Preliminary design of a helium cryogenic system for SAND detector at LBNF-DUNE near site

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Abstract. The Long-Baseline Neutrino Facility (LBNF) is providing a helium cryogenic system to support the superconducting solenoid magnet of the System for on-Axis Neutrino Detection (SAND) for the Deep Underground Neutrino Experiment (DUNE) Near Site at Fermilab in Batavia, IL. The design started in 2020 and construction is set to begin in the mid 2020's.The helium cryogenic system primarily consists of a helium refrigerator system, distribution valve boxes, vacuum-jacketed helium and nitrogen transfer lines, warm gaseous helium transfer system, instruments and control system, and gaseous helium storage tanks. It is designed to provide supercritical helium at around 3 bara and 5 K with expansion from 3 to 1.2 bara in the SAND cryostat and 70K forced cold gas helium to cool the thermal shields of the SAND cryostat. The SAND superconductive magnet is indirectly cooled through a liquid helium thermosiphon cycle. A pair of 3 kA leads is cooled by the gas helium vaporized from the liquid helium reservoir in the cryostat turret. The helium system will share the liquid nitrogen tank and liquid nitrogen phase separator with the Near Site Liquid Argon system. The helium recycle compressor system, GHe tanks and LN2 tank will be located on the Surface. The cryogenic facilities including refrigerator cold box, valve boxes and LN2 phase separator will be located on the shaft cryo-mezzanine in the underground cavern. The shaft connecting surface and cavern is more than 60 meter deep. The helium vacuum-jacketed transfer line between the cold box and the SAND magnet is more than 50 meter long. This paper presents the preliminary design of the helium cryogenic system including the design scheme, process flow diagram, heat load estimates, layout plan and so on.

1. Introduction

The Deep Underground Neutrino Experiment (DUNE), an international experiment with a US contribution, 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. It consists of underground detectors at two sites: Near Site (Fermilab, Illinois) and Far Site (Sanford Underground Research Facility, South Dakota).

The Long-Baseline Neutrino Facility (LBNF) is US Department of Energy (DOE) funded project with international contributions hosted by Fermilab. It provides the detector caverns and support infrastructure such as power and cooling to install and operate the DUNE detectors, and also provides a beamline to support 1.2 MW (upgradeable to 2.4MW later) proton beam used to produce high-intensity muon neutrino beam for the DUNE experiment.

The LBNF near site (NS) cryogenics will provide a set of helium cryo-system to support the superconducting solenoidal magnet in the near detector (ND) System for on-Axis Neutrino Detection

(SAND) component. The cryogenic infrastructure is designed to support the SAND magnet and has provisions to host a second refrigerator to support a Future Superconducting Magnet (FSCM), which would be incorporated in the scope at a later date.

The SAND helium cryo-system is primarily comprised of a helium refrigerator system, a SAND distribution valve box (SAND VB) with a build-in helium sub-cooler, vacuum-jacketed cryogen (helium and nitrogen) transfer lines (VJTLs), warm piping and valve system, gaseous helium storage and buffer tanks, liquid nitrogen system, instruments, monitoring and control system, and cryo-safety system including safety relief system and ODH analyses. The liquid nitrogen system supplied by the NS Cryo liquid argon system will provide liquid nitrogen for precooling the helium refrigerator cold boxes, cooling FSCM thermal shields and cooling FSCM high temperature superconducting current leads. The SAND helium system will share a LN2 phase separator with the near site LAr system.

This paper presents the preliminary design of the SAND helium cryogenic system including the design scheme, process flow diagram, heat load estimates, layout plan and so forth.

2. Cooling requirements

2.1. SAND superconducting solenoid magnet

The magnetized SAND beam monitor consists of a massive plastic scintillator target surrounded by low-mass tracking and an electromagnetic calorimeter (ECAL) inside a large superconducting solenoidal magnet. The electromagnetic calorimeter (ECAL) and superconducting solenoid magnet of the KLOE experiment built at INFN in Italy, which took data from April 1999 to March 2018, will be employed by the SAND at Fermilab [1].

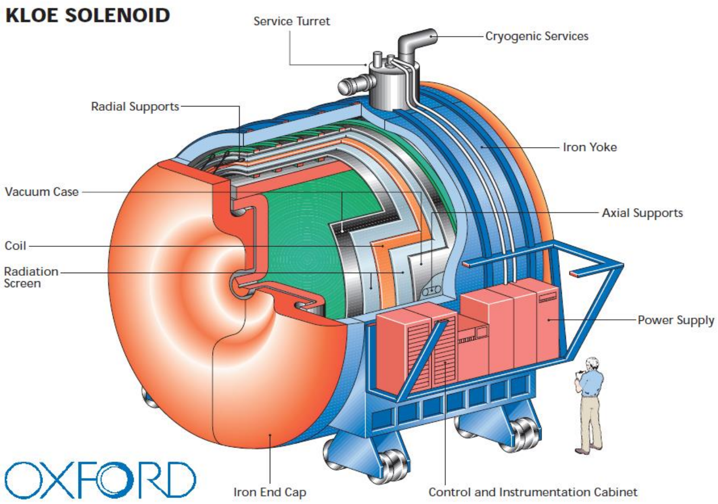

Figure 1. Original layout of the KLOE magnet (now renamed SAND).

The SAND magnet is an iron shielded superconducting solenoid coil indirectly cooled by a liquid helium thermosiphon cycle. It was manufactured by Oxford Instruments A.T.G. in England and named KLOE [1-3]. As shown in figure 1[2-3] , it was designed in conjunction with its iron yoke to produce 0.6 T field over a 4.3 m long, 4.8 m diameter volume. The coil is operated at a nominal current of 2.902 kA and the stored energy is 14.32 MJ. The coil is contained inside a cryostat positioned inside the return yoke. The cryostat has outer diameter of 5.76 m, inner diameter of 4.86 m and overall length of 4.40 m. The overall cold mass is about 8.5 tons and the mass of the SAND return yoke is 475 tons. The cryostat of SAND solenoid possesses its own local valve box (called as Service Turret), a JT valve and a liquid helium reservoir of about 150 liters. All the controls associated with magnet functioning including cool down and warm up are an integral part of the magnet system. Table 1 summarizes main parameters of SAND solenoid and its cryostat [1-3].

Table 1. Main parameters of SAND magnet and its cryostat with service turret.

Coil assembly	
Central Field (T)	0.6
Layers	2
Turns/layer	368
Ampere-turns	2.14 MA-T
Operating/Design Current (A)	2902/3000
Inductance at full field (H)	3.4
Stored energy (MJ)	14.32
Discharge voltage (V)	250
Peak Quench Temperature (K)	80
Conductor	10 mm x 5 mm Al stabilized NbTi Rutherford cable, wrapped with two half lapped layers of 0.125 mm glass tape.
Coil winding method	internally wound coil
Coil support bobbin	5083 Aluminium cylinder
Coil shell inner diameter (m)	5.19
Coil Cold mass (ton)	~8.5
Radiation shield	two 5 mm thick solid aluminium cylinders with cooling pipes attached to the outside of each
Service Turret	supply and control of LHe including JT valve, supply and control of 70 K helium for radiation shields, gas cooled 3 kA current leads, Instrumentation connections to the coil and radiation screens, LHe reservoir: ~150 liter

2.2. Cooling requirement of SAND magnet

Table 2 presents the cooling requirement of SAND magnet [4].

Table 2. Cooling requirements of SAND magnet.

Coil cooling scheme	Indirectly cooled through a LHe thermosiphon cycle; gaseous helium at 5.2 K is injected at 3 bara from the helium refrigerator and liquefied through a Joule-Thomson valve into a LHe reservoir.
Thermal shield cooling method	cooled by 50~70 K forced gas helium flow from the helium refrigerator system
Current leads	A pair of 3 kA leads, cooled directly by liquid helium from LHe reservoir in the Turret, 300 K GHe returns to the suction side of helium recycle compressor of the refrigerator system.
4 K heat radiation and conduction (W)	55
Current leads' GHe cooling flow (g/s)	0.4 g/s (test data)
70 K heat radiation and conduction (W)	530
Operating temperature (K)	4.42~4.5
Operating pressure (bara)	1.2~1.3
300-70K cool down scheme	300 K and 70 K GHe mixing forced flow, 4~5 bara, ~2 weeks
70-4K cool down scheme	5.2 K 3 bara GHe forced flow, ~1 week

2.3. FSCM for ND-GAr detector

A superconducting magnet (FSCM) consisting of solenoid coils to work at less than 5 K has been under R&D to provide the 0.5 T magnetic field for the ND-Gar detector [5-6]. The ND-GAr detector is a high pressure gaseous argon (10bar) time projection chamber (HPgTPC) to be surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field.

2.4. Cooling requirement of FSCM magnet

According to the current conceptual design of the FSCM [5], the solenoid coils are designed to be indirectly cooled through liquid helium thermosiphon cycle. The gaseous helium at 5.2 K is injected at 3 bara from the helium refrigerator and liquefied through a Joule-Thomson valve into a LHe reservoir connected to the coils using cooling piping attached to their bobbins. The 70 K thermal shields surrounding the coil cold mass will be cooled by liquid nitrogen. The binary leads (5~10 kA) comprised of copper and high temperature superconductor (HTS) will be applied for the FSCM coils. The joints of cold ends of Cu leads and warm ends of HTS leads are cooled by liquid nitrogen circuit, and the cold ends of HTS leads are cooled by liquid helium. Since the FSCM cryostat and its coil cooling system is still under conceptual design, and there are no further detailed cooling requirements available such as estimates of heat loads.

3. Design Scheme

The preliminary design of the DUNE NS helium cryogenic system has been carried out since Dec-2019, According to the above cooling requirements of SAND magnet, considering later installation of FSCM still under development, two individual helium refrigerator systems sharing gas helium storage tanks and liquid nitrogen phase separator are proposed for the DUNE NS helium cryo-system, as shown in Figure 2. Figure 3 shows the preliminary design of the process flow diagram (PFD) of SAND helium cryogenic system. The SAND magnet and one local KLOE valve box connected with a multiple-channel vacuum jacketed helium transfer line (MCTL, 5-in-1) will be supplied by INFN, Italy. The 5-in-1 MCTL is used for connection between the KLOE valve box and the SAND magnet service turret. The KLOE valve box is used for connection between the 5-in-1 MCTL and a 4-in-1 MCTL from the refrigerator system. The 5-in-1 MCTL is composed of a 70 K GHe supply line, a 80 K GHe return, a 3 bara/5 K supercritical helium (SHe) supply line, a 4.4~4.5 K return line, a 300-10 K cool down GHe return line and a vacuum piping to enclose all the five lines in it [4]. The designed helium cryo-system will provide the SAND magnet with the following streams of helium gas:

- Supercritical Helium (SHe) at 5.2 K and at appropriate pressure (3 bara). Inside the service turret on top of the magnet cryostat, after the final expansion from 3 bara to 1.2 or 1.3 bara, the liquid helium necessary to the operation of the superconducting magnet is collected in the liquid helium reservoir, and then delivered to the magnet by thermos-syphon circuit. It is also used for the cooling down of the magnet from 70-100K to around 5 K.
- Helium gas at intermediate temperature (50 -70 K, 4-5 bara): necessary for the cooling down of the magnet from room temperature to 70-100K and to run the 70 K thermal radiation shields of the magnets.
- Helium gas at room temperature (-300 K, 13~15 bara and 4~5 bara): necessary for purge and pumping of the whole cryogenic system and the cooling down of the magnets from room temperature to 70-100 K through mixing with 70 K GHe.

The multi-channel vacuum jacketed helium transfer line (MCTL, 4-in-1) connecting the refrigerator system with the magnet is about 55 m long. The heat load generated by the MCTL is estimated about 27.5 W. The heat load from the MCTL will cause temperature increasing of the supercritical helium before the J-T valve in the magnet service turret, and then result in no enough liquid helium production through the J-T valve to cool the magnet. One liquid helium vessel with a built-in heat exchanger is adopted to cool the supercritical helium delivered from cold box to the magnet with a temperature lower than 5 K. The built-in heat exchanger is made of coiled copper tube and called as LHe sub cooler.

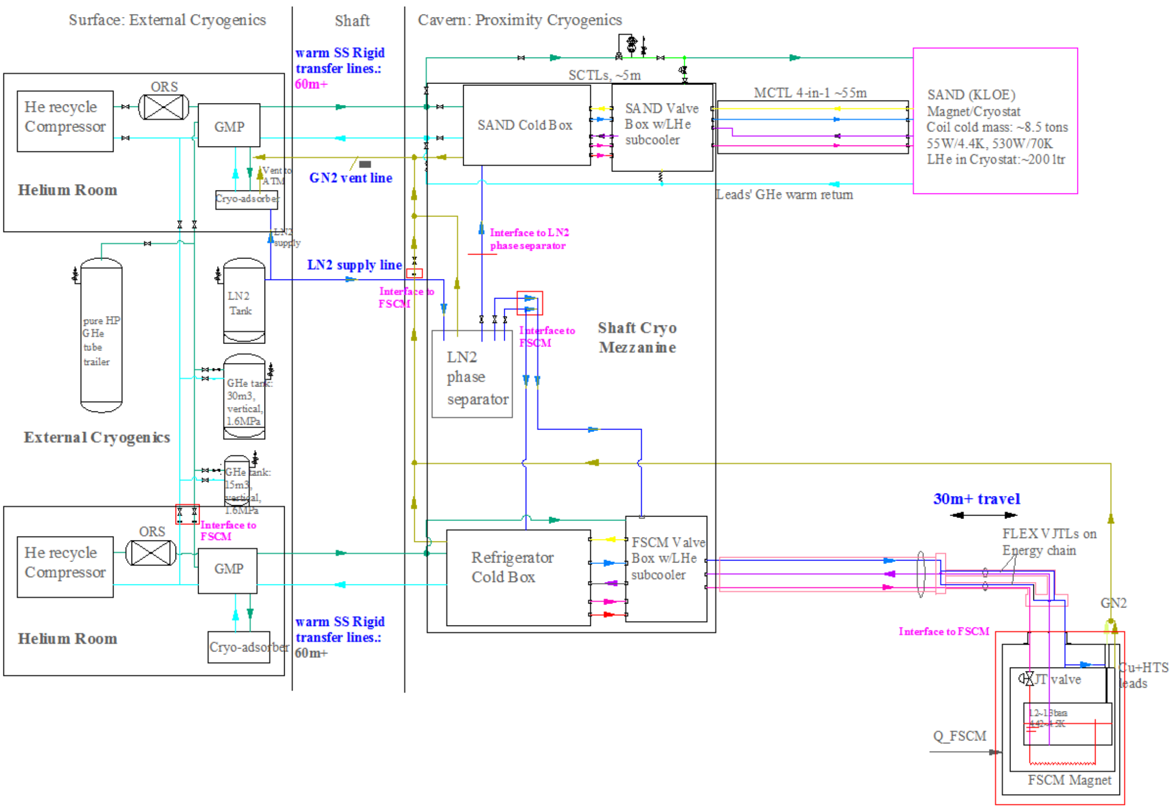

Figure 2. Design scheme of DUNE NS helium cryo-system

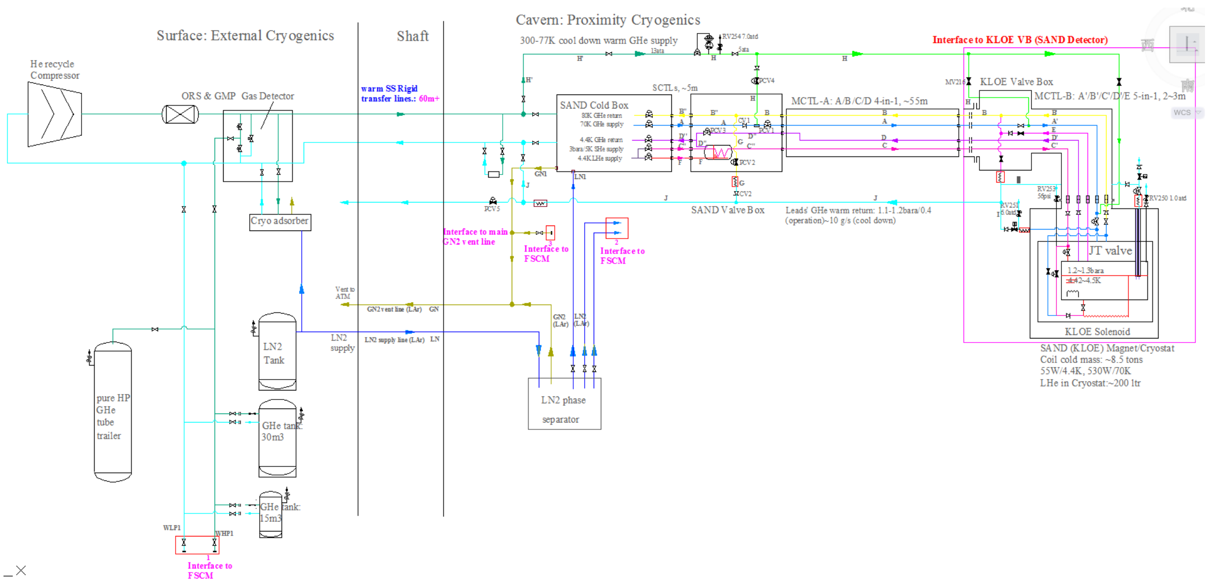

Figure 3. Preliminary PFD of DUNE NS SAND helium cryo-system

4. Operation Modes

The SAND helium cryo-system is designed to implement the following operation modes and protect the SAND magnet from damage at various failure modes:

- Cool down:
    1) to cool down magnet and thermal shields from room temperature to 70-100 K (300-77 K mode) by mixed 300K and 70K forced GHe flow;

2) to cool down magnet and current leads from 70-100 K to 4.4 K (77-4 K mode) by supercritical helium flow, and the thermal shields will be kept cooled at 70 K by 70 K GHe flow.

- Steady state operation: to continuously provide necessary cooling capacity and support SAND magnet at stable operation.
- Quench process: The quench phenomenon is the sudden return to a condition of normal conductivity of a superconducting conductor. During quench process, the joule heating of the conductor caused by its electrical resistance and the discharge into the magnet of the energy stored in the magnetic field generated by itself, causes a very fast and impressive overheating of the superconducting coil which probably results in permanent damage to the magnet. All the liquid helium contained in the magnet suffers a dramatic and sudden (e.g., few seconds) evaporation to absorb the heating generated by the magnet and keep the magnet from burning out. Once quench occurs, the magnet stops operating, must be set in a safe situation. As shown in Table 1, the storage energy of SAND magnet is 14.32 MJ and its peak quench temperature is 80 K.
- Re-cool down after quench: After quench, the magnet can be re-cooled down to superconducting condition and then fully re-energized.
- Warm up: bring magnet from 4K to 300K respecting the magnet thermal constraints.
- Failure modes include the following possible scenarios: power outage, loss of insulating vacuum, refrigerator malfunction and so forth; the cryo-system and SAND magnet will be set in a safe situation at various failure modes.

5. Cryogenic Facilities

As shown in figure 3, the SAND helium cryo-system is primarily comprised of:

- A customized helium refrigerator system with a cold box adapting liquid nitrogen pre-cooling and advanced turbine expanders. The cold box is customized with controls and ports of 70 K GHe supply, 80 K GHe return, 3bara supercritical helium supply, 4.4 K LHe supply and 4.4 K GHe return. The refrigerator scope of supply also includes a single water-cooled oil-flooded screw compressor, an oil removal skid, gaseous helium management panel and cryo-adsorber.
- A SAND distribution valve box with a built-in LHe sub cooler (100~150 litre): its functions could be integrated into the refrigerator cold box.
- Single-channel vacuum-jacketed helium cryo-transfer lines (SCTLs, ~5m long) between cold box and SAND VB includes: one 5 K 3 bara supercritical helium supply, one 4.4 K liquid helium supply to LHe subcooled vessel, one 4.4~4.5 K 1.2~1.3 bara gas helium return from coil, one 50~70 K gas helium supply for cool down & thermal shields, and one 60~80 K gas helium return from thermal shields.
- Refrigerator cold box (CB) precooling liquid nitrogen supply SCTL (~20m long) and cold gas nitrogen return SCTL (~20m long) between LN2 phase separator and CB.
- A 4-in-1 MCTL between SAND VB and local KLOE VB (~55m long) includes: one 5 K 3 bara supercritical helium supply, one 4.4~4.5 K/1.2~1.3 bara gas helium return from coil, one 50~70 K gas helium supply for cool down & thermal shields, one 60~80 K gas helium return from thermal shields, and the above four cryo-lines are enclosed in a warm vacuum jacket. The 60~80 K gas helium return will be also used for cooling the intermediate temperature thermal shield in the MCTL in order to lower down the heat load to 4 K lines.
- Warm GHe piping and valve system runs 60m deep from the Surface building through the Shaft into the Cavern. It includes 300 K 13 bara compressor discharge, 5 bara gas helium used for cool down, pumping and backfill, and 300 K 1.05-1.3 bara gas helium low pressure return from leads, quench, cool down, any failure, etc.
- Gas helium storage/buffer tanks: vertical, one 15m^3 and one 30m^3, 1.6MPa design pressure.
- Instrumentation, gas analysis, controls and human-machine interface.
- Cryo-safety features including overpressure relief system and Oxygen Deficiency Hazard (ODH) mitigation.

6. Layout Plan

Figure 4 shows the overall layout plan of the NS LHe cryo-system. Two GHe storage/buffer tanks and helium compressor system will be located outside near the surface building. The warm helium recycle compressor (WCS), oil removal system and gas management panel (ORS & GMP), control cabinet of the WCS & ORS, external LN2-cooled cryo-adsorber will be accommodated in surface Helium Room. The cryogenic facilities including cold box (CB), SAND VB and LN2 phase separator will be located on the Cryo-Mezzanine in the underground Cavern. The shaft connecting ground and underground is more than 60 meter deep. Underground, the horizontal distance between the refrigerator and the SAND magnet is at least 30 meters.

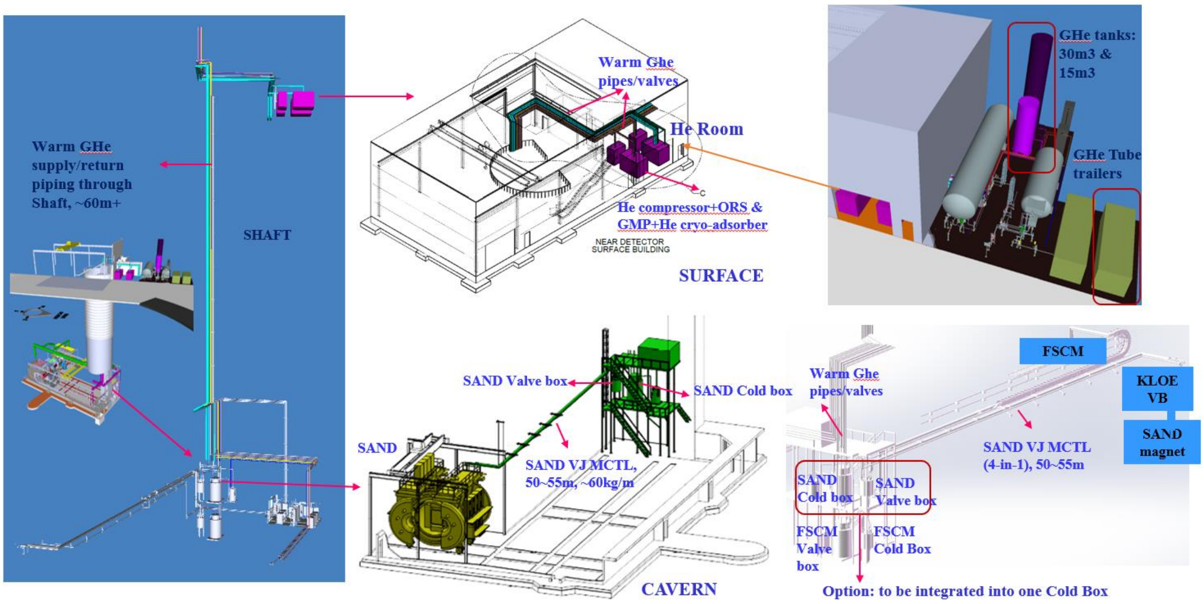

Figure 4. Overall layout plan of the NS Cryo LHe cryo-system

7. Estimated Heat Loads

Table 3-4 presents the estimated heat loads based on the current preliminary design of the SAND helium cryogenic system.

Table 3. Estimates of heat loads at 4 K.

	q_4K (W/m)	L (m)	Q_4K (W)
Single rigid cryo-transfer lines between CB & SAND VB	0.50	5	2.5
	0.50	5	2.5
	0.50	5	2.5
4-in-1 Multi-channel Rigid cryo-transfer lines	0.50	55	27.5
SAND VB			7.7
Sub-total			**42.7**
Sub-total Heat load from transfer system w/50% contingency			64.0
SAND (KLOE) cryostat & turret			55.0
Sub-total 4K load			**119.0**
3KA Current leads' cooling flow		one pair	0.4 g/s
4 K total heat load w/contingency			153.0

Table 4. Estimates of Heat loads at 70 K.

	q_70K (W/m)	L (m)	Q_70K (W)
Single rigid cryo-transfer lines between CB & SAND VB	0.50	5	2.5
	0.66	5	3.3
4-in-1 Multi-channel Rigid cryo-transfer lines	3.00	55	165.0
SAND VB			16.5
Sub-total			**187.3**
Sub-total Heat load w/50% contingency			281.0
SAND (KLOE) cryostat & turret			530.0
70K heat load w/contingency			**811.0**

Based on table 3-4, the required cooling capacity is summarized as follows:

- ≥ 120 W at 4.4 K
- 0.4 g/s GHe flow for cooling current leads
- ≥ 811 w at 70 K

8. Conclusion

The preliminary design of LBNF/DUNE-US Near Site helium cryogenic system to support SAND magnet has been carried out since Dec-2019, which is upgradable to serve the Future Super conducting Magnet of ND-GAr detector later as well. The design scheme for the NS cryo helium system was proposed and studied. The preliminary P&IDs were designed, the preliminary layout plans were developed, and the preliminary calculations and analyzes were performed. At present, the final design is being carried out. The procurement and fabrication will start at the end of this year. The installation is planned to start end of 2026.

9. References

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