Thermal conductance modeling and characterization of the SuperCDMS SNOLAB sub-Kelvin cryogenic system

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Abstract. The detectors of the Super Cryogenic Dark Matter Search experiment at SNOLAB (SuperCDMS SNOLAB) will operate in a seven-layered cryostat with thermal stages between room temperature and the base temperature of 15 mK. The inner three layers of the cryostat, which are to be nominally maintained at 1 K, 250 mK, and 15 mK, will be cooled by a dilution refrigerator via conduction through long copper stems. Bolted and mechanically pressed contacts, flat and cylindrical, as well as flexible straps are the essential stem components that will facilitate assembly/dismantling of the cryostat. These will also allow for thermal contractions/movements during cooldown of the sub-Kelvin system. To ensure that these components and their contacts meet their design thermal conductance, prototypes were fabricated and cryogenically tested. The present paper gives an overview of the SuperCDMS SNOLAB sub-Kelvin architecture and its conductance requirements. Results from the conductance measurements tests and from sub-Kelvin thermal modeling are discussed.

1. Introduction
SuperCDMS SNOLAB is a dark matter direct detection experiment that aims to measure nuclear recoil energies produced by scattering of dark matter particles from collisions with nuclei of germanium and silicon. The germanium and silicon detector crystals and the signal sensors need to operate as cold as 15 mK to achieve the detection sensitivity for low-mass dark matter (<10 GeV/c²) [1]. The detectors and sensors will be housed in a cryostat at the heart of which is a three-layered sub-Kelvin enclosure kept cold by a 3He-4He dilution refrigerator. The refrigerator will conductively remove heat from the cryostat via long copper stems. Stable and uninterrupted operation of the experiment over year-long periods of time requires robust thermal design of the sub-Kelvin system.

Based on the thermal requirements of the detectors, we have developed a structural and thermal model of the SuperCDMS SNOLAB sub-Kelvin system. This paper describes key structural components of this system and summarizes the thermal modeling methodology and results. Emphasized are the low temperature thermal transport measurements that have enabled designing a viable sub-Kelvin cooling network.
2. The SuperCDMS SNOLAB sub-Kelvin system

An overview of the complete SuperCDMS SNOLAB cryogenics system is presented in an accompanying paper [2] and so only the sub-Kelvin system is emphasized here. Figure 1 shows a sectional view of the sub-Kelvin system. To the top-right in figure 1 is a seven layered cryostat, called the SNOBOX, whose thermal stages progressively cool from room temperature to the base temperature of 15 mK. Only the three inner layers that constitute the sub-Kelvin network are shown in figure 1. Dark matter detectors are stacked to form a tower (only one is shown for clarity) that is thermally anchored to the three inner SNOBOX layers at 1 K, 250 mK, and 15 mK. Concentric tubular stems called C-stems transport heat from these SNOBOX layers to the still (ST), cold plate (CP), and mixing chamber (MC) stages of a dilution refrigerator (to the left in figure 1). We will refer to the three SNOBOX and C-stem layers as the MC layer, CP layer, and ST layer according to the refrigerator stage they connect to. At the SNOBOX end, the horizontally laid C-stems connect to the SNOBOX layers with cylindrical clamps. At each SNOBOX layer, a C-stem is pressed between the two semi-circular halves of the clamp as depicted in the right inset of figure 1. Going away from the SNOBOX, the tubular C-stems transition to hollow square channels to which flexible thermal straps made of copper are bolted (left inset of figure 1). The conduction stems downstream of the flexible straps have a smooth 90 degree elbow bend enabling their transition from horizontal to vertical. These elbow sections of the conduction stems are called the refrigerator-tails. Finally the refrigerator-tails are bolted to the MC, CP, and ST stages of the dilution refrigerator operating in the typical vertical orientation.

Table 1 lists the parameters governing the thermal design of the sub-Kelvin system. The parameters include the specified tower temperatures and the refrigerator cooling budget at the MC, CP, and ST stages. The rightmost column of table 1 gives the expected heat loads on the MC, CP, and ST layers of the SNOBOX. These loads have been calculated taking into account heat transfer modes of 1) thermal radiation between adjacent SNOBOX thermal stages, 2) conduction through inter-layer suspension, and 3) heat dissipation from the tower electrical components. Further details of the heat load model are given in [2].

Figure 1. CAD rendering of the SuperCDMS SNOLAB sub-Kelvin system showing the heat conduction elements. Insets show the mechanically pressed contacts and flexible straps.
Table 1. Parameters governing thermal design of the sub-Kelvin system

<table>
<thead>
<tr>
<th>Stage</th>
<th>Specified tower temperature</th>
<th>Dilution refrigerator cooling budget</th>
<th>Expected heat load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing chamber (MC)</td>
<td>15 mK</td>
<td>5 $\mu$W @ 10 mK</td>
<td>1.6 $\mu$W</td>
</tr>
<tr>
<td>Cold plate (CP)</td>
<td>250 mK</td>
<td>350 $\mu$W @ 230 mK</td>
<td>115 $\mu$W</td>
</tr>
<tr>
<td>Still (ST)</td>
<td>1 K</td>
<td>15 mW @ 800 mK</td>
<td>4.1 mW</td>
</tr>
</tbody>
</table>

Table 1 shows that the chosen dilution refrigerator has cooling capacity of about thrice the calculated heat load on each stage of the sub-Kelvin system. The principal requirement in the sub-Kelvin system design is then its ability to conductively transport the expected heat loads to the refrigerator without letting the towers warm up above their specified temperatures. Subsequent sections describe the thermal modeling and characterization efforts that have yielded a design meeting this requirement.

3. Thermal conductance characterization

Each of the three conduction paths from the towers to the dilution refrigerator is divided into the following for characterizing their thermal conductance: 1) solid components *viz.* SNOBOX lids and cans, the round tubes and square channels on the conduction stem, 2) pressed contacts *viz.* bolted flat connections and clamped cylindrical connections, and 3) flexible thermal straps.

3.1. Solid components

The experiment will employ UNS C101 copper for all the solid copper components. Copper with RRR 50 required for the cans and lids is commercially available. The targeted RRR of 150 for the stem components can be achieved by vacuum annealing (4 hours at 450°C) the commercial RRR 50 copper as described in [3]. Bulk thermal conductivity of copper with RRR 50 and 150 available from [3] are used to evaluate thermal conductance of the solid copper components. These are given by $K_{RRR50}[W/m-K] = 70T[K]$ and $K_{RRR150}[W/m-K] = 170T[K]$, where $K$ is thermal conductivity and $T$ is temperature. The expressions are stated to be valid between 30 mK and 150 mK.

3.2. Pressed contacts

The design of sub-Kelvin copper-copper contacts on the conduction stem must provide high thermal conductance as well as preserve the contact surface preparation between several cycles of assembly-dismantling. Strict cleanliness and radiopurity requirements of the experiment forbids the use of conforming interposer materials such as indium or grease that are commonplace with copper-copper contacts [4]. All copper-copper thermal contacts on the SuperCDMS SNOLAB conduction stem will be gold plated, which brings in two advantages. First, gold being inert will inhibit oxidation/tarnishing of the contacting surfaces thereby relaxing the need of rigorously cleaning the surfaces between make and breaks. Second, gold contacts offer higher thermal conductance than contacts made of bare copper [5].

As depicted in figure 1, the conduction stems will carry bolted flat and clamped cylindrical contacts. Prototype joints in both the geometries were fabricated of C101 copper and plated with gold. Figure 2 displays photographs of these prototypes while table 2 lists details of contact preparation, gold plating, and joint assembly.
Figure 2. Prototype joints constructed for contact conductance measurement: (a) flat joint (b) clamped cylindrical joint. The contacting surfaces are gold plated. The joints are instrumented with heaters and thermometers as per the two-heater one-thermometer method [6].

The joints in figure 2 were instrumented with heaters and thermometer following the ‘two-heater one-thermometer’ method of thermal conductance measurement [6]. Thermal conductance was then measured in the temperature range of 0.06 K - 10 K using refrigerator apparatus in-house and at collaborating institutions [7]. Figure 3 presents thermal conductance data of these joints as a function of temperature. The power-law fits to each data set bring out near-linear variation of the conductance with temperature, which is indicative of electronic heat conduction being dominant across the contact [5].

3.3. Flexible thermal straps
Flexible straps are needed to accommodate thermal contraction of the stem and to dampen vibrations crossing from the dilution refrigerator to the SNOBOX. Being on the conduction

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>Base Metal</th>
<th>Apparent Contact Area</th>
<th>Surface Finish</th>
<th>Plating</th>
<th>Bolting Assembly</th>
<th>Estimated Bolt Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>C101 copper</td>
<td>6.45 cm²</td>
<td>0.2 µm</td>
<td>0.5 µm gold over 1.3 µm nickel</td>
<td>One SS-304 bolt, size 10-32</td>
<td>3 kN</td>
</tr>
<tr>
<td>Clamped cylindrical</td>
<td>C101 copper</td>
<td>MC-stem size: 28.7 cm²; Scaled-down: 4.5 cm²</td>
<td>0.4 µm</td>
<td>7.4 µm gold</td>
<td>Two phosphor bronze bolts, size 1/2-20</td>
<td>4.5 kN</td>
</tr>
</tbody>
</table>
stem, the straps need to have high thermal conductance below 1 K and even in the 10-15 mK temperature range. Characterization by measurement was necessary because conductance data of flexible straps at such low temperature, to the best of our knowledge, are not available.

The straps chosen for characterization are solder-free copper rope straps available from Technology Applications, Inc. (TAI). These straps are made by cold-swaging ends of strand woven OFHC copper ropes in blocks of solid OFHC copper. Two straps (model P5-502) of rope length 100 mm and 150 mm were tested between 0.13 K – 10 K using the two-heater one-thermometer method. Figure 4 displays the measured thermal conductance vs. temperature of the two straps.

Initial 4 K – 10 K measurements on the 150 mm strap, as seen in figure 4, show a linear decrease of thermal conductance with temperature. However, low temperature measurements

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**Figure 3.** Thermal conductance data of pressed contacts. The variation with temperature is near-linear.

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**Figure 4.** Thermal conductance test data of flexible straps before and after e-beam welding the end connectors.
revealed that the linear trend no longer continues below 1.5 K and here the conductance falls steeper with temperature. The off-the-shelf strap therefore will have extremely low conductance near 15 mK and hence was deemed unsuitable for the conduction stem. Further investigations [8] revealed the cause of this observation—the rope thermal conductivity (that of bulk copper, which varies linearly with temperature due to electronic conduction) controls the conductance at higher temperature while the low temperature ‘non-linear’ conductance is dominated by contact conductance at the cold-swaged ends.

To improve the sub-Kelvin conductance, the copper ropes were fused with the end-connectors by electron beam (e-beam) welding. To achieve the fusion, an e-beam was passed along the end-connector width with weld-penetration equal to the end-connector thickness. A 100 mm long strap was used for welding. Figure 5 depicts the strap end connector before and after the e-beam pass. The sub-Kelvin strap conductance improved remarkably after welding as seen in figure 4. Additionally, the conductance now scales linearly with temperature even down to 0.13 K. The linearity points to a fused rope-connector contact exhibiting electronic conduction in the welded strap. Note that the welded strap conductance in figure 4 appears to be higher than the linear part of the un-welded strap. This is simply because the braid of the welded strap is shorter than that of the un-welded one.

Although no conductance data were measured around 15 mK where the coldest stem operates, we highlight that all of our contacts and the welded strap show near-linear temperature dependence of their conductance. The heat conduction through these components is therefore predominantly electronic, and this provides a physical basis for linear extrapolation of the measured data to the lowest working temperatures.

4. Thermal conduction modeling
The model uses thermal transport properties either carefully chosen from the literature (solid copper) or measured experimentally (contacts, straps). These have been detailed out in Section 3. Solid components (tubes, channels) use commercially available sizes. Adjacent thermal layers (viz. MC, CP, and ST) are given sufficient spatial clearance so that they do not short thermally due to relative motion caused by thermal contraction during cooldown. Each conduction layer is equipped with sufficient number of thermal straps and bolted contacts so that the thermal conductance requirements set in table 1 are met.

For thermal conduction modeling, each of the MC, CP, and ST conduction path is broken down into a series of thermal resistances. Figure 6 schematically shows this break-out as well as the labels assigned to each thermal resistance. The three paths assume heat flows equal to the expected heat loads (table 1) going from the towers to the refrigerator. Taking the dilution refrigerator as a thermal sink with known temperature (table 1) and with the resistance...
Figure 6. Series representation of thermal resistances that constitute each of the three layers of the sub-Kelvin conduction system.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Cylindrical section</th>
<th>Strap qty.</th>
<th>Refrigerator-tail</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>84.7</td>
<td>2.41</td>
<td>2</td>
</tr>
<tr>
<td>CP</td>
<td>75.1</td>
<td>2.16</td>
<td>8</td>
</tr>
<tr>
<td>ST</td>
<td>70.7</td>
<td>3.34</td>
<td>12</td>
</tr>
</tbody>
</table>

‘K’ known (bolted flat contact), the temperature upstream of K is obtained. The procedure progresses from K obtaining the temperature upstream of each resistance and eventually yields the tower temperature at A. The thermal design is then iteratively improved to force the towers below the specified temperature on each layer. Figure 7 displays temperature profiles on the MC layer, CP layer, and ST layer of the conduction network. These have been calculated using C-stem dimensions given in table 3. Clearly, the design can keep the tower stages below their specified temperatures.

5. Summary
We have designed a sub-Kelvin cooling system for the SuperCDMS SNOLAB experiment. The design leverages the data obtained from our direct low temperature thermal transport measurements on component prototypes. An accompanying thermal model using these and other data from the established literature shows that our sub-Kelvin system can hold the detectors below their specified temperature.

6. References
Figure 7. Calculated temperature profiles between the refrigerator and the tower on (a) MC layer (b) CP layer and (c) ST layer of the sub-Kelvin conduction system.


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