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# The cryogenics design of the SuperCDMS SNOLAB experiment

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**Abstract.** The Super Cryogenic Dark Matter Search (SuperCDMS) experiment is a direct detection dark matter experiment intended for deployment to the SNOLAB underground facility in Ontario, Canada. With a payload of up to 186 germanium and silicon crystal detectors operating below 15 mK, the cryogenic architecture of the experiment is complex. Further, the requirement that the cryostat presents a low radioactive background to the detectors limits the materials and techniques available for construction, and heavily influences the design of the cryogenics system. The resulting thermal architecture is a closed cycle (no liquid cryogen) system, with stages at 50 and 4 K cooled with gas and fluid circulation systems and stages at 1 K, 250 mK and 15 mK cooled by the lower temperature stages of a large, cryogen-free dilution refrigerator.

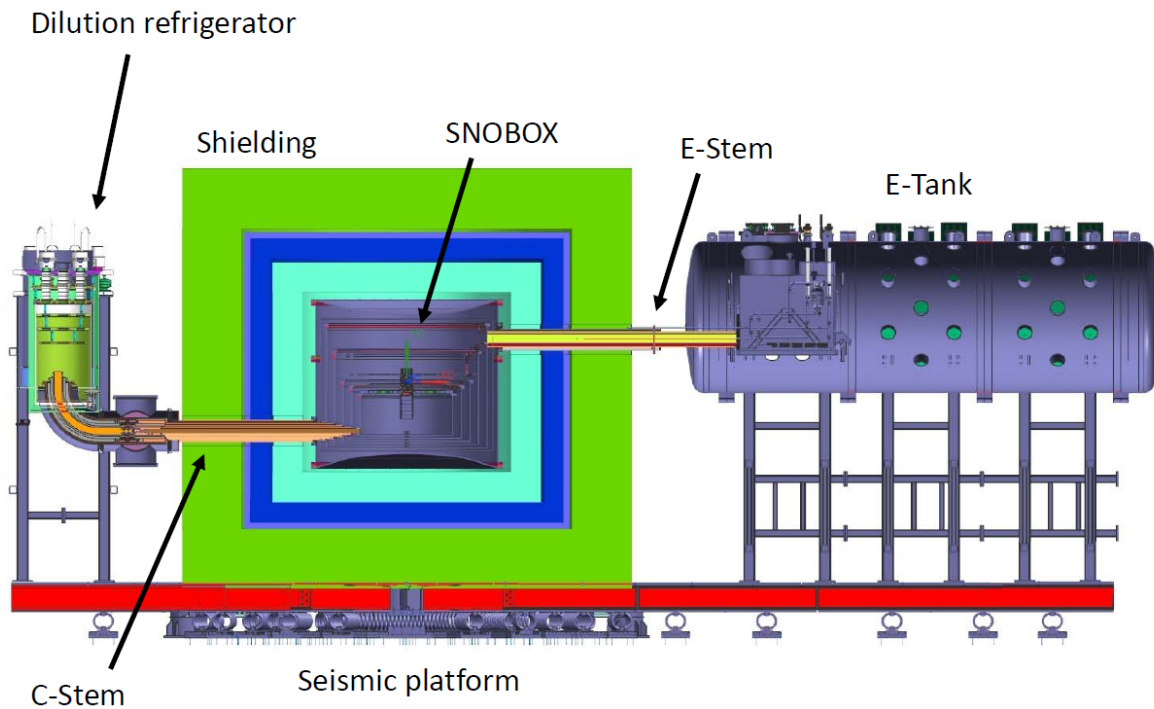
This paper describes the thermal design of the experiment, including details of the cooling systems, mechanical designs and expected performance of the system under operational conditions.

## 1. Introduction

Substantial evidence supports the existence of vast amounts of dark matter at all scales in the Universe [1]. Although its nature is still unknown, the possibility that dark matter is made from elementary particles beyond the Standard Model makes its detection and identification one of the greatest challenges of modern physics. Direct detection experiments attempt to spot the rare interaction of dark matter particles in our neighborhood of the galaxy with normal matter targets in deep underground laboratories. The Cryogenic Dark Matter Search (CDMS) experiments employ cryogenically-cooled germanium and silicon crystals capable of measuring the very small nuclear recoil energies produced by elastic scattering of low mass ( $<10 \text{ GeV}/c^2$ ) dark matter particles with nuclei [2]. The latest generation of the experiment, SuperCDMS SNOLAB, is undergoing the preliminary stages of construction and will subsequently deploy to the Canadian SNOLAB deep underground laboratory facility near Sudbury, Ontario. At over 2000 m depth, SNOLAB is currently the second deepest particle physics facility in the world, housing the Sudbury Neutrino Observatory+ (SNO+) experiment, among others.

The first phase of the SuperCDMS SNOLAB experiment will deploy a mixed payload of 24 Si and Ge detector crystals, with operations scheduled to begin in 2020. Later phases of the experiment could deploy up to 186 detector crystals. The cryogenic system is designed to operate this maximum payload of detectors at a stable base temperature  $\leq 15 \text{ mK}$  for extended runs of at least a year at a time with minimal operator intervention. Unlike previous generations of the CDMS experiment, SuperCDMS SNOLAB will utilize an entirely closed cycle cryogenic system centered around a large cooling capacity cryogen-free dilution refrigerator. This paper describes the cryomechanical design of the SuperCDMS SNOLAB experiment and discusses the anticipated performance of the cryogenics system.





**Figure 1.** Cross-sectional view of the mechanical design of the SuperCDMS SNOLAB experiment. The detector payload is mounted within a cryostat, the SNOBOX, enclosed by layers of high density shielding to protect the detectors from background radiation. Connections to external services are made via stem assemblies that minimize the size of penetrations through the shielding structures. The entire experiment is mounted on a platform that isolates experiment from the floor of the laboratory to protect the equipment during major seismic events. More details are included in the text.

## 2. SuperCDMS SNOLAB Mechanical Design

The operation of direct detection dark matter experiments such as SuperCDMS SNOLAB presents a number of unique requirements on the design of cryogenic systems. One of the most critical is that a low radioactive background must be presented to the detector crystals in order to achieve the required sensitivity to real dark matter events. This is addressed by careful selection of construction materials, assay measurements and extensive cleaning and handling procedures in order to minimize the introduction of contamination into the experiment. The overall layout of the experiment is shown in cross-section in figure 1. The detectors are contained within a cryostat, referred to as the “SNOBOX”, constructed almost entirely from UNS C10100 oxygen-free high conductivity (OFHC) copper, comprising an outer vacuum chamber (OVC) with a diameter of 1.84 m and a height of 1.7 m and six nested copper shields at progressively lower temperature. Each layer acts as a radiative and conductive intercept for the next colder layer. The OVC has been designed with concave dished heads in order to withstand the 20 psia external pressure environment at the SNOLAB facility without using excessively thick flat heads. The SNOBOX will be fabricated using electron beam welding to avoid the use of filler materials that contain radioactively unclean materials. The stages of the SNOBOX and the corresponding nominal temperatures are defined in Table 1.

The cryogenic stages of the SNOBOX are supported by suspending the cans from loops of aramid rope, with three loops per layer. The loops are formed from single lengths of rope by splicing the strands of the free ends together. Since the ropes strands are woven together, no epoxy, knot or cable clamp is

**Table 1.** Thermal stages and nominal temperatures of the SuperCDMS SNOLAB experiment.

Stage	Nominal temperature
Outer vacuum can, OVC	300 K
Floating radiation shield	255 K
Shield, SH	50 K
Liquid Helium, LH	4.5 K
Still, ST	1 K
Cold Plate, CP	250 mK
Mixing Chamber, MC	15 mK

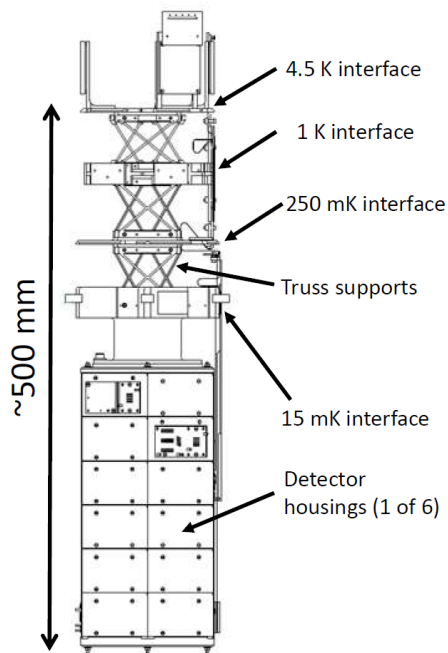
required, any of which would be a weak point in the loop. The rope loops are designed to give high safety factors ( $>10$ ), while minimizing the conducted heat and mass of material to address the aforementioned radioactive backgrounds requirement. The ropes, with diameters between 3.2 and 12.7 mm, are 12 strand, single braid Kevlar® 29 fabricated by Novabraid [3]. The suspension ropes allow the cans to move in the horizontal plane with respect to one another in response to seismic motions in the SNOLAB facility. To limit the amplitude of these horizontal motions, a further set of three aramid rope loops are used at each layer. For these horizontal restraints, the rope loop passes around a sheave such that part of the loop is in the horizontal plane. The mounting position of these loops can be adjusted such that the cans are not over-constrained in the neutral position, but that the rope loops only become tight when the can is displaced horizontally.

The SuperCDMS SNOLAB detector payload is designed to be modular, with up to six detector crystals assembled as a “tower” with multiple thermal stages. Details of the design of the detector towers are outside the scope of this work, but are provided here briefly for information. A schematic of the tower assembly with the major features indicated is shown in figure 2. The three upper stages of the tower are cooled by the Cold Plate, Still and LH stages of the cryogenic system via a system of compliant thermal links. Electrical connections to the detectors are achieved with superconducting rigid-flex cables, one per detector, custom fabricated using Niobium Titanium on polyimide. The cryogenic system is designed to support a full payload of 31 such towers (186 detectors) to allow for future upgrades to the experiment without requiring extensive modification of the cryostat and associated hardware.

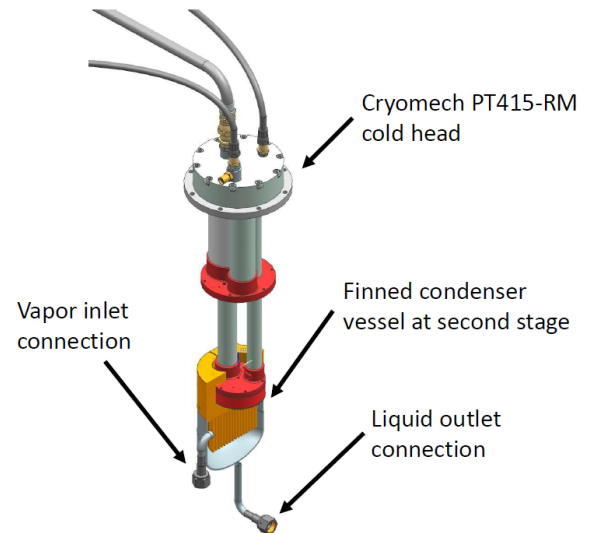
The SNOBOX assembly is enclosed by layers of shielding to reduce the environmental radioactivity to which the detectors are exposed. The shielding consists of layers of high density polyethylene, lead and water tanks. Services, such as the detector readout cabling, are connected to the SNOBOX via two stems to minimize the size of the penetrations through the shield layers. The stems are carefully positioned so that there is no direct line of sight through the shield penetrations to the detectors. The upper stem, referred to as the “E-Stem” carries the detector readout cables and cryogenic fluid lines that cool the outer layers of the SNOBOX. The detector cables are of the woven ribbon type, similar to that described in [4], with 49 twisted pairs of AWG 32 Phosphor-Bronze and two pairs of AWG 30 copper wires woven with Nomex thread.

The E-Stem connects to a vessel outside of the shield assembly referred to as the “E-Tank”. This is a 1.5 m diameter stainless steel vessel that provides mechanical support for the higher temperature cryogenic systems and connections for the detector readout electronics. The vessel contains a cold enclosure cooled by the SH layer 50 K cooling system that provides a heat sinking point for the detector readout cables. The readout cables subsequently connect to multilayer circuit boards that provide a vacuum break to the ambient environment at 300 K.

At the opposite side of the SNOBOX, a second stem (the “C-Stem”) connects the inner three stages of experiment to the lower stages of a large dilution refrigerator. Since the dilution refrigerator is



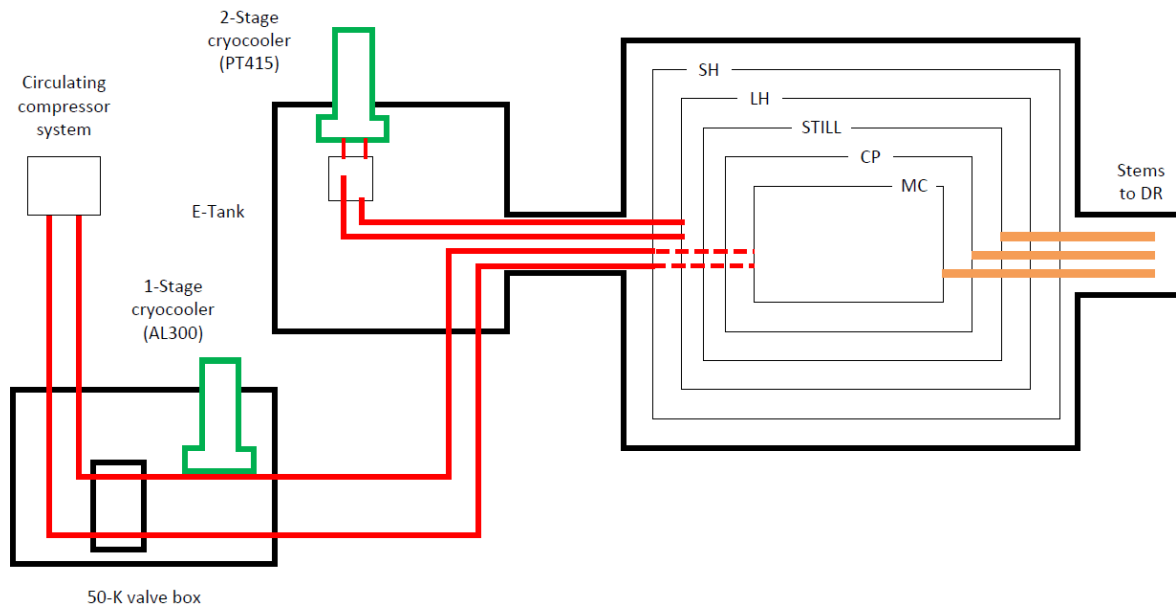
**Figure 2.** Schematic of the SuperCDMS SNOLAB detector tower assembly with major components indicated. The tower is approximately 500 mm high and 110 mm in diameter with a hexagonal cross-section. The upper stages of the tower are heat sunk to progressively higher temperature stages in the cryostat, with the uppermost stage at 4.5 K. Image courtesy of M. Oriunno/Stanford Linear Accelerator Laboratory.



**Figure 3.** The 4-K condensing pulse tube cooler assembly. The finned condenser is clamped to the second stage of the Cryomech PT415-RM cold head. The vapor from the thermosiphon phase separator enters from the upper side connection, condenses on the fins and then flows out of the lower connection under gravity back to the liquid phase of the circuit.

constructed from radioactive materials, it must be placed outside the shielding around the detectors. The C-Stem conductively cools the Mixing Chamber, Cold Plate and Still layers of the SNOBOX with the associated detector components. The C-Stem also includes layers at the LH and SH thermal stages, although these provide radiation shielding to the colder layers rather than the cooling path for those stages of the cryostat (see further discussion in § 3). The C-Stem is composed of concentric copper tubes and includes flexible links to allow for differential movement during cool down and seismic events. The construction and performance of the C-Stem is discussed in more detail in a companion paper [5], while more details on the dilution refrigerator are given in § 3.1.

The entire volume of the cryostat, including the dilution refrigerator, SNOBOX, E-Tank and both stems, forms a single common vacuum space. Initial evacuation will be achieved using turbomolecular pumps mounted directly to the experiment, one on the E-Tank and one at the C-Stem. Once operational, these pumps will be isolated and shut down to avoid injection of electronic noise into the cryostat that would affect the detectors. The vacuum quality will be maintained during extended runs using a third turbomolecular pump mounted some distance from the cryostat and connected via a large diameter, high-conductance pumping line. Permeation of atmospheric helium into the vacuum space is minimized through the use of double o-ring seals on all the large cryostat vacuum flanges, with the interstitial space pumped to medium vacuum.



**Figure 4.** Schematic of the SuperCDMS SNOLAB cooling systems. The connections for the fluid cooling systems at the SH and LH layers are shown to left, mechanically associated with the E-Tank, while the C-Stem and connections to the dilution refrigerator are shown to the right of the SNOBOX.

### 3. Thermal Design

Earlier generations of the CDMS experiments used liquid nitrogen and helium cryogenic systems. Although these systems were ultimately upgraded with reliquifiers to reduce the need for cryogen transfers [7], SuperCDMS SNOLAB has been designed with an entirely closed cycle, cryocooler-based cryogenics system. The major part of the cryogenics system is a high power dilution refrigerator, provided by Leiden Cryogenics,[6] that cools the three sub-Kelvin stages of the cryostat. Although the dilution refrigerator has cryocoolers operating at 50 K and 4 K, these stages are not used to cool the corresponding stages of the experiment cryostat. Instead, independent cooling systems are provided at the SH and LH stages of the experiment. A schematic of the cooling systems is shown in figure 4, with more information in the following sections. This approach allows the cooling at the different stages of the cryostat to be optimized separately, and provides additional performance margins in the event that heat load at one stage is found to be much higher than anticipated.

Careful accounting of all heat transfer paths was made by developing a detailed thermal model of the system. Material data was either obtained from existing literature (using more conservative values where a range of data was available), or based on measurements carried out specifically for the experiment in the case of more exotic materials (for example, [8]). This was particularly true for the lowest temperature ranges where material conductivity data is sparse. A summary of the heat loads at each stage of the experiment appears as Table 2, along with the cooling power available at each thermal stage. It should be noted that these heat loads are for a future upgrade of the experiment with 186 detectors. At the highest temperature stages, the heat load is dominated by direct blackbody radiation, with detector readout cables and cold electronics becoming increasing dominant at the lowest temperature stages. The high radiation load at the Shield layer is the result of the use of a radiatively cooled copper radiation shield in the SNOBOX rather than multilayer insulation. This design choice was made to address the concern of the radioactive background presented by aluminium- or gold-coated films and the potential for trapping of

**Table 2.** Summary of heat loads by thermal stage. The design deliberately includes a factor of  $>2$  margin on the available cooling power at each stage. The heat loads assume a full payload of 186 detectors to account for future upgrades to the experiment.

	Mixing chamber	Cold Plate	Still	LH	SH
Stage temperature	15 mK	250 mK	1 K	4.5 K	50 K
Radiation	17 pW	6.1 nW	3.7 $\mu$ W	165 mW	69.1 W
Suspension	650 nW	28.5 $\mu$ W	0.31 mW	273 mW	9.8 W
Cooling system parasitics	90 nW	3.0 $\mu$ W	70 $\mu$ W	173 mW	1.4 W
Readout cable	750 nW	82.8 $\mu$ W	3.5 mW	478 mW	8.5 W
Cold electronics	50 nW	0.57 $\mu$ W	0.22 mW	74 mW	n/a
<b>Total heat load</b>	<b>1.54 <math>\mu</math>W</b>	<b>115 <math>\mu</math>W</b>	<b>4.1 mW</b>	<b>1.16 W</b>	<b>88.8 W</b>
<b>Cooling power</b>	<b>5 <math>\mu</math>W</b>	<b>350 <math>\mu</math>W</b>	<b>15 mW</b>	<b>2.80 W</b>	<b>180 W</b>

particulate contamination between layers. The use of gold plating to stabilize the emissivity of the copper surfaces has also been avoided due to quantity of gold required to plate the large surface areas of the cans. Instead, the copper will be passivated using a citric acid process developed at Pacific Northwest National Laboratory [9]. This process has been used in other cryogenic systems, and is able to produce a low emissivity ( $<3\%$ ) finish on copper that appears to be stable against oxidation [10].

### 3.1. Dilution refrigerator

The dilution refrigerator is a modified version of the Leiden CF-2100-Maglev-2PT, capable of providing a no-load base temperature of 7 mK and 2100  $\mu$ W of cooling power at 120 mK. The refrigerator is built around two Cryomech [11] PT-420-RM pulse tube coolers, each providing 1.8 W of heat uplift at 4.2 K. The gas handling system for the refrigerator uses oil free or oil sealed pumps, with twin maglev turbo pumps, a large claw pump and a double-membrane compressor to circulate helium at up to 2.8 mmol/s. Since parts of the gas circulation lines are at subatmospheric pressure, the refrigerator system operates with cold traps in order to remove air contamination from the circulating helium. While such air leaks are small, during long duration operation small amounts of contamination can accumulate the freeze out to block the fine capillary tubing in the refrigerator. The Leiden system is supplied with liquid nitrogen traps as standard, and a liquid helium trap will be added. Both cold traps are designed with parallel, independant flow channels to allow the traps to be regenerated with interrupting operation of the refrigerator, while both cold trap dewars will incorporate mechanical coolers as reliquifiers to maintain closed-cycle operation. The liquid helium dewar uses a standard Cryomech PT-415 pulse tube reliquifier, while the liquid nitrogen dewar incorporates a custom reliquifier based on a Cryomech AL60 Gifford-McMahon cooler.

### 3.2. 50-K cooling

The shield cooling system uses cooled helium gas at approximately 100 psig, circulating at up to 8 grams per second. Gas cooling is provided by a single-stage Cryomech AL300 Gifford-McMahon mechanical cooler. The lower temperatures achievable with mechanical coolers offer advantages over the use of liquid nitrogen by lowering the thermal loads on the colder stages of the experiment. Helium gas is circulated using a Cryomech CP1000-series compressor package. This unit combines a scroll compressor and an after-cooling water heat exchanger to remove the heat of compression. This compressor will be located away from the experiment to eliminate coupling of acoustic or vibration noise into the cryostat. The gas is circulated to the cold part of the system through solid tubes over a distance of approximately 37 m in each direction. The cooled part of the circuit begins when the circulating helium enters a vessel

containing a counter flow heat exchanger and the cryocooler, mounted adjacent to the experiment. The warm gas first flows through one channel of a brazed plate heat exchanger, while the returning cold gas from the experiment at  $\approx 50$  K flows in the other channel to cool the inflowing gas. It is important to minimize the approach temperature of the streams to minimize the loading on the cryocooler following the heat exchanger. The current design of this exchanger has a 2–3 K approach between the two streams in a compact footprint. The output of the counterflow heat exchanger then flows through a heat exchanger attached to the single-stage cryocooler. This heat exchanger comprises a copper block with machined rectangular channels that are then closed with vacuum brazed plates. The exchanger is bolted directly to the cold head.

Two separate cryocooler vessels are connected to the experiment cryostat via a distribution box. When the experiment is initially cooling down, this second cryocooler system feeds cold gas to the inner stages of the cryostat to cool those stages to near 50 K before the cool down is handed off to the dedicated cooling systems for those stages. Once the precool is complete, the second AL300 cryocooler is available as an installed spare for the primary 50 K circuit in the event of the cooler failure. The distribution box incorporates pneumatic valves such that the second cooler can be switched into the circuit automatically by the cryogenic control system in the event of failure of the primary, while the other cold head can be isolated and removed for servicing.

### 3.3. 4-K cooling

Cooling at the LH layer is provided by a two-phase helium mixture flowing in a thermosiphon arrangement. The vapor fraction of the two-phase helium is recondensed back into the single phase liquid by Cryomech PT-415 two-stage pulse tube cryocoolers, each providing 1.4 W of capacity at 4.5 K. A phase separator vessel is mounted within the E-Tank, providing sufficient pressure head on the single phase side of the circuit to drive the fluid flow in the horizontal section of the thermosiphon that passes through copper tubing along the E-Stem and around the LH can. Heat is absorbed by the liquid, causing a small fraction to evaporate and form a two-phase mixture. The flow rate in the thermosiphon is rather slow, approximately 4.5 g/s with 1% vapor fraction.

Upon returning to the phase separator, the liquid returns directly to the single phase side of the circuit under gravity, while the vapor is condensed on copper fins attached to the second stage of the cryocoolers. The condenser design, shown in figure 3, is similar to that used for the VENUS cryogenics system [12]. The liquid returns to the single phase fluid in the phase separator vessel from the bottom of the condenser vessel. The cryocoolers are separated from the phase separator vessel by stainless steel tubes that provide a thermal break, allowing coolers to be switched off when not required to maintain liquid in the thermosiphon circuit. Based on the anticipated load at the LH layer, it is expected that a single cooler will be sufficient for normal operations, with the other coolers available as installed spares in the event of a failure of the operating cooler.

## 4. Summary

The SuperCDMS SNOLAB experiment is designed to detect low-mass dark matter particles by measuring the energy of nuclear recoils from scattering of those particles from nuclei in cryogenically-cooled silicon and germanium crystals. The detector payload must be maintained at low temperatures for extended periods at an underground laboratory site with limited maintenance access. The cryogenic design discussed in this paper is built around a high cooling power cryogen-free dilution refrigerator capable of providing uninterrupted operation below 15 mK, while independent closed-cycle cooling systems cool the higher temperature stages of the cryostat. Expected to deploy to the SNOLAB facility starting in 2019, the SuperCDMS SNOLAB experiment will begin an initial run with a 24 detector payload in 2020.

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