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Cryocooled cold trap system for the SuperCDMS dilution refrigerator

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Abstract. Operating 6,800 feet underground at the SNOLAB facility in Sudbury, Ontario, Canada, the dilution refrigerator-cooled SuperCDMS SNOLAB (Super Cryogenic Dark Matter Search at the Sudbury Neutrino Observatory Laboratory) experiment has been designed for maximum cryogenic up-time and remote operations. A key element in achieving these goals is a pair cold traps in the helium circulation stream of the dilution refrigerator; the first operating near liquid nitrogen temperatures and the second operating near liquid helium temperatures. Previous experience with the CDMS experiment, located underground at the Soudan Under-ground Laboratory, has given significant operational experience with dilution refrigerator cold traps and has solidified the demand of a system of dual cold traps. Unlike the CDMS-era system, the new SuperCDMS system will feature a cryocooler powered liquid nitrogen re-liquefying system (as opposed to regular under-ground re-filling of cold trap dewars using portable nitrogen dewars) and a cryogen-free 4 K cold trap, which eliminates the need for a bath of liquid helium.

1. Introduction

SuperCDMS SNOLAB is an experimental collaboration searching for dark matter using extremely sensitive germanium and silicon detectors cooled to milli-Kelvin temperatures. The experiment must operate at approximately 2,070 meters (6,800 feet) below ground at the SNOLAB underground laboratory in Ontario, Canada [1] to achieve its physics goals, as described in [2], amongst others. To reach and sustain the required milli-Kelvin temperatures, a Leiden Cryogenics BV [3] model LC-CF2500-Maglev-2PT dilution refrigerator will be used. The refrigerator has been specified to provide the following performance specifications simultaneously:

Table 1. Performance parameters of the Leiden Cryogenics BC model LC-CF2500-Maglev-2PT dilution refrigerator used for the SuperCDMS SNOLAB experiment.

Dilution refrigerator stage	Available cooling power
Still	15 mW at 800 mK
Cold plate	350 μW at 230 mK
Mixing chamber	5 μW at 10 mK

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The SuperCDMS SNOLAB collaboration will modify the Leiden Cryogenics dilution refrigerator system based on previous extended-uptime dilution refrigerator operational experience gained during operational runs of the CDMS experiment, as described in [4] for example. For reference, the CDMS experiment has sustained base dilution refrigerator temperatures or similar for periods approaching one year in duration.

Perhaps the most significant modification to the as-built Leiden Cryogenics system will be the addition of custom liquid nitrogen and 4 K cold traps into the helium circulation stream. These cold traps will enable the removal of contamination in the helium mixture circulation stream of the dilution refrigerator and offer the ability of cold trap regeneration quickly and in situ. The details of both these cold trap systems and their design considerations are discussed herein.

2. Overall system design

From a cryo-mechanical perspective, the extreme depths put constraints onto system design typically not seen in sea-level applications. Some of these constraints include remote operations and sensor readback abilities, sizing limitations due to the space available on the elevator cage which travels from the surface to the 2,070 meter (6,800 foot) level of the mine, an elevated ambient pressure of 127.6 ± 6.9 kPa absolute (18.5 ±1 psia) (depending on HVAC system loads, which maintains the underground lab space at levels exceeding Class 2000 cleanroom specifications), and the difficulty of transporting items such as trained personnel or portable Dewars of liquid cryogen down into the laboratory space. Additional details of the overall cryogenic system design of the SuperCDMS SNOLAB experiment are provided elsewhere, such as in [5], however, the understanding of all the mentioned constraints (and others) were instrumental in the design of the cold trap systems discussed in this paper.

Both cold trap systems are located in succession to each other between the gas handling system and the dilution refrigerator unit (with the liquid nitrogen cold traps being placed upstream of the 4 K cold traps). To clarify, a cold trap system refers to an assembly of individual cold traps, vacuum and pressure vessels, cryocoolers, and miscellaneous fittings, instrumentation, and other accessories whereas the term 'cold trap' refers to the individual piping system in which the dilution refrigerator helium mixture circulation stream gets filtered and flows through. The SuperCDMS SNOLAB cold trap system as a whole contains a single liquid nitrogen cold trap system which can hold a quantity of 4x individual liquid nitrogen cold traps (liquid nitrogen cold traps are designed and manufactured by Leiden Cryogenics) and a single 4 K cold trap system which can hold a quantity of 2x individual 4 K cold traps (designed at Fermilab). A piping and instrumentation diagram can be seen in Figure 1 for the liquid nitrogen cold trap system (containing in this case 2x individual liquid nitrogen cold traps, as seen in off-plot connectors 947 and 949) and in Figure 2 for the 4 K cold trap system. Isometric views of three dimensional models of these systems are seen in Figure 3 for the liquid nitrogen cold trap system and Figure 4 for the 4 K cold trap system.

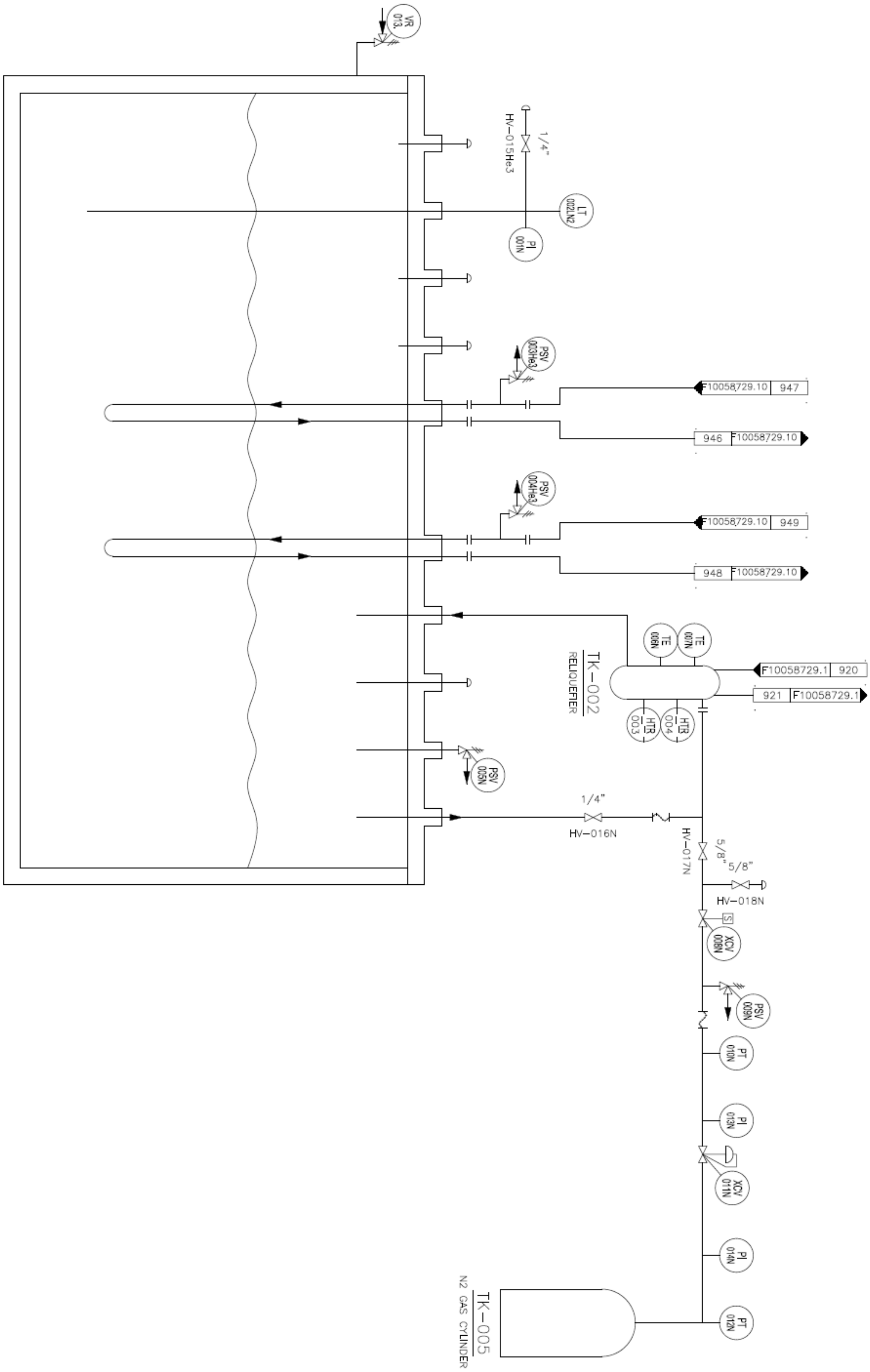

Figure 1. Liquid nitrogen cold trap system Piping and Instrumentation Diagram.

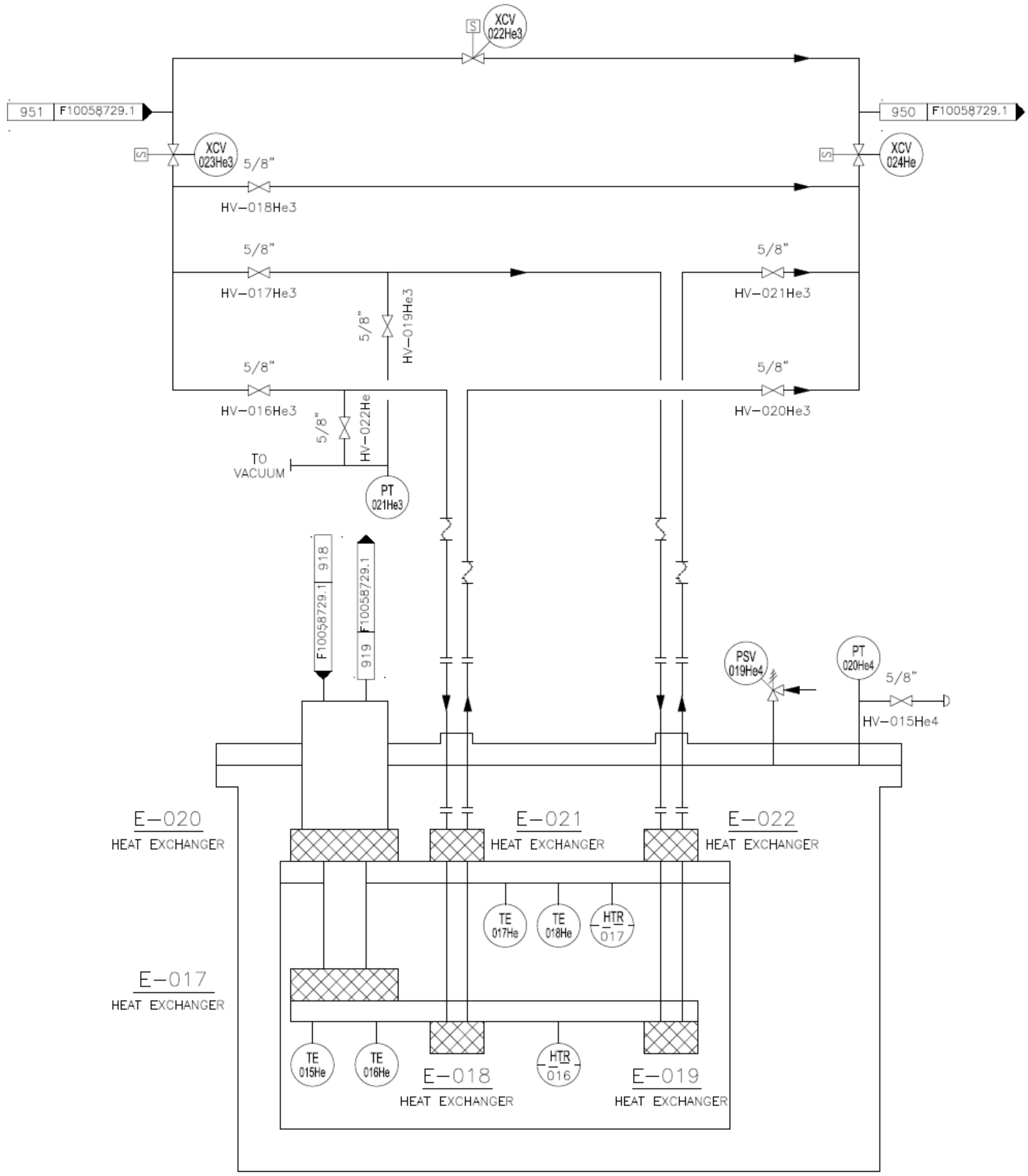

Figure 2. 4 K cold trap system Piping and Instrumentation Diagram.

3. Liquid nitrogen cold trap system

The objective of this system is to provide a sealed space where charcoal liquid nitrogen cold traps mounted to KF-50 flanges (customized from a standard Leiden Cryogenics design and provided by Leiden Cryogenics) can reside inside a bath of liquid nitrogen near ambient external pressure. The bath of nitrogen will remain near liquid temperatures by utilizing the cooling power available from a Cryomech [6] AL60 Gifford-McMahon cryocooler with heaters affixed near its cold head (controlled by a Lake Shore Cryotronics [7] Model 336 temperature controller) to appropriately regulate temperature. Operational experience gained during system commissioning indicates that system temperatures do not approach the freezing temperature of nitrogen – conduction heat loads, either through metal walls or through the nitrogen gas in contact with warm walls of the inner vessel, provide enough heat load to keep the aforementioned cryocooler running above 65 K at all times.

To perform this function in a quasi-closed cycle mode, the liquid nitrogen cold trap system Dewar integral to the vacuum shell of the system is initially filled with liquid nitrogen via a bayonet from a 160 L portable liquid nitrogen dewar until the internal liquid nitrogen cold trap system nitrogen storage space is cold and filled appropriately with liquid nitrogen. During this process, excess nitrogen vapor is vented through at minimum one open KF-50 port on the top plate. Next, the portable liquid nitrogen Dewar bayonet is removed from the system, any open ports are sealed, and the cryocooler is turned on and regulated to the appropriate temperature. As heat enters the system and boils off the liquid nitrogen, excess vapor leaves the dewar space of the liquid nitrogen cold trap system through the multiple connection port of Figure 3 (which is also valve HV-016N as seen in Figure 1) and makes its way into the reliquefier cryocooler. Inside of the reliquefier, an approximately 3 inch square by 6 inch long finned copper block with embedded temperature sensors and heaters (epoxied into the block of copper) is bolted to the cryocooler cold head. As the boil off nitrogen vapor passes by the fins of the aforementioned attachment, it condenses into a liquid and drains back into the system liquid nitrogen dewar space of the liquid nitrogen cold trap system (as seen in the bottom left line exiting TK-002 of Figure 1). Liquid nitrogen level is monitored by the output of transmitter LT-002N2, which is an American Magnetics, Inc. [8] capacitive probe with a Model 1700 readout, and can be tuned by adding warm gaseous nitrogen from a cylinder TK-005 of Figure 1. System pressure is constantly maintained at 20.7 kPa (3 psid) by PSV-005N, which has been sized for the cases of cryocooler failure and loss of insulating vacuum.

If, for whatever future reason, the liquid nitrogen cold trap system needs to be pumped out (for example, leak detection with a helium mass spectrometer leak detector) manual valve HV-018N can be utilized. Overall, the design of the liquid nitrogen cold trap system greatly reduces the amount of monitoring and intervention needed by trained operators, as opposed to traditional dry dilution refrigerator cold trap systems immersed in an open dewar of liquid nitrogen. Tasks such as LN2 filling, do not need to be performed locally (note valve XCV-008N is a solenoid actuated control valve in Figure 1) or at all with this system. Maintenance (such as charcoal trap regeneration) will be performed on an as-needed basis, utilizing this systems ability for in situ cold trap removal.

To perform an in situ cold trap regeneration (if required), system pressure is vented through manual valve HV-018N of Figure 1, until the over-pressure protection ring of the KF-50 flange being removed (containing an individual Leiden Cryogenics cold trap) can be safely removed. After the individual cold trap is removed and set aside for regeneration, a blank KF-50 flange is put onto the port of the removed cold trap, and the liquid nitrogen cold trap system, at this point containing at least a single operating cold trap, can continue to run.

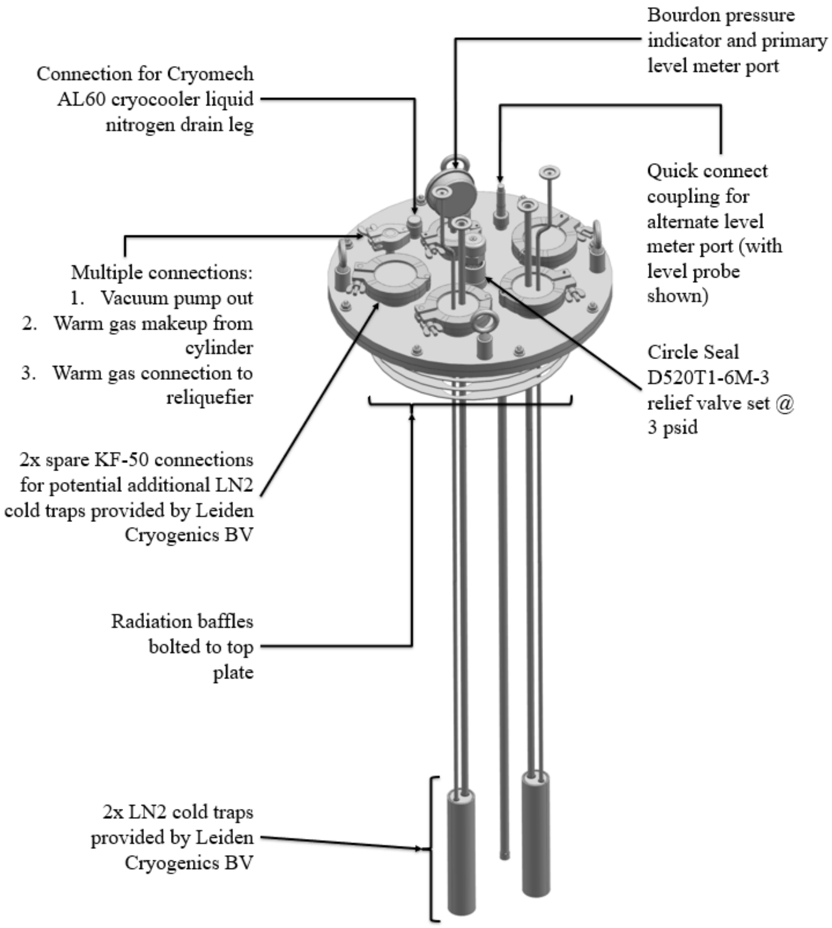

Figure 3. Liquid nitrogen cold trap system 3D model.

4. 4 K cold trap system

This system provides an additional trap for the helium mixture circulation stream near 4 K to remove any impurities not removed by the liquid nitrogen cold trap system (such as neon). This 4 K trap system consists of stainless steel tubing brazed onto machined copper blocks which are bolted to the respective stages of a Cryomech PT-415 HeRL cryocooler. This system does not contain helium in the form of a liquid bath, as all low temperature regulation is done via conduction cooling through thermal-mechanical adapter plates using the heat removal available from the cryocooler.

This system is easy-to-install as each cold trap contains demountable Swagelok [9] VCR® connectors near the upper KF flange attaching the cold traps to the 4 K cold trap system. Each stage of the cryocooler has an adapter plate affixed to it via bolts, and onto this adapter plate, the respective heat sinking copper block of the cold trap gets bolted onto. Thermal isolation between the PT1 and PT2 stages is accommodated with Hose Master [10] Pressureflex HP corrugated metal hoses.

As with all low temperature helium mixture circulation cold traps, the inside of the tubing of the SuperCDMS SNOLAB 4 K cold traps does not contain charcoal; instead, contamination simply "freezes out" onto the inside diameter of the tubing. Basic calculations were performed when sizing this system, which studied the variation of gas temperature and tube wall temperature with respect to length of tube between different heat sinking stages (such as 300 K, 50 K, and 4 K), so that the overall length of the 4 K cold trap tubing would suffice per the requirements of the overall SuperCDMS SNOLAB dilution refrigerator system. The aforementioned calculation also took into account the pressure drop of the helium circulation stream, which was deliberately kept to a reasonable minimum, so that the added contribution of fluid frictional heating could be dismissed. Other aspects, such as thermal contact resistance between the 'adapter plate bolted to the PT2 stage' and the PT2 stage of the cryocooler (see Figure 4), were not studied during the design of this system. If the reader is interested, an excellent review of pressed copper and gold-plated copper contacts is presented by Dhuley in [11].

This system does not offer hot-swapping capabilities. If a regeneration is desired, the 4 K cold trap system can be bypassed by remotely closing pneumatically actuated control valves XCV-023He3 and XCV-024He3, as seen in Figure 2, and by opening control valve XCV-022He3 and relying temporarily on a small internal 4 K cold trap integral to the dilution refrigerator (provided by Leiden Cryogenics). The 4 K cold traps of the 4 K cold trap system can then be warmed up and pumped out by opening valves HV-019He3 and HV-022He3. After the traps are cleared, the valve actuating process is reversed and the system is again ready to serve as the primary 4 K cold trap for the dilution refrigerator system. It is estimated that the regeneration of the 4 K cold trap system will take 24 hours to complete.

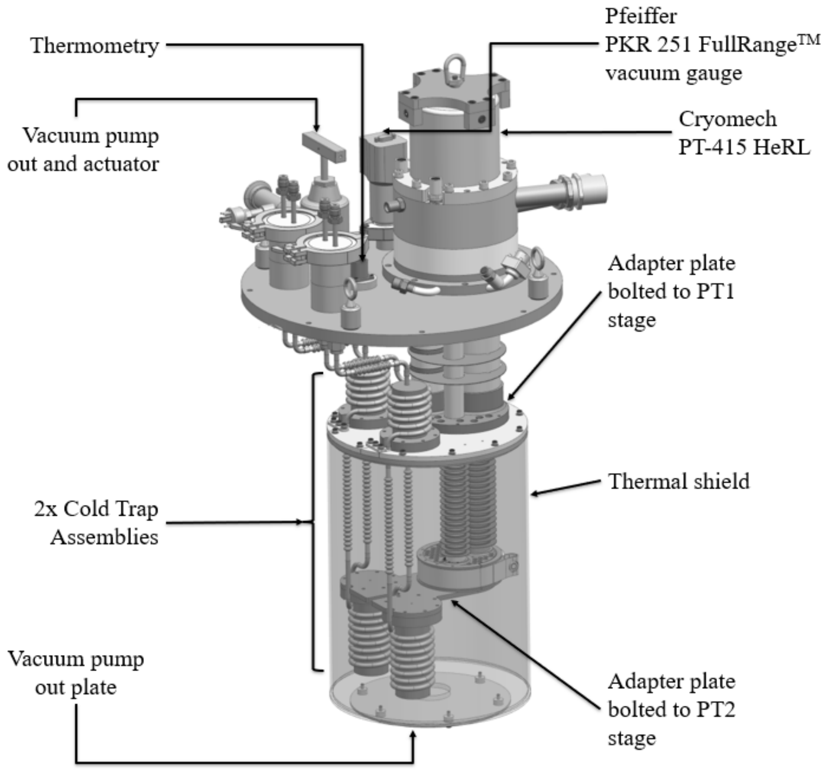

Figure 4. 4 K cold trap system 3D model.

5. Summary

Based on experience gained during the operation of the CDMS experiment, the SuperCDMS SNOLAB dilution refrigerator system has been modified with customized cryocooled liquid nitrogen and 4 K helium cold trap systems to enhance dilution refrigerator base temperature uptime and remote operations capabilities. It is the goal of the SuperCDMS SNOLAB collaboration to, amongst others, finish the testing of both the dilution refrigerator and cold trap systems at Fermilab, ship and install both systems underground at the SNOLAB facility, and begin experimental operations within the next two years.

For visual reference, a photograph of both liquid nitrogen and 4 K cold trap systems is provided below in Figure 5.

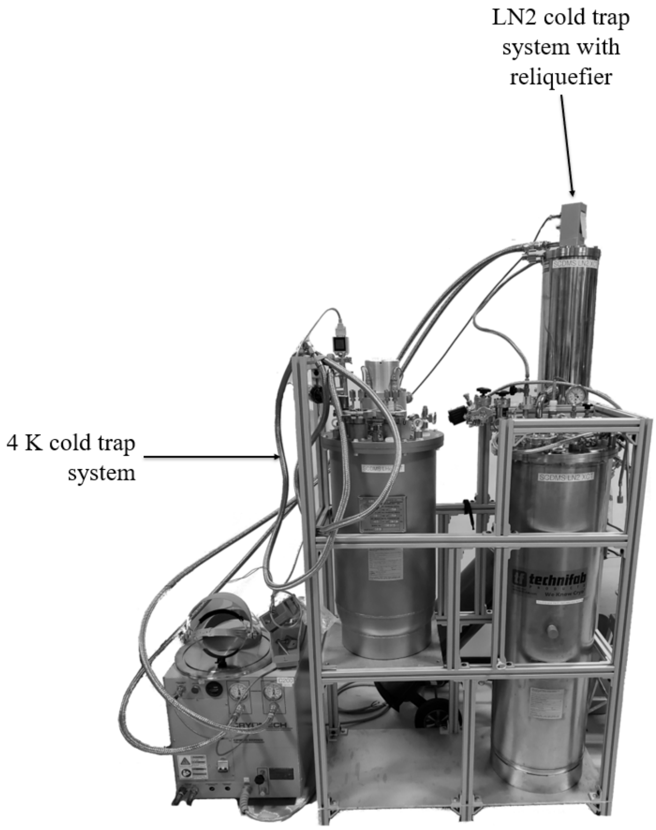

Figure 5. Complete SuperCDMS SNOLAB cold trap system with Cryomech CP800 series compressor on the left for scale.

6. References

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[6] Cryomech Incorporated, 113 Falso Drive, Syracuse NY 13211

[7] Lake Shore Cryotronics, 550 Tressler Drive, Westerville OH, 43082-7587

[8] American Magnetics Incorporated, 112 Flint Road, Oak Ridge TN, 37830

[9] Swagelok Company, 29500 Solon Road, Solon OH, 44139

[10] Hose Master Incorporated, 1233 East 222nd Street, Cleveland OH, 44117

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Acknowledgements

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