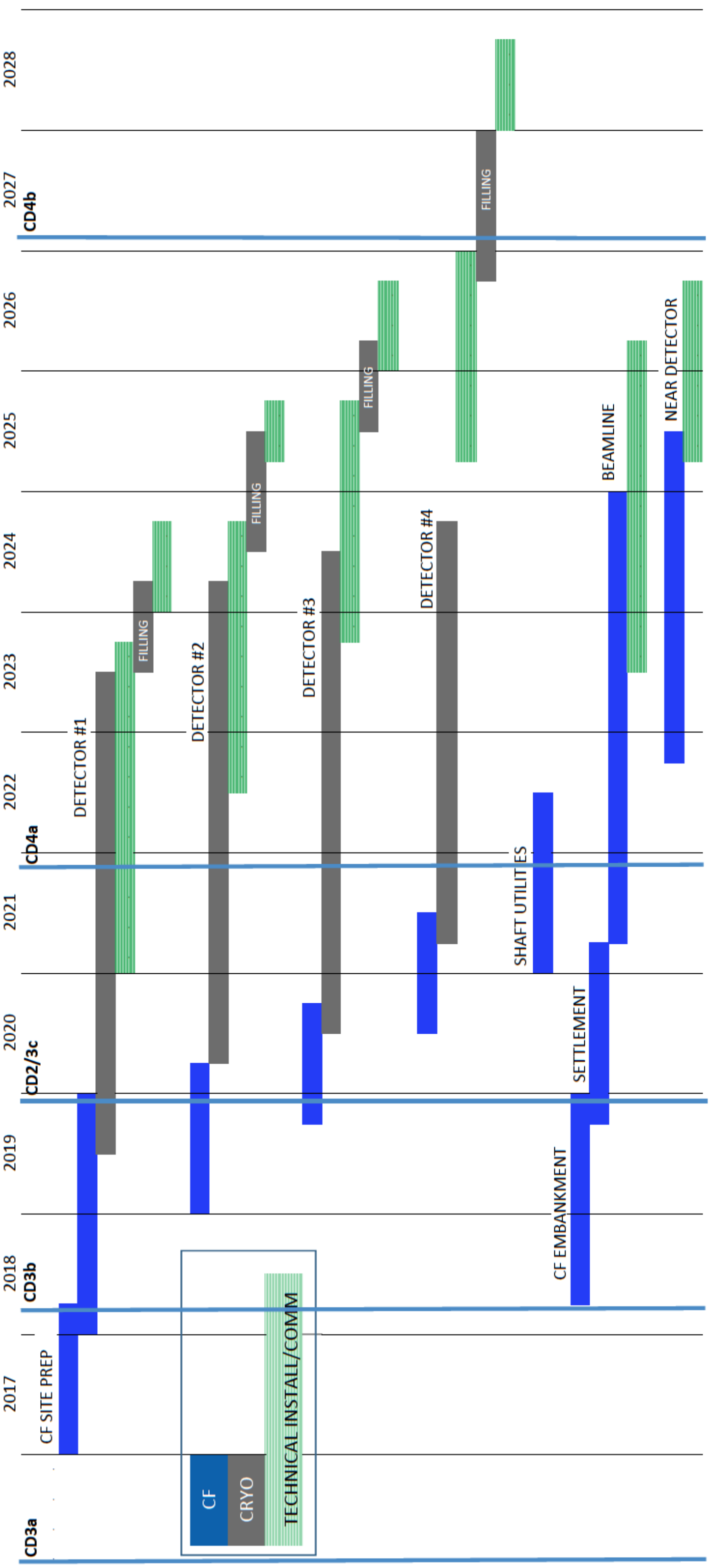

Figure 1.1: High-level summary of LBNF/DUNE schedule

fig:summ

the cryostat and cryogenics system work proceeds, followed by detector installation, filling and commissioning. The far detector module #1 is to be operational by 2024 with modules #2 and #3 completed one and two years later, respectively, and module #4 completed by early 2027.

The near site work is delayed with respect to the far site due to the anticipated funding profile. The near site CF and beamline work essentially slows to nearly a stop until design restarts in late 2017. Optimization decisions about the beamline that affect the CF design will need to be made by late 2018 in order to be ready for the CF design process. The embankment is constructed and then allowed to settle for at least twelve months before the majority of the beamline CF work proceeds. The beneficial occupancies of the various beamline facilities are staggered to allow beamline installation to begin as soon as possible. With this timescale, the far detector science program starts with the first module installed and no beam, focusing on non-accelerator-based science for slightly more than one year until the beamline installation is completed.

The near detector CF construction overlaps that for the beamline, but lags due to available funding. The near detector assembly begins on the surface before beneficial occupancy, after which the detector is installed, complete at about the same time as far detector module #4.

The DOE project management process requires approvals at Critical Decision milestones, which allow the LBNF/DUNE Project to move to the next step. In fall 2015 the far site CF will seek CD-3a approval for construction of some of the CF and cryogenics systems at SURF. In spring 2018 LBNF near site CF will seek CD-3b construction approval for Advanced Site Preparation to build the embankment. In 2020 LBNF and DUNE will seek to baseline the LBNF/DUNE scope of work, cost and schedule, as well as construction approval for the balance of the Project scope of work. The Project concludes with CD-4 approval to start operations.

Chapter 2

DUNE Science

:science

DUNE will address fundamental questions key to our understanding of the universe. These include:

- **What is the origin of the matter-antimatter asymmetry in the universe?** Immediately after the Big Bang, matter and antimatter were created equally, but now matter dominates. By studying the properties of neutrino and antineutrino oscillations, LBNF/DUNE will pursue the current most promising avenue for understanding this asymmetry;

- **What are the fundamental underlying symmetries of the universe?** The patterns of mixings and masses between the particles of the Standard Model is not understood. By making precise measurements of the mixing between the neutrinos and the ordering of neutrino masses and comparing these with the quark sector, LNBF/DUNE could reveal new underlying symmetries of the universe;

- **Is there a Grand Unified Theory of the Universe?** Results from a range of experiments suggest that the physical forces observed today were unified into one force at the birth of the universe. Grand Unified Theories (GUTs), which attempt to describe the unification of forces, predict that protons should decay, a process that has never been observed. DUNE will search for proton decay in the range of proton lifetimes predicted by a wide range of GUT models;

- **How do supernovae explode and what new physics will we learn from a neutrino burst?** Many of the heavy elements that are the key components of life were created in the super-hot cores of collapsing stars. DUNE would be able to detect the neutrino bursts from core-collapse supernovae within our galaxy (should any occur). Measurements of the time, flavor and energy structure of the neutrino burst will be critical for understanding the dynamics of this important astrophysical phenomenon, as well as bringing information on neutrino properties and other particle physics.

2.1 DUNE Scientific Objectives

The DUNE scientific objectives are categorized into: the *primary science program*, addressing the key science questions highlighted by the particle physics project prioritization panel (P5); a high-priority *ancillary science program* that is enabled by the construction of LBNF and the DUNE; and *additional scientific objectives*, that may require further developments of the LArTPC technology. A detailed description of the physics objectives of DUNE is provided in Volume 2 of the CDR.

2.1.1 The Primary Science Program

The primary science program of LBNF/DUNE focuses on fundamental open questions in neutrino and astroparticle physics:

- precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations with the goal of

  – measuring the charge-parity (CP) violating phase δ_{CP}, where a value differing from zero or π would represent the discovery of CP violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe

  – determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino *mass hierarchy*

  – precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\overline{\nu}_\mu$ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;

- search for proton decay in several important decay modes, for example $p \to K^+\overline{\nu}$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces
- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of the DUNE experiment

2.1.2 The Ancillary Science Program

The intense neutrino beam from LBNF, the massive DUNE LArTPC far detector and the high-resolution DUNE near detector provide a rich ancillary science program, beyond the primary mission of the experiment. The ancillary science program includes

- other accelerator-based neutrino flavor transition measurements with sensitivity to Beyond

Standard Model (BSM) physics, such as: non-standard interactions (NSIs); the search for sterile neutrinos at both the near and far sites; and measurements of tau neutrino appearance

- measurements of neutrino oscillation phenomena using atmospheric neutrinos

- a rich neutrino interaction physics program utilizing the DUNE near detector, including: a wide-range of measurements of neutrino cross sections; studies of nuclear effects, including neutrino final-state interactions; measurements of the structure of nucleons; and measurement of $\sin^2\theta_{\mathrm{W}}$

- the search for signatures of dark matter

Furthermore, a number of previous breakthroughs in particle physics have been serendipitous, in the sense that they were beyond the original scientific objectives of an experiment. The intense LBNF neutrino beam and novel capabilities for both the DUNE near and far detectors will probe new regions of parameter space for both the accelerator-based and astrophysical frontiers, providing the opportunity for discoveries that are not currently anticipated.

2.2 Long-Baseline Neutrino Oscillation Physics

Precision neutrino oscillation measurements lie at the heart of the DUNE scientific program. The 1300-km baseline, coupled with the wide-band high-intensity neutrino beam from LBNF, establishes one of DUNE's key strengths, namely sensitivity to the matter effect. This effect leads to a discrete asymmetry in the $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities, the sign of which depends on the presently unknown mass hierarchy (MH). At 1300 km the asymmetry,

$$\mathcal{A} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{2.1}$$

is approximately $\pm 40\%$ in the region of the peak flux in the absence of CP-violating effects. This is larger than the maximal possible CP-violating asymmetry associated with the CP-violating phase, δ_{CP}, of the three-flavor PMNS mixing matrix in the region of the peak flux. The CP asymmetry is larger in the energy regions below the peak flux while the matter asymmetry is smaller. As a result, the LBNF wide-band beam will allow DUNE to determine unambiguously both the MH and δ_{CP} with high confidence within the same experiment. The DUNE science reach is described in detail in Volume 2: *The Physics Program for DUNE at LBNF*, where it is presented in terms of exposure expressed in units of kt · MW · year. For instance, seven years of data (3.5 years in neutrino mode plus 3.5 years in antineutrino mode[1]) with a 40-kt detector and a 1.07-MW beam (based on a 80-GeV primary proton beam) correspond to an exposure of 300 kt · MW · year.

The DUNE far detector will be built as four 10-kt modules, which will come online sequentially over the course of several years, as described in Chapter ??. This staged program enables an early scientific output from DUNE, initially focused on the observation of natural sources of neutrinos,

[1] unless otherwise stated, the results presented in the CDR assume equal running in neutrino and antineutrino mode.

searches for nucleon decays and measurements of backgrounds. Soon afterwards, About a year after commissioning the first detector module, the LBNF neutrino beam at FNAL will commence operation sending neutrinos over the 1300-km baseline, commencing the LBL oscillation physics program with a beam power of up to 1.2 MW. Prior to the operation of the near detector (ND), which is likely to start after the initial beam running, the early physics program will be statistically limited. However, the constraints from comparison of the ν_μ disappearance spectrum with that from ν_e appearance mitigate, in part, the absence of a direct flux measurement from the ND. Subsequently, the ND measurements will provide powerful constraints on the beam flux, providing the necessary control of systematic uncertainties for the full exploitation of LBNF/DUNE.

The evolution of the projected DUNE sensitivities as a function of real time (for the first 15 years of operation) was estimated based on an assumed deployment plan with the following assumptions:

- Year 1: 10 kt far detector mass, 1.07-MW 80-GeV proton beam with 1.47×10^{21} protons-on-target per year beam, and no ND
- Year 2: Addition of the second 10-kt far detector module, for a total far detector mass of 20 kt
- Year 3: Addition of the third 10-kt far detector module, for a total far detector mass of 30 kt; and first constraints from the preliminary ND data analysis
- Year 4: Addition of the fourth 10-kt far detector module, for a total far detector mass of 40 kt
- Year 5: Inclusion of constraints from a full ND data analysis
- Year 7: Upgrade of beam power to 2.14 MW for a 80-GeV proton beam

The staging of the detectors and facility in the resource loaded schedule leads to a similar evolution of physics sensitivity as a function of time. In addition, it was assumed that the knowledge from the near detector can be retroactively applied to previous data sets, such that each improvement in the knowledge of systematic uncertainties [2] is applied to the full exposure up to that point.

The discriminating power between the two MH hypotheses is quantified by the difference, denoted $\Delta\chi^2$, between the $-2\log\mathcal{L}$ values calculated for the normal and inverted hierarchies. As the sensitivity depends on the true value of the unknown CP-violating phase, $\delta_{\rm CP}$, all possible values of $\delta_{\rm CP}$ are considered[3]. In terms of this test statistic, the MH sensitivity of DUNE with an exposure of 300 kt · MW · year is illustrated in Figure 2.1 for the case of normal hierarchy and the

[2] A detailed discussion of the systematic uncertainties assumed, given a near detector, is presented in Volume 2: *The Physics Program for DUNE at LBNF*. For studies without a near detector an uncertainty of 10% is assumed on the unoscillated flux at the far detector based on the current performance of the NuMI beam simulation, with uncertainties on physics backgrounds $\geq 10\%$ depending on the background.

[3] For the case of the MH determination, the usual association of this test statistic with a χ^2 distribution for one degree of freedom is incorrect; additionally the assumption of a Gaussian probability density implicit in this notation is not exact. The discussion in Chapter 3 of Volume 2: *The Physics Program for DUNE at LBNF* provides a brief description of the statistical considerations.

current best-fit value of $\sin^2\theta_{23} = 0.45$. For this exposure, the DUNE determination of the MH will be definitive for the overwhelming majority of the $\delta_{\rm CP}$ and $\sin^2\theta_{23}$ parameter space. Even for unfavorable combinations of the parameters, a statistically ambiguous outcome is highly unlikely.

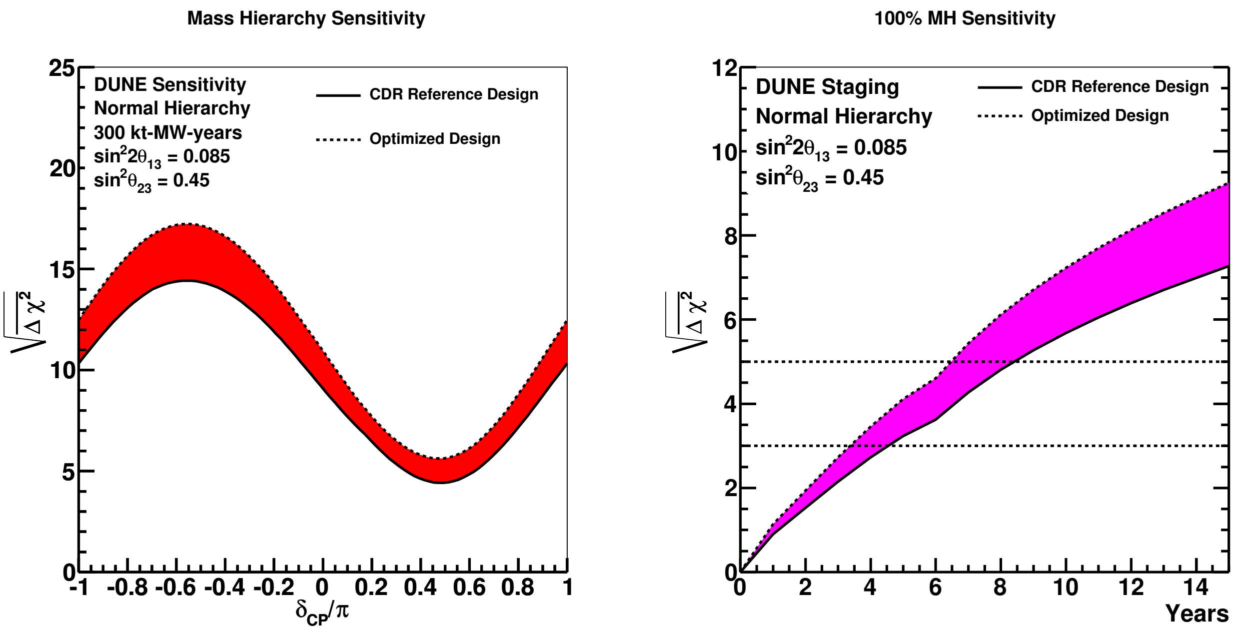

Figure 2.1: The square root of the mass hierarchy discrimination metric $\Delta\chi^2$ is plotted as a function of the unknown value of $\delta_{\rm CP}$ for an exposure of 300 kt · MW · year (left). The minimum significance — the lowest point on the curve on the left — with which the mass hierarchy can be determined for all values of $\delta_{\rm CP}$ as a function of years of running under the staging plan described in the text (right). The shaded region represents the range in sensitivity corresponding to the different beam design parameters.

Figure 2.1 shows the evolution of the sensitivity to the MH determination as a function of years of operation, for the least favorable scenario, corresponding to the case in which the MH asymmetry is maximally offset by the leptonic CP asymmetry. For the reference design beam an exposure of 400 kt · MW · year (which corresponds to 8.5 years of operation) is required to distinguish between normal and inverted hierarchy with $|\Delta\chi^2| = \overline{|\Delta\chi^2|} = 25$. This corresponds to a $\geq 99.9996\%$ probability of determining the correct hierarchy. Investments in a more capable target and horn focusing system can lower the exposure needed to reach this level of sensitivity from 400 kt · MW · year to around 230 kt · MW · year (6.5 years of running in the example staging plan). The dependence of the mass hierarchy sensitivity on systematics is still under evaluation, but current studies indicate a only weak dependence on the assumptions for the achievable systematic uncertainties. This indicates that a measurement of the unknown neutrino mass hierarchy with very high precision can be carried out during the first few years of operation with an optimized beamline design, discussed in Volume 3: *The Long-Baseline Neutrino Facility for DUNE*. Concurrent analysis of the corresponding atmospheric-neutrino samples in an underground detector will improve the precision and speed with which the MH is resolved.

DUNE will search for CP violation using the ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation channels, with two objectives. First, DUNE aims to observe a signal for leptonic CP violation independent of the underlying nature of neutrino oscillation phenomenology. Such a signal will be observable in comparisons of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations of the LBNF beam neutrinos in a wide range of neutrino energies over the 1300-km baseline. Second, DUNE aims to make a precise determination of the value of $\delta_{\rm CP}$ within the context of the standard three-flavor mixing scenario described by the PMNS neutrino mixing matrix. Together, the pursuit of these two goals provides a thorough test of the standard three-flavor scenario.

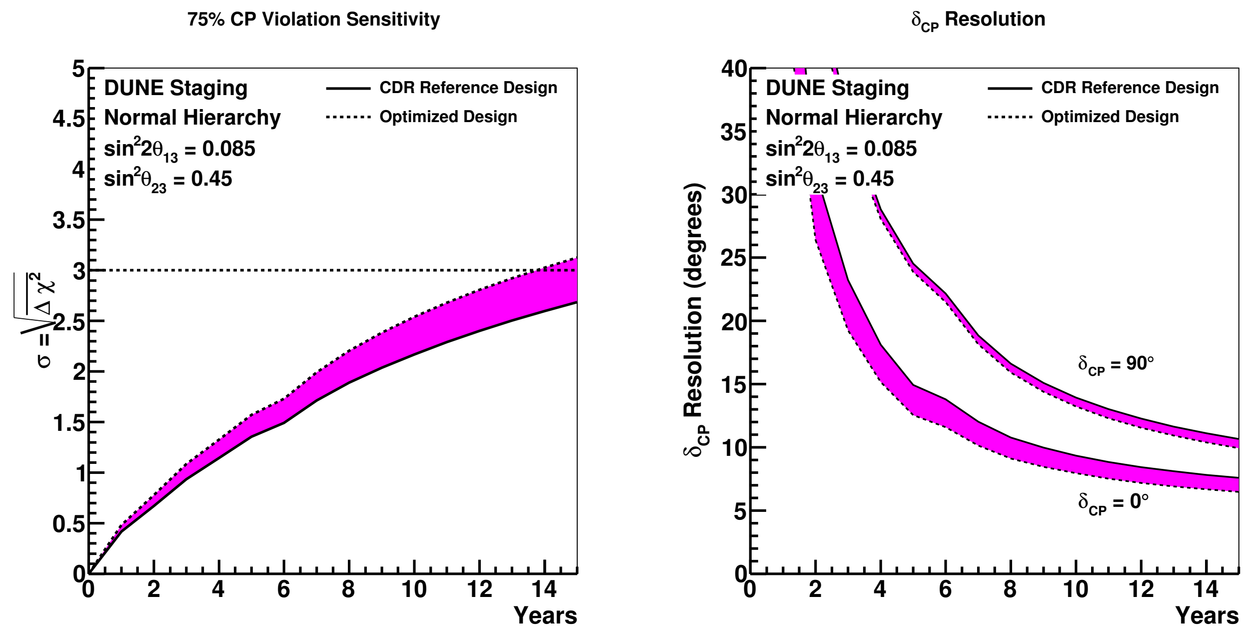

Figure 2.2: The significance with which CP violation can be determined for 75% of $\delta_{\rm CP}$ values (left) and the expected 1σ resolution (right) as a function of exposure in years using the proposed staging plan outlined in this Chapter. The shaded region represents the range in sensitivity due to potential variations in the beam design. This plot assumes normal mass hierarchy.

Figure 2.2 shows, as a function of time, the expected sensitivity to CP violation expressed as the minimum significance with which CP violation can be determined for 75% of $\delta_{\rm CP}$ values. Also shown is the 1σ resolution for $\delta_{\rm CP}$ as a function of time for $\delta_{\rm CP} = 0$ (no CP violation) and $\delta_{\rm CP} = 90°$ (maximal CP violation). In both figures the staging scenario described above was assumed. The exposure required to measure $\delta_{\rm CP} = 0$ with a precision better than 10° ranges from 290 to 450 kt · MW · year depending on the beam design. A full-scope LBNF/DUNE operating with multi-megawatt beam power can eventually achieve a precision comparable to the current precision on the CP phase in the CKM matrix in the quark sector (5%).

Table **??** summarizes the exposures needed to achieve specific oscillation physics milestones, calculated for the current best-fit values of the known neutrino mixing parameters. Values for both the reference beam design and the optimized beamline design are shown. For example, to reach 3σ sensitivity for 75% of the range of $\delta_{\rm CP}$, a DUNE exposure in the range of 850 to 1320 kt · MW · year is needed for the optimized and reference beamline designs. Changes in the assumed value of θ_{23} impact CP-violation and MH sensitivities the most (discussed in Volume 2: *The Physics Program for DUNE at LBNF*) and can either reduce or increase the discovery potential for CP violation. To reach this level of sensitivity a highly-capable near neutrino detector is required to control systematic uncertainties at a level lower than the statistical uncertainties in the far detector. No experiment can provide coverage at 100% of $\delta_{\rm CP}$ values, since CP-violating effects vanish as $\delta_{\rm CP} \to 0$ or π. Potential improvements in beamline geometry, focusing and target element designs can significantly lower the exposure required for CP violation discovery potential. Several such potential improvements are discussed in CDR Volume 2: *The Physics Program for DUNE at LBNF*and Volume 3: *The Long-Baseline Neutrino Facility for DUNE.*

Table 2.1: The exposure in mass (kt) × proton beam power (MW) × time (years) needed to reach certain oscillation physics milestones. The numbers are for normal hierarchy using the current best fit values of the known oscillation parameters. The two columns on the right are for different beam design assumptions.

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\rm CP} = 0$)	450	290
CPV at 5σ ($\delta_{\rm CP} = -\pi/2$)	525	320
CPV at 5σ 50% of $\delta_{\rm CP}$	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of $\delta_{\rm CP}$	1320	850

In long-baseline experiments with ν_μ beams, the magnitude of ν_μ disappearance and ν_e appearance signals is proportional to $\sin^2 2\theta_{23}$ and $\sin^2 \theta_{23}$, respectively, in the standard three-flavor mixing scenario. Current ν_μ disappearance data are consistent with close to maximal mixing, $\theta_{23} = 45^\circ$. To obtain the best sensitivity to both the magnitude of its deviation from 45° as well the θ_{23} octant, a combined analysis of the two channels is needed [**?**]. As demonstrated in Volume 2, a 40-kt DUNE detector with sufficient exposure will be able to resolve the θ_{23} octant at the 3σ level or better for θ_{23} values less than 43° or greater than 48°. The full LBNF/DUNE scope will allow θ_{23} to be measured with a precision of 1° or less, even for values within a few degrees of 45°.

To summarize, DUNE long-baseline program will complete our understanding of the oscillation phenomenology. DUNE has great prospects to discover CP violation or, in the absence of the effect, set stringent limits on the allowed values of $\delta_{\rm CP}$. DUNE will also determine the neutrino mass hierarchy with better than a 5σ C.L.

2.3 The Search for Nucleon Decay

The DUNE far detector will significantly extend lifetime sensitivity for specific nucleon decay modes by virtue of its high detection efficiency relative to water Cherenkov detectors and its low background rates. As an example, DUNE has enhanced capability for detecting the $p \to K^+\bar{\nu}$ channel, where lifetime predictions from supersymmetric models extend beyond, but remain close to, the current (preliminary) Super-Kamiokande limit of $\tau/B > 5.9 \times 10^{33}$ year (90% CL), obtained from a 260-kt · year exposure [?][4]. The signature for an isolated nearly-monochromatic charged kaon in a LArTPC is highly distinctive, with multiple distinguishing features.

The DUNE LArTPC far detector deep underground will reach a limit of 3×10^{34} year after 10–12 years of operation (Figure 2.3) depending on the deployment scenario, and would see nine events with a background of 0.3 should τ/B be 1×10^{34} year, just beyond the current limit. A 40-kt detector will improve the current limits by an order of magnitude after running for two decades. Even a 10-kt detector could yield an intriguing signal of a few events after a ten-year exposure.

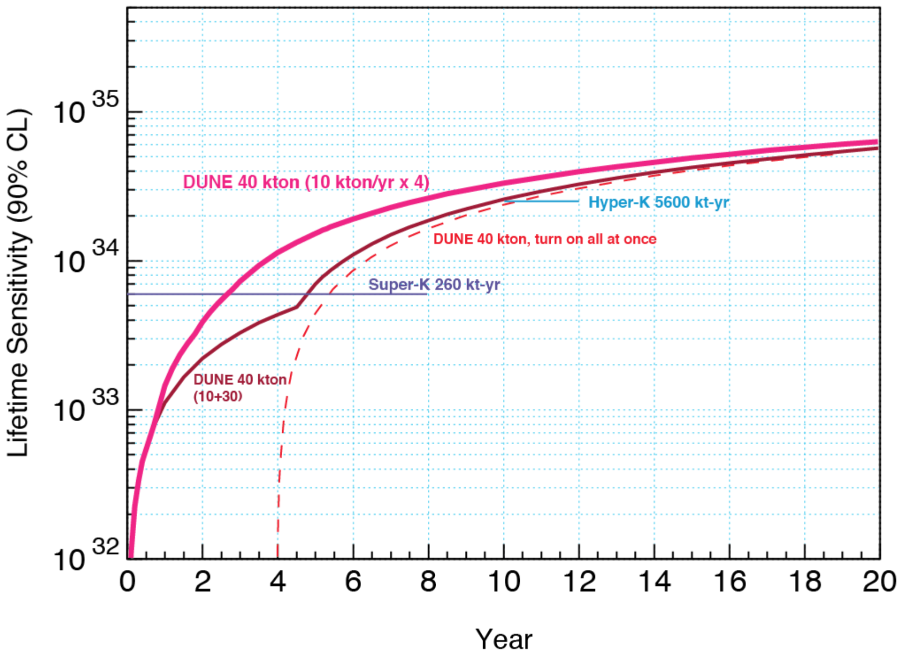

Figure 2.3: Sensitivity to the decay $p \to K^+\bar{\nu}$ as a function of time for different DUNE LArTPC module deployment strategies. For comparison, the current limit from SK is also shown, as well as the projected limit from the proposed Hyper-K experiment with 5600 kt · year of exposure and a timeline based on a 1-Mt detector. The limits are at 90% C.L., calculated for a Poisson process including background, assuming that the detected events equal the expected background.

Many models in which the $p \to K^+\bar{\nu}$ channel mode is dominant, e.g. certain supersymmetric GUT models, also favor other modes involving kaons in the final state, thus enabling a rich program of searches for nucleon decay in the DUNE LArTPC detectors.

2.4 Supernova-Neutrino Physics and Astrophysics

The neutrinos from a core-collapse supernova are emitted in a burst of a few tens of seconds duration, with about half of the signal in the first second. The neutrino energies are mostly in the

[4] The lifetime shown here is divided by the branching fraction for this decay mode, τ/B, and as such is a *partial lifetime*.

range 5–50 MeV, and the luminosity is divided roughly equally between the three known neutrino flavors. Current experiments are sensitive primarily to electron antineutrinos ($\bar{\nu}_e$), with detection through the inverse-beta decay process on free protons[5], which dominates the interaction rate in water and liquid-scintillator detectors. Liquid argon has a unique sensitivity to the electron-neutrino (ν_e) component of the flux, via the absorption interaction on ^{40}Ar,

$$\nu_e + {}^{40}\mathrm{Ar} \ \rightarrow \ e^- + {}^{40}\mathrm{K}^*.$$

This interaction can be tagged via the coincidence of the emitted electron and the accompanying photon cascade from the ^{40}K* de-excitation. About 3000 events would be expected in a 40-kt fiducial mass liquid argon detector for a supernova at a distance of 10 kpc. In the neutrino channel the oscillation features are in general more pronounced, since the ν_e spectrum is always significantly different from the ν_μ (ν_τ) spectrum in the initial core-collapse stages, to a larger degree than is the case for the corresponding $\bar{\nu}_e$ spectrum. Detection of a large neutrino signal in DUNE would help provide critical information on key astrophysical phenomena such as

- the neutronization burst
- formation of a black hole
- shock wave effects
- shock instability oscillations
- turbulence effects

In addition to yielding unprecedented information on the mechanics of the supernova explosion, the observation of a core-collapse supernova in DUNE will also probe particle physics, providing neutrino oscillation signatures (with sensitivity to mass hierarchy and "collective effects" due to neutrino-neutrino interactions), as well as tests for new physics such as Goldstone bosons (e.g., Majorons), neutrino magnetic moments, new gauge bosons ("dark photons"), "unparticles" and extra-dimensional gauge bosons.

2.5 Precision Measurements with the DUNE Near Detector

The DUNE near detector will provide precision measurements of neutrino interactions that are essential for controlling the systematic uncertainties in the long-baseline oscillation physics program. The near detector will include argon targets and will measure the absolute flux and energy-dependent shape of all four neutrino species, ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$, to accurately predict for each species the far/near flux ratio as a function of energy. It will also measure the four-momenta of secondary hadrons, such as charged and neutral mesons, produced in the neutral- and charged-current interactions that constitute the dominant backgrounds to the oscillation signals.

[5] This refers to neutrino interactions with the nucleus of a hydrogen atom in H_2O in water detectors or in hydrocarbon chains in liquid scintillator detectors.

The near detector will also be the source of data for a rich program of neutrino-interaction physics in its own right. For an integrated beam intensity of 1×10^{20} protons-on-target at 120 GeV, the expected number of events per ton is 170,000 (59,000) ν_μ ($\bar{\nu}_\mu$) charged-current and 60,000 (25,000) neutral-current interactions in the ν ($\overline{\nu}$) beam[6]. These numbers correspond to 10^5 neutrino interactions on argon per year for the range of beam configurations and near detector designs under consideration. Measurement of fluxes, cross sections and particle production over a large energy range of 0.5 GeV to 50 GeV are the key elements of this program. These data will also help constrain backgrounds to proton-decay signals from atmospheric neutrinos. Furthermore, very large samples of events will be amenable to precision reconstruction and analysis, and will be exploited for sensitive studies of electroweak physics and nucleon structure, as well as for searches for new physics in unexplored regions, such as heavy sterile neutrinos, high-Δm^2 oscillations, light Dark Matter particles, and so on.

2.6 Summary

In summary, the primary science goals of DUNE are drivers for the advancement of particle physics. The questions being addressed are of wide-ranging consequence: the origin of flavor and the generation structure of the fermions, the physical mechanism that provides the CP violation needed to generate the baryon asymmetry of the universe, and the high-energy physics that would lead to the instability of matter. Achieving these goals requires a dedicated, ambitious and long-term program. No other proposed long-baseline neutrino oscillation program with the scientific scope and sensitivity of DUNE is as advanced in terms of engineering development and project planning. The staged implementation of the far detector as four 10-kt modules will enable exciting physics in the intermediate term, including a definitive mass hierarchy determination and possibly a measurement of the CP phase, while providing the fastest route toward achieving the full range of DUNE's science objectives. Should DUNE find that the CP phase is not zero or π, it will have found strong indications ($> 3\sigma$) of leptonic CP violation.

The DUNE experiment is a world-leading international physics experiment, bringing together the international neutrino community as well as leading experts in nucleon decay and particle astrophysics to explore key questions at the forefront of particle physics and astrophysics. The highly capable beam and detectors will enable a large suite of new physics measurements with potential groundbreaking discoveries.

[6]With PIP-II, the integrated protons-on-target per year is expected to be around 1.1×10^{21} at 120 GeV. The mass of the Ar target in the DUNE ND is expected to be approximately 100 kg.

Chapter 3

Technical Overview

3.1 LBNF Project

LBNF will provide facilities at Fermilab and at SURF to enable the scientific program of DUNE. These facilities are geographically separated into the Near Site Facilities, those to be constructed at Fermilab, and the Far Site Facilities, those to be constructed at SURF.

3.1.1 Near Site Facilities

The scope of LBNF at Fermilab is provision of the beamline plus the conventional facilities (CF) for this beamline as well as for the DUNE near detector. The layout of the near site facilities is shown in Figure **??**. The science requirements as determined by the DUNE Collaboration drive the performance of the beamline and near detector, which then provide requirements for the components, space, and functions necessary to construct, install, and operate the beamline and near detector. ES&H and facility operations requirements (i.e., *programmatic* requirements) also provide input to the design.

The beamline is designed to provide a neutrino beam of sufficient intensity and appropriate energy range to meet the goals of DUNE for long-baseline neutrino oscillation physics. The design is a conventional, horn-focused neutrino beamline. The components of the beamline will be 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 that are focused by the neutrino horns. The focussed charged particles then decay producing neutrinos (for example $\pi^+ \to \mu^+ \nu_\mu$) to create the neutrino beam directed towards the near and far detectors.

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 plan is for twenty years of operation, while the lifetime of the Beamline Facility, including the shielding, is for thirty years. It is assumed that operations during the first five years will be at 1.2 MW and the remaining fifteen years at 2.4 MW. The

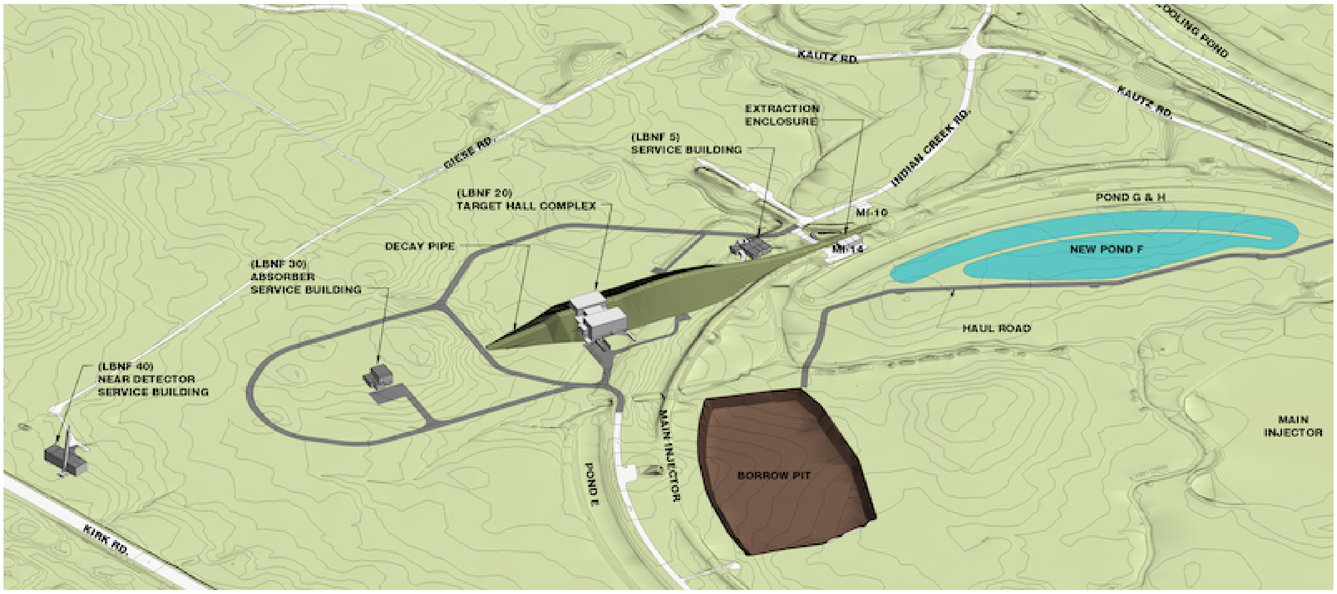

Figure 3.1: Layout of LBNF Near Site

experience gained from the various neutrino projects has contributed extensively to the reference design. In particular, the NuMI beamline serves as the prototype design. Most of the subsystem designs and the integration between them follow, to a large degree, from previous projects.

The proton beam will be extracted at a new point at MI-10. After extraction, this primary beam will travel horizontally heading west-northwest toward the far detector. It is then bent upward to an apex before being bent downward at the appropriate angle. This requires construction of an earthen embankment, or hill, whose dimensions are commensurate with the bending strength of the dipole magnets required for the beamline. The raised design of the primary beam minimizes expensive, underground construction; it also significantly enhances ground-water radiological protection.

The narrow proton beam impinges on a target, producing a more diffuse, secondary beam of particles that in turn decay to produce the neutrino beam. The secondary pions and kaons are then focussed by the neutrino horn system into a long unobstructed decay tunnel. The decay tunnel in the reference design is a pipe of circular cross section with its diameter and length optimized such that decays of the pions and kaons result in neutrinos in the energy range useful for the experiment. The decay tunnel is followed immediately by the absorber, which removes the remaining beam hadrons.

Radiological protection is integrated into the LBNF beamline reference design in two important ways. First, shielding is optimized to reduce exposure of personnel to radiation dose and to minimize radioisotope production in ground water within the surrounding rock. Secondly, the handling and control of tritiated ground water produced in or near the beamline drives many aspects of the design.

Beamline CF includes an enclosure connecting to the existing Main Injector at MI-10, concrete underground enclosures for the primary beam, targetry, horns, absorber, and related technical support systems. Service buildings will be constructed to provide support utilities for the primary proton beam at LBNF 5 and to support the absorber at LBNF 30 (shown in Figure ??). The Target Hall Complex at LBNF 20 houses the targetry system. Utilities will be extended from nearby existing services, including power, domestic and industrial water, sewer, and communications.

Near Detector CF includes a small muon alcove area in the Beamline Absorber Hall and a separate underground Near Detector Hall that houses the near detector. A service building called LBNF 40 with two shafts to the underground supports the near detector. The underground hall is sized for the reference design near detector.

3.1.2 Far Site Facilities

The scope of LBNF at SURF includes both conventional facilities and cryogenic infrastructure to support the DUNE far detector. Figure ?? shows the layout of the underground caverns that will house the detector modules with a separate cavern to house utilities and cryogenic systems. The requirements derive from DUNE Collaboration science requirements, which drive the space and functions necessary to construct and operate the far detector. ES&H and facility operations (programmatic) requirements also provide input to the design. The far detector is modularized into four 10-kt fiducial mass detectors. The designs of the four detector pits in two caverns and the services to the caverns will be as similar to one another as possible for efficiency in design and construction as well as operation.

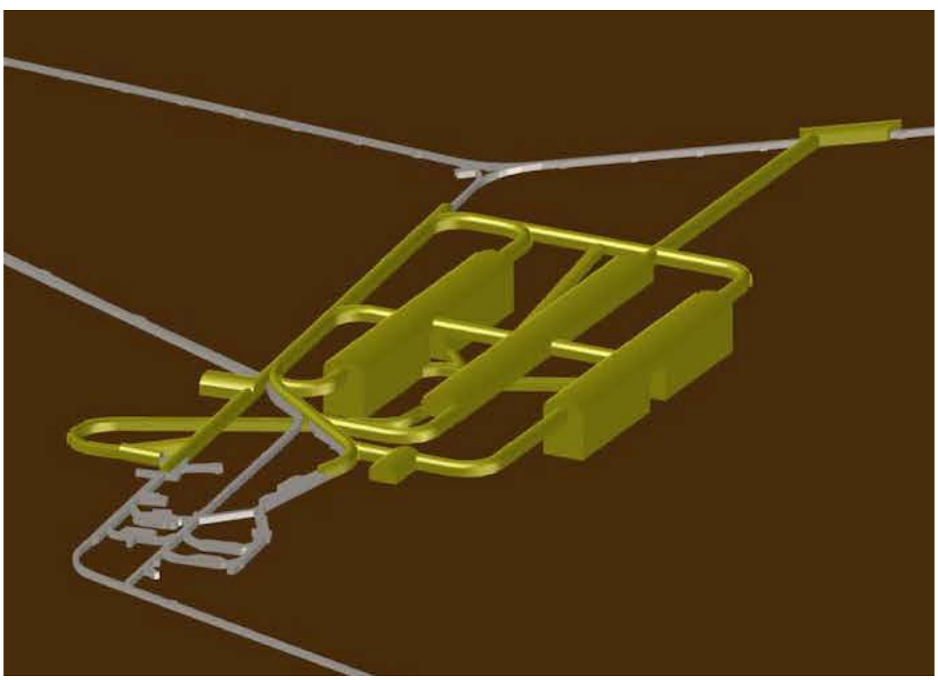

Figure 3.2: LBNF Far Site cavern configuration

The scope of the Far Site CF includes design and construction for facilities both on the surface and underground. The underground conventional facilities include new excavated spaces at the 4850L for the detector, utility spaces for experimental equipment, utility spaces for facility equipment, drifts for access, as well as construction-required spaces. Underground infrastructure provided by CF for the experiment includes power to experimental equipment, cooling systems and cyberinfrastructure. Underground infrastructure necessary for the facility includes domestic (potable) water, industrial water for process and fire suppression, fire detection and alarm, normal and standby power systems, a sump pump drainage system for native and leak water around the detector, water drainage to the facility-wide pump discharge system, and cyberinfrastructure for communications and security. In addition to providing new spaces and infrastructure underground, CF will enlarge and provide infrastructure in some existing spaces for LBNF and DUNE use, such as the access drifts from the Ross Shaft to the new caverns. New piping will be provided in the shaft for cryogens (gas argon transfer line and the compressor suction and discharge lines) and domestic water as well as power conduits for normal and standby power and cyberinfrastructure.

SURF currently has many surface buildings and utilities, some of which will be utilized for LBNF. The scope of the above-ground CF includes only that work necessary for LBNF, and not for the general rehabilitation of buildings on the site, which remains the responsibility of SURF. Electrical substations and distribution will be upgraded to increase power and provide standby capability for life safety. Additional surface construction includes a small control room in an existing building and a new building to support cryogen transfer from the surface to the underground near the existing Ross Shaft.

To reduce risk of failure of essential but aging support equipment during the construction and installation period, several SURF infrastructure operations/maintenance activities are included as early activities in the LBNF Project. These include completion of the Ross Shaft rehabilitation, rebuilding of hoist motors, and replacement of the Oro Hondo fan; if not addressed, failure of this aging infrastructure is more likely, which could limit or remove access to the underground areas.

The scope of the LBNF cryogenics infrastructure includes the design, fabrication and installation of four cryostats to contain the liquid argon (LAr) and the detector components. It also includes a comprehensive cryogenic system that meets the performance requirements for purging, cooling and filling the cryostats, for achieving and maintaining the LAr temperature, and for purifying the LAr outside the cryostats.

Each cryostat is composed of a free-standing steel-framed structure with a membrane cryostat installed inside, to be constructed in one of the four excavated detector pits. The cryostat is designed for a total LAr mass capacity of 17.1 kt. Each tank has a stainless-steel liner (membrane) as part of the system to provide full containment of the liquid. The hydrostatic pressure loading of the LAr is transmitted through rigid foam insulation to the surrounding structural steel frame which provides external support for the cryostat. All penetrations into the interior of the cryostat will be made through the top plate to minimize the potential for leaks, with the exception of the sidewall penetration that is used for connection to the LAr recirculation system.

Cryogenic system components are located both on the surface and within the cavern. The cryogen receiving station is located on the surface near the Ross Shaft to allow for receipt of LAr deliveries for the initial filling period; it also has a buffer volume to accept liquid argon during the extended fill period. A large vaporizer for the nitrogen circuit feeds gas to one of four compressors located in the Cryogenic Compressor Building; the compressor discharges high-pressure nitrogen gas to pipes in the Ross shaft. The compressors are located on the surface because the electrical power and thermal cooling requirements are less stringent than for an installation at the 4850L.

Equipment at the 4850L includes the nitrogen refrigerator, liquid nitrogen vessels, argon condensers, external LAr recirculation pumps, and filtration equipment. Filling each cryostat with LAr in a reasonable period of time is a driving factor for the refrigerator and condenser sizing. Each cryostat will have its own argon recondensers, argon-purifying equipment and overpressure-protection system located in the Central Utility Cavern. Recirculation pumps will be placed outside of and adjacent to each cryostat in order to circulate liquid from the bottom of the tank through the purifier.

3.2 Strategy for Developing the LBNF Beamline

The neutrino beamline described in this CDR is a direct outgrowth of the design [?] developed for the LBNE CD 1 review in 2012. That design was driven by the need to minimize cost, while delivering the performance required to meet the scientific objectives of the long-baseline neutrino program. It includes many features that followed directly from the successful NuMI beamline design as updated for the NOvA experiment. It utilizes a target and horn system based on NuMI designs, with the spacing of the target and two horns set to maximize flux at the first, and to the extent possible, second oscillation maxima, subject to the limitations of the NuMI designs for these systems. The target chase volume — length and width — are set to the minimum necessary to accommodate this focusing system, and the temporary morgue space to store used targets and horns is sized based on the size of the NuMI components. Following the NuMI design, the decay pipe is helium-filled, while the target chase is air-filled.

The LBNF beamline is designed to utilize the Main Injector proton beam, as will be delivered after the PIP-II upgrades [?]. The proton beam energy can be chosen to be between 60 and 120 GeV, with the corresponding range of beam power from 1.0 to 1.2 MW. The ability to vary the proton beam energy is important for optimizing the flux spectrum and to understand systematic effects in the beam production, and to provide flexibility to allow the facility to address future questions in neutrino physics that may require a different neutrino energy spectrum. To allow for the higher beam power that will be enabled by future upgrades to the Fermilab accelerator complex beyond PIP-II, the elements of the beamline and supporting conventional facilities that cannot be changed once the facility is built and has been irradiated are designed to accommodate beam power in the range of 2.0 to 2.4 MW for the corresponding proton beam energy range of 60 to 120 GeV. These elements include primary beam components, target hall, decay pipe and absorber, as well as the shielding for them. Components that can be replaced, such as targets and horns, are designed for the 1.2-MW initial operation. Additional R&D will be required to develop these components for operation at the higher beam power.

Since the 2012 CD-1 review, the beamline design has evolved in a number of areas, as better understanding of the design requirements and constraints has developed. Some of these design changes have come to full maturity and are described in this CDR. Others require further development and evaluation to determine if and how they might be incorporated into the LBNF neutrino beamline design. They offer the possibility of higher performance, flexibility in implementation of future ideas, and/or greater reliability and will be developed by the DUNE Collaboration in the near future. The beamline facility is designed to have an operational lifetime of 20 years, and it is important that it be designed to allow future upgrades and modifications that will allow it to exploit new technologies and/or adapt the neutrino spectrum to address new questions in neutrino physics over this long period. The key alternatives and options under consideration and the strategy for evaluating and potentially implementing them are summarized below. They are described in more detail in the other volumes of this CDR and in its Annexes.

Further optimization of the target-horn system has the potential to substantially increase the neutrino flux at the first and especially second oscillation maxima and to reduce wrong-sign neutrino background, thereby increasing the sensitivity to CP violation and mass hierarchy determination, as discussed in Volume 2: *The Physics Program for DUNE at LBNF*. This optimization work is ongoing and may yield further improvements beyond those currently achieved. Engineering studies of the proposed horn designs and methods of integrating the target into the first horn must be performed to turn these concepts into real structures that can be built and that satisfy additional requirements in areas such as reliability and longevity. These studies will be carried out between CD-1 and CD-2 to determine the baseline design for the LBNF target-horn system. Since targets and horns must be replaceable, it is also possible to continue development of the target-horn system in the future and replace the initial system with a more advanced design or one optimized for different physics. Such future development, beyond that necessary to establish the baseline design at CD-2, would be done outside of the LBNF Project.

The more advanced focusing system, called the "optimized beam configuration" in Volume 2: *The Physics Program for DUNE at LBNF*, utilizes horns that are longer and larger in diameter and that are spaced farther apart than in the reference design, which would require a target chase approximately 9 m longer and 0.6 m wider than the reference design. It cannot be ruled out that further optimization, or future designs that would allow exploration of new questions may require additional space beyond this. Also, the larger horns will require a larger space for temporary storage of used, irradiated components, requiring, in turn, an increase in the size of the morgue or a revision of the remote handling approach. Between CD-1 and CD-2, studies will be done to determine not only the geometric requirements from the final baseline target-horn system, but also to estimate the dimensions needed to accommodate potential future designs.

The material, geometry and structure of the target assembly itself can have significant impact both on the effective pion production and the energy spectrum of pions, which in turn affect the neutrino spectrum, and on the reliability and longevity of the target, which affects the integrated beam exposure. Potential design developments range from incremental (e.g., changing from the reference design rectangular cross section, water-cooled graphite target to a cylindrical helium-cooled target), to more substantial (e.g., changing target material from graphite to beryllium), to radical (e.g., implementing a hybrid target with lighter material upstream and heavier material downstream and perhaps constructed of a set of spheres captured in a cylindrical skin). New designs beyond the current reference design are also needed in order to accommodate the higher beam power (up to 2.4 MW) that will be provided by the PIP-III upgrade. Target development will largely be carried out in the context of worldwide collaborations on high-power targetry such as the Radiation Damage In Accelerator Target Environments (RaDIATE [?]) collaboration, and not within the LBNF Project. The LBNF design must be such that it can fully exploit future developments in target design.

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 increase at higher energies; a larger diameter allows the capture and decay of lower-energy pions, increasing the neutrino flux at lower energies as described in Volume 2: *The Physics Program for DUNE at LBNF*. The dimensions also affect the electron-neutrino and wrong-sign backgrounds. Unlike targets and horns, the decay pipe cannot be modified after the facility is built, making the choice of geometry particularly important. The reference design values of 204 m length and 4 m diameter appear well matched to the physics of DUNE but studies to determine the optimal dimensions continue. The cost of increasing the decay pipe length or diameter is relatively large, including the impact on the absorber. Therefore, studies of the decay pipe must include evaluation of the relative advantages of investment in the decay pipe versus investment in other systems, e.g., a larger target hall complex, more advanced target-horn systems, or more far detector mass. Studies currently in progress will continue to be carried out jointly by LBNF and DUNE between CD-1 and CD-2 to determine the baseline decay-pipe geometry.

3.3 DUNE Detectors

The DUNE detectors to be installed at SURF (the far site) and FNAL (the near site) will enable the scientific program of DUNE. The detector requirements derive from the DUNE science goals.

3.3.1 The Far Detector

The far detector will be located deep underground at the 4850L and have a fiducial mass of 40 kt to perform sensitive studies of long-baseline oscillations with a 1300-km baseline as well as a rich astroparticle physics program and nucleon decay searches. The far detector will be composed of four similar modules, each instrumented as a liquid argon time-projection chamber (LArTPC). The concept of the LArTPC provides excellent tracking and calorimetry performance, hence it is ideal for massive neutrino detectors such as the DUNE far detector, which require high signal efficiency and effective background discrimination, an excellent capability to identify and precisely measure neutrino events over a wide range of energies, and an excellent reconstruction of the kinematical properties with a high resolution. The full imaging of events will allow study of neutrino interactions and other rare events with an unprecedented resolution. The huge mass will allow collection of sufficient statistics for precision studies, as discussed in Chapter 2.

The LArTPC, pioneered in the context of the ICARUS project, is a mature technology. It is the outcome of several decades of worldwide R&D. Nonetheless, the size of a single 10-kt DUNE module represents an extrapolation of over one order of magnitude compared to the largest operated detector, the ICARUS T600. To address this challenge, DUNE is developing two far detector options, the reference design and the alternative design, and is engaged in a comprehensive prototyping effort. At this stage, the development of two options is a strength made possible by the merging of the worldwide neutrino community into DUNE. The two detector concepts are illustrated in Figure **??**.

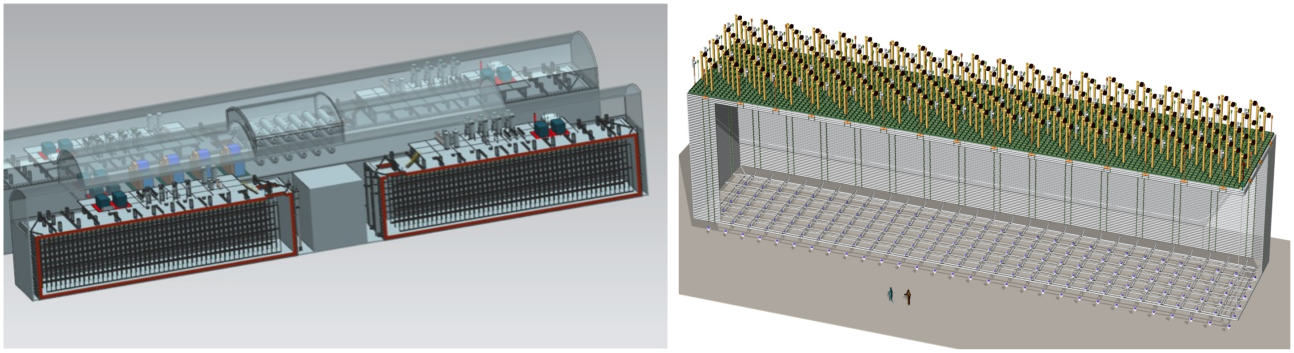

Figure 3.3: 3D models of two 10-kt detectors using the single-phase reference design (left) and the dual-phase alternative design (right) for the DUNE far detector to be located at 4850L.

Interactions in LAr produce ionization charge and scintillation light. The ionization electrons are drifted with a constant electric field away from the cathode plane and towards the segmented anode plane. The prompt scintillation light, detected by photo-detectors, provides the absolute time of the event. The reference design adopts a single-phase readout, where the readout anode is composed of wire planes in the LAr volume. The alternative design implements a dual-phase approach, in which the ionization charges are extracted, amplified and detected in gaseous argon (GAr) above the liquid surface. The dual-phase design would allow for a finer readout pitch (3 mm), a lower detection-energy threshold, and better pattern reconstruction of the events. The photon-detection schemes used in the two designs are complementary, one is distributed within the LAr volume, the other is concentrated at the bottom of the tank.

The 10-kt reference design TPC is described in Chapter 4 of Volume 4: *The DUNE Detectors at LBNF*. Its active volume is 12 m high, 14.5 m wide and 58 m long, instrumented with anode plane assemblies (APAs), which are 6.3 m high and 2.3 m wide, and cathode plane assemblies (CPAs), 3 m high by 2.3 wide. Vertical stacks of two APAs and four CPAs instrument the 12 m height of the active volume. The 12.5-m width of the detector is spanned by three stacks of APAs and two stacks of CPAs in an APA:CPA:APA:CPA:APA arrangement, resulting in four 3.6-m drift volumes, while the 58-m length of the active volume is spanned by 25 such stack arrangements placed edge to edge. Hence a 10-kt far detector module consists of 150 APAs and 200 CPAs. The CPAs are held at $-180\,\mathrm{kV}$, such that ionization electrons drift a maximum distance of 3.6 m in the electric field of $500\,\mathrm{V\,cm^{-1}}$. The highly modular nature of the detector design allows for manufacturing to be distributed across a number of sites.

A comprehensive prototyping strategy for both designs is actively pursued (see Chapter 9 of Volume 4: *The DUNE Detectors at LBNF*). The reference design, closer to the original ICARUS design, is currently being validated in the 35-t prototype LAr detector at Fermilab. The alternative design, representing a novel approach, has been proven on several small-scale prototypes. Presently a 20-t dual-phase prototype (WA105) with dimensions $3\times1\times1$ m^3 is being constructed at CERN, and should be operational in 2016. The ultimate validation of the engineered solutions for both designs of the FD is foreseen in the context of the neutrino activities at the CERN North Area extension (EHN1 area) around 2018, where full-scale engineering prototypes will be assembled and commissioned. Following this milestone, a test-beam data campaign will be executed to collect a large sample of charged-particle interactions in order to study the response of the detector with high precision. A comprehensive list of synergies between the reference and alternative designs has been identified (Chapter 6 of Volume 4: *The DUNE Detectors at LBNF*). Common solutions for DAQ, electronics, HV feed-throughs, and so on, will pursued and implemented, independent of the details of the TPC design. The ongoing and planned efforts will provide the ideal environment to exploit such synergies and implement common solutions. There is recognition that the LArTPC technology will continue to evolve with (1) the large-scale prototypes at the CERN Neutrino Platform and the experience from the Fermilab SBN program, and (2) the experience gained during the construction and commissioning of the first 10-kt module. The staged approach with the deployment of consecutive modules will enable an early science program while allowing implementation of improvements and developments during the experiment's lifetime. The strategy for implementing the far detector is presented in Section **??**.

3.3.2 The Near Detector

The primary role of the DUNE near detector system is to characterize the energy spectrum and the composition of the neutrino beam at the source, in terms of both muon- and electron-flavored neutrinos and antineutrinos, and to provide measurements of neutrino interaction cross sections. This is necessary to control systematic uncertainties with the precision needed to fulfill the DUNE primary science objectives. The separation between fluxes of neutrinos and antineutrinos requires a magnetized neutrino detector to charge-discriminate electrons and muons produced in the neutrino charged-current interactions. As the near detector will be exposed to an intense flux of neutrinos, it will collect an unprecedentedly large sample of neutrino interactions, allowing for an extended science program. The near detector will therefore provide a broad program of fundamental neutrino interaction measurements, which are an important part of the ancilliary scientific goals of the DUNE collaboration. The reference design for the near detector design is the NOMAD-inspired fine-grained tracker (FGT), illustrated in Figure **??**. Its subsystems include a central straw-tube tracker and an electromagnetic calorimeter embedded in a 0.4-T dipole field. The steel of the magnet yoke will be instrumented with muon identifiers. The strategy for implementation of the near detector is presented in Section **??**.

The near detector will be complemented by a Beamline Measurement System (BLM) located in the region of the beam absorber at the downstream end of the decay region. The BLM aims to measure the muon fluxes from hadron decay and is intended to monitor the beam profile on a spill-by-spill basis. It will operate for the life of the experiment.

3.4 Strategy for Implementing the DUNE Far Detector

The LBNF project will provide four separate cryostats to be located on the 4850L at the Sanford Underground Research Facility (SURF). Instrumentation of the first cryostat will commence in 2021. As part of the deployment and risk mitigation strategies, the cryostat for the second detector must be available when the first cryostat is filled. The aim is to install the third and fourth cryostats

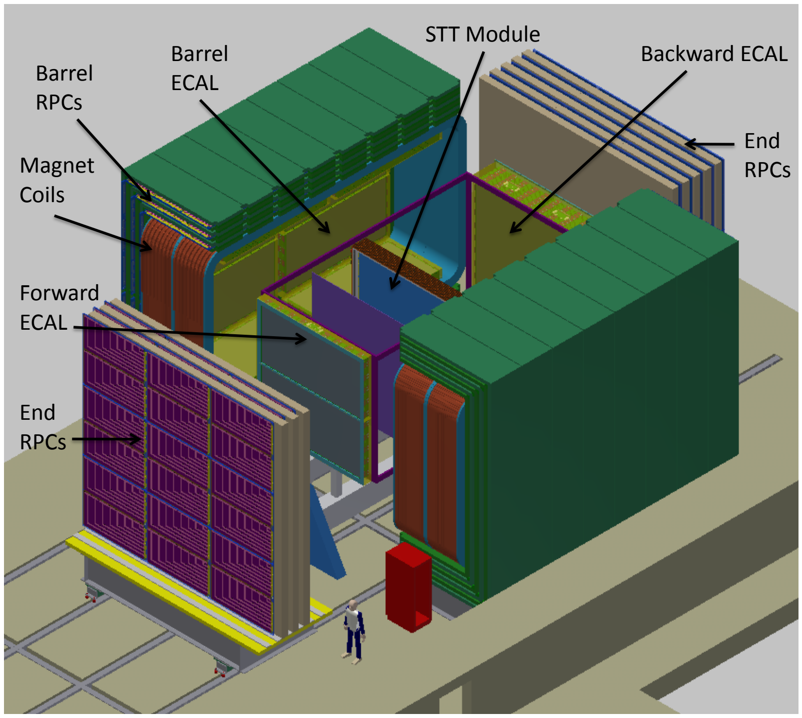

Figure 3.4: A schematic drawing of the fine-grained tracker design fig:FGT_

as rapidly thereafter as funding allows.

The DUNE collaboration aims to deploy four 10-kt (fiducial) mass FD modules based on the LArTPC technology, the viability of which has been proven by the ICARUS experiment. Neutrino interactions in liquid argon produce ionization and scintillation signals. While the basic detection method is the same, DUNE contemplates two options for the readout of the ionization signals: single-phase readout, where the ionization is detected using readout (wire) planes in the liquid argon volume; and the dual-phase approach, where the ionization signals are amplified and detected in gaseous argon above the liquid surface. The dual-phase approach, if demonstrated, would allow for a 3-mm readout pitch, a lower detection energy threshold, and better reconstruction of the events. The DUNE single-phase readout design is being validated in the 35-t prototype detector at Fermilab. A 20-t dual-phase readout prototype is being constructed at CERN and will operate in 2016. An active development program for both technologies is being pursued in the context of the Fermilab Short-Baseline Neutrino (SBN) program and the CERN Neutrino Platform. A flexible approach to the DUNE far detector designs offers the potential to bring additional interest and resources into the experimental collaboration.

3.4.1 Guiding Principles for the DUNE Far Detector

- The lowest-risk design for the first 10-kt module satisfying the requirements will be adopted, allowing for its installation at SURF to commence in 2021. Installation of the second 10-kt module should commence before 2022.

- There is recognition that the LArTPC technology will continue to evolve with: (1) the large-scale prototypes at the CERN Neutrino Platform and the experience from the Fermilab SBN program, and (2) the experience gained during the construction and commissioning of the first 10-kt module. It is assumed that all four modules will be similar but not necessarily identical.

- In order to start installation on the timescale of 2021, the first 10-kt module will be based on the APA/CPA design, which is currently the lowest risk option. There will be a clear and transparent decision process (organized by the DUNE Technical Board) for the design of the second and subsequent far detector modules, allowing for evolution of the LArTPC technology to be implemented. The decision will be based on physics performance, technical and schedule risks, costs and funding opportunities.

- The DUNE Collaboration will instrument the second cryostat as soon as possible.

- A comprehensive list of synergies between the reference and alternative designs has been identified and summarized in Volume 4: *The DUNE Detectors at LBNF*. Common solutions for DAQ, electronics, HV feed-throughs, etc., will be pursued and implemented, independent of the details of the TPC design.

3.4.2 Strategy for the First 10-kt Far Detector Module

strategy

The viability of wire-plane LArTPC readout has already been demonstrated by the ICARUS T600 experiment, where data were successfully accumulated over a period of three years. An extrapolation of the observed performance and the implementation of improvements in the design (such as immersed cold electronics) will allow the single-phase approach to meet the LBNF/DUNE far detector requirements. In order to start the FD installation by 2021, the first 10-kt module will be based on the single-phase design using anode and cathode plane assemblies (APAs and CPAs), described in Chapter 4 of Volume 4: *The DUNE Detectors at LBNF*. Based on previous experience and the future development path in the Fermilab SBN program and at the CERN Neutrino Platform, this choice represents the lowest-risk option for installation of the first 10-kt FD module by 2021. For these reasons, the APA/CPA single-phase wire plane LArTPC readout concept is the *reference design* for the far detector. The design is already relatively advanced for the conceptual stage. From this point on, modifications to the reference design will require approval by the DUNE Technical Board. A preliminary design review will take place as early as possible, utilizing the experience from the DUNE 35-t prototype; the design review will define the baseline design that will form the basis of the TDR (CD-2). At that point, the design will be put under a formal change-control process.

A single-phase engineering prototype, comprising six full-sized drift cells of the TDR engineering baseline, is planned as a central part of the risk-mitigation strategy for the first 10-kt module. It will be validated at the CERN Neutrino Platform in 2018 (pending approval by CERN). Based on the performance of this prototype, a final design review will take place towards the end of 2018 and construction of the readout planes will commence in 2019, to be ready for first installation in 2021. The design reviews will be organized by the DUNE Technical Coordinator.

In parallel with preparation for construction of the first 10-kt far detector module, the DUNE collaboration recognizes the potential of the dual-phase technology and strongly endorses the already approved development program at the CERN Neutrino Platform (the WA105 experiment), which includes the operation of the 20-t prototype in 2016 and the $6\times6\times6\,\mathrm{m}^3$ demonstrator in 2018. Participation in the WA105 experiment is open to all DUNE collaborators. A concept for the dual-phase implementation of a far detector module is presented as an *alternative design* in Volume 4: *The DUNE Detectors at LBNF*. This alternative design, if demonstrated, could form the basis of the second or subsequent 10-kt modules, in particular to achieve improved detector performance in a cost-effective way.

3.4.3 DUNE at the CERN Neutrino Platform

WA105 has signed an MoU with the CERN Neutrino Platform to provide a large $\sim8\times8\times8\,\mathrm{m}^3$ cryostat by October 2016 in the new EHN1 extension, and it is foreseen that a second large cryostat to house the single-phase LArTPC will be provided on a similar timescale. Both will be exposed to charged-particle test beam spanning a range of particle types and energies.

The DUNE collaboration will instrument one of these cryostats with an arrangement of six APAs and six CPAs, in a APA:CPA:APA configuration providing an engineering test of the full-size drift volume. These will be produced at two or more sites with the cost shared between the DOE project and international partners. The CERN prototype thus provides the opportunity for the production sites to validate the manufacturing procedure ahead of large-scale production for the far detector. Three major operational milestones are defined for this single-phase prototype: (1) engineering validation (successful cool-down); (2) operational validation (successful TPC readout with cosmic-ray muons); and (3) physics validation with test-beam data. Reaching milestone 2, scheduled for early 2018, will allow the retirement of a number of technical risks for the construction of the first 10-kt module. The proposal for the DUNE single-phase prototype will be presented to the CERN SPS Scientific Committee in June 2015.

In parallel, the WA105 experiment approved by the CERN Research Board in 2014 and supported by the CERN Neutrino Platform has a funded plan to construct and operate a large-scale demonstrator utilizing the dual-phase readout in the test beam by October 2017. Successful operation and demonstration of long-term stability of the WA105 demonstrator will establish this technological solution as an option for the second or subsequent far detector modules. The DUNE dual-phase design is based on independent $3\times3\,\mathrm{m}^2$ charge readout planes (CRP) placed at the gas-liquid interface. Each module provides two perpendicular "collection" views with 3-mm readout pitch. A 10-kt module would be composed of 80 CRPs hanging from the top of the cryostat, decoupled from the field cage and cathode. The WA105 demonstrator will contain four $3\times3\mathrm{m}^2$ CRPs of the DUNE type giving the opportunity to validate the manufacturing procedure ahead of large-scale production. WA105 is presently constructing a $3 \times 1\,\mathrm{m}^2$ CRP to be operated in 2016. The same operational milestones (engineering, operational, physics) are defined as for the single-phase prototype.

The DUNE program at the CERN Neutrino Platform will be coordinated by a single L2 manager. Common technical solutions will be adopted wherever possible for the DUNE single-phase engineering prototype and the dual-phase (WA105) demonstrator. The charged-particle test-beam data will provide essential calibration samples for both technologies and will enable a direct comparison of the relative physics capabilities of the single-phase and dual-phase TPC readout.

3.4.4 Strategy for the Second and Subsequent 10-kt Far Detector Modules

For the purposes of cost and schedule, the reference design for the first module is taken as the reference design for the subsequent three modules. However, the experience with the first 10-kt module and the development activities at the CERN Neutrino Platform are likely to lead to the evolution of the TPC technology, both in terms of refinements to single-phase design and the validation of the operation of the dual-phase design. The DUNE technical board will instigate a formal review of the design for the second module in 2020; the technology choice will be based on risk, cost (including the potential benefits of additional non-DOE funding) and physics performance (as established in the CERN charged-particle test beam). After the decision, the design of the second module will come under formal change control. This process will be repeated for the third and fourth modules.

This strategy allows flexibility with respect to international contributions, enabling the DUNE collaboration to adopt evolving approaches for subsequent modules. This approach provides the possibility of attracting interest and resources from a broader community, and space for flexibility to respond to the funding constraints from different sources.

3.5 Strategy for Implementing the DUNE Near Detector(s)

The primary scientific motivation for the DUNE near detector is to determine the beam spectrum for the long-baseline neutrino oscillation studies. The near detector, which is exposed to an intense flux of neutrinos, also enables a wealth of fundamental neutrino interaction measurements, which are an important part of the scientific goals of the DUNE collaboration. Within the former LBNE collaboration the neutrino near detector design was the NOMAD-inspired fine-grained tracker (FGT), which was established through a strong collaboration of U.S. and Indian institutes.

3.5.1 Guiding Principles for the DUNE Near Detector

It is recognized that a detailed cost-benefit study of potential near detector options has yet to take place and such a study is of high priority to the DUNE Collaboration. The primary design considerations for the DUNE near neutrino detector include

- the ability to adequately constrain the systematic errors in the DUNE LBL oscillation analysis; this requires the capability to precisely measure exclusive neutrino interactions
- the self-contained non-oscillation neutrino physics program

3.5.2 DUNE Near Detector Reference Design

The NOMAD-inspired fine-grained tracker (FGT) concept is the *reference design* for CD-1 review. The cost and resource-loaded schedule for CD-1 review will be based on this design, as will the near site conventional facilities. The Fine-Grained Tracker consists of: central straw-tube tracker (STT) of volume $3.5\,\mathrm{m}\times3.5\,\mathrm{m}\times6.4\,\mathrm{m}$; a lead-scintillator sandwich sampling electromagnetic calorimeter (ECAL); a large-bore warm dipole magnet, with inner dimensions of $4.5\,\mathrm{m}\times4.5\,\mathrm{m}\times8.0\,\mathrm{m}$, surrounding the STT and ECAL and providing a magnetic field of 0.4 T; and RPC-based muon detectors (MuIDs) located in the steel of the magnet, as well as upstream and downstream of the STT. The reference design is presented in Chapter 7 of Volume 4: *The DUNE Detectors at LBNF*.

For ten years of operation in the LBNF 1.2-MW beam (5 years neutrinos + 5 years antineutrinos), the near detector will record a sample of more than 100 million neutrino interactions and 50 million antineutrino interactions. These vast samples of neutrino interactions will provide the necessary strong constraints on the systematic uncertainties for the LBL oscillation physics — the justification is given in Section 6.1.1 of Volume 2: *The Physics Program for DUNE at LBNF*. The large samples of neutrino interactions will also provide significant physics opportunities, including numerous topics for PhD theses.

The contribution of Indian institutions to the design and construction of the DUNE FGT neutrino near detector is a vital part of the strategy for the construction of the experiment. The reference design will provide a rich self-contained physics program. From the perspective of an ultimate LBL oscillation program, there may be benefits of augmenting the FGT with, for example, a relatively small LArTPC in front of the FGT that would allow for a direct comparison with the far detector. A second line of study would be to augment the straw-tube tracker with a high-pressure gaseous argon TPC. At this stage, the benefits of such options have not been studied; alternative designs for the near detector are not presented in the CDR and will be the subject of detailed studies in the coming months.

3.5.3 DUNE Near Detector Task Force

A full end-to-end study of the impact of the near detector design (in particular of the fine-grain tracker) on the LBL oscillation systematics has yet to be performed. Many of the elements of such a study are in development, for example the Monte Carlo simulation of the FGT and the adaptation of the T2K framework for implementing ND measurements as constraints in the propagation of systematic uncertainties to the far detector.

After the CD-1-R review, the DUNE collaboration will initiate a detailed study of the optimization of the near detector. To this end a new task force will be set up with the charge of:

- delivering the simulation of the near detector reference design and possible alternatives
- undertaking an end-to-end study to provide a quantitative understanding of the power of the near detector designs to constrain the systematic uncertainties on the LBL oscillation measurements
- quantifying the benefits of augmenting the reference design with a LArTPC or a high-pressure gaseous argon TPC

High priority will be placed on this work and the intention is to engage a broad cross section of the collaboration in this process. The task force will be charged to deliver a first report by July 2016. Based on the final report of this task force and input from the DUNE Technical Board, the DUNE Executive Board will refine the DUNE strategy for the near detector.

Chapter 4

Organization and Management

4.1 Overview

To accommodate a variety of international funding model constraints, LBNF and DUNE are organized as separate projects. As mentioned in the Introduction, the LBNF Project is responsible for design and construction of the conventional facilities, beamlines, and cryogenic infrastructure needed to support the experiment. The DUNE Project is responsible for the construction and commissioning of the detectors used to pursue the scientific program. LBNF is organized as a DOE/Fermilab project incorporating international partners. DUNE is an international project organized by the DUNE Collaboration with appropriate oversight from stakeholders including the DOE.

4.2 LBNF

4.2.1 Project Structure and Responsibilities

The LBNF Project is charged by Fermilab and DOE to design and construct the conventional and technical facilities needed to support the DUNE Collaboration. LBNF works in close coordination with DUNE to ensure that the scientific requirements of the program are satisfied through the mechanisms described in Section **??**. LBNF also works closely with SURF management to coordinate the design and construction of the underground facilities required for the DUNE far detector.

LBNF consists of two major L2 subprojects coordinated through a central Project Office located at Fermilab: Far Site Facilities and Near Site Facilities. Each L2 Project incorporates several large L3 subprojects as detailed in the WBS structure presented in Figure **??**.

The Project team consists of members from Fermilab, CERN, South Dakota Science and Technology Authority (SDSTA), and BNL. The team, including members of the Project Office as well as the L2 and L3 managers for the individual subprojects, is assembled by the Project Director. The Project team to WBS Level 3 of the WBS is shown in Figure **??**. Line management for environment, safety and health, and quality assurance flows through the Project Director.

Through their delegated authority and in consultation with major stakeholders, the L2 Project Managers determine which of their lower-tier managers will be Control Account Managers (CAMs) for the Project WBS. L2 and L3 Project Managers are directly responsible for generating and maintaining the cost estimate, schedule, and resource requirements for their subprojects and for meeting the goals of their subprojects within the accepted baseline cost and schedule.

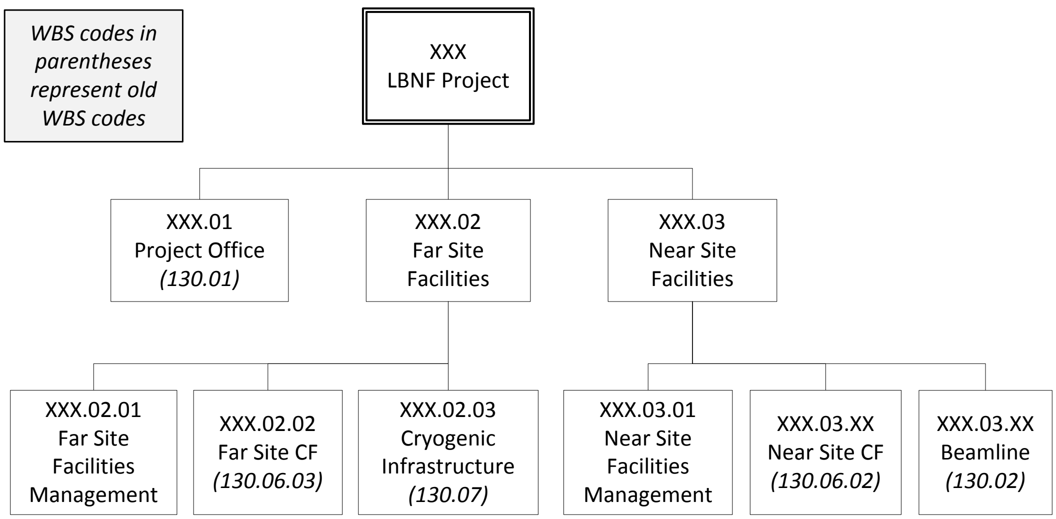

Figure 4.1: LBNF Work Breakdown Structure (WBS) to level 3

The design and construction of LBNF is supported by other laboratories and consultants/contractors that provide scientific, engineering, and technical expertise. A full description of LBNF Project Management is contained within the LBNF Project Management Plan[**?**].

4.2.2 SDSTA and SURF

LBNF plans to construct facilities at SURF to house the DUNE far detector. SURF is owned by the state of South Dakota and managed by the SDSTA.

Current SURF activities include operations necessary for allowing safe access to the 4850L of the mine, which houses the existing and under-development science experiments. The DOE is presently funding SDSTA ongoing operations through Lawrence Berkeley National Laboratory (LBNL) and its SURF Operations Office through FY16; this is expected to change to funding through Fermilab starting in FY17.

The LBNF Far Site Facilities Manager is also an employee of SDSTA and is contracted to Fermilab to provide management and coordination of the Far Site Conventional Facilities (CF) and

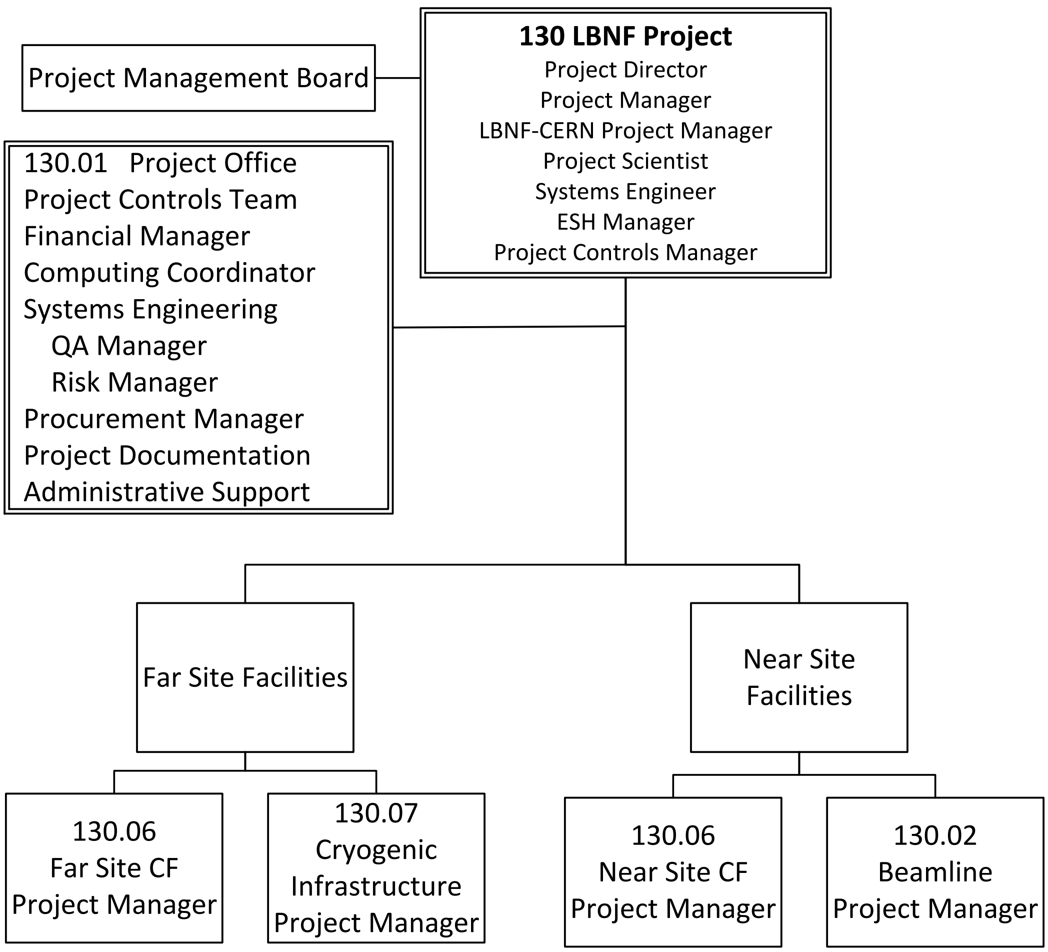

Figure 4.2: LBNF organization

Cryogenics Infrastructure subprojects. LBNF contracts directly with SDSTA for the design of the required CF at SURF; whereas the actual construction of the CF will be directly contracted from Fermilab. Coordination between SDSTA and the LBNF Project is necessary to ensure efficient operations at SURF. This will be facilitated via an agreement being developed between SDSTA and Fermilab regarding the LBNF Project

[new reference]

that defines responsibilities and methods for working jointly on LBNF Project design and construction. A separate agreement will be written for LBNF Operations.

4.2.3 CERN

The European Organization for Nuclear Research (CERN) is expected to significantly contribute to LBNF with technical components, required to support the deployment of the DUNE detectors and of the neutrino beamline.

4.2.4 Coordination within LBNF

The LBNF Project organization is headed by the LBNF Project Director who is also the Fermilab Deputy Director for LBNF and reports directly to the Fermilab Director. Within Fermilab's organization, two new divisions are being created to execute the Far Site Facilities and Near Site Facilities subprojects. The heads of these divisions will report to the LBNF Project Manager. Any personnel working more than half-time on these subprojects would typically be expected to become a member of one of these divisions, while other contributors will likely be matrixed in part-time roles from other Fermilab Divisions. The heads of the other Fermilab Divisions work with the L1 and L2 project managers to supply the needed resources on an annual basis. The management structure described above is currently being transitioned into and will not be fully in place until the Fall of 2015.

The LBNF WBS defines the scope of the work. All changes to the WBS must be approved by the LBNF Project Manager prior to implementation. At the time of CD-1-Refresh, the LBNF WBS is in transition. Both the current and the post CD-1-R WBS is shown in Figure **??** fig:lbnf-wbs to demonstrate how the scope will map from one WBS to the other. SDSTA assigns engineers and others as required to work on specific tasks required for the LBNF Project at the SURF site. This is listed in the resource-loaded schedule as contracted work from Fermilab for Far Site CF activities. CERN and Fermilab are developing a common cryogenics team to design and produce the Cryogenics Infrastructure subproject deliverables for the far site. CERN provides engineers and other staff as needed to complete their agreed-upon deliverables. LBNF has formed several management groups with responsibilities as described below.

Project Management Board: LBNF uses a Project Management Board to provide formal advice to the Project Director on matters of importance to the LBNF Project as a whole. Such matters include (but are not limited to) those that:

- have significant technical, cost, or schedule impact on the Project
- have impacts on more than one L2 subproject
- affect the management systems for the Project
- have impacts on or result from changes to other Projects on which LBNF is dependent
- result from external reviews or reviews called by the Project Director

The Management Board serves as the

- LBNF Change Control Board, as described in the Configuration Management Plan[?] CMP-10760
- Risk Management Board, as described in the Fermilab Risk Management Procedure for Projects [?] fnal-risk-mgmt

Beamline Technical Board: The role of the LBNF Beamline Technical Board (TB) is to provide recommendations and advice to the Beamline Project Manager on important technical decisions that affect the design and construction of the Beamline. The members of the Technical Board must have knowledge of the Project objectives and priorities in order to perform this function. The Beamline Project Manager chairs the Beamline TB. The Beamline Project Engineer is the Scientific Secretary of the Board and co-chairs the Beamline TB as needed.

FSCF Neutrino Cavity Advisory Board: The Far Site CF (FSCF) Project has engaged three international experts in hard rock underground construction to advise it periodically through the design and construction process regarding excavation at SURF. The Board meets at the request of the FSCF-PM, generally on site to discuss specific technical issues. The Board produces a report with its findings and conclusions for Project information and action.

4.3 DUNE

4.3.1 DUNE Collaboration Structure

The DUNE Collaboration brings together the members of the international science community interested in participating in the DUNE experiment. The Collaboration defines the scientific goals of the experiment and subsequently the requirements on the experimental facilities needed to achieve these goals. The Collaboration also provides the scientific effort required for the design and construction of the DUNE detectors, operation of the experiment, and analysis of the collected data. There are four main entities within the DUNE organizational structure:

- DUNE Collaboration, including the General Assembly of the Collaboration and the Institutional Board.

- DUNE Management, consisting of the two Co-Spokespersons, the Technical Coordinator, and the Resource Coordinator. These four along with the chair of the Institutional Board and five additional members of the Collaboration form the DUNE Executive Committee.

- DUNE Project Management, containing the Project Office, headed by the Project Manager, and the managers of the DUNE detector and prototyping groups.

- DUNE Science Coordination, incorporating the coordinators of the DUNE detector and prototyping groups, the Physics and Software/Computing Coordinators, as well as the DUNE Technical and Finance Boards.

The connections between the different members of these entities is illustrated in Figure ??. fig:dune-org

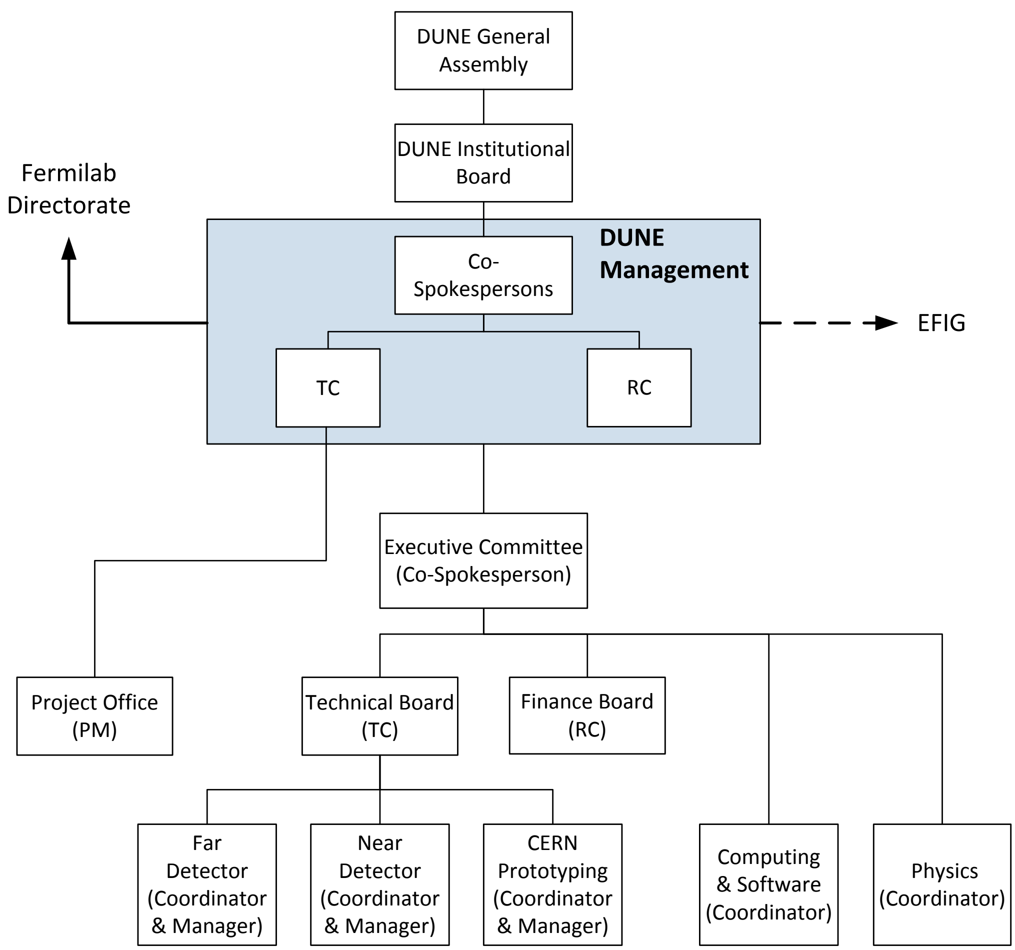

Figure 4.3: DUNE Project and Collaboration organization fig:dune

4.3.2 DUNE Management Structure

The main responsibilities of each of the roles are summarized below:

- **DUNE General Assembly** is composed of the full membership of the Collaboration. It is consulted on all major strategic decisions through open plenary sessions at Collaboration meetings and is provided regular updates on issues affecting the Collaboration at weekly Collaboration meetings. The Collaboration General Assembly elects the co-spokespersons through a process defined by the Institutional Board.

- **DUNE Institutional Board (IB)** is the representative body of the Collaboration institutions. It has responsibility for the governance of the Collaboration. The IB has final authority over Collaboration membership issues and defines the requirements for inclusion of individuals on the DUNE author list. The IB is also responsible for the process used to select the co-spokespersons and the Executive Committee. The IB chairperson serves on the Executive Committee and runs the Institutional Board meetings.

- **DUNE Co-Spokespersons** are elected by the Collaboration to serve as its leaders. They direct Collaboration activities on a day-to-day basis and represent the Collaboration in interactions with the host laboratory, funding agencies, and the broader scientific community.

- **DUNE Executive Committee (EC)** is the primary decision-making body of the Collaboration and is chaired by the longest serving Co-Spokesperson. The membership of the EC consists of the Co-Spokespersons, the Technical Coordinator, the Resource Coordinator, the chair of the IB, and five additional members of the Collaboration (three elected IB representatives and two additional members selected by the Co-Spokespersons). The EC operates as a decision-making body through consensus. In cases where the EC is unable to reach a consensus, final decision-making authority is assigned to the Co-Spokespersons. If the Co-Spokespersons are unable to reach their own consensus, the Fermilab Director will step in to resolve the issue.

- **Technical Coordinator (TC)** is jointly appointed by the Co-Spokespersons and the Fermilab Director and has reporting responsibilities to both. In the context of the international DUNE Project, the TC serves as the project director and is responsible for implementing the scientific and technical strategy of the Collaboration. Currently, the TC also serves as project director for the DOE-funded portion of the DUNE Project. In addition to managing the Project Office, the TC chairs the Collaboration Technical Board which coordinates activities associated with the design, construction, installation, and commissioning of the detector elements.

- **Technical Board (TB)** is chaired by the TC and has a membership that includes the coordinators and managers of the Collaboration detector and prototyping groups. It may also include additional members of the Collaboration, nominated by the TC and approved by the EC, who are expected to bring useful knowledge and expertise to its discussions on technical issues. The TB is the primary forum for discussion of issues related to detector design, construction, installation and commissioning. This body serves as a Project change-control board for change requests with schedule and cost impacts that lie below pre-determined thresholds necessitating EC approval. Change requests that have impacts on interfaces with the LBNF Project, potential impacts on DUNE science requirements, or that require modifications of formal Memoranda of Understanding (MOU) with one or more contributing funding agencies, are discussed within the TB; however these require higher-level approvals, starting with the EC. The TB is also the primary forum for discussing technological design choices faced by the Collaboration. Based on these discussions, the TB is expected to make a recommendation on the preferred technology choice to the TC, who is then charged with making a final recommendation to the EC.

- **Resource Coordinator (RC)** is jointly appointed by the Co-Spokespersons and the Fermilab Director and has reporting responsibilities to both. The RC chairs the Collaboration Finance Board and is tasked with preparing the formal MOUs that define the contributions and responsibilities of each institution. The RC is also responsible for management of the common financial resources of the Collaboration (common fund). Project change requests approved by the EC that involve modification of MOUs with one or more of the participating funding agencies are taken by the RC first to the Collaboration Finance Board for discussion and then, in cases where consensus is obtained, to the Resources Review Board for final approval.

- **Finance Board (FB)** is chaired by the RC and has a membership that includes a single representative from each group of collaborating institutions whose financial support for participating in the DUNE experiment originates from a single, independent funding source. These Collaboration representatives are either nominated through their respective group of institutions and approved by the associated funding agency, or directly appointed by the funding agency. The FB discusses issues related to Collaboration resources such as contributions to Project common funds and division of Project responsibilities among the collaborating institutions. The FB is also responsible for vetting proposed Project change requests prior to their submission to the Resource Research Board for approval.

- **DUNE Science Coordinators** include the coordinators of the detector and prototyping groups as well as the coordinators of the DUNE physics and computing/software efforts. Science coordinators are nominated by the Co-Spokespersons (jointly with the TC in the case of detector and prototyping group coordinators) and approved by the EC. These coordinators are expected to establish additional Collaboration sub-structures within their assigned areas to cover the full scope of Collaboration activities within their areas of responsibility. Detector and prototyping group coordinators report to the EC through the TB, while coordinators of the physics and software/computing efforts report directly to the EC.

- **DUNE Project Office (PO)** provides the project management for the design, construction, installation, and commissioning of the DUNE near and far detectors. Members of the Project Office, including the Project Manager (PM), are appointed by the TC. The DUNE Project will be run as an international project following DOE guidelines. The PO will have control over common funds collected from the U.S. and international stakeholders. Other contributions to the DUNE Project are expected to be in the form of deliverables as defined through formal MOUs. The PO will maintain a full schedule for the entire DUNE Project and track contributions through detailed subproject milestones. The entire DUNE Project (including international contributions) will follow the DOE critical decision process incorporating a CD-2 approval of its baseline cost and schedule and a CD-3 approval for moving forward with construction. The current high-level WBS structure of the DUNE Project, which will be evolving in the near future to best take advantage of the additional resources available within the new Collaboration, is illustrated in Figure **??**.

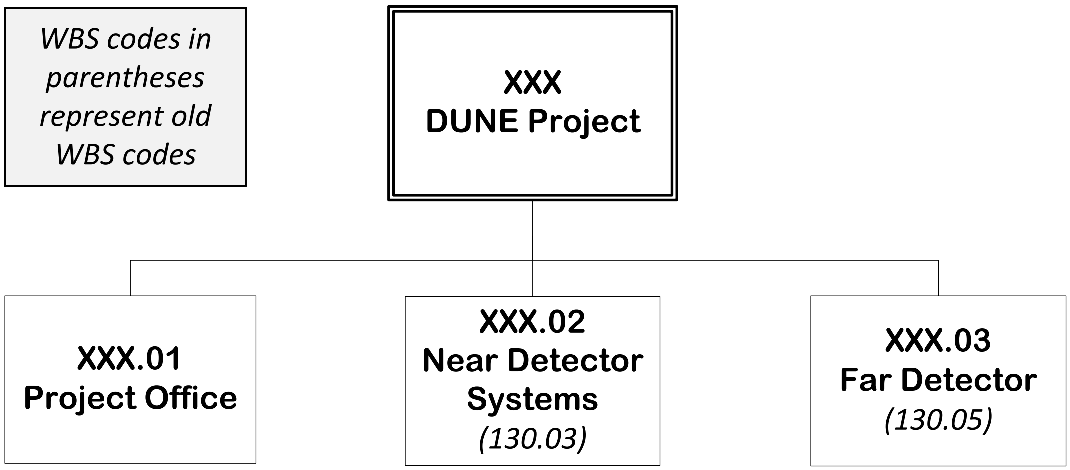

Figure 4.4: DUNE Work Breakdown Structure (WBS)

- **DUNE Detector and Prototyping Managers** provide the required interface between the DUNE Project and the members of the Collaboration contributing to these efforts. These managers sit within the detector and prototyping groups where all matters related to the design, construction, installation, and commissioning of the individual detector elements are discussed. These managers are tasked with implementing the plans developed within their group and are part of a joint management team which addresses issues associated with Project interfaces and coordination of detector and prototyping group efforts.

4.4 LBNF/DUNE Advisory and Coordinating Structures

A set of structures is established to provide coordination among the participating funding agencies, oversight of the LBNF and DUNE projects, and coordination and communication between the two projects. These structures and the relationships among them are shown in Figure **??** and are described in this section.

4.4.1 International Advisory Council (IAC)

The International Advisory Council (IAC) is composed of regional representatives, such as CERN, and representatives of funding agencies that make major contributions to LBNF infrastructure or to DUNE. The IAC acts as the highest-level international advisory body to the U.S. DOE and the FNAL Directorate and facilitates high-level global coordination across the entire enterprise

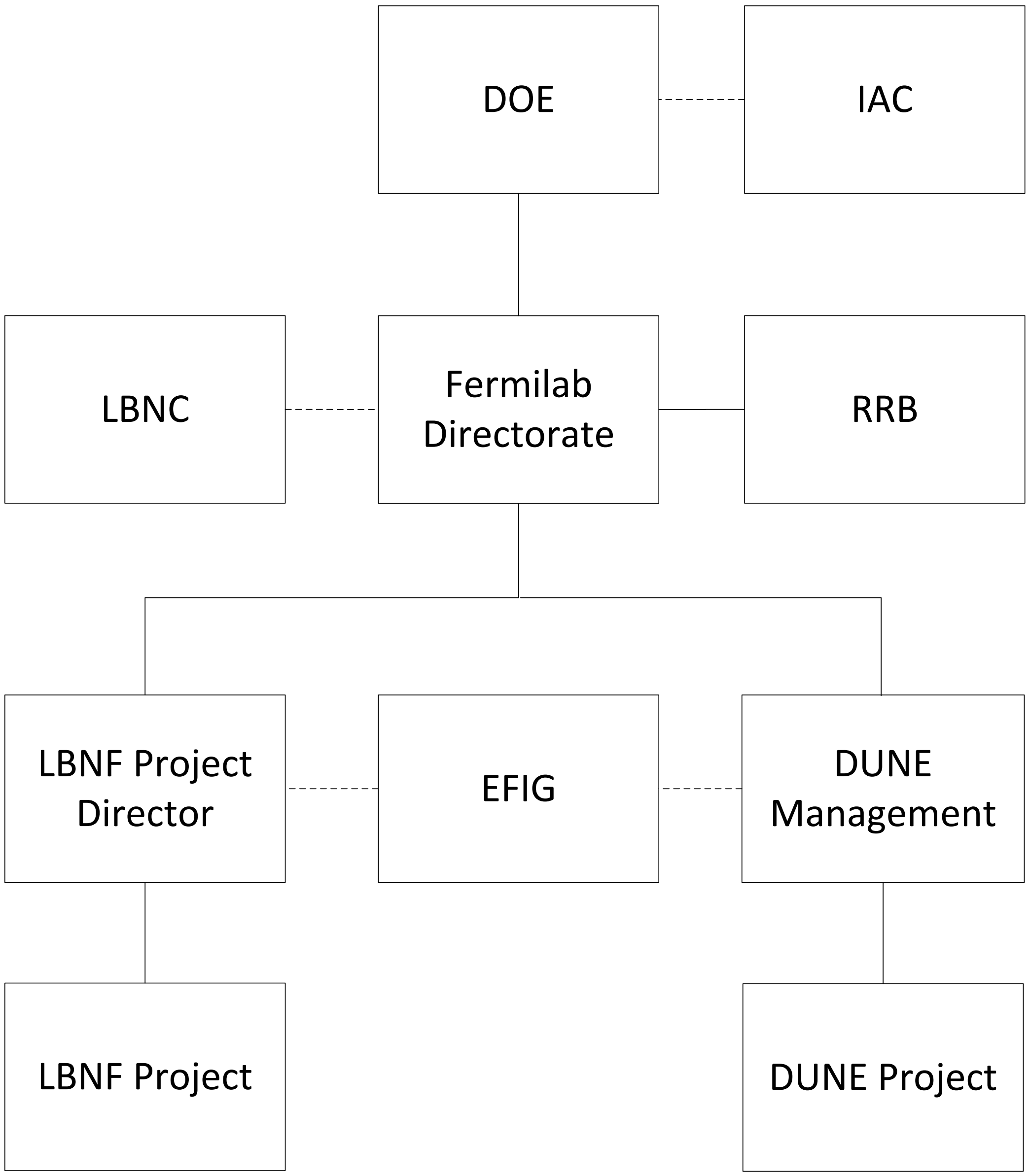

Figure 4.5: Joint LBNF/DUNE management structure

fig:lbnf

(LBNF and DUNE). The IAC is chaired by the DOE Office of Science Associate Director for High Energy Physics and includes the FNAL Director in its membership. The council meets as needed and provides pertinent advice to LBNF and DUNE through the Fermilab Director.

Specific responsibilities of the IAC include, but are not limited to, the following:

- During the formative stages of LBNF and DUNE the IAC helps to coordinate the sharing of responsibilities among the agencies for the construction of LBNF and DUNE. Individual agency responsibilities for LBNF will be established in bilateral international agreements with the DOE. Agency contributions to DUNE will be formalized through separate agreements.

- The IAC assists in resolving issues, especially those that cannot be resolved at the Resources Review Boards (RRB) level, e.g., issues that require substantial redistributions of responsibilities among the funding agencies.

- The IAC assists as needed in the coordination, synthesis and evaluation of input from Project reports charged by individual funding agencies, LBNF and DUNE Project management, and/or the IAC itself, leading to recommendations for action by the managing bodies.

The initial membership, as of May 19, 2015, of the IAC is as follows: James Siegrist (DOE HEP, Chair), Sergio Bertolucci (CERN), Arun Srivastava (DAE), Carlos Henrique de Brito Cruz (FAPESP), Fernando Ferroni (INFN), Fabiola Gianotti (CERN), Rolf Heuer (CERN), Stavros Katsanevas (ApPEC), Frank Linde (ApPEC), Nigel Lockyer (FNAL), Reynald Pain (IN2P3/CNRS), John Womersley (STFC) and Agnieszka Zalewska (IFJ).

The DUNE Co-Spokespersons and/or other participants within the Fermilab neutrino program will be invited to sessions of the IAC as needed. Council membership may increase as additional funding agencies from certain geographic regions make major contributions to LBNF and DUNE.

4.4.2 Resources Review Boards (RRB)

The Resources Review Boards (RRB) are composed of representatives of all funding agencies that sponsor LBNF and DUNE, and of the Fermilab management. The RRB provides focused monitoring and detailed oversight of each of the Projects. The Fermilab Director in coordination with the DUNE RC defines its membership. A representative from the Fermilab Directorate chairs the boards and organize regular meetings to ensure the flow of resources needed for the smooth progress of the enterprise and for its successful completion. The managements of the DUNE Collaboration and the LBNF Project participates in the RRB meetings and make regular reports to the RRB on technical, managerial, financial and administrative matters, as well as status and progress of the DUNE Collaboration.

There are two groups within the RRB: RRB-LBNF and RRB-DUNE. Each of these groups monitors progress and addresses the issues specific to its area while the whole RRB deals with matters that concern the entire enterprise. The RRB will meet biannually; these meetings will start with a plenary opening session and be followed by RRB-LBNF and RRB-DUNE sessions. As DUNE progresses toward experimental operations, RRB-Computing sessions will convene.

DUNE Finance Board members who serve as National Contacts from the sponsoring funding agencies will be invited to RRB sessions.

The RRB employs standing DUNE and LBNF *Scrutiny Groups* as needed to assist in its responsibilities. The scrutiny groups operate under the RRB, and provide detailed information on financial and personnel resources, costing, and other elements under the purview of the RRB.

Roles of the RRB includes:

- assisting the DOE and the FNAL Directorate, with coordinating and developing any required international agreements between partners
- monitoring and overseeing the Common Projects and the use of the Common Funds
- monitoring and overseeing general financial and personnel support
- assisting the DOE and the FNAL Directorate with resolving issues that may require reallocation of responsibilities among the Project's funding agencies
- reaching consensus on a maintenance and operation procedure, and monitoring its function
- approving the annual construction, and maintenance and operation common fund budget of DUNE

4.4.3 Fermilab, the Host Laboratory

As the host laboratory, Fermilab has a direct responsibility for the design, construction, commissioning and operation of the facilities and infrastructure (LBNF) that support the science program. In this capacity, Fermilab reports directly to the DOE through the Fermilab Site Office (FSO). Fermilab also has an important oversight role for the DUNE Project itself as well as an important coordination role in ensuring that interface issues between the two Projects are completely understood.

Fermilab's oversight of the DUNE Collaboration and detector construction project is carried out through

- regular meetings with the Collaboration leadership
- approving the selection of Collaboration spokespersons
- providing the Technical and Resource Coordinators
- convening and chairing the Resources Review Boards

- regular scientific reviews by the PAC and LBNC
- Director's Reviews of specific management, technical, cost and schedule aspects of the detector construction project
- other reviews as needed

4.4.4 DUNE Collaboration

The Collaboration, in consultation with the Fermilab Director, is responsible for forming the international DUNE Project team responsible for designing and constructing the detectors. The Technical Coordinator (TC) and Resource Coordinator (RC) serve as the lead managers of this international project team and are selected jointly by the spokespersons and the Fermilab Director. Because the international DUNE Project incorporates contributions from a number of different funding agencies, it is responsible for satisfying individual tracking and reporting requirements associated with the different contributions.

4.4.5 Long-Baseline Neutrino Committee (LBNC)

The Long-Baseline Neutrino Committee (LBNC), composed of internationally prominent scientists with relevant expertise, provides external scientific peer review for LBNF and DUNE regularly. The LBNC reviews the scientific, technical and managerial decisions and preparations for the neutrino program. It acts in effect as an adjunct to the Fermilab Physics Advisory Committee (PAC), meeting on a more frequent basis than the PAC. The LBNC may employ DUNE and LBNF Scrutiny Groups for more detailed reports and evaluations. The LBNC members are appointed by the Fermilab Director. The current membership of the LBNC is: David MacFarlane (SLAC, Chair), Ursula Bassler (IN2P3), Francesca Di Lodovico (Queen Mary), Patrick Huber (Virginia Tech), Mike Lindgren (FNAL), Naba Mondal (TIFR), Tsuyoshi Nakaya (Kyoto), Dave Nygren (UT Arlington), Stephen Pordes (FNAL), Kem Robinson (LBNL), Nigel Smith (SNOLAB) and Dave Wark (Oxford and STFC). Among these members, David McFarlane and Dave Wark are also members of the Fermilab PAC.

4.4.6 Experiment-Facility Interface Group (EFIG)

Close and continuous coordination between DUNE and LBNF is required to ensure the success of the combined enterprise. An Experiment-Facility Interface Group (EFIG) was established in January 2015 to oversee and ensure the required coordination both during the design/construction and operational phases of the program. This group covers areas including:

- interface between the near and far detectors and the corresponding conventional facilities

- interface between the detector systems provided by DUNE and the technical infrastructure provided by LBNF
- design and operation of the LBNF neutrino beamline

The EFIG is chaired by two deputy directors of Fermilab. Its membership includes the LBNF Project Director, Project Manager and Project Scientist, and the DUNE Co-Spokespersons, Technical Coordinator, Resource Coordinator and the CERN-LBNF Project Manager. In consultation with the DUNE and LBNF management, the EFIG Chairs will extend the membership as needed to carry out the coordination function. In addition, the DOE Federal Project Director for LBNF, the Fermilab Chief Project Officer, and a designated representative of the South Dakota Science and Technology Authority (SDSTA) will serve ex officio. The EFIG Chairs designate a Secretary of the EFIG, who keeps minutes of the meetings and performs other tasks as requested by the Chair.

It is the responsibility of the EFIG Chairs to report EFIG proceedings to the Fermilab Director and other stakeholders. It is the responsibility of the DUNE spokespersons to report EFIG proceedings to the rest of the Collaboration. The EFIG meets weekly or as needed.

The current membership of the EFIG is: Joe Lykken (representing Fermilab Director, Chair), Nigel Lockyer (acting LBNF Project Director), Elaine McCluskey (LBNF Project Manager), Jim Strait (LBNF Project Scientist), André Rubbia (DUNE co-spokesperson), Mark Thomson (DUNE co-spokesperson), Eric James (DUNE Technical Coordinator), Chang Kee Jung (DUNE Resource Coordinator), Marzio Nessi (CERN), David Lissauer (BNL), Jim Stewart (BNL), Jeff Dolph (BNL, Secretary), Mike Lindgren (FNAL Chief Project Officer, ex officio), Pepin Carolan (DOE, ex officio), and Mike Headley (SDSTA, ex officio).

Chapter 5

Summary

LBNF/DUNE will be a world-leading facility for pursuing a cutting-edge program of neutrino physics and astroparticle physics. The combination of the intense wide-band neutrino beam, the massive LArTPC far detector and the highly capable near detector will provide the opportunity to discover CP violation in the neutrino sector as well as to determine the neutrino mass ordering and provide a precision test of the three-flavor oscillation paradigm. The massive, deep-underground far detector will offer unprecedented sensitivity for theoretically favored proton decay modes and for observation of electron neutrinos from a core-collapse supernova, should one occur in our galaxy during the operation of the experiment.

In addition to summarizing the compelling scientific case for LBNF/DUNE, this document presents an overview of the technical designs of the facility and experiment and the strategy for their implementation. This strategy delivers the science goals described in the 2014 report of the Particle Physics Project Prioritisation Panel (P5) on a competitive timescale. Furthermore, a detailed management plan for the organization of LBNF as a U.S.-hosted facility and the DUNE experiment as a broad international scientific collaboration has been developed, thus satisfying the goal of internationalizing the project as highlighted in the P5 report.

References