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Design of the cryogenic systems for the Near and Far LAr-TPC detectors of the Short-Baseline Neutrino program (SBN) at Fermilab

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Abstract. The Short-Baseline Neutrino (SBN) physics program at Fermilab and Neutrino Platform (NP) at CERN are part of the international Neutrino Program leading to the development of Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) science project. The SBN program consisting of three Liquid Argon Time Projection Chamber (LAr-TPC) detectors positioned along the Booster Neutrino Beam (BNB) at Fermilab includes an existing detector known as MicroBooNE (170-ton LAr-TPC) plus two new experiments known as SBN's Near Detector (SBND, ~260 tons) and SBN's Far Detector (SBN-FD, ~760 tons). All three detectors have distinctly different design of their cryostats thus defining specific requirements for the cryogenic systems. Fermilab has already built two new facilities to house SBND and SBN-FD detectors. The cryogenic systems for these detectors are in various stages of design and construction with CERN and Fermilab being responsible for delivery of specific sub-systems. This contribution presents specific design requirements and typical implementation solutions for each sub-system of the SBND and SBN-FD cryogenic systems.

1. Introduction

In January 2015, an official proposal was introduced for a three-detector Short-Baseline Neutrino (SBN) program in the Fermilab Booster Neutrino Beam (BNB) [1]. The SBN program is designed to address the search of short-baseline neutrino oscillations and test the existence of light sterile neutrinos with unparalleled sensitivity. The SBN program relies on the deployment of three high precision neutrino detectors, all built in the LAr-TPC technology, at different distances along a single high-intensity neutrino beam. Each of the LAr-TPC detectors is essentially a cryostat filled with highly purified liquid argon and equipped with an electronic readout that measures the ionization charge produced by the passage of charged particles. Neutrino interactions with the liquid argon inside the detector volume produce ionization electrons that drift along the electric field until they reach finely segmented and instrumented anode wire planes of TPC upon which they produce signals that are utilized for imaging and analyzing the event that occurred. LAr-TPC detector provides three-dimensional imaging and acts as a calorimeter of very fine granularity and high accuracy.

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The SBN Program consists of three neutrino detectors, namely MicroBooNE, SBN's Near Detector (SBND, also previously known as LAr1-ND) and SBN's Far Detector (SBN-FD, also known as ICARUS-T600). As stated in the 2015 proposal [1]: "The ICARUS-T600 detector, which was operated by INFN at Gran Sasso National Laboratory, is the first successful large-scale LAr-TPC to be exposed to a neutrino beam and to this point the largest LAr-TPC for neutrino physics. The MicroBooNE detector is the largest LAr-TPC built in the US and will have been operational for several years at the start of the three-detector program. The new near-detector, LAr1-ND, is being developed by an international team with experience from ArgoNeuT, MicroBooNE and LBNE prototypes".

Many of the principal design solutions for LAr cryogenic systems have been tested at CERN, INFN and Fermilab. The cryogenic system for ICARUS-T600 (operational 2010-2013) was designed to support operations of two identical T300 aluminum detector vessels (total 760 ton) in the same warm structure, including shielding at liquid nitrogen temperature, argon vapor condensing and filtration, and liquid argon recirculation and filtration [2]. The cryogenic system for MicroBooNE (operational since 2015) was designed to support operations of the foam insulated horizontal cylindrical ASME-coded detector vessel (170 ton), including argon vapor condensing and filtration, and liquid argon recirculation and filtration [3]. Many design solutions for the MicroBooNE cryogenic system were borrowed from the cryogenic system for Fermilab's LBNE 35T (operational since 2012) [4].

Fermilab and CERN are collaborating to share the cryogenic system design, construction and installation for SBND and SBN-FD [5,6], but are using different approaches for fulfilling these deliveries; while Fermilab uses in-house resources, CERN outsources design, construction and installation to commercial vendors within the European Union (EU). A major challenge for the projects rests in the integration of the EU and US- made components to assure that safety levels commensurate to those required per Fermilab's contract with the US Department of Energy.

2. Design requirements for SBND and SBN-FD cryogenic systems

The SBN-FD has dual T300 aluminium detector vessels housed in a common warm vessel and shielded at LN_2 temperature. The SBND is a single detector vessel based on GTT® (Gaztransport and Technigaz) membrane technology. However, the designs of the cryogenic systems for these detectors are being developed with a goal to use common design solutions for the LAr/GAr and LN_2 process equipment as much as possible while supporting unique designs of the cryostats.

Table 1 and table 2 show the requirements for the SBND and SBN-FD cryogenic systems.

Table 1. Requirements and Specifications for SBND cryogenic system.

Requirements: SBND	Value
Cryostat type and size	Membrane (GTT) with self-supported steel structure: 5.202 m × 5.423 m × 7.027 m, ~270 tons (~2% ullage). Gas purge for insulation space.
Contamination for LAr delivery	$O_2 < 1$ ppm, $H_2O < 1$ ppm, $N_2 < 2$ ppm
LAr purity in cryostat	> 3 ms electron lifetime (<100 ppt O_2 equivalent), $N_2 < 2$ ppm
Design pressure	Internal 345 mbarg (~5 psig), external 50 mbar
Operating gas pressure	70 mbar (~1 psig) with ± 5%
Initial purification technique	GAr Piston purge with rate of rise 1.2 m/hr
Cooldown technique	LAr spray with GAr and GAr momentum (< 10-15 K/hr)
TPCs cool-down rate restriction	< 40 K/hr, < 10 K/m (vertically)
LAr recirculation rate	2.5 – 8.0 m^3/hr (10 – 35 gpm)
Number of side/bottom penetrations	1 (use of Protego® internal valve or external safety valves)
Included sub-systems	LAr and LN_2 storage and transport, O_2-N_2-H_2O contamination monitoring, LAr and GAr recirculation and filtration, GAr condensing and recovery, safety and process controls
Grounding and noise requirement	Electrical isolation of noise from cryostat and its electronics

Table 2. Requirements and Specifications for SBN-FD cryogenic system.

Requirements: SBN-FD	Value
Cryostat type and size	Dual aluminium vessels with common LN_2 shields within a warm self-standing steel structure with GTT-style insulation: 3.6 m × 19.6 m × 3.9 m, ~380 tons each (~2% ullage). Gas purge for insulation space.
Contamination for LAr delivery	$O_2 < 1$ ppm, $H_2O < 1$ ppm, $N_2 < 2$ ppm
LAr purity in cryostat	> 3 ms electron lifetime (<100 ppt O_2 equivalent), $N_2 < 2$ ppm
Design pressure	Internal 345 mbarg (~5 psig), external up to 1 barg
Operating gas pressure	150 mbar (~2 psig) with ± 5%
Initial purification technique	Pump down to full vacuum
Cooldown technique	Initial with LN_2 shield, final with LAr fill at 2 K/hr
TPCs cool-down rate restriction	< 70 K/hr, < 50 K/m (vertically)
LAr recirculation rate	2.5 – 8.0 m^3/hr (10 – 35 gpm)
Number of side/bottom penetrations	1 side and 1 bottom (per cryostat) (use of external safety valves)
Included sub-systems	LAr and LN_2 storage and transport, O_2-N_2-H_2O contamination monitoring, LAr and GAr recirculation and filtration, GAr condensing and recovery, safety and process controls
Grounding and noise requirement	Electrical isolation of noise from cryostat and its electronics

3. Description of cryogenics and design solutions for SBND and SBN-FD

As Fermilab and CERN engage in SBN partnership, an agreement has been established for naming cryogenic sub-systems, some of which are deliverables of Fermilab and others are deliverables of CERN [5]. CERN is responsible for delivery of the proximity sub-systems for each detector. Fermilab is responsible for delivery of external sub-systems for each detector, internal sub-system for SBND and integration of sub-systems via common safety and controls for entire cryogenic systems. INFN is responsible for delivery of internal sub-system for SBN-FD.

To satisfy all design requirements shown in table 1 and table 2, the overall cryogenic system must include LAr and LN_2 storage and distribution, O_2-N_2-H_2O contamination monitoring, LAr and GAr recirculation and filtration, GAr condensing and recovery, safety and process controls.

The main design requirement is to achieve electron lifetimes in argon (τ) exceeding 3 milliseconds [ms] to allow drift electrons sufficient time to reach the anode. The electron lifetime in argon is connected to the impurity concentration (ρ), mostly oxygen, by an inverse linear relationship shown below in equation (1).

$$\tau\ [\mathrm{ms}] \approx \frac{300\ [\mathrm{ms} \cdot \mathrm{ppt\ Oxygen\ Equivalent}]}{\rho\ [\mathrm{ppt\ Oxygen\ Equivalent}]} \tag{1}$$

In order for the lifetime to exceed 3 ms, the impurity measured in parts of oxygen should be below 100 ppt (10^{-10} parts). As the commercial argon has impurities far exceeding this number, and since the components inside the cryostat and piping outgas impurities, the cryogenic system must be designed to remove water and oxygen from LAr to achieve impurity concentrations below ppb level before TPC could be turned on. While the MicroBooNE cryostat was directly filled with commercial grade argon of measured concentrations of impurities well below 1 ppm, and then purified by circulating of LAr through the molecular sieve and copper filters, the SBND and SBN-FD cryogenic systems are designed to first receive the commercial grade argon into the storage tanks and then fill the cryostat while filtering liquid argon through the in-line filters of various sizes filled with molecular sieve and copper media. To remove contamination from outgassing and back-diffusion from atmosphere, the LAr volume of the cryostat must be continuously circulated and filtrated with cryostat volume change every 5-8 days.

Typical modes of operations are shown in table 3 below. The External, Proximity and Internal cryogenic sub-systems are designed for these modes.

Table 3. Typical modes of operations of SBND and SBN-FD cryostats.

Operation	SBND (membrane cryostat)	SBN-FD (aluminum vessels)
Initial cleanup	Piston purge with gaseous argon	Pump down to full vacuum for up to 90 days
Final cleanup	Internal circulation via a membrane pump through a purification system	None
Cooldown	Spray LAr through nozzles with GAr, plus GAr momentum (< 10-15 K/hr)	Initial with LN_2 shield, final with LAr fill at 2 K/hr
Fill	From LAr storage	From LAr storage
Purification	Circulation by LAr pumps through external molecular sieve and Cu filters	Circulation by LAr pumps through inline molecular sieve and Cu filters
Normal operation	Maintaining level, pressure and purity	Maintaining level, pressure and purity
Regeneration of filters	Regeneration filters in place with heated GAr / 2.5% H_2 mix	Regeneration removed cartridges with heated GAr / 2.5% H_2 mix

3.1. External cryogenics

Per requirements shown in table 1 and table 2, an External cryogenic sub-system includes the cryogenic dewars and piping to store and transfer the cryogenic fluids needed for the operation of the Proximity Cryogenics and the detector overall. Both installations will re-use 30,000 litre LAr dewars from the ICARUS experiment to receive LAr from an industrial supplier, verify contamination levels, transfer LAr and GAr to cryostats and manage GAr losses. Both installations will also re-use 34,000 and 75,000 litre LN_2 dewars from Fermilab Dzero experiment to supply nitrogen for re-condensing gaseous argon boiloff from the ullage space, as well as for LN_2 thermal shields in the SBN-FD design. The dewars are sufficient to provide several days of cooling capacity in the event of a vendor delivery interruption. The estimated heat leak rates through passive insulation to atmosphere for SBND and SBN-FD detector vessels are low enough to allow using open loop system with vendor deliveries around the clock typical of other cryogenic facilities operated at Fermilab. An External cryogenic sub-system includes commercially available gas analysers, e.g. by Servomex, for continuous monitoring of impurities at ppb level from various strategic sample ports in the systems, storage of GAr/H_2 mixture in high-pressure tube trailers and delivery of heated GAr/H_2 mixture to filtration skids for regeneration of copper and molecular sieve media. An External cryogenic sub-system also includes control and safety systems based on Siemens S7 and Beckhoff PLCs and GE iFix operator interface.

3.2. Proximity cryogenics

Per requirements shown in table 1 and table 2, a Proximity cryogenic sub-system includes transfer of cryogenic fluids from the External cryogenic sub-system through filtration skids, recovery of GAr from cryostat, recirculation, filtering and returning LAr to cryostat via components of the Internal cryogenic sub-system at the required pressure, temperature, purity, quality, and mass flow rate. The designs of Proximity cryogenics for the SBND and SBN-FD are being developed with a goal to use common features and equipment for the LAr/GAr and LN_2 process equipment as much as possible. The construction of the cold portion of the Proximity cryogenic sub-systems is awarded to Demaco. Portions of the cryogenic system used previously at Gran Sasso Laboratory for the ICARUS-T600 detector are to be used, including filter housings which will now contain copper, rather than previously used Oxysorb^{TM}, together with molecular sieve. Previously used LN_2 cryogenerator units will be replaced with LN2 dewar supply as the new cryogenics vessel design heat leak allows for this solution. This has the added positive impact of having a virtually maintenance free LN_2 supply system. Typical examples of several major components are shown on figure 1 and figure 2 below. The design of the boiloff gas condenser-filter (1 out of 2 per cryostat) for the SBN-FD ICARUS detector is shown on figure 1. This illustrates several important design features implemented for the Proximity cryogenics. One of them is grouping and placement of all process equipment, valves and instrumentation in dedicated valve boxes, which are then interconnected via vacuum jacketed transfer lines. The other is the use of removable filter cartridges, which could be regenerated offline.

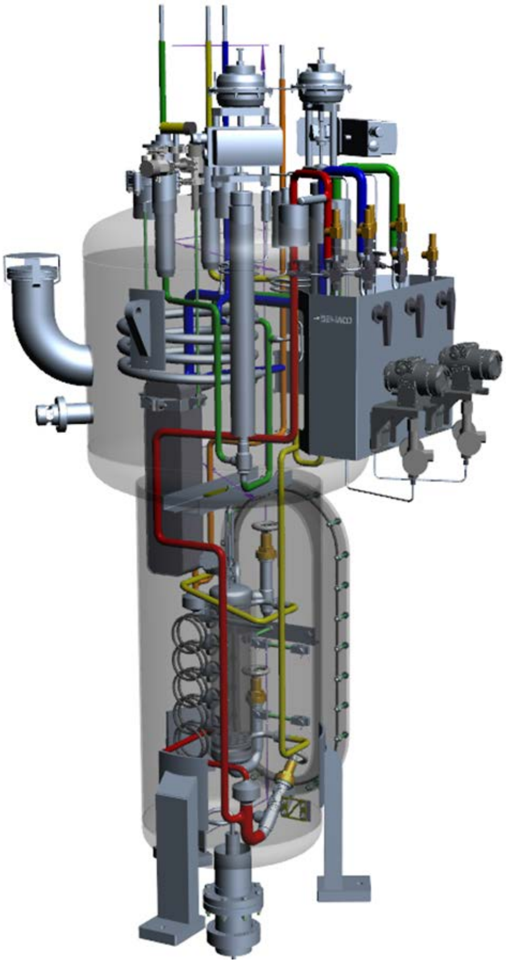
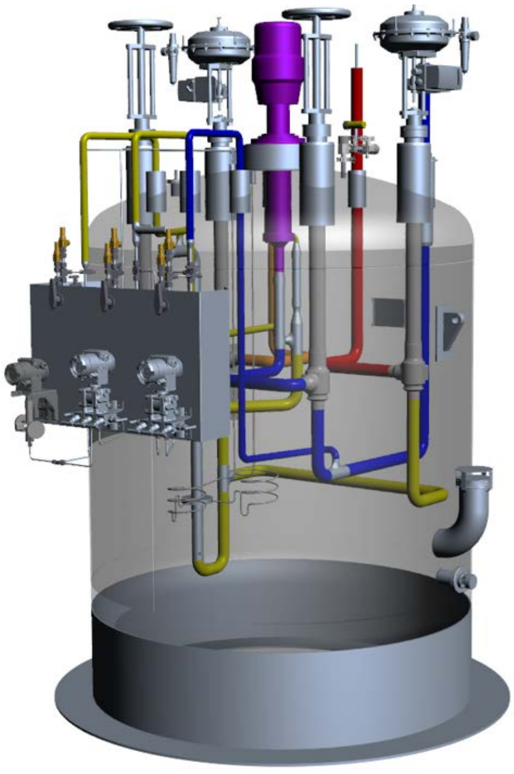


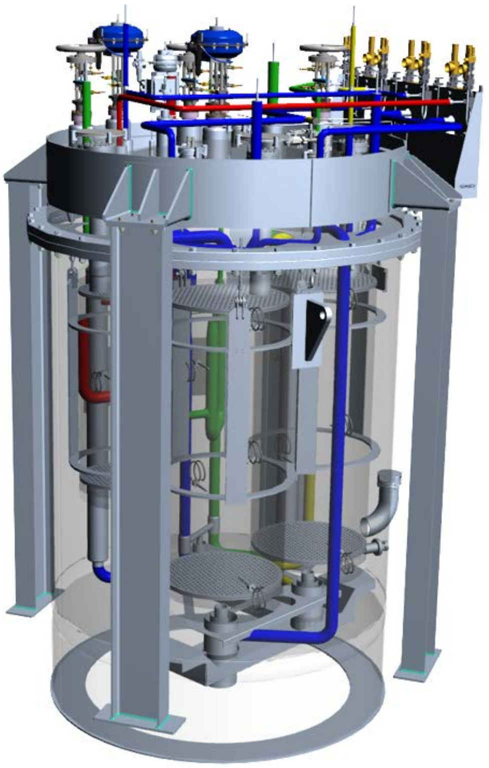
Figure 1. Condenser – Filter valve box for SBN-FD.

The design and packaging of a LAr pump is shown on figure 2. There are two LAr pumps installed in parallel for SBND cryostat and there is one LAr pump per each of the SBN-FD cryostat vessels. In addition, there are three LN2 pumps installed in parallel for SBN-FD nitrogen circuit. The design and packaging of the LAr filter skid is shown on figure 3. This skid has 620 kg of Cu and 80 kg of molecular sieve. It will be used initially for SBN-FD as a fill filter skid in addition to the stationary inline recirculation filters, and later moved to SBND to serve as the fill and inline recirculation filter skid.



Courtesy of Demaco

Figure 2. LAr pump.



Courtesy of Demaco

Figure 3. Portable LAr filter skid.

The Proximity cryogenics sub-system interfaces both an External and an Internal sub-system. The most intricate design solutions are for connecting the vacuum-jacketed piping carrying LAr and cold GAr to the ports on the top plate of a cryostat where ceramic electrical insulators need to be used to protect the cryostat electronics from the external noise.

The most critical penetration to the cryostat is the side penetration to the liquid volume. The design of the SBN-FD aluminium vessel provides for side penetration pipeline from the cold pressure vessel to the outside of the warm vessel with transition from bare to vacuum-jacketed pipe inside the insulation space. Immediately outside the cryostat, each pipeline is equipped with two safety shut-off valves installed in series upstream of the ceramic electrical insulator. The design of the SBND membrane cryostat requires special considerations due to a unique “sandwich” construction of the cryostat. Additionally, to prototype the technical solutions for the LBNF/DUNE project, SBND cryostat needs to use a cryogenic safety valve with a valve seal is inside the cryostat. Therefore, SBND cryostat, as well as other membrane cryostats installed at CERN, will have in-tank valves designed by Protego®. The advantage of Protego® in-tank valve design is that it prevents any leakage from the tank in the event of any external parts of the assembly getting damaged. It also means that maintenance work can be carried out on the actuator without any need to dismantle the pipeline or empty the tank. Protego® modified its SI/DP in-tank valve model to adapt to the “sandwich” design by GTT by incorporating vacuum jacket and expansion joints to eliminate forces from thermal contraction acting on each layer of the “sandwich”. An additional safety shut-off valve is installed downstream of the Protego® valve but upstream of the ceramic electrical insulator.

3.3. *Internal cryogenics*

The Internal cryogenics of the SBN-FD T300 cryostats is mostly reused from the ICARUS installation. One significant part that neither belongs to the Internal nor the Proximity sub-system of SBN-FD is the LN_2 shield, which is constructed of 42 extruded aluminum panels common to both cold vessels and positioned in between them and the passive insulation of the warm vessel.

Per requirements shown in table 1 and table 2, the Internal cryogenic sub-system of SBND is designed to provide LAr and GAr for piston-purge, cooldown, fill and normal operations via piping supported off the fixed top plate and positioned in the space outside the TPC volume, as shown on figure 4. The internal piping returns the LAr and GAr from cryostat to the condenser. The design of the Internal cryogenic infrastructure was shown to be successful in the Fermilab 35T cryostat operations [4].

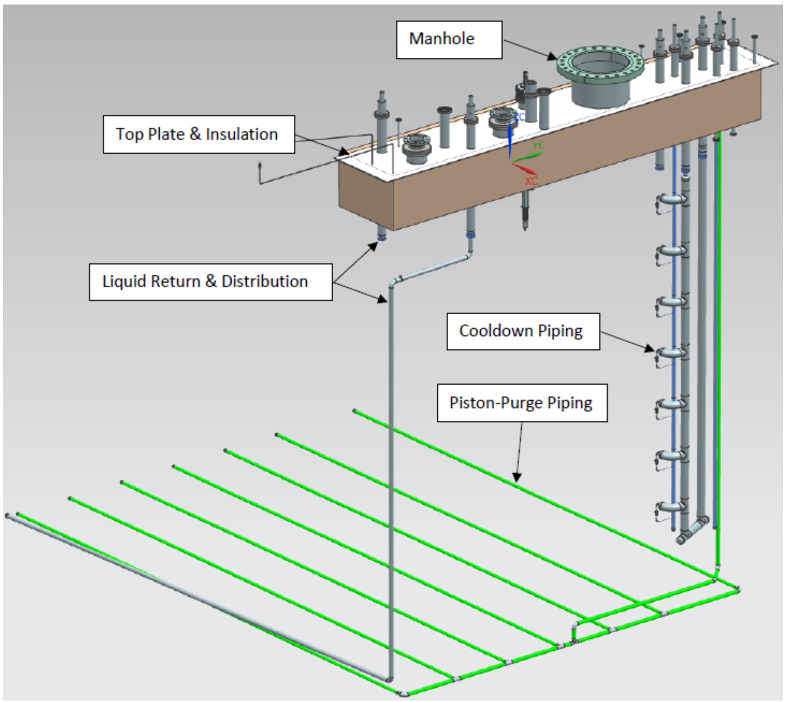


Figure 4. Piping layout of the SBND Internal cryogenic sub-system.

3.4. *Integration of External, Proximity and Internal cryogenic sub-systems*

The integration of three cryogenic sub-systems into a complete cryogenic plant presents several major challenges. As each of the cryogenic sub-systems is designed and manufactured by different institutions (CERN, INFN, Fermilab), they need to be integrated through piping, electrical and controls interfaces, fit into specific locations in the SBND and SBN-FD buildings (as shown on figure 5 for SBN-FD), and validated for safe operation per requirements under Fermilab contract with U.S. DOE. One of the requirements for successful integration is procedural acceptance of equipment designed per European standards for operations at Fermilab by demonstrating equivalency in safety levels compared to the U.S. governing codes listed in the Fermilab contract with DOE. It applies to standard components, e.g. vessels, piping or electrical, and unique components, e.g. cryostats. Fermilab is undertaking a major effort in establishing equivalency in safety performance between appropriate U.S. and International engineering design codes and standards. By mid-2017, Fermilab demonstrated such equivalency for pressure vessels, piping, certain pressure safety devices and electrical components designed and manufactured per European standards. Still, for number of unique components, e.g. SBND membrane cryostat and SBN-FD ICARUS cryostats, the validation is a thorough cross-institutional effort between CERN and Fermilab.

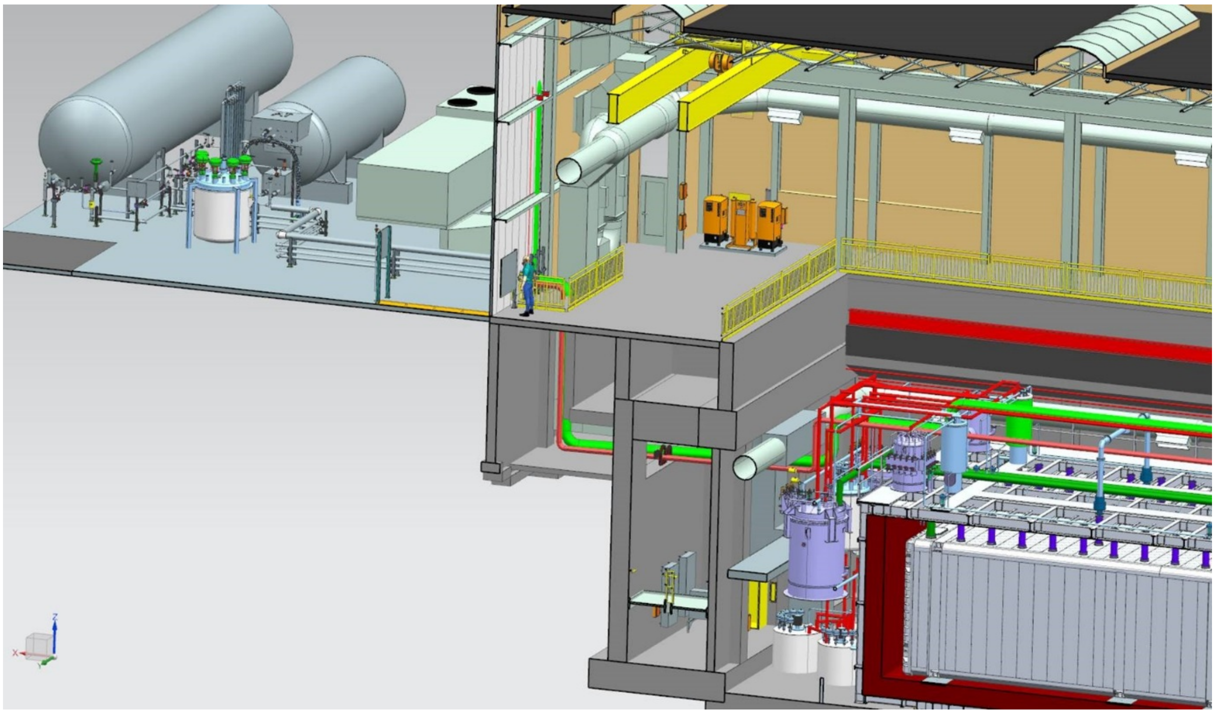


Figure 5. Proposed integration of cryogenic systems in the SBN FD building.

4. Conclusion

Fermilab and CERN are working together in the area of cryogenics to add two new neutrino detectors to the Neutrino Campus and Neutrino program based at Fermilab. Each laboratory has responsibilities and deliverables to start bringing systems online as early as in 2018. Each laboratory is in the design and fabrication mode at the time of this paper's writing. Equipment for External cryogenics is beginning to populate the two new buildings constructed for these detectors. In Europe, the Proximity cryogenics is being designed and fabricated by a commercial vendor under CERN engineering guidance.

Acknowledgments

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