Status of LBNF/DUNE near site liquid argon proximity and external cryogenics systems development.

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Abstract. The Deep Underground Neutrino Experiment (DUNE) near site located at Fermilab will host the neutrino beam complex. It includes a high voltage liquid argon time projection chamber located 60-meter underground used as beamline instrumentation. The LAr cryogenic system provided by the Long-Baseline Neutrino Facility (LBNF) regulates thermohydraulic conditions of the membrane cryostat hosting the detector with 285 Ton purified LAr. The purification system uses molecular sieve and copper oxide pellets to manage the argon contamination below 100 ppt (parts per trillion) oxygen equivalent. The detector and its cryogenics are capable to move a stroke of 30 meters on/off beam. The cryogenic system modes of operation include the cryostat pressure test, purge in open loop, detector cooldown, cryostat fill, closed loop purification, liquid empty, and purification system activation/regeneration process. The system design status and schedule, and technical details such as operating modes and interfaces are reported in this paper.

1. Introduction to LBNF/DUNE Near Site

Deep Underground Neutrino Experiment (DUNE) will be a world-class neutrino observatory and nucleon decay detector designed to answer fundamental questions about elementary particles and their role in the universe. The Long-Baseline Neutrino Facility (LBNF) hosted at Fermilab, provides the infrastructure, including cryogenics, for the DUNE observatory at the Illinois and South Dakota sites.
The Near Detector (ND) is composed of three detectors (see fig 1): System for on-Axis Neutrino Detection (SAND), Near Detector LAr (ND-LAr) and Temporary Muon Spectrometer (TMS). The cryogenic system described in this paper will support the ND-LAr and provides nitrogen supply and exhaust for the SAND Helium Refrigerator and Argon Tracker. Both the ND-LAr and TMS detectors are designed to move off the beam axis thanks to a motorized rail system called the DUNE Precision Reaction-Independent Spectrum Measurement (DUNE-PRISM). A cable carrier will maintain supply/return of cryogens, electric power, and controls signals between the moving detector and the building.

2. Liquid Argon cryogenics
The ND-LAr detector will be composed of 35 modules of the ArgonCube Time Projection Chamber (TPC) detector located inside a membrane cryostat, with requirements listed in Section 2.1. The cryogenic system will regulate the thermohydraulic conditions inside the vessel and will provide cryogens in liquid and gaseous form to perform the modes of operation described in Section 2.2.

2.1. Requirements

**ND-LAr detector requirements**
- Electron lifetime: 500 \( \mu \)s (Threshold)
  - 3 ms (Goal)
- Liquid distribution to each row: 125 g/s
- Electronics heat load: 8.0 kW
- Period between shutdowns: 10 years
- Electrical decoupling of process connections from detector ground

**Membrane cryostat requirements**
- Cryostat heat in-leak: \( \leq 2.7 \) kW
- Cryostat emptying: < 2 months
- Cryostat internal volume: 228 m3
- Cryostat fill volume: 204 m3
- Cryostat cavern depth: 63 meters

2.2. Plant modes of operation
After construction, pressure tests, leak tests, weld inspections and controls checkout are complete, the plant will go through the eight modes of operation (see fig 2) presented in the subsections below:

2.2.1. Mode 1: Pre-commissioning. Vacuum pump and backfill all volumes designated to contain purified argon. Coolodown of receiving vessels and delivery of the first batches of Liquid Argon, Liquid Nitrogen and Argon/Hydrogen pressurized gas charge.

2.2.2. Mode 2: Pressure test. The membrane cryostat vessel hosting the detector will be go through a qualification test prior to experiment cooldown authorization. The procedure will involve gradually pressurizing the vessel up to the test pressure currently defined as >0.03 MPa g while monitoring the pressure decay, structure stress and deformation at key points.

2.2.3. Mode 3: Activation/Regeneration. The argon purification system will be activated at commissioning. In this process, the oxygen and water contamination removal system will receive a stream of non-flammable Ar/H\(_2\) heated at 500K, with more details on the process described in [3] and [4]. Once in operation, the regeneration cycle will involve draining the vessel of liquid, warming it up, performing regeneration process, cooling it down and filling it again.
2.2.4. **Mode 4: Purge in open loop.** Since air inside a membrane cryostat can’t be evacuated, gaseous argon will be injected at the bottom creating a piston purge for up to 10 volume changes.

2.2.5. **Mode 5: Cryostat and detector cooldown.** A tube-shell argon/nitrogen heat exchanger with a cooling power of 16kW will be used to liquefy gaseous argon, dripping at the top of each detector row while monitoring cooldown constraints. In this mode of operation, the shaft liquid nitrogen phase separator and energy chain LN$_2$ line will be cooled down for the first time.

2.2.6. **Mode 6: Cryostat fill.** The cryostat will be filled at a rate of one cryogenics deliver truck load per day, each batch delivering 20 short Tons of liquid argon. A 10% truck-to-cryostat inventory loss is assumed. The shaft liquid argon phase separator and energy chain LAr line will be cooled down for the first time in this mode of operation.

2.2.7. **Mode 7: Closed loop LAr purification.** The circulation pump located near the cryostat side penetration will discharge 875 grams/second at 5 bara into the purification vessel. The purification process will be based on in-line-flow through porous media with two underlying processes: water desorption with a molecular sieve and oxygen contamination management with cooper oxide coated alumina pellets. The purification discharge stream will be depressurized in a phase separator with the liquid phase flowing back to the cryostat and the gas phase returning to the condenser. Target purity is planned to be achieved after 4 weeks closed loop circulation. Every time there will be an interruption in circulation, the pump and filter will need to go repeat the start-up and cooldown process.

2.2.8. **Mode 8: Cryostat LAr emptying.** Due to its underground location, the circulation pumps are not optimized to push argon up the shaft. A dedicated 45kW heater will be installed in the side penetration to boil off the liquid in two months. After venting, the cryostat will be cycled with respirable air to help create the conditions for confined space access.

**Figure 2:** Process flow diagram with functions grouped by location in the surface, static and moving with the detector.
2.3. Plant layout

Cryogen storage vessels will be placed on a concrete slab outside of the service building (see fig 3), sharing space with the SAND cryoplant gaseous helium inventory supply trailer and storage tanks. Dewar vessels with horizontal configuration are required to reduce the vessel liquid column contribution to the experiment 63m deep shaft.

A liquid argon phase separator will operate at the base of the shaft: First to help cool down the argon transfer line and mitigate geyser effect. Second, to reduce the operating pressure of the flexible argon transfer line in the energy chain.

The nitrogen phase separator will serve the same purpose described for the liquid argon, but it will also feature multiple outlets to supply liquid nitrogen to SAND cryogenics and a Future Superconducting Magnet (FSCM) that would replace TMS. In case a single cryogenic system needs to be shut down, the valve box will enable single user Lockout-Tagout (LOTO) after pulling U-tubes.

The LAr moving detector will be attached to a three-story platform that will host the proximity cryogenics and serve as means of access to the detector top cap. The proximity cryogenics functions located in the moving platform were established to minimize the number of lines in the energy chain.

The first floor of the platform will be at the level of the cryostat side penetration, to have direct access to the vessel liquid head, the circulation pump and the empty heater are in this level.

The second floor will host the liquid and gaseous argon purification vessels, as well as the regeneration skid with multiple supply/return and isolation valves for each vessel. It will also host the valve skid managing membrane cryostat pressurization, depressurization, and purge.

The third floor will host vessels that deliver liquid to the cryostat top penetrations. At the highest point, the condenser will gravity feed liquid argon to the cryostat via the phase separator.

The liquid argon circulation valve box, the liquid argon condenser and the liquid and gaseous argon purification vessels are In-Kind contribution from CERN, planned to be reused from ProtoDUNE [4].

Figure 3: Layout detail of the surface and underground cryogenics.
2.4. Development status and challenges
The project went through Preliminary Design Review in 2020 and is currently progressing through Final Design Phase with the goal to have a full thermohydraulic design, 2D/3D complete and procurement specifications for all long lead items. Based on cryogenic system requirements and Integration and Interoperability work, an Architecture and Engineering (A/E) firm has reached 90% Final Design for the Near Detector surface building and cavern conventional facilities.

Cryogenic engineering challenges for this project include: first, the design and installation of cryogenics vessels and piping down a 63-meter-deep shaft with limited space. Second, the design, prototyping, installation, and commissioning of vacuum jacketed piping in a 27-meter-long chain with requirements to operate for a minimum of 10 years uninterruptedly. Third, integrating the moving cryogenic system and shaft cryogenics within a very limited footprint and overhead clearance.

2.5. Interfaces
The ND LAr cryogenic system interfaces with the membrane cryostat group that takes care of the top cap interfaces and internal cryogenics piping (see fig 4). The interface with ArgonCube detector covers data exchange on purity measurement and detector temperatures that enable monitoring and operating within the detector constraints. ND-LAr provides gaseous nitrogen to the membrane cryostat insulation space to prevent moisture from building up inside. The cryogenic system interfaces with PRISM for the implementation of fluid transfer lines in the energy chain. ND Controls will supply the control system for ND LAr cryogenics including uninterrupted power supply, programmable logic controllers, variable frequency drives and heater controllers. Conventional facilities will provide the low voltage power and standby power for the cryogenic system. ND LAr cryogenics will provide liquid nitrogen and instrument air for the helium compressors/purifier in the surface, underground for the SAND Helium Refrigerator and the SAND argon tracker.

![Figure 4: Interfaces between the different services](image-url)
2.6. Safety and project risks
Once in operation, the membrane cryostat and proximity cryogenics systems will contribute to the facility Oxygen Deficiency Hazard (ODH) risk. Several strategies are planned to mitigate this: First, a secondary egress shaft with positive ventilation pressure will be built in the facility to help users egress at the cavern level in case of fire or ODH alarm. Second, the HVAC system will provide a South-North continuous circulation of 40,000 cubic feet per minute (cfm) air and a minimum fresh air of 7,500 cfm. An ODH alarm will be triggered in case the HVAC fresh air intake fans fail.

ArgonCube detector is currently undergoing single module test and will soon be on a 4-module 2x2 test assembly. New requirements after lessons learned from this testing campaign are identified as a risk that can impact the thermohydraulic design of this system nearing final design completion.

2.7. Conclusions
The cryogenic system to support the Near Detector with 285 tons of purified argon is presented. Development status has been described including requirements, plant layout, modes of operation, interfaces, and safety aspects. Through Final Design, the project is heavily involved in the integration effort to specify the surface building and cavern conventional facilities requirements.

3. References
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