Deep Underground Neutrino Experiment (DUNE)

Technical Proposal

Volume 3: The Dual-Phase Far Detector Module Design

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Slow Controls and Cryogenics Instrumentation

1.1 Slow Controls and Cryogenics Instrumentation Overview

1.1.1 Introduction

The cryogenic instrumentation and slow controls (CISC) system provides comprehensive monitoring for all detector module components as well as for the LAr quality and behavior, both being crucial to guarantee high-quality of the data. Beyond passive monitoring, CISC also provides a control system for some of the detector components. The structure of the CISC consortium is quite complex. A subsystem chart for the CISC system is shown in Figure 1.1.

Two main branches can be distinguished: cryogenic instrumentation and slow controls. The former includes a set of devices to monitor the quality and behavior of the LAr volume in the cryostat interior, ensuring the correct functioning of the full cryogenics system and the suitability of the liquid argon (LAr) for good quality physics data. Those devices are purity monitors, temperature monitors, gas analyzers, LAr level monitors, and cameras with their associated light emitting system.

Cryogenic instrumentation also requires significant physics and simulation work such as E field simulations and cryogenics modeling studies using computational fluid dynamics (CFD). E field simulations are required to identify desirable locations for instrumentation devices in the cryostat so that they are not in regions of high E field and that their presence do not induce large field distortions. CFD simulations are needed to understand the expected temperature, impurity and velocity flow distributions and guide the placement and distribution of instrumentation devices inside the cryostat.

From the organizational point of view cryogenic instrumentation has been divided into three main

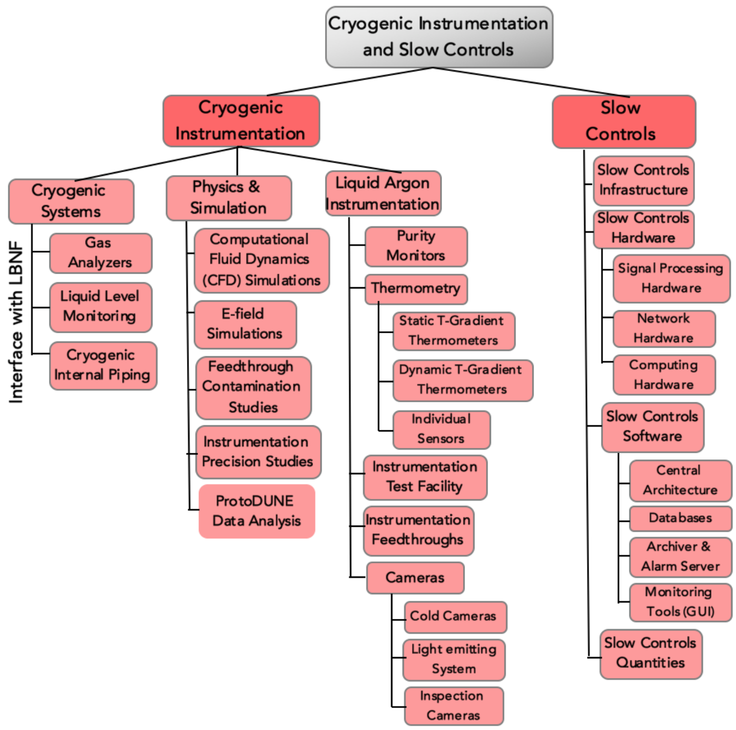

Figure 1.1: CISC subsystem chart

parts: (1) cryogenics systems, which includes all components directly related to the external cryogenics system as liquid level monitoring, gas analyzers and internal cryogenic piping, all having substantial interfaces with LBNF; (2) LAr instrumentation, which includes all other instrumentation devices; and (3) physics and simulation.

The second branch of CISC is the slow controls system, in charge of monitoring and control most detector elements, as power supplies, electronics, racks, instrumentation devices, calibration devices, etc. It includes four main components: hardware, infrastructure, software, and firmware. The slow controls hardware and infrastructure consists of networking hardware, signal processing hardware, computing hardware, and relevant rack infrastructure. The slow controls software and firmware is needed for signal processing, alarms, archiving, and control room displays.

Two other systems have been included by the DUNE management as part of the CISC consortium, a test facility for the instrumentation devices and the cryogenic piping inside the cryostat. Those are included inside the cryogenic instrumentation branch.

1.1.2 Design Considerations

For all LAr instrumentation devices, ProtoDUNE-DP designs are considered as the baseline, and requirements for most design parameters are extrapolated from ProtoDUNE. Hence a critical step for the CISC consortium is to analyze data from ProtoDUNE when available to validate the instrumentation designs and understand their performance. For example, a crucial design parameter, which should be evaluated in ProtoDUNE, is the maximum noise level induced by instrumentation devices on the readout electronics that can be tolerated to avoid confusing event reconstruction.

Some of the common design considerations for instrumentation devices include stability, reliability and longevity such that the devices can survive for a period of at least 20 year. Since it is uncommon for any device to have such a long lifetime, provisions are made in the overall design to allow replacement of devices where possible.

As for any other element inside the cryostat, the electric field on the instrumentation devices is required to be less than 30 kV/cm, so that the risk of dielectric breakdown in LAr is minimized. This requirement imposes stringent constraints on the location and mechanical design of some devices. Electrostatic simulations will be performed to compute the expected field on the boundaries of instrumentation devices and to design the appropriate E field shielding in the case the electric field approaches the limit.

Another common consideration for all instrumentation devices is their support structure design, which is expected to be substantially different from the one used in ProtoDUNE.

For slow controls, the system needs to be designed such that it is robust enough to support a large number of monitored variables, a broad range of monitoring and archiving rates, and has the capability of interfacing with a large number of systems to establish two-way communication for control and monitoring. Table tab:dp-cisc-requirements **??** shows some of the important CISC system design requirements.

There are several aspects specific to the DP design impacting the CISC system design requirements:

- At the level of the cryogenic instrumentation, additional care is needed in order to monitor the gas phase above the liquid level. The temperature and the pressure of the gas phase affect the gas density, and consequently, the LEM gain calibration. The gas pressure must be accurately monitored. In proximity to the liquid surface the temperature gradient of the gas is measured with an array of temperature probes with a vertical pitch of about 1 cm. Each charge-readout plane (CRP) is also equipped with 36 thermometers to sample the temperature across its structure.
- The CRP-specific instrumentation also includes:
  - the pulsing system for charge injection in the anode strips,
  - the precision level meters implemented only on the CRPs located at the cryostat borders, and
  - the measurement of the LEM-grid capacitance allowing to know

    which provides

    the position of the CRP with respect to the liquid level for all CRPs, what makes the measurement?

  - the control of the stepping motors,

control mechanism?

which allows positioning each CRP parallel to the liquid level (keeping the extraction grid immersed in the liquid and the LEMs in the gas phase).

- The slow control system generates and controls the high voltage (HV) for biasing the LEMs (41 channels/CRP) and the extraction grid (1 channel/CRP), at maximum voltages of $-5\,\mathrm{kV}$/channel and $-10\,\mathrm{kV}$/channel, respectively;

- The requirements related to the photon detection system (PDS) include the generation and control of HV biasing for the photomultiplier tubes (PMTs) (up to $-3\,\mathrm{kV}$) and the control of the calibration of the PMTs, performed with a light distribution system with a common light source and a network of optical fibers;

- The front-end (FE) electronics requires the control of the Micro Telecommunications Computing Architecture (μTCA) crates, the control of the analog FE cards, the control of the LV and of the charge injection system connected to the pre-amplifiers mounted on the FE cards;

- The DP design also enables surveying from the cryostat roof the position of reference points connected to the CRP suspension system, to ensure proper CRP alignment. This aspect needs as well to be integrated in the alignment scheme.

IS integrated?

1.1.3 Scope

yo-scope

fig:sp-slow-cryo-subsys

As described above, and shown schematically in Figure 1.1, the scope of the CISC system spans a broad range of activities. In the case of cryogenics systems (gas analyzers, liquid level monitors and cryogenic internal piping), LBNF provides the needed expertise and is responsible for the design, installation, and commissioning activities while the CISC consortium provides the resources as needed. In the case of LAr Instrumentation devices (purity monitors, thermometers, cameras and light-emitting system; and their associated feedthroughs) and instrumentation test facility, CISC is responsible from design to commissioning in the far detectors (FDs).

From the slow controls side, CISC provides control and monitoring of all detector elements that provide information on the health of the detector module or conditions important to the experiment. The scope of systems that slow controls includes is listed below:

Table 1.1: Important design requirements on the dual phase CISC system design

Design Parameter	Requirement	Motivation	Comment
Electron lifetime measurement precision	$< 1.4\,\%$ at 3 ms	Per DUNE-FD Task Force [?], needed to keep the bias on the charge readout in the TPC to below 0.5 % at 3 ms	Purity monitors do not directly sample TPC; see Section **??**
Thermometer precision	< 5 mK	Driven by CFD simulation validation; based on ProtoDUNE-SP design	Expected ProtoDUNE performance 2 mK
Pressure meters precision (DP)	$< 1 mbar$	To measure the pressure (density) of the gas phase; based on ProtoDUNE-DP design	WA105 DP demonstrator / ProtoDUNE-DP design $<$ 1 mbar
Thermometer density	$> 2/\text{m}$ (vert.), $\sim$ 0.2 m (horiz.)	Driven by CFD simulation.	Achieved by design.
Thermometer density gas phase (DP)	$> 1/\text{cm}$ (vert.), $\sim$ 1 m (horiz.)	Vertical array of thermometers with finer pitch close to the liquid level to measure the temperature gradient in the gas phase.	Achieved by design.
Thermometer density CRP structure (DP)	36 thermometers on each CRP	Monitoring the temperature across the CRP structure.	Achieved by design.
Liquid level meters precision (DP)	$<$ 1 mm	Maintain constant CRP alignment with respect to the liquid surface	WA105 DP demonstrator / ProtoDUNE-DP design 0.1 mm
Cameras	— multiple requirements imposed by interfaces: see Table **??** —		
Cryogenic Instrumentation Test Facility cryostat volumes	0.5 to 3 m^3	Based on filling costs and turn around times	Under design
Max. E-field on instrumentation devices	$<$ 30 kV/cm	The mechanical design of the system should be such that E field is below this value, to minimize the risk of dielectric breakdown in LAr	ProtoDUNE designs based on electrostatic simulations
Noise introduced into readout electronics	Below significant levels	Keep readout electronics free from external noise, which confuses event reconstruction	To be evaluated at ProtoDUNE
Total no. of variables	50 to 100k	Expected number based on scaling past experiments; requires robust base software model that can handle large no. of variables.	Achievable in existing control systems; DUNE choice in progress.
Max. archiving rate per channel	1 Hz (burst), 1 min^{-1} (avg.)	Based on expected rapidity of interesting changes; impacts the base software choice; depends on data storage capabilities	Achievable in existing control system software; DUNE choice in progress.

- **Slow Controls Base Software and Databases**: provides the central tools needed to develop control and monitoring for various detector systems and interfaces.
  - Base input/output software,
  - Alarms; archiving; display panels; operator interface tools,
  - Slow controls system documentation and operations guidelines.
- **Slow Controls for External Systems**: export data from systems external to the detector and provide status to operators and archiving.
  - Beam status; cryogenics status; data acquisition (DAQ) status; facilities systems status,
  - For the systems above, import other interesting monitoring data as needed (e.g., pumps data from cryogenics system, heaters data from facility systems, etc.),
  - Building controls; detector hall monitoring; ground impedance monitoring,
  - Interlock status bit monitoring (but not the actual interlock mechanism).
- **Slow Controls for Detector Hardware Systems**: develop software interfaces for detector hardware devices
  - Monitoring and control of all power supplies,
  - Full rack monitoring (rack fans, thermometers and rack protection system),
  - Instrumentation and calibration device monitoring (and control to the extent needed),
  - Power distribution units monitoring; computer hardware monitoring,
  - HV system monitoring through cold cameras,
  - Detector components inspection through warm cameras.

In terms of slow controls hardware, CISC develops, installs and commissions any hardware related to rack monitoring and control. While most power supplies might only need a cable from the device to an Ethernet switch, some power supplies might need special cables (e.g., GPIB or RS232) for communication. The CISC consortium is responsible for providing such control cables.

In addition to the listed activities, CISC also has activities that span outside the scope of the consortium and require interfacing with other groups. This is discussed in Section ??.

1.2 Cryogenics Instrumentation

yo-instr

Instrumentation inside the cryostat must ensure that the condition of the LAr is adequate for operation of the TPC. This instrumentation includes devices to monitor the impurity level of the argon, e.g., the purity monitors, which provide high precision electron lifetime measurements, and gas analyzers to ensure that the levels of atmospheric contamination drop below certain limits during the cryostat purging, cooling and filling. The cryogenics system operation is monitored by temperature sensors deployed in vertical arrays and at the top and bottom of the detector, providing a detailed 3D temperature map which can help to predict the LAr purity across the entire cryostat. The cryogenics instrumentation also includes LAr level monitors and a system of internal cameras to help in locating sparks in the cryostat and for overall monitoring of the cryostat interior. As mentioned in the Introduction, cryogenics instrumentation requires simulation work to identify the proper location for these devices inside the cryostat and for the coherent analysis of the instrumentation data.

fig:sp-slow-cryo-ports

Figure **??** shows the current map of cryostat ports for the SP module, highlighting the ones assigned to instrumentation devices, as well as the preliminary location for some of these devices. Vertical temperature profilers are located behind the anode plane assemblies (APAs) (T_S) and behind the east end wall (T_D). They are complemented by a coarser 2D grid of sensors at the top and bottom of the cryostat (not shown in the figure). Purity monitors as well as level meters are planned in each detector side, behind the two front end walls. Inspection cameras will use some of the multipurpose instrumentation ports, but their exact locations are yet to be decided.

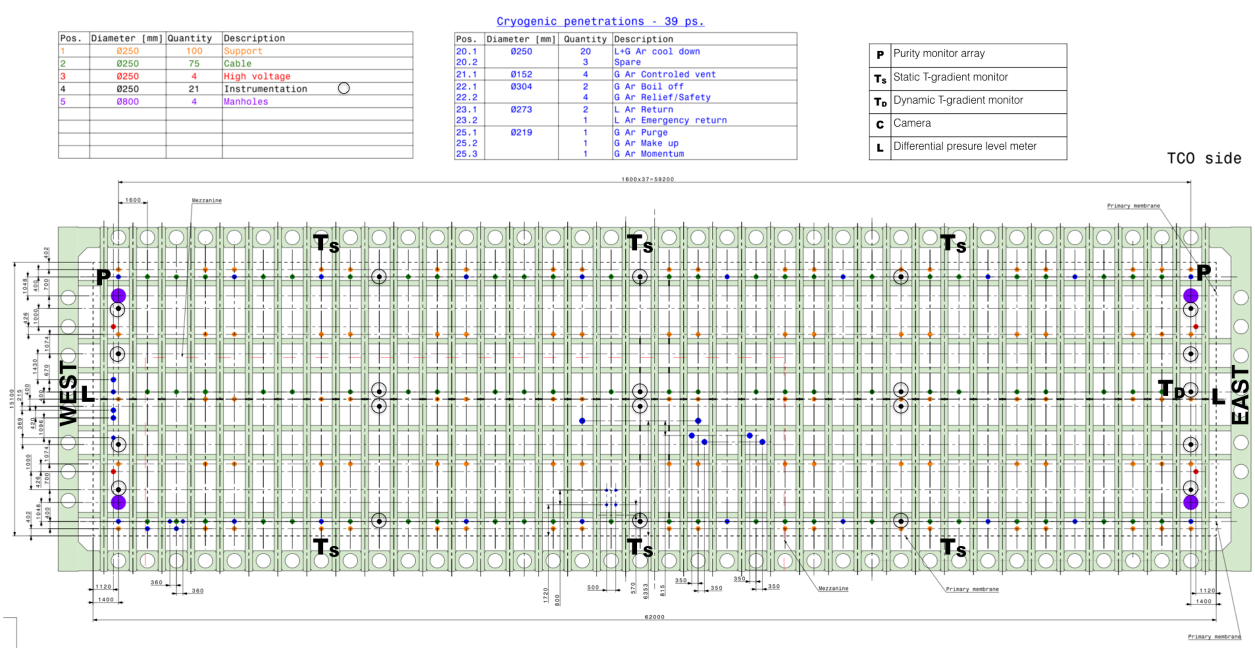

Figure 1.2: Cryostat ports and preliminary location of some instrumentation devices.

fig:sp-s

1.2.1 Fluid Dynamics Simulations

Proper placement of purity monitors, thermometers, and liquid level monitors within the detector module requires knowledge of how LAr behaves within the cryostat in terms of its fluid dynamics, heat and mass transfer, and distribution of impurity concentrations. Fluid motion within the cryostat is driven primarily by small changes in density from thermal gradients, although pump flow rates and inlet and outlet locations also contribute. Heat sources include exterior heat from the surroundings, interior heat from the electronics, and heat flow through the pump inlet.

The fluid flow behavior can be determined through simulation of LAr flow within the detector using ANSYS CFX[1], a commercially available computational fluid dynamics (CFD) code. Such a model must include proper definition of the fluid characteristics, solid bodies and fluid-solid interfaces, and a means for measuring contamination, while still maintaining reasonable solve times.

compute times?

Although simulation of the detector module presents challenges, there exist acceptable simplifications for accurately representing the fluid, the interfacing solid bodies, and variations of contaminant concentrations. Because of the magnitude of thermal variation within the cryostat, modeling of the LAr is simplified through use of constant thermophysical properties, calculation of buoyant force through use of the Boussinesq Model (using constant a density for the fluid with application of a temperature dependent buoyant force), and a standard shear stress transport turbulence model. Solid bodies that contact the LAr include the cryostat wall, the cathode planes, the anode planes, the ground plane, and the field cage (FC). As in previous CFD models of the DUNE 35 ton prototype and ProtoDUNE by South Dakota State University (SDSU)[**?**], the FC planes, anode planes, and ground plane (GP) can be represented by porous bodies. Since impurity concentration and electron lifetime do not impact the fluid flow, these variables can be simulated as passive scalars, as is commonly done for smoke releases [**?**] in air or dyes released in liquids.

some of this sounds very SP to me -anne

Significant discrepancies between real data and simulations can have potential impacts on detector performance, as simulation results contribute to decisions about where to locate sensors and monitors, as well as definitions of various calibration quantities. However, methods of mitigating such risks include well established convergence criteria, sensitivity studies, and comparison to results of previous CFD simulation work by SDSU and Fermilab. Additionally, the simulation will be improved with input from temperature measurements and validation tests.

Figure **??** shows an example of the temperature distribution on a plane intersecting a LAr inlet and at a plane halfway between an inlet and an outlet; the geometry used for this simulation is shown in Figure **??**. Note the plume of higher temperature LAr between the walls and the outer APA on the inlet plane. The current locations of instrumentation in the cryostat as shown in Figure **??** were determined using the temperature and impurity distributions from these previous

[1]ANSYS™, `https://www.ansys.com/products/fluids/ansys-cfx`.

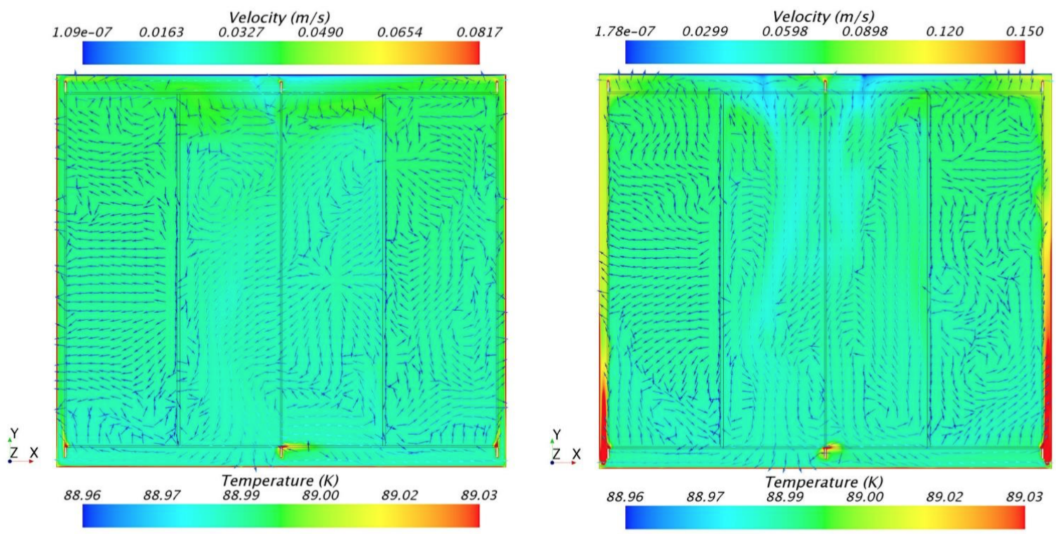

Figure 1.3: Distribution of temperature on a plane intersecting an inlet (right) and halfway between an inlet and an outlet (left), as predicted by SDSU CFD simulations [?]. (See Figure ?? for geometry.)

simulations.

The initial strategy for the future computational fluid dynamics (CFD) simulation effort is to understand the performance of ProtoDUNE cryogenics system and model the FDs to derive requirements for instrumentation devices. The following is a prioritized set of studies planned to help drive the requirements for other systems:

1. Review the DUNE FD cryogenics system design and verify the current implementation in simulation; this is important to ensure that the model represents what will be built.

2. Model the ProtoDUNE-DP liquid and gas regions with the same precision as the FD. Presently only the liquid model exists. The liquid model is needed to interpret the thermometer data, and the gas model is needed to understand how to place thermometers in the ullage and verify the design of the gaseous argon purge system.

3. Perform a CFD study to determine the feasibility of a wier for DP; this helps to determine if it can be used to clean the LAr surface before the extraction grid is submerged in the DP module.

4. Verify the SP module SP CFD model in simulation performed by LBNF; this defines the requirements for instrumentation devices (e.g., thermometry).

5. Model the ProtoDUNE-DP liquid and gas regions with the same precision as the FD.

same as a previous bullet

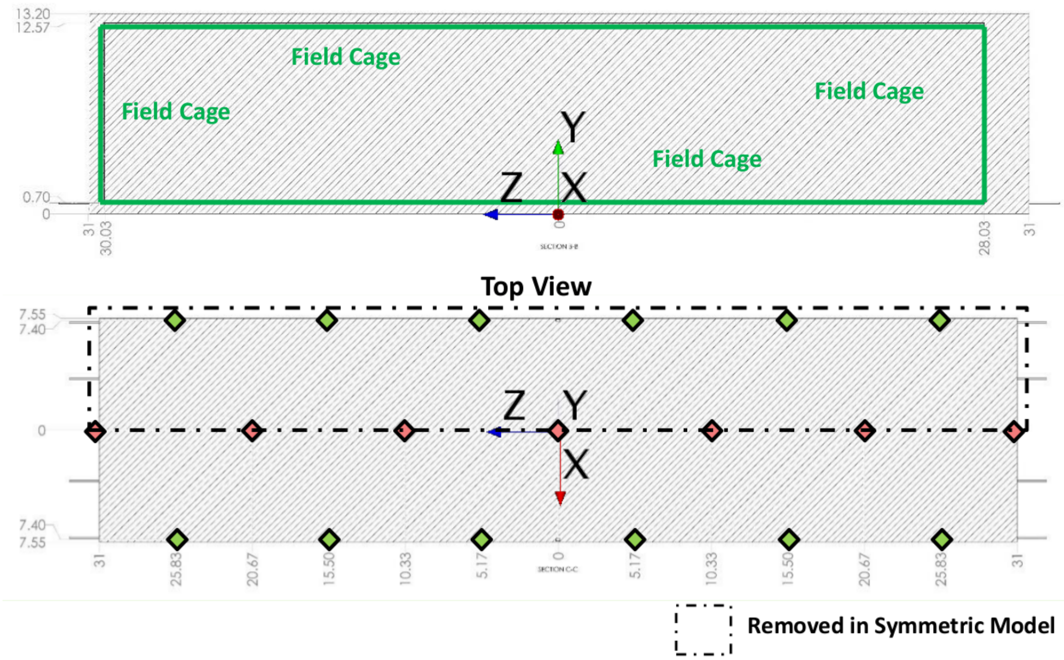

Figure 1.4: Layout of the TPC within the cryostat (top) and positions of LAr inlets and outlets (bottom) as modeled in the SDSU CFD simulations [?]. The Y axis is vertical and the X axis is parallel to the TPC drift direction. Inlets are shown in green and outlets are shown in red.

1.2.2 Purity Monitors

A fundamental requirement of a LAr TPC is that ionization electrons drift over long distances in LAr. Part of the charge is inevitably lost due to the presence of electronegative impurities in the liquid. To keep such loss to a minimum, purifying the LAr during operation is essential, as is the monitoring of impurities.

Residual gas analyzers are an obvious choice when analyzing argon gas and can be exploited for the monitoring of the gas in the ullage of the tank. Unfortunately, commercially available and suitable mass spectrometers have a detection limit of ∼10parts per billion (PPB), whereas DUNE requires a sensitivity down to the parts per trillion (PPT) level. Instead, specially constructed purity monitors measure LAr purity in all the phases of operations, and enable the position-dependent purity measurements necessary to achieve DUNE's physics goal.

Purity monitors also serve to mitigate LAr contamination risk. The large scale of the detector modules increases the risk of failing to notice a sudden unexpected infusion of contaminated LAr being injected back into the cryostat. If this condition were to persist, it could cause irreversible contamination to the LAr and terminate useful data taking. Strategically placed purity monitors mitigate this risk.

Purity monitors are placed inside the cryostat, but outside of the detector TPC, as well as outside the cryostat within the recirculation system before and after filtration. Continuous monitoring of the LAr supply lines to the detector module provides a strong line of defense against contaminated LAr. Gas analyzers (described in Section ??) provide a first line of defense against contaminated gas. Purity monitors inside the detector module provide a strong defense against all sources of contamination in the LAr volume and contamination from recirculated LAr. Furthermore, multiple purity monitors measuring lifetime with high precision at carefully chosen points can provide key inputs to CFD models of the detector, such as vertical gradients in impurity concentrations.

Purity monitors have been deployed in the ICARUS detector and in the 35-ton prototype detector at Fermilab. In particular during the first run of the 35 ton prototype, two out of four purity monitors stopped working during the cooldown, and a third was intermittent. It was later found out that this was due to poor electrical contacts of the resistor chain on the purity monitor. A new design was then implemented and successfully tested in the second run. The ProtoDUNE-SP and ProtoDUNE-DP employ purity monitors based on the same design principles. ProtoDUNE-SP utilizes a string of purity monitors similar to that of the 35 ton prototype, enabling measurement of the electron drift lifetime as a function of height. A similar system design is exploited in the DUNE FD, with modifications made to accommodate the instrumentation port placement relative to the purity monitor system and the requirements and constraints coming from the different geometric relations between the TPC and cryostat.

1.2.2.1 Physics and Simulation

A purity monitor is a small ionization chamber that can be used to independently infer the effective free electron lifetime in the LArTPC. The operational principle of the purity monitor consists of generating a known electron current via illumination of a cathode with UV light, followed by collecting at an anode the current that survives after drifting a known distance. The attenuation of the current can be related to the electron lifetime. The electron loss can be parameterized as $N(t) = N(0)e^{-t/\tau}$, where $N(0)$ is the number of electrons generated by ionization, $N(t)$ is the number of electrons after drift time t, and τ is the electron lifetime.

For the SP module, the

max?

drift distance is 3.53 m and the E field is $500\,\mathrm{V\,cm^{-1}}$. Given the drift velocity at this field of approximately $1.5\,\mathrm{mm\,\mu s^{-1}}$, the time to go from cathode to anode is around ∼2.4 ms [?]. The LAr TPC signal attenuation, $[N(0) - N(t)]/N(0)$, is to be kept less than 20 % over the entire drift distance [?]. The corresponding electron lifetime is $2.4/[-\ln(0.8)] \simeq 11$ ms.

For the DP module, the maximum drift distance is 12 m, therefore the requirement on the electron lifetime is much higher.

The 35 ton prototype at Fermilab was instrumented with four purity monitors. The data taken with them during the first part of the second phase is shown in Figure **??** and clearly shows the ability to measure the electron lifetime between 100 µs and 3.5 ms.

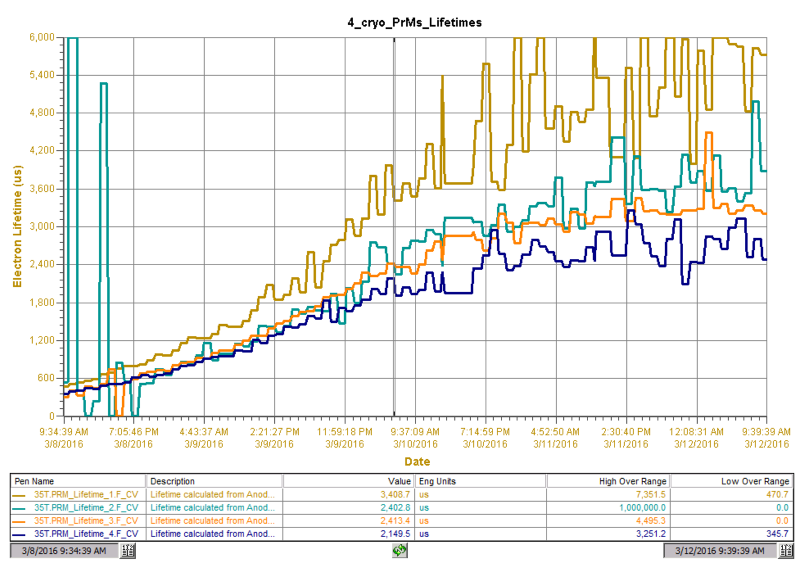

Figure 1.5: The measured electron lifetimes in the four purity monitors as a function of time at Fermilab 35 ton prototype.

1.2.2.2 Purity Monitor Design

The basic design of a purity monitor is based on those used by the ICARUS experiment (Figure **??**)[**?**]. It is a double-gridded ion chamber immersed in the LAr volume. The purity monitor consists of four parallel, circular electrodes: a disk holding a photocathode, two grid rings (anode and cathode), and an anode disk. The cathode grid is held at ground potential. The cathode, anode grid, and anode are electrically accessible via modified vacuum grade high-voltage feedthroughs and separate bias voltages held at each one. The anode grid and the field shaping rings are connected to the cathode grid by an internal chain of 50 MΩ resistors to ensure the uniformity of the E fields in the drift regions. A stainless mesh cylinder is used as a Faraday cage to isolate the purity monitor from external electrostatic backgrounds.

The purity monitor measures the electron drift lifetime between its anode and cathode. The electrons are generated by the purity monitor's UV-illuminated gold photocathode via the photoelectric effect. As the electron lifetime in LAr is inversely proportional to the electronegative impurity concentration, the fraction of electrons generated at the cathode that arrive at the anode (Q_A/Q_C) after the electron drift time t gives a measure of the electron lifetime τ: $Q_A/Q_C \sim e^{-t/\tau}$.

It is clear from this formula that the purity monitor reaches its sensitivity limit once the electron lifetime becomes much larger than the drift time t. For $\tau >> t$ the anode to cathode charge ratio becomes ~ 1. But, as the drift time is inversely proportional to the E field, by lowering the drift field one can in principle measure any lifetime no matter the length of the purity monitor (the lower the field, the lower the drift velocity, i.e., the longer the drift time). In practice, at very low fields it is hard to drift the electrons all the way up to the anode. Currently, specific sensitivity limits for purity monitors with a drift distance of the order of ∼20 cm are still to be determined in a series of tests. If the required sensitivity is not achieved by these "short" purity monitors, longer ones may be developed.

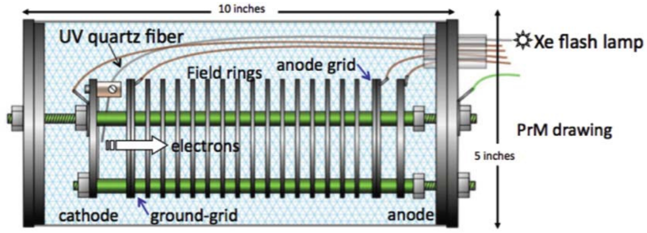

Figure 1.6: Schematic diagram of the basic purity monitor design [?].

The photocathode that produces the photoelectrons is an aluminum plate coated with 50 Å of titanium and 1000 Å of gold and attached to the cathode disk. A xenon flash lamp is used as the light source in the baseline design, although this could potentially be replaced by a more reliable and possibly submersible light source in the future, perhaps LED driven. The UV output of the lamp is quite good around $\lambda = 225\,\mathrm{nm}$, which is close to the work function of gold (4.9 eV to 5.1 eV). Several UV quartz fibers are used to carry the xenon UV light into the cryostat to illuminate the gold photocathode. Another quartz fiber is used to deliver the light into a properly biased photodiode outside of the cryostat to provide the trigger signal for when the lamp flashes.

1.2.2.3 Electronics, DAQ and Slow Controls Interfacing

The purity monitor electronics and DAQ system consist of FE electronics, waveform digitizers, and a DAQ PC. The block diagram of the system is shown in Figure ??.

The baseline design of the FE electronics is the one used for the purity monitors at the 35 ton prototype, LAPD, and MicroBooNE. The cathode and anode signals are fed into two charge amplifiers contained within the purity monitor electronics module. The amplified outputs of the anode and cathode are recorded with a waveform digitizer that interfaces with a DAQ PC.

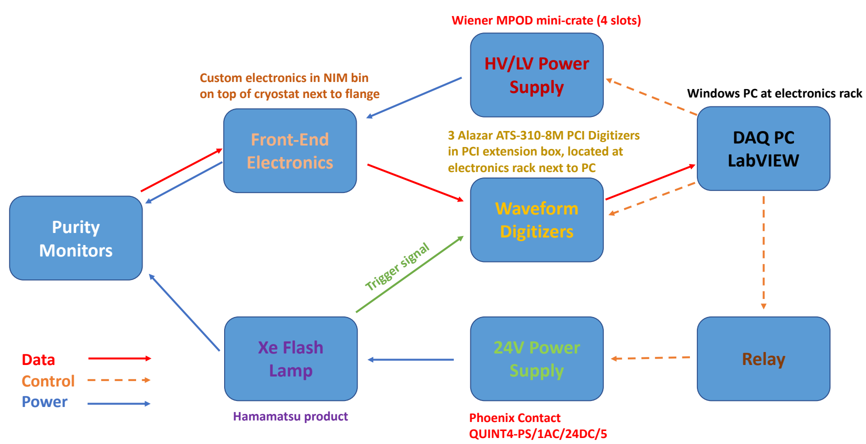

Figure 1.7: Block diagram of the purity monitor system.

A custom LabVIEW application running on the DAQ PC is developed and executes two functions:

it controls the waveform digitizers and the power supplies, and it monitors the signals and key parameters. The application configures the digitizers to set the sampling rate, the number of waveforms to be stored in the memory, pre-trigger data, and a trigger mode. A signal from a photodiode triggered by the xenon flash lamp is directly fed into the digitizer as an external trigger to initiate data acquisition. The LabVIEW application automatically turns on the xenon flash lamp by powering a relay at the start of data taking and then turns it off when finished. The application continuously displays the waveforms and important parameters, such as measured electron lifetime, peak voltages, and drift time of electrons in the purity monitors, and shows these parameters over time.

The xenon flash lamp and the FE electronics are installed close to the purity monitor flange, to reduce light loss through the optical fiber and prevent signal loss. Other pieces of equipment are mounted in a rack separate from the cryostat. They distribute power to the xenon flash lamp and the FE electronics, as well as collect data from the electronics. The slow control system communicates with the purity monitor DAQ software and has control of the HV and LV power supplies of the purity monitor system. As the optical fiber has to be very close to the photocathode (less than 0.5 mm) for efficient photoelectron extraction, no interference with the PDS is expected. Nevertheless light interference will be evaluated more precisely at ProtoDUNE.

Conversely the electronics of purity monitors may induce noise in the TPC electronics, largely coming from the current surge in the discharging process of the main capacitor of the purity monitor xenon light source when producing a flash. This source of noise can be controlled by placing the xenon flash lamp inside its own Faraday cage allowing for proper grounding and shielding; the extent of mitigation will be evaluated at ProtoDUNE. If an unavoidable interference problem is found to exist, then software can be implemented to allow the DAQ to know if and when the purity monitors are running and to veto purity monitor measurements in the event of a supernova neutrino burst (SNB) alert or trigger.

1.2.2.4 Production and Assembly

Production of the individual purity monitors and their assembly into the string that gets placed into the detector module cryostat follows the same methodology that is being developed for ProtoDUNE. Each of the individual monitors is fabricated, assembled and then tested in a smaller test stand. After confirming that each of the individual purity monitors operates at the required performance, they are assembled together via the support tubes used to mount the system to the inside of the cryostat such that three purity monitors are grouped together to form one string, as shown in Figure **??**. Each monitor is assembled as the string is built from the top down, and in the end three individual purity monitors hang from a single string. The assembly of the string concludes once the purity monitors are each in place, but with the Faraday cages removed and the HV cables and optical fibers yet to be run. This full string assembly is then shipped to the FD site for installation into the cryostat.

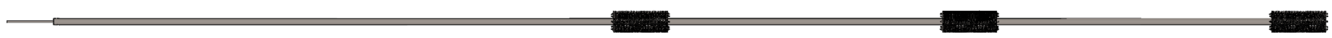

Figure 1.8: Design of the purity monitor string that will contain three purity monitors.

1.2.3 Thermometers

A detailed 3D temperature map is important to monitor the correct functioning of the cryogenics system and the LAr uniformity. Given the complexity and size of purity monitors, those can only be installed on the cryostat sides to provide a local measurement of the LAr purity. While a direct measurement of the LAr purity across the entire cryostat is not viable, a sufficiently detailed 3D temperature map can be used to predict the LAr purity using CFD simulations. Measuring the vertical temperature profile is especially important since this is closely related to the LAr recirculation and uniformity.

High-precision temperature sensors are distributed near the TPC walls in two ways: (1) in high-density ($>$ 2 sensors/m) vertical arrays (the T-gradient monitors), and (2) in coarser ($\sim$ 1 sensor/5 m) 2D arrays at the top and bottom of the detector, which are the most sensitive regions (the individual sensors).

Since temperature variations inside the cryostat are expected to be very small (0.02 K, see Figure **??**), to properly measure the 3D temperature map sensors must be cross-calibrated to better than 0.005 K. Most sensors are calibrated in the laboratory, prior to installation, as described in Section **??**. This is in fact the only viable method for sensors in areas where the available space is restricted: on the long sides of the detector (behind the APAs for SP, and behind the lateral endwall field cage (endwall FC) for DP) and top/bottom of the detector. Given the precision required and the unknown longevity of the sensors (which could require a new calibration after some time), a complementary method is used for T-gradient monitors behind the front endwalls, at least for the SP module. In those areas there is sufficient space for a movable system that can be used to cross-calibrate in situ the temperature sensors.

In the baseline design for all three systems mentioned above, three elements are common: sensors, cables and readout system. Platinum sensors with 100 Ω resistance, PT100 series, produced by Lakeshore[2], are adequate for the temperature range of interest, 83 K to 92 K, since in this range those sensors have $\sim$ 5 mK reproducibility and absolute temperature accuracy of 100 mK. In addition, using four-wire readout greatly reduces the issues related to the lead resistance, any parasitic resistances, connections through the flange, and general electromagnetic noise pick-up. The Lakeshore PT102 sensors have being previously used in the 35 ton prototype and ProtoDUNE-SP detector, giving excellent results. For the inner readout cables a custom cable made by Axon[3] is the baseline. It consists of four AWG28 teflon-jacketed copper wires forming two twisted pairs, with a metallic external shield and an outer teflon jacket. The readout system is described below in Section **??**.

Another set of lower-precision sensors is used to monitor the filling of the cryostat in its initial stage.

[2] Lakeshore™, `https://www.lakeshore.com/Pages/Home.aspx`.
[3] Axon™, `http://www.axon-cable.com/en/00_home/00_start/00/index.aspx`

Those sensors are epoxied into the cryostat bottom membrane with a density to be determined, not to exceed one sensor every 5 m. Finally, the inner walls and roof of the cryostat are instrumented with the same type of sensors in order to monitor their temperature during cooldown and filling. The baseline distribution has three vertical arrays of sensors epoxied to the membrane: one behind each of the two front endwall FCs and the third one in the middle of the cryostat (behind the APAs for SP and behind the lateral endwall FCs for DP).

1.2.3.1 Static T-gradient Monitors

Several vertical arrays of high-precision temperature sensors cross-calibrated in the laboratory are installed near the lateral walls (behind the APAs for SP and behind the lateral endwall FCs for DP). For the SP module, since the electric potential is zero behind the APAs, no E field shielding is required, simplifying enormously the mechanical design. This does not apply for the DP module, for which the proper shielding must be provided.

Sensors are cross-calibrated in the lab using a well controlled environment and a high-precision readout system, described below in Section **??**. Although the calibration procedure will certainly improve, the one currently used for ProtoDUNE-SP is described here. Four sensors are placed as close as possible (such that identical temperature can be assumed for all of them) inside a small cylindrical aluminum capsule, which protects the sensors from thermal shocks and helps in minimizing convection. One of the sensors acts as reference while the other three are calibrated. Five independent calibrations are performed for each set of three sensors, such that the reproducibility of each sensor can be computed. For each calibration the capsule is introduced in a programmable logic array (PLA) box of size $9.5 \times 9.5 \times 19\,\mathrm{cm}^3$, with two concentric independent volumes of LAr and surrounded by a polystyrene box with 15 cm thick walls. A small quantity of LAr is used to slowly cool down the capsule to $\sim 90\,\mathrm{K}$, avoiding thermal shocks that could damage the sensors. Then the capsule is covered by

immersed in?

LAr such that it penetrates inside, fully covering the sensors. Once the temperature stabilizes to the 1-2 mK level (after 5-15 minutes) measurements are taken. Then the capsule is taken out from LAr and exposed to room temperature until it reaches 200 K. As mentioned above, this procedure is repeated five times, before going to the next set of three sensors. As shown in Figure **??** a reproducibility (RMS of the mean offset in the flat region) of $\sim 2\,\mathrm{mK}$ has been achieved in the ProtoDUNE-SP design.

The baseline design for the mechanics of the SP system consists of two stainless strings anchored at top and bottom corners of the cryostat using the available M10 bolts (see Figure **??**). One of the strings is used to route the cables while the other, separated by 340 mm, serves as support for temperature sensors. Given the height of the cryostat, the need of intermediate anchoring points is under discussion. For the DP module no baseline design exists yet, since additional complications due to the required E field shielding must be taken into account. Figure **??** shows the baseline design of the PCB support for temperature sensors, with an IDC-4 male connector. It has a size of $52 \times 15\,\mathrm{mm}^2$. Each four-wire cable from the sensor to the flange has an IDC-4 female connector on the sensor side; on the other side, it is directly soldered into the inner pins of male SUBD-25 connectors on the flanges. The CF63 side ports on the detector support system (DSS)/cryogenic ports are used to extract the cables.

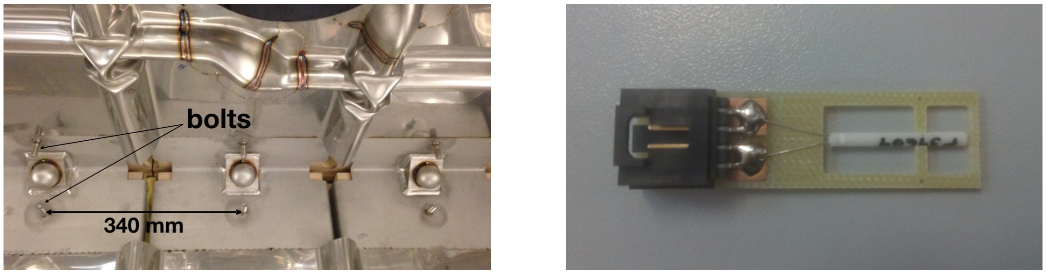

Figure 1.9: Left: bolts at the bottom corner of the cryostat. Right: Lakeshore PT102 sensor mounted on a PCB with an IDC-4 connector. fig:sens

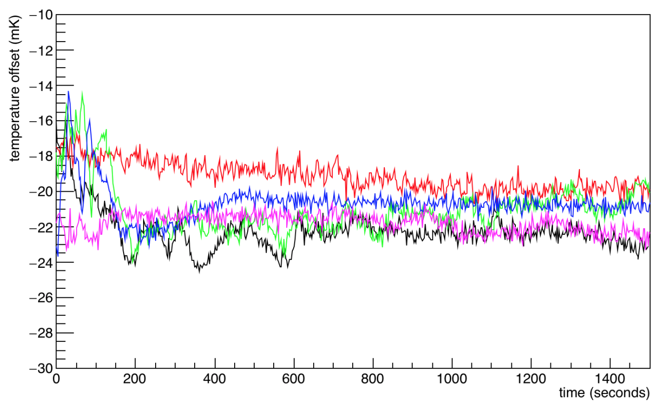

Figure 1.10: Temperature offset between two sensors as a function of time for five independent inmersions in LAr. The reproducibility of those sensors, defined as the RMS of the mean offset in the flat region, is ~ 2 mK, The resolution for individual measurements, defined as the RMS of one of the offsets in the flat region, is better than 1 mK. fig:Trep

1.2.3.2 Dynamic T-gradient Monitors

The dynamic temperature monitor is a vertical array of high precision temperature sensors with the goal of measuring vertical temperature gradient with precision of few mK. The design of the system is driven by two factors:

- A few-mK uncertainty in the measured vertical temperature profile over the entire detector height is required in order to monitor LAr purity and provide useful feedback of efficiency of cryogenic recirculation and purification.

- Simulations of the cryogenic recirculation predict very slow change in temperature at meter scale except at the bottom and top of the cryostat. Thus, sensors are placed every 50 cm along the detector module height with increased frequency in the first 50 cm, closest to the bottom of the cryostat and the last 50 cm, closest to the top of the cryostat, where spacing between sensors is reduced to 10 cm.

In order to address concerns related to possible differences in the sensor readings prior to and after installation in a detector module, a dynamic temperature monitor allows cross-calibration of sensors in situ.

difference in voltage, or differences in the sensor reading that may happen? I think the latter... (anne)

Namely, this T-gradient monitor can move vertically while installed in the detector module, which allows for precise cross-calibration between the sensors in situ at predefined locations, as well as in between them.

not clear

The procedure for cross-calibrations is the following: the temperature reading is taken at the lowest position with all sensors. The stepper motor then moves the carrier rod up 50 cm, putting all sensors in the previous location of their neighbor that was 50 cm above them. Then the second reading is taken. In this manner, except for the lowest position we have temperature measurement at each location with two adjacent sensors, and by linking the temperature offsets between the two readings at each location, temperature readings from all sensors are cross-calibrated in situ, cancelling all offsets due to electromagnetic noise or any parasitic resistances that may have prevailed despite the four point connection to the sensors that should cancel most of the offsets. These measurements are taken with very stable current source, which ensures high precision of repeated temperature measurements over time. The motion of the dynamic T-monitor is stepper motor operated, delivering measurements with high spatial resolution.

1.2.3.3 Dynamic T-gradient Monitor Design

A dynamic T-gradient monitor consists of three distinct parts: a carrier rod on which sensors are mounted, an enclosure above the cryostat housing the space that allows vertical motion of the carrier rod 1.5 m above its lowest location, and the motion mechanism. The motion mechanism consists of a stepper motor connected to a gear and pinion through a ferrofluidic dynamic seal. The sensors have two pins that are soldered to a printed circuit board (PCB). Two wires are soldered to the common soldering pad for each pin, individually. There is a cutout in the PCB around the sensor that allows free flow of argon for more accurate temperature reading. Stepper motors typically have very fine steps allowing high-precision positioning of the sensors. Figure ?? shows the overall design of the dynamic T-gradient monitor with the sensor carrier rod, enclosure above the cryostat and the stepper motor mounted on the side of the enclosure. The enclosure consists of two parts connected by 6-cross flange. One side of the six-way cross flange is used to for the signal wires, another side is used as a viewing window, while the two other ports are spares. Figure ?? (left) shows the mounting of the PCB board on the carrier rod and mounting on the sensor on the PCB along with the four point connection to the signal readout wires. Finally, Figure ?? (right) shows the stepper motor mounted on the side of the rod enclosure. The motor is kept outside, at room temperature and its power and control cables are also kept outside.

above pgraph needs some work

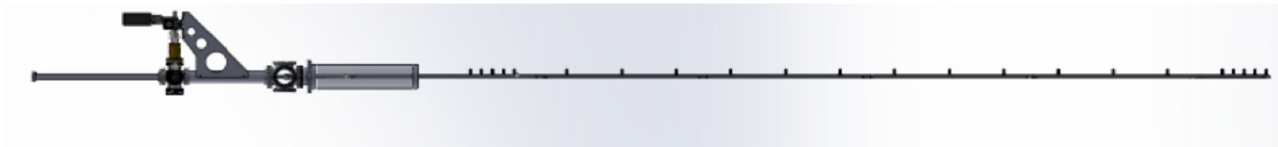

Figure 1.11: An overview of the dynamic T-gradient monitor.

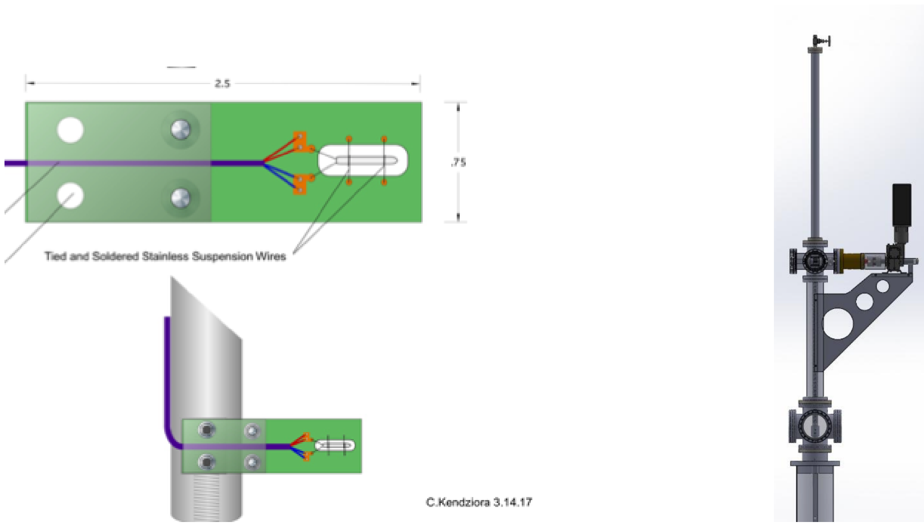

Figure 1.12: Left: Sensor mounted on a PCB board and PCB board mounted on the rod. Right: The driving mechanism of the dynamic T-gradient monitor. It consists of a stepper motor driving the pinion and gear linear motion mechanism.

1.2.3.4 Individual Temperature Sensors

T-Gradient monitors provide a vertical temperature profiling outside the TPCs. They are complemented by a coarser 2D array at the top and bottom of the detector. Sensors, cables and readout system are the same as for the T-gradient monitors.

In principle, a similar distribution of sensors is used at top and bottom. Following the ProtoDUNE-SP design, bottom sensors use the cryogenic pipes as a support structure, while top sensors are anchored to the GPs. Teflon pieces (see Figure **??**) are used to route cables from the sensors to the CF63 side ports on DSS-cryogenics ports, which are used to extract the cables. The PCB sensor's support, cables and connection to the flanges are the same as for the static T-gradient monitors.

1.2.3.5 Readout System for Thermometers

A high precision and very stable system is required to achieved the design precision of $< 5\,\mathrm{mK}$. The proposed readout system is the one used in ProtoDUNE-SP, which is based on a variant

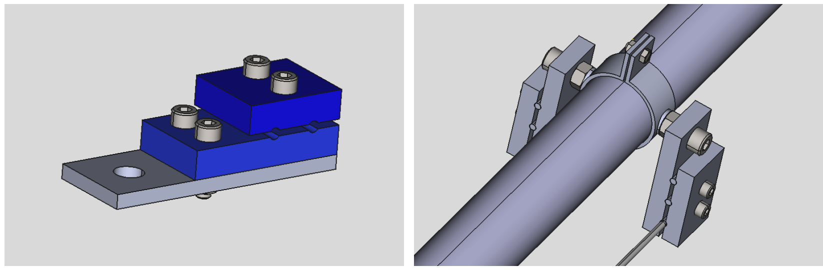

Figure 1.13: Left: support for two cables on ground planes. Right: Supports for three cables mounted on cryogenics pipes using split clamps

of an existing mass PT100 temperature readout system developed at CERN for one of the LHC experiments. The system consists of three parts:

- An accurate current source for the excitation of the temperature sensors, implemented by a compact electronic circuit using a high-precision voltage reference from Texas Instruments [4];
- A multiplexing circuit based on an Analog Devices ADG707[5] multiplexer electronic device;
- A high-resolution and accuracy voltage signal readout module based on National Instruments [6] NI9238, which has 24 bit resolution over a 1 V range. This module is inserted in a National Instruments compact RIO device that distributes the temperature values to the main slow control software through the standard OPC UA protocol. The Ethernet DAQ also includes the multiplexing logic.

The current mode of operation averages over 2000 samples taken every second for each sensor. As inferred from Figure ?? the system has a resolution better than 1 mK, the RMS of one of the offsets in the stable region.

1.2.4 Liquid Level Monitoring

The goals for the level monitoring system are basic level sensing when filling, and precise level sensing during static operations.

For filling the detector module the differential pressure between the top of the detector and known points below it can be converted to depth with the known density of LAr. The temperatures of RTDs at known heights may also be used to determine when the cold liquid has reached each RTD.

During operation, the purpose of liquid level monitoring is twofold: the cryogenics system uses it to tune the LAr flow and the detector module uses it to guarantee that the top GPs are always submerged (otherwise the risk of dielectric breakdown is high). Two differential pressure level

[4] Texas Instruments™, http://www.ti.com/.

[5] Analog Devices™, http://www.analog.com/media/en/technical-documentation/data-sheets/ADG706_707.pdf.

[6] National Instruments™, http://www.ni.com/en-us.html/.

meters are installed as part of the cryogenics system, one on each side of the detector module. They have a precision of 0.1 %, which corresponds to 14 mm at the nominal LAr surface. This precision is sufficient for the single phase detector, since the plan is to kept the LAr surface at least 20 cm above the GPs (this is the value used for the HV interlock in ProtoDUNE-SP); thus, no additional level meters are required for the single phase. However, in the DP LAr system the surface level should be controlled at the millimeter level, which can be accomplished with capacitive monitors. Using the same capacitive monitor system in each detector reduces design differences and provides a redundant system for the SP. Either system could be used for the HV interlock.

Table **??** summarizes the requirements for the liquid level monitor system.

Table 1.2: Liquid level monitor requirements

Requirement	Physics Requirement Driver
Measurement accuracy (filling) $\sim$ 14 mm	Understand status of detector during filling
Measurement accuracy (operation, DP) $\sim$ 1 mm	Maintain correct depth of gas phase. (Exceeds SP requirements)
Provide interlock with HV	Prevent damage to detector module from HV discharge in gas

Cryogenic pressure sensors will be purchased from commercial sources. Installation methods and positions will be determined as part of the cryogenics internal piping plan. Sufficient redundancy will be designed in to ensure that no single point of failure compromises the level measurement.

Multiple capacitive level sensors are deployed along the top of the fluid to be used during stable operation and checked against each other.

During operations of the WA105 DP demonstrator, the cryogenic programmable logic controller (PLC) continuously checked the measurements from one level meter on the charge readout plane (CRP) in order to regulate the flow from the liquid recirculation to maintain a constant liquid level inside the cryostat. Continuous measurements from the level meters around the drift cage and the CRP illustrated the stability of the liquid level within the 100 µm intrinsic precision of the instruments. The observation of the level was complemented by live feeds from the custom built cryogenic cameras, hereby providing qualitative feedback on the position and flatness of the surface.

In addition to the installed level meters, the liquid height in the extraction region of the CRP could be inferred by measuring the capacitance between the grid and the bottom electrode of each LEM. Averaging over all 12 LEMs the measured values of this capacitance typically ranged from 150 pF with the liquid below the grid to around 350 pF when the LEMs are submerged.This method offers the potential advantage of monitoring the liquid level in the CRP extraction region with a $50{\times}50\,\mathrm{cm}^2$ granularity and could be used for the CRP level adjustment in a DUNE DP module where, due to the space constraints, placement of the level meters along the CRP perimeter is not possible.

1.2.5 Gas Analyzers

Gas analyzers are commercially produced modules that measure trace quantities of specific gases contained within a stream of carrier gas. The carrier gas for DUNE is argon, and the trace gases of interest are oxygen (O_2), water (H_2O), and nitrogen (N_2). Oxygen and water impact the electron lifetime in LAr, while N_2 impacts the efficiency of scintillation light production. In the LAr environment, these trace gases represent contaminants that need to be kept at levels below 0.1 ppb. The argon is sampled from either the argon vapor in the ullage or from the LAr by the use of small diameter tubing run from the sampling point to the gas analyzer. Typically the tubing runs from the sampling points are connected to a switchyard valve that is used to route the sample points to the desired gas analyzers. Figure **??** is a photo of such a switchyard.

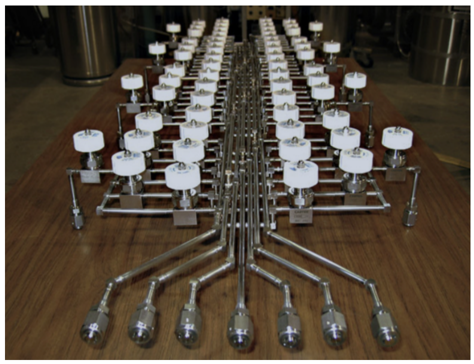

Figure 1.14: A Gas Analyzer switchyard that routes sample points to the different gas analyzers.

Three examples of gas analyzer usage:

1. A proven procedure to eliminate the air atmosphere from the cryostat after detector installation to levels low enough to begin cooldown is an argon piston purge followed by a recirculation of the remaining argon gas through the filtration system. This process is described more fully in Section **??**. Figure **??** shows the evolution of the N_2, O_2, and H_2O levels from gas analyzer data taken during the purge and recirculation stages of the DUNE 35 ton prototype phase 1 run.

2. High-precision O_2 and H_2O analyzers can track the trace contaminants from the tens of ppb to the 100s of ppt. This is useful when other means of monitoring the impurity level (e.g., purity monitors, or TPC tracks) are not yet sensitive. Figure **??** shows an example plot of the O_2 level at the beginning of LAr purification from one of the later 35t HV runs.

3. The gas analyzers can also monitor the tanker LAr deliveries purity during the cryostat-filling period. This allows tracking the impurity load on the filtration system and rejecting any deliveries that are out of specifications. Likely specifications for the delivered LAr are in the ten ppm range per contaminant.

As any one gas analyzer covers only one contaminant species and 3 to 4 orders of magnitude of range, multiple units are needed both for the three contaminant gases and to cover the ranges that are seen between the cryostat closure to the beginning of TPC operations: 20 % to $\lesssim$ 100 ppt for O_2, 80 % to $\lesssim$ 1 ppm for N_2, and $\sim$ 1 % to $\lesssim$ 1 ppb for H_2O. Since the total cost of these

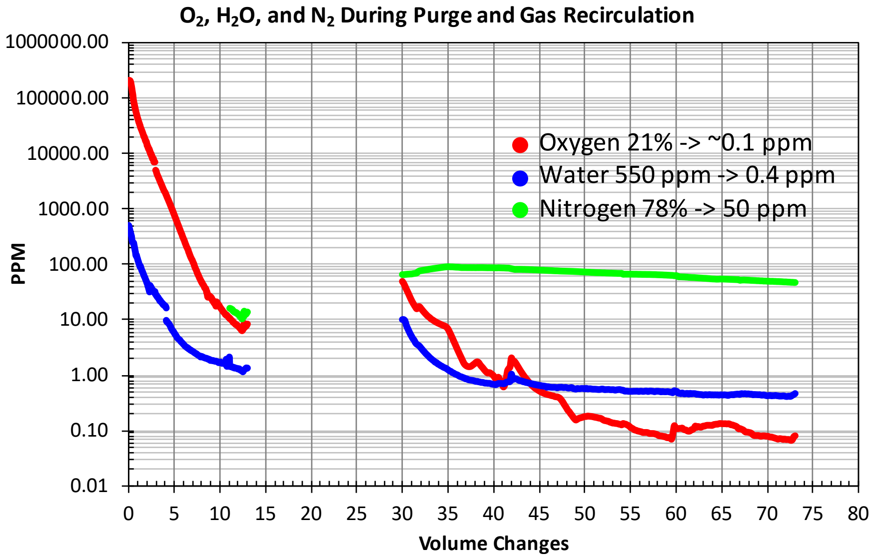

Figure 1.15: Plot of the O_2, H_2O, and N_2 levels during the piston purge and gas recirculation stages of the 35t phase 1 run. fig:GA-p

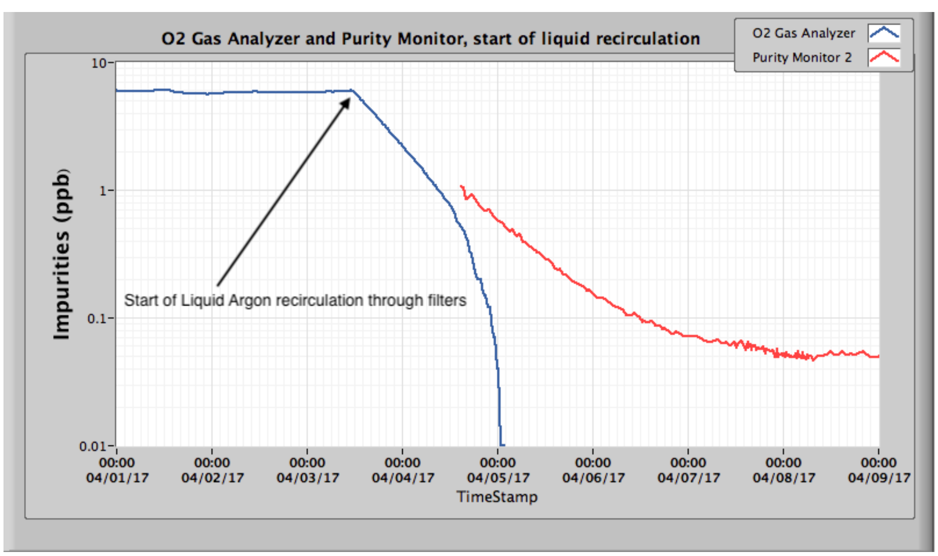

Figure 1.16: O_2 as measured by a precision O_2 analyzer just after the 35 ton prototype was filled with LAr, continuing with the LAr pump start and beginning of LAr recirculation through the filtration system. As the gas analyzer loses sensitivity, the purity monitor is able to pick up the impurity measurement. Note that the purity monitor is sensitive to both O_2 and H_2O impurities giving rise to its higher level of impurity. fig:GA-O

analyzers exceeds \$100 k, it is useful to be able sample more than a single location or cryostat with the same gas analyzers. At the same time, the tubing run lengths from the sample point should be as short as possible in order to keep the response of the gas analyzer timely. This puts some constraints on the sharing of devices since, for example, the argon deliveries are at the surface, perhaps necessitating a separate surface gas analyzer.

1.2.6 Cameras

Cameras provide direct visual information about the state of the detector module during critical operations and when damage or unusual conditions are suspected. Cameras in the WA105 DP demonstrator allowed spray from cool-down nozzles to be seen, and the level and state of the LAr to be observed as it covered the CRP [?]. A camera was used in the Liquid Argon Purity Demonstrator cryostat[?] to study HV discharges in LAr, and in EXO-100 during operation of a TPC [?]. Warm cameras viewing LAr from a distance have been used to observe HV discharges in LAr in fine detail [?]. Cameras are commonly used during calibration source deployment in many experiments (*e.g.,* the KamLAND ultra-clean system [?]).

In DUNE, cameras are used to verify the stability, straightness, and alignment of the hanging TPC structures during cool-down and filling; to ensure that there is no bubbling near the GPs (SP) or CRPs (DP); to inspect the state of movable parts in the detector module (calibration devices, dynamic thermometers) as needed; and to closely inspect parts of the TPC as necessary following any seismic activity or other unanticipated occurrence. These functions are performed using set of fixed *cold* cameras permanently mounted at fixed points in the cryostat for use during filling and commissioning, and a movable, replaceable *warm* inspection camera that can be deployed through any free instrumentation flange at any time throughout the life of the experiment. Table **??** summarizes the requirements for the camera system.

The following sections describe the design considerations for the cold and warm cameras and the associated lighting system. The same basic design may be used for both the single and dual phase detectors.

1.2.6.1 Cryogenic Cameras (Cold)

The fixed cameras monitor the following items during filling:

- Positions of corners of APA or CRP, cathode plane assembly (CPA) or cathode, FCs, GPs (1 mm resolution);
- Relative straightness and alignment of APA/CRP, CPA/cathode, and FC ($<\sim$ 1 mm);
- Relative position of profiles and endcaps (0.5 mm resolution);
- State of LAr surface: i.e., bubbling, debris.

Table 1.3: Camera system requirements

Requirement	Physics Requirement Driver
General	
No component may contaminate the LAr.	High LAr purity is required for TPC operation.
No component may produce bubbles in the liquid argon if the HV is on.	Bubbles increase risk of HV discharge.
No point in the camera system shall have a field greater than 15 kV/cm when the drift field is at nominal voltage.	Fields must be well below 30 kV/cm to avoid risk of HV discharge.
The camera system shall not produce measurable noise in any detector system.	Low noise is required for TPC operation.
Cameras provide the viewing functionality as agreed upon with the other subsystems for viewing, as documented in the ICDs with the individual systems.	
Cold cameras	
minimal heat dissipation when camera not in operation	do not generate bubbles when HV is on
longevity exceeds 18 months	cameras must function throughout cryostat filling and detector commissioning
Frame rate ≥ 10 /s	observe bubbling, waves, detritus, etc.
Inspection cameras	
low heat transfer to LAr when in operation	do not generate bubbles, some use cases may require operation when HV is on
deployable without exposing LAr to air	keep LAr free N2 and other electronegative contaminants
replaceable camera enclosure	replace broken camera, or upgrade, throughout life of experiment
Light emitting system	
no emitted wavelength shorter than 400 nm	avoid damaging tetra-phenyl butadiene (TPB) waveshifter
longevity exceeds 18 months	lighting for fixed cameras must function throughout cryostat filling and detector commissioning

eras-req

There are published articles and unpublished presentations describing completely or partially successful operation of low-cost, off-the-shelf CMOS cameras in custom enclosures immersed in cryogens. (e.g., EXO-100: [?]; DUNE 35 ton prototype test [?]; WA105 DP demonstrator: [?].) Generally it is reported that such cameras show poor performance and ultimately fail to function below some temperature of order 150 K to 200 K, but some report that their cameras recover fully after being stored (not operated) at temperatures as low as 77 K and then brought up to minimum operating temperature.

However, as with photon sensors, experience has also shown that it is non-trivial to ensure reliable and reproducible mechanical and electrical integrity of such cameras in the cryogenic environment. (*E.g.*, [?] and [?].) Off-the-shelf cameras and camera components are generally only specified by the vendors and original manufacturers for operation down to −40 °C or −50 °C. In addition, many low-cost cameras use digital interfaces not intended for long distance deployment, such as USB ($2 \sim 5$ m) or CSI (circuit board scale), leading to signal degradation and noise problems.

The design for the DUNE fixed cameras uses an enclosure based on the successful EXO-100 design[?], which was also used successfully in LAPD. (See Figure reffig:gen-fdgen-cameras-enclosure) The enclosure is connected to a stainless steel gas line to allow the enclosure to be flushed with argon gas at low enough pressure to prevent liquification, using the same design asthe gas line for the beam plug tested in the 35 ton prototype HV test and in ProtoDUNE. A thermocouple in the enclosure allows temperature monitoring, and a heating element provides temperature control. The camera transmits its video signal using either a composite video signal over shielded coax or Ethernet over optical fiber. Most importantly, the DUNE CISC consortium must work with vendors to design camera circuit boards that are robust and reliable in the cryogenic environment.

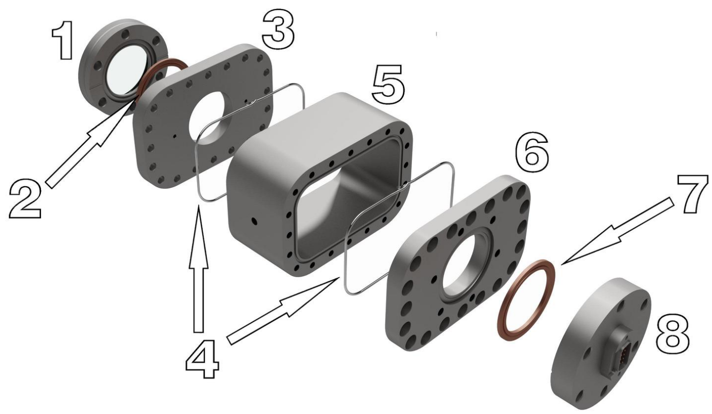

Figure 1.17: CAD exploded view of vacuum-tight camera enclosure suited for cryogenic applications from [?]. (1) quartz window, (2 and 7) copper gasket, (3 and 6) flanges, (4) indium wires, (5) body piece, (8) signal feedthrough.

1.2.6.2 Inspection Cameras (Warm)

The inspection cameras are intended to be as versatile as possible. However, the following locations have been identified as likely to be of interest:

- Status of HV feedthrough and cup;
- Status of FC profiles, endcaps (0.5 mm resolution);
- y-axis deployment of calibration sources;
- Status of thermometers, especially dynamic thermometers;
- HV discharge, corona, or streamers on HV feedthrough, cup, or FC;
- relative straightness and alignment of APA/CRP, CPA/cathode, and FC (1 mm resolution);
- gaps between CPA frames (1 mm resolution);
- relative position of profiles and endcaps (0.5 mm resolution);
- sense wires at top of outer wire planes in SP APA (0.5 mmresolution).

Unlike the fixed cameras, the inspection cameras need operate only as long as inspection lasts, as the camera can be replaced in case of failure. It is also more practical to keep the cameras continuously *warm* (above −150 °C) during deployment; this offers more options for commercial cameras, e.g., the same model camera used successfully to observe discharges in LAr from 120 cm away [?].

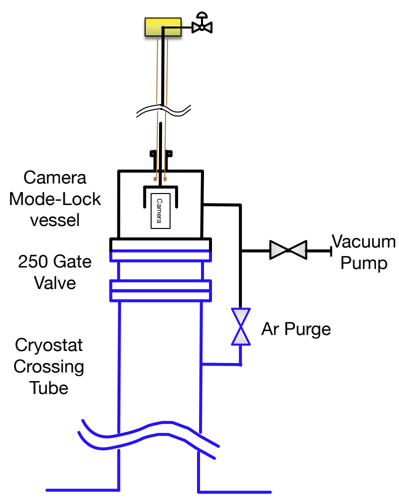

Figure 1.18: An overview of the inspection camera design.

The design for the inspection camera system employs the same basic enclosure design as for cold cameras, but mounted on an insertable fork using a design similar to the dynamic temperature probes. (See Figure ?? and Figure ??.) The entire system is sealed to avoid contamination with air. In order to avoid contamination, the camera can only be deployed through a feedthrough equipped with a gate valve and a purging system, similar to that used for the vertical axis calibration system at KamLAND [?]. The entire system is purged with pure argon gas before the gate valve is opened.

Motors above the flange allow rotation and vertical movement of the fork. A chain drive system, with motor mounted on the end of the fork, allows tilting of the camera assembly, creating a point-tilt mount with vertical motion capability. Taking into account the room above the cryostat flanges and the thickness of the cryostat insulation, a vertical range of motion of 1 m inside the cryostat is achievable. The motors for rotation and vertical motion are located outside the sealed volume, coupled mechanically using ferrofluidic seals, thus reducing contamination risks and allowing for manual rotation of the vertical drive in the event of a motor failure. A significant protyping and testing effort is needed to finalize and validate this design.

1.2.6.3 Light-emitting system

The light-emitting system is based on LEDs with the capability of illuminating the interior with selected wavelengths (IR and visible) that are suitable for detection by the cameras. Performance criteria for the light-emission system are based on the efficiency of detection with the cameras, in conjunction with adding minimal heat to the cryostat. The use of very high-efficiency LEDs helps reduce heat generation; as an example, one 750 nm LED has a specification of 32 % conversion of electrical input power to light.

While data on the performance of LEDs at cryogenic temperatures is sparse, some studies related to NASA projects [?] indicate that LED efficiency increases with reduced temperature, and that the emitted wavelengths may change, particularly for blue LEDs. The wavelength changes cited would have no impact on illumination, however, since in order to avoid degradation of wavelength-shifting materials in the PDS, such short wavelength LEDs would not be used.

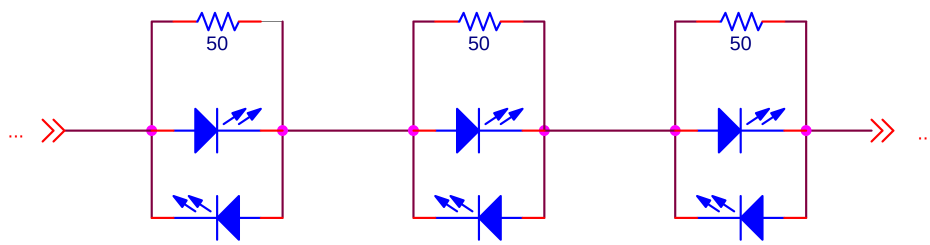

Figure 1.19: Suggested LED chain for lighting inside the cryostat, with dual-wavelength and failure-tolerant operation.

shoulds and woulds...

A *chain* of LEDs should be connected in series and driven with a constant-current circuit. It would be advantageous to pair each LED in parallel with an opposite polarity LED and a resistor (see Figure **??**). This allows two different wavelengths of illumination with a single installed chain (by changing the direction of the drive current) and continued use of an LED chain even if individual LEDs fail.

The LEDs should be placed as a *ring light* around the outside of each camera lens, pointing in the same direction as the lens, to illuminate the part of the detector module within the field of view of the camera. Commercially available LEDs can be obtained with a range of angular spreads, and can be matched to the needs of the cameras without additional optics.

1.2.7 Cryogenics Test Facility

The cryogenics test facility is intended to provide the access to a small (< 1 ton) to intermediate ($\sim$ 4 tons) volumes of purified TPC-grade LAr. Hardware that needs liquid of purity this high include any device intending to drift electrons for millisecond time periods. Not all devices require purity this high, but may need a relatively large volume to provide the needed prototyping environment. Of importance is a relatively fast turn-around time of approximately a week for short prototyping runs.

Figure **??** shows the Blanche test stand cryostat at Fermilab.

Figure 1.20: Blanche Cryostat at Fermilab. This cryostat holds ~ 0.75 tons of LAr.

1.2.8 Cryogenic Internal Piping

The cryogenic internal piping comprises several manifolds to distribute the liquid and gaseous argon inside the cryostat during all phases (e.g., gaseous purge, liquid distribution, cool down) and various pipe stands to return argon to the outside (e.g., boil-off gaseous argon). Vacuum-insulated pipe stands are needed to transition from inside to outside in a way that does not affect the purity and does not introduce a significant heat load.

LBNF has the expertise for engineering design and installation of the detector internal piping, while the CISC consortium has the expertise on the physics requirements, the relevant risk registries, and the interfaces with other detector systems. Ultimate responsibility for costing the internal cryogenic piping system also lies with the CISC consortium. It is important for these two groups to interact closely to ensure that the system enables achievement of the physics, avoids interference with other detector systems, and mitigates risks.

We have formed a cryogenics systems working group with conveners from both the CISC consortium and LBNF. This group has both LBNF and CISC members and provides an official forum where we interface and establish the final design.

The initial design for the cryogenic internal piping calls for some 750 m of pipe per cryostat for purging and filling, laid out as shown in Figure **??**-Left, and 20 flange-pipes assemblies, as the one shown on the right pannel of Figure **??**, with a CF DN250 flange penetrated by two ~ 2.2 m long pipes.

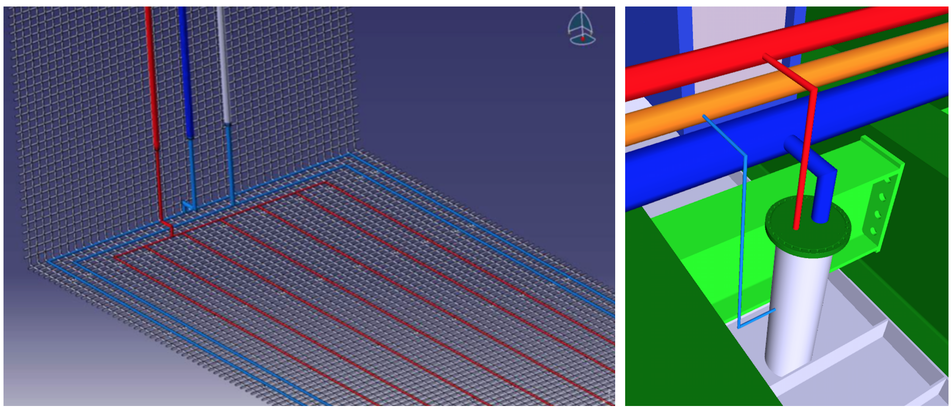

Figure 1.21: Left: Cryogenic internal piping for purging (red) and filling (blue). Right: Cool-down pipes, LAr in blue (vacuum jacketed) and gaseous argon in red.

1.3 Slow Controls

The slow controls system collects, archives, and displays data from a broad variety of sources, and provides real time alarms and warnings for detector operators. Data is acquired via network interfaces. Figure **??** shows the connections between major parts of the slow controls system and other systems.

1.3.1 Slow Controls Hardware

The slow controls requires a small amount of dedicated network and computing hardware as described below. It also relies on common infrastructure, as described in Section **??**.

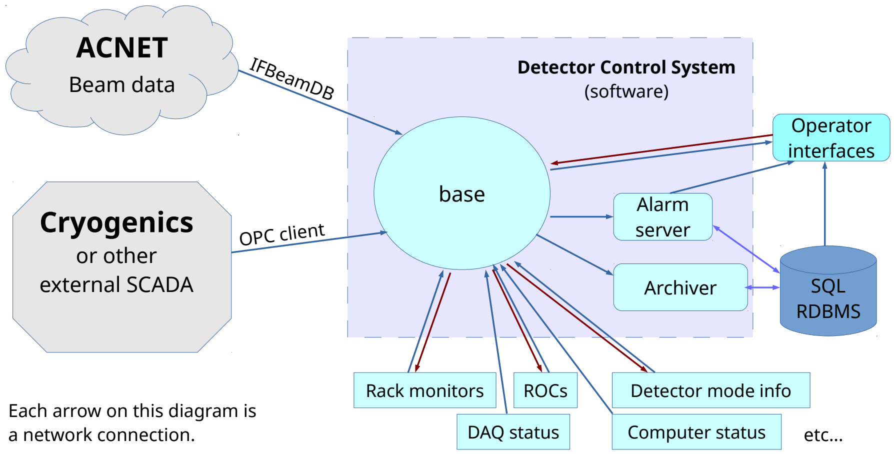

Figure 1.22: Typical Slow Controls system connections and data flow

1.3.1.1 Slow Controls Network Hardware

The slow controls data originates from the cryogenic instrumentation discussed in Section **??** and from other systems, and is collected by software running on servers (Section **??**) housed in the underground data room in the central utility cavern, where data is archived in a central CISC database. The instrumentation data is transported over conventional network hardware from any sensors located in the cryogenic plant. However, the readouts that are located in the racks on top the cryostats have to be careful about grounding and noise. Therefore, each rack on the cryostat has a small network switch that sends any network traffic from that rack to the CUC via a fiber transponder. This is the only network hardware specific to slow controls; network infrastructure requirements are described in Section **??**.

1.3.1.2 Slow Controls Computing Hardware

Two servers (a primary server and a replicated backup) suitable for the needed relational database discussed in Section **??** are located in the CUC data room, with an additional two servers to perform FE monitoring interface services: for example, assembling dynamic CISC monitoring web pages from the adjacent databases. Any special purpose software, such as iFix or EPICS, would also run here. It is expected that one or two more servers will accommodate these programs. Replicating this setup on a per-module basis would allow for easier commissioning and independent operation, accommodate different module design (and the resulting differences in database tables), and ensure sufficient capacity. Including four sets of networking hardware, this would fit tightly into one rack or very comfortably into two.

1.3.2 Slow Controls Infrastructure

The total number of slow controls quantities and the update rate are low enough that the data rate will be in the tens of kilobytes per second range (Section **??**), placing minimal requirements on the local network infrastructure. Network traffic out of SURF to Fermilab will be primarily database calls to the central CISC database: either from monitoring applications, or from database replication to the offline version of the CISC database. This traffic is of a low enough bandwidth that the proposed general purpose links both out of the mine and back to Fermilab can accommodate it.

Up to two racks of space and appropriate power and cooling are available in the CUC's DAQ server room for CISC usage. Somewhat less space than that is currently envisioned, as described in **??**.

1.3.3 Slow Controls Software

The slow controls software includes the following components in order to provide complete monitoring and control of detector subsystems:

- Control systems base that performs input and output operations and defines processing logic, scan conditions, alarm conditions, archiving rate, etc.;
- Alarm server that monitors all channels and sends alarm messages to operators;
- Data archiver that performs automatic sampling and storage of values for history tracking;
- Integrated operator interface that provides display panels for controls and monitoring.

An additional requirement for the software is the ability to indirectly interface with external systems (e.g., cryogenics control system) and databases (e.g., beam database) to export data into slow controls process variables (or channels) for archiving and status displays. This allows integrating displays and warnings into one system for the experiment operators, and provides integrated archiving for sampled data in the archived database. In this case, one can imagine an input output controller (IOC) running on a central DAQ server provides soft channels for these data. Figure **??** shows a typical workflow of a slow controls system.

In terms of key features of the software, a highly evolved software is needed that is designed for managing real-time data exchange, scalable to large number of channels and high bandwidth if needed. The software should be well documented, supported, and known to be reliable. The base software should also allow easy access of any channel by name. The archiver software should allow data storage in an SQL database with adjustable rates and thresholds such that one can easily retrieve data for any channel by using channel name and time range. Among the key features, the alarm server software should remember state, support arbitrary number of clients and provide logic for delayed alarms and acknowledging alarms. As part of the software, a standard naming convention for channels is followed to aid dealing with large number of channels and subsystems.

1.3.4 Slow Controls Quantities

The final set of quantities to monitor will ultimately be determined by the needs of the subsystems being monitored, as documented in appropriate interface control documents (ICDs), and continually revised based on operational experience. The total number of quantities to monitor has been very roughly estimated by taking the total number of quantities monitored in MicroBooNE and scaling by the detector length and the number of planes, giving a number in the range of 50 to 100k. Quantities are expected to update on average no faster than once per minute. The subsystems to be monitored include the cryogenic instrumentation described in this chapter, the other detector systems, and relevant infrastructure and external devices. Table **??** lists the kind of quantities expected from each system.

Table 1.4: Slow controls quantities

System	Quantities
Detector Cryogenic Instrumentation	
Purity monitors	anode and cathode charge, bias voltage and current, flash lamp status, calculated electron lifetime
Thermometers	temperature, position of dynamic thermometers
Liquid level	liquid level
Gas analyzers	purity level readings
Cameras	camera voltage and current draw, temperature, heater current and voltage, lighting current and voltage
Cryogenic internal piping	feedthrough gas purge flow and temperature
Other Detector Systems	
HV systems	Drift HV voltage, current; end-of-field cage current, bias; ground plane currents
TPC electronics	voltage and current to electronics
photon detector (PD)	bias, current, electronics
DAQ	warm electronics currents and voltages; run status; DAQ buffer sizes, trigger rates, data rates, GPS status, etc.; computer and disk health status; other health metrics as defined by DAQ group
CRP / APA	bias voltages and currents
Infrastructure and external systems	
Cryogenics (external)	status of pumps, flow rates, inlet and return temperature and pressure (via OPC or similar SCADA interface)
Beam status	protons on target, rate, target steering, beam pulse timing (via IFBeamDB)
Near detector	near detector run status (through common slow controls database)
Racks power and status	PDU current and voltage, air temperature, fan status if applicable, interlock status (fire, moisture, etc.)

1.3.5 Local Integration

The local integration for the slow controls consists entirely of software and network interfaces with systems outside of the scope of the detector module. This includes the following:

- readings from the LBNF-managed external cryogenics systems, for status of pumps, flow rates, inlet and return temperature and pressure, which are implemented via OPC or a similar SCADA interfaces;

- beam status, such as protons on target, rate, target steering, beam pulse timing, which are retrieved via IFBeamDB;

- near detector status, which can be retrieved from a common slow controls database.

This integration occurs after both the slow controls and non-detector systems are in place. The LBNF-CISC interface is managed by the Cryogenics Systems working group described in Section **??**. IFBeamDB is already well established. An internal near-detector–FD working group may be established to coordinate detector status exchange between near and far sites interfacing.

1.4 Interfaces

The CISC consortium interfaces with all other consortia, task forces (calibration), working groups (physics, software/computing) and technical coordination. This section provides a brief summary.[7]

There are obvious iterfaces with detector consortia since CISC provides full rack monitoring (rack fans, thermometers and rack protection system), interlock status bit monitoring (not the actual interlock mechanism) and monitoring and control for all power supplies. The CISC consortium must maintain close contacts with all other consortia to ensure that specific hardware choices have acceptable slow controls (SC) solutions. Also, installation of instrumentation devices interferes with other devices and must be coordinated with the respective consortia. On the software side CISC must define, in coordination with other consortia, the quantities to be monitored and controlled by slow controls and the corresponding alarms, archiving and GUIs.

A major interface is the one with the cryogenics system. As mentioned in Section **??** purity monitors and gas analyzers are essential to mitigate the liquid argon contamination risk. The appropriate interlock mechanism to prevent the cryonenics system from irreversible contamination must be designed and implemented.

Another important interface is the one with the HV system [**?**] since several aspects related with safety must be taken into account. For all instrumentation devices inside the cryostat, E field simulations are needed to guaranty proper shielding is in place. Although this is a CISC responsibility, input from HV is crucial. During the deployment of inspection cameras, generation of

[7] [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**], [**?**].

bubbles must be avoided when HV is on, as it can lead to discharges.

There are also interfaces with the PDS [?]. Purity monitors and the light-emitting system for cameras both emit light that might damage PDs. Although this should be understood and quantified, CISC and the SP PDS may have to define the necessary hardware interlocks that avoid turning on any other light source accidentally when PDs are on.

The DAQ-CISC interface [?] is described in Section ??. CISC data is stored both locally (in CISC database servers in the central utility cavern (CUC)) and offline (the databases are replicated back to Fermilab) in a relational database indexed by timestamp. This allows bidirectional communications between DAQ and CISC by reading or inserting data into the database as needed for non-time-critical information.

CISC also interfaces with the beam and cryogenics group since at least the status of these systems must be monitored.

Assuming that the scope of software & computing SWC group includes scientific computing support to project activities, there are substancial interfaces with that group [?]. The hardware interfaces resposibility of the SWC include networking installation and maintenance, maintenance of SC servers and any additional computing hardware needed by instrumentation devices. CISC provides the needed monitoring for power distribution units (PDUs). Regarding software interfaces the SWC group provides: (1) SC database maintenance, (2) API for accessing the SC database offline, (3) UPS packages, local installation and maintenace of software needed by CISC, and (4) SWC creating and maintaining computer accounts on production clusters. Additionally CISC provides the required monitoring and control of SWC quantities including alarms, archiving, and GUIs, where applicable.

CISC has profound hardware interfaces with the not-as-yet formed calibration consortium [?]. Indeed, since CISC and CTF ports are multi-purpose to enable deploying various devices, both systems must interact in terms of flange design and sharing space around the ports. Also, CISC might use calibration ports to extract cables from CISC devices. At the software level, CISC is responsible for calibration device monitoring (and control to the extent needed) and monitors the interlock bit status for laser and radioactive sources.

CISC indirectly interfaces to physics through the CTF devices. One specific need for physics is to extract instrumentation or slow controls data to correlate high-level quantities to low-level or calibration data. This requires tools to extract data from the slow controls database (see CISC-SWC interface document [?]). A brief list of what CISC data is needed by physics is given in the CISC-Physics interface document [?].

Interfaces between CISC and technical coordination are detailed in the corresponding interface documents for the facility [?], installation [?] and integration facility [?].

Interfaces with technical coordination has to be expanded

1.5 Installation, Integration and Commissioning

1.5.1 Cryogenics Internal Piping

The installation of internal cryogenic pipes occurs soon after the cryostat is completed or towards the end of the cryostat completion, depending on how the cryostat work proceeds. A concrete installation plan will be developed by the company designing the internal cryogenics. It depends on how they address the thermal contraction of the long horizontal and vertical runs. We are investigating several options, which each have different installation sequences. All involve delivery and welding together of prefabricated spool pieces inside the cryostat, and vacuum insulation of the vertical lines. The horizontal lines are bare pipes.

The cool-down assemblies are installed in dedicated cool-down feedthroughs at the top, arranged in two rows of ten each in the long direction of the cryostat. Each one features a LAr line connected to a gaseous argon line via a mixing nozzle and a gaseous argon line with spraying nozzles. The mixing nozzles generate droplets of liquid that are circulated uniformly inside the cryostat by the spraying nozzles. They are prefabricated at the vendor's site and delivered as full pieces, then mounted over the feedthroughs.

The current 3D model of the internal cryogenics is developed and archived at CERN as part of the full cryostat model. CERN is currently responsible for the integration of the detector cavern: cryostat, detector, and proximity cryogenics in the detector cavern, including cryogenics on the mezzanine and main LAr circulation pumps.

The prefabricated spool pieces and the cool down nozzles undergo testing at the vendor before delivery. The installed pieces are helium leak-checked before commissioning, but no other integrated testing or commissioning is possible after the installation, because the pipes are open to the cryostat volume. The internal cryogenics are commissioned once the cryostat is closed.

1.5.2 Purity Monitors

The purity monitor system is built in a modular way, such that is can be assembled outside of detector module cryostat. The assembly of the purity monitors themselves occurs outside of the cryostat and includes everything described in the previous section. The installation of the purity monitor system can then be carried out with the least number of steps inside the cryostat. The assembly itself is transported into the cryostat with the three individual purity monitors mounted to the support tubes but before installation of HV cables and optical fibers. The support tube at the top and bottom of the assembly is then mounted to the brackets inside the cryostat that could be attached to the cables trays or the detector support structure.

brackets attached to trays or DSS depending on SP vs DP?

In parallel to this work, the FE electronics and light source can be installed on the top of the cryostat, along with the installation of the electronics and power supplies into the electronics rack.

Integration begins by running the HV cables and optical fibers to the purity monitors, coming from the top of the cryostat. The HV cables are attached to the HV feedthroughs with enough length to reach each of the respective purity monitors. The cables are run through the port reserved for the purity monitor system, along cable trays inside the cryostat until they reach the purity monitor system, and are terminated through the support tube down to each of the purity monitors. Each purity monitor has three HV cables that connect it to the feedthrough, and then along to the FE electronics. The optical fibers are run through the special optical fiber feedthrough, into the cryostat, and guided to the purity monitor system either using the cables trays or guide tubes. Whichever solution is adopted for running the optical fibers from the feedthrough to the purity monitor system, it must protect the fibers from accidental breakage during the remainder of the detector and instrumentation installation process. The optical fibers are then run inside of the purity monitor support tube and to the respective purity monitors, terminating at the photocathode of each.

Integration continues with the connection of the HV cables between the feedthrough and the system FE electronics, and then the optical fibers to the light source. The cables connecting the FE electronics and the light source to the electronics rack are also run and connected at this point. This allows for the system to turn on and the software to begin testing the various components and connections. Once it is confirmed that all connections are successfully made, the integration to the slow controls system is made, first by establishing communications between the two systems and then transferring data between them to ensure successful exchange of important system parameters and measurements.

The purity monitor system is formally commissioned once the cryostat is purged and a gaseous argon atmosphere is present. At this point the HV for the purity monitors is ramped up without the risk of discharge through the air, and the light source is turned on. Although the drift electron lifetime in the gaseous argon is very large and therefore not measurable with the purity monitors themselves, comparing the signal strength at the cathode and anode gives a good indication of how well the light source is generating drift electrons from the photocathode and whether they drift successfully to the anode.

1.5.3 Thermometers

nstal-th

Individual temperature sensors on pipes and cryostat membrane are installed prior to any detector component, right after the installation of the pipes. First, all cable supports are anchored to pipes. Then each cable is routed individually starting from the sensor end (with IDC-4 female connector but no sensor) towards the corresponding cryostat port. Once a port's cables are routed, they are cut to the same length such that they can be properly soldered to the pins of the SUBD-25 connectors on the flange. To avoid damage, the sensors are installed at a later stage, just before unfolding the bottom GPs.

Static T-gradient monitors are installed before the outer APAs, e.g., after the installation of the pipes and before the installation of individual sensors. This proceeds in several steps: (1) installation of the two stainless steel strings to the bottom and top corners of the cryostat, (2) tension and verticality checks, (3) installation of cable supports in one of the strings, (4) installation of sensor supports in the other string, (5) cable routing starting from the sensor end towards the corresponding cryostat port, (6) cutting all cables at the same point in that port, and (7) soldering cable wires to the pins of the SUBD-25 connectors on the flange. Then, at a later stage, just before moving corresponding APA into its final position, (8) the sensors are plugged into IDC-4 connectors.

For the SP, individual sensors on the top GP must be integrated with the GPs. For each CPA (with its corresponding four GP modules) going inside the cryostat, cable and sensor supports are anchored to the GP threaded rods as soon as possible. Once the CPA is moved into its final position and its top FC is ready to be unfolded, sensors on those GPs are installed. Once unfolded, cables exceeding the GP limits can be routed to the corresponding cryostat port either using neighboring GPs or DSS I-beams.

prev pgraph needs work

Dynamic T-gradient monitors are installed after the completion of the detector. The monitor comes in several segments with sensors and cabling already in place. Additional slack is provided at segment joints to ease the installation process. Segments are fed into the flange one at the time. The segments being fed into the detector module are held at the top with a pin that prevents the segment from sliding in all the way. Then the next segment is connected. The pin is removed, and the segment is pushed down until the next segment top is held with the pin at the flange. Then this next segment is installed. The process continues until the entire monitor is in its place inside the cryostat. Use of a crane is foreseen to facilitate the process. Extra cable slack at the top is provided again in order to ease the connection to the D-Sub standard connector flange and to allow vertical movement of the entire system. Then, a four-way cross with flange electric feedthroughs on one side and a window on the other side.

window, I presume? Also, sentence missing verb

The wires are connected to the D-sub connector on the electric flange feedthrough on the side. On the top of the cross, a moving mechanism is then installed with a crane. The pinion is connected to the top segment. The moving mechanism will come reassembled with motor on the side in place and pinion and gear motion mechanism in place as well. The moving mechanism enclosure is then connected to top part of the cross and this completes the installation process of the dynamic T-gradient monitor.

prev pgraph needs work

Commissioning of all thermometers proceeds in several steps. Since in a first stage only cables are installed, the readout performance and the noise level inside the cryostat are tested with precision resistors. Once sensors are installed the entire chain is checked again at room temperature. The final commissioning phase occurs during and after cryostat filling.

1.5.4 Gas Analyzers

Prior to the piston purge and gas recirculation phases of the cryostat commissioning, the gas analyzers are installed near the tubing switchyard. This minimizes tubing runs and is convenient for switching the sampling points and gas analyzers. Since each is a standalone module, a single rack with shelves, should be adequate to house the modules.

Concerning the integration, the gas analyzers typically have an analog output (4 to 20 mA or 0 to 10V) that maps to the input range of the analyzers. They also usually have a number of relays that indicate the scale they are currently running. These outputs can be connected to the slow controls for readout. However, using a digital readout is preferred since this directly gives the analyzer reading at any scale. Currently there are a number of digital output connections, ranging from RS-232, RS-485, USB, and Ethernet. At the time of purchase, one can choose the preferred option, since the protocol is likely to evolve. The readout usually responds to a simple set of text commands. Due to the natural time scales of the gas analyzers, and lags in the gas delivery times (depending on the length of the tubing runs), sampling at the minute level most likely is adequate.

"sampling on timescales of a minute..." otherwise 'minute' may strike reader as pronounced "minoot"

Before the beginning of the gas phase of the cryostat commissioning, the analyzers must be brought online and calibrated. Calibration varies for the different modules, but often requires using argon gas with both zero contaminants (usually removed with a local inline filter) for the zero of the analyzer, and argon with a known level of the contaminant to check the scale. Since the start of the gas phase begins with normal air, the more sensitive analyzers are valved off at the switchyard to prevent overloading their inputs and potentially saturating their detectors. As the argon purge and gas recirculation progress, the various analyzers are valved back in when the contaminant levels reach the upper limits of the analyzer ranges.

1.5.5 Liquid Level Monitoring

Multiple differential pressure level monitors are installed in the cryostat, connected both to the side penetration of the cryostat at the bottom and to dedicated instrumentation ports at the top.

The capacitance level sensors are installed at the top of the cryostat in coordination with the TPC installation. Their placement relative to the upper ground plane (single phase) or CRP (dual phase) is important as these sensors will be used for a hardware interlock on the HV, and, in the case of the DP module, to measure the LAr level at the millimeter level as required for DP operation. Post installation in situ testing of the capacitive level sensors can be accomplished with a small dewar of liquid.

1.5.6 Cameras and Light-Emitting System

Fixed camera installation is in principle simple, but involves a considerable number of interfaces. Each camera enclosure has threaded holes to allow bolting it to a bracket. A mechanical interface is required with the cryostat wall, cryogenic internal piping, or DSS. Each enclosure is attached to a gas line for maintaining appropriate underpressure in the fill gas; this is an interface with cryogenic internal piping. Each camera has a cable for the video signal (coax or optical), and a multiconductor cable for power and control, to be run through cable trays to flanges on assigned instrumentation feedthroughs.

The inspection camera is designed to be inserted and removed on any instrumentation feedthrough equipped with a gate valve at any time during operation. Installation of the gate valves and purge system for instrumentation feedthroughs falls under cryogenic internal piping.

Installation of fixed lighting sources separate from the cameras would require similar interfaces as fixed cameras. However, the current design has lights integrated with the cameras, which do not require separate installation.

1.5.7 Slow Controls Hardware

Slow controls hardware installation includes installing multiple servers, network cables, any specialized cables needed for device communication, and possibly some custom-built rack monitoring hardware. The installation sequence is interfaced and planned with the facilities group and other consortia. The network cables and rack monitoring hardware are common across many racks and are installed first as part of the basic rack installation, led by the facilities group. The installation of specialized cables needed for slow controls and servers is done after the common rack hardware is installed, and will be coordinated with other consortia and the DAQ group respectively.

1.5.8 Transport, Handling and Storage

Most instrumentation devices are shipped to SURF in pieces and mounted in situ. Instrumentation devices are in general small except the support structures for purity monitors and T-gradient monitors, which will cover the entire height of the cryostat. Since the load on those structures is relatively small (< 100 kg) they can be fabricated in parts of less than 3 m, which can be easily transported to SURF. These parts are also easy to transport down the shaft and through the tunnels. All instrumentation devices except the dynamic T-gradient monitors, which are introduced into the cryostat through a dedicated cryostat port,

above something?

can be moved into the cryostat without the crane.

Cryogenic internal piping needs special treatment given the number of pipes and their lengths. Purging and filling pipes will be most likely pre-assembled by the manufacturer as much as possible, using the largest size that can be shipped and transported down the shaft. Assuming 6 m long sections, pipes could be grouped in bunches of 10 to 15 pipes and stored in five pallets or boxes of about 6.2 m × 0.8 m × 0.5 m. These would be delivered to the site, stored, transported down to the detector cavern, and stored again before they are used. Depending on when they are installed, they could be stored inside the cryostat itself or in one of the drifts. Cool-down pipes are easier to handle. They could be transported in 20 boxes of 2.2 m × 0.6 m × 0.6 m, although there is room for saving some space using a different packaging scheme. Once in the cavern they could be stored on top of the cryostat.

1.6 Quality Control

-cryo-qc

The purpose of quality control (QC) is to ensure that the equipment is capable of performing its intended function. The QC includes post-fabrication tests and also tests to run after shipping and installation. A series of tests should be done by the manufacturer and the institute in charge of the device assembly. In case of a complex system, the whole system performance will be tested before shipping. Additional QC procedures can be performed at the integration and test facility (ITF) and underground after installation if possible. The planned tests for each subsystem are described below.

the organization of prev pgraph is confusing

1.6.1 Purity Monitors

yo-qc-pm

The purity monitor system undergoes a series of tests to ensure the performance of the system. This starts with testing the individual purity monitors in vacuum after each one is fabricated and assembled. This test looks at the amplitude of the signal generated by the drift electrons at the cathode and the anode. This ensures that the photocathode is able to provide a sufficient number of photoelectrons for the measurement with the required precision, and that the field gradient resistors are all working properly to maintain the drift field and hence transport the drift electrons to the anode. A follow-up test in LAr is then performed for each individual purity monitor, ensuring that the performance expected in LAr is met.

The next step is to assemble the entire system and make checks of the connections along the way. Ensuring that the connections are all proper during this time reduces the risk of having issues once the system is finally assembled and ready for the final test. The assembled system is placed into the shipping tube, which serves as a vacuum chamber, and tested. Next, assuming an adequate LAr test facility is available, a test at LAr temperature is made to ensure the required performance.

and what if no LAr facility exists there? Orig sentence: If there is a LAr test facility with the height or length required for the full purity monitor system and it is available for use, then a final full system test would be made there ensuring that the full system operates in LAr and achieves the required performance.

1.6.2 Thermometers

1.6.2.1 Static T-Gradient Thermometers

Three type of tests are carried out at the production site prior to installation. First, the mechanical rigidity of the system is tested such that swinging is minimized (< 5 cm) to reduce the risk of touching the APAs. This is done with a 15 m stainless steel string, strung horizontal anchored to two points; its tension is controlled and measured. Second, all sensors are calibrated in the lab, as explained in Section **??**. The main concern is the reproducibility of the results since sensors could potentially change their resistance (and hence their temperature scale) when undergoing successive immersions in LAr. In this case the QC is given by the calibration procedure itself since five independent measurements are planned for each set of sensors. Sensors with reproducibility (based on the RMS of those five measurements) beyond the requirements (2 mK for ProtoDUNE-SP) are discarded. The calibration serves as QC for the readout system (similar to the final one) and of the PCB-sensor-connector assembly. Finally, the cable-connector assemblies are tested: sensors must measure the expected values with no additional noise introduced by the cable or connector.

If the available LAr test facility has sufficient height or length to test a good portion of the system, an integrated system test is conducted there ensuring that the system operates in LAr and achieves the required performance. Ideally, the laboratory sensor calibration will be compared with the in situ calibration of the dynamic T-gradient monitors by operating both dynamic and static T-gradient monitors simultaneously.

The last phase of QC takes place after installation. The verticality of each array is checked and the tensions in the horizontal strings are adjusted as necessary. Before soldering the wires to the flange, the entire readout chain is tested with temporary SUBD-25 connectors. This allows testing the sensor-connector assembly, the cable-connector assembly and the noise level inside the cryostat. If any of the sensors gives a problem, it is replaced. If the problem persists, the cable is checked and replaced if needed.

1.6.2.2 Dynamic T-Gradient Thermometers

The dynamic T-gradient monitor consists of an array of high-precision temperature sensors mounted on a vertical rod. The rod can move vertically in order to perform cross-calibration of the temperature sensors in situ. Several tests are foreseen to ensure that the dynamic T-gradient monitor delivers vertical temperature gradient measurements with precision at the level of a few mK.

- Before installation, temperature sensors are tested in LN to verify correct operation and to set the baseline calibration for each sensor with respect to the absolutely caibrated reference sensor.
- Warm and cold temperature readings are taken with each sensor after mounting on the PCB board and soldering the readout cables.
- The sensor readout is taken for all sensors after the cold cables are connected to electric feedthroughs on the flange and the warm cables outside of the cryostat are connected to the temperature readout system.
- The stepper motor is tested before and after connecting to the gear and pinion system.
- The fully assembled rod is connected to the pinion and gear, and moved with the stepper motor on a high platform many times to verify repeatability, possible offsets and uncertainty in the positioning. Finally, by repeating the test a large number of times, the sturdiness of the system will be verified.
- The full system is tested after installation in the cryostat: both motion and sensor operation are tested by checking sensor readout and vertical motion of the system.

1.6.2.3 Individual Sensors

yo-qc-is

The method to address the quality of individual precision sensors is the same as for the static T-gradient monitors. The QC of the sensors is part of the laboratory calibration. After mounting six sensors with their corresponding cables, a temporary SUBD-25 connector will be added and the six sensors tested at room temperature. All sensors should work and give values within specifications. If any of the sensors gives problems, it is replaced. If the problem persists the cable is checked and replaced if needed.

1.6.3 Gas Analyzers

yo-qc-ga

The gas analyzers will be guaranteed by the manufacturer. However, once received, the gas analyzer modules are checked for both *zero* and the *span* values using a gas-mixing instrument. This is done using two gas cylinders with both a zero level of the gas analyzer contaminant species and a cylinder with a known percentage of the contaminant gas. This should verify the proper operation of the gas analyzers. When eventually installed at SURF, this process is repeated before the commissioning of the cryostat. It is also important to repeat the calibrations at the manufacturer-recommended periods over the gas analyzer lifetime.

1.6.4 Liquid Level Monitoring

The pressure sensors will be purchased requiring a QC by the manufacturer. While the capacitive and thermal sensors can be tested with a modest sample of LAr in the lab, the pressure sensors require testing over a greater range. They do not necessarily need to be tested in LAr over the whole range, lab tests can be done in LAr over a range of a meter or two to ensure operation at cryogenic temperatures. Depth tests can be accomplished with a pressurization chamber with water.

1.6.5 Cameras

Before transport to SURF, each cryogenic camera unit (comprising the enclosure, camera, and internal thermal control and monitoring) is checked for correct operation of all operating features, for recovery from 87 K non-operating mode, for no leakage, and for physical defects. Lighting systems are similarly checked for operation. Operations tests will include verification of correct current draw, image quality, and temperature readback and control. The movable inspection camera apparatus is inspected for physical defects, and checked for proper mechanical operation before shipping. A checklist is completed for each unit, filed electronically in the DUNE logbook, and a hard copy sent with each unit.

Before installation, each fixed cryogenic camera unit is inspected for physical damage or defects and checked in the CTF for correct operation of all operating features, for recovery from 87 K non-operating mode, and for no contamination of the LAr. Lighting systems are similarly checked for operation. Operations tests include correct current draw, image quality, and temperature readback and control. After installation and connection of wiring, fixed cameras and lighting are again checked for operation. The movable inspection camera apparatus is inspected for physical defects and, after integration with a camera unit, tested in CTF for proper mechanical and electronic operation and cleanliness, before installation or storage. A checklist is completed for each QC check and filed electronically in the DUNE logbook.

1.6.6 Light-emitting System

The complete system is checked before installation to ensure the functionality of the light emission.

to ensure it meets requirements?

Initial testing of the light-emitting system (see Figure **??**) is done by first measuring the current when a low voltage (1 V) is applied, to check that the resistive LED failover path is correct. Next, measurement of the forward voltage is done with the nominal forward current applied, to check that it is within 10 % of the nominal forward voltage drop of the LEDs, that all of the LEDs are illuminated, and that each of the LEDs is visible over the nominal angular range. If the LEDs are infrared, a video camera with IR filter removed is used for the visual check. This procedure is then duplicated with the current reversed for the LEDs oriented in the opposite direction.

These tests are duplicated during installation to make sure that the system has not been damaged in transportation or installation. However, once the LEDs are in the cryostat a visual check could be difficult or impossible.

1.6.7 Slow Controls Hardware

Networking and computing systems will be purchased commercially, requiring quality assurance (QA). However, the new servers are tested after delivery to confirm no damage during shipping. The new system is allowed to *burn in* overnight or for a few days, running a diagnostics suite on a loop. This should turn up anything that escaped the manufacturer's QA process.

The system can be shipped directly to the underground,

maybe "once the system arrives on-site, it can be transported down to the 4850L"

where an on-site expert peforms the initial booting of systems and basic configuration. Then the specific configuration information is pulled over the network, after which others may log in remotely to do the final setup, minimizing the number of people underground.

1.7 Safety

Several aspects related to safety must be taken into account for the different phases of the CISC project, including R&D, laboratory calibration and testing, mounting tests and installation. The initial safety planning for all phases is reviewed and approved by safety experts as part of the initial design review, and always prior to implementation. All component cleaning, assembly, testing and installation procedure documentation includes a section on safety concerns relevant to that procedure, and is reviewed during the appropriate pre-production reviews.

Areas of particular importance to CISC include:

- Hazardous chemicals (e.g., epoxy compounds used to attach sensors to cryostat inner membrane) and cleaning compounds: All chemicals used are documented at the consortium management level, with an MSDS (Material safety data sheet) and approved handling and disposal plans in place.
- Liquid and gaseous cryogens used in calibration and testing: LN and LAr are used for calibration and testing of most of the instrumentation devices. Full hazard analysis plans will be in place

are being developed?

at the consortium management level for all module or module component testing involving cryogenic hazards, and these safety plans will be reviewed in the appropriate pre-production and production reviews

- HV safety: Purity monitors have a voltage of ∼2000 V. Fabrication and testing plans will demonstrate compliance with local HV safety requirements at the particular institution or lab where the testing or operation is performed, and this compliance will be reviewed as part of the standard review process.

- Working at heights: Some aspects of the fabrication, testing and installation of CISC devices require working at heights. This is the case of T-gradient monitors and purity monitors, which are quite long. Temperature sensors installed near the top cryostat membrane and cable routing for all instrumentation devices require working at heights as well. The appropriate safety procedures including lift and harness training will be designed and reviewed.

- Falling objects: all work at height comes with associated risks of falling objects. The corresponding safety procedures, including the proper helmet ussage and the observation of well delimited safety areas, will be included in the safety plan.

1.8 Organization and Management

1.8.1 Slow Controls and Cryogenics Instrumentation Consortium Organization

The organization of the CISC consortium is shown in Figure **??**. The CISC consortium board is currently formed from institutional representatives from 17 institutes as shown in Table **??**. The consortium leader acts as the spokesperson for the consortium and is responsible for the overall scientific program and management of the group. The technical leader of the consortium is responsible for the project management for the group. Currently five working groups are envisioned in the consortium (leaders to be appointed):

Cryogenics Systems gas analyzers, liquid level monitors and cryogenic internal piping; CFD simulations

LAr Instrumentation purity monitors, thermometers, cameras and lightemitting system, and instrumentation test facility; feedthroughs; E field simulations; instrumentation precision studies; ProtoDUNE data analysis coordination efforts

Slow Controls Base Software and Databases Base software, alarms and archiving databases, and monitoring tools; variable naming convention and slow controls quantities

Slow Controls Detector System Interfaces Signal processing software and hardware interfaces (e.g., power supplies); firmware; rack hardware and infrastructure

Slow Controls External Interfaces Interfaces with external detector systems (e.g., cryogenics system, beam, facilities, DAQ)

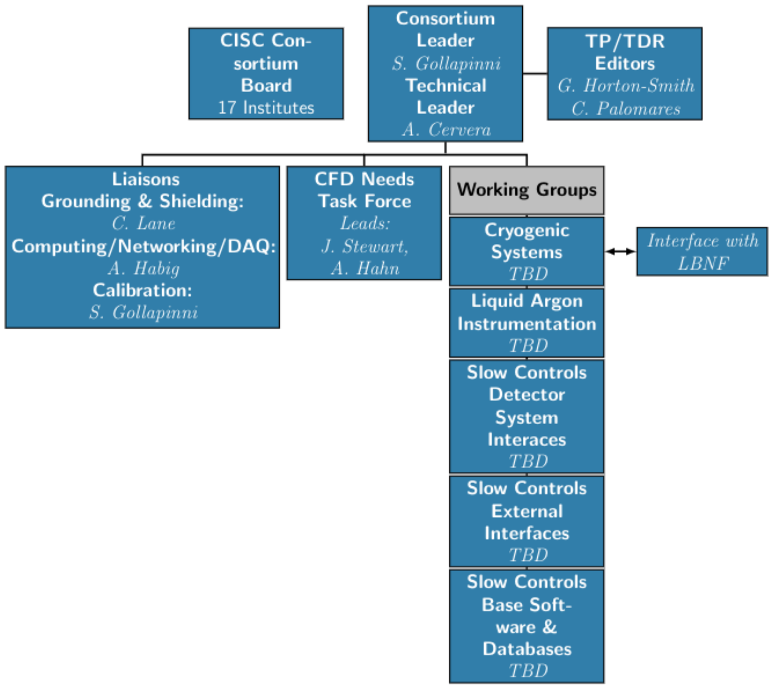

Figure 1.23: CISC consortium organizational chart

Additionally, since the CISC consortium broadly interfaces with other groups, liaisons have been identified for various roles as listed in Figure **??**. A short-term focus group was recently formed to understand the needs for cryogenics modeling for the consortium. Currently members from new institutes are added to the consortium based on consensus from the consortium board members.

1.8.2 Planning Assumptions

The slow controls and cryogenic instrumentation is a joint effort for SP and DP. A single slow controls system will be implemented to serve both SP and DP.

Design and installation of cryogenics systems (gas analyzers, liquid level monitoring, internal piping) is coordinated with LBNF, with the consortium providing resources, and effort and expertise provided by LBNF. ProtoDUNE designs for LAr instrumentation (purity monitors, thermometers, cameras, test facility) provide the basis for DUNE designs. Design validation, testing, calibration, and performance will be evaluated through ProtoDUNE data.

Table 1.5: Current CISC Consortium Board Members and their institutional affiliations

Member Institute	Country	Consortium Board Representative
CIEMAT	Spain	Ines Gil Botella
Instituto de Fisica Corpuscular	Spain	Anselmo Cervera
University of Warwick	United Kingdom	Gary Barker
University College London	United Kingdom	Mario Campanelli
Argonne National Lab	USA	Jim Grudzinski
Brookhaven National Lab	USA	Jim Stewart
University of California (Irvine)	USA	Jianming Bian
Drexel University	USA	Charles Lane
Fermi National Accelerator Lab	USA	Alan Hahn
University of Hawaii	USA	Jelena Maricic
University of Houston	USA	Andrew Renshaw
Idaho State University	USA	Ed Tatar
Kansas State University	USA	Glenn Horton-Smith
University of Minnesota (Duluth)	USA	Alec Habig
Notre Dame University	USA	John LoSecco
University of Tennessee at Knoxville	USA	Sowjanya Gollapinni
Virginia Tech	USA	Camillo Mariani

cryo-org

1.8.3 High-level Schedule

Table ?? shows key milestones on the path to commissioning of the first two DUNE detector modules.

Table 1.6: Key CISC milestones leading towards commissioning of the first two DUNE detector modules.

Date	Milestone
Aug. 2018	Validate instrumentation designs using data from ProtoDUNE
Jan. 2019	Complete architectural design for slow controls ready
Feb. 2019	Full final designs of all cryogenic instrumentation devices ready
Feb. 2023	Installation of Cryogenic Internal Piping for Cryostat 1
Apr. 2023	Installation of support structure for all instrumentation devices for Cryostat 1
Oct. 2023	All Instrumentation devices installed in Cryostat 1
Feb. 2024	All Slow Controls hardware and infrastructure installed for Cryostat 1
May 2024	Installation of Cryogenic Internal Piping for Cryostat 2
July 2024	Installation of support structure for all instrumentation devices for Cryostat 2
Jan. 2025	All Instrumentation devices installed in Cryostat 2
Apr. 2025	All Slow Controls hardware and infrastructure installed for Cryostat 2
July 2025	Full Slow controls systems commissioned and integrated into remote operations