

Status of the LBNF Cryogenic System

D Montanari¹, M Adamowski¹, J Bremer², M Delaney¹, A Diaz², R Doubnik¹, K Haaf¹, S Hentschel¹, B Norris¹, E Voirin¹

¹ Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510 USA

² CERN, 1211 Geneva-23, Switzerland

dmontana@fnal.gov

Abstract. The Sanford Underground Research Facility (SURF) will host the Deep Underground Neutrino Experiment (DUNE), an international multi-kiloton Long-Baseline neutrino experiment that will be installed about a mile underground in Lead, SD. In the current configuration four cryostats will contain a modular detector and a total of 68,400 tons of ultrapure liquid argon, with a level of impurities lower than 100 parts per trillion of oxygen equivalent contamination. The Long-Baseline Neutrino Facility (LBNF) provides the conventional facilities and the cryogenic infrastructure to support DUNE. The system is comprised of three sub-systems: External/Infrastructure, Proximity and Internal cryogenics. An international engineering team will design, manufacture, commission, and qualify the LBNF cryogenic system. This contribution presents the modes of operations, layout and main features of the LBNF cryogenic system. The expected performance, the functional requirements and the status of the design are also highlighted.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) collaboration and the Long-Baseline Neutrino Facility (LBNF) are developing the detectors and infrastructure for a multi-kiloton Long-Baseline neutrino experiment to be located at the Sanford Underground Research Facility (SURF) in Lead, SD. The detectors, Time Projection Chambers (TPC), will be located about one mile underground inside large cryostats, filled with a total of 68,400 tons of ultrapure liquid argon, with the level of impurities lower than 100 parts per trillion (ppt) of oxygen equivalent contamination [1, 2]. The LBNF provides the conventional facilities and the cryogenic infrastructure to support DUNE. After commissioning, the DUNE detectors will detect neutrinos from a new improved beamline from Fermilab, and enable their study.

The LBNF/DUNE installation includes four cryostats and the associated cryogenic systems necessary to receive, transfer, store, and purify the large quantity of liquid argon (LAr) required by the experiment, as well as the liquid nitrogen (LN₂) refrigeration system needed to re-condense the boil-off gaseous argon (GAr) and the system to cool down the cryostat and the detectors [3]. Each cryostat measures 62.0 m in length, 15.1 m in width, 14.0 m in height (internal dimensions) and is passively insulated with 0.8 m of polyurethane foam. A steel support structure, consisting of a 0.012 m thick stainless-steel plate and I-beams of different dimensions (the highest being 1.1 m), surrounds the insulation and bears the load of the liquid and gaseous argon as well as the weight of the insulation.

To qualify the technologies for the cryogenic system, the cryostats, and the detectors, a strong prototyping effort is ongoing [4]. Two detector technologies are being developed: Single Phase (SP), with the detector fully submerged in liquid argon, and Dual Phase (DP), with part of the detector in the

gas phase as well. Two prototypes are already operational, the 35-ton at Fermilab [5] and the WA105 1x1x3 at CERN. Several other detectors of increasing size with associated cryostats and cryogenics systems are being designed and constructed with the goal of being in operations within 1-2 years. Two of them are part of the Short Baseline Neutrino (SBN) program at Fermilab: the SBN Near Detector (SBND) and Far Detector (SBN-FD) [6]. The other two are part of the DUNE prototyping program at CERN: ProtoDUNE-SP and ProtoDUNE-DP. Table 1 shows a summary of the main features of these prototypes.

Table 1. Summary of the main features of the prototypes.

Design Parameter	35-ton ^a	WA 105 1x1x3 ^a	SBND	SBN-FD ^b	ProtoDUNE- SP	ProtoDUNE- DP
Detector technology	SP	DP	SP	SP	SP	DP
Cryostat type	Membrane cryostat	Membrane cryostat	Membrane cryostat	Aluminum extruded	Membrane cryostat	Membrane cryostat
Inner dimensions of cryostat	4.8 m (L)	4.8 m (L)	7.0 m (L)	19.6 m (L)	8.5 m (L)	8.5 m (L)
	2.7 m (W)	2.4 m (W)	5.2 m (W)	3.6 m (W)	8.5 m (W)	8.5 m (W)
	2.7 m (H)	2.0 m (H)	5.4 m (H)	3.9 m (H)	7.9 m (H)	7.9 m (H)
Depth of LAr	2.5 m	1.6 m	5.2 m	3.8 m	7.5 m	7.0 m
LAr Total Mass	35,000 kg	25,600 kg	270,000 kg	2x380,000 kg	764,000 kg	712,000 kg
Insulation thickness	0.4 m	1.0 m	0.6 m	0.6 m	0.8 m	0.8 m
Operating pressure	70 mBarg	50 mBarg	70 mBarg	150 mBarg	70 mBarg	50 mBarg
Design pressure	350 mBarg	160 mBarg	345 mBarg	345 mBarg	350 mBarg	350 mBarg

^a Already in operation.

^b Consists of two twin cryostats side by side. Values listed are per cryostat, except the total LAr mass.

2. Description of the LBNF cryogenic system

The LBND cryogenic system is comprised of three sub-systems: External/Infrastructure, Proximity and Internal cryogenics [3].

The External/Infrastructure cryogenics consists of the infrastructure and equipment to store, produce and distribute the cryogenics fluids needed for the operation of the Proximity Cryogenics. It includes the receiving facilities for the liquid nitrogen and argon on the surface, the piping connecting the surface to the underground campus, valves and instrumentation, and the liquid nitrogen refrigeration system.

The Proximity cryogenics consists of all the systems that take the cryogenic fluids from the External/Infrastructure cryogenics and deliver them to the Internal at the pressure, temperature, mass flow rate, quality and purity required by the detector inside the cryostat. It includes the argon purification systems for liquid and gas phase, the phase separators for liquid nitrogen and argon, the argon condensers, the piping connecting the various parts, valves and instrumentation.

The Internal cryogenics consists of all the cryogenic equipment located inside the cryostat. It includes the distribution systems for the liquid and gaseous argon, the systems to cool down the cryostats and the detectors, and all the piping that connect the proximity cryogenics to the inside of the cryostat.

2.1. Modes of operations

The cryogenic system must fulfill the following modes of operations:

- **Gaseous argon purge.** This is the initial phase to remove the contaminants from the cryostat, which at the beginning is filled with air. A slow gaseous argon flow pushes the impurities from the cryostats bottom to the top and out. The argon is flowing in open loop and vented, pushing out the air initially contained inside the cryostat. Contaminants, primarily oxygen, water and nitrogen, are reduced to the parts per million (ppm) level prior to the next phase.

- **Gaseous argon circulation.** The argon is now circulated in closed loop and through a dedicated gas purification system before being re-injected at the bottom of the tanks. When the contaminants are reduced to sub-ppm the cool-down can commence.
- **Cool-down.** Purified liquid argon is mixed with gaseous argon and distributed through dedicated sprayers near the roof of the cryostat to slowly cool down the cryostat and the detector to their operating temperature in a controlled way. Additional sprayers circulate the mist of liquid and gas inside to ensure a uniform process. The cooling power is provided by the vaporization of liquid nitrogen inside the condensers.
- **Filling.** Gaseous argon is transferred from the receiving facilities and recondensed underground. Once the cryostat and TPCs are cold, liquid argon flows from the condensers into each cryostat filling it with 17,100 tons of purified liquid argon. The duration varies between 5 and 10 months depending on the available cooling power for each cryostat.
- **Steady state operations.** The liquid argon contained inside each cryostat is continuously circulated through the liquid purification system by means of external pumps. Once the purity is achieved the circulation rate is reduced to maintain the required purity, reducing the heat load. At the same time the boil-off gaseous argon is re-condensed in condensers located outside the cryostat and purified as liquid in the same purification system before being reintroduced in the cryostat.
- **Emptying.** This is the final phase, following the completion of the experiment. The cryostat is emptied and the liquid argon removed from the system.

2.2. Relevant design parameters

Table 2 shows some of the design parameters for the LBNF cryogenic system. The flow rate of the gaseous argon during the purge is calculated to avoid back diffusion of oxygen (main contaminant of the air that initially fills the cryostat) in argon, and the capability of the two to mix. The chosen linear speed of 1.2 m/hr is higher than the back-diffusion rate and has been experimentally verified in the Liquid Argon Purity Demonstrator (LAPD) [7], the 35-ton prototype [5] and MicroBooNE [8].

The maximum cool-down rate of the detector and the maximum temperature differential between any two points in the detector are needed to ensure mechanical stability of the TPCs during cool-down and steady state operations.

The maximum available cooling power is the sum of the estimated heat loads during peak operations and some operational margin [9].

During steady state operations, the detector needs to be able to drift electrons with a lifetime greater than 3 milliseconds (ms). Equation (1) shows the empirical correlation between electron lifetime and oxygen equivalent contamination in liquid argon [10].

$$Lifetime[s] = \frac{3 \cdot 10^{-13} [s \cdot \text{parts of Oxygen}]}{\text{Contaminant} [\text{parts of Oxygen}]} \quad (1)$$

Table 2. Selection of design parameters.

Design Parameter	Value (per cryostat)
Gaseous argon flow rate during piston purge	254 m ³ /hr
Maximum cool-down rate of the detector	40 K/hr
Maximum temperature differential between any two points in the detector	50 K
Maximum available cooling power	100
Required electron lifetime	> 3 ms
Corresponding required liquid argon purity (oxygen equivalent contamination)	< 100 ppt
Maximum liquid argon turnover (5 days/volume change)	36.12 kg/s
Cryostat operating pressure	130 mBarg
Cryostat design pressure	350 mBarg

2.3. Process flow diagram

Figure 1 shows the Process Flow Diagram (PFD) of the system being developed to satisfy the modes of operations and design requirements [3, 9]. The scope and location of each sub-system is shown, as well as the boundaries between sub-systems. There are four main areas and the drifts interconnecting the underground locations:

- **Surface.** It is above ground and includes the cryogenics receiving facilities and the gaseous nitrogen compressors of the liquid nitrogen refrigeration system.
- **Detector cavern.** It is underground and includes the cryostat and the Proximity cryogenics in the detector cavern (condensers, phase separators, liquid argon circulation pumps).
- **Central Utility Cavern (CUC).** It is underground and includes the cold boxes and expanders of the liquid nitrogen refrigeration system, the liquid and gaseous argon purification systems and associated equipment, including particulate filters and regeneration systems.
- **Ross shaft.** It connects the above ground area to the underground one and includes the pipes to transfer the gaseous argon and nitrogen from the surface to underground.
- **Underground drifts.** They connect the underground areas and include interconnecting piping to transfer liquid and gaseous argon and nitrogen.

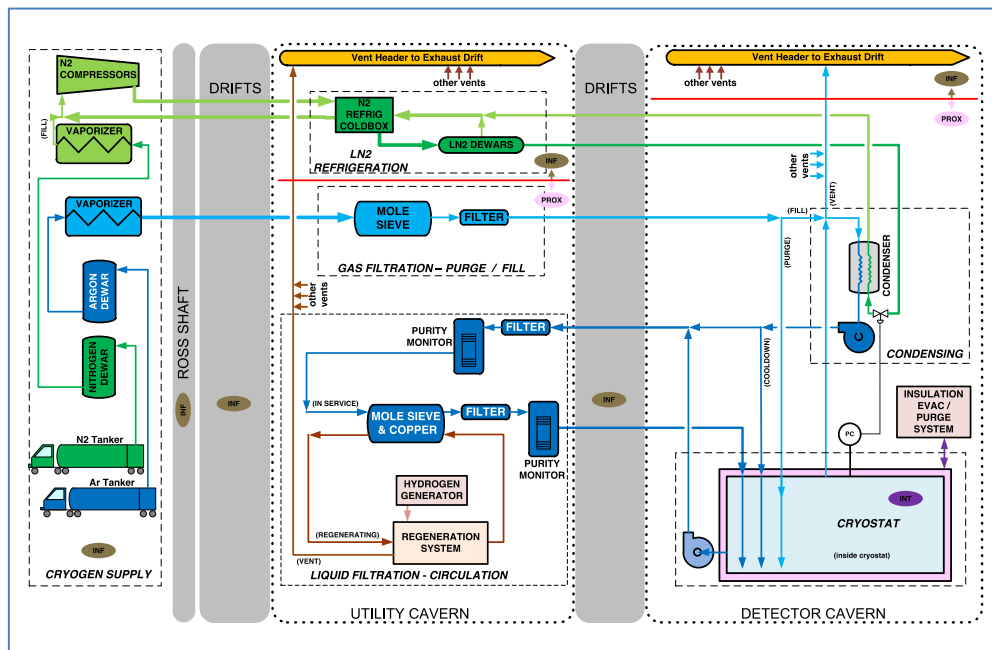


Figure 1. Process Flow Diagram.

2.4. External/Infrastructure cryogenics

The External/Infrastructure cryogenics is common to all four cryostats. The main components are the cryogenics receiving facilities on the surface, the piping connecting them to the underground campus, and the liquid nitrogen refrigeration system.

2.4.1. Cryogenics receiving facilities. The cryogenics receiving facilities are located on the surface, nearby the Ross shaft. They consist of the offloading facilities for liquid argon and liquid nitrogen, storage tanks, vaporizers, interconnecting piping, valves and instrumentation to sample the liquid argon before offloading it and before transferring it underground.

2.4.2. Argon and nitrogen transfer lines. The cryogenics are vaporized on the surface and transferred underground in the gas phase via piping in the Ross shaft, for safety and economic reasons. Figure 2

shows the pipes: two 16-inch low pressure and two 8-inch high pressure nitrogen pipes, and one 8-inch argon pipe [9].

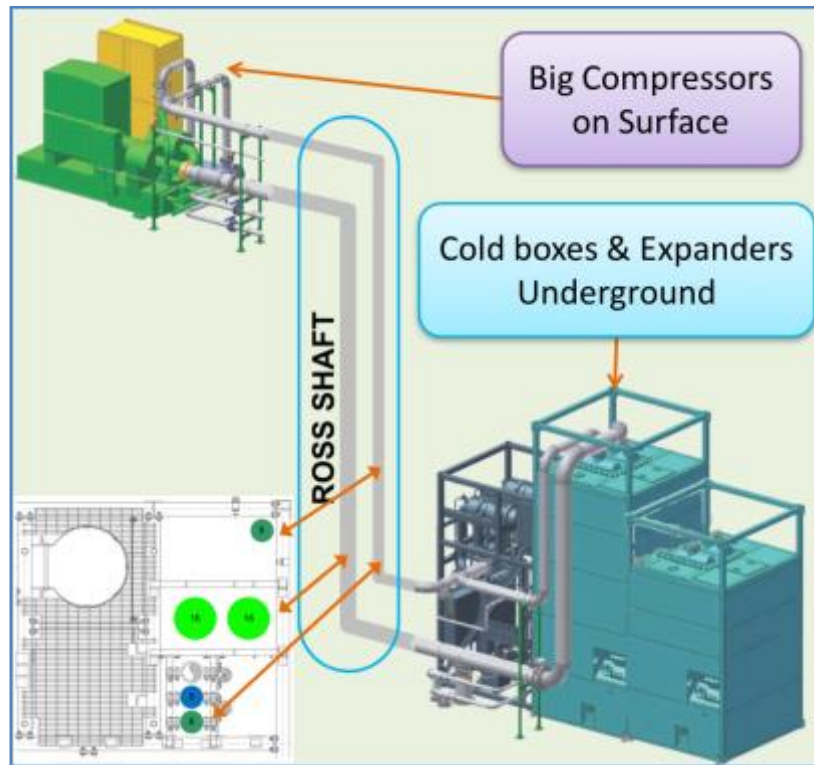


Figure 2. General layout of the liquid nitrogen refrigeration system: argon pipe in blue; low-pressure nitrogen in light green; high-pressure nitrogen in dark green.

2.4.3. Liquid nitrogen refrigeration system. The liquid nitrogen refrigeration system consists of four commercial units with cold boxes and return gas boosters (needed to overcome the ~ 1.5 km vertical drop) in the CUC and gaseous nitrogen compressors above ground, in the compressors building, near the Ross shaft. There currently are three units for cryostats 1 and 2 and a fourth unit is added for cryostats 3 and 4. During the cool-down of each cryostat, all available units are used to minimize the duration of the process. During normal operations, each cryostat uses a dedicated refrigeration unit, operating at a reduced load. After achieving the required argon purity, only three units are needed to re-condense the boil-off argon of four cryostats. A full unit is available as spare or is being serviced. This is because the number of liquid argon circulation pumps is reduced once the argon is pure to maintain purity. Each refrigeration unit has a nominal cooling power of 100 kW, enough to condense the gaseous argon during the cool-down and fill processes and to re-condense the boil-off argon during steady state operations [9]. Figure 2 shows the general layout of the system with actual-size components from one potential vendor. It fits within the available space and respects the modularity needed for the transportation in the shaft.

2.5. Proximity cryogenics

Each cryostat has its own dedicated Proximity cryogenics. The main components are in the CUC and in the detector cavern.

2.5.1. Proximity cryogenics in CUC. The Proximity cryogenics in the CUC consists of the argon purification system, which is composed of liquid and gaseous filters, their regeneration equipment,

particulate filters, interconnecting piping, valves and instrumentation. The argon purification filters contain mol sieve and copper pellets to respectively remove water and oxygen from gaseous and liquid argon. Currently, each cryostat has a dedicated set of liquid filters, regeneration equipment and particulate filters, while the gaseous argon filters are common for cryostats 1-2 and 3-4, since they are needed only during the argon purge phase. The liquid filters are used during the filling and steady state operations to achieve and maintain the required purity of 100 ppt. All filters are sized to accept and purify argon with the following initial contaminants: 5 ppm oxygen and 10 ppm water. The nitrogen content, 10 ppm, is not actively filtered. To guarantee continuous operations, each cryostat has one set of liquid filters in operation and another set in regeneration. Once the first set saturates, it is regenerated and the regenerated set is put in operation. The regeneration is done with a hot (200-220 Celsius) mix of few percentages hydrogen in argon. Figure 3 shows the current layout of the central utility cavern, with the Proximity cryogenics in the CUC on the left side and the cold boxes and booster compressors of the liquid nitrogen refrigeration system on the right. Also visible are the liquid nitrogen storage dewars that are connected to the refrigeration system to provide a buffer of about 40 hours of uninterrupted cooling capacity in case of a power outage.

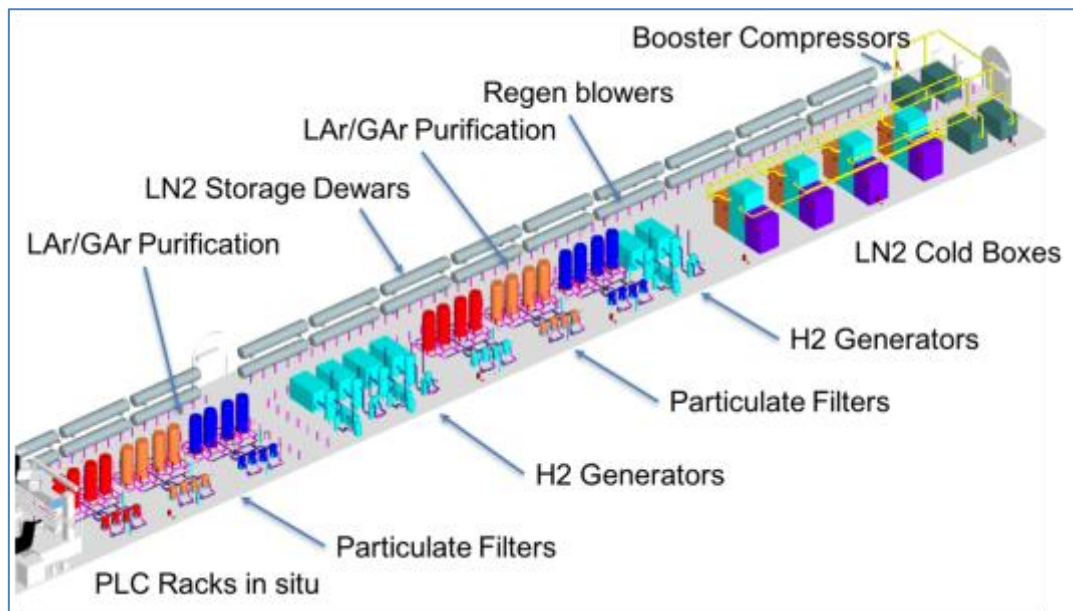


Figure 3. Current layout of the cryogenics in the CUC.

2.5.2. Proximity cryogenics in detector cavern. Each cryostat is equipped with a mezzanine level about 2.3 m over its roof. It measures 35.0 m in length and 12.0 m in width spanning more than half the length and half the width of the cryostat. All the equipment that connect to the cryostat top is located here. The purified liquid argon from the CUC is returned to the cryostat through phase separators. The boil-off argon is re-condensed in condensers and sent to the liquid purification in the CUC via dedicated liquid pumps. The liquid nitrogen from the refrigeration system in the CUC passes through phase separators and provides the cooling power inside the heat exchangers of the condensers. The cryostat pressure control is located here and connected to the condensers and the main vent header. The pressure and vacuum safety valves are on the mezzanine as well and connected to the main vent header. PLC racks and a warm gas panel are also housed on the mezzanine.

At the opposite end of the cryostat, on the ground at the lowest level, are the liquid argon pumps that circulate the bulk of the argon. Argon is withdrawn through four side penetrations and sent to the liquid purification system for continuous purification. The side ports are equipped with inline safety valves with the seal located inside the cryostat, model SI/DP from Protego. They are normally closed

and will close shut in case of an emergency or another trigger event. Figure 4 shows the detailed drawing of the valve as installed in the ProtoDUNE's cryostats at CERN on the left and a photo of the unit installed on ProtoDUNE-SP on the right. If successful, the same device will be used in LBNF.

Figure 5 shows the mezzanine area on the left and the liquid argon pumps on the right.

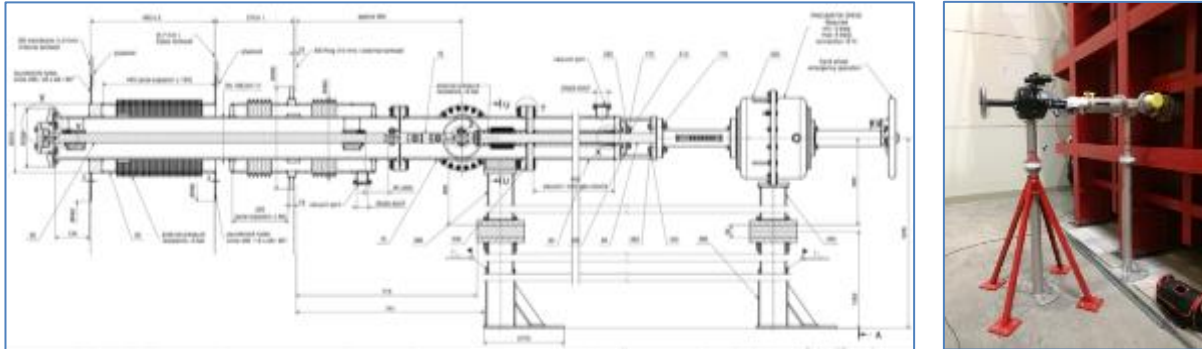


Figure 4. In-line safety valve: drawing on the left and photo of the unit installed on ProtoDUNE-SP on the right.

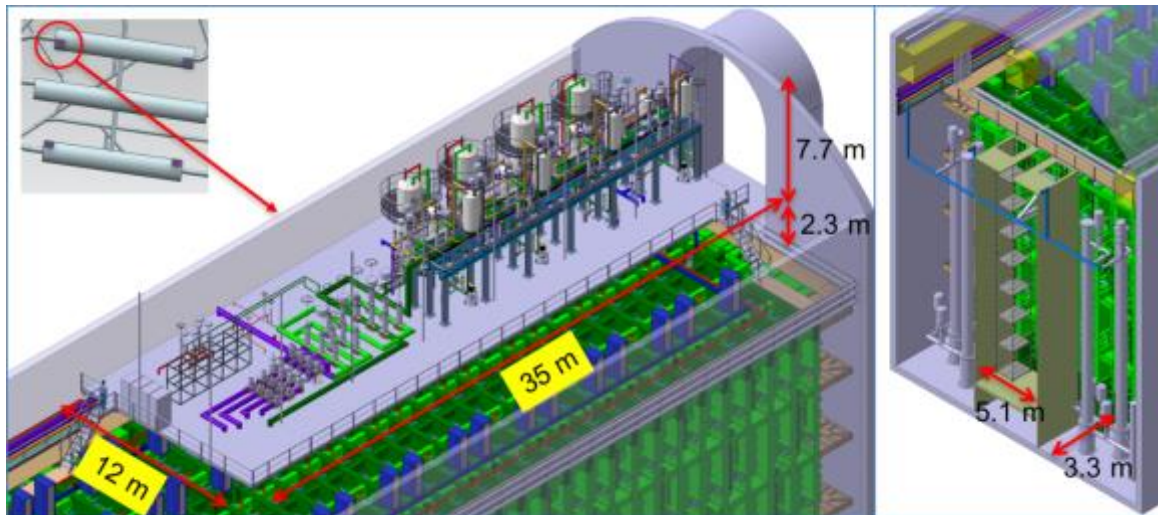


Figure 5. Current layout of the Proximity cryogenics in the detector cavern: mezzanine area on the left and main liquid argon pumps on the right.

2.6. Internal cryogenics

Each cryostat has a dedicated Internal cryogenics, which distributes the liquid and gaseous argon during all phases. It consists of several manifolds (gaseous argon purge, liquid distribution, cool-down), and vacuum insulated pipe sections to connect the inside to the Proximity cryogenics (e.g. the boil-off argon). The cryostats use passive polyurethane insulation. Vacuum insulated pipe sections are needed to transition from inside to outside while maintaining the purity and without introducing a significant heat. The impurities are collected in the ullage region at the top of the cryostat. To maintain the required level of purity, the impurities are removed with the boil-off argon, which is purified before being returned to the cryostat. Uninsulated pipes carrying liquid or cold gaseous argon through the ullage would condense the impurities on the outside. The impurities would then fall back into the bulk liquid argon and contaminate it. Another important aspect is to use only materials compatible

with high purity liquid argon. E.g. materials that do not negatively affect the electron lifetime [11]. This is true for all wetted parts, not just the internal cryogenics.

3. Summary and future steps

This contribution presented the main features of the LBNF/DUNE cryogenics systems as currently designed. The functional requirements specifications for the liquid nitrogen refrigeration system are being prepared with the goal of awarding a contract for the design and fabrication in the second half of 2018. The design of the Proximity cryogenics in the central utility cavern and detector cavern continues, to inform the conventional facilities final design. The definition of the size and location of all feedthroughs through the roof is in progress, to inform the cryostat design.

Through a consultant the project has engaged with the potential liquid argon suppliers to understand the supply chain and economics of such a large procurement.

Acknowledgements

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