The DUNE experiment

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Abstract. The upcoming DUNE experiment heavily relies on Time Projection Chambers (TPCs) for their suitability for constructing large-scale detectors with excellent performance in tracking and energy reconstruction. DUNE will construct four 17 kton Far Detector Modules which will use Liquid Argon TPC technology. A R&D program is underway, testing at large-scales different designs of these detectors. The designs of the first two modules have been chosen, and detector construction is underway. The Near Detector comprises three components. A fixed on-axis detector, SAND, will monitor the beam. A large Liquid Argon TPC, NDLAr, serves to collect interactions with high statistics in a detector functionally similar to the Far Detectors whilst coping with the high interaction rate from the world's most powerful neutrino beam. Downstream of NDLAr, The Muon Spectrometer (TMS), measures escaping muons. Both NDLAr and TMS can be moved up to 30m off-axis allowing to measure neutrino interactions at different beam energies. In Phase 2 of the experiment, DUNE will upgrade the Near Detector replacing TMS with a high performance gaseous argon TPC, NDGAr. In this article, the DUNE experiment is described and the construction status given.

1 Introduction

DUNE is a next-generation neutrino experiment supported by more 1400 scientists and engineers from over 200 institutions world-wide. The experiment aims to further our knowledge of neutrino oscillation by:

- determining the Neutrino Mass Ordering
- measuring the CP Violating phase over a wide range of values
- measuring precisely the oscillation parameters
- testing the 3-flavour paradigm

DUNE will achieve this by operating a high power wide-band beam operating in neutrino (anti-neutrino) mode produced at FNAL (Chicago). Deep underground at the Sanford Underground Research Facility (South Dakota), some 1,300 km away, four gigantic Far Detector (FD) modules will measure ν_μ ($\bar{\nu_\mu}$) disappearance, ν_e ($\bar{\nu_e}$) and ν_τ ($\bar{\nu_\tau}$) appearance. Conceived to be highly sensitive to the matter effect, DUNE will be able to unambiguously determine both the neutrino mass ordering and CP Violating phase δ_{CP}. In addition to the neutrino beam oscillation program, DUNE has a wide science program including two key physics goals; the search for Nucleon Decay and the potential observation of a Galactic Core Collapse Supernova.

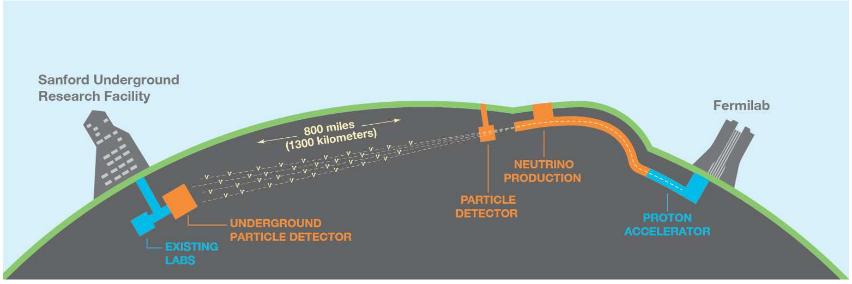

Figure 1: The DUNE experimental setup, showing the neutrino beam production site and Near Detector complex at Fermilab. With a baseline of 1300 km, the Far Detector site is located deep underground at the Sanford Underground Research Facility.

2 Experimental Setup

The DUNE experiment requires a high power wide-band beam, with neutrino energies ranging up to 10 GeV, capable of operating in neutrino or anti-neutrino modes, which will be produced by 60-120 GeV protons from Fermilab's main injector. Initially, this beam will operate at a power of 1.2 MW, but will be upgradable to 2.4 MW. Downstream of the beam, the Near Detector System, further described in Section 2.1, will fully characterise the beam with the aim of extrapolating the unoscillated spectrum to the Far Detector. The Far Detector modules are gigantic Liquid Argon Time Projection Chambers (LArTPCs), each holding 17 ktons of liquid argon.

The DUNE experiment will be built in two phases; Phase 1 and Phase 2. Phase 1 will comprise two Far Detector modules (FD1 and FD2), a Near Detector System with a neutrino beam power of 1.2 MW. In this phase, substantial advances will be made in the determination of the neutrino mass ordering and 3σ sensitivities can be achieved on the measurement of the CP-violating phase δ_{CP} if δ_{CP} is $\pm 90^\circ$ (independent of the neutrino mass ordering). To go further on the measurement of δ_{CP} requires adding an additional two Far Detector modules (FD3 and FD4), upgrades to the Near Detector System and increasing the neutrino beam power to 2.4 MW.

DUNE was conceived to be long baseline, 1300 km, as to enhance the matter effect on the neutrino beam which disentangles completely the neutrino mass ordering from the CP-violating phase δ_{CP}. In addition, DUNE will use a wide-band neutrino beam and make a spectral measurement (in neutrino and anti-neutrino mode). The measurement will therefore span two oscillation peaks. The amplitude and positions of these two peaks changes depending on the value of δ_{CP}. The spectral measurement, therefore, brings additional power to the measurement.

Neutrino interactions can be complex, depending on the energy of the interaction, interaction process and presence of nuclear effects. In practice, multiple products and showers are produced. The neutrino flavour can be well determined via the measurement of the outgoing lepton, however, determining the neutrino energy is dependent on our knowledge of neutrino interactions. In addition, not all products may be visible depending on the detection technique. To understand neutrino interactions across a wide energy range, highly performing near and far detectors are required.

At the Far Detector, massive detectors will be constructed. Liquid argon TPC technology is the only way to construct colossal detectors capable of producing fine-grain 'images' of neutrino interactions. Simulations, as well as recent experiments such as μBooNE [1], indicate good neutrino flavour separation, good energy reconstruction and low energy thresholds can be obtained with this technology. In order to build LArTPCs holding 17-ktons of liquid argon, a significant R&D program was launched with the aim of prototyping at large scales. To date, three different technologies have been tested at scale at the CERN neutrino platform.

The first, based upon a long history of LArTPCs was ProtoDUNE Single-Phase. This TPC follows a modular design with the detector divided into 3.5m drift volumes, by alternating planes of anodes and cathodes. High voltages applied to the cathodes result in drift fields of 0.5 kV/cm. Signals are obtained from a novel wrapping of three wire planes at the anode (Anode Plane Assembly). Electrons drifting, induce signals of these wire planes; producing bipolar signals on the first (U) and second (V) and a unipolar signal on the third (Y). The wires are orientated such that reconstruction of the hit positions can be made unambigously. To detect scintillation light in this TPC, novel large area low format photon detectors were developed, known as Arapuca [2], which could be inserted into the Anode Plane Assemblies. Construction of the ProtoDUNE Single-Phase [3] was completed during 2018, and it successfully took data with a charged particle beam allowing to characterise the detector response over the energy range of interest for DUNE ($\sim$ 0.5 to 8 GeV) [4, 5].

In parallel a second TPC design was trialled, ProtoDUNE Dual-Phase [6]. The idea was to form a monolithic detector, requiring the application of -600 kV on a bottom cathode such that electrons would drift upwards through 12m of liquid argon [7]. Charge readout would then be made at the top of the detector in the argon gas phase. The charge signal would be formed by two collection planes, angled at 90°, printed on PCB. Specially conceived chimneys allowed to install the cryogenic part of the charge read-out electronics close to the strips whilst maintaining accessibility. This access allows replacement of the electronics which is advantageous for long-term detector operations. ProtoDUNE Dual-Phase was filled with liquid argon during August 2019, however, suffered significant technical problems.

Based on these two experiences, a new detector concept, known as Vertical Drift [8] emerged. In this design, features from Single and Dual Phase were merged. Charge read-out would be made in liquid argon using induction and collection strips using printed PCBs instead of wire-planes. The Vertical Drift concept and large-scale components have been extensively tested in a large testing facility at the CERN neutrino platform known as the cold-box. ProtoDUNE Dual-Phase has been reconverted to ProtoDUNE Vertical Drift which is due to be filled with liquid argon during summer/autumn of 2024. Tests with a charged particle beam will be made.

Based on the results from this large-scale prototyping, the DUNE collaboration has decided to build two Far Detector modules (for Phase 1) using the Vertical Drift [8] and Single Phase [9], now known as Horizontal Drift, designs. These Far Detector modules are discussed further in Section 2.2.

2.1 Near Detectors

The Near Detector system sits 575m downstream of the beam in a shallow underground laboratory. Its role is to form the prediction neutrino spectrum at the Far Detector. To do so, the system must perform the following:

- Measure interactions on Ar
- Measure neutrino energy
- Constrain x-section model
- Measure neutrino flux
- Obtain data with different fluxes
- Monitor the neutrino beam

To achieve these tasks a suite of high performance detectors will be employed [10]. The lay-out of the Phase 1 Near Detector System is shown in Figure 2.

The neutrino beam first encounters NDLAr - a 150 ton liquid argon TPC shown in Figure 2 (Top, Centre). The detector is large enough to contain almost all hadronic showers and side-ways going muons. Additionally measurements of ν_e scattering will be possible which will allow to constrain the neutrino flux. With such a large detector, neutrino pileup will occur, expecting of the order of 50ν per beam spill. To operate a large detector in such a high neutrino flux environment, the detector consists of a 7x5 array of optically separated TPCs with pixel read-out. Figure 2 (Top, Right) gives an example event-display from a single beam spill, in which multiple neutrino interactions are reconstructed.

Muons produced in neutrino interactions within NDLAr can escape the detector. Downstream of the beam, therefore, a second detector is located to sample these escaping muons. In Phase 1, this detector is The Muon Spectrometer (TMS) - a magnetised steel range stack capable of measuring the sign and momenta of escaping muons.

For Phase 2, it is planned to replace TMS with NDGAr shown Figure 2(Bottom, Centre). NDGar is a high pressure gaseous argon TPC with Electromagnetic CALorimeter (ECAL) and muon system all within a 0.5T magnetic field [11]. NDGAr will perform higher precision measurements of neutrino interactions able to measure lower momentum, higher power particle identification (including proton/pion separation), multiplicity etc. Its measurements will provide important constraints on neutrino interaction processes on Ar. Figure 2(Bottom, Right) shows a simulated example of a neutrino interaction, illustrating the fine detail achievable with this gaseous TPC. The coloured tracks indicate the particle identification obtained through the measurement of dE/dx. In this event, the presence of neutral pion emitted in this interaction is inferred through the tagging of the two disintegration gamma rays in the surrounding ECAL.

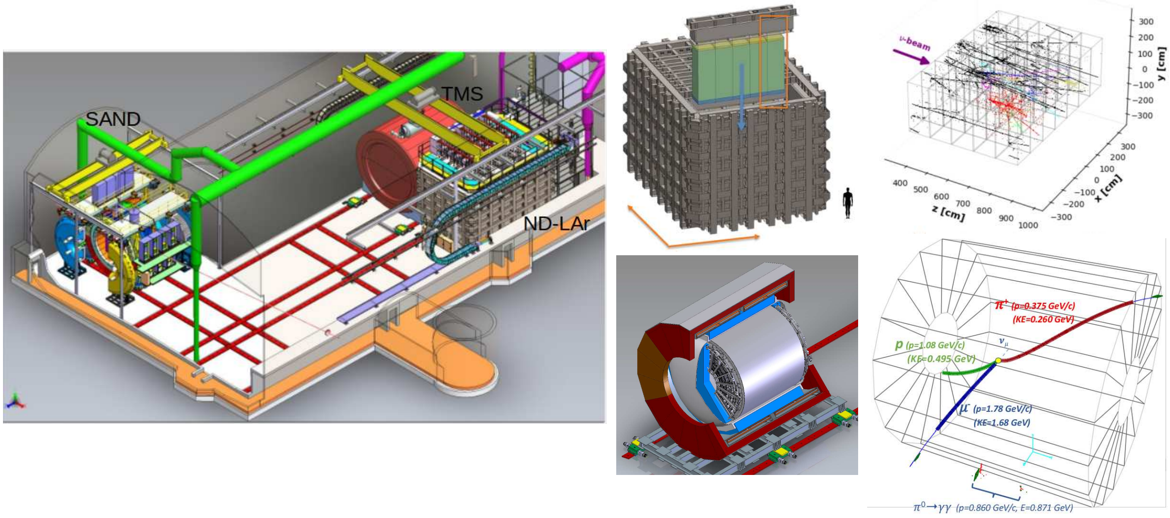

Figure 2: Left, the Phase I Near Detector System showing the fixed component SAND and movable component ND-LAr and TMS. Right (top) shows an image of NDLAr and simulated response to a beam spill which includes multiple neutrino interactions. Right (bottom) shows the NDGAr detector, which will replace TMS in phase 2 of the experiment. With NDGAr finer details of neutrino interactions will be explored, as illustrated by the simulated neutrino event.

In DUNE, the Near detectors, NDLAr and NDGAr, use the same nuclear target (Ar) as the Far Detectors. NDLAr is designed to be as functionally similar to the Far Detector as far as possible whilst operating within a high flux environment.

In order to obtain data at different neutrino fluxes, DUNE will employ the PRISM concept, with NDLAr and TMS (NDGAr) mounted on rails so they can be moved up to 30m off-axis. Varying off-axis position modifies the mean neutrino energy, allowing studies with different neutrino fluxes with the same detectors. Combining weighted data from different off-axis positions is a means of obtaining the oscillated FD prediction.

Finally, the SAND detector, a magnetized LAr Target (GRAIN), tracking (STT) and calorimeter (ECAL), serves as an on-axis beam monitor.

2.2 Far Detectors

The Sanford Underground Research Facility is located in Lead, South Dakota. Two large caverns, at a depth of 1.48 km underground, will house the DUNE Far Detector modules. Excavation of these two caverns has recently been completed (2024).

Figure 3 shows the two Far Detector module designs, Horizontal Drift and Vertical Drift, side-by-side. In a LArTPC, incoming particles interact with the liquid argon producing tracks of excited and ionised argon atoms. With an applied electric field, ionisation electrons drift towards the anodes. The Horizontal Drift module comprises alternative planes of anode and cathodes, as shown in Figure 3, forming four 3.5m drift volumes. High Voltage fed to the cathode planes produces drift fields of 0.5 kV/cm. In each drift volume, electrons drift horizontally towards the anode wire planes. In Vertical Drift, High Voltage is delivered to the central cathode. A potential of -300 kV is required to achieve the 0.5 kV/cm drift field. In Vertical Drift, electrons drift 6m upwards (downwards) in the top (bottom) volumes towards the Charge Readout Planes.

In Horizontal Drift, Charge Readout is made at the anode using 3 wire-planes. Signals are formed similarly in Vertical Drift, however, in this detector the planes are formed from strips printed on a stack of PCBs perforated with tiny holes through which the electrons drift.

Signals, read-out, either on wires or strips, can be reduced due to the electronegative impurities in liquid argon which quench the drifting electrons. This gives important requirements on the liquid argon purity, the drifting distance and the applied electric field. Knowing the distance the charge has drifted allows to correct for any charge attenuation that might occur. This information is obtained from the

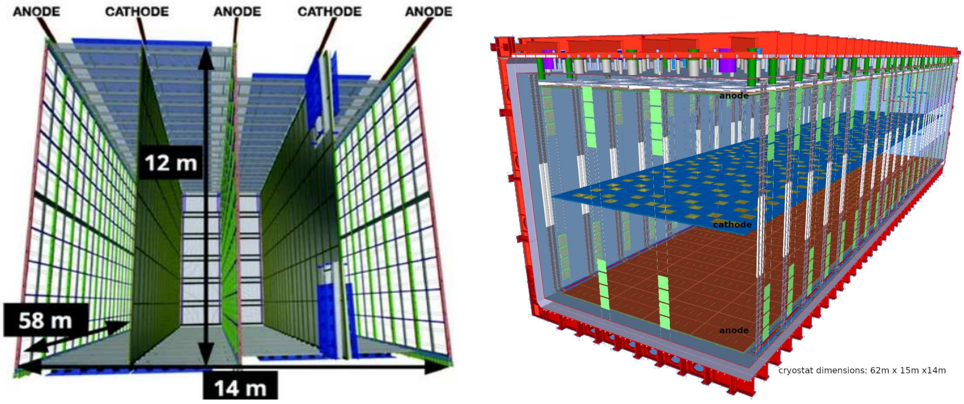

Figure 3: The two Far Detector designs. Left, the Horizontal Drift design, and on the right, the Vertical Drift design.

time difference between the arrival of the charge signal to that of the scintillation light.
In both detectors this light is detected by X-Arapuca [12], which is a large area photon detector consisting of a sandwich of transparent materials with different optical properties. VUV light from scintillation is shifted to longer wavelengths (350nm) due to a first wavelength-shifting coating. The next layer is a dichroic filter which allows these wavelengths to enter the lower layers. A final wavelength shifting plate, shifts the light again to visible wavelengths (430nm). Total internal reflection between the surfaces of the layers keeps the light trapped within the structure. Silicon PhotoMultipliers (SiPM) line the outer edge of the device to detect the reflected light.
In Horizontal Drift, the Photon Detectors form bars of 210cm x 12cm, and are inserted into the anode assemblies. It is not possible to do this with Vertical Drift due to the opaque PCB stack, so 60cm square Photon Detectors tile two locations. Photon Detectors tile the upper (lower) segment for the top (bottom) volume of the outer cryostat membrane external to the TPC field cage. The field cage openings are widened to allow better light collection. Photon Detectors are also inserted into the cathode, remembering that the cathode is at a potential of -300 kV. To operate Photon Detectors in this location requires delivering the power for the SiPMs and conditioning electronics via optical fiber, using a system known as Power-over-Fiber. The analog signal, each signal resulting from a ganged sum of 80 SiPMs, is transmitted off the cathode via optical fiber using a laser driving circuit. This over-Fiber system which operates in liquid argon (87K) has been recently developed and successfully demonstrated in tests at the CERN neutrino cold-box facility.

3 Conclusions

DUNE's ambitious program is based on high Performance TPCs; high-pressure gaseous (NDGAr) and various designs of liquid argon TPCs that are modular, wire or PCB-based charge readout (NDLAr and the FDs). At the CERN neutrino platform, large-scale testing of liquid argon TPCs is ongoing. From this effort, two designs for the Far Detector have emerged; Horizontal Drift and Vertical Drift.
Currently, the experiment is in the construction period of Phase 1 of the experiment. The excavation of the two halls, which will house the Far Detectors, has recently been completed in 2024. The installation of the first FD1 module will begin in 2026, such that FD1 will begin data-taking during 2028. The installation of the second module FD2 will begin later in 2029.
Both the neutrino beam and complete Phase 1 Near Detector System will be operational by 2031. Recent sensitivity studies have been performed [13] using realistic Near and Far Detector simulation, reconstruction and systematics. With Phase 1 of the experiment, the neutrino mass ordering can be determined to 3σ (5σ) with an exposure of 66 (100) kt-MW-years, independent on the value of the CP-violating phase. For the measurement of the CP-violating phase, δCP, during phase 1, if δCP is $\pm 90^\circ$, 3σ sensitivity can be achieved, independent of the neutrino mass ordering. For improved sensitivity, Phase 2 of the experiment is required.
Phase 2 of the experiment comprises two additional FD modules (FD3 and FD4). These detectors are aimed to be higher performing with the view to increasing the physic scope of the experiment. The neutrino beam will also be upgraded to 2.4 MW, and the Near Detector System will be upgraded to include NDGAr. In this phase, if δCP is $\pm 90^\circ$, 5σ can be achieved in 7 years. For 50% of all δCP

values, 5σ precision can be achieved with 12 years of data-taking. The range in precision obtainable on δCP values will be between 6 and 16°.
Additionally to the neutrino beam physics, DUNE has a wide off-beam program including the measurement of atmospheric neutrinos and neutrinos from astrophysical sources. Searches for Beyond the Standard Model physics will be made at both Near and Far detectors, in particular searching for deviations from 3-flavour mixing (sterile neutrinos, Non-Standard Interactions, non-unitarity of the PMNS matrix, CPT violations etc). With gigantic detectors deep underground, DUNE will perform a search for Nucleon Decay being particularly sensitive to kaon-producing decays. The Far Detectors will also be prepared to detect supernova neutrinos in case of a galactic core-collapse supernova occuring during the lifetime of the experiment. These ambitious physics goals are only achievable at DUNE through the development and deployment of multiple large size and highly performing TPCs.

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