Development of LArTPC Vertical Drift Solutions with PCB Anode Readouts for DUNE

[1] *Beykent University, Istanbul, Turkey*
[2] *Instrumentation Division, Brookhaven National Laboratory, Upton, NY, USA*
[3] *Physics Department, Brookhaven National Laboratory, Upton, NY, USA*
[4] *University of California Berkeley, Berkeley, CA, USA*
[5] *University of California Irvine, Irvine, CA, USA*
[6] *University of California Santa Barbara, Santa Barbara, CA, USA*
[7] *Universidade Estadual de Campinas, Campinas - SP, Brazil*
[8] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[9] *University of Chicago, Chicago, IL, USA*
[10] *Colorado State University, Fort Collins, CO, USA*
[11] *Universidade Federal de São Carlos, Araras - SP, Brazil*
[12] *Universidade Federal do ABC, Santo André - SP, Brazil*
[13] *Neutrino Division, Fermi National Accelerator Laboratory, Batavia, IL, USA*
[14] *Istituto Nazionale di Fisica Nucleare Sezione di Milano Bicocca, Milano, Italy*
[15] *Istituto Nazionale di Fisica Nucleare Sezione di Milano, Milano, Italy*
[16] *Harvard University, Cambridge, MA, USA*
[17] *Iowa State University, Ames, Iowa, USA*
[18] *Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[19] *Department of Physics Astronomy, Louisiana State University, Baton Rouge, LA, USA*
[20] *Michigan State University, East Lansing, MI, USA*
[21] *Universita del Milano-Bicocca, Milano, Italy*
[22] *University of Pennsylvania, Philadelphia, PA, USA*
[23] *University of Pittsburgh, Pittsburgh, PA, USA*
[24] *Stony Brook University, SUNY, Stony Brook, New York, USA*
[25] *Syracuse University, Syracuse, NY, USA*
[26] *University of Texas at Arlington, Arlington, TX, USA*
[27] *University of Wisconsin Madison, Madison, WI, USA*

(Dated: September 1, 2020)

Primary Contact Information:
Xin Qian (Brookhaven National Laboratory) [xqian@bnl.gov]

Liquid Argon Time Projection Chamber (LArTPC) with its superior capability in particle tracking and energy calorimetry may hold the key to answer some critical questions about our Universe including i) why is matter dominating antimatter? ii) can the proton decay? iii) how do core-collapse supernovae happen? iv) are there additional neutrino flavors? v) What is the dark matter? LArTPC is the chosen detector technology for the Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) [1], which is a top priority of U. S. High Energy Physics (HEP). LBNF will provide excavated underground space for four 10-kton LArTPCs. The success of the first-generation LArTPC experiments: ICARUS [2], MicroBooNE [3], and single-phase ProtoDUNE (NP04) [4, 5], has led to the decision that the first 10-kt DUNE detector module is going to be a single-phase LArTPC [6] utilizing multiple wire-plane readout with cold electronics [7] inside LAr. The design of the remaining 10-kt detector modules is open, and a detector upgrade program is essential for the development of LArTPCs with improved performance and cost-effective robust construction/operation to support international partners. We thus propose to develop the next-generation LArTPC detector technology with improved physics capability and more robust performance, aiming to be implemented in the future 10-kt detector modules in DUNE. R&D on the next-generation LArTPC technology is critical to ensure international investment and funding of the overall project.

I. A VERTICAL DRIFT SOLUTION

The first generation of LArTPCs use multiple layers of wires with different orientations. The construction of these anode plane assemblies is a time consuming, costly, and labor-intensive endeavor. Leveraging the recent development and existing European investment in the Printed Circuit Board (PCB) anode plane structure in the dual-phase ProtoDUNE (NP02) detector [8], a new concept was introduced at CERN in which a modified large electron multiplier (LEM) PCB is submerged in the LAr to sense ionization signals without any electron amplification [9]. This anode PCB construction avoids several challenges in the dual-phase LArTPC design, while allowing for a vertical ionization electron drift. The latter can take advantage of existing development in constructing and installing field cage and advancement in the high voltage. The vertical drift LArTPC design can also support use of the 3D pixelated charge readout PCB anode that are in development [10, 11].

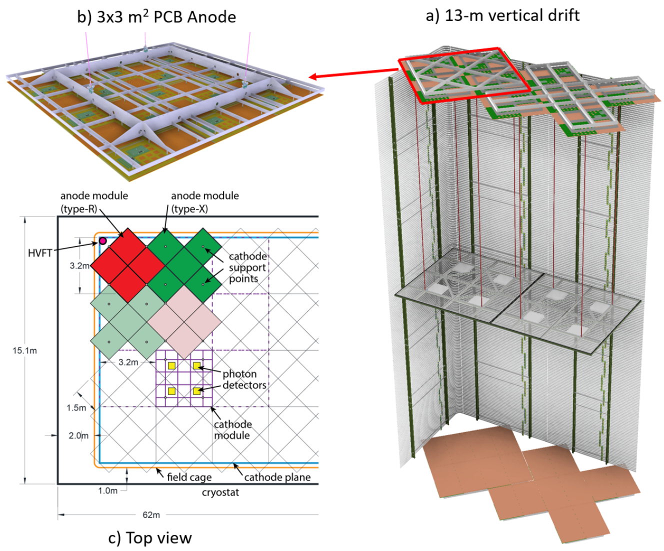

FIG. 1. Next-generation LArTPC concept: a Vertical Drift Solution with the PCB Anode Readout.

The concept of the vertical drift is presented in Fig. 1a. Two separate drifts volumes of 6.5 m each in DUNE, divided by a cathode plane in the middle. Two anode readout planes, one on the top, serving the upper vertical drift volume, one in the bottom serving the lower drift volume. Each anode-plane module is of 3x3 m^2 (Fig. 1b). The necessary homogeneous electrical vertical field is provided by a large field cage, placed as near as possible to the cryostat vertical walls to maintain an electric field of 500 V/cm. Photon detectors (PD) will be instrumented on the cathode planes, following the technologies developed for the NP04 demonstrator. The SiPMs in the PDs on the cathode are powered using power over fiber (PoF), and the output signals are also transmitted through optical fibers.

A. PCB Anode Plane with Cold Electronics

The new design of PCB anode plane TPC readout has several advantages with respect to the wire readout. One such example is the inefficient induction plane signal processing for the prolonged TPC signals that have long extension in the drift time [12, 13]. With LEM PCB, the ionization electrons are forced to go through the small hole. The closest distance between the ionization electrons and the induction electrode can be much smaller than that of the wire readout leading to a larger induced signal in the induction plane. The increased signal size, paired with reduced electronics noise with cold electronics [14] and the advanced signal processing procedure incorporating deep learning techniques [15], is expected to significantly reduce the inefficiency of the induction-plane readout. The most recent test of the anode PCB, adapted a set of cold electronics developed for ProtoDUNE [16] demonstrated excellent signal to noise ratio in a small LArTPC at CERN. Another example is the ambiguities when particles are traveling close to parallel to the anode plane, which is directly visualized with 3D event reconstruction [17]. Such ambiguities is reduced in the vertical drift solution because of a finite angle between the anode plane and the neutrino beam direction.

Figure 1c illustrates a possible layout of a TPC using horizontal PCB anode modules. Each module is a 1.5 m $\times$ 1.5 m basic anode panel with two sets of orthogonal strips 1.5 m long. To optimize the readout strip angle with respect to the beam, the PCBs are rotated 45 degrees. There are two types of anode module configurations: a 4 panel rhombus shape and a 5 panel X shape. These two types of modules are interleaved to tile the entire top and bottom of the detector, forming a 4 row, 18 column array. If a 5 mm strip pitch is used, there will be a total of 388,800 readout channels in the entire detector, similar to that of the first detector module with wire readout. A 3-view readout configurations can be achieved by splitting the collection view into two as the design in NP02. Jumpers may be used to connect some channels from adjacent PCB modules together to reduce the overall number of channels. To enhance the light collection efficiency for the near anode events, the induction strips that are on the front side of the PCB can be coated with an insulating layer with wavelength-shifting (WLS) material.

B. Photon Detector with PoF transmission and High Voltage System

Photon detectors (PD) in LArTPCs are generally used for t_0 determination and triggering purposes. In case an efficient photon detector with sufficient coverage, the use of scintillation light can be extended to calorimetric energy reconstruction, as recently demonstrated in ProtoDUNE-SP. This opens the way to improvement of detection efficiency and energy resolution by combination of both the charge and the light signals, particularly important for detection and reconstruction of low energy underground events. In the first DUNE 10-kt module, thin bar-shaped PD modules (ARAPUCA technology) are integrated in the APA frames, occupying the space between the two ground mesh planes. Silicon photo-sensors (SiPM) are used to convert the light to electrical signals, which are brought out of the cryostat on copper cables. In the Vertical Drift LArTPC layout, the PCB plane structure is largely opaque and does not permit for PD installation at the anode side of the TPC. Photon detector modules will thus be integrated in the cathode plane, ie promoting the cathode plane into a photo-sensitive cathode plane, with the photo-sensors operated on HV surfaces (-325 kV). To overcame this non trivial constraint, the SiPMs are powered on the cathode using power-over-fiber (PoF) technology, and the output signals are also transmitted off the cathode through optical fibers. A basic PoF based PD module, embedded inside a cathode module, consists of an ARAPUCA cell, a photo-voltaic converter, and an optical transceiver. The optical power sources, and the signal readout system are installed outside of the cryostat.

To reach the -325 kV bias voltage, some further improvements on the HV feedthroughs (HVFT) used by NP04 and NP02 (tested at 300 kV) are needed. A 6.5 m long HV extender is required to be installed between the HVFT and the cathode. Several design concepts exist to improve what has been implemented in NP02. A HVFT penetration at the mid height of the cryostat is also being considered. NP02 has demonstrated the simplicity of constructing, and installing a field cage in a vertical drift TPC. An improved version of this field cage design, which has been developed for the DUNE dual-phase far detector module, can be directly applied. The cathode plane, consisting of 3.2 m $\times$ 3.2 m $\times$ 5 cm modules, will be a complete new design. The 3.2 m dimension matches the 1.6 m cryostat warm structure pitch simplifying the detector support penetration layout. The cathode is constructed from a fiber reinforced plastic (FRP) frame covered with stainless steel wire mesh on the two sides. Photon detector modules are mounted to the FRP frame inside a few selected pockets and enclosed by the stainless steel mesh to prevent charging up in the TPC in addition to the physical protection. This cathode module is supported through 4 FRP round tubes to the upper anode plane. The power and output fibers for the PDs can be embedded in these support hangers to reach the top of the cryostat. Additional light conversion and containment can be achieved by installing reflector foils with WLS coating in the empty cells in the cathode frame and the field cage.

II. SUMMARY

While LBNF will provide excavated underground space for four 10-kton LArTPCs and the design and construction plan of the first detector module is determined, the design of additional detector modules is open. R&D on the next-generation LArTPC technology is critical to support international partners. Leveraging the existing development in Europe, the development of the vertical drift solution with the PCB anode readout concept is critical to ensure international investment and the overall funding of DUNE.

[1] R. Acciarri et al. Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE): Conceptual Design Report, Volume 1: The LBNF and DUNE Projects. 1 2016.

[2] S. Amerio et al. Design, construction and tests of the ICARUS T600 detector. *Nucl.Instrum.Meth.*, A527:329–410, 2004.

[3] R. Acciarri et al. Design and Construction of the MicroBooNE Detector. *JINST*, 12(02):P02017, 2017.

[4] B. Abi et al. The Single-Phase ProtoDUNE Technical Design Report. 2017.

[5] B. Abi et al. First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform. 7 2020.

[6] Babak Abi et al. Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV Far Detector Single-phase Technology. 2 2020.

[7] Veljko Radeka et al. Cold electronics for 'Giant' Liquid Argon Time Projection Chambers. *J. Phys. Conf. Ser.*, 308:012021, 2011.

[8] B. Abi et al. The DUNE Far Detector Interim Design Report, Volume 3: Dual-Phase Module. 7 2018.

[9] B. Baibussinov et al. Operation of a LAr-TPC equipped with a multilayer LEM charge readout. *JINST*, 13(03):T03001, 2018.

[10] D.A. Dwyer et al. LArPix: Demonstration of low-power 3D pixelated charge readout for liquid argon time projection chambers. *JINST*, 13(10):P10007, 2018.

[11] David Nygren and Yuan Mei. Q-Pix: Pixel-scale Signal Capture for Kiloton Liquid Argon TPC Detectors: Time-to-Charge Waveform Capture, Local Clocks, Dynamic Networks. 9 2018.

[12] C. Adams et al. Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative evaluation with MicroBooNE simulation. *JINST*, 13(07):P07006, 2018.

[13] C. Adams et al. Ionization electron signal processing in single phase LArTPCs. Part II. Data/simulation comparison and performance in MicroBooNE. *JINST*, 13(07):P07007, 2018.

[14] R. Acciarri et al. Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC. *JINST*, 12(08):P08003, 2017.

[15] Haiwang Yu et al. Augmented Signal Processing in Liquid Argon Time Projection Chamber with Deep Neural Network, arXiv:2007.12743. 7 2020.

[16] D. Adams et al. The ProtoDUNE-SP LArTPC Electronics Production, Commissioning, and Performance. *JINST*, 15(06):P06017, 2020.

[17] Xin Qian, Chao Zhang, Brett Viren, and Milind Diwan. Three-dimensional Imaging for Large LArTPCs. *JINST*, 13(05):P05032, 2018.