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

April 2, 2015

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Chapter 1

Detector Development Program

ch:randd

1.1 Introduction

This chapter describes the development program designed to ensure a successful and cost-effective construction and operation of the massive, dual-cryostat LArTPC detector for LBNE and to investigate possibilities for enhancing the performance of the detector. The feasibility of the LArTPC as a detector has been demonstrated most impressively by the ICARUS experiment.

add ref?

It is understood that for successful operation an LArTPC has stringent requirements on

- argon purity, which must be of order 200 ppt O_2 equivalent or better
- long-term reliability of components located within the liquid argon; in particular, the TPC and field cage must be robust against wire-breakage and must support a cool-down of over 200 K
- the front-end electronics, which must achieve a noise level ENC of 1000e or better

The design of the LBNE LArTPC has evolved significantly from earlier concepts based on standard, above-ground, upright cylindrical LNG storage tanks which envisioned single TPC sense and high-voltage planes spanning the full width of the tank – essentially a direct scaling of previous detectors. Problems with the actual construction of such massive planes and with the logistics of being able to construct the TPC only after the cryostat was complete are avoided in the present design. In this design, TPC 'panels' are fully assembled and tested — including the electronics — independently of the cryostat construction. This modular approach is a key feature of the design. It has the benefit not only of improving the logistics of detector construction, but also the individual components can be of manageable size. It should also be noted that the cryostat itself is formed of modular panels designed for quick and convenient assembly.

1.2 Components of the Development Program

This section needs review

Programs of ongoing and planned development to allow the construction of massive LArTPCs in the U.S. have been developed and described in the *Integrated Plan for LArTPC Neutrino Detectors in the US* [1]. To advance the technology to the detectors proposed for LBNE, the U.S. program has three aspects:

- a demonstration that the U.S program can reproduce the essential elements of the existing technology of the ICARUS program
- a program of development on individual elements to improve the technology and/or make it more cost-effective
- a program of development on how to apply the technology to a detector module

A summary of the items in the program is given in the following tables. Table 1.1 lists the activities that are part of the LBNE Project ("on-project") described in this chapter, a short description of the information needed and the LBNE milestone corresponding to when the information is required. Table 1.2 lists off-project activities, the aspect of these activities that is applicable to LAr-FD and the LBNE milestone at which the information is required. These aspects will be described in more detail in the following sections. As will be explained below, these are not R&D activities, but rather elements of the preliminary engineering design process.

1.3 Materials Test System

An area for LAr detector development, shown in Figure 1.1, has been established in the Proton Assembly Building at Fermilab. The Materials Test System (MTS) has been developed to determine the effect on electron-drift lifetime of materials and components that are candidates for inclusion in LAr-FD. The system essentially

Table 1.1: LBNE on-project development activities

Activity	LAr-FD Information	Need by
In-liquid Electronics	Low noise readout, long lifetime	CERN prototype construction
TPC Construction	Mechanical design	CERN prototype construction
35t Prototype	Cryostat construction	CERN prototype cryostat procurement
CERN prototype	detector integration	TPC construction

tab:on-project

Table 1.2: LBNE off-project development activities

Activity	LAr-FD Applicability	Status	Need by
Yale TPC	None	Completed	NA
Materials Test System	Define requirements	Completed	NA
	Materials testing	Operating	As Req'd
Electronics Test Stand	Electronics testing	Operating	As Req'd
LAPD	Purity w/o evac.	Operating	LBNE CD2
	Convective flow	Operating	LBNE CD2
Scintillator Development	Photon Det. Definition	Completed	CERN prototype Construction
	Industrialization	Not started	LBNE CD3
ArgoNeuT	Analysis tools	On-going	LBNE CD2
MicroBooNE	Electronics tests	Construction	LBNE CD3
	DAQ algorithms	In development	LBNE CD3
	Analysis tools	In development	LBNE CD2
	Lessons learned	Not started	LBNE CD3

ab:off-project

consists of a source of clean argon ($<$ 30 ppt O_2 equivalent), a cryostat, a sample chamber that can be purged or evacuated, a mechanism for transferring a sample from the sample chamber into the cryostat, a mechanism for setting the sample height in the cryostat so that it can be placed either in the liquid or in the gas ullage above the liquid, a temperature probe to measure the temperature of the sample, and an electron-lifetime monitor. The system is fully automated and the lifetime data are stored in a single database along with the state of the cryogenic system.

Figure 1.1: Liquid argon area at the Proton Assembly Building at Fermilab fig:PAB

A noteworthy feature is the novel bubble-pump filter inside the cryostat. In case of argon contamination, this can filter the cryostat volume in a few hours, allowing continuation of studies without having to refill. A schematic of the MTS is shown in Figure 1.2.

The major conclusions of the studies are summarized here. No material has been found that affects the electron-drift lifetime when the material is immersed in liquid argon – this includes, for example, the common G-10 substitute, FR-4. On the other hand, materials in the ullage can contaminate the liquid; this contamination is dominated by the water outgassed by the materials and as a result is strongly

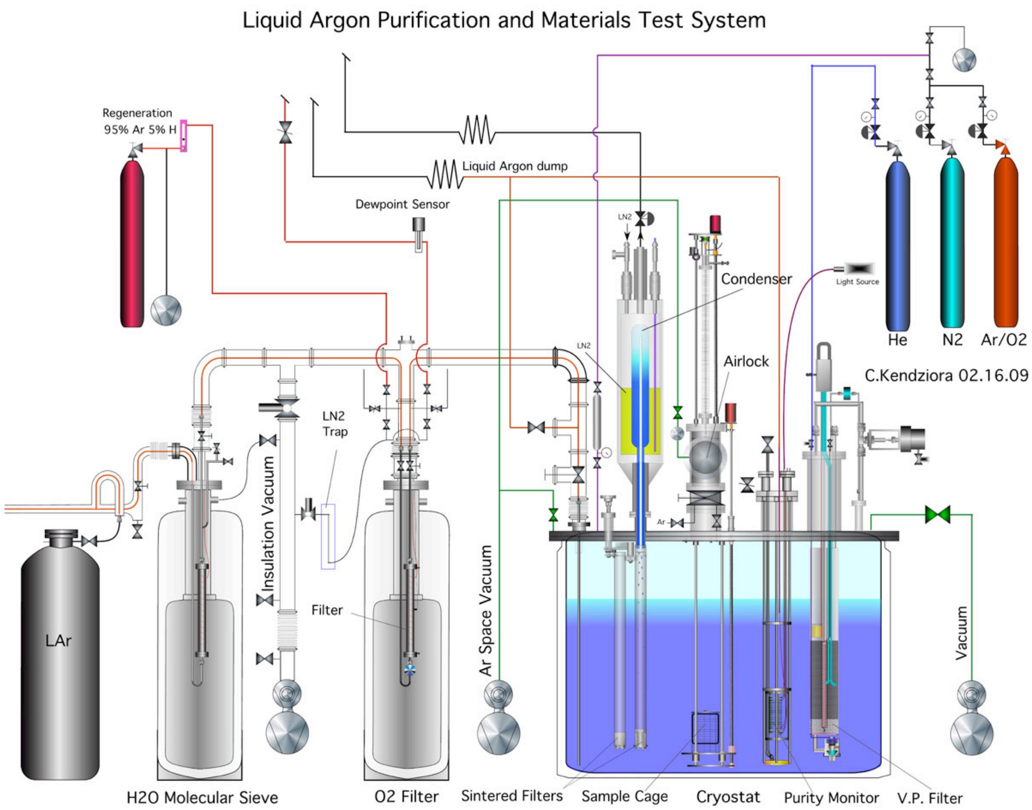

Figure 1.2: Schematic of the Materials Test System (MTS) cryostat at Fermilab fig:MTS_Schem

temperature-dependent. Any convection currents that transport water-laden argon into the LAr and any cold surfaces on which water-laden argon can condense will fall into the LAr and reduce the electron lifetime. Conversely, a steady flow of gaseous argon of a few ft/hr away from the LAr prevents any material in the gas volume from contaminating the LAr.

These results are taken into account in the design of both MicroBooNE and LAr-FD. For LBNE they have been cast as detector requirements. The MTS will continue to be used by MicroBooNE and LBNE to test detector materials such as cables that will reside in the ullage.

1.4 TPC Design

A string of recent events in several liquid argon setups, such as Long Bo, DarkSide50, ArgonTube and MicroBooNE, in which the sustainable high voltage (HV) was much lower than designed voltages

incomplete sentence

. These experiences prompted a reevaluation of the breakdown strength of liquid argon, especially at “detector grade” purity. Recent studies [2][3] have revealed that the HV-breakdown strength depends on factors such as electrode feature size, distance, stress area/volume, and LAr purity. Although no conclusive threshold was found, the results indicate that the safe operating field in LAr is well under 100 kV/cm.

With the uncertainty in the liquid argon HV dielectric strength, attention will be focused on the HV-related aspects of the TPC design; this appears to involve the CPAs and field cage modules.

right?

An R&D document has been compiled for the far detector

add citation

(docdb 10006) that contains a section on the proposed R&D topics and activities to reduce the HV-related risks. Apart from the HV feedthrough, which will be designed and tested above the operating voltages, there is a plan to improve the designs of the CPAs and field cage modules.

The current TPC design directly interconnects all CPAs on a cathode plane. Two of the outer cathode planes face the grounded cryostat walls. The stored energy between one of the outer cathode planes and the cryostat wall, with the full bias voltage applied, is more than 150 joules add citation

(LBNE docdb 8920). This amount of energy, if released suddenly in an event of a high voltage discharge, is sufficient to raise the temperature of a cube of stainless steel with 2-mm sides by 4000°K, resulting in a leak in the membrane cryostat. Moreover, a sudden collapse of the cathode voltage will also inject very large current pulses into the front-end ASICs connected to the first induction plane wires, causing damage to the electronics.

To minimize these risks, the logical steps are:

- minimize the stored energy when possible by swapping the locations of the APA and CPA planes such that no CPAs are against the cryostat wall.
- slow the voltage collapse in a discharge by constructing the cathode planes out of highly resistive material to form a long RC time constant for discharge
  - study the electrical behavior of CPAs constructed from highly resistive material
  - identify and test a resistive coating that is robust at cryogenic temperature and able to maintain good adhesion to the cathode structure
  - design the new CPAs with all resistive elements

Techniques for applying a highly resistive coating over the current 35t-style printed circuit board-based panels on the field cage are being developed in order to remove field concentration around the conductor edges. In parallel, a fall back solution for reducing the field using roll-formed electrodes with a much larger edge radius is being developed.

For the APAs, a simple and effective method to contain a broken outer layer wire must be developed; such a wire must be prevented from drifting far into the drift volume and making contact with the field cage.

1.5 35-ton Prototype: Phase 1

35tonprototype

When first conceived, the 35t prototype cyrostat was constructed to demonstrate that a non-evacuable membrane cryostat can satisfy the less-than-200-parts-per-trillion (ppt) requirement on oxygen contamination of the liquid argon in the detector and maintain that level stably. It was intended to prototype a wide variety of issues that construction and operation of the far detector would need to address, including procurement of materials and services, safety and the processes involved with ensuring the cryostat can maintain high-purity liquid argon. Later it was decided to extend its scope, and to install and operate a small-scale LArTPC and photon detector in the cryostat; this phase will focus on the performance of active detector elements placed directly in the volume of liquid argon.

The membrane cryostat demonstration, completed in 2014, is referred to as "Phase 1" and the operation of the TPC is called "Phase 2." Phase 2 is currently under construction and it is planned to take data in summer 2015.

Needed a bit more introduction before going into the details; I added info above. Please check.

1.5.1 Phase 1 Construction

The construction of the 35t cryostat addressed a number of issues. First were project-related issues, such as gaining detailed construction experience, developing the procurement and contracting model, and incorporating the design and approval mechanism in the Fermilab ES&H manual, which was necessary because membrane cryostats are designed in accordance with European and Japanese standards. Secondly, it addressed technical issues such as high-purity operation in this type of cryostat and the suitability of the planned LAr-FD construction techniques and materials.

The LBNE project contracted with the Japanese company IHI to build the 35t cryostat at Fermilab. It was built in Fermilab's PC-4 facility where the Liquid Argon Purity Demonstrator (LAPD) [4] is also located, which allowed for re-use of a large portion of the cryogenic-process equipment installed for LAPD. The proximity and size (30 tons) of LAPD also offers the possibility using LAPD as a partial storage vessel for LAr if the 35t ever needs to be emptied. The 35t employs a submersible pump to pump the LAr from the cryostat to the filters. Two pumps were installed for redundancy, but only one is used at a time. Figure 1.3 shows the layout of the 35t prototype at Fermilab's PC-4 facility. Figure 1.4 shows a cutaway view of the cryostat and a photograph of the interior of the completed cryostat.

Table 1.3 gives the details of the construction materials and the dimensions for the 35t. More information can be found in [5]. The insulation thickness is 0.4 m rather than the 1.0 m chosen for the reference design. The techniques of membrane-cryostat construction were demonstrated to be a fit for high-purity TPC service. Welding of corrugated panels, removal of leak-checking dye penetrant or ammonia-activated leak-detecting paints, and post-construction-cleaning methods were tested for suitability of service.

In principle, a thin-walled membrane cryostat is as suitable as a thick-walled

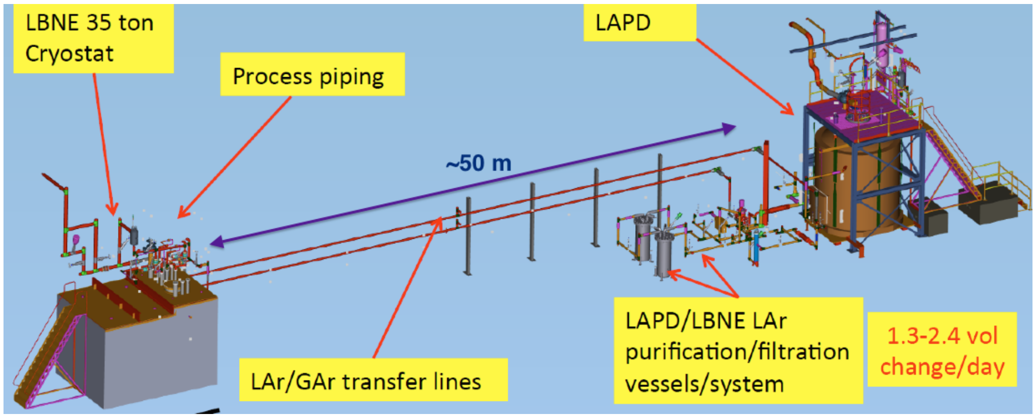

Figure 1.3: Layout of 35t prototype at Fermilab's PC-4 facility. fig:35cryo

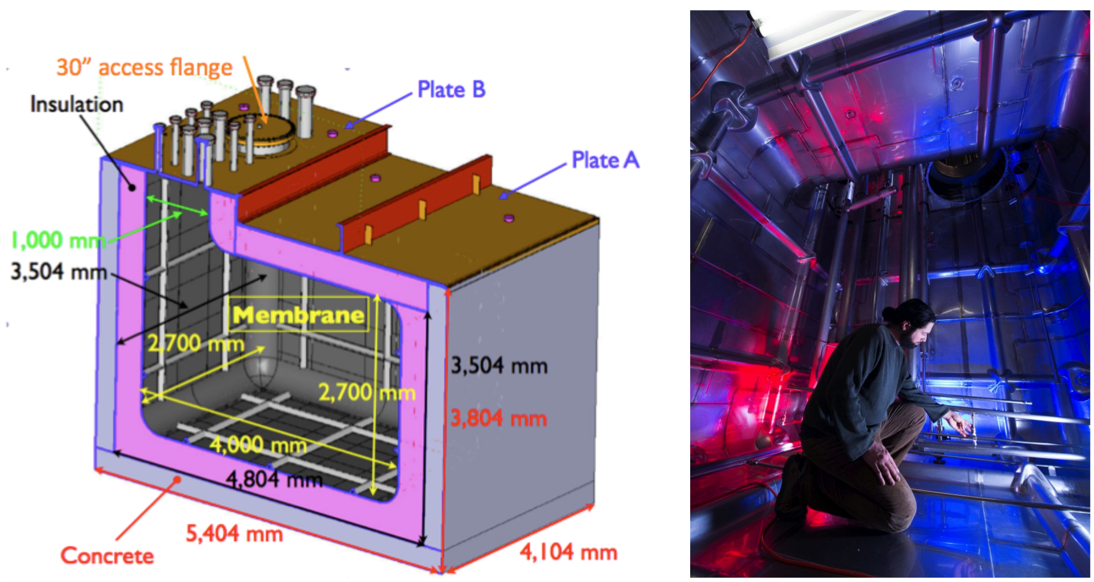

Figure 1.4: (left) Cutaway view of the 35t cyrostat; (right) Interior photograph of the completed cryostat. fig:35cutaway

Table 1.3: 35t Details and Dimensions

Parameter	Value
Cryostat Volume	29.16 m3
Liquid Argon total mass	38.6 metric tons
Inner dimensions	4.0 m (L) x 2.7 m (W) x 2.7 m (H)
Outer dimensions	5.4 m (L) x 4.1 m (W) x 4.1 m (H)
Membrane	2.0 mm thick corrugated 304 SS
Insulation	0.4 m polyurethane foam
Secondary barrier system	0.1 mm thick fiberglass
Vapor barrier Normal	1.2 mm thick carbon steel
Steel reinforced concrete	0.3 m thick layer

:35Tdimensions

cryostat for use with high-purity LAr. Both are constructed with 304 stainless steel with a polished surface finish. Both use passive insulation. The total length of interior welds required for construction would be similar in both cases. The leak-checking procedure would be the same in both cases.

The significant difference between membrane cryostats and thick-walled cryostats is the depth of the welds used to construct the vessel. The majority of membrane-cryostat welds are completed in one or two passes with automatic welding machines. A second difference, and a major advantage, is that the membrane cryostat is a standard industrial design that has been in use for over 40 years. A thick-walled cryostat vessel would be custom designed and would require significant engineering and testing. A third difference, and another major advantage, is the ability to purge the membrane cryostat insulation space with argon gas so that a leak cannot affect the purity if it escapes detection and repair.

1.5.2 Phase 1 Cryogenics Instrumentation

The 35t includes a full complement of standard commercial transducers and sensors that are used to monitor and control the cryogenic environment. They include temperature sensors, pressure transducers (absolute and gauge), flow meters, and level sensors. These devices are typically read out directly into the Control System and data-logged.

A number of commercial gas analyzers are available

have been implemented?

that can measure trace impurity levels (O_2, H_2O, and N_2) in the argon. Some have sensitivities at the 100 ppt level. A gas distribution switchyard feeding the gas analyzers allows the sampling points in the 35t to be reconfigured.

There were also two purpose-built pieces of instrumentation for the monitoring of the high-purity LAr environment, the purity monitors (PrMs) and the RTD Spooler. The PrMs are used to measure electron lifetimes in the LAr, and the RTD Spooler is used to make precision measurements of the temperature profile of the cryostat as a function of depth. These instruments were originally constructed for the LAPD run and are fully described in bib:lapdP07005 [4].

1.5.3 Phase 1 Operations

> This needs an initial sentence stating what the operations are, e.g., air purge, cooldown/fill, LAr purification. I added the following, please check

The operational portion of Phase 1 involved three main steps:

1. removal of the air from the cryostat, leaving only Ar gas (the Piston Purge)
2. cooldown and fill of the cryostat with high-purity LAr
3. maintenance of the high purity level of the LAr

The first two steps above are part of the purification process, which also involves

1. cleaning the liquid Ar as it comes from the supplier
2. removal of any impurities that are generated by materials outgassing within the cryostat.

LAPD, referred to in Section sec:rnd:35t1:construction 1.5.1, had already demonstrated that it is not necessary to evacuate a cryostat in order achieve LAr purity levels sufficient for LBNE.

> something about 'but it didn't demonstrate it for the type of cryostat planned for use in the far detector ...' In other words, why did we still need the 35t for phase 1?

This is of paramount importance since the costs of multi-kiloton cryostats that could withstand evacuation is prohibitive. The 35t followed the procedure LAPD bib:lapdP07005 [4] established to obtain and maintain pure LAr.

Gas Phase

When the phase 1 test began, "dry" air had been purging the cryostat for approximately three weeks.

The first step of the "gas phase" portion of the process, the Piston Purge, removes the air in the cryostat; during this step argon gas is flooded into the bottom of the cryostat. Since argon is heavier than air, the argon layer rises, analogous to a mechanical piston, pushing the air up and out of the cryostat. This gas

initially 100% air?

is vented to the outside atmosphere. The venting stage continues for 32 hours, approximately the equivalent of 12 volume changes. Figure fig:35TPurge 1.5 graphically shows step 1 of the purification process, removal of the ambient air. The initial state, $t = 0$, reflects the initial values for oxygen, water and nitrogen in the "dry air" state. This is followed by the Piston Purge. These measurements are made by a variety of monitors that sample the gas in the cryostat.

After the purge, the exiting gas

which is mostly/all argon?

is re-routed to circulate through the filtration system that removes O_2 and H_2O. (N_2 is not materially removed by the filters.) Any leaks to the outside atmosphere can be detected during this step. As shown in "Debugging" gap in Figure fig:35TPurge 1.5, a leak was found and mitigated. Once leaks have been eliminated the recirculation continues until the O_2 level drops to the sub-ppm level. As can be seen in the plot, the H_2O level plateaus at a much higher level than O_2. This is due to the outgassing of materials inside the 35t, including the cryostat walls, which are

remain?

at room temperature during

throughout?

the recirculation step.

Cooldown and LAr Fill

A gas/liquid spray method is used to cool down the cryostat. This generates a turbulent mixing of cold gas in the cryostat and cools the entire surface. The cooldown rate was maintained lower (slower) than the maximum rate specified by the membrane cryostat manufacturer. The cooldown, as well as the initial fill, is shown in Figure fig:35TCooldown 1.6. The temperature measurements (red traces) in this plot were made by

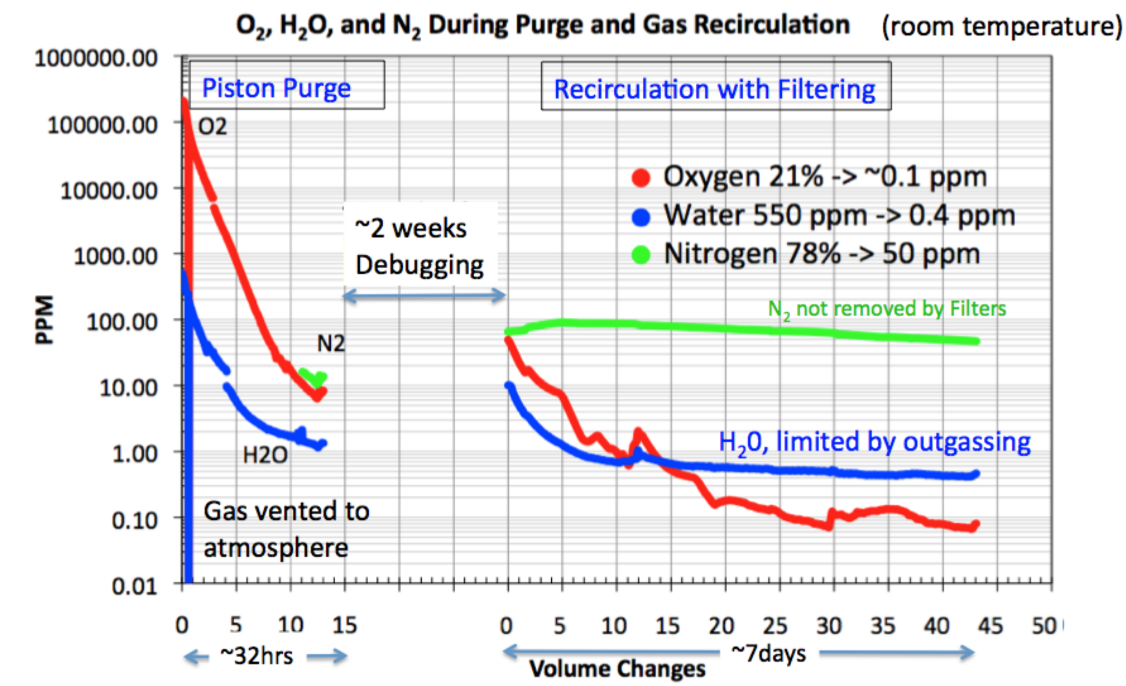

Figure 1.5: Gas phase of removing impurities in the 35t. These quantities are being measured by various gas analyzers. The first stage of the purification is a process called the “Piston Purge”. The second stage is “Recirculation with Filtering”. The gap between the two steps was due to troubleshooting a leak. fig:35TPurge

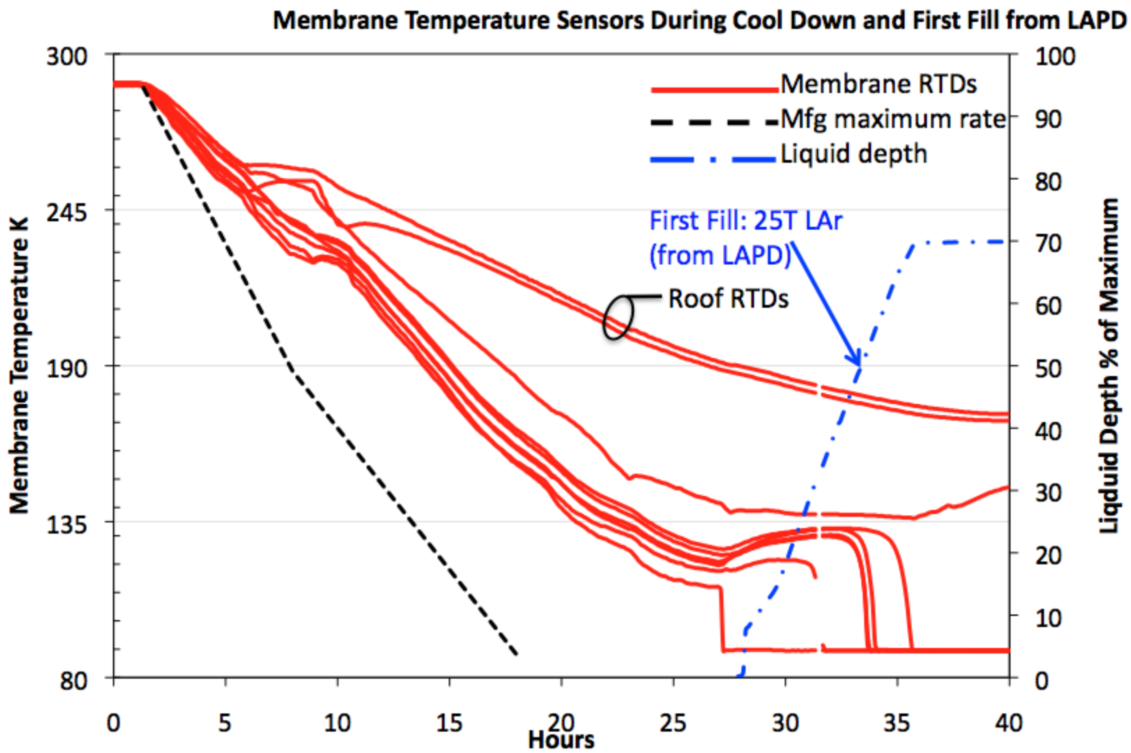

Figure 1.6: Cooldown and filling the 35t. The measurements (red trace) are made from RTDs afixed to the cryostat walls. The black dashed curve is the manufacturer's maximum allowed cooldown rate. The filling (blue trace) was from the transfer of LAr from LAPD, This quantity of LAr is less than the capacity of the 35t. The RTD traces drop to the LAr temperature when the level of the LAr covers reaches their mounting height. fig:35TCooldow

RTDs that are glued to the membrane walls of the cryostat. The black dashed trace is the manufacturer specification for the cooldown rate.

Once the cooldown was complete, the LAr transfer into the cryostat began. In this case the LAr came from LAPD, where it had been used by that system in its own recently completed second run[4].

LAPD contained about 30 tons of LAr, of which only 25 tons could be transferred to the 35t providing a$\sim$70% fill. It was decided to begin the initial commissioning of the Phase 1 run at this point since several components of the 35t could be commissioned at this fill level. After running with the partial fill for approximately eighteen days, additional LAr was added to bring the capacity to 100%, the full 35 tons.

LAr Purification

The Fermilab Material Test System (MTS)[6, 7] (see Section 1.3) has shown that contaminants released inside LAr-filled cryostats come from materials outgassing in the warm ullage regions above the LAr surface. Typical detector materials submersed in LAr have negligible impact of LAr purity levels.

only because the materials have to be tested for this, right?

Figure 1.7 depicts how impurities generated by outgassing materials in the relatively warm ullage under Plate B are swept up by the normal Ar boil-off in the 35t. This impure vapor is condensed in the LN_2-cooled LAr condensor. The impure condensate is returned to the 35t just inside the intake manifold of the interior submersible LAr pump. From there it is pumped to the filtration system where the impurities are removed.

It is worth noting that the electron lifetime of

'in'?

the LAr exiting the filters, as measured by the inline PrM was always > 30 ms (corresponding to a purity $\sim$10 ppt O_2 equivalent). This indicates that the filters are very efficient at removing all trace amounts of O_2 and H_2O. This was true for the entire 35t phase 1 run, including the filling periods.

Figure 1.8 shows the electron lifetime from the start of the LAr Pump operation until the end of the Phase 1 run. In general, the electron lifetime improved as a function of pump on-time, but there were several incidents that spoiled the lifetime.

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These will be discussed in the next section.

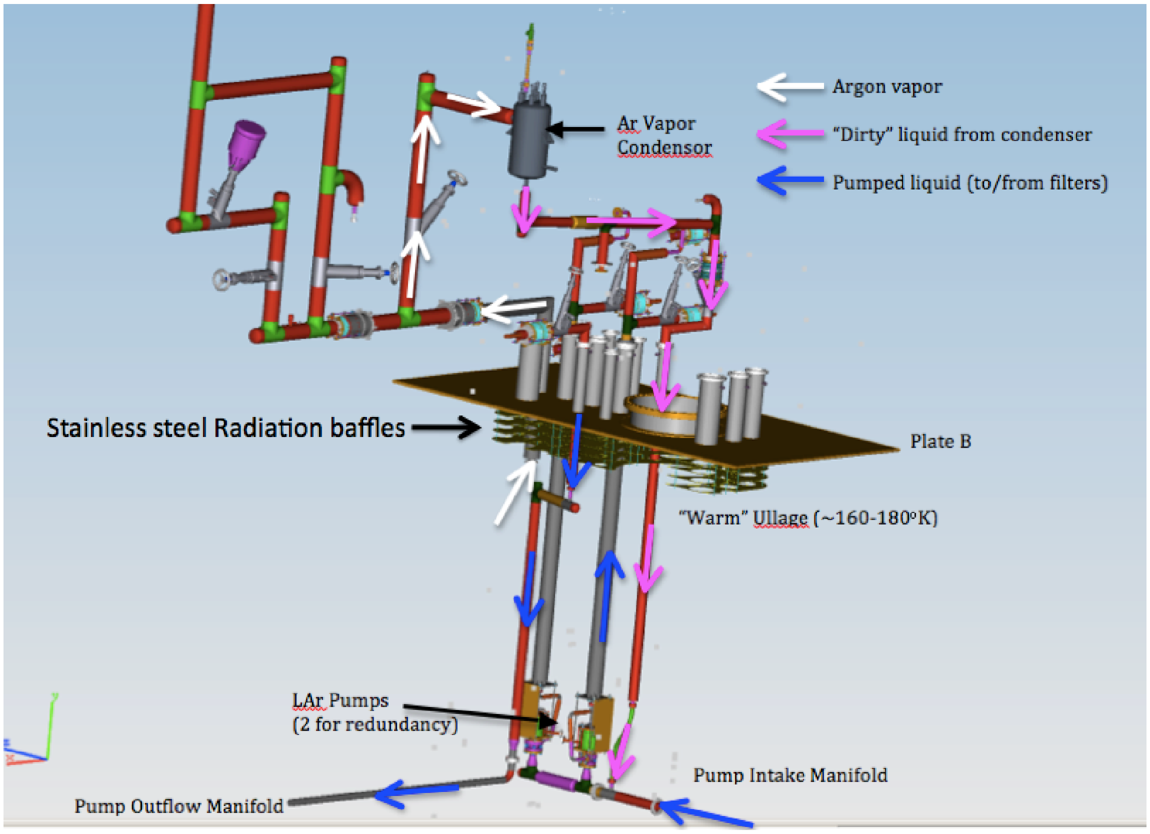

Figure 1.7: Drawing of Boiloff/Outgassing Vapor Flow (white arrows) from the 35t cryostat, with condensate return (violet arrows) from the condensor into the Pump Intake Manifold. LAr flow into the pump, and return from the Purification filters are shown by blue arrows. Also shown is the location of the Stainless Steel Radiation baffles beneath Plate B. This location just beneath Plate B is the warmest location and presumably the principal source of outgassing within the cryostat. fig:35TVaporFl

1.5.4 Phase 1 Stability of Operation

The goals of the 35t Phase 1 run included not only achieving the required purity/lifetime levels, but to also hold those levels and provide

demonstrate?

a stable operation of the cryostat. The 35t Phase 1 LAr run lasted a relatively short ∼2 months.Electron lifetimes in the 2-3 ms range were achieved, as can be seen in Figure 1.8.

The electron lifetimes were severely impacted, however, whenever one LAr pump would switch to another. The drops in purity coincided with the turn on of the previously-inactive pump (see annotations in Figure 1.8). The issue is believed to lie with the procedure used to start the pumps; it will be modified for future operations in the 35t Phase 2 run.

A second stability question is keeping the temperature stable in the cryostat. Currently the 35t controls system regulates the gauge pressure of the cryostat, keeping the internal pressure to 6.69(02) kPa above ambient atmospheric pressure. However this leaves the thermodynamics of the LAr sensitive to normal atmospheric pressure changes.

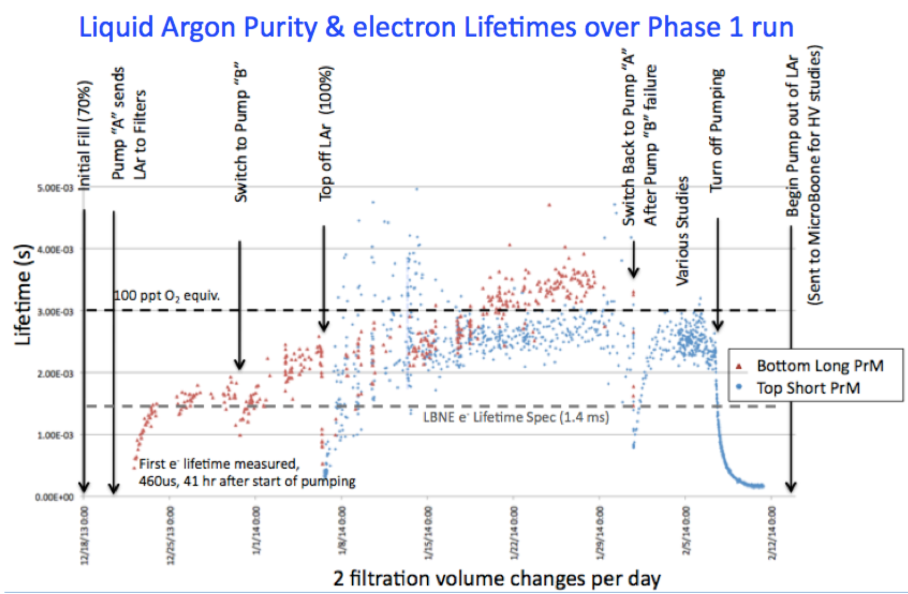

Figure 1.8: LAr electron lifetmes as measured by Cryostat Purity Monitors. Significant events are annotated on the plot. Major divisions on horizontal axis are one week periods. Equivalent purity levels are shown as dashed horizontal lines.

Figure 1.9 shows a plot over a nine-day period of the cryostat absolute pressure (blue trace), bulk LAr temperature (white dashed trace) and the normalized drift time of three PrMs, one short and long inside the cryostat, and the long inline PrM exterior to the cryostat. The temperature is taken from the RTD Spooler measurements by requiring that the RTDs be at least 15 cm below the LAr surface.

prev sentence doesn't make sense to me. You take a temperature by requiring some condition to be in place?

The temperature curve lags the pressure changes ($\Delta P \sim$ 3.5 kPa over this period) due to the thermal inertia of the LAr. However

need 'however'?

the normalized drift time (= drift time/(average drift time for this period) is directly correlated to the LAr temperature. The LAr temperature excursion range was $\Delta T \sim$ 0.3 K. Fitting the normalized drift velocity (inverse of normalized drift time) gives the result

$$\Delta_{driftspeed/\overline{driftspeed}} = -0.022/001\ K$$

The electron drift velocities for these three PrMs varied from (0.3 to 0.4) mm/μs depending on the individual PrM's drift field.

The RTD Spooler was intended to provide a precision measurement of the vertical temperature profile. This measurement is a means of testing the Computational Fluid Dynamics Simulations [5]

that are being made on the fluid motion in the cryostat. Experimentally measuring the actual motion does not appear to be feasible at this time. The CFD calculations are being used to understand whether there might be dead areas in the cryostat where impurities might collect. Figure 1.10 shows the result of one RTD scan. This scan was taken from a period where the barometric pressure was relatively constant so that the temperature would remain constant during the scan. Since a scan takes up to 6 hours in one direction (up or down) and as can be seen in Figure 1.9, pressure changes can impact the bulk temperature of the LAr. These profiles seen in Figure 1.10 are in nominal agreement with the current CFD calculations [5]

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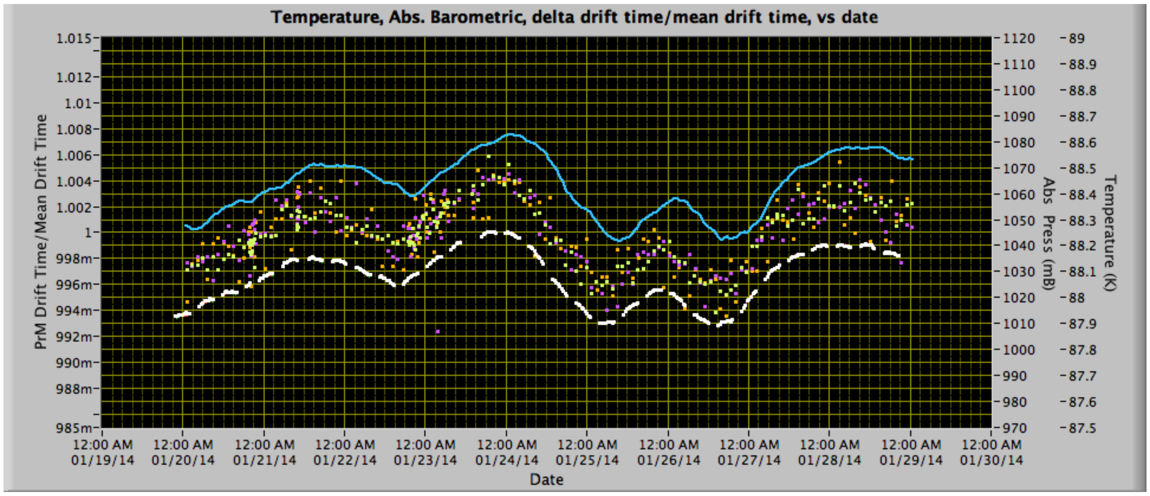

Figure 1.9: Interior Cryostat Absolute Pressure (blue trace), bulk LAr temperature (white dashed trace), and PrM drift times (dots) over a nine-day period. Major divisions on horizontal axis are one day intervals. The PrM drift times are from three PrMs, two in the cryostat, and the third from the inline PrM. The lag between the temperature and pressure is due to the thermal inertia of the LAr.

fig:35TTempSta

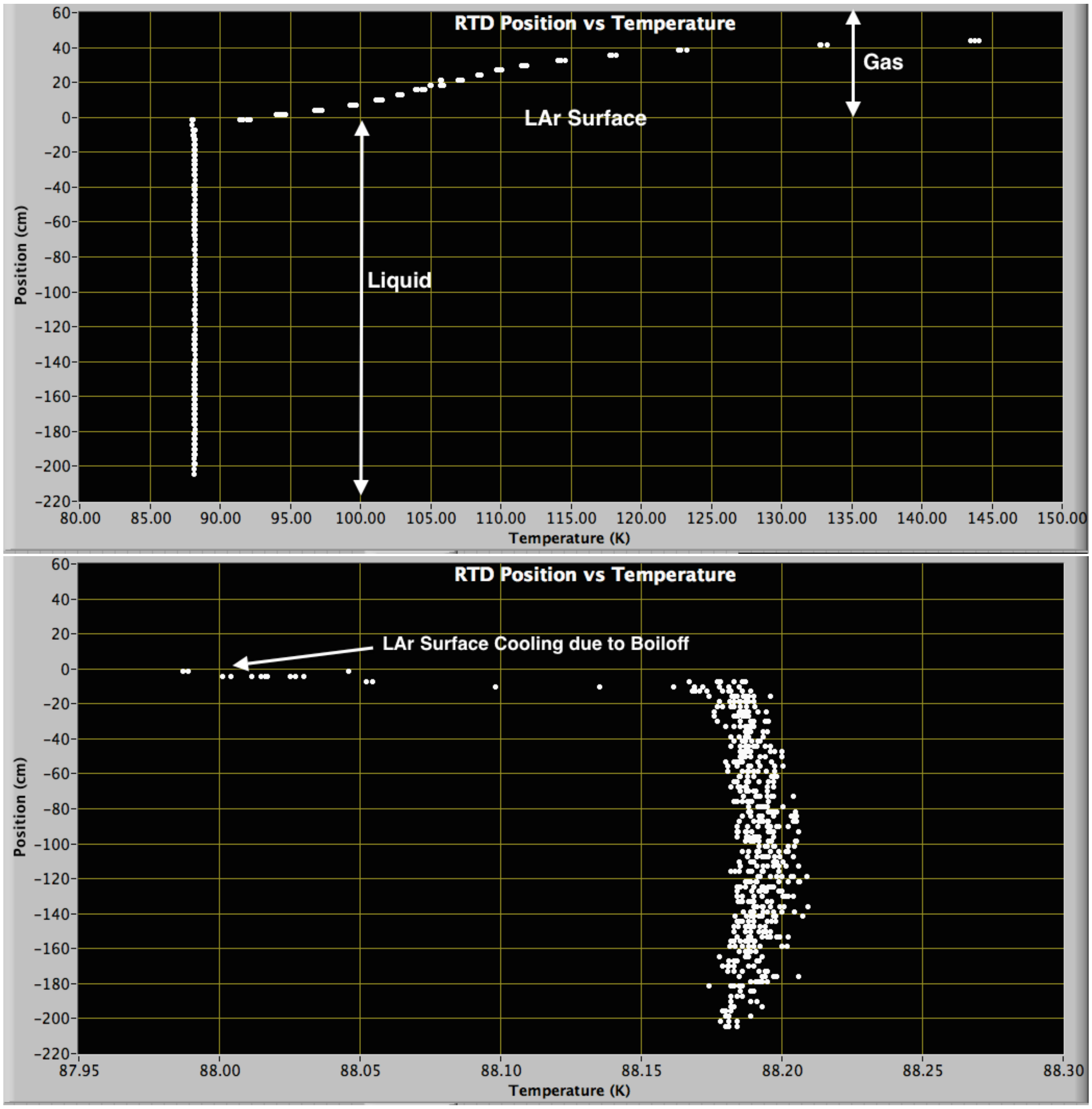

Figure 1.10: (top) RTD Spooler Vertical Temperature scan of the 35t Cryostat under Plate B showing both the liquid and vapor temperature. (bottom) Expanded horizontal axis around 88.12 K. Note that the horizontal divisions on the lower plot are 50 mK. fig:SpoolerSca

1.5.5 Phase 1 Conclusions

The 35t Phase 1 run has shown that the membrane cryostat technology has no innate difficulties with achieving the stated goals of the LBNE Conceptual Design Far Detector. Some of the 35t issues (e.g., loss of purity when pumps are switched) are most likely unique to the 35t. It also seems likely that in a future design, the pumps will be externally located, to avoid coupling acoustical vibrations into the Far Detector cryostat and to facilitate maintenance and repair.

1.6 35t Prototype Phase 2

Phase 2 of the the 35t prototype involves installing a fully operational TPC and photon detector into the previously built cryostat. The prototype will be filled with liquid argon and operated for a several-month-long cosmic ray run. External plastic scintillator paddles placed around the cryostat will be used to produce trigger signals as well as rough position measurements of the incoming cosmic rays. Installation of the TPC into the cryostat is expected in April 2015 and commissioning is expected to begin in June 2015. Figure 1.11 shows a model of the TPC inside the cryostat and a trial assembly of the TPC done outside of the cyrostat.

1.6.1 35t Phase 2 TPC Design

The Phase 2 prototype incorporates many of the design elements described in previous sections of this document. In many cases, these include novel features that have never previously been tested in an operational TPC. Rather than reiterate them all here, some of the more important aspects are collected in Table 1.4.

the xrefs in this table need to be fixed

1.6.2 Phase 2 Simulation, Reconstruction and Analysis

As can be seen from Table 1.4, successful tests of many of the new design features requires simulation, reconstruction and analysis of 35t data. This will be done with the help of the LarSoft package, which is also used to simulate and reconstruct data from the ArgoNeuT and MicroBoone experiments. Reuse of software developed for those experiments can greatly facilitate 35t development. However, the novel hardware features of the 35t prototype necessitate new software developments as well. Among the required new software developments are:

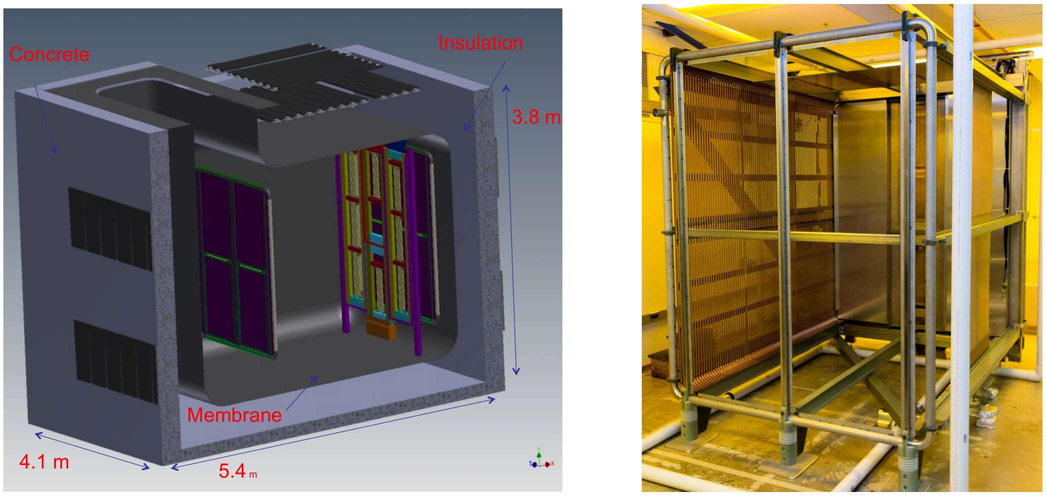

Figure 1.11: (left) 35t Cryostat with TPC and photon detectors installed. Note separate drift regions on "near" and "far" sides. The near side drift length is close to what is proposed for the far detector. The far side has a shorter drift length due to lack of space. (right) A trial assembly of the TPC. fig:35TTPC

Table 1.4: 35t Design Elements

Design Aspect	Section	How Tested
Modular APAs with wrapped wires	subsec:v5-tpc-chamber-apa **??**	Build small-scale APA Modules with FD design
Vertical Gaps between APAs	subsec:v5-tpc-chamber-apa **??**	Assemble APAs side-by-side. Study reco'd tracks that cross the gaps.
Horizontal Gaps between APAs	subsec:v5-tpc-chamber-apa **??**	Build two shorter APAs and stack vertically Study reco'd tracks that cross the gaps
APAs immersed in active volume	subsec:v5-tpc-chamber-apa **??**	Study reco'd tracks that cross APAs
Cold Digital Electronics	subsec:fe_CMOS_digital **??**	Measure noise performance etc. *in situ*
Waveguide-style Photon Detector	subsec:fe_CMOS_digital **??**	Install in APAs. Measure lightyield
Triggerless-capable DAQ	sec:daq_intro **??**	Take data using multiple DAQ modes

tab:35TDesign

- Code to break up the wrapped wires into as many as five individual linear segments. A hit on a single electronic channel can, in principle, be related to an induced signal on any of these segments.
- "Disambiguation" code to identify which of the possible wire segments was actually responsible for the observed hit
- Code for determining the start time of the event (t_0). Since the 35t prototype DAQ can run "triggerless," methods are needed for finding the t_0 in data. Information from the external scintillator paddles as well as the internal photon detectors can be used.
- Code for "stitching" together track segments observed in different tracking volumes. Since hits can come from either side of the four APAs, there are effectively eight separate tracking volumes, which are treated as separate TPCs.

With these simulation and reconstruction tools in hand, "physics" analysis of the data can be undertaken. In addition to the analyses needed to validate the new detector design elements, there are also some analyses of basic LArTPC performance that are needed as well. Among the highest priority analysis tasks are:

- Basic detector performance: signal/noise, purity measured with tracks, track direction resolution, photon detector light yield
- Measurement of distortions due to space charge and field non-uniformity
- Measurements of different types of particles: muons, protons, neutrons, pions

The results obtained by operating the 35t Phase 2 prototype and the analysis of its data are expected to be very valuable in defining the final far detector design.

1.7 Prototype Detector at CERN to Test Physics Sensitivity

The physics sensitivity of DUNE

this is the LBNE closeout; do we want to mention DUNE?

has been estimated based on detector-performance characteristics published in the literature, simulation-based estimates and on a variety of assumptions about the anticipated performance of the future detector, event reconstruction and particle-identification algorithms. A single-phase LAr prototype detector has been proposed for testing in a CERN beam with the goal of replacing these assumptions with measurements. The prototype will implement a full-scale detector element; this will mitigate the risks associated with extrapolating from small-scale versions of the single-phase LAr TPC technology and allow benchmarking of the operation of full-scale detector elements in a well-characterized charged-particle beam.

The detector will need to accurately identify and measure the energy of the particles produced in the neutrino interaction with argon, which will range from hundreds of MeV to several GeV. The beam measurements will serve as a calibration data set to tune the Monte Carlo simulations and serve as a reference data set for the detector.

The prototype is expected to identify any potentially problematic components and lead to future improvements and optimizations of the detector design.

1.8 Physics Experiments with Associated Detector-Development Goals

Two projects, ArgoNeuT and MicroBooNE, which are physics experiments in their own right, are also contributing to the development of the LBNE experiment. Their most important role is in providing data and motivation for the development of event reconstruction and identification software.

1.8.1 ArgoNeuT - T962

The Argon Neutrino Test (ArgoNeuT) is a 175-liter LArTPC which completed a run in the NuMI neutrino beam in 2010. The 0.5 m $\times$ 0.5 m $\times$ 1 m LArTPC was positioned directly upstream of the MINOS near detector, which served as a muon catcher for neutrino interactions occurring in ArgoNeuT.

ArgoNeuT began collecting data using the NuMI muon antineutrino beam in October 2009 and ran until March 1, 2010. ArgoNeuT's $\sim$10k events motivate the development of analysis tools, and are the basis for the first measurements of neutrino cross sections on argon. An event with two π^0 decays is shown in Figure 1.12. fig:2pi0 ArgoNeuT was also the first LArTPC to be exposed to a low-energy neutrino beam and only the second worldwide to observe beam-neutrino interactions. The ArgoNeuT collaboration is currently preparing (1) a NIM paper that documents the detector performance using NuMI beam muons and (2) the first physics paper on muon-neutrino charged-current differential cross sections on argon. See Figures 1.14 and 1.15.

A deconvolution scheme using an FFT has been applied to the ArgoNeuT data. This procedure eliminates a problem with the ArgoNeuT electronics (which were D-Zero spares and could not be modified for ArgoNeuT). Another more significant benefit of deconvolution is that bi-polar induction-plane signals can be transformed into uni-polar collection-plane signals. An example of this is shown in Figure 1.13. A selection of figures from the draft NIM paper are reproduced below.

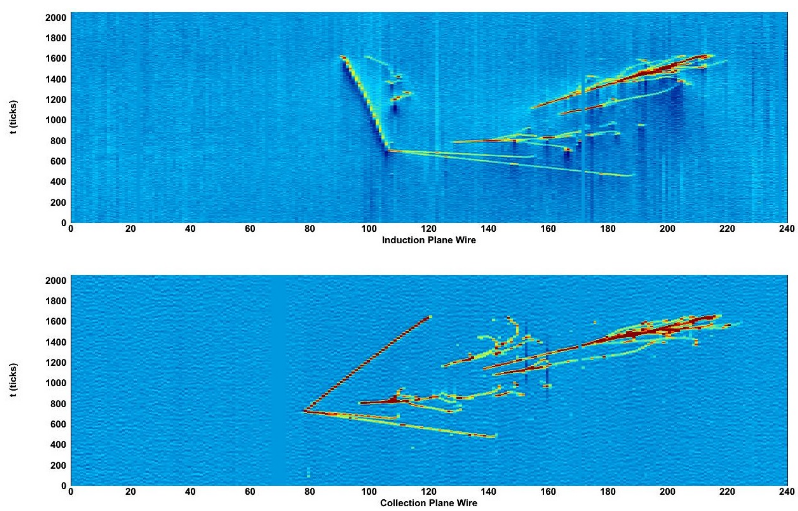

Figure 1.12: A neutrino event with four photon conversions in the ArgoNeuT detector. The top (bottom) panel shows data from the induction (collection) plane after deconvolution.

The applicability of ArgoNeuT is that it provides a set of data in the same range of energy as the LBNE neutrino beam, enabling the development of analysis algorithms that can be utilized for LAr-FD physics analysis with little or no modification.

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1.8.2 MicroBooNE E-974

The MicroBooNE experiment is an 89-ton active mass LArTPC, (170-ton total

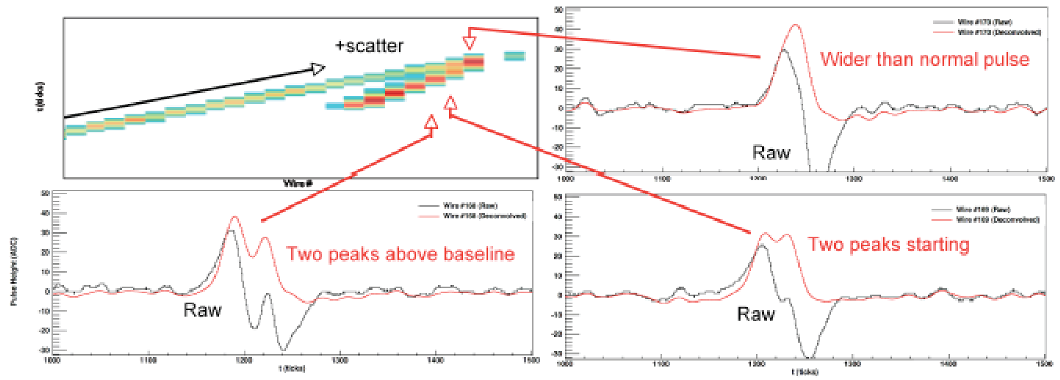

Figure 3: (Upper left) A set of tracks as seen on the (deconvoluted) induction plane. The wire views on three adjacent wires are also shown in order to demonstrate the effects of deconvolution on the raw wire pulses. The raw data can be seen in black and the deconvoluted data can be seen in red.

Figure 1.13: Figure from the ArgoNeuT draft NIM paper fig:Argo-decon

check

argon mass) in the commissioning phase. It has both a physics program and LArTPC development goals.

MicroBooNE received stage 1 approval from the Fermilab director in 2008, partial funding through an NSF MRI in 2008 and an NSF proposal in 2009. MicroBooNE received DOE CD-0 Mission Need in 2009, CD-1 review in 2010, CD-2/3a review in 2011, CD-3b review in 2012 and CD-4 review in December 2014. The construction of MicroBooNE experiment has been completed successfully, and detector commissioning is ongoing. It plans to start running in mid 2015.

As well as pursuing its own physics program, MicroBooNE will collect a large sample (∼100k) of low-energy neutrino events that will serve as a library for the understanding of neutrino interactions in LAr. Because MicroBooNE is at the surface, it will also have a large sample of cosmic rays with which it can study potential backgrounds to rare physics. The process of designing MicroBooNE has naturally stimulated several developments helpful to the LBNE program. Studies of wire material, comparing Be-Cu with gold-plated stainless steel in terms of their electrical and mechanical properties at room and LAr temperatures, and techniques for wire-tension measurement are immediately relevant. Expertise has been developed generating simulations of electrostatic-drift fields as well as simulations of temperature

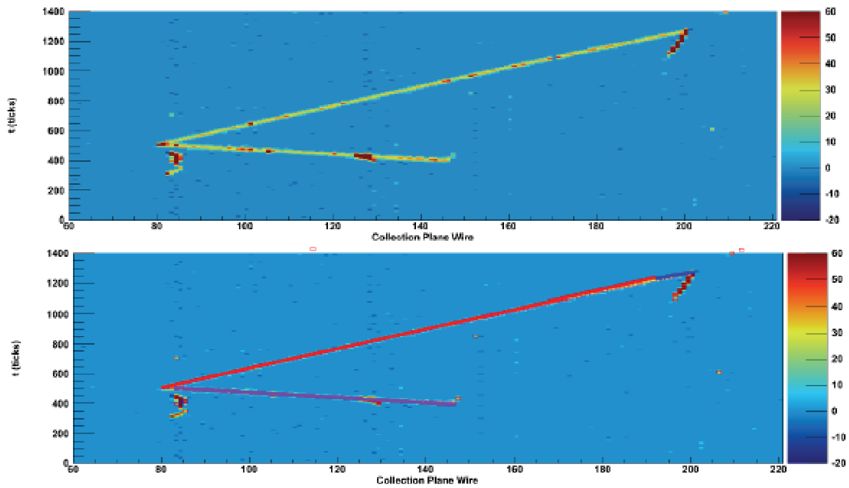

Figure 6: (Top) A neutrino candidate in ArgoNeuT as seen on the collection plane. (Bottom) The Hough lines found with the line-finding algorithm overlaid on the particle tracks.

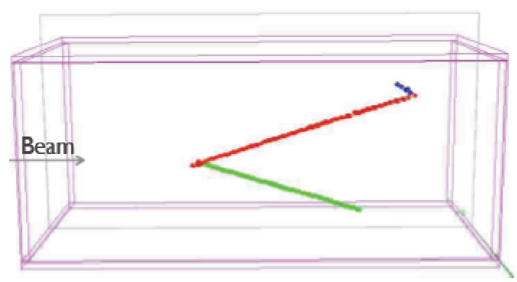

Figure 7: The neutrino event shown in Figure 6 reconstructed in three dimensions.

Figure 1.14: Figure from the ArgoNeuT draft NIM paper showing the status of 3D reconstruction fig:ArgoNeuT_3

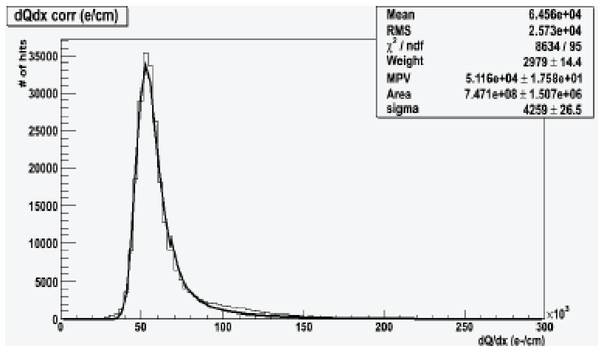

Figure 13: dQ_0/dx distribution (in ADC/cm) obtained for the through-going muon data sample having corrected for the electron lifetime and quenching effect on the ionization charge and properly taken into account the contribution due to δ-rays, as reported in the previous Section. A Landau-Gaussian fit is also reported.

Figure 1.15: Figure from the ArgoNeuT draft NIM paper showing the status of calorimetric reconstruction. fig:ArgoNeuT-c

and flow distributions in LAr cryostats which is being applied to the LAr-FD TPC and cryostat. MicroBooNE will use the front end of the proposed in-liquid electronics as the wire-signal amplifiers and the DAQ developed for MicroBooNE will exploit compression and data-reduction techniques to record data with 100% livetime.

In summary, MicroBooNE's LArTPC development goals that are pertinent to LAr-FD are

- large-scale testing of LBNE cryogenic front-end electronics, similar in scale to the CERN prototype
- testing of continuous data-acquisition algorithms
- refinement of the analysis tools developed in ArgoNeuT
- provide costing and construction lessons-learned

1.9 Summary

Impressive progress has been made in the development of LArTPC technology over the last few years. All elements of the development program have completed the

R&D phase. Credible conceptual designs exist for all systems in LAr-FD. The technical activities described in this chapter are properly characterized as preliminary engineering design.

The most significant deficiency is the lack of fully-automated event reconstruction. Algorithms have been developed within the LAr community and are being successfully applied to ArgoNeuT data as well as to simulated MicroBooNE data. The algorithms have individually shown that the high efficiency and excellent background rejection capabilities of a LArTPC are achievable. The task remains to combine them into a single package.

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