# Project Strategy

Recommendation 12 of the Report of the Particle Physics Prioritization Panel (P5) states that for a Long-Baseline Neutrino Oscillation Experiment to proceed “The minimum requirements to proceed are the identified capability to reach an exposure of 120 kt x MW x yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to a 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 (Vol. 3) and the detectors (Vol. 4), the strategy presented here meets these criteria. The P5 recommendations are also in line with 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.

**Global DUNE-LBNF Strategy**

The project strategy presented in this CDR has been developed to meet the requirements set out in the P5 report and taking into account the recommendations of the European ESPP strategy, adopting a model where the DOE and international funding agencies share costs on the DUNE detectors, and CERN provides large in-kind contributions to the supporting infrastructure.

The long-baseline neutrino facility (LBNF) provides:

* excavation of four underground caverns, each capable of hosting a cryostat with a 10 kt fiducial mass LAr-TPCs. The full excavation, which will be completed by 2022, comes under a single contract;
* the outfitting of the caverns, four free-standing steel-supported cryostats, and the cryogenic facilities. The first two cryostats will be available for filling by 2024, allow for a rapid deployment of the first two 10 kt far detector modules. The intention is to install third and fourth cryostats as rapidly as funding will allow.
* the conventional facilities for the near detector systems at Fermilab;
* a 1.2 MW neutrino beam utilizing the PIP-II upgrade of the Fermilab accelerator complex, operational at the latest by 2026, upgradable to 2.4 MW with the proposed PIP-III upgrade;

The Deep Underground Neutrino Experiment (DUNE) will provide:

* Four LAr-TPCs, each with a fiducial mass of at least 10 kt. The division of the far detector into four equal mass detectors, allows the project flexibility in the installation and funding (DOE vs non-DOE) in the case of new resources being identified, mitigates risks, and allows for an early and graded science return;
* The near detector systems, consisting of a highly-capable neutrino near detector and the muon monitoring system to reach the precision requirements needed to fully exploit the statistical power of the very massive FD coupled to the powerful MW-class neutrino beam.

Based on the reference design described below and in Vols. 2, 3 and 4 of the LBNF-DUNE CDR, the resource-loaded schedule will see the first two 10 kt far detector modules operational by 2025, with first beam shortly afterward. At this time the cavern space for the all four 10 kt far detector modules will be available, allowing for an accelerated installation schedule, if sufficient resources (likely international) to the experiment can be established.

The project strategy described above meets these goals, reaching an exposure of 120 kt x MW x yr by 2032, and potentially earlier if additional resources are identified. The P5 recommendation of sensitivity to CP-violation of 3σ for 75% of δCP values can be reached with an exposure of 850 kt x MW x yr with an optimized beam.

**A Strategy for Implementing the DUNE Far detectors**

The LBNF project will provide four separate cryostats on the 4850 level at the Sanford Underground Research Facility (SURF). Instrumentation of the first cryostat will commence in 2021/2022. As part of the deployment and risk mitigation strategy, the cryostat for the second detector must be available when the first cryostat is filled. The aim is to install third and fourth cryostats as rapidly as funding will allow.

The DUNE collaboration aims to deploy four 10 kt (fiducial) mass FD modules based on the Liquid Argon Time Projection Chamber (LAr-TPC) technology. The viability of the basic LAr-TPC technology has been proven by 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 read out of the ionization signals: single-phase readout, where the ionization is detected using 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 3mm readout pitch, a lower detection energy threshold, and better pattern reconstruction of the events. The DUNE single-phase read-out design is being currently being validated in the 35 t detector at Fermilab. A 20 t dual-phase read out 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 SBN program and the CERN neutrino platform. At this moment, the development of the dual-phase technology is being fully funded from outside the DOE project, although interest from DOE groups has been expressed in the context of the CERN Neutrino Platform. A flexible approach to the DUNE Far Detectors designs offers the potential to bring additional interest and resources into the experimental collaboration. The vision for the FD is consolidated in line with the requirements set by the CD-milestones.

**Guiding Principles for the DUNE Far Detector:**

* The lowest-risk design for the first 10 kt FD module satisfying the requirements will be adopted, allowing for installation at SURF to commence in 2021/2022. Installation of the second 10 kt module should commence before 2023.
* Recognition that the LAr TPC technology will continue to evolve with: i) the large-scale prototypes at the CERN Neutrino Platform and the experience from the Fermilab SBN program, and ii) the experience gained during the construction and commissioning of the first 10 kt FD module. It is assumed that all four FD detectors will be similar but not necessarily totally identical.
* In order to start the FD installation on the timescale of 2021/2022, the first 10 kt module will be based on the APA/CPA design, subject to risks identified in the register. There will be a clear and transparent decision process for the design of the second and subsequent far detector modules, allowing for evolution of the LAr TPC technology to be implemented in the FD detectors. 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 design has been identified and summarized in the CDR Vol. 4. Common solutions for DAQ, electronics, HV feed-throughs, etc., will pursued and implemented, independent of the details of the TPC design.

**Strategy for the First 10 kt Far Detector TPC**

Wire plane LAr-TPC readout has already been demonstrated in by the ICARUS T600 experiment, where data was successfully accumulated over a period of three years. An extrapolation of the observed performance and the implementation of improvements in the design (such as e.g. immersed cold electronics) will allow the single-phase approach to meet detector requirements. In order to start the FD installation on by 2022, the first 10 kt module will be based on the single-phase APA/CPA design, subject to risks identified in the register. 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 the first 10 kt FD Module by 2021/2022. For these reasons, the APA/CPA single-phase wire plane LAr-TPC readout concept, described in Volume 4 of the DUNE CDR, is the *reference design* for the far detector. The 10 kt TPC active volume is 12 m high, 14.5 m wide and 58 m long. The active volume is instrumented with anode plane assemblies (APAs), which are 6 m high and 2.3 m in width. Two APAs are stacked vertically to instrument the 12 m height of the active volume. Three stacks of APAs span the width of the detector. With 25 APA stacks, placed edge-to-edge, spanning 58 m active length of the detector. Cathode plane assemblies (CPAs) at -180 kV are located in between the APAs. The CPAs are formed from 3 m high by 2.5 wide cathode planes stacked in fours to reach the 12 m height of the detector. The width of the detector is thus spanned by four 3.6 m long drift regions (APA:CPA:APA:CPA:APA). The 10 kt far detector consists of 150 APAs and 200 CPAs. Ionization electrons drift a maximum distance of 3.6 m in the electric field of 500 V/cm. The highly modular nature of modular design enables manufacturing to be distributed across a number of sites.

The *reference design* is already relatively advanced for a conceptual design report. At this stage modifications of the reference design will need to be approved by the DUNE technical board. A preliminary design review will take place as early as possible, utilizing the experience from the DUNE 35-ton prototype; the design review will define the baseline design that will form the basis of the TDR (CD-2). Once defined, the changes to the baseline will fall under a formal change-control process. The validation of six full-sized drift cells of the TDR engineering design will be validated at the CERN neutrino platform in 2018 (pending approval by CERN). This single-phase engineering prototype at CERN is a central part of the risk mitigation strategy for the first 10 kt FD module and is part of the DOE-funded DUNE project. Based on the experience at the CERN neutrino platform, a final design review will take place towards the end of 2018 and construction of the readout planes will commence in 2019, ready for first installation in 2021/2022. 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 (WA105 experiment), which includes the operation of the 20-ton prototype in 2016 and the 6 x 6 x 6 m3 demonstrator in 2018. Participation to the WA105 experiment is open to all DUNE Collaborators. A concept for the dual-phase implementation of a FD module is presented in detail as an *alternative design* in Volume 4 of the DUNE CDR. This alternative design, if demonstrated, could form the basis of the second or subsequent 10 kt far detector modules, in particular to achieve improved detector performances in a cost-effective way.

**DUNE at the CERN Neutrino Platform**

WA105 has signed an MoU with the CERN Neutrino Platform to provide a large ~ 8 x 8 x 8 m3 cryostats by October 2016 in the new EHN1 extension, and it is foreseen a second large cryostat to house the single phase LAr-TPC will be provided on a similar timescale. Both will be exposed to charged-particle test beam in 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. The first 10 kt far detector module will contain 150 APAs and 200 CPAs. These will be produced in 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 FD module. The proposal for the DUNE single-phase prototype will be presented to the CERN SPSC in June 2015.

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 double phase design is based on independent 3x3m2 charge readout planes (CRP) placed at the gas-liquid interface. Each module provides two perpendicular “collection” views with 3mm readout pitch. A 10 kt FD 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 3x3m2 CRPs of the DUNE type giving the opportunity to validate the manufacturing procedure ahead of large-scale productions. WA105 is presently constructing a 3x1 m2 CRP to be operated in 2016. The same operational milestones (engineering, operational, physics) are defined as for the single phase.

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 benefits of the single-phase and dual-phase TPC readout.

**Strategy for the Second and Subsequent 10 kton Far Detector TPC modules**

For the purposes of cost and schedule, the reference design for the first FD module is adopted as the reference design for the subsequent three FD modules. However, the experience with the first 10 kt FD module and the development activities at the CERN 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 FD TPC module in 2020. The technology choice for the second TPC 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 TPC will come under formal change control. This process will be repeated for the third and fourth FD module in 2022.

This strategy allows flexibility with respect to international contributions with a path where the DUNE collaboration decides that the second and third TPCs respectively adopt evolving approaches. This option 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.

A Strategy **for Implementing the DUNE Near Detector(s)**

The LBNF project will provide the civil facilities for the DUNE near detector systems (muon monitors and near neutrino detector). The primary scientific motivation for the DUNE near detector system is to constrain the beam spectrum for the long-baseline neutrino oscillation studies. It also provides high-statistics for precision studies of neutrino-argon interactions. The near detector, which is exposed to an intense flux of neutrinos, also provides an opportunity for a wealth of fundamental neutrino interaction measurements, which are an important part of the secondary scientific goals of the DUNE collaboration. Within the former LBNE collaboration the neutrino near detector (NND) design was the NOMAD-inspired fine-grained tracker (FGT), which was built through a strong collaboration of U.S. and Indian institutes.

**Guiding Principles for the DUNE Near Detector:**

* Recognition of the central importance of the reference design for NND;
* The primary design consideration of the DUNE neutrino near detector is the ability to adequately constrain the systematic errors in the DUNE LBL oscillation analysis;
* The secondary design consideration for the DUNE NND is the self-contained non-oscillation neutrino physics program;
* It is recognized that a detailed cost-benefit study of potential ND options has yet to take place and such a study is of high priority to the DUNE project.

**The 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 m x 3.5 m x 6.4 m; a lead-scintillator sandwich sampling electromagnetic calorimeter (ECAL); a large-bore warm dipole magnetic, with inner dimensions of 4.5 m x 4.5 m x 8.0 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 Vol. 4 of the DUNE CDR.

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 shall 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 of the DUNE CDR. The large samples of neutrino interactions will also provide a wealth of physics opportunities beyond the main scientific goal of long-baseline oscillations for DUNE collaborators, including numerous topics for PhD theses.

**DUNE Strategy for the Near Detector**

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 LAr-TPC 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 of the NND with a High-Pressure Gaseous Argon TPC. At this stage, the benefits of such options have not been studied and alternative designs for the NND are not presented in the CDR and will be the subject of details studies in the coming months.

**DUNE Near Detector Task Force**

A full end-to-end study of the impact of the FGT NND design 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 adaption of the T2K framework for implementing ND measurements as constraints in the propagation of systematic uncertainties to the FD.

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

* Delivering the simulation of the reference design of the NND and possible alternatives;
* Undertaking an end-to-end study to provide a quantitative understanding of the power of the NND designs to constrain the systematic uncertainties on the LBL oscillation measurements;
* Quantifying the benefits of augmenting the reference design with a LAr-TPC 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 report by July 2016. Based on the 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.