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Design, construction and commissioning of the proximity cryogenics systems serving two large-scale prototypes of the future DUNE neutrino detector

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Abstract. In the context of the Neutrino Platform, CERN has designed, constructed, and commissioned the proximity cryogenics systems that serve two CERN based large-scale prototypes of future neutrino detectors. Each of these prototypes features a high voltage time projection chamber placed inside a membrane cryostat being submerged in 600m3 of liquid argon at about 1.0 bar. A copper and molecular sieve based cryogenic purification system has to ensure that the argon in the cryostat has a contamination level below 100 ppt oxygen equivalent. The two proximity cryogenics systems provide the purging, cool-down, filling, normal operation and emptying modes for each cryostat. This paper reports on the design, construction and commissioning of the ProtoDUNE proximity cryogenics facilities.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) is a leading-edge, large scale international experiment for neutrino and proton decay studies. The European Organization for Nuclear Research (CERN) established the CERN Neutrino Platform (NP) in order to foster and contribute to the neutrino physics fundamental research across the world.

The DUNE experiment will feature four 17,000 tons fiducial mass liquid argon cryostats. With the mandate to develop and test the technologies required to perform very large scale liquid argon science experiments, CERN is hosting the two DUNE prototypes, called ProtoDUNE NP-02 and ProtoDUNE NP-04, featuring different detection strategies.

2. The detector requirements

Separate beam lines from the CERN Super Proton Synchrotron (SPS) beam deliver particles to the NP-02 and NP-04 detectors. During their flight inside the time projection chambers, particles interact with the liquid argon releasing free electrons. Fully submerged in liquid argon, the single phase NP-04 detector [1] collects electrons in a wire chamber under a 180 kV horizontal voltage field. The dual phase NP-02 detector [2] features a vertical 300 kV high voltage field capable to extract the electrons across the liquid surface reaching the gas phase collection grid, amplifying a low signal with a limited noise creation. However, the amplification parameters are very sensitive and require precise regulation of ±1 mm liquid level and ±1 mbar internal pressure. To ensure an electron lifetime of 3 ms, the liquid argon contamination needs to be better than 100 ppt oxygen equivalent. Auxiliary detector functions also require nitrogen contamination below 10 ppm. Both detectors have to be cooled down at a maximum rate of 40 K/hour and temperature uniformity of 50 K.

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3. Cryostat and internal cryogenics

The detector containment vessel technology is a spin-off from the maritime liquid natural gas (LNG) storage membrane cryostat [3] and has an internal size of 8.5 m high, 8.5 m wide and 7.9 m high. Filled with liquid argon at 87 K temperature, the vessel is designed to have an insulation heat flux of 5 W/m^2 and bear the liquid column with a maximum ullage pressure of 1.35 bar a. The liquid argon is contained inside a corrugated stainless steel membrane absorbing the internal volume changes during the cool-down. Two 0.4 m thick polyurethane foam layers provide the bulk of the thermal insulation. They are separated by a polymer membrane acting as a second vapour barrier. The third containment layer is a 10 mm stainless steel plate welded directly to the cryostat external structure bearing the cryostat internal pressure. Two 25 m3 insulation space exist in the free volume between the vapour barriers, each is flushed continuously with 0.1 m^3/h dry nitrogen.

The internal cryogenic system is composed of several distribution lines delivering gaseous and liquid argon inside the cryostat. The cryostat ullage is fitted with vertical chimneys containing the cryostat pressurization and gas make-up port, the cryostat depressurizing port, the overpressure safety relief valve port, the supply manifold port for gas/liquid mixing cool down nozzles, all the detector cable ports and the instrumentation ports. The NP-02 and NP-04 roofs feature 60 and 42 chimneys respectively, which are also used to collect the warm ullage gas. Contamination sources can be located precisely thanks to pneumatic purge valves which can isolate each chimney separately. Only one penetration is present at the bottom of the cryostat, giving access to a liquid argon circulation pump. Given emergency conditions, this opening is closed by a pneumatic normally closed inline valve.

All cabling and piping elements connected to the detector vessel have to be electrically decoupled from the building ground.

4. Proximity cryogenics plant

The two proximity cryogenics plants have to manage the cryostat pressure and temperature in the different operating modes: purge in open loop, purge in closed loop, cool down, normal operation, emptying and purification system regeneration. The control system is conceived to safely perform each mode with minimal human supervision.

In open loop purge mode, the cryostat gas content is purged via the piston purge method. The air contaminants are pushed up injecting gaseous argon at the bottom of the cryostat with a flow rate of 10 volume changes per day and a linear speed of 1.2 m/hour. The gas leaving the cryostat is vented to air.

In closed loop purge mode, the goal is to find air leaks after the purge. A membrane pump flows 5 g/s of gas through the oxygen and water gas purifier after which it is analysed and sent back to the cryostat. A miniature pump feeds oxygen, nitrogen and water gas analysers that receive sample gas from the cryostat vent line. Nitrogen accumulation in this mode can be a signal of air leaks. Samples can also be taken from the condenser, the cryostat chimneys, the gas purifier or the liquid purifier.

In the cool down phase, the condenser provides 24 kW cooling power to bring the detector and the cryostat from 300 K to 87 K. The condenser is based on the liquid nitrogen cooled vertical shell tube heat exchanger principle.

In the filling phase, two 20,000 kg liquid argon containers are delivered per day to fill the cryostat in one month. The suppliers are contractually required to control the supply chain contamination in order to deliver the fluid with less than 1ppm oxygen and 2 ppm nitrogen. Upon delivery, the liquid argon is analysed and filtered through a 0.5 µm mechanical filter made of sintered stainless steel located inside a valve box. It is also purified in a single pass through the liquid purification valve box.

During normal operation, gas accumulated in the ullage is particularly exposed to outgassing of cables and metallic surfaces. The impure gas is pumped by the membrane pump through a gas treatment filter. The liquid recirculating pump placed at the bottom of the cryostat pushes 1.6 kg/s argon through the liquid purification system, renovating the cryostat volume every 5 days [4]. Liquid returns to the cryostat via the phase separator. The purified gas, the phase separator gas and the cryostat boil-off are condensed and sent back into the liquid recirculating pump. The heat load from the cryostat and cryogenics plant is estimated under 8 kW. In NP-02, the cryostat pressure is too low for the gas to naturally flow to the condenser. This requirement is fulfilled with a dedicated cold compressor transferring the boil-off gas to the heat exchanger.

Two 50 m^3 tanks storing liquid argon and liquid nitrogen are used to fill the cryostats and to provide cooling fluid to the condensers. A third 11 m^3 vessel provides high pressure gaseous argon that is mixed with hydrogen for the activation and regeneration of the purification system. An external warm panel can deliver up to 200 g/s of warm gaseous argon for the system purge, 170 g/h of nitrogen to pressurize the cryostat insulation space and up to 100 g/s argon/hydrogen regeneration flow. For each plant, the warm panel is installed in the proximity of the detector vessel with the function of controlling the cryostat pressure and switching pressure between the different make-up gas nozzles.

5. Purification system

Each cryogenic plant is equipped with separate liquid and gaseous argon purification systems based on porous media. Water is absorbed by 4 Å molecular sieve that is activated flowing argon gas at 430 K for 6 hours. Copper coated alumina pellets adsorb 1 ppm oxygen contamination in the argon after activation. The first step is to pre-heat the oxygen purifier to 420 K with argon. After that, a non-flammable gas mix of argon and 1 % hydrogen at 420 K reduces the CuO coating of the alumina pellets. The exothermal process reaches local temperature peaks over 500 K observed in a heat wave moving in the direction of the flow. Temperature sensors along the length of the purification vessel monitor the phenomena. To avoid moisture diffusion, the copper is activated before the molecular sieve is desorbed.

$$CuO\,(s) + H_2\,(g) \rightarrow Cu\,(s) + H_2O\,(g) \qquad (1)$$

$$Ar\,(l) + \tfrac{1}{2}O_2\,(l) + Cu\,(s) \rightarrow CuO\,(s) + Ar\,(l) \qquad (2)$$

The ProtoDUNE purification valve boxes are much larger than other liquid argon purification system constructed to date [4]. They contain roughly 10 times the amount of media, which required a different design. Instead of a single vessel with separation grids, the cryogenic fluid flows through three in line vessels simplifying the pressure vessel requirements and helping avoid overheating during activation and regeneration. The first vessel contains 80 kg of 4 Å molecular sieve, followed by two identical vessels hosting 300 kg Cu coated alumina each. The cryogenic valve box footprint is still large with 2 m diameter and 4 m in height. The transfer lines and the purification vessel fill ports are on top of the valve box. To allow space for the vacuum vessel to be removed, the purifier is elevated from the floor. Placed next to the purification valve box, the regeneration panel contains the warm bellows insulated valves required to isolate and activate each vessel separately with the use of a 15 kW electrical heater.

6. Safety

The experiment safety procedures are centred on the mitigation of an Oxygen Deficiency Hazard (ODH) during a potential liquid argon spill. The building was designed with two separate 10 m deep pits where the cryostats are installed. A potential spill of liquid argon or cold nitrogen would be contained inside this restricted access area below ground level. Each pit features 5000 m^3/h forced air extraction. Fixed ODH sensors placed in strategic locations and loss of insulation vacuum can trigger an ODH alarm increasing the ventilation in the affected pit to 13,000 m^3/h. Each overpressure safety valve is sized to relief up to 6 kg/s from the cryostat volume in case of an uncontrolled pressure increase. The gas is vented to the bottom of the pit, close to the air extraction point.

In case of power failures, the control system power is backed by UPS and by diesel generators. There is also a 12 hour emergency supply of compressed air to operate the pneumatic valves.

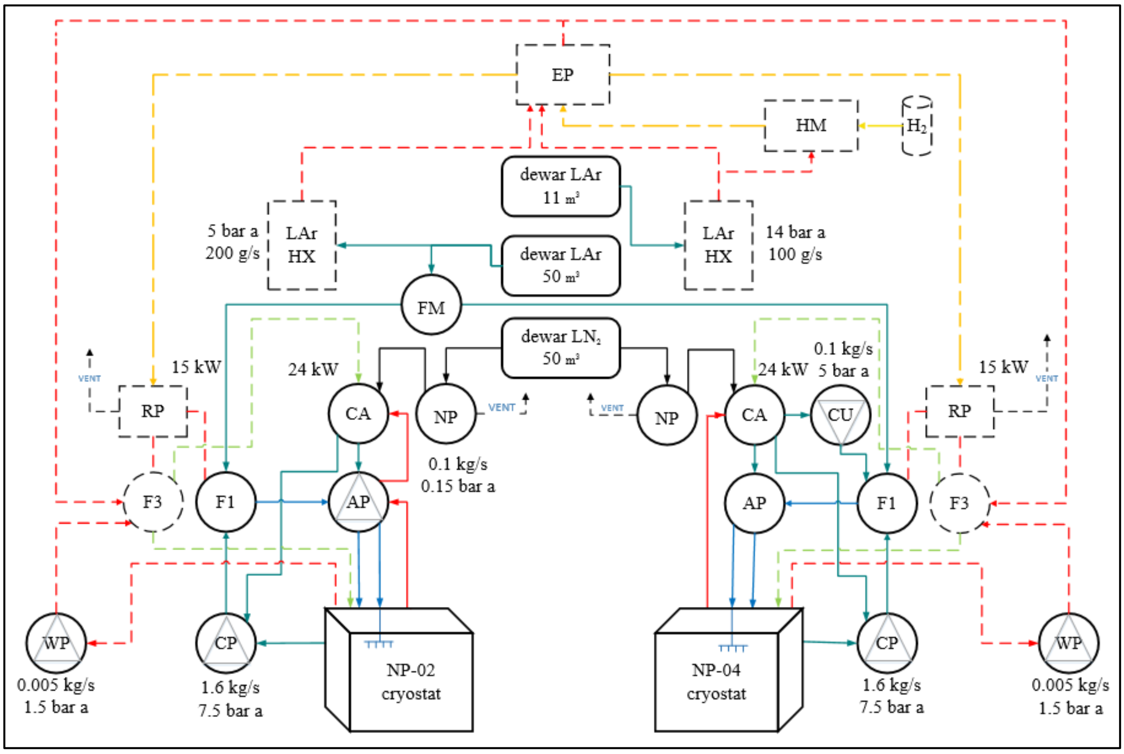

Figure 1. ProtoDUNE cryostat plant schematic. Legend: NP=nitrogen phase separator, CA=argon condenser, AP=argon separator, F1=liquid argon purifier, CP=liquid argon pump, WP=warm panel, RP=regeneration panel, CU=liquid pump, F3=gaseous argon purifier, FM=liquid mechanical filter, HM=regeneration argon/hydrogen mixer.

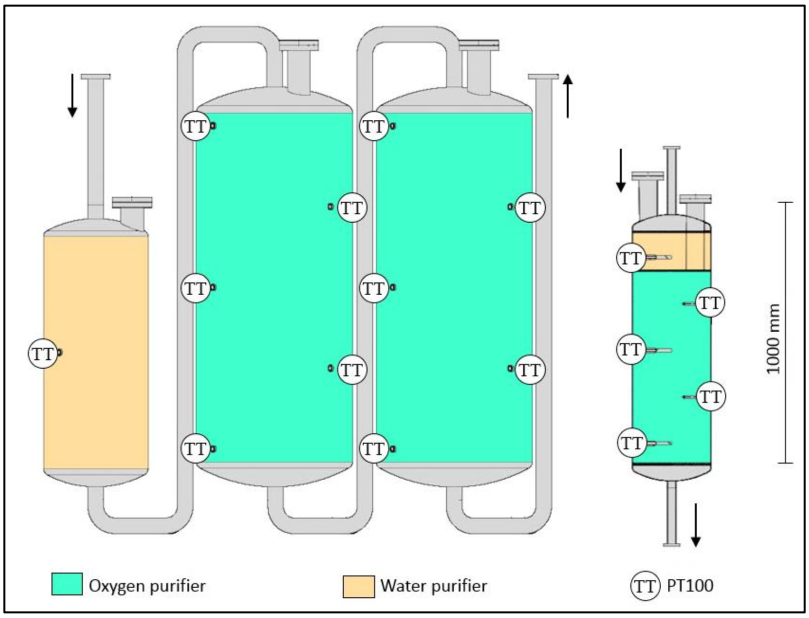

Figure 2. ProtoDUNE (left) and dual phase prototype [2] (right) purifier vessels.

7. Construction and commissioning

The EHN1 extension building broke ground in 2015 and was completed in 2016. Detector parts manufacturing in the US and Europe started in 2016. Detector cleanroom assembly, cold test and installation took 8 months, with the cryostat closure in May 2018. After 20 months of procurement and manufacturing, the installation of the cryogenic valve boxes, the transfer lines, the storage tanks and the warm piping was completed in June 2018.

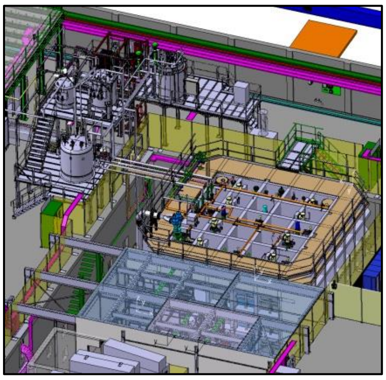

Figure 3. NP-04 plant.

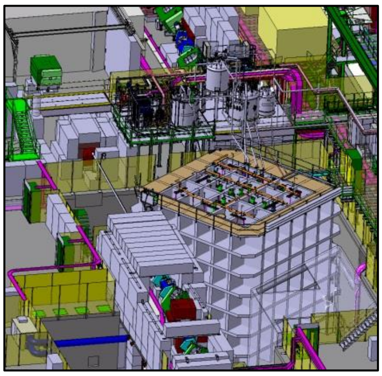

Figure 4. NP-02 plant.

The NP-04 is under commissioning. The purge in open loop achieved an oxygen contamination of 2 ppm. Liquid argon has been delivered with quality better than 1 ppm. The cryostat is being filled with a level exceeding 50 %. Purity monitors indicate a quality of 0.01 ppm oxygen equivalent after the liquid has passed through the purification system only once. The 100 ppt liquid oxygen equivalent target should be achieved directly in normal operation with continuous purification of the liquid [5].

8. Conclusions

Two new cryogenic plants and the common infrastructure supporting the ProtoDUNE detectors have been successfully designed and built at CERN. Strategies have been implemented to purge, cool-down, fill, purify and manage the contamination inside the 600 m^3 closed volume. The construction and operation of this large cryogenic neutrino detectors and associated cryogenics is the necessary step to identify technical challenges, consolidate results and develop strategies towards the construction of the DUNE experiment and the cryogenic system supporting it.

9. References

[1] Abi B, et al. *The Single-Phase ProtoDUNE Technical Design Report.* DUNE Collaboration. FERMILAB-DESIGN-2017-02,2017. Available from: arxiv.org/abs/1706.07081.

[2] Aimard B, et al 2018 A 4 tonne demonstrator for large-scale dual-phase liquid argon time projection chambers. To be published in *J. Inst.* [Preprint] 2018. Available from: arxiv.org/abs/1806.03317.

[3] Montanari D, Bremer J, Gendotti A, Geynisman M, Hentschel S, Loew T, et al. Development of membrane cryostats for large liquid argon neutrino detectors. *IOP Conf. Ser.: Mater. Sci. Eng.* 2015;101(1): 012049.

[4] Tope T, Adamowski M, Carls B, Hahn A, Jaskierny W, et al. Extreme argon purity in a large, non-evacuated cryostat. *AIP Conf. Proceedings. 2014;*1573: 1169.

[5] Adamowski M, Carls B, Dvorak E, Hahn A, Jaskierny W, Johnson C, et al. The Liquid Argon Purity Demonstrator. *J. Inst. IOP Publishing*. 2014**;**9(7): P07005.

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