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A LArTPC with Vertical Drift for the DUNE Far Detector

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The Far Detector of the Deep Underground Neutrino Experiment (DUNE) will be a large LAr detector located at a baseline of 1300 kilometers, 1.5 km deep underground. It is planned to be made up of four modules, each with a total mass of 17 kt of LAr, at least the first two of which will consist in Liquid Argon Time Projection Chambers (LArTPCs). To prove the feasibility of the LArTPC technology at the kiloton scale, the ProtoDUNE Single and Dual-Phase detectors were constructed and operated at the CERN Neutrino facility.

This document describes the Vertical Drift detector concept, which is proposed to instrument the second DUNE module. It consists of a TPC where the electrons drift vertically, with a cathode suspended at mid-height, towards anodes placed at the bottom and top of the detector. The anodes would be made out of printed PCBs instead of wires, and the new disposition would allow the top readout electronics to be accessible during the lifetime of the experiment. An enhanced photo-detection system is also proposed, with the photo-sensors placed on the cryostat walls and the cathode, but posing a challenge in terms of power and signal transmission. Studies are ongoing both to overcome the technical challenges of this new design and to finalize the concept.

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¹for the DUNE Collaboration

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1. The DUNE experiment

The Deep Underground Neutrino Experiment (DUNE) is a long-baseline neutrino experiment that aims to address the major open questions in fundamental physics, like understanding the matter- antimatter asymmetry of the universe and the determination of the neutrino mass hierarchy. A 1.2 MW beam (upgradeable to 2.4 MW) that can operate in either neutrino or anti-neutrino mode will be generated using the proton accelerator complex at Fermilab. A Near Detector located at Fermilab characterizes the beam and provides real-time beam monitoring. The Far Detector (FD) is located 1300 km away, at the Sanford Underground Research Facility in South Dakota. An underground cavern is currently under construction 1.5 km deep, to contain the four gigantic detector modules. At least two of these will be instrumented with Liquid Argon Time Projection Chambers (LArTPC), with masses of 17 kilotons each. These are the largest LArTPC detectors ever attempted, to be housed in $60 \times 15 \times 14 \text{ m}^3$ cryostats. LArTPC technology has proved to be adequate to build large volume detectors. Thanks to its high imaging capabilities, it is capable of providing excellent kinematic reconstruction of events, with millimetric spatial resolution.

The first module (FD-1) will be a Horizontal Drift (HD) LArTPC [1], for which the prototype ProtoDUNE-SP was built and operated at the CERN Neutrino Platform. Containing 780 tons of LAr and full-scale components, it was the first operation of a LArTPC at the kiloton scale. The tests at CERN showed that it is possible to achieve very high levels of Ar purity, allowing detectors with longer drift lengths without the need of amplification, as was attempted in the ProtoDUNE-DP. Based on this experience, the Vertical Drift Time Projection Chamber (VD-TPC) concept, consisting of a LArTPC in which electrons drift vertically over 6.5 m, is proposed for the second module [2] (FD-2).

2. The Vertical Drift LAr Time Projection Chamber

A schematic drawing of the proposed VD-TPC detector is presented in figure 1. The cathode is hanging at mid-height, with a bias voltage of -300 kV, and is the only structure within the active volume. The electrons drift 6.5 m vertically towards the anodes are placed at the top and bottom of the detector. The surrounding field cage is an independent structure that ensures the electric field uniformity at 500 V/cm. Because the anodes are opaque, the photon-sensors are placed on the cathode and on the cryostat membrane behind the field cage.

2.1 Anode Design

The anodes of the detector are perforated printed circuit boards (PCBs), so that they can be hung horizontally without suffering significant deformations. Figure 2a shows a schematic drawing of the anode, consisting of two PCB boards. The first with a protective shield and the first induction plane, and holes through which the electrons drift towards the second induction plane and the collection plane. A Wire-Cell [3] simulation of the expected electric field is also shown. The design of the strips width and direction, hole diameter, and other specifications is being optimized; one of the tested configuration is shown in the picture in figure 2b, as well as the clear signals of crossing muons on an induction (bipolar pulse) and collection (unipolar pulse) plane.

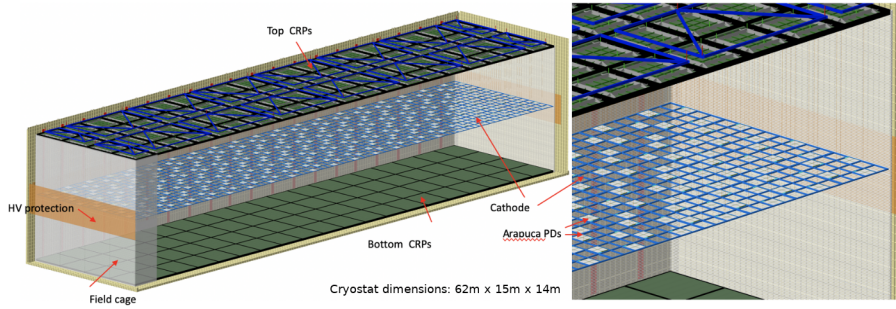


Figure 1: Drawing of the full VD-LArTPC, with a close-up to the mounting of the photo-sensors.

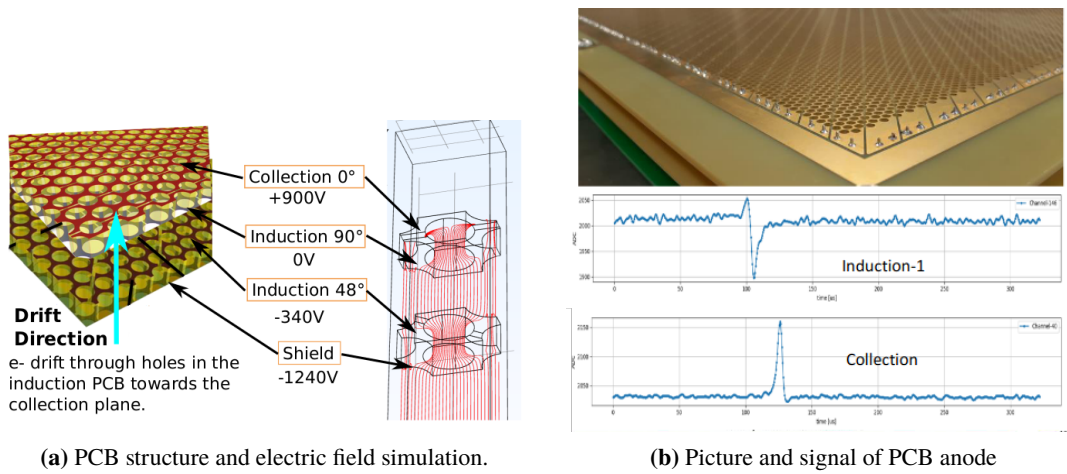


Figure 2: (2a) Schematic drawing of the anode, showing the electron drift, the different views and the simulation of the electric field. (2b) Picture of a tested anode and example signals from the first induction view (bipolar pulse) and the collection view (unipolar pulse).

The anodes are mounted within charge readout plane (CRP) structures, which are different for the top and bottom. The top CRP, presented in figure 2a has a stainless steel frame that hangs from kevlar wires. The position is adjusted with motors, in order to achieve the planarity requirements of less than 10 mm of deformation over 3 m. The transparency should be above 15% to allow LAr flow. Because this anode is close to the cryostat roof, it is possible to install the readout electronics inside chimneys, accessible throughout the detector’s lifetime for repairing if needed. The bottom CRP is held by adjustable feet directly posed on the cryostat floor, as shown in figure 3b. It is lighter and more transparent than the top because the steel support frame is not needed. The readout electronics are represented as pink boxes, connected from the bottom.

Both top and bottom electronics are required to have below $1000e^-$ system noise levels, around $1 \mu s$ front-end shaping and 12-bit digitization at a 2 MHz rate to have a negligible noise contribution and correctly match the shaping. They’ve been under development since 2006 and tested in ProtoDUNE SP and DP.

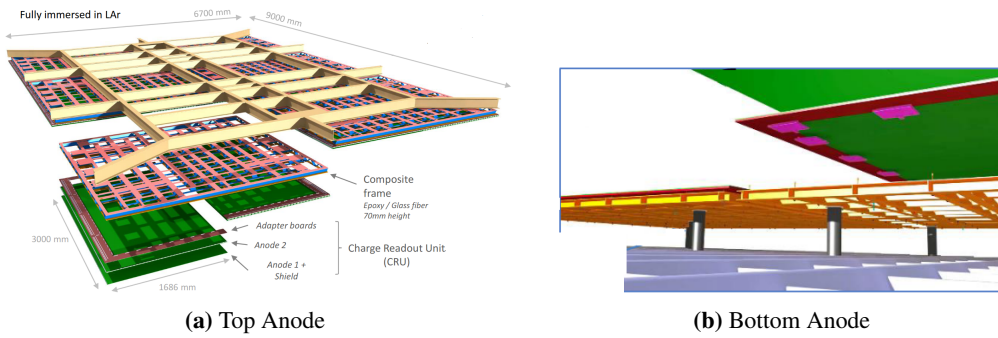


Figure 3: Schematic drawing of the top (3a) and bottom (3b) charge readout plane structures of the anodes. The structural frames and PCB boards are shown in both cases.

3. Photon Detection System (PDS)

The photons of LAr scintillation are detected to provide the trigger and time-stamp of events. This is particularly important in non-beam events and in low-energy physics. The detectors of the PDS can be placed on the cryostat walls behind a field cage with increased transparency, or on the cathode surface. The latter considerably improves the performance of the PDS by expanding the coverage, but requires that both power supply and signal transmission be done using only non-conductive materials.

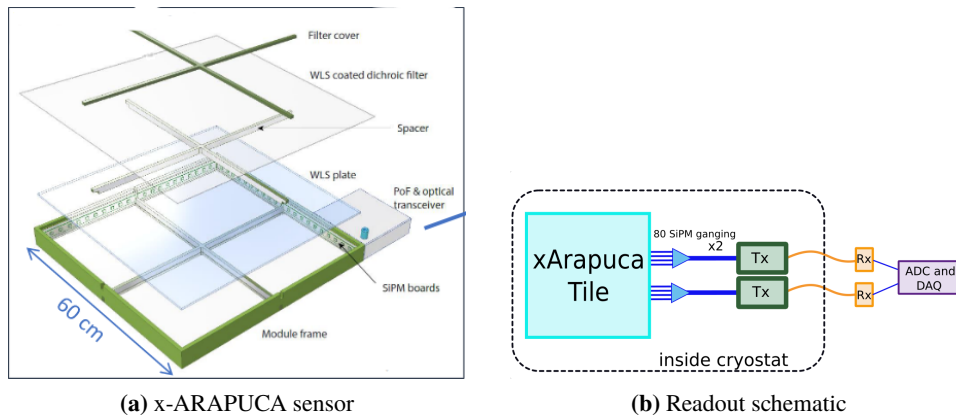


Figure 4: (4a) Drawing of an x-ARAPUCA detector. (4b) Readout schematic of the PD sensors with 160 SiPMs, using an analog optical transmitter inside the cryostat, and receiver and digitization in warm.

3.1 Photo-detectors

The x-ARAPUCA [4], first developed for the FD-1, has been re-designed for use in the VD-TPC concept as shown in figure 4a. It consists of a double or single-sided (cathode or wall) $60 \times 60 \text{ cm}^2$ tile around which 160 (or 80) SiPMs are placed. A VUV-light trap consisting of a dichroic filter and a wavelength-shifting plate enhances and guides the light signal towards the SiPMs. It is planned to add around 10 ppm of Xe doping to increase the photon scattering length.

3.2 Signal and Power over Fiber

An analog optical transmitter is being developed to transmit the signals of the SiPMs outside of the cryostat, to be digitized in warm. No commercial option was found that could be adapted to function in LAr, but an in-house designed circuit has been implemented in a prototype and tested with promising results. Digitizing in cold is also being considered, but is a more complex development that will take more time to demonstrate.

The power of the PDS will be supplied over fiber. The light of a high-power photonic laser module will be transmitted using specially selected multi-mode shielded fibers, to a photovoltaic power converter placed inside the cryostat and close to the photo-sensors.

4. Development status

Since the proposal of the VD-TPC concept, an intense R&D campaign has been on-going to test and validate the different systems. A setup in a 50 lt cryostat (figure 2b) was used for a proof of concept, testing the anode design, signal-to-noise ratio and transparency, and the HV connectors.

With the HV supply of the cathode being one of the most complex challenges, a stand-alone test is being conducted in one of the large ProtoDUNE cryostats at CERN.

Starting in October 2021, a test of the full-sized components is being conducted in a smaller, $4 \times 4 \times 1 \text{ m}^3$ cryostat at CERN. The goal is to test both the mechanics and the performance of the anodes, including both top and bottom full readout chains. It will also allow a proof of concept test of the baseline PDS design, with sensors operating on the cathode at 10 kV.

5. Conclusions

DUNE has a long and rich list of physics goals[5], beyond the long-baseline neutrino beam measurements. It will look into atmospheric, solar and supernovae neutrinos, as well as proton decays, thanks to its large size and deep underground construction.

DUNE's sensitivity estimations envisage a 40 kton Far Detector and assume the performance of a single-phase, horizontal drift detector. The VD-TPC concept, introduced at the end of 2020 as an option for the FD-2, must achieve an equal or improved performance with respect of this reference. A point to consider is for example that the drift length is much longer, therefore the LAr purity should be <50 ppt and the strip length shortened to achieve an equivalent TPC signal quality. Preliminary studies show similar performances of the HD and VD anodes, which have similar pitch and orientation for the collection view but the induction views differ slightly. Lastly, there is an on-going effort to explore how photon-detector calorimetry can expand DUNE's low-energy physics reach. Preliminary results show improvements in the energy and spatial resolution in this regime, a timing resolution above 10 ns and 100% trigger efficiency above 5 MeV up to a distance of 4 m from the cathode.

A very intensive R&D campaign has been put in place to prove the concept's feasibility and address the main identified risk factors. As mentioned before, these are the HV supply of the cathode at -300 kV and the operation of the enhanced PDS on the cathode surface. Concerning the latter, it should be mentioned that alternatively sensors can be mounted only on the cryostat wall, posing no risk. A Conceptual Design Report has been written and is under review [2].

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