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Chapter 1

Executive Summary

1.1 Overview

1.1.1 The DUNE Science Program

The preponderance of matter over antimatter in the early universe, the dynamics of the supernova neutrino bursts (SNBs) that produced the heavy elements necessary for life, and whether protons eventually decay — these mysteries at the forefront of particle physics and astrophysics are key to understanding the early evolution of our universe, its current state, and its eventual fate. The Deep Underground Neutrino Experiment (DUNE) is an international world-class experiment dedicated to addressing these questions.

Experiments carried out over the past half century have revealed that neutrinos are found in three states, or *flavors*, and can transform from one flavor into another. These results indicate that each neutrino flavor state is a mixture of three different nonzero mass states, and to date offer the most compelling evidence for physics beyond the standard model. In a single experiment, DUNE will enable a broad exploration of the three-flavor model of neutrino physics with unprecedented detail. Chief among its potential discoveries is that of matter-antimatter asymmetries (through the mechanism of charge-parity symmetry violation (CPV)) in neutrino flavor mixing — a step toward unraveling the mystery of matter generation in the early universe. Independently, determination of the unknown neutrino mass ordering and precise measurement of neutrino mixing parameters by DUNE may reveal new fundamental symmetries of nature.

Neutrinos emitted in the first few seconds of a core-collapse supernova carry with them the potential for great insight into the evolution of the universe. DUNE's capability to collect and analyze this high-statistics neutrino signal from a supernova within the Milky Way would provide a rare opportunity to peer inside a newly formed neutron star and potentially witness the birth of a black hole.

Grand unified theories (GUTs), which attempt to describe the unification of the known forces, predict rates for proton decay that cover a range directly accessible with the next generation of large underground detectors such as the DUNE far detector. The experiment's sensitivity to key proton decay channels will offer unique opportunities for the ground-breaking discovery of this phenomenon.

1.1.2 The DUNE Detectors and Supporting Facilities

To achieve its goals, the international DUNE experiment, hosted by the U.S. Department of Energy's Fermi National Accelerator Laboratory (Fermilab) in Illinois, comprises three central components: (1) a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab, (2) a massive far detector (FD) situated 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, and (3) a composite near detector (ND) installed just downstream of the neutrino source. Figure 1.1 illustrates the layout of these components. The far detector, the subject of this technical design report (TDR), will be a modular liquid argon time-projection chamber (LArTPC) with a fiducial (sensitive) mass of 40 kt[1] (40 Gg) of liquid argon (LAr), a cryogenic liquid that must be kept at 88 K (−185°C). This detector will be able to uniquely reconstruct neutrino interactions with image-like precision and unprecedented resolution [1].

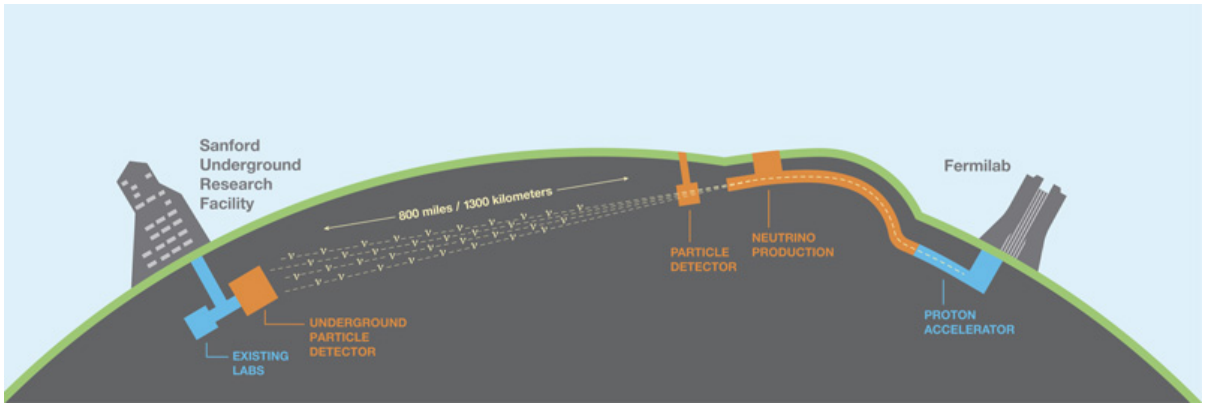


Figure 1.1: Cartoon illustrating the configuration of the LBNF beamline at Fermilab, in Illinois, and the DUNE detectors in Illinois and South Dakota, separated by 1300 km.

The Long-Baseline Neutrino Facility (LBNF) project, also hosted by Fermilab, provides the beamline and the civil construction, called conventional facilities (CF), for the DUNE experiment. The organization and management of LBNF is separate from that of the experiment; its design and construction are organized as a U.S. DOE/Fermilab project incorporating international partners.

The LBNF beamline at Fermilab will deliver the world's most intense neutrino beam to the near and far detectors in an on-axis configuration. The upgrade to the Proton Improvement Plan II (PIP-II) [2], a leading-edge, superconducting, linear proton accelerator under construction at Fermilab, will deliver between 1.0 and 1.2 MW of proton beam power from the Fermilab Main Injector to LBNF, which will aim and focus the beam, whereupon the protons, in a wide energy

[1] For comparison, this is nearly twice the mass of the Statue of Liberty and nearly four times that of the Eiffel Tower.

band of 60 GeV to 120 GeV, will collide with a high-power production target, creating a secondary beam from which the intense neutrino flux will emerge, traveling in the direction of the DUNE detectors (Figure 1.2). A further planned upgrade of the accelerator complex could provide up to 2.4 MW of beam power by 2030, potentially extending the DUNE science reach. The upgrade will also increase the reliability of the Fermilab accelerator complex and provide the flexibility to produce customized beams tailored to specific scientific needs.

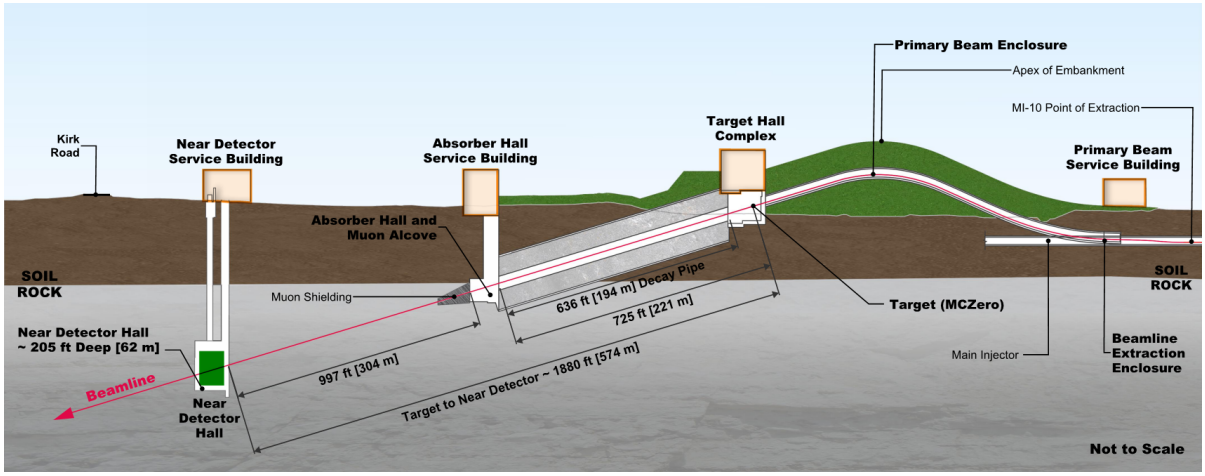


Figure 1.2: Neutrino beamline and DUNE near detector hall at Fermilab in Illinois

The intense, wide-band neutrino beam, the massive LArTPC detector at the far site, and the composite (i.e., multi-purpose) ND will provide a rich ancillary science program for the DUNE experiment, beyond its primary goals, including accelerator-based neutrino flavor-transition measurements with sensitivity to physics beyond the standard model, measurements of tau neutrino appearance, measurements of neutrino oscillation phenomena using atmospheric neutrinos, and a rich neutrino interaction physics program using the DUNE ND, including a wide range of measurements of neutrino cross sections, studies of nuclear effects, and searches for dark matter. Further advances in LArTPC technology during FD construction may open up possibilities to observe very low-energy phenomena such as solar neutrinos or even the diffuse supernova neutrino flux – measurements that require a sensitivity that is presently beyond our reach.

1.1.3 The DUNE Collaboration

The DUNE collaboration is a global organization with more than 1000 scientists and engineers from 31 countries (Figure 1.3). It represents the combination of several worldwide efforts that developed independent paths toward a next-generation long-baseline neutrino experiment over the last decade. DUNE was formed in April 2015, combining the strengths of the LBNE project in the U.S. and the Long Baseline Neutrino Observatory (LBNO) project in Europe, adding many new international partners in the process. DUNE thus 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. DOE and Fermilab to support a significant expansion of the underground infrastructure at SURF in South Dakota and to create a megawatt neutrino-beam facility at Fermilab.

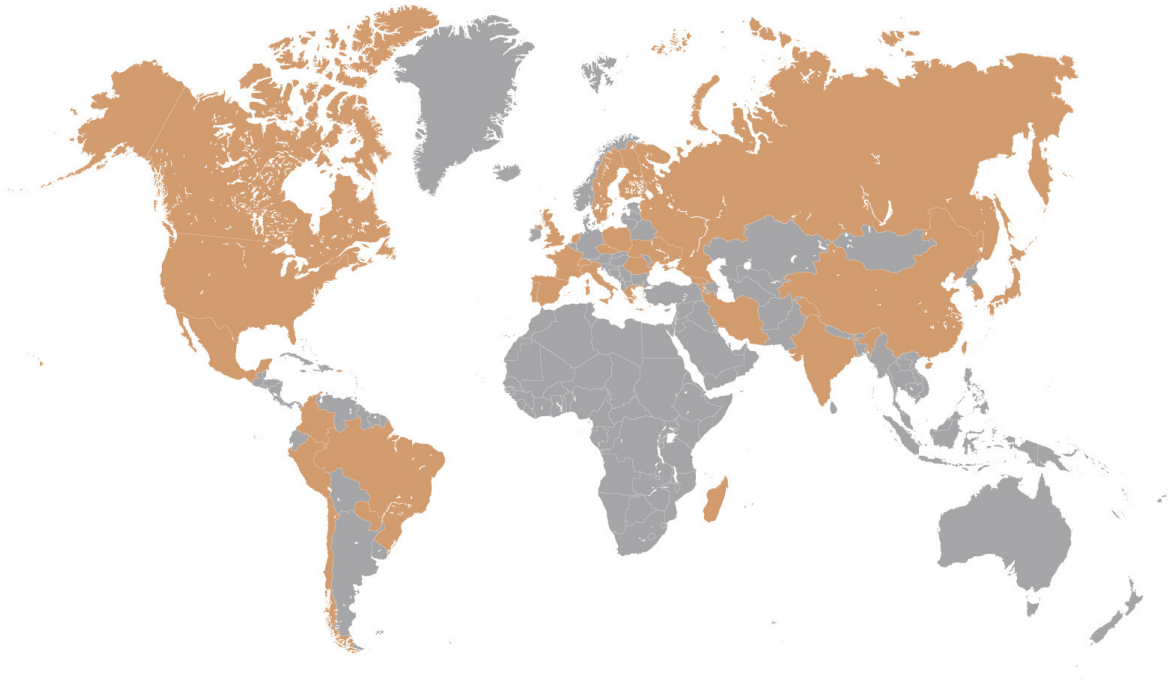


Figure 1.3: The international DUNE collaboration. Countries with DUNE membership are in light brown.

1.1.4 Strategy for the DUNE Far Detector Design

DUNE and LBNF have developed the strategy presented in this TDR to meet the requirements laid out in the report of the U.S. Particle Physics Project Prioritization Panel (P5) in 2014. The strategy also takes into account the recommendations of the European Strategy for Particle Physics (ESPP) adopted by the European Organization for Nuclear Research (CERN) Council in 2013, which classified the long-baseline neutrino program as one of the four scientific objectives requiring significant resources, sizable collaborations, and sustained commitment.

The P5 report [3] set the goal of determining leptonic CPV with a precision of three standard deviations ($3\,\sigma$) or greater (i.e., a precision of at least 0.03 %), over more than 75 % of the range of possible values (0 through 2π) of the unknown CP-violating phase $\delta_{\rm CP}$. It is impossible to provide coverage of 100 % since CPV effects vanish as the value of $\delta_{\rm CP}$ approaches 0 or π. Based partly on this goal, the report stated that "the minimum requirements to proceed are the identified capability to reach an exposure of $120\,{\rm kt}\cdot{\rm MW}\cdot{\rm year}$ [2] by the 2035 time frame, 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 neutrino bursts (SNBs) and for proton decay, providing a significant improvement in discovery sensitivity over current searches for proton decay."

[2] $1\,{\rm kt}\cdot{\rm MW}\cdot{\rm year}$ is the amount of exposure a detector of target mass 1 kt of LAr would get in one year using a 1 MW proton beam to generate the neutrinos. Exposure increases linearly as each of the factors increases.

Here we briefly address how the LBNF and DUNE project (LBNF/DUNE) strategy and designs will satisfiy each of these requirements and deliver a world-leading neutrino program. The following chapters and the other volumes of this TDR elaborate on these concepts, providing a full picture of this ambitious enterprise.

Reach at least 120 kt · MW · year exposure by the 2035 timeframe and 1.2 MW beam power: To reach the necessary precision on its measurements, DUNE will need to collect a few thousand neutrino interactions over a period of about ten years. The number of interactions is the product of (1) the intensity of the neutrino beam, (2) the probability that a neutrino will oscillate (approximately 0.02), (3) the interaction cross section, and (4) the detector mass. Currently, the highest-power proton beam that a beam target can safely withstand is between 1 and 2 MW, which caps the achievable neutrino beam intensity. This points to a required a detector mass in the tens-of-kilotons range. The DUNE FD cryostats will hold 17.5 kt of LAr each, for a total of nearly 70 kt, of which at least 40 kt will be encompassed by the four detector modules as fiducial mass. Higher usable fractions of the total volume are under study.

Moreover, the DUNE concept builds on the notion that a highly-performant detector technology with excellent neutrino energy reconstruction and background rejection capabilities can optimize sensitivity and cost with an on-axis exposure to an intense, wide-band, conventional (magnetic horn-focused) beam. The current generation of long-baseline neutrino experiments have benefited from narrow-band beam characteristics associated with off-axis detector deployment, which offers a low background rate in both electron neutrino (ν_e) appearance and muon neutrino (ν_μ) disappearance channels. However, this advantage comes at a cost of flux and spectral information relative to an on-axis detector configuration [1, 4].

Situated underground: Given the rate of cosmic rays at the surface (165 kHz) and the neutrino beam parameters, the ratio of neutrino events to cosmic rays would be less than one to a million and the discovery potential for DUNE's oscillation physics goals would be vanishingly small. Roughly 1500 m underground at the SURF site, this ratio becomes slightly higher than 1, raising the discovery potential to a very achievable level. Supernova neutrinos have energies on the order of 100 times lower than beam neutrinos, and despite the fact that they arrive in a few-second burst, would be nearly impossible to identify on the surface. A meaningful search for nucleon decay is not possible at the surface. All three of the experiment's primary goals require significant overburden for the FD, which the SURF site provides.

Use of liquid argon (LAr): This requirement implies the use of the LArTPC technology, which enables finer resolution for kiloton-scale particle detectors than earlier technologies do. The enhanced resolution leads to greater efficiency in distinguishing signal events from background, which in turn leads to a reduction in the necessary size of the detector and potentially broadens the physics program. It is especially important for the long-baseline program with a wide-band neutrino beam. Additionally, the choice of LArTPC technology provides valuable complementarity to other existing and planned detectors pursuing many of the same goals. As an example, the sensitivity of DUNE to the ν_e component of supernova neutrino flux, prevalent in the neutronization phase of the explosion, provides distinct information relative to that provided by water or organic scintillator-based detectors in which electron antineutrino ($\bar{\nu}_e$) interactions dominate.

Sensitivity to CPV: The physics that DUNE will pursue demands measurements at the few-percent

level. With just a FD, the neutrino fluxes would be known only to about 10 % and interaction rates to at best 20 %. To adequately reduce these uncertainties, is necessary to measure the neutrinos at a near location, e.g., 500 m from the neutrino source and at a far location, e.g., 1300 km away, using the same target nucleus in both detectors, and to extract the physics measurements from differences between the two. The ND can be smaller than the FD, but it must be multi-functional since the differences in the measurements are not due solely to oscillations. The detector rate is the product of the neutrino flux, the detector response, and the interaction cross section, the first two of which will differ between the ND and FD due to other factors as well, e.g., event rate and geometry. The ND must be able to measure the factors that go into the detector rate separately.

The optimal FD distance (baseline) to determine the mass hierarchy (MH), observe CPV, and observe δ_{CP} is between 1000 and 2000 km; at shorter baselines the optimal neutrino energy is lower, the second oscillation maximum is too low in energy to be visible, and charge parity (CP) sensitivity is reduced by ambiguities from the unknown mass ordering. At longer baselines CP sensitivity is harmed by matter effects that increase with baseline. The 1300 km baseline offered by locating the FD at SURF is optimized for the neutrino oscillation physics goals of the DUNE program.

The scientific basis for DUNE's foundational experimental design choices has been examined and validated through extensive review, undertaken at all stages of DUNE development. Recent experimental and theoretical developments have only strengthened the scientific case for DUNE and its basic configuration. The technical underpinnings for these choices have also been strengthened over time through a worldwide program of R&D and engineering development, as described in a suite of LBNF/DUNE project documents including this TDR, as well as through independent experiments and development activities.

1.2 The Long-Baseline Neutrino Facility (LBNF)

As mentioned above, the LBNF project will provide the beamline and the conventional facilities (CF) for both detectors of the DUNE experiment. At the far site, SURF in South Dakota, LBNF will construct a facility to house and provide infrastructure for the DUNE 10 kt fiducial mass FD modules; in particular LBNF is responsible for:

- the excavation of three underground caverns at SURF, north and south detector caverns and a central utility cavern (CUC) for the detector's ancillary systems; this requires the removal of 800 kt of rock[3];
- free-standing, steel-supported cryostats to contain each detector module in a bath of 17.5 kt of LAr;
- the required cryogenics systems for rapidly deploying the first two modules;
- surface, shaft, and underground infrastructure at SURF to support installation, commissioning, and operation of the detector; and
- the LAr required to fill the first two cryostats.

[3]This is roughly the mass of the Golden Gate Bridge including its anchorage and approaches.

DUNE intends to install the third and fourth FD modules as rapidly as funding will allow. When finished, the north and south caverns will each house two modules and the CUC will house cryogenics and data acquisition facilities for all four modules.

Figure 1.4 shows the cavern layout for the FD in the SURF underground area, also referred to as the 4850 (foot) level or 4850L.

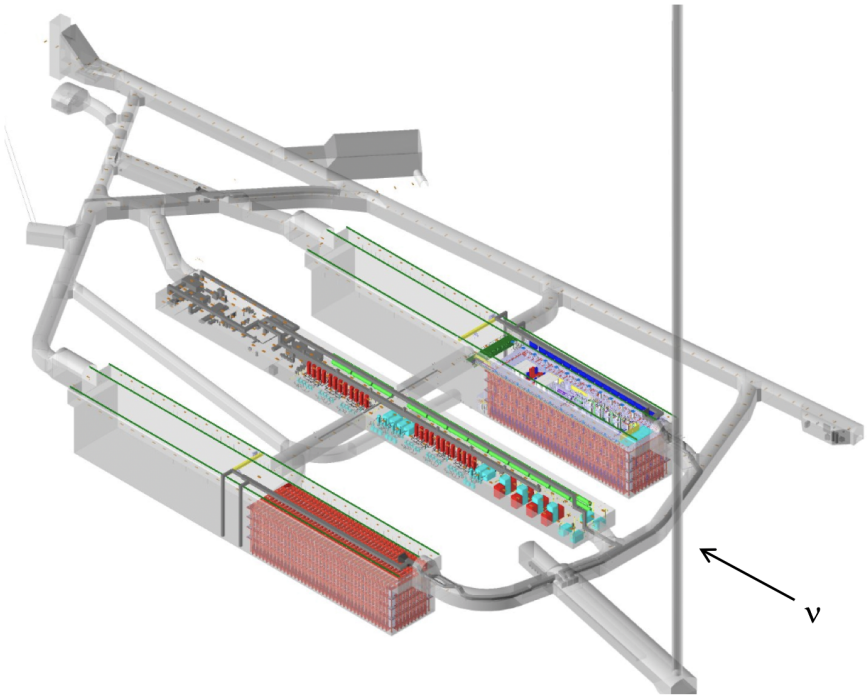


Figure 1.4: Underground caverns for the DUNE FD and cryogenics systems at SURF in South Dakota. The drawing shows the cryostats (red) for the first two FD modules in place at the 4850L. The Ross Shaft, the vertical shaft that will provide access to the DUNE underground area, appears on the right. Each cryostat is 65.8 m long (216 ft, approximately the length of two and a half tennis courts), 18.9 m wide, and 17.8 m tall (about three times as tall as an adult giraffe). The two detector caverns are each 144.5 m long, 19.8 m wide, and 28.0 m high, providing some room around the cryostats.

1.3 The DUNE Detectors

1.3.1 Far Detector

The DUNE FD will consist of four LArTPC detector modules, each with a LAr mass in the sensitive region of the cryostat (fiducial mass) of at least 10 kt, installed approximately 1.5 km underground. excellent tracking and calorimetry performance, making it an ideal choice. Each LArTPC fits inside a cryostat of internal dimensions 15.1 m (w) × 14.0 m (h) × 62.0 m (l) containing a total LAr mass of about 17.5 kt. The design of the four identically sized modules is sufficiently flexible for staging construction and evolving the LArTPC technology.

DUNE is planning for and currently developing two LArTPC technologies: single-phase (SP) in which all the detector elements inside the cryostat are immersed in liquid; and dual-phase (DP), in which some components operate in a layer of gaseous argon above the liquid.

- In the SP technology, ionization charges drift horizontally in the LAr under the influence of an electric field (E field) towards a vertical anode, where they are read out. This design requires very low-noise electronics to achieve readout with a good signal-to-noise (S/N) ratio because no signal amplification occurs inside the cryostat. This technology was pioneered in the ICARUS project, and after several decades of worldwide R&D, is now mature. It is the technology used for Fermilab's currently operating MicroBooNE detector, as well as the SBND detector, which is under construction. Figure 1.5 shows the operating principle of an SP LArTPC.
- The DP technology was pioneered at a large scale by the WA105 DP demonstrator collaboration at CERN. It is less mature than the SP technology, and whereas it presents some challenges, it offers several advantages. Here, ionization charges drift vertically upward in LAr and are transferred into a layer of argon gas above the liquid. Devices called large electron multipliers (LEMs) amplify the signal charges in the gas phase before they reach a horizontal anode. The gain achieved in the gas reduces the stringent requirements on the electronics noise and the overall design increases the possible drift length, which, in turn, requires a correspondingly higher voltage. Figure 1.6 shows the operating principle of a DP LArTPC.

In both technologies, the drift volumes are surrounded by a field cage (FC) that defines the active detector volume and ensures uniformity of the E field within that volume.

Argon is an excellent scintillator at a wavelength of 126.8 nm (UV), a property that both detector designs exploit. This fast scintillation light (photons), once shifted into the visible spectrum, is collected by photon detectors (PDs) in both designs. The light collection provides an initial start time (t_0) for every event recorded by the time projection chamber (TPC), indicating when the ionization electrons begin to drift. Comparing the time at which the ionization signal reaches the anode relative to this start time allows reconstruction of the event topology in the drift coordinate (i.e., horizontal and transverse to the beam for SP and vertical for DP); the precision of the measured t_0, therefore, directly corresponds to the precision of the spatial reconstruction in this direction.

Two key factors affect the performance of the DUNE LArTPCs: LAr purity and noise on the readout electronics. First, the LAr purity must be quite high to minimize charge and light attenuation over the longest drift lengths in the detector module. The SP and DP designs have slightly different purity requirements (expressed in minimum electron lifetimes of 3 ms versus 5 ms) due to the different maximum drift lengths. Second, the electronic readout of the LArTPC requires very low noise levels for the signal from the drifting electrons to be clearly discerned over the baseline of the electronics. This requires using low-noise cryogenic electronics, especially in the case of the SP design.

The DUNE collaboration is committed to deploying both technologies. The full DUNE FD requires four modules. In this TDR, we describe plans for the first three modules: two SP modules, one

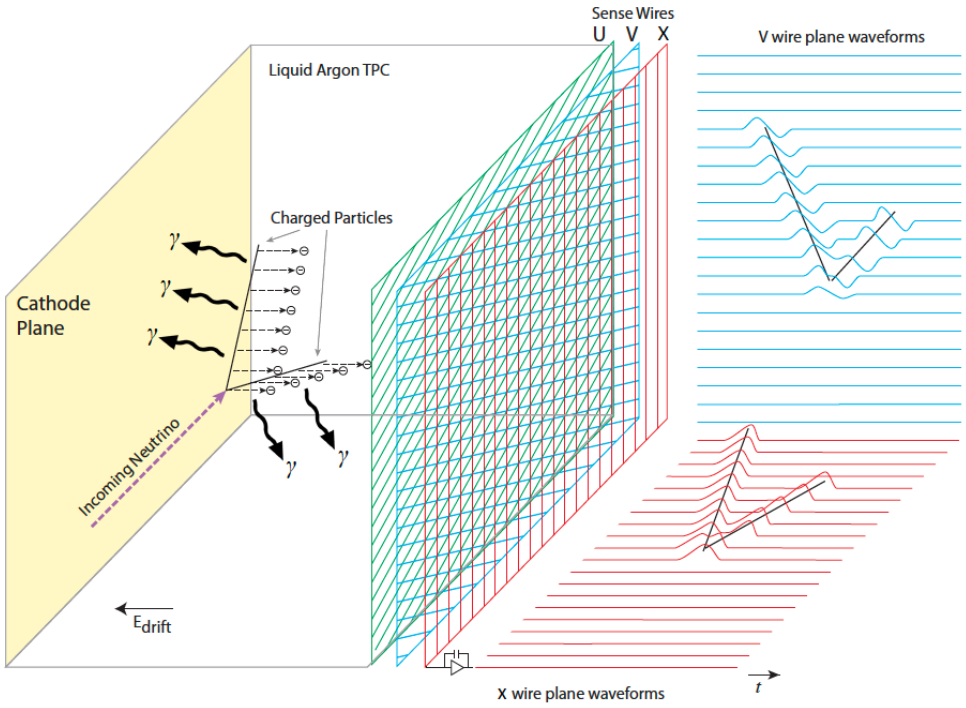


Figure 1.5: The general operating principle of the SP LArTPC. Negatively charged ionization electrons from the neutrino interaction drift horizontally opposite to the E field in the LAr and are collected on the anode, which is made up of the U, V and X sense wires. The right-hand side represents the time projections in two dimensions as the event occurs. Light (γ) detectors (not shown) will provide the t_0 of the interaction.

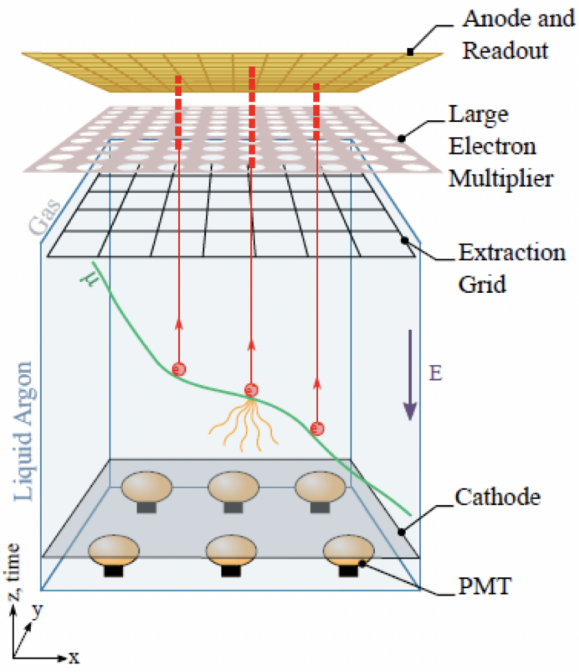


Figure 1.6: The general operating principle of the DP LArTPC. The ionization charges drift vertically upward in LAr and are transferred into a layer of argon gas above the liquid where they are amplified before collection on the anode. The light detectors (PMTs) sit under the cathode.

of which will be the first module installed, and one DP module. The actual sequence of detector module installation will depend on results from the prototype detectors, described below, and on available resources. Plans for the fourth detector module, which may use a more advanced design, remain to be determined.

The plans for the SP and DP modules are described briefly in the following sections, more fully in Chapters **??** and **??**, and finally in great detail in Volumes IV and V of this TDR.

1.3.1.1 A Single-Phase Far Detector Module

The operating principle of an SP LArTPC (Figure 1.5) has been demonstrated by ICARUS [5], MicroBooNE [6], ArgoNeuT [7], LArIAT [8], and ProtoDUNE-SP [9]. Charged particles passing through the TPC ionize the argon, and the ionization electrons drift in an E field to the anode planes. Figure 1.7 shows the configuration of a DUNE SP module. Each of the four drift volumes of LAr is subjected to a strong E field of 500 V/cm, corresponding to a cathode high voltage (HV) of 180 kV. The maximum drift length is 3.5 m.

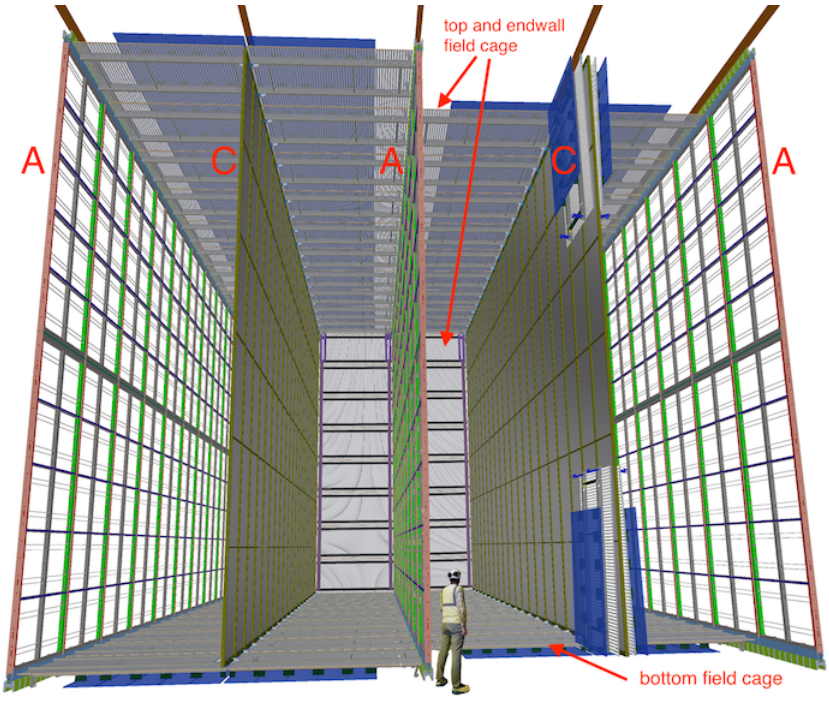


Figure 1.7: A 10 kt DUNE FD SP module, showing the alternating 58.2 m long (into the page), 12.0 m high anode (A) and cathode (C) planes, as well as the field cage (FC) that surrounds the drift regions between the anode and cathode planes. On the right-hand cathode plane, the foremost portion of the FC is shown in its undeployed (folded) state.

An SP module is instrumented with three module-length (58.2 m) anode planes constructed from 6 m high by 2.3 m wide anode plane assemblies (APAs), stacked two APAs high and 25 wide, for 50 APAs per plane, and 150 total. Each APA consists of an alumninum frame with three layers of active wires, strung at angles chosen to reduce ambiguities in event reconstruction, that form a grid on each side of the APA. The relative voltage between the layers is chosen to ensure

transparency to the drifting electrons of the first two layers (U and V). These layers produce bipolar induction signals as the electrons pass through them. The final layer (X) collects the drifting electrons, resulting in a unipolar signal. The pattern of ionization collected on the grid of anode wires provides the reconstruction in the remaining two coordinates perpendicular to the drift direction (Figure 1.5).

Novel silicon photomultiplier (SiPM) based photon detectors (PDs) called ARAPUCAs[4] are placed in the inactive space between the innermost wire planes of the APAs, installed through slots in the APA frame. Each APA holds ten PD modules, for a total of 1500 per SP module. Of these, 500 are mounted in the APAs of the central anode plane and collect light from both directions, and 500 each are mounted in the outer APA frames and collect light from only the inner-facing direction.

1.3.1.2 A Dual-Phase Far Detector Module

The DP operating principle, illustrated in Figure 1.6, is very similar to that of the SP. Charged particles that traverse the active volume of the LArTPC ionize the medium while also producing scintillation light. The ionization electrons drift, in this case vertically, along an E field toward a segmented anode where they deposit their charge. Any scintillation light that is produced is measured in PDs that view the interior of the volume from below.

In this design, shown in Figure 1.8, ionization electrons drift upward toward an extraction grid just below the liquid-vapor interface. After reaching the grid, an E field stronger than the 500 V/cm drift field extracts the electrons from the liquid up into the gas phase. Once in the gas, the electrons encounter micro-pattern gas detectors, called LEMs, with high-field regions in which they are amplified. The amplified charge is then collected and recorded on a 2D anode consisting of two sets of gold-plated copper strips that provide the x and y coordinates (and thus two views) of an event. An array of photomultiplier tubes (PMTs) coated with a wavelength-shifting material sits below the cathode to record the time (t_0) and pulse characteristics of the incident light.

The extraction grid, LEM, and anode are assembled into three-layered sandwiches with precisely defined inter-stage distances and inter-alignment, which are then connected horizontally into 9 m^2 modular detection units called charge-readout planes (CRPs).

The precision tracking and calorimetry offered by both the SP and DP technologies provide excellent capabilities for identifying interactions of interest while mitigating sources of background. Whereas the SP design has multiple drift volumes, the DP module design allows a single, fully homogeneous LAr volume with a much longer drift length.

[4] An "arapuca" is a South American bird trap; the name is used here as an analogy to the way the devices trap photons. These devices have been developed by DUNE collaborators in Brazil.

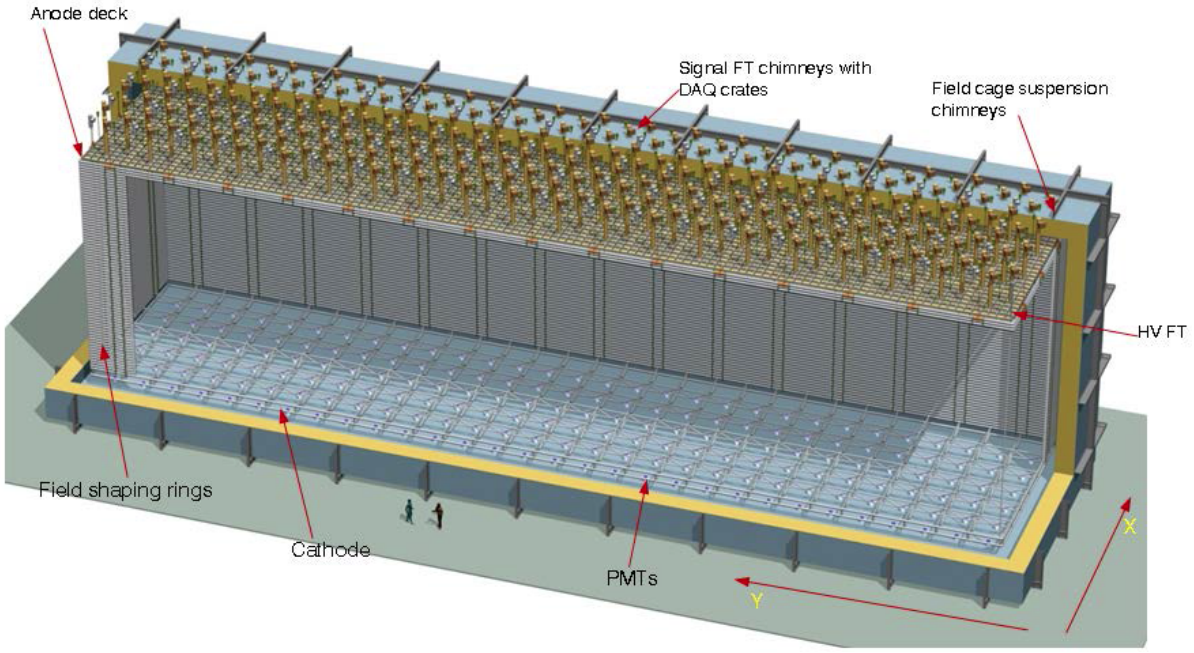


Figure 1.8: Schematic of a 10 kt DUNE FD DP detector module with cathode, PMTs, FC, and anode plane with signal feedthrough chimneys (SFT chimneys). The drift direction is vertical in the case of a DP module. The scale is indicated by the figures of two people standing in front of the model.

1.3.2 ProtoDUNEs: Far Detector Prototypes

The DUNE collaboration has constructed and operated two large prototype detectors, ProtoDUNE-SP, and ProtoDUNE-DP, at CERN. Each is approximately one-twentieth the size of the planned FD modules but uses components identical in size to those of the full-scale module. ProtoDUNE-SP has the same 3.5 m maximum drift length as the full SP module. ProtoDUNE-DP has a 6 m maximum drift length, half that planned for the DP module. Figure 1.9 shows the two cryostats, ProtoDUNE-SP in the foreground and ProtoDUNE-DP at an angle in the rear. Figure 1.10 shows one of the two drift volumes of ProtoDUNE-SP on the left and the single drift volume of ProtoDUNE-DP on the right.

This massive prototyping program was undertaken with both engineering and scientific goals in mind, namely:

1. production of components: stress-test the production and quality assurance (QA) processes of detector components and mitigate the associated risks for the FD;

2. validation of installation procedures: test the interfaces between the detector elements and mitigate the associated risks for the FD;

3. operation of the detector with cosmic rays: validate the detector designs and performance; and

4. collection of test beam data: measure the physics response of the detector.



Figure 1.9: ProtoDUNE-SP and ProtoDUNE-DP cryostats in the CERN Neutrino Platform in CERN's North Area.

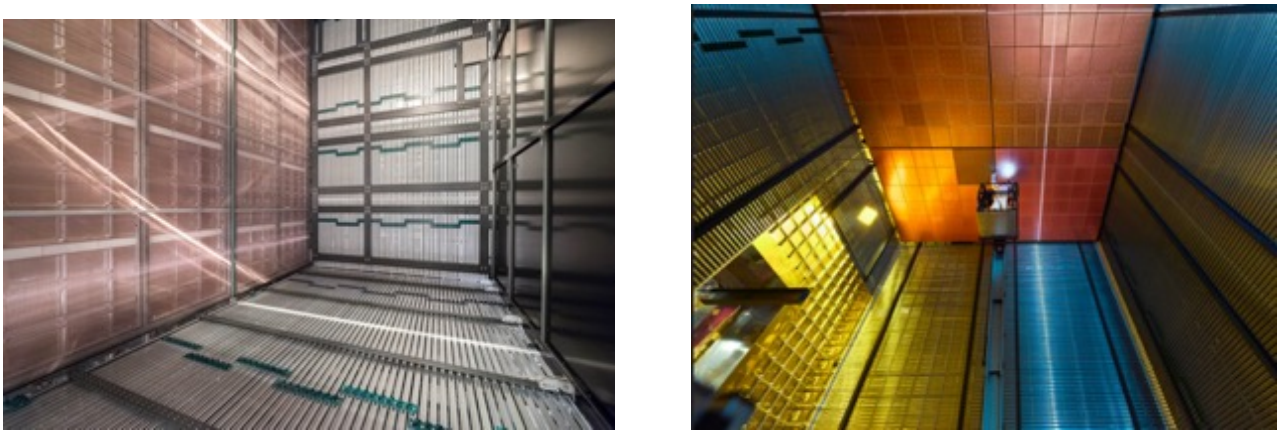


Figure 1.10: Left: View of one of the two drift volumes in ProtoDUNE-SP; the APA is on the left, the cathode plane assembly (CPA) is on the right, and two of the four the FC surfaces bounding the drift volume are at the center and bottom of the image. Right: the single ProtoDUNE-DP drift volume (still incomplete when the image was taken), looking up; the CRPs (orange) are at the top. Three sides of the surrounding FC are shown, but the cathode is not visible.

Construction of the ProtoDUNE-SP detector was finished in July 2018 and filled with LAr the following month. It collected hadron beam and cosmic ray data during the fall of 2018 and continues to collect cosmic ray data. Construction of the ProtoDUNE-DP detector was complete in June of 2019, and the detector started operations in September 2019.

The data taken with ProtoDUNE-SP demonstrate the detector's excellent performance and have already provided valuable information on the design, calibration, and simulation of the DUNE FD. In all, 99.7 % of the 15360 TPC electronics channels are responsive in the LAr. The equivalent noise charge (ENC) amounts to $\approx 550\ e^-$ on the collection wires and $\approx 650\ e^-$ on the induction wires, roughly half of the allowed maximum. An average S/N of 38 for the collection plane is measured using cosmic-ray muons, while for the two induction planes, the S/N is 14 (U) and 17 (V), easily exceeding the requirement of 4 for the DUNE FD.

When an interaction occurs, we convert the charge deposited along the track to the energy loss (dE/dx) using stopping cosmic ray muons. Calibration constants have been derived with this method, which are applied to the energy deposits measured for the beam particles – muons, pions, protons, and positrons. Figure 1.11 (left) shows the calibrated dE/dx values as a function of the track residual range for protons in the 1 GeV/c beam, in good agreement with expectations.

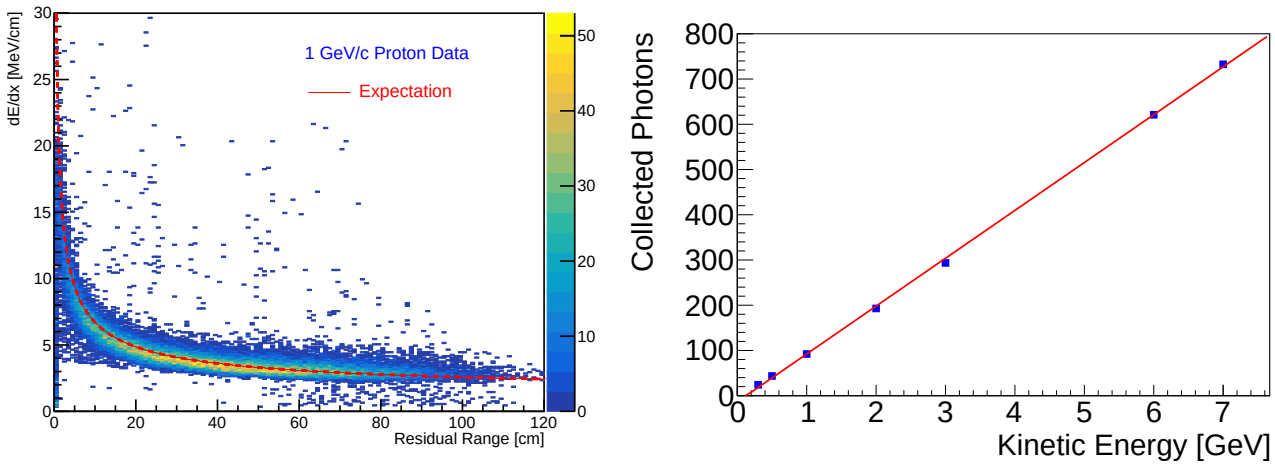


Figure 1.11: Left: Calibrated dE/dx (energy loss over distance) versus residual range measured by a TPC for 1 GeV/c stopping protons. Right: Response in ProtoDUNE-SP of an ARAPUCA PD module in APA3 as a function of incident electron kinetic energy.

The ProtoDUNE-SP beam run provides a unique set of high-quality data for detector performance characterization, physics studies, and calibration, and will allow us to perform hadron-argon cross section measurements, which are relevant for future DUNE neutrino oscillation analyses. Data collected during the beam run will also be used to characterize the photon detection system (PD system) response to light signals. Other useful data sets include beam data with triggers determined by the beam instrumentation; cosmic ray data from random triggers or from those in coincidence with the cosmic ray tagger (CRT) modules; and calibration data, with triggers enabling programmed light pulses. The response and gain for each of the 256 readout channels of the PD system have been determined from calibration data, and the initial analysis results indicate very good performance and stability for this system.

Figure 1.11 (right) shows the response of an ARAPUCA PD module (not corrected for geometry and detection efficiency) as a function of incident electron kinetic energy measured in ProtoDUNE-SP. This preliminary analysis demonstrates the achieved energy linearity for beam electrons contained in the detector. In addition to verifying the PD system response and calibration, ProtoDUNE-SP shows excellent correlation between TPC timing and the PD system timing. The latter will enable the further optimized physics reach of DUNE.

1.3.3 Near Detector

Although not the subject of this TDR, an understanding of DUNE's capabilities would be impossible without some description of the ND's crucial contribution to the experiment. The ND will serve as the experiment's control, constraining systematic errors and measuring the initial unoscillated ν_μ and ν_e energy spectra (and that of the corresponding antineutrinos). Comparing the measured neutrino energy spectra near the beam source, before any oscillation takes place, and again at the far site allows us to disentangle the different energy-dependent effects that modulate the beam spectrum and to reduce the systematic uncertainties to the level required for discovering CPV. Its other key role in this arena is to measure neutrino-argon interactions with high precision using both gaseous and liquid argon, which will further reduce the systematic uncertainties associated with modeling these interactions.

The ND will have a physics program of its own, as well, independent of the FD. This program will include measuring neutrino interactions to explore the two pillars of the standard model: electroweak physics and quantum chromodynamics. It will also explore physics beyond the standard model, searching for non-standard interactions, sterile neutrinos, dark photons, and other exotic particles.

The ND will be located 574 m downstream from the neutrino beam source and will include three primary detector components, illustrated in Figure 1.12:

- a LArTPC called ArgonCube;
- a high-pressure gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field, together called the multi-purpose detector (MPD); and
- an on-axis beam monitor called System for on-Axis Neutrino Detection (SAND).

These components serve important individual and overlapping functions in the mission of the ND. The first two can move off-axis relative to the beam, providing access to different neutrino energy spectra. The movement off-axis, called DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM), provides a crucial extra degree of freedom for the ND measurements and is an integral part of the DUNE ND concept.

The ArgonCube detector contains the same target nucleus and shares some aspects of form and functionality with the FD. This similarity in target nucleus and, to some extent, technology, reduces sensitivity to nuclear effects and detector-driven systematic uncertainties in extracting the oscillation signal at the FD. ArgonCube is large enough to provide high statistics (1×10^8 ν_μ charged

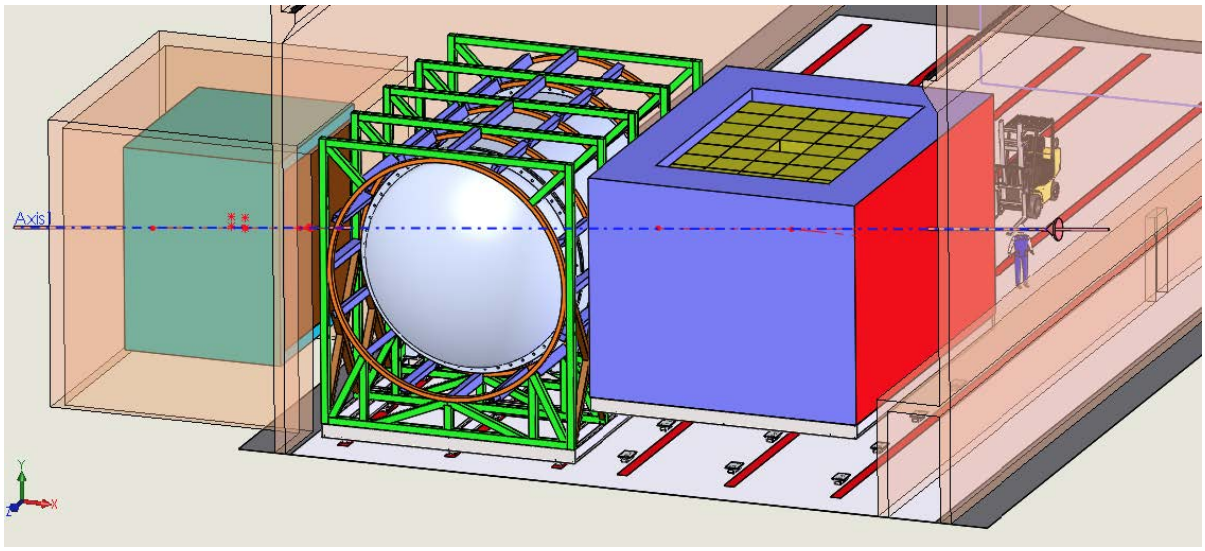


Figure 1.12: DUNE ND. The axis of the beam is shown as it enters from the right. Neutrinos first encounter the LArTPC (right), the MPD (center), and then the on-axis beam monitor (left).

current events/year on-axis), and its volume is sufficiently large to provide good hadron containment. The tracking and energy resolution, combined with the LAr mass, will allow measurement of the neutrino beam using several techniques.

A LArTPC energy acceptance falls off for muons with a measured momentum higher than $\sim$ 0.7 GeV/c because the muons will not be contained in the LArTPC volume. Since muon momentum is critical to determining the incoming neutrino's energy, a magnetic spectrometer is needed downstream of the LArTPC to measure the momentum and charge of the muons. In the DUNE ND concept, the MPD will make these measurements. The HPgTPC provides a lower density medium with excellent tracking resolution for muons from the LArTPC.

The LArTPC and MPD can be moved sideways up to 33 m to take data in positions off the beam axis (DUNE-PRISM). As the detectors move off-axis, the incident neutrino flux spectrum changes, with the mean energy dropping and the spectrum becoming more monochromatic. The DUNE concept is based on reconstructing the energy-dependent neutrino spectrum and comparing measurements at the far and near sites. The ability to take measurements at the near site in off-axis locations will allow us to disentangle otherwise degenerate effects due to systematic biases of the energy reconstruction.

The final component of the DUNE ND suite is the beam monitor that remains on-axis at all times and serves as a dedicated neutrino spectrum monitor. It can also provide an excellent on-axis neutrino flux determination that can be used as an important point of comparison and a systematic crosscheck for the flux as determined by ArgonCube.

Chapter **??** of this TDR volume presents a more complete introduction to the ND and further details of the system can be found in the appendices. The DUNE collaboration is now in the process of finalizing studies for the ND Conceptual Design Report.

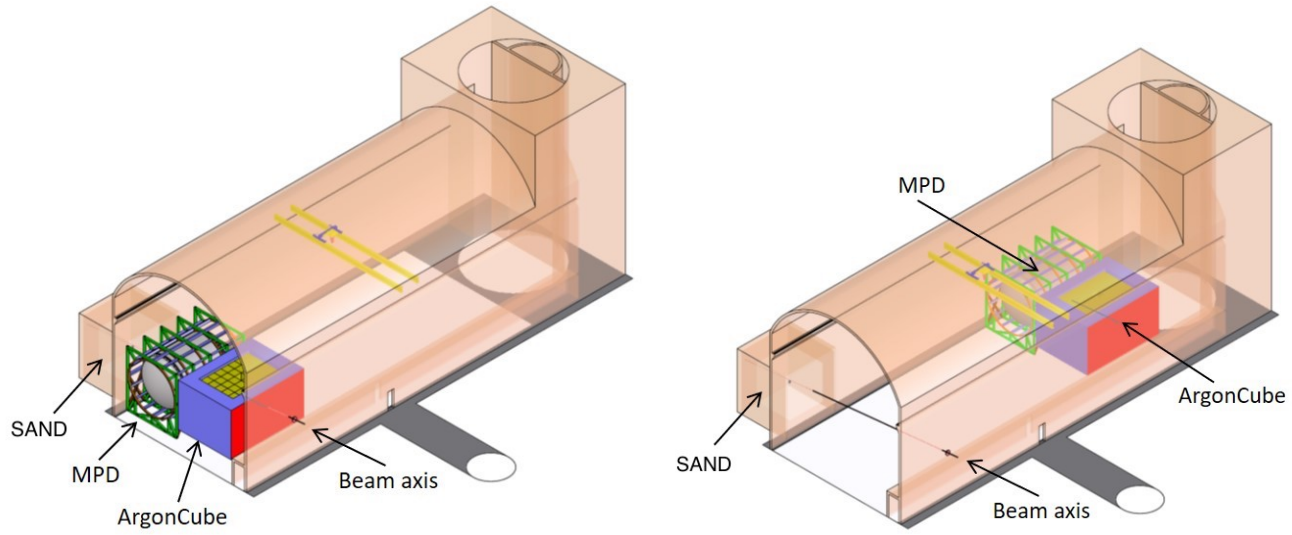


Figure 1.13: DUNE ND hall shown with component detectors all in the on-axis configuration (left) and with the LArTPC and MPD in an off-axis configuration (right). The beam monitor (SAND) is shown in position on the beam axis in both figures. The beam is shown entering the hall at the bottom traveling from right to left.

1.4 DUNE Project Organization and Responsibilities

DUNE is the first large-scale science project to be built in the U.S. conceived as a fully international collaboration with majority international participation. As such, DUNE requires a new organizational and governance model that takes into account the international nature of the project and its relationship to LBNF. The model used by CERN to manage constructing and operating the LHC and its experiments served as a starting point for the management structure of both DUNE and LBNF, and our model continues to evolve as the DUNE project moves forward in concert with LBNF to build this experiment and the supporting facilities. The DUNE project is organized by the DUNE collaboration (Section 1.5) with appropriate oversight from all its international stakeholders. In contrast, LBNF (Section 1.2) is organized as a DOE-Fermilab project incorporating international partners.

A set of organizational structures has been established to coordinate the participating funding agencies, overseeing the LBNF and DUNE projects, and coordinating and communicating between the two. These structures and the relationships among them are shown in Figure 1.14. They include the following committees[5]:

- International Neutrino Council

  The International Neutrino Council (INC) is part of the international project governance structure for the LBNF and the PIP-II projects. The INC comprises representatives from the international funding agencies and CERN that make major contributions to the infrastructure. The INC acts as the highest-level international advisory body to the U.S. DOE and

[5]The LBNF Strategic Project Advisory Committee (LBNF SPAC) advises the Fermilab director on LBNF only, and thus is not described here. PIP-II is introduced in Section 1.1.2.

the Fermilab directorate on anything related to the program, including coordination among the international partners. The associate director for HEP in the DOE Office of Science chairs the INC, and the INC includes the Fermilab director as a member. The council meets once a year and provides pertinent advice on the LBNF and PIP-II projects.

- Resources Review Board (RRB)

  A Resources Review Board (RRB) is part of DUNE's international project governance structure, established to coordinate among funding partners and oversee the DUNE project. It includes representatives from all funding agencies that sponsor the project and from Fermilab management. The RRB provides focused monitoring of the DUNE collaboration and also receives updates on the progress of LBNF, PIP-II, and the Short-Baseline Neutrino (SBN) program. The RRB receives periodic reports from both the Long-Baseline Neutrino Committee (LBNC) and Neutrino Cost Group (NCG), described here. A representative from the Fermilab directorate chairs the RRB and calls regular meetings to monitor progress on the DUNE project.

- Long-Baseline Neutrino Committee (LBNC)

  The Fermilab director has charged the LBNC to review the scientific, technical, and managerial progress, as well as plans and decisions associated with the DUNE project. The LBNC, comprising internationally prominent scientists with relevant expertise, provides regular external scientific peer review of the project. It also provides regular reports and candid assessments to the Fermilab director, which are also made available to the RRB, LBNF, and DUNE collaboration leadership, as well as the funding agencies that support these international projects. The LBNC reviews the TDRs for DUNE and, if acceptable, recommends endorsing the TDRs to the Fermilab director and the RRB. Upon request by the Fermilab director, the LBNC may task other DUNE and LBNF groups with providing more detailed reports and evaluations of specific systems. The chair of the LBNC participates as a delegate to both the Fermilab-managed RRB and the DOE-managed INC. At meetings of the RRB and INC, the LBNC chair reports on LBNC deliberations to the international delegates. The chair of the LBNC is an ex-officio member of Fermilab's Physics Advisory Committee.

- Neutrino Cost Group (NCG)

  The Fermilab director has charged the NCG to review the cost, schedule, and associated risks of the DUNE project and to provide regular reports to the Fermilab director and the RRB. This group comprises internationally prominent scientists with relevant experience. The NCG reviews the TDRs for DUNE and provides a recommendation to the Fermilab directorate and the RRB on endorsing the TDRs. The chair of the NCG participates as a delegate to both the RRB and INC. At meetings of the RRB and INC, the NCG chair reports on NCG deliberations to the international delegates.

- Experiment-Facility Interface Group (EFIG)

  Coordination between the DUNE and LBNF projects must be close and continuous to ensure the success of the combined enterprise. The Experimental Facilities Interface Group (EFIG) (green box in Figure 1.14) oversees coordination between them, especially during design and construction, but will continue during experiment operations. This group examines interfaces between the detectors and their corresponding conventional facilities, between individual detector systems and the LBNF infrastructure, and between design and operation of the LBNF neutrino beamline, which may have issues that affect both LBNF and DUNE.

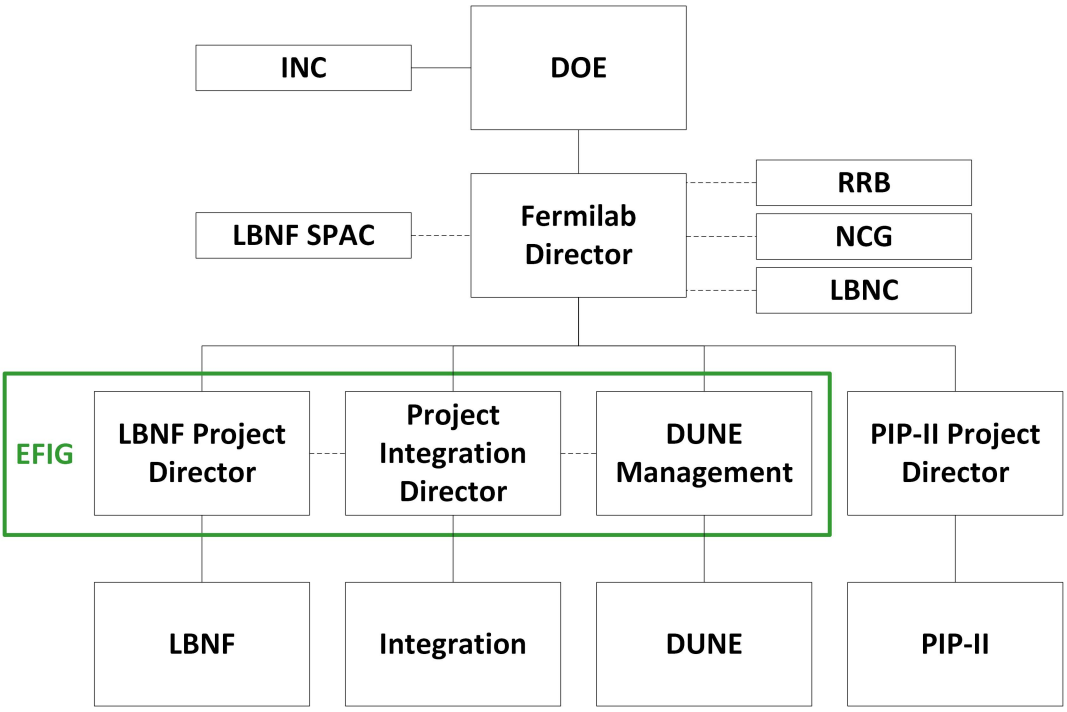


Figure 1.14: Top-level organization structure for oversight of the DUNE and LBNF projects, and flowdown.

1.5 DUNE Collaboration Organization and Management

The DUNE collaboration organizes and manages DUNE in its entirety. Stakeholders include all collaborating institutions, the funding agencies participating in DUNE, and Fermilab as the host laboratory. All collaborating institutions have a representative on the DUNE institutional board (IB), which is responsible for establishing the governance rules of the collaboration and regulating governance-related issues. The collaboration is responsible for the design, construction, installation, commissioning, and operation of the detectors and prototypes used to pursue the scientific program. The DUNE executive board (EB), described below, is the primary management body of the collaboration and approves all significant strategic and technical decisions.

The top-level DUNE collaboration management team consists of two elected co-spokespersons, a technical coordinator (TC), and a resource coordinator (RC). The TC and RC are selected jointly by the co-spokespersons and the Fermilab director. The management team is responsible for the day-to-day management of the collaboration and for developing the overall collaboration strategy, which is presented for approval to the EB. The EB comprises the leaders of the main collaboration activities and currently includes the top-level management team, institutional board chair, physics coordinator, beam interface coordinator, computing coordinator, ND coordinator, and leaders of the FD consortia, described below. It is responsible for ensuring that all stakeholders in the collaboration have a voice in making decisions (see Figure 1.15). Once the DUNE FD TDR is accepted, consortium leaders and coordinators of other major collaboration activities will become elected positions.

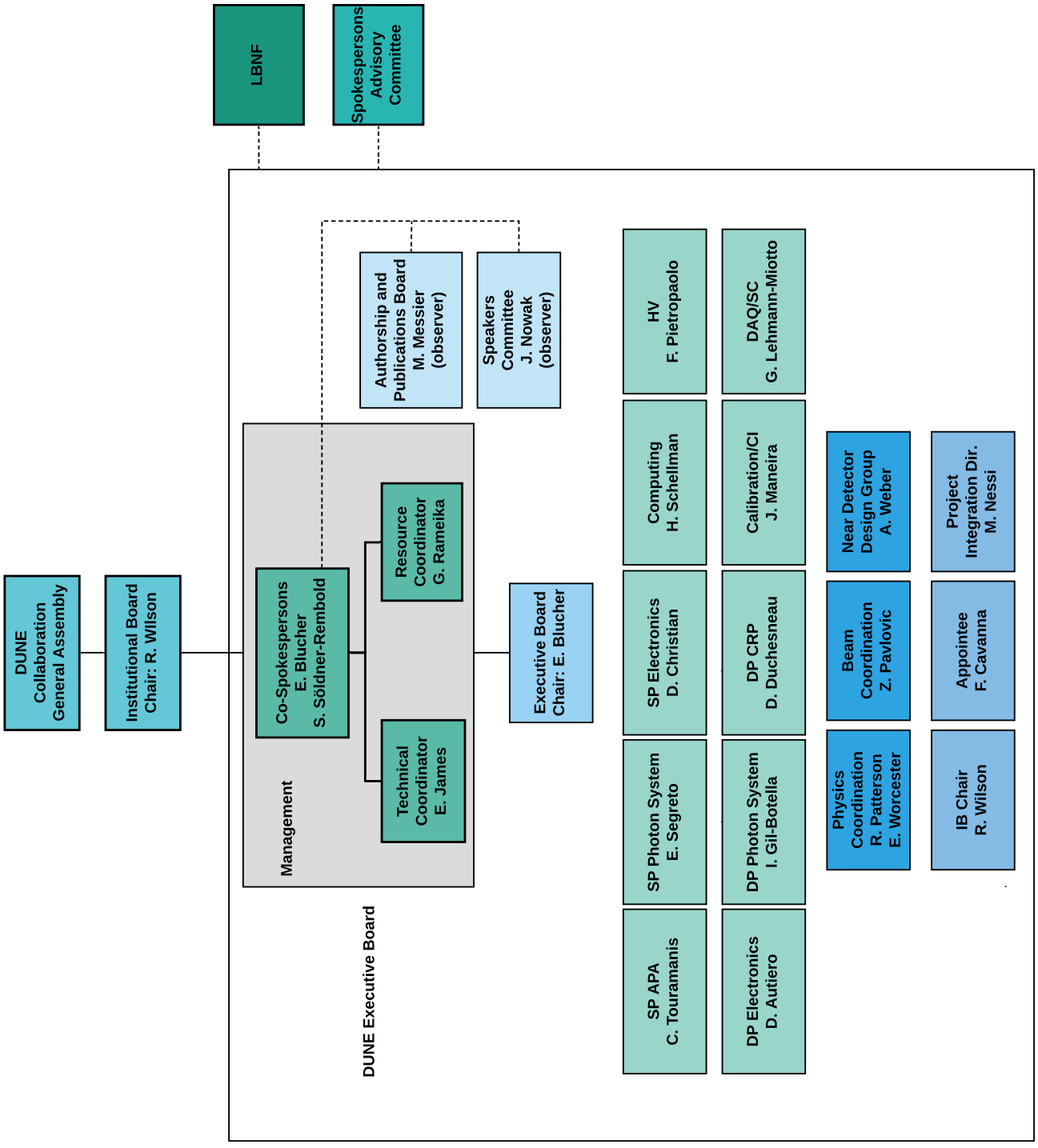


Figure 1.15: DUNE Executive Board.

To carry out design and construction work for the DUNE FD, DUNE has formed consortia of institutions, each of which is responsible for an individual detector subsystem. A similar structure will be formed for the ND once the final detector concept is selected. The FD currently includes eleven consortia, including three specific to SP, three specific to DP, and five common to both technologies:

- (SP) anode plane assemblies (APAs),
- (SP) time projection chamber (TPC) electronics,
- (SP) photon detection system (PD system),
- (DP) charge-readout planes (CRPs),
- (DP) time projection chamber (TPC) electronics,
- (DP) photon detection system (PD system),
- (common) high voltage system (HVS),
- (common) data acquisition (DAQ),
- (common) cryogenic instrumentation and slow controls (CISC),
- (common) calibration, and
- (common) computing.

Each consortium has an overall leader, a technical lead, and a consortium board with representatives from each participating institution. The consortia have full responsibility for their subsystems and for developing a work breakdown structure (WBS), and are expected to understand and document all interfaces with other systems, prepare final technical designs, and draft their own sections of the TDR. Following approval of the TDR, they will be responsible for constructing their respective detector subsystems.

Chapter **??** of this volume introduces the DUNE management and organization specifically as it relates to the FD; and Volume III, DUNE Far Detector Technical Coordination, of the TDR provides more detail.

1.6 Milestones for the First Two Far Detector Modules

The plan for construction and commissioning of the first two FD modules includes a set of key milestones and dates that will be finalized once the international project baseline is established. Table 1.1 shows some key dates and milestones (colored rows) and indicates how the detector consortia will add subsystem-specific milestones based on these dates (no background color).

The schedule for the design and construction of LBNF and DUNE has two critical parallel paths: one for the far site (SURF) and another for the near site (Fermilab). The schedule for initial work is driven by the design and construction of the conventional facilities (CF).

During the initial phase of the project, the far site CF has been given priority. Early far site preparation is complete as of fall 2019, following completion of the rehabilitation work on the Ross

Table 1.1: DUNE schedule milestones for first two far detector modules. Key DUNE dates and milestones, defined for planning purposes in this TDR, are shown in orange. Dates will be finalized following establishment of the international project baseline.

Milestone	Date
Final design reviews	2020
Start of APA production	August 2020
Start photosensor procurement	July 2021
Start TPC electronics procurement	December 2021
Production readiness reviews	2022
South Dakota Logistics Warehouse available	April 2022
Start of ASIC/FEMB production	May 2022
Start of DAQ server procurement	September 2022
Beneficial occupancy of cavern 1 and CUC	October 2022
Finish assembly of initial PD modules (80)	March 2023
CUC DAQ room available	April 2023
Start of DAQ installation	May 2023
Start of FC production for detector module #1	September 2023
Start of CPA production for detector module #1	December 2023
Top of detector module #1 cryostat accessible	January 2024
Start TPC electronics installation on top of detector module #1	April 2024
Start FEMB installation on APAs for detector module #1	August 2024
Start of detector module #1 TPC installation	August 2024
Top of detector module #2 cryostat accessible	January 2025
Complete FEMB installation on APAs for detector module #1	March 2025
End DAQ installation	May 2025
End of detector module #1 TPC installation	May 2025
Start of detector module #2 TPC installation	August 2025
End of FC production for detector module #1	January 2026
End of APA production for detector module #1	April 2026
End detector module #2 TPC installation	May 2026
Start detector module #1 operations	July 2026

Shaft that leads to the DUNE underground area, and excavation can now begin. As each detector cavern is excavated and sufficient utilities are installed, the cryostat construction and cryogenics system installation begins, followed by detector installation, filling with LAr, and commissioning. The first detector module is scheduled to be operational in 2026.

U.S. DOE project management requires approval at critical decision (CD) milestones before allowing the LBNF/DUNE project to move on to the next step. CD-1R was granted in 2015, and CD-3A for LBNF far site construction was granted in 2016. In 2020, DUNE and LBNF will seek CD-2/3b and CD-2/3 for the near site. The project will conclude with CD-4 approval to start operations.

Glossary

4850L The depth in feet (1480 m) of the top of the cryostats underground at SURF; used more generally to refer to the DUNE underground area. Called the "4850 level" or "4850L". 8

anode plane assembly (APA) A unit of the SP detector module containing the elements sensitive to ionization in the LAr. It contains two faces each of three planes of wires, and interfaces to the cold electronics and photon detection system. 11, 12, 14, 15, 22

ARAPUCA A photon detection system (PD system) design that consists of a light trap that captures wavelength-shifted photons inside boxes with highly reflective internal surfaces until they are eventually detected by silicon photomultiplier (SiPM) detectors or are lost. 12, 15, 16

ArgonCube The name of the core part of the Deep Underground Neutrino Experiment (DUNE) near detector (ND), a liquid argon time-projection chamber (LArTPC). 16, 17

ArgoNeuT The ArgoNeuT test-beam experiment and LArTPC prototype at Fermi National Accelerator Laboratory (Fermilab). 11

critical decision (CD) The U.S. DOE's Order 413.3B outlines a series of staged project approvals, each of which is referred to as a critical decision (CD). 24

European Organization for Nuclear Research (CERN) The leading particle physics laboratory in Europe and home to the ProtoDUNEs. (In French, the Organisation Européenne pour la Recherche Nucléaire, derived from Conseil Européen pour la Recherche Nucléaire. 5, 9, 13, 14, 18

conventional facilities (CF) Pertaining to construction and operation of buildings and conventional infrastructure, and for LBNF and DUNE project (LBNF/DUNE), CF includes the excavation caverns. 3, 7, 22

cryogenic instrumentation and slow controls (CISC) Includes equipment to monitor all detector components and liquid argon (LAr) quality and behavior, and provides a control system for many of the detector components. 22

charge parity (CP) Product of charge and parity transformations. 7

cathode plane assembly (CPA) The component of the SP detector module that provides the drift HV cathode. 14

charge-parity symmetry violation (CPV) Lack of symmetry in a system before and after charge and parity transformations are applied. For CP symmetry to hold, a particle turns into its corresponding antiparticle under a charge transformation, and a parity transformation inverts its space coordinates, i.e., produces the mirror image. 2, 5–7, 16

charge-readout plane (CRP) In the dual-phase (DP) technology, a collection of electrodes in a planar arrangement placed at a particular voltage relative to some applied E field such that drifting electrons may be collected and their number and time may be measured. 12, 14, 22

cosmic ray tagger (CRT) Detector external to the TPC designed to tag TPC-traversing cosmic ray particles. 15

central utility cavern (CUC) The utility cavern at the 4850L of Sanford Underground Research Facility (SURF) located between the two detector caverns. It contains utilities such as central cryogenics and other systems, and the underground data center and control room. 7, 8

data acquisition (DAQ) The data acquisition system accepts data from the detector front-end (FE) electronics, buffers the data, performs a trigger decision, builds events from the selected data and delivers the result to the offline secondary DAQ buffer. 22

detector module The entire DUNE far detector is segmented into four modules, each with a nominal 10 kt fiducial mass. 7–9, 11, 13, 24

DOE U.S. Department of Energy. 3, 4, 18, 19, 24

dual-phase (DP) Distinguishes one of the DUNE far detector technologies by the fact that it operates using argon in both gas and liquid phases. 9–13, 22

DP module dual-phase DUNE far detector (FD) module. 11–13

Deep Underground Neutrino Experiment (DUNE) A leading-edge, international experiment for neutrino science and proton decay studies. 2–9, 11, 13, 15–24

DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM) a mobile near detector that can perform measurements over a range of angles off-axis from the neutrino beam direction in order to sample many different neutrino energy distributions. 16, 17

executive board (EB) The highest level DUNE decision-making body for the collaboration. 20

electromagnetic calorimeter (ECAL) A detector component that measures energy deposition of traversing particles (in the near detector conceptual design). 16

Experimental Facilities Interface Group (EFIG) The body responsible for the required high-level coordination between the Long-Baseline Neutrino Facility (LBNF) and DUNE projects. 19

equivalent noise charge (ENC) The equivalent noise charge is the input charge that corresponds to a S/N = 1. 15

European Strategy for Particle Physics (ESPP) The cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the European Organization for Nuclear Research (CERN) Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the USA and Japan in order to ensure coordination between regions and optimal use of resources globally. 5

field cage (FC) The component of a LArTPC that contains and shapes the applied E field. 9, 11, 13, 14

far detector (FD) The 70 kt total (40 kt fiducial) mass LArTPC DUNE detector, composed of four 17.5 kt total (10 kt fiducial) mass modules, to be installed at the far site at SURF in Lead, SD, USA. 3, 4, 6–9, 11, 13, 15, 16, 20, 22

Fermi National Accelerator Laboratory (Fermilab) U.S. national laboratory in Batavia, IL. It is the laboratory that hosts DUNE and serves as its near site. 3, 4, 9, 18–20, 22

grand unified theory (GUT) A class of theories that unifies the electro-weak and strong forces. 3

high-pressure gaseous argon TPC (HPgTPC) A time projection chamber (TPC) filled with gaseous argon; a possible component of the DUNE ND. 16, 17

high voltage (HV) Generally describes a voltage applied to drive the motion of free electrons through some media, e.g., LAr. 11

high voltage system (HVS) The detector subsystem that provides the TPC drift field. 22

ICARUS A neutrino experiment that was located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, then refurbished at CERN for re-use in the same neutrino beam from Fermilab used by the MiniBooNE, MicroBooNE and SBND experiments. The ICARUS detector is being reassembled at Fermilab. 9, 11

International Neutrino Council (INC) A highest-level international advisory body to the U.S. DOE and the Fermilab directorate on matters related to the LBNF and the Proton Improvement Plan II (PIP-II) projects. This council is composed of representatives from the

international funding agencies and CERN that make major contributions the infrastructure. 18, 19

liquid argon (LAr) Argon in its liquid phase; it is a cryogenic liquid with a boiling point of −90 °C (87 K) and density of 1.4 g/ml. 3, 5–12, 15, 17, 24

LArIAT The repurposed ArgoNeuT LArTPC, modified for use in a charged particle beam, dedicated to the calibration and precise characterization of the output response of these detectors. 11

liquid argon time-projection chamber (LArTPC) A TPC filled with liquid argon; the basis for the DUNE FD modules. 3, 4, 6, 8–12, 16–18

Long-Baseline Neutrino Committee (LBNC) The committee, composed of internationally prominent scientists with relevant expertise, charged by the Fermilab director to review the scientific, technical, and managerial progress, plans and decisions associated with DUNE. 19

LBNE Long Baseline Neutrino Experiment (a terminated US project that was reformulated in 2014 under the auspices of the new DUNE collaboration, an internationally coordinated and internationally funded program, with Fermilab as host). 4

Long-Baseline Neutrino Facility (LBNF) The organizational entity responsible for developing the neutrino beam, the cryostats and cryogenics systems, and the conventional facilities for DUNE. 3, 5, 7, 18–20, 22, 24

LBNF Strategic Project Advisory Committee (LBNF SPAC) A committee charged by the host laboratory director to provide expert, independent advice on significant issues and strategies related to LBNF project organization, management, and risks. 18

LBNF and DUNE project (LBNF/DUNE) The overall global project, including LBNF and DUNE. 6, 7

Long Baseline Neutrino Observatory (LBNO) A terminated European project that, during its six-year duration, assessed the feasibility of a next-generation deep underground neutrino observatory in Europe). 4

large electron multiplier (LEM) A micro-pattern detector suitable for use in ultra-pure argon vapor; LEMs consist of copper-clad PCB boards with sub-millimeter-size holes through which electrons undergo amplification. 9, 12

LHC Large Hadron Collider. 18

mass hierarchy (MH) Describes the separation between the mass squared differences related to the solar and atmospheric neutrino problems. 7

MicroBooNE The LArTPC-based MicroBooNE neutrino oscillation experiment at Fermilab. 9,

11

multi-purpose detector (MPD) A component of the near detector conceptual design; it is a magnetized system consisting of a high-pressure gaseous argon TPC (HPgTPC) and a surrounding electromagnetic calorimeter (ECAL). 16–18

Neutrino Cost Group (NCG) A group of internationally prominent scientists with relevant experience that is charged by the Fermilab director to review the cost, schedule, and associated risks for the DUNE experiment. 19

near detector (ND) Refers to the detector(s) installed close to the neutrino source at Fermilab. 3, 4, 7, 16–18, 20, 22

photon detector (PD) The detector elements involved in measurement of the number and arrival times of optical photons produced in a detector module. 9, 12, 15, 16

photon detection system (PD system) The detector subsystem sensitive to light produced in the LAr. 15, 16, 22

Proton Improvement Plan II (PIP-II) A Fermilab project for improving the protons on target delivered delivered by the LBNF neutrino production beam. This is version two of this plan and it is planned to be followed by a PIP-III. 3, 18, 19

photomultiplier tube (PMT) A device that makes use of the photoelectric effect to produce an electrical signal from the arrival of optical photons. 12, 13

ProtoDUNE-DP The DP ProtoDUNE detector at CERN. 13–15

ProtoDUNE-SP The single-phase (SP) ProtoDUNE detector at CERN. 11, 13–16

quality assurance (QA) The set of actions taken to provide confidence that quality requirements are fulfilled, and to detect and correct poor results. 13

resource coordinator (RC) A member of the DUNE management team responsible for coordinating the financial resources of the project effort. 20

Resources Review Board (RRB) A part of DUNE's international project governance structure, composed of representatives of all funding agencies that sponsor the project, and of Fermilab management, established to provide coordination among funding partners and oversight of DUNE. 19

signal-to-noise (S/N) signal-to-noise ratio. 9, 15

System for on-Axis Neutrino Detection (SAND) The beam monitor component of the near detector that remains on-axis at all times and serves as a dedicated neutrino spectrum monitor. 16

Short-Baseline Neutrino (SBN) A Fermilab program consisting of three collaborations, MicroBooNE, SBND, and ICARUS, to perform sensitive searches for ν_e appearance and ν_μ disappearance in the Booster Neutrino Beam. 19

SBND The Short-Baseline Near Detector experiment at Fermilab. 9

signal feedthrough chimney (SFT chimney) In the DP technology, a volume above the cryostat penetration used for a signal feedthrough. 13

silicon photomultiplier (SiPM) A solid-state avalanche photodiode sensitive to single photoelectron signals. 12

supernova neutrino burst (SNB) A prompt increase in the flux of low-energy neutrinos emitted in the first few seconds of a core-collapse supernova. It can also refer to a trigger command type that may be due to this phenomenon, or detector conditions that mimic its interaction signature. 2, 5

single-phase (SP) Distinguishes one of the DUNE far detector technologies by the fact that it operates using argon in its liquid phase only. 9–12, 22

SP module single-phase DUNE FD module. 9, 11–13

Sanford Underground Research Facility (SURF) The laboratory in South Dakota where the LBNF far site conventional facilities (FSCF) will be constructed and the DUNE FD will be installed and operated. 3, 4, 6–8, 22

technical coordinator (TC) A member of the DUNE management team responsible for organizing the technical aspects of the project effort; is head of technical coordination. 20

technical design report (TDR) A formal project document that describes the experiment at a technical level. 3, 5–7, 9, 11, 16, 17, 19, 20, 22

time projection chamber (TPC) A type of particle detector that uses an E field together with a sensitive volume of gas or liquid, e.g., LAr, to perform a 3D reconstruction of a particle trajectory or interaction. The activity is recorded by digitizing the waveforms of current induced on the anode as the distribution of ionization charge passes by or is collected on the electrode. 9, 11, 15, 16, 22

WA105 DP demonstrator The $3 \times 1 \times 1\,\mathrm{m}^3$ WA105 DP prototype detector at CERN. 9

work breakdown structure (WBS) An organizational project management tool by which the tasks to be performed are partitioned in a hierarchical manner. 22

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