Chapter 9

Prototyping Strategy

Large detector installations as envisioned for DUNE require prototyping efforts to inform the design process. The action of fabrication and assembly can expose details not obvious in design drawings, and the procedures for fabrication and assembly can be better developed. Such engineering-level prototypes can help address various uncertainties in the production process and pave the way for a predictable construction phase without ever being operated. Operational prototypes - for DUNE Far Detector concepts this requires the use of cryostats and cryogenics systems - involve additional effort but provide invaluable feedback on the basic performance assumptions used to set the detector requirements and also used in simulations to estimate the experiment's physics sensitivities. Detector protoyping is not limited to the Far Detector concepts. Detectors to measure the muon flux in the secondary beam are part of the Near Detector (Section 7.5), and prototypes of these are described in this Chapter as well. DUNE prototyping efforts cover both engineering and operational aspects, and these efforts allow the collaboration to acquire and practice the skills and knowledge needed to implement all DUNE detectors.

Not all prototypes must be executed by DUNE in order for DUNE to benefit. The present far detector concepts build upon LAr-TPC R&D efforts performed over many years in Europe and more recently in the U.S. Many of these R&D efforts continue to the present, and some R&D elements are being incorporated into experiments pursuing physics results. At Fermilab, the Liquid Argon Purity Demonstrator (LAPD) established the viability of using a gaseous argon piston purge, without first evacuating the cryostat, to attain the argon purity required for large LAr-TPC detectors. The MicroBooNE detector follows many design elements from ICARUS while utilizing the piston purge and introducing cold electronics, placing wire signal pre-amplifiers in liquid argon, as a step along an electronics development path for

DUNE which places nearly all of the wire readout in liquid argon. The DUNE 35-ton electronics represent the next step on this path, adding the ADC to the readout components in the liquid argon. The Short-Baseline Near Detector (SBND) plans to use the follow-on step, which adds a cold FPGA. The SBND has also adapted the DUNE 35-ton APA-CPA-Field Cage design for its TPC, minus the wrapped-wire feature. The Fermilab Short Baseline neutrino program places three LAr-TPCs – SBND, MicroBooNE and ICARUS – on the Booster Neutrino Beam (BNB), with SBND and ICARUS being installed and operated on a time scale similar to the DUNE single-phase prototype at CERN. A recent proposal places the CAPTAIN LAr-TPC near the BNB target, to study low energy off-axis neutrinos, as these have an energy spectrum similar to that expected for super-nova neutrinos; the results could inform DUNE supernova sensitivity estimates. There is also a proposal to place CAPTAIN in the NuMI beam to study higher energy neutrino interactions in a LAr-TPC. Returning to the present, the Fermilab LArIAT program places LAr-TPC detectors, starting with a refurbished ArgoNeuT, in a charged particle beam; it is dedicated to precise characterization of protons, pions, electrons and muons in LArTPCs with results intended for general simulation and reconstruction techniques across all such detectors.

The DUNE LAr-TPC prototyping strategy is to focus its efforts on the hardware specific to its Far Detector reference designs, but be aware of and receptive to results and observations from all other LAr-TPC efforts currently in progress and planned for the near future.

9.1 The 35-ton Prototype

sec:proto-35t

The 35-ton prototype was initially conceived to demonstrate that a non-evacuable membrane cryostat could satisfy the DUNE requirement that oxygen contamination of the liquid argon be less than 200 parts per trillion (ppt), and that such a cryostat could also stably maintain that level. In addition, the 35-ton prototype also served to identify requirements for procurement of materials and services, to inform procedures for construction, and to inform best practices for safe operation. This phase of the project was successfully completed in 2014.

The scope of the 35-ton prototype was then extended to a second phase, with the decision to install and operate a small-scale LAr-TPC and photon detector in the membrane cryostat. Phase-2 focuses on the performance of active detector elements within the liquid argon volume. Phase-2 is currently under construction and plans to take data in summer 2015.

9.1.1 35-ton: Phase-1

The 35-ton cryostat was built by a Japanese company, IHI [?], contracted by the DUNE project. It was built in Fermilab's PC-4 facility where the Liquid Argon Purity Demonstrator (LAPD) [?] is also located. This location 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 offered the possibility of using LAPD as a partial storage vessel for LAr if it ever became necessary to empty the 35-ton cryostat.

The 35-ton system employed a submersible pump to move LAr from the cryostat to the filters. Figure 9.1 shows a cutaway view of the cryostat and a photograph of the interior of the completed cryostat.

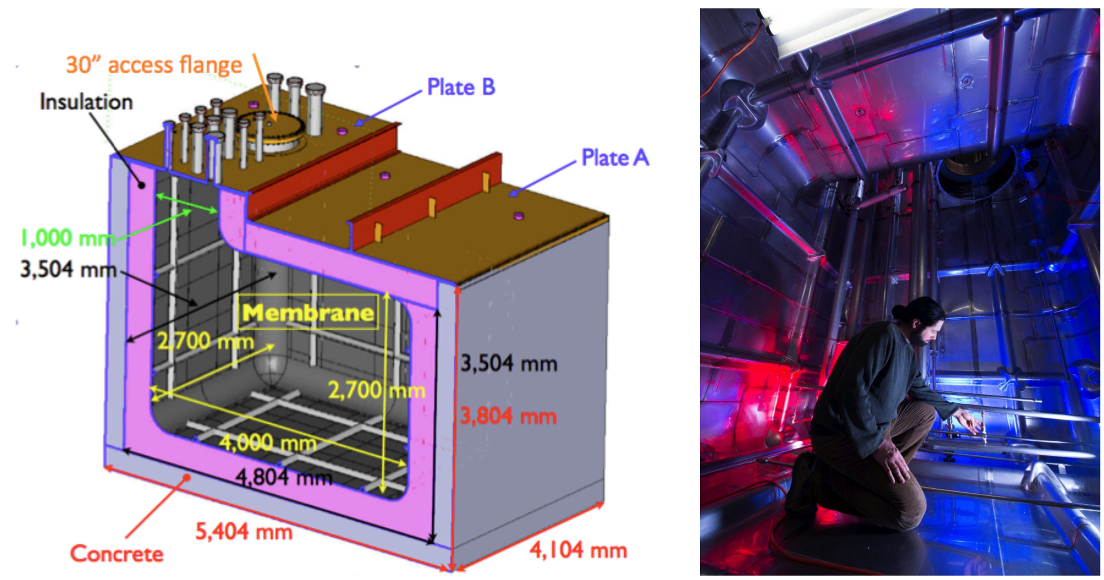

Figure 9.1: (left) Cutaway view of the 35-ton cryostat. (right) Interior photograph of the completed cryostat.

Table 9.1 gives the details of the construction materials and the dimensions for the 35-ton prototype. More information can be found in [?]. The techniques of membrane-cryostat construction were demonstrated to be suitable for high-purity TPC service. In particular, welding of corrugated panels, removal of leak-checking dye penetrant or ammonia-activated leak-detecting paints, and post-construction-cleaning methods were tested and found to be suitable.

As was demonstrated in LAPD, initial removal of impurities within the cryostat can be achieved by purging with gaseous argon. Accordingly, this procedure was

Table 9.1: 35-ton Details and Dimensions

Parameter	Value
Cryostat volume	29.16 m^3
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

adopted for the 35-ton as well. Figure 9.2 graphically shows the first step of the purification process: removal of the ambient air, called the "piston purge." The initial state, $t = 0$, reflected the initial values for oxygen, water, and nitrogen in the "dry air" state.

Once the room-temperature gas purge was no longer improving purity, the cooldown and LAr fill stage began. A gas/liquid spray method was used to cool down the cryostat. This generated a turbulent mixing of cold gas in the cryostat and cooled the entire surface. The cooldown rate was maintained below the maximum rate specified by the manufacturer. Upon completion of the cooldown, liquid argon was transferred into the cryostat and recirculating purification was begun.

During recirculation and purification, dedicated purity monitors were used to measure electron lifetime, which can be translated to equivalent oxygen contamination levels. Figure 9.3 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; there were also several events that spoiled the lifetime, but the DUNE electon lifetime specification (> 1.4 ms) was easily achieved.

The 35-ton Phase-1 run successfully demonstrated that there is nothing innate to membrane cryostat technology that would prohibit achieving the stated goals of the DUNE Far Detector. In addition, experience gained in operating the 35-ton system will inform future design decisions, e.g., the loss of purity when switching pumps is undesireable, and can likely be avoided by improved system design. Future system designs could also avoid coupling acoustical vibrations into the cryostat by choosing to locate the pumps externally, which would have the added benefit of facilitating maintenance and repair.

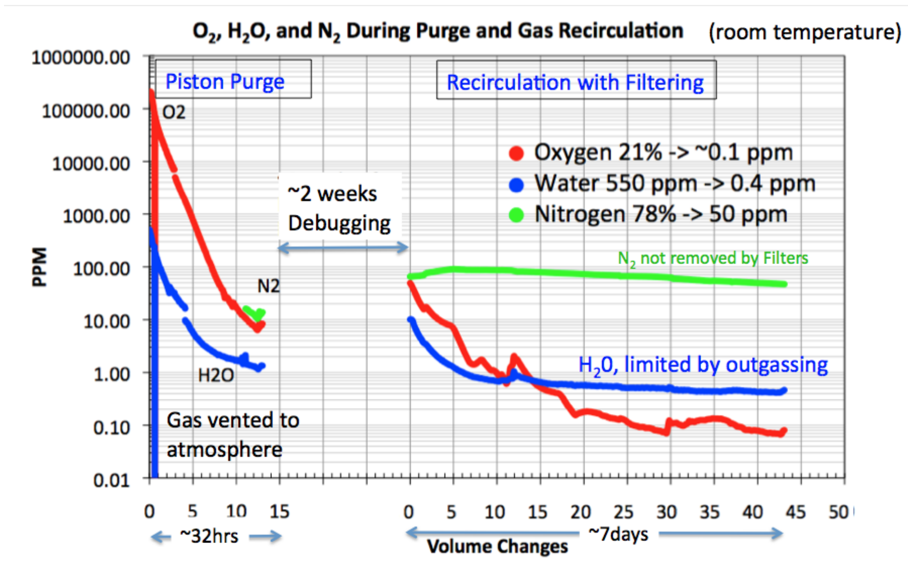

Figure 9.2: Gas phase of removing impurities in the 35-ton cryostat. These quantities were measured by gas analyzers that sampled gas in the cryostat. The first stage of the purification is a process called the "piston purge." The second stage is "recirculation with filtering". The gap between the two steps was due to troubleshooting a leak. fig:35TPurge

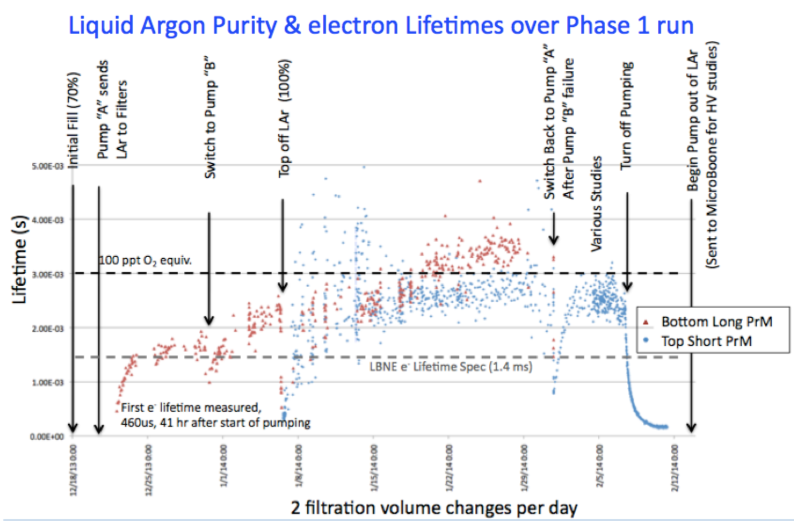

Figure 9.3: LAr electron lifetimes as measured by purity monitors in the cryostat. Significant events are annotated on the plot. Major divisions on horizontal axis are one-week periods. Equivalent purity levels are shown as dashed horizontal lines. fig:35TElectro

9.1.2 35-ton: Phase-2

Phase-2 of the 35-ton prototype extends the scope to include a fully operational LAr-TPC and photon detector in the previously built Phase-1 cryostat. Installation of the LAr-TPC into the cryostat is expected in May 2015 and commissioning is expected to begin in July 2015. Phase-2 operation is planned for a several-month-long cosmic ray run. External plastic scintillator paddles placed around the cryostat will provide the trigger as well as rough position measurements of the incoming cosmic rays.

Figure 9.4 shows a model of the LAr-TPC inside the cryostat and a trial assembly of the TPC done outside of the cryostat.

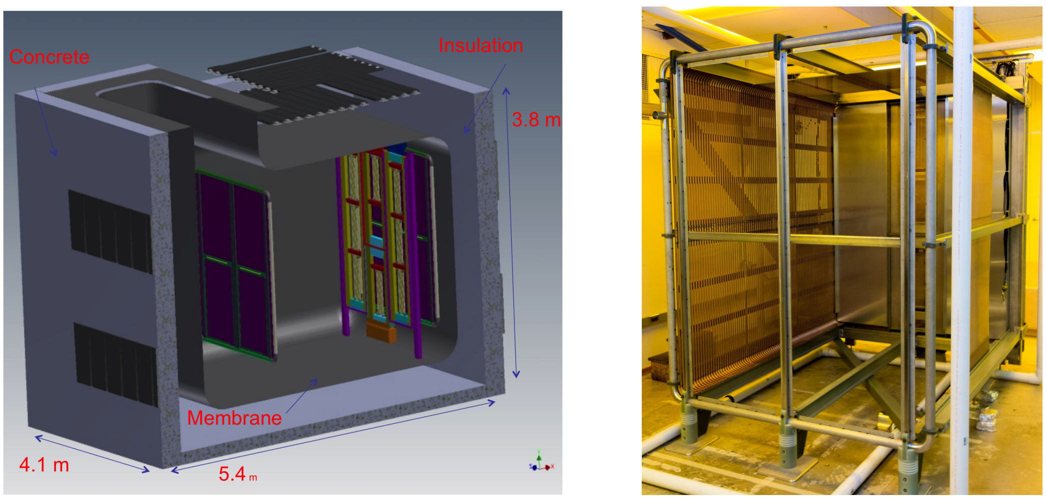

Figure 9.4: (left) Rendering of 35-ton cryostat with installed LAr-TPC and photon detectors. Note separate drift regions on “near” and “far” sides. The near side drift length is close to what is proposed for the far detector. The far side has a shorter drift length due to lack of space. (right) A trial assembly of the LAr-TPC.

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. Some of the more important aspects are collected in Table 9.2.

As can be seen from Table 9.2, successful tests of many of the new design features require simulation, reconstruction, and analysis of 35-ton data. This will be done with the help of the LarSoft package, which is also used to simulate and reconstruct data from ArgoNeuT, MicroBooNE, and LArIAT. Reuse of software developed for those experiments will greatly facilitate 35-ton development, however, the novel

Table 9.2: 35-ton Design Elements

Design Aspect	Section	How Tested
Modular APAs with wrapped wires	4.2.2	Build small-scale APA Modules with FD design
Vertical Gaps between APAs	4.2	Assemble APAs side-by-side. Study reco'd tracks that cross the gaps.
Horizontal Gaps between APAs	4.2	Build two shorter APAs and stack vertically Study reco'd tracks that cross the gaps
APAs immersed in active volume	4.2	Study reco'd tracks that cross APAs
Cold Digital Electronics	4.4	Measure noise performance etc. *in situ*
Waveguide-style Photon Detector	4.5	Install in APAs. Measure light yield
Triggerless-capable DAQ	4.3	Take data using multiple DAQ modes

hardware features of the 35-ton prototype necessitate new software developments as well.

Among the required new software developments are:

- Code to divide 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 35-ton 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" analyses of the data can be undertaken, where both validation of new detector design elements and analysis of basic LAr-TPC performance are needed. 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 35-ton Phase-2 prototype and the analysis of its data are expected to be very valuable in defining the final DUNE Far Detector design.

9.2 The CERN Single-Phase Prototype

The CERN single-phase prototype detector is a crucial milestone toward construction and operation of the first 10 kton DUNE Far Detector module. The prototype detector and beam test serve two principal functions. The first is to serve as an engineering prototype for validation of the performance of all detector components, to establish and commission production sites, and to test the installation procedure. The second is to collect and study physics data in response to charged particles of different type and energy. Results from these measurements, coupled with those from LArIAT, MicroBooNE, SBND, and other LAr-TPCs, serve to validate MC simulations, serve as data input to DUNE sensitivity studies, and allow validation and tuning of event reconstruction and particle identification tools.

To mitigate the risks associated with extrapolating small-scale versions of the single-phase LAr-TPC technology to a full-scale detector element, it is essential to benchmark the operation of full-scale detector elements and perform measurements in a well-characterized charged particle beam.

The basic detector performance can be established with cosmic ray muons; these results are critical to inform the production of the first 10 kton DUNE far detector components. These data will aid in identification of potentially problematic components, leading to future improvements and optimizations of the detector design. A well-defined charged particle test beam can further enhance detector performance measurements. In particular, the following checks are anticipated:

1. characterize performance of full scale LAr-TPC module
2. verify functionality of cold LAr-TPC electronics under LAr cryogenic conditions
3. perform full-scale structural test under LAr cryogenic conditions
4. study performance of the photon detection system

5. verify argon contamination levels and associated mitigation procedures
6. develop and test installation procedures for full-scale detector components
7. test and evaluate the performance of detector calibration tools (e.g. laser system)
8. identify flaws and inefficiencies in the manufacturing process

In order to achieve these measurements, the detector will need to accurately identify and measure the energy of the particles produced in neutrino interactions with argon, which will range from hundreds of MeV to several GeV.

More specifically, the goals of the prototype detector beam test measurements include the the use of a charged particle beam to:

1. measure the detector calorimetric response for hadronic and electromagnetic showers
2. study e/γ-separation capabilities
3. measure event reconstruction efficiencies as a function of energy and particle type
4. measure performance of particle identification algorithms as function of energy for realistic detector conditions
5. assess single particle track calibration and reconstruction
6. validate accuracy of Monte Carlo simulations for relevant energy ranges and directions
7. study other topics with the collected data sets
   (a) pion interaction kinematics and cross sections
   (b) kaon interaction cross section to characterize proton decay backgrounds
   (c) muon capture for charge identification

The CERN single-phase detector and beam test program is in preparation and an invited technical proposal [?] to the CERN SPSC will be submitted in June 2015. The plan foresees the first beam data run in 2018, before the long shutdown of the LHC. Experience gained from construction, installation, and commissioning of the CERN single-phase prototype detector as well as performance tests with cosmic ray data are expected to lead to an optimization of equivalent phases of the DUNE Far Detector.

9.2.1 Detector Configuration and Components

Since the CERN single-phase prototype detector serves as an engineering prototype detector for the first 10 kton module of the DUNE far detector, all components have exactly the same dimensions and features as those described in Chapters 4.2 and 4.5. That is, all TPC and photon detector components, as well as their positioning and spacing within their cryostat, are exactly as planned for the DUNE far detector modules.

TPC configuration

The size of the CERN single-phase prototype detector is determined by the physics requirement of the previously listed physics measurements. The particle containment of hadronic showers initiated by charged pions or protons is a critical feature for calorimetric measurements. Simulation studies indicate that showers initiated by 10 GeV primary pions and protons can be contained within a volume measuring 6 m in the longitudinal and $5{\times}5$ m^2 in the transverse directions. With the basic APA unit measuring $6{\times}2.3$ m^2, an arrangement of two times 3 APAs side-by-side, a central cathode and two drift volumes with 3.6 drift length each, was identified as the arrangement which satisfies the requirements. Figure 9.5 shows a view of the CERN single phase TPC along with the field cage and also a view of the TPC within the cryostat.

For descriptions of the TPC readout, photon-detection system, DAQ, slow control, and monitoring, as well as the key issues of the installation procedure we refer to the corresponding sections of the DUNE far detector in Chapter 4.

Cryostat

The single-phase TPC test at CERN will use a membrane tank technology with internal dimensions of 7.8 m (tranverse)$\times$ 8.9 m (parallel)$\times$8.1 m (height). It can contain 725 tons of LAr, equivalent to about 520 m^3. The active (fiducial) detector mass of liquid argon amounts to 400 tons (300 tons).

The cryostat design is based on a scaled up version of the 35-ton prototype [**?**], described in Chapter 9.1. The cryostat will use a steel outer supporting structure with a metal liner inside to isolate the insulation volume, similar to that of the dual-phase WA105 $1 \times 1 \times 3$ detector prototype described in Chapter 9.3 and to the Fermilab Short-Baseline Near Detector. The support structure will rest on I-beams, to allow for air circulation underneath in order to maintain the temperature within the allowable limits. In this vessel, a stainless steel membrane contains the

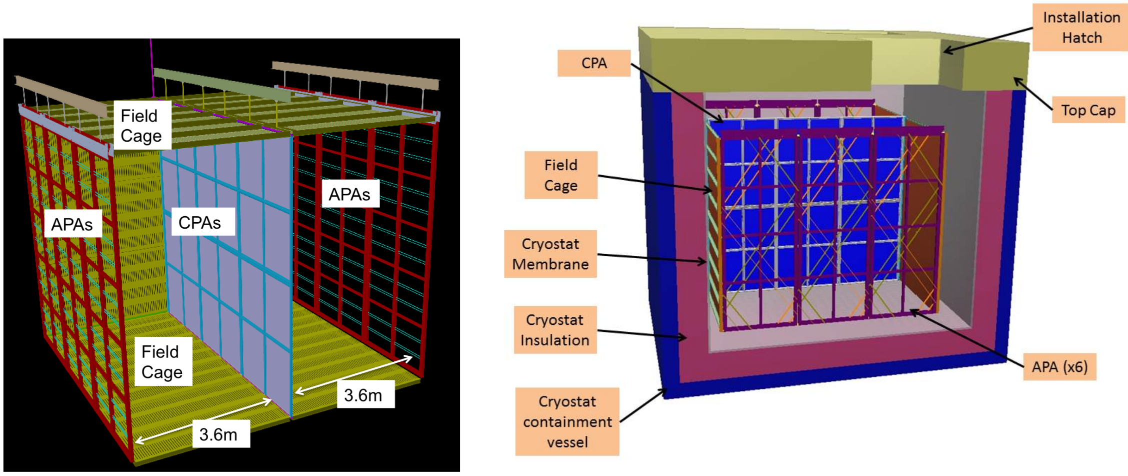

Figure 9.5: View of the CERN single-phase detector TPC (left) and inserted in the cryostat (right). fig:CERN_singl

liquid cryogen. The pressure loading of the liquid cryogen is transmitted through rigid foam insulation to the surrounding outer support structure, which provides external support. The membrane is corrugated to provide strain relief resulting from temperature-related expansion and contraction. The vessel is completed with a top cap that uses the same technology. The external cryostat dimensions are 10.6 m (tranverse)× 11.7 m (parallel)×10.9 m (height).

For the cryostat top cap, several steel reinforced plates are welded together. The stainless steel primary membrane, intermediate insulation layers, and vapor barrier continue across the top of the detector, providing a leak-tight seal. The secondary barrier is neither used nor required at the top. The cryostat roof is a removable steel truss structure that also supports the detector. Stiffened steel plates are welded to the underside of the truss to form a flat vapor barrier surface onto which the roof insulation attaches directly. The penetrations are clustered in the back region. The top cap will have two large openings for TPC installation, and a manhole to enter the tank after the hatches have been closed.

The truss structure rests on the top of the supporting structure, where a positive structural connection between the two is made to resist the upward force caused by the slightly pressurized argon in the ullage space. The hydrostatic load of the LAr in the cryostat is carried by the floor and the sidewalls. In order to meet the maximum deflection allowed between APA and CPA and to decouple the detector from possible sources of vibrations, the TPCs will be connected to an external bridge over the top of the plate supported on the floor of the building. Everything else within the cryostat (electronics, sensors, cryogenic and gas plumbing connections) is supported by the steel plates under the truss structure. All piping and electrical penetrations into the interior of the cryostat are made through this top plate, primarily in the region of the penetrations to minimize the potential for leaks.

Cryogenic System

The main goal of the LAr system is to purge the cryostat prior to the start of the operations (with GAr in open and closed loop), cool down the cryostat, and fill it with LAr. Then continuously purify the LAr and the boil-off GAr to maintain the required purity. The design requirement calls for a 10 ms electron lifetime (30 ppt O_2 equivalent) which is measured by the detector.

The LAr receiving facility includes a storage dewar and an ambient vaporizer to deliver LAr and GAr to the cryostat. The LAr travels through the liquid argon handling and purification system, whereas the GAr passes through the gaseous argon purification system before entering the vessel. Studies are ongoing to standardize the filtration scheme and select the optimal filter medium for all future generation detectors, including this test prototype.

During operation, an external LAr pump circulates the bulk of the cryogen through the LAr purification system. The nominal LAr purification flow rate allows for 5.5 days for a full volume exchange. The boil-off gas is first recondensed and then is sent to the LAr purification system before re- entering the vessel.

The proposed liquid argon system is based on the design of the DUNE 35-ton prototype, the MicroBooNE detector system, and the current plans for the DUNE Far Detector.

9.3 The WA105 Prototype

The WA105 experiment is a full-scale demonstration of the GLACIER-type detector described in Chapter 5 as a DUNE Alternative Far Detector design. The experiment was approved by CERN in 2013, for operation in a charged hadrons/electrons/muons beam-line from 0.5 to 20 GeV/c. A detailed description of the experiment is available in the Technical Design Report of 2014 [?] and an up to date picture of the technical developments in WA105 can be found in the Status Report Document submitted to the SPSC CERN committee in March 2015 [?].

The WA105 demonstrator is a double-phase liquid argon TPC with an active volume of $6 \times 6 \times 6\ m^3$. These dimensions are motivated by the fact that the basic readout component of the large-scale LAGUNA/LBNO 20-50 kton detectors are 4×4 m^2 Charge Readout Plane units. The 6×6 m^2 is consistent with having a fiducial volume corresponding to that readout unit and with a full containment of hadronic showers. Surface operation prohibits drift lengths above 6 m. The footprint of the active volume corresponds to 1:20 of the surface of the LBNO 20 kton detector. The active volume contains about 300 tons of liquid argon. The basic parameters of the detector are presented in Table 9.3 and a 3D drawing and two cut views are available in Figure 9.6, Figure 9.7 and Figure 9.8.

Table 9.3: Main parameters of the WA105 demonstrator

Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	$8.3 \times 8.3 \times 8.1$
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr area	m^2	36
Charge readout module (0.5 x0.5 m^2)		36
N of signal feedthrough		12
N of readout channels		7680
N of PMT		36

A general description of how a double-phase liquid argon TPC works can be found in Chapter 5.1. The drift path in the WA105 demonstrator reaches 6 m, as compared to 12 m in the full scale alternative Far detector. The drift field is expected to be 0.5 kV/cm and 1 kV/cm, corresponding to a voltage applied to the cathode respectively of -300kV and -600 kV. The CRP has an active surface of 36 m^2 subdivided in strips of 3.125 mm pitch and 3 m length for a total of 7680 readout channels.

The WA105 detector is intended to demonstrate all the techniques developed for the 20 and 50 kton LBNO detectors:

- Tank construction technique based on the LNG industry with non evacuated vessel

- Purification system
- Long drift
- HV system 300-600 kV, large hanging field cage
- Large area double-phase charge readout
- Accessible cryogenic front end electronics and cheap data acquistion electronics
- Long term stability of UV light readout

At the same time the $6 \times 6 \times 6\ m^3$ exposed to the test-beam line has a rich physics programme:

- Assessing the detector performance in reconstructing hadronic showers; most demanding task in neutrino interactions
- Measurements in hadronic and electromagnetic calorimetry and PID performance
- Full-scale software development, simulation and reconstruction
- Collection of high statistic hadronic interaction samples unprecedented granularity and resolution for the study of hadronic interactions and nuclear effects
- Assessment of the impact on the physics capabilities of a better detector performance wrt single phase LAr TPC: high S/N ratio, 3 mm pitch, absence of materials in long drift space, two collection views, no ambiguities
- Study of the systematics for the long baseline experiment related to the reconstruction of the hadronic system (resolution and energy scale), electron identification efficiencies and pi0 rejection. Particles dE/dx identification for proton decay

The $6 \times 6 \times 6\ m^3$ WA105 detector is scheduled to begin operations in 2018, and will be located in the extension of the EHN1 Hall, currently under construction. All WA105 components are in an advanced state of design/prototyping or pre-production. Since the submission of the TDR last year, the completion of the WA105 detector design and the preparation of its construction have been progressing very quickly. Many technical aspects of the design have largely benefited of the possibility of performing a pre-production and direct practical implementation on a

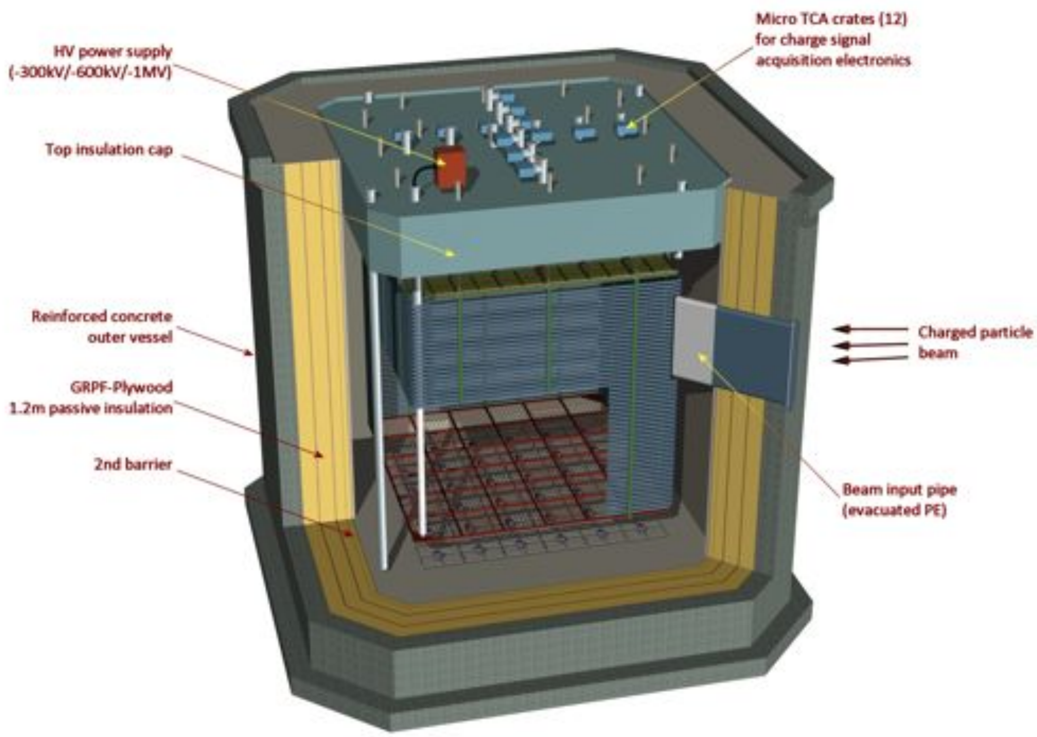

Figure 9.6: Illustration of the $6 \times 6 \times 6\ m^3$ with the inner detector inside the cryostat fig:6by6_open

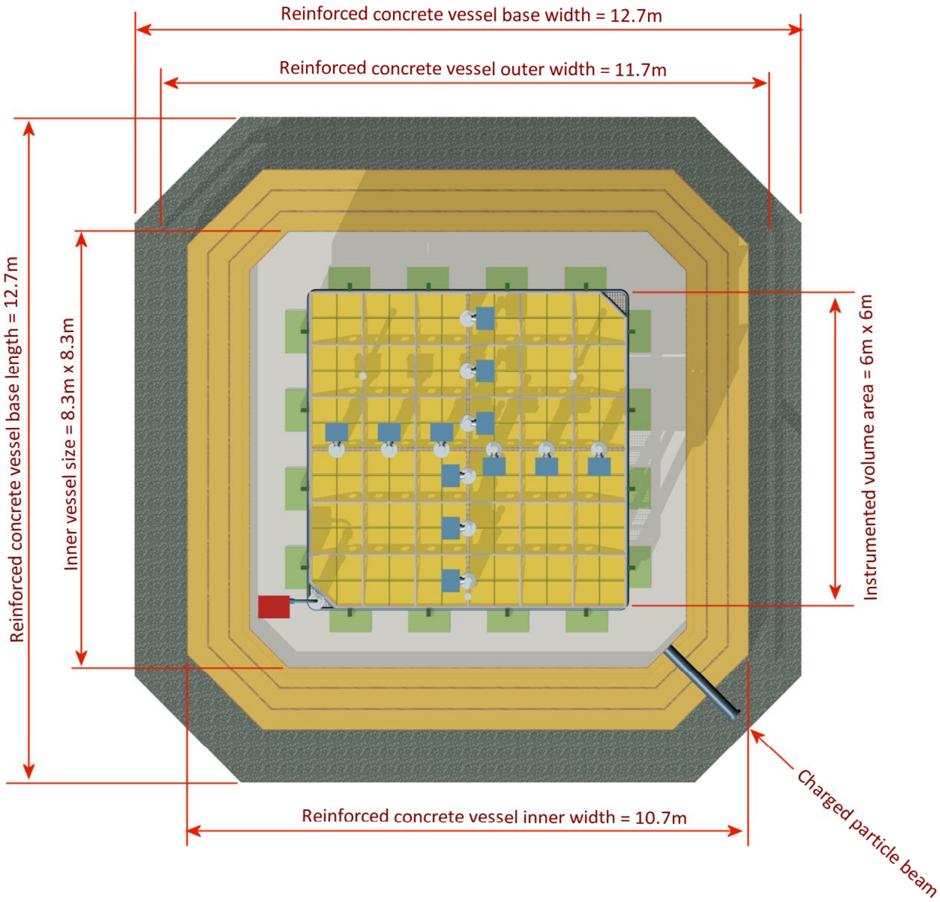

Figure 9.7: Plan view section of the $6 \times 6 \times 6\ m^3$

fig:6by6_plan

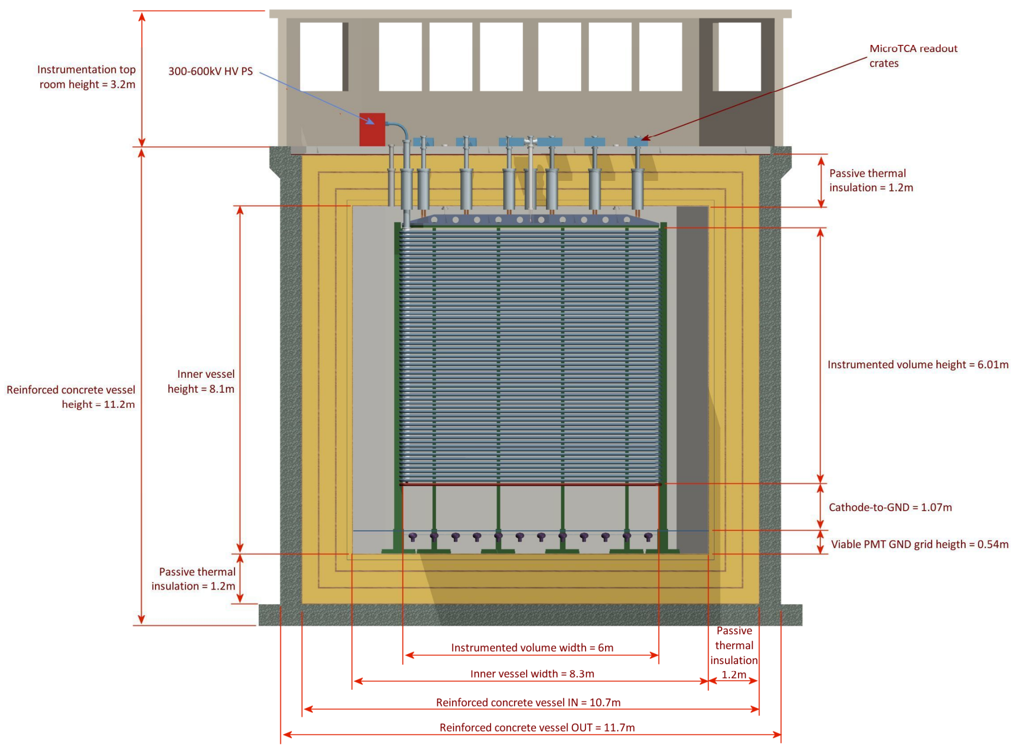

Figure 9.8: Vertical cross section of the $6 \times 6 \times 6\ m^3$ fig:6by6_vert

$3 \times 3 \times 1\ m^3$ setup which has the minimal size of a readout unit in the final detector. This allowed to have a first overview of the complete system integration; to produce a fully engineered prototype version of many detector parts including all their installation details and ancillary services; to set up full Quality Assessment (QA), construction, installation and commissioning chains, to anticipate legal and practical aspects related to the procurement of the different components and to validate the cost estimations and time schedule for WA105. The $3 \times 3 \times 1\ m^3$ represents a technical playground and integration exercise to speed up the design, procurement, QA and commissioning activities needed for the $6 \times 6 \times 6\ m^3$ detector. In particular a complete procedure for the construction of tanks based on the GTT licenced corrugated membrane technology has been set up with CERN and a full chain for the procurement, processing, assembly and commissioning of the LEM detectors and of the anodes had been also implemented.

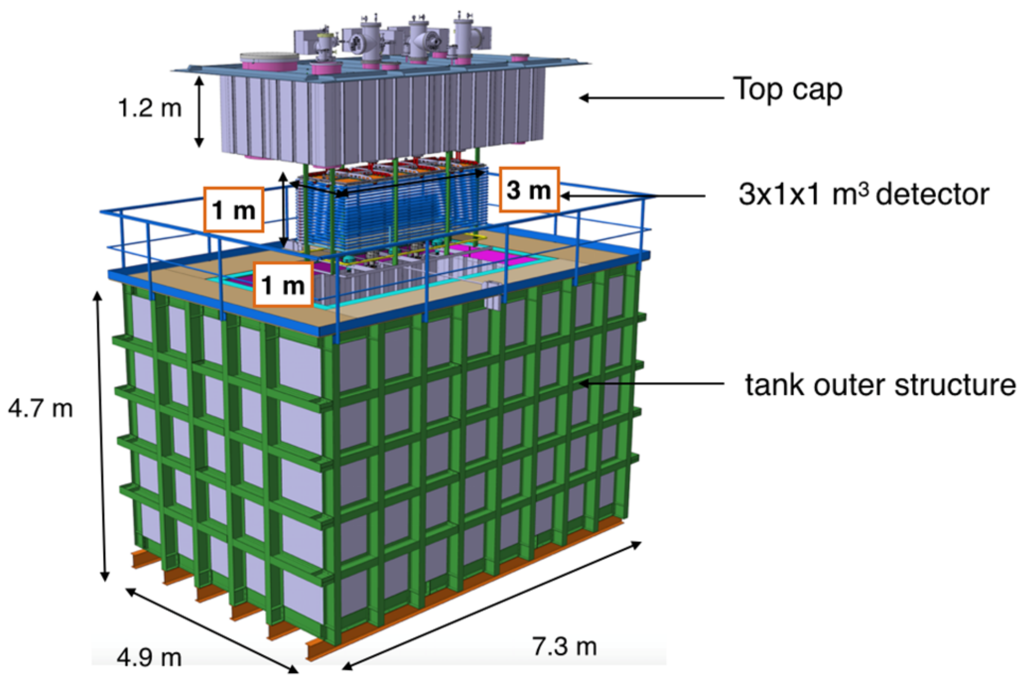

Figure 9.9: Exploded view of the $3 \times 3 \times 1\ m^3$ prototype fig:3by1

9.4 The ND Beamline Measurements Prototyping Plan

9.4.1 Prototype Development for the Cherenkov and Ionization Detectors

A prototype Cherenkov counter, along with associated fully automated gas systems, HV systems, and data acquisition system has been constructed and is undergoing testing in the NuMI neutrino beam's muon alcove 2. In addition, three diamond detectors [?] for ionization measurements have also been installed into the alcove. Figure 9.10 shows the prototype detectors in NuMI alcove 2.

The counter has an automated gas system with a settable pressure that ranges from vacuum to 20 atm, corresponding to muon Cherenkov thresholds of 200 GeV/c and 1 GeV/c respectively. When operated at vacuum, the PMT registers all background light unrelated to the gas, e.g. transition radiation, light from particles hitting the window and PMT glass. Those contributions are observed to be very small relative to the coherent, directional Cherenkov light.

The counter is constructed with a 1 meter long radiator section as shown in Figure **??** . A 20 foot extension allows the reflected Cherenkov light to travel to a sapphire pressure window viewed by a photo multiplier tube.

The prototype is now fully integrated into NuMI operations and real-time waveforms can be viewed online as shown in Figure 9.11. The top panel shows the waveform from the Cherenkov counter at 2 atm gas pressure, that corresponds to a muon momentum threshold of 3 GeV/c. The second panel shows the waveform from a $9mm \times 9mm$ diamond detector mounted to the front flange of the Cherenkov radiator section as shown in the inset of Figure 9.10.

The extracted NuMI proton beam, Resistive Wall Monitor (RWM) signal is also recorded with an identical digitizer. That allows a direct, bucket-by-bucket (individual proton pulses) comparison of the proton current onto the NuMI primary proton target, and the muons measured after the absorber with a 400ps time resolution.

9.4.2 Prototype Development of the Stopped Muon Counters

Prototype development activity for the Michel-electron detectors will be divided into studies of the rate and radiation environment where the detectors will be located and development of the counters themselves.

The radiation environment will be studied both with Monte Carlo simulations and by measurements from initial prototype detectors in the NuMI muon alcoves [?]. The prototypes will be installed into the alcoves in 2016 and 2017. Studies will be

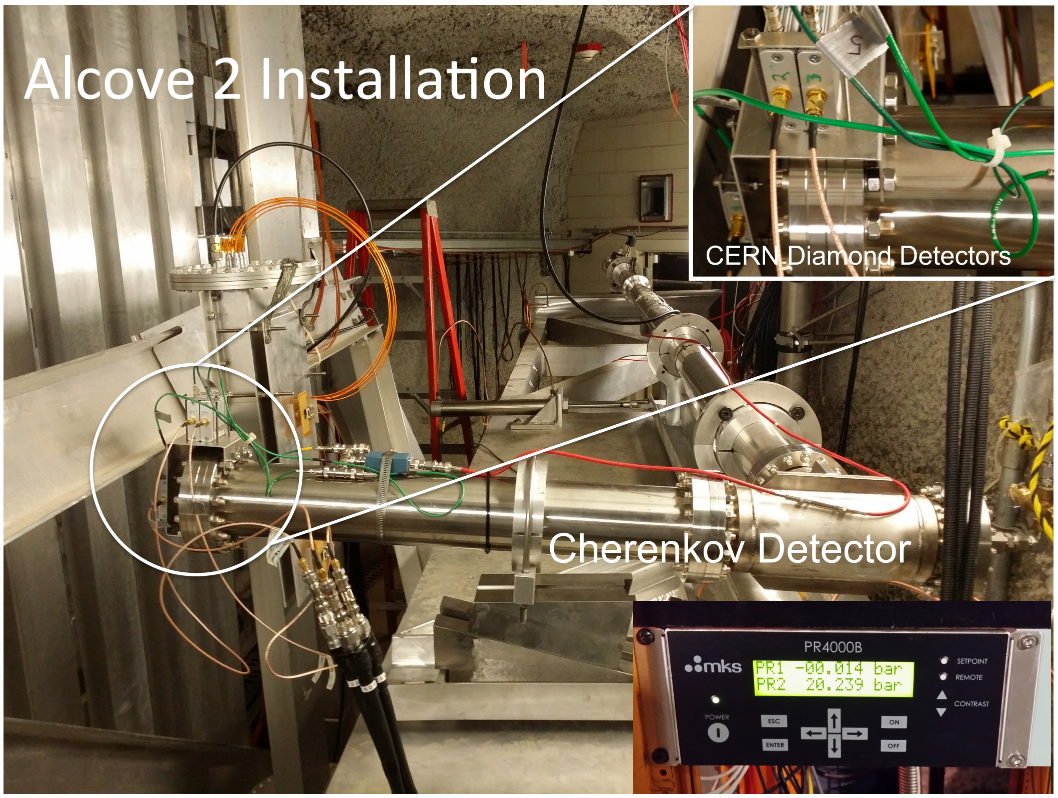

Figure 9.10: A prototype muon gas Cherenkov detector for DUNE. Muons travel through an L-shaped 4" Conflat pipe filled with a pressurized gas. A flat mirror mirrors directs the optical photons to a photo multiplier. The lower right inset shows the 20 bar MKS pressure reading achieved by the Cherenkov gas system, and the inset on the upper right shows the CERN/Cividec diamond detectors mounted to the Cherenkov housing. fig:Alcove2Che

Figure 9.11: The realtime display of the muon detector prototypes in operation on the NuMI beam line. The top two panels are the Cherenkov counter and CERN diamond detector [?], The signals are transmitted through low-loss heliax cable, and then the waveform is digitized at 2.5 GHz with a 12 bit dynamic range, and the recorded onto disk storage for analysis. The signal from the muons is contained in the short beam pulse "buckets" created by the accelerator RF structure. The fast timing allows the prompt muon signal to be easily separated from potential backgrounds such as stopped muon decays, beta decays, and neutrons.

performed to determine if the photon sensors can survive the radiation environment at the location of the Michel detector. If the sensors can survive, they can be attached directly to the Cherenkov medium; if not, optical guides will have to bring the light to a lower-radiation area to the side of the beam. Potential radiation damage to the Cherenkov radiator itself will also be studied.

The detector design will focus on selecting radiator and shielding material, photon-detection technology and control/readout hardware. Possible radiators include aerogel, which may be designed to be replaced periodically, and flowing liquids such as H_2O or mineral oil. Long-timescale saturation from the very high-rate environment of the beam spill could affect the photon-counting devices [**?**]. Thus, it will likely be necessary to design fast-switching, high-voltage circuits that turn on the photon counters in the first few microseconds after the spill is over. A similar system was developed in the 1990s for the Brookhaven Muon (g-2) Experiment [**?**] .

9.4.3 Current Prototyping Activities

A second set of muon detectors, the final DUNE design, are being constructed at this time (2015). They are being installed directly behind the NuMI proton beam dump (muon alcove 1). The detectors will be mounted on a movable stand which has undergone an engineering review at Fermilab. The entire setup, detectors and stand, will be suitable for use in the DUNE beam.

The entire setup will be eventually transferred the DUNE absorber hall. The higher radiation environment of alcove 1 will be more similar to the eventual DUNE installation. It will allow the DUNE muon detectors to be calibrated in the NuMI beam and ready for use in the DUNE beam.