A Design for a Deep Underground Single-Phase Liquid Argon Time Projection Chamber for Neutrino Physics and Astrophysics

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Chapter 1

Introduction

1.1 Overview

The former LBNE Far Detector Project team has prepared this design document which describes a single-phase liquid argon time projection chamber (LArTPC) of fiducial mass 10 kt. Throughout this document it is referred to as the LAr-FD. The LAr-FD is proposed as the basis for the design of the LBN far detector, with the intention of building four 10-kt modules to reach the desired fiducial mass of 40 kt., and would enable a compelling research program in long-baseline and underground neutrino physics and in nucleon decay. The ultimate goal in the operation of the facility and experimental program is to measure fundamental physical parameters, explore physics beyond the Standard Model and better elucidate the nature of matter and antimatter.

The basic components of this detector type are a cryostat to contain the liquid argon (LAr), a TPC detection mechanism immersed in the LAr, readout electronics and a cryogenic system to keep the LAr temperature at 89 K and maintain the required purity. The cryostat and cryogenics systems will be managed by LBNF, thus independently of the detector, and therefore descriptions of these systems are not included in this document. The location, orientation and configuration of the caverns that will hold the detector modules will be described

in the CDR, I presume.

fig:10kt-fiducial-mass

The fiducial mass of one 10-kt detector module is shown in Figure 1.1.

In a LArTPC, a uniform electric field is created within the TPC volume between cathode planes and anode wire planes. Charged particles passing through the TPC release ionization electrons that drift to the anode wire planes. The bias voltage is set on the anode plane wires so that ionization electrons drift between the first

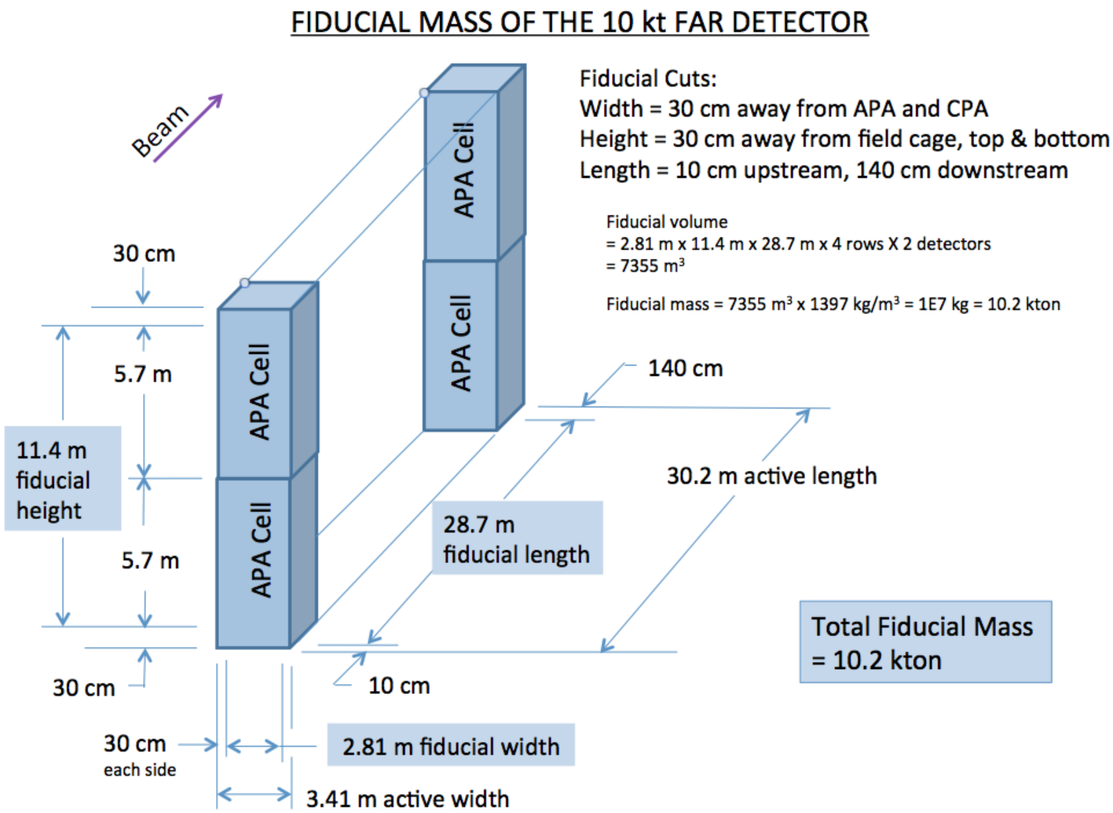

Figure 1.1: Fiducial mass of 10-kton detector

fig:10kt-fiduc

several (induction) planes and are collected on the last (collection) plane. Readout electronics amplify and continuously digitize the induced waveforms on the sensing wires at several MHz, and transmit these data to the data acquisition (DAQ) system for processing. The wire planes are oriented at different angles allowing a 3D reconstruction of the particle trajectories. In addition to these basic components, a photon-detection system provides a trigger for proton decay and galactic supernova neutrino interactions.

The design of the LAr-FD has been developed and refined over the past five years. The starting point was the ICARUS T600 system [?], and the process was informed and guided by the experience with small LArTPCs in the U.S., particularly ArgoNeuT [?], the development of designs for MicroBooNE [?]. The LAr-FD concept is designed for assembly from small, independent elements which can be repeated almost indefinitely in any dimension to form the entire assembly within a large cryostat. Each of the elements provides an independent mechanical structure to support the elements it contains. To a large extent, scaling from detector volumes containing anywhere from a few to several hundred such elements is straightforward with small and predictable risk. Scaling in other areas of LArTPC detector technology, namely cryostat construction, LAr purification and electronics readout has been incorporated into the design.

1.2 LAr-FD Components

1.2.1 Time Projection Chamber

The Time Projection Chamber (TPC) is the active detection element of the LAr-FD. The construction concept is shown schematically in Figures 1.2 and 1.3. A TPC is located inside each cryostat vessel and is completely submerged in LAr at 89 K. Five planes line up across the width: three Cathode Plane Assemblies (CPA) interleaved with two Anode Plane Assemblies (APA). These planes are oriented vertically and parallel to the beamline such that the electric fields applied between them are perpendicular to the beamline. The TPC's active volume within the cryostat is 12 m high, 14 m wide and 30 m along the beam direction.

A "drift cell" is associated with one APA and the two CPAs on either side of it; it is defined as the volume between the enclosed APA's two surrounding CPAs, and bordered by the CPAs' edges. The maximum electron-drift distance between a CPA and an adjacent APA (half of the drift cell) is 3.4 m. Both the CPAs and APAs measure 2.3 m along beamline dimension and 6 m in height; they are each a few cm wide.

Each row of CPAs and APAs is stacked two-high to instrument the 12-m active depth. Each row contains 13 such stacks placed edge-to-edge along the beam direction, forming the 30-m active length of the cryostat's TPC and resulting in a total of 52 APAs and 78 CPAs per cryostat. A "field cage" surrounds the top and ends of the cryostat to ensure uniformity of the electric field. The field cage is assembled from panels of FR-4 sheets with parallel copper strips connected to resistive divider networks.

Each APA has three wire planes that are connected to readout electronics; two induction planes (labeled U and V in Figure 1.2) and one collection plane (X). A fourth wire plane, grid plane (G), is held at a bias voltage but is not instrumented with readout electronics. The grid plane improves the signal-to-noise ratio on the U plane and provides electrostatic discharge protection for the readout electronics.

1.2.2 Electronics, Readout and Data Acquisition

Separate into CE and DAQ, or ok as is?

CMOS technology, with a noise minimum at 89 K, permits the front-end electronics to reside in the LAr (henceforth "cold electronics"), as close to the anode wires as is practical. This minimizes capacitance and therefore signal noise, and benefits LAr purity by not residing in the ullage gas. Figure 1.4 shows the cold electronics architecture, which comprises a front-end shaping/filtering stage (FE ASIC), an analog-to-digital conversion stage (ADC ASIC), and a communication/control stage (digital ASIC). The signal feedthroughs are all located on top of the cryostat, where they are most accessible, are at low hydrostatic pressure, and pose no risk of LAr leakage. The cold electronics multiplex at 1:32, which lowers the cable-count to what can be accomodated by the planned number of feedthroughs, and mitigates contamination from cable outgassing by reducing the volume of cables in the ullage gas.

1.2.3 Photon-Detection System

Identification of the different possible charged-particle types depends on accurate measurements of ionization along tracks. This requires accurate determination of the time of interaction, or event time, t_0, which leads to the absolute location of the event along the drift axis, and allows the determination of Q_0, the true ionization charge.

For non-accelerator physics events, t_0 is not known a priori. However, LAr is an excellent scintillator, generating of order 10^4 128-nm photons per MeV of deposited

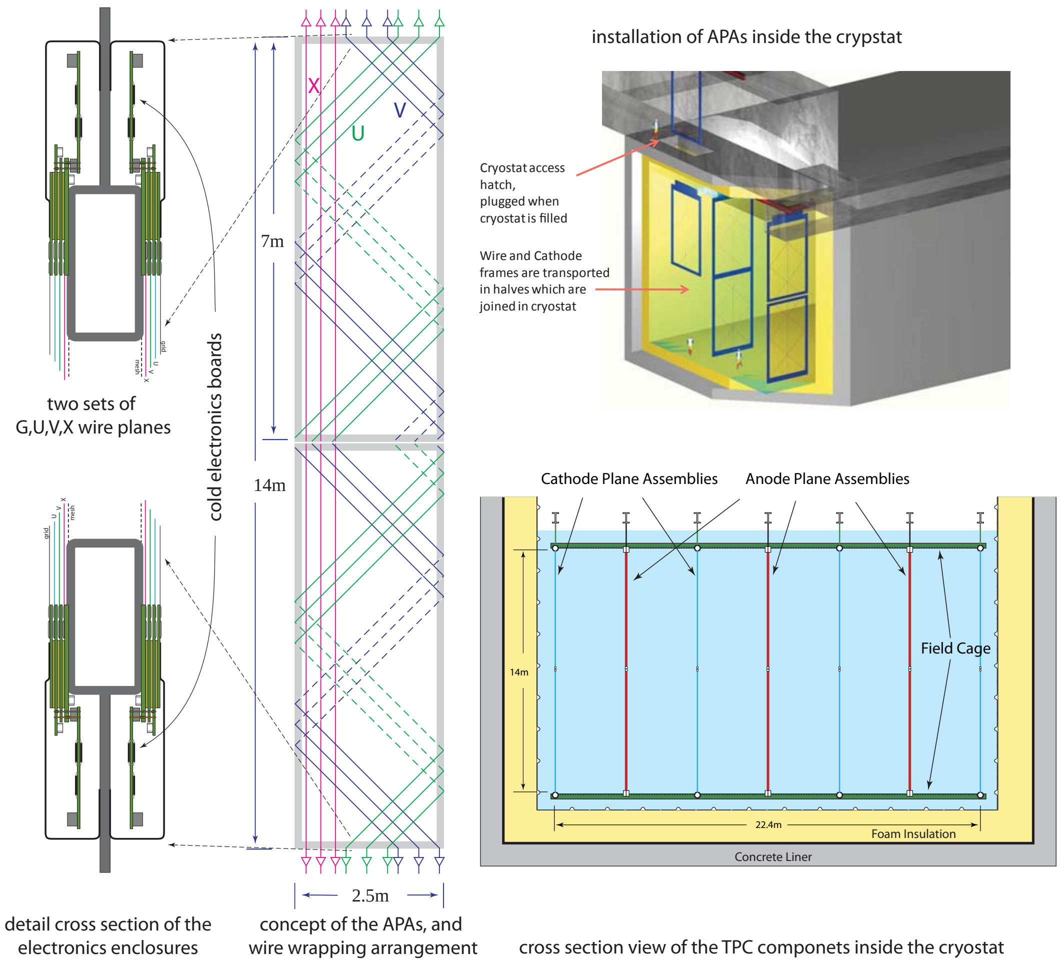

Figure 1.2: TPC modular construction concept; the APA and CPA arrangement has been changed to two APAs and three CPAs as of 2014, see Figure 1.3.

fig:cpa-apa-arrangement-2014

fig:tpc-concep

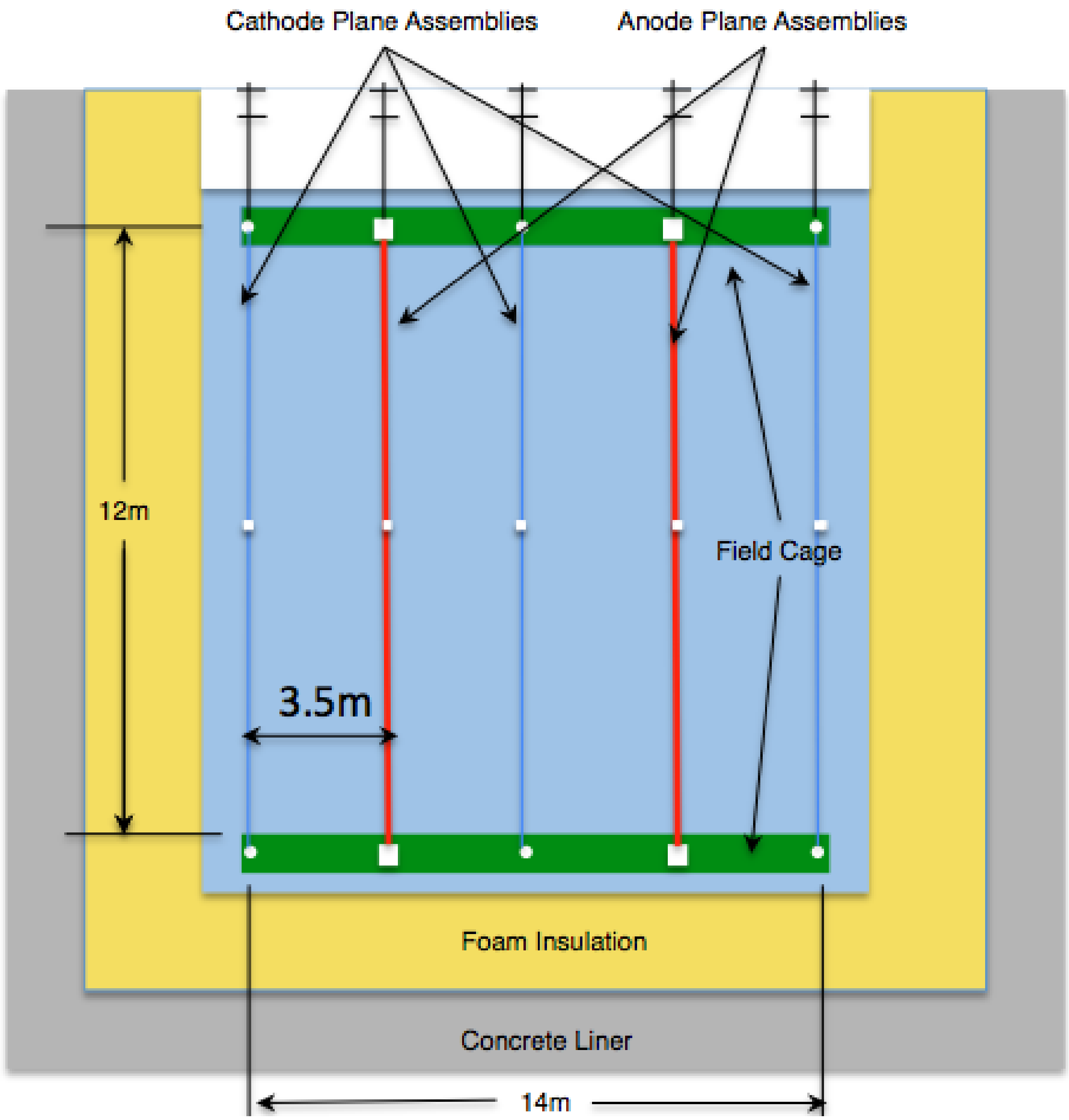

Figure 1.3: APA and CPA arrangement, 2014

fig:cpa-apa-ar

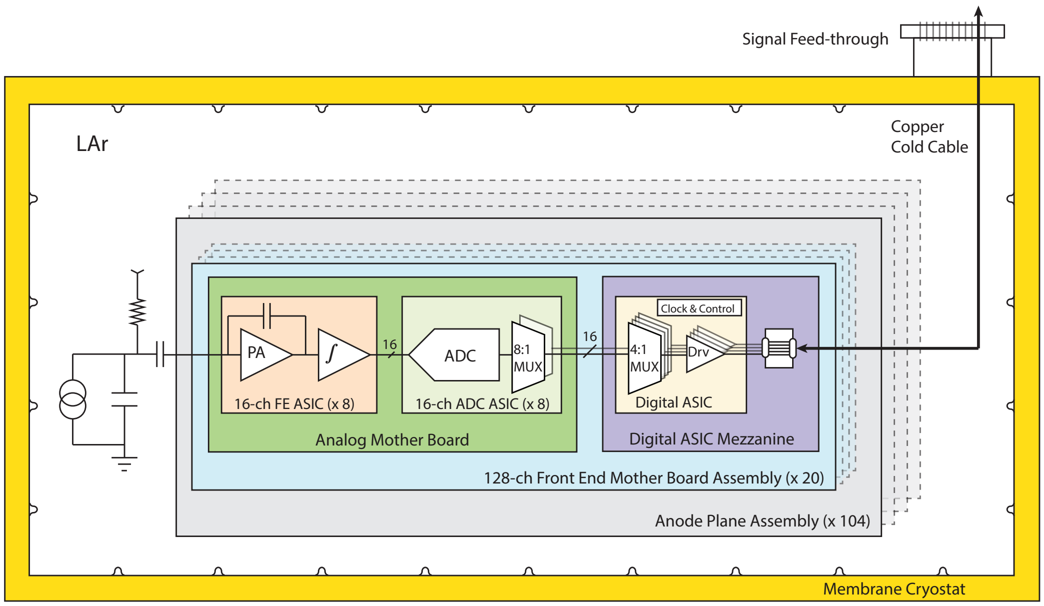

Figure 1.4: Front-end electronics architecture. The ADCs multiplex at 8:1, while the digital ASICs multiplex at 4:1, together giving 32:1.

fig:elect_sche

energy. Detection of scintillation photons provides a prompt signal that allows unambiguous location of particle positions along the drift axis.

The reference design for the photon detection system is based on acrylic bars, which are either coated in TPB or doped in bulk. The 128 nm photons interact with the TPB on the surface and 430 nm light is re- emitted. The signals will be routed out of the cryostat to standard readout electronics.

Twenty light-guide and SiPM assemblies, or “paddles”, will be installed within each APA frame prior to wire winding. The SiPM signals will be used as a software “trigger” in the DAQ to define the event time, t_0, for non-accelerator events. This system provides a t_0 signal throughout the entire detector in contrast to a system similar to that used in MicroBooNE and ICARUS, where light is detected outside the detector volume.

1.3 Detector Installation and Operation

ec:det-install

Detector components will be shipped in sealed containers to the Far Site by truck and lowered to the cavern. Shipping containers will be moved to a clean area over the septum area between the cryostats. There the components will be unpacked from the sealed container and lowered through an access hatch into the cryostat.

The construction of the two cryostats and the installation and commissioning activities will be staged such that both TPCs can be tested cold while one cryostat still remains available as a potential LAr storage vessel. The LAr in one cryostat can be transferred to the other, and back again, if necessary, until all the tests complete successfully. Once both TPCs are known to work properly at LAr temperature, the second fill will take place.

To protect the membrane on the floor of the cryostat during TPC installation, a temporary floor will be installed. After each pair of APAs is installed, they will be connected to the DAQ system and the wire integrity tested. All wires on previously installed APA pairs will also be tested. The wire integrity test will be performed during cryostat cool-down as well. A relatively slow cool-down rate will ensure that the temperature-induced stresses in the APA frames and wires are kept well below the level experienced during testing.

An installation and integration detector mock-up will be constructed at Fermilab to confirm that interfaces between detector systems are well defined and to refine the installation procedures.

1.4 Principal Parameters

The principal parameters of the LAr-FD are given in Table 1.1.

Table 1.1: LAr-FD Principal Parameters for 10-kton Detector

Parameter	Value
Active (Fiducial) Mass	13.8 (10.2) kton
Number of Detector Modules (Cryostats)	2
Drift Cell Configuration within Module	2 wide $\times$ 2 high $\times$ 13 long
Drift Cell Dimensions	2 $\times$ 3.4 m wide (drift) $\times$ 6 m high $\times$ 2.3 m long
Detector Module Dimensions	14 m wide $\times$ 12 m high $\times$ 30 m long
Anode Wire Spacing	$\sim$4.8 mm
Wire Planes (Orientation from vertical)	Grid (0°), Induction 1 (36°), Induction 2 (-36°), Collection (0°)
Drift Electric Field	500 V/cm
Maximum Drift Time	2.1 ms

1.5 Design Considerations

TPCs operated to date have been constructed with an anode wire spacing in the range of 3 mm (ICARUS) to 4.8 mm (Fermilab cosmic-ray stand). The amount of ionization charge collected on the wires increases with larger wire spacing, resulting in a better signal-to-noise ratio without serious consequences (the radiation length of LAr is $\sim$ 30 times larger than the typical wire spacing). The electron-π^0 separation efficiency of a TPC with 5-mm wire spacing is only a few percent lower than one with 3-mm wire spacing. It is also clear that a TPC with larger wire spacing requires fewer wires and readout channels, resulting in lower cost.

Only two wire planes are required to reconstruct events in three dimensions, however three wire planes will be implemented to provide N+1 redundancy. The third will improve the pattern-recognition efficiency for a subset of multi-track events in which trajectories can overlap in two views. The collection-plane wires are most commonly used for calorimetric reconstruction and are oriented vertically (0°) to minimize both the wire length and the electronics noise.

Editor's Note: The following paragraph refers to a wire orientation of 45 degrees. The chosen wire orientation has been changed to 35.7 degrees from vertical. The study and documentation justifying this choice is in LBNE-docdb-9374.

We should just fix this and remove the note.

A study of wire orientation has shown that for a TPC with three instrumented wire planes, the optimum orientation of the induction plane wires should be between $\pm 40°$ and $\pm 60°$ when the collection plane wires are at $0°$. The ideal orientation for the more isotropic low-energy events, e.g., supernova-neutrino interactions, is $\pm 60°$. The selected induction-plane wire orientation of $\pm 45°$ has better position resolution in the vertical direction than $\pm 30°$ and has shorter wires compared to a wire orientation of $\pm 60°$. The induction plane wires are wrapped around the APA frames so that the readout electronics can be located on the top or bottom of the TPC. As a result, it is natural to arrange the APAs vertically in a two-high configration.

Access to the top of the cryostat is required to install and connect cabling. Therefore, risk of personnel injury and detector damage, both of which increase with height, form the primary considerations for the the detector height, 12 m. The The height of the APA has been chosen, accordingly, to be 6 m, resulting in 6-m-long collection-plane wires and 7.3-m-long induction plane wires.

The 2.3 m width of the APA was chosen to facilitate construction and to allow standard, over-the-road transport.

The choice of cryostat width is based on the desired cryostat shape and cavern span. From a cryogenics standpoint, the ideal cryostat for a modular TPC would be a cube since membrane-cryostat capital and operating costs scale linearly with the surface area. This shape is not ideal for cavern excavation, however. In the absence of a geotechnical investigation for the cavern location, the cavern span has been limited to $\sim$30 m on the advice of rock engineers. A detector width of 14 m results after making allowance for cryostat insulation, and personnel access both above and within the cryostat.

A drift field of 500 V/cm was chosen based on experience from similar detectors such as ICARUS, ArgoNeuT and the Fermilab cosmic-ray test stand. At this electric field, $\sim$ 30% of the ionization electrons produced by the passage of a minimum ionizing particle (MIP) recombine and create scintillation light that provides a fast trigger. The remaining ionization electrons drift to the APA and produce wire-plane signals. The TPC could function at higher or lower drift fields but the relative yields of scintillation light and ionization electrons would change. The use of a higher drift field would require more care in the design of the high-voltage systems. The electron drift velocity is 1.6 mm/μs at 500 V/cm.

The 14 m width of the the detector can be divided into four drift cells with a maximum drift length of 3.41 m each. This drift cell length was chosen based on experience from other detectors, the required minimum signal-to-noise ratio and high-voltage considerations. The required minimum signal-to-noise ratio of 9:1 ensures that the tracking efficiency will be 100% throughout the entire drift cell. The TPC must be capable of detecting the smallest signal (1 MeV) produced in interactions that LBNE will study. This situation occurs when a MIP travels parallel to a wire plane and perpendicular to the orientation of the wires in the plane. A MIP loses 2.1 MeV of energy in each cm of travel, producing $\sim$ 40,000 ionization electrons along every 5 mm section of the track. About 28,000 electrons escape recombination and, ignoring the effects of LAr purity and diffusion, would all drift to one collection plane wire. The capacitance due to the maximum-length 7.3 m wire is 164 pF resulting in an equivalent noise charge (ENC) of 500 electrons in the CMOS amplifiers. The signal-to-noise ratio would therefore be 53:1 if all of the ionization electrons arrived at the wire. For a maximum drift distance of 3.41 m and a drift field of 500 V/cm, the required voltage on the cathode plane is 173 kV. This is within the range of commercially available high-voltage cables and within the range of current designs for cryogenic feedthroughs. Additional R&D would be needed for longer maximum drift lengths.

Ionization electrons will be lost due to impurities in the LAr. The fraction that survive passage to the anode planes is $e^{t/\tau}$, where$t$ is the drift time and τ is the drift-electron lifetime. The maximum drift time is the maximum drift length divided by 1.6 mm/μs which equals 2.3 ms for LBNE. The ICARUS detector has achieved a drift electron lifetime of 6 – 7 ms. The Materials Test Stand (described in Section sec:mts **??**) regularly achieves a drift-electron lifetime of 8 – 10 ms. The Fermilab Liquid Argon Purity Demonstrator achieved a liftime of $>$ 3 ms during initial tests. Based on this experience, and by careful selection of materials in the ullage, a drift-electron lifetime at least as good as ICARUS is expected. The signal-to-noise ratio would be 36:1 for a drift electron lifetime of 6 ms. A minimum lifetime of 1.4 ms is required to meet the 9:1 signal-to-noise ratio requirement.

The cloud of drifting ionization electrons will spread out in space due to the effects of diffusion. The maximum transverse RMS width of the electron cloud is 2.4 mm for the chosen drift distance and drift field. This is well matched to the 5 mm wire spacing.

1.6 Detector Development Program

needs update, then remove note

As mentioned above, the design of the LAr-FD has benefited greatly from other experiments and related development activities. Development activities in the U.S. are described in the *Integrated Plan for LArTPC Neutrino Detectors in the US* [**?**]. This program includes non-LBNE activities such as the Fermilab Materials Test Stand, Fermilab electronics test stand, LAPD, photon detection, ArgoNeuT and MicroBooNE as well as LBNE activities such as the 35-ton prototype and LAr1. The development plan is described in detail in Chapter **??**.

Editor's Note: The far detector prototyping plan known as LAr1 has been replaced by a plan to build and test a prototype with full-size TPC components at CERN.

1.7 Participants

The design for the LAr-FD was carried out by an LBNE subproject team, headed at Fermilab but with participants also from Brookhaven National Laboratory, Argonne National Laboratory and Indiana University, in conjunction with an engineering design firm, Arup USA, Inc. that assisted with cryostat and cryogenic-plant design.