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Development of cryogenic installations for large liquid argon neutrino detectors

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Abstract. A proposal for a very large liquid argon (68,000 kg) based neutrino detector is being studied. To validate the design principles and the detector technology, and to gain experience in the development of the cryostats and the cryogenic systems needed for such large experiments, several smaller scale installations will be developed and implemented, at Fermilab and CERN.
The cryogenic systems for these installations will be developed, constructed, installed and commissioned by an international engineering team. These installations shall bring the required cooling power under specific conditions to the experiments for the initial cool-down and the long term operation, and shall also guarantee the correct distribution of the cooling power within the cryostats to ensure a homogeneous temperature distribution within the cryostat itself. The cryogenic systems shall also include gaseous and liquid phase argon purification devices to be used to reach and maintain the very stringent purity requirements needed for these installations (parts per trillion of oxygen equivalent contamination).
This paper gives an overview of the installations involved in these cryogenic projects, describes the functional demands made to these cryogenic systems and presents the initial studies on which these future cryogenic systems will be based.

1. Introduction
An international collaboration called Deep Underground Neutrino Experiment (DUNE) is studying the installation of a 68,000 kg liquid argon Time Projection Chamber (TPC) divided over four underground caverns at the Sanford Underground Research Facility (SURF), South-Dakota, US. The facilities will be developed, constructed and installed by the Long Baseline Neutrino Facilities (LBNF). These TPCs will be used to study a neutrino beam coming from Fermilab at a distance of about 1350 km. Four experimental caverns will be excavated at a depth of about 1,500 m from the surface. Each of these caverns will be equipped with a 17,000 kg liquid argon (corresponding to a volume of about 12000 m^3) cryostat containing the detectors.
The detector is foreseen to operate for several decades and the cryogenic system supporting it shall guarantee the safe and reliable operation of the four cryostats over this time period.
The cryogenic system shall cover the following operational modes: piston purge, recirculation, cool-down, filling, normal operation, purification of the argon contained in the cryostats, emptying, warm-up and airing of the system. The cryogenic system shall be designed such that the functioning of this installation shall not be interrupted over its lifetime by eventual power outages, compressed air failures and/or cooling water problems.

Prototypes of the foreseen cryogenic installations will be developed for several liquid argon TPCs prototypes to be constructed and installed at Fermilab and CERN.

2. Cryogenic systems prototypes to be developed

The cryogenic systems foreseen to service the liquid argon TPCs to be installed at SURF will be prototyped on several smaller scale experiments housing reduced scale TPCs operating in liquid argon. All the prototype cryostats will be of the membrane cryostat type [1,2], the same type of cryostat as foreseen for the DUNE detector. These cryostats are based on a stainless steel membrane, which is in contact with the cryogenic liquid, and is surrounded by a layer of polyurethane used as thermal insulation. The following prototype installations have been foreseen:

- One 19 m^3 two phase (liquid and gaseous) argon TPC, to be installed at CERN. This detector, as well as all the others mentioned later on, will be placed in a prototype cryostat, based on passive thermal insulation (i.e. non vacuum). The total heat load to be absorbed by the cryogenic system is estimated at about 1,560 W. This experiment will not be placed in a beam-line.
- Two 485 m^3 argon TPCs, one based on the single phase (liquid) principle, and one based on the two phase principle, both to be installed at CERN. The cryogenic system foreseen for these installations shall be able to supply the necessary cooling power to both of them independently, such that one of them can be in cool-down mode, while the other is under normal operating conditions. The total heat load to be absorbed by the cryogenic system is estimated at 6,500 W for the two cryostats only. The heat load contribution of the liquid pumps, the purification vessels, the cabling, the electronics, and the piping has yet to be evaluated. These two installations will be placed in the CERN EHN1 beam line.
- One 189 m^3 liquid argon TPC, placed as a near detector in the Fermilab Short Baseline Neutrino (SBN) program. The heat load to be absorbed by the cryogenic system is estimated at 2,400 W for the cryostat only, plus the contribution of the liquid pumps, purification vessels, cabling, electronics and piping that is yet to be evaluated.
- One 545 m^3 liquid argon TPC, placed as a far detector in the Fermilab SBN program. The total heat load to be absorbed by the cryogenic system is estimated at 12,000 W.

3. Description of the cryogenic modes

Liquid nitrogen in open loop will be used as cooling source for all the prototype installations mentioned, while the DUNE-LBNF project at SURF will use nitrogen refrigerators. This choice has been made based on the foreseen operations time of the different installations and the price of liquid nitrogen. Since nitrogen refrigerators can be bought as standard equipment from the industry and CERN and Fermilab already have experience in the development and operation of such refrigerators in a closed nitrogen loop, it was not deemed necessary to prototype them.

One of the key aspects of this prototyping effort is the liquid argon purification, using commercial absorbers (molecular sieve and copper) to remove impurities in the liquid argon to the required level of 100 parts per trillion (ppt) oxygen equivalent contamination. The 35 ton prototype at Fermilab already demonstrated that this level is achievable in a membrane cryostat. These progressively larger installations shall validate the technique at larger scale.

In general the cryogenic system to be developed and deployed in the different installations mentioned above, shall be able to perform the following modes:

- Open loop piston purge of the cryostat. Cryostats are typically evacuated to remove impurities prior to filling and operations. These installations use membrane cryostats where evacuation is possible but only under highly controlled procedures and instead the piston purge technique will be used to remove the impurities. Gaseous argon is distributed and injected at the bottom of the tank to sweep the impurities while slowly rising to the top of the tank where it is vented. Test performed at Fermilab in the Liquid Argon Purity Demonstrator (LAPD) and the LBNE

35 ton prototype have shown that in several volume changes the piston purge can reduce oxygen and water, the main contaminants, down to parts per million (ppm) level.

- Closed loop recirculation. Once the concentration of impurities reaches the ppm level, the gaseous argon used for the purge is no longer vented, but recirculated through a gas purifier that removes the impurities collected inside the tank and sends the purified gaseous argon back to the bottom of the tank. This step continues until the oxygen and water content reach sub-ppm levels. The gaseous argon purifier uses molecular sieve to remove water and activated copper based pellets to remove oxygen. The purity level at the entrance of the purifier will be monitored to identify the eventual presence of air leaks into the cryostat or the cryogenic system.
- Cryostat cool down. The cool down will be done by atomizing liquid argon and distributing it inside the cryostat volume to cool it down slowly and uniformly, following the cryostat manufacturer's guidelines and the TPC requirements. Liquid argon, mixed with high speed gaseous argon, will be injected in the system via atomizers. An additional argon gas stream will provide the circulation inside the cryostat volume. The pressure in the cryostat will be regulated to a value just above ambient pressure. The gas will be sent to the external condenser, purified in the liquid form and returned to the cryostat to continue the cool down process. The condenser is based on liquid nitrogen cooled surfaces on which the argon shall condense. The pressure, and thus the temperature of the saturated nitrogen bath, will be regulated to a value, such that the liquid argon re-enters the cryostat at a temperature close to the saturation temperature of argon at 0.1 MPa (about 87.2 K). The temperature of the liquid nitrogen will however also be regulated such that the argon cannot be cooled below its triple point (about 83.8 K) to assure that no solid argon will be formed in the process. If the pressure inside the cryostat increases beyond the condenser capacity, gaseous argon will be released through pressure relieving devices. During this phase, the maximum temperature difference between any two points in the cryostat shall remain below 50 K. If this value is exceeded, the process will be stopped and restarted again once the temperature difference has lowered to about 40 K. This procedure will be continued until the warmest point in the cryostat has reached a temperature of at least 130 K, after which the filling can start. This cool down method has been effectively tested in the LBNE 35 ton prototype and will be tested in the membrane cryostats as part of this prototyping effort.
- Cryostat filling. The liquid argon is taken from an external storage tank and purified in the liquid phase through a cold purification system. This system is based on the same principle as the warm purifier. The liquid then goes through a phase separator: the gas eventually created during the transfer and the purification process is separated from the liquid and sent to the condenser while the liquid is directly transferred to the cryostat. Because of the volume of the different cryostats, the external argon storage tank has to be re-filled several times by the supplier. For the LBNF cryostats it has been decided to use a different fill method. There is only gaseous argon transfer from the surface to underground. Liquid is generated onsite in the condenser and from there it is transferred into the cryostat.
- Normal operations. Once the cryostat has been filled to its nominal level, the liquid argon flow from the storage tank will be stopped. The liquid argon pump has already been turned on at the moment its running conditions had been fulfilled, and liquid argon is circulated and purified. Liquid argon is sent from the bottom of the tank through the cold purification system and back to the tank. This step is essential to meet the high level of purity (100 ppt oxygen equivalent contamination) required for the proper functioning of the detector. At the same time the boil off gas is condensed, mixed inline with the stream of liquid argon from the cryostat and sent to the cold liquid argon purification system for continuous purification. There are several contributions to the boil off: the static heat load of the cryostat, signal cabling, heat deposited by the liquid argon circulation pump, and heat leak of the transfer lines. They all contribute to an increase of argon gas production, which leads in turn to an

increase of the cryostat pressure. A regulation system maintains the cryostat system at a stable pressure, while also providing re-condensation and purification of the boil off gas. A control system is in place to protect the cryostat system against under or over pressure situations: if everything fails, it will ultimately vent argon gas in a controlled way in case of over-pressure, while supplying a clean flow of gaseous argon to the cryostat in case of under-pressure.

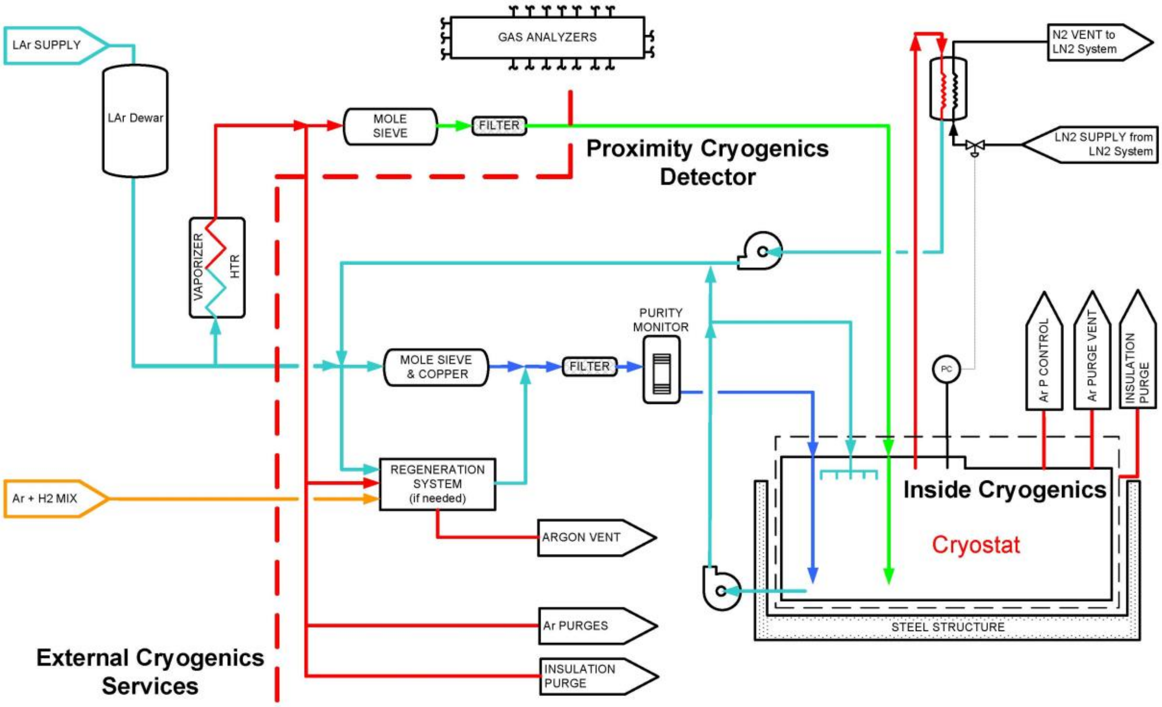

Figure 1. PFD for the general liquid argon system

- Emptying. In the exceptional case that access is needed into the cryostat, or at the end of the lifetime of the experiment, the liquid argon will be transferred from the cryostat to the external liquid argon storage vessel, by the use of the liquid argon pump. This external liquid argon storage tank has to be emptied several times by the supplier. Also during this emptying process, the pressurization and de-pressurization system will be operational, guaranteeing that the cryostat system will be maintained within its operation limits. Once the cryostat argon level is below the minimum NPSH, the pumps are shut off and warm gas is supplied to the cryostat to boil off the remaining liquid argon and to warm up the cryostat. Similar to the cool-down process, care shall be taken that no temperature differences bigger than 50 K are created between any two points in the cryostat volume. This procedure will be different for LBNF. At the moment it is not envisaged to transfer liquid argon between above ground and the underground caverns or vice-versa. The liquid argon inside the cryostat will be boiled off in a controlled way and directed towards the surface, using a gas blower. The use of mobile dewars is also still under study. On the surface it will be recondensed and transferred to a temporary storage tank, from which it might be returned to the supplier in several transfers.
- Accessing the tank. Once the warm-up has been accomplished, ambient air will be supplied to the cryostat until the oxygen concentration exceeds 18%. At that point it can be opened and, upon reaching 20.5% access to personnel is granted.

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4. Safety considerations for handling large quantities of liquid argon

Safety handling of large quantities of liquid argon in a closed building, or even in an underground cavern, shall be addressed early on in the project. It should be assured that in case of eventual damage to the equipment, personnel shall be able to safely leave the experimental area. Some of the safety considerations taken into account when designing the systems:

The cryostats containing the large liquid argon volumes will have a passive insulation made of several layers of polyurethane foam. This insulation will create a higher heat-load into the liquid argon volume as would have been the case for a vacuum insulated cryostat. The size of the DUNE cryostats is however such that the vacuum insulation is neither practical nor economically advantageous. A big advantage of the passive insulation method from a safety point of view is that the loss of vacuum scenario does not have to be considered.

The systems needed for the basic functioning of the cryostat, will be electrically fed via an UPS, guaranteeing an autonomous operation time of at least two hours. This system includes the PLC based control system, the supervision system and the instrumentation, but not the non-essential equipment (for example the liquid argon circulation pumps).

The Oxygen Deficiency Hazard (ODH) analysis is the guiding principle of these installations. The area in which the cryogenic installations and the cryostats will be placed will be equipped with ODH measures and warning systems that will activate the evacuation alarm once the measured oxygen contain in the measured air sample falls below 18%, or even before if pre-warning systems can be implemented (for example loss of insulation vacuum of transfer lines).

In the newly equipped areas, an air ventilation system will be installed, which in case of activation of the ODH alarm will increase its extraction capacity to a value needed to exhaust the highest estimated argon gas production in case of the worst credible accident.

5. Conclusions

Several cryogenic systems supporting the needs of large volume liquid argon neutrino detectors are being developed. The cryostats vary in size between 19 m^3 and 12000 m^3, and are placed in various locations, ranging from the surface, via a pit at a few tens of meters below ground level, to deep underground (1500 meters) caverns. The cryogenic systems foreseen shall be standardized such that these principles can be applied to the different experiments, with the necessary scaling and customization required by the needs of each individual project. The first cryogenic system is foreseen to become operational in the first half of 2016, while the one for the first two 12,000 m^3 cryostats of LBNF shall become available in 2024.

6. References

[1] Adamowski M et al, 2014 The Liquid Argon Purity Demonstrator, *JINST* **9** P07005.

[2] Montanari D et al, 2014 Performance and results of the LBNE 35 ton membrane cryostat prototype, ICEC 25 – ICMC 2014. Phys. Proc.: in publication.