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

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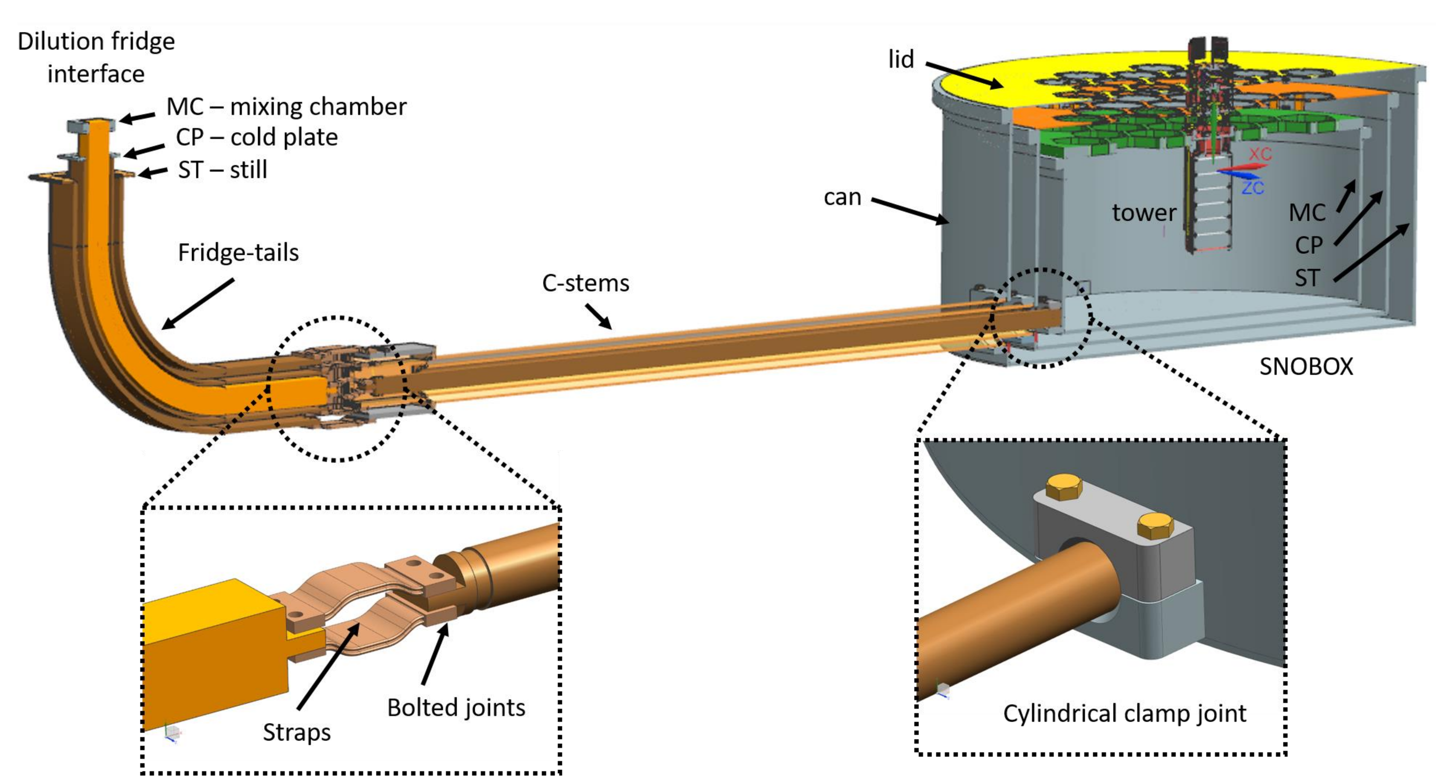
Introduction

SuperCDMS-SNOLAB is a direct dark matter detection experiment that aims to measure nuclear recoil energies produced by scattering of dark matter particles from collisions with nuclei of germanium and silicon [1]. The germanium and silicon detector crystals and the signal sensors need to operate as cold as 15 mK to achieve the detection sensitivity for <10 GeV/c^2 dark matter. 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 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.

The SuperCDMS-SNOLAB sub-Kelvin cryogenic system

As depicted in the figure below, the detector towers are housed in a three-layered sub-Kelvin enclosure whose layers are called MC layer, CP layer, and ST layer. Three long copper stems (rods, tubes) connect these layers to the mixing chamber (MC), cold plate (CP), and still (ST) stages of a dilution fridge. The copper stems comprise of solid components, bolted flat and cylindrical joints, and thermal straps.



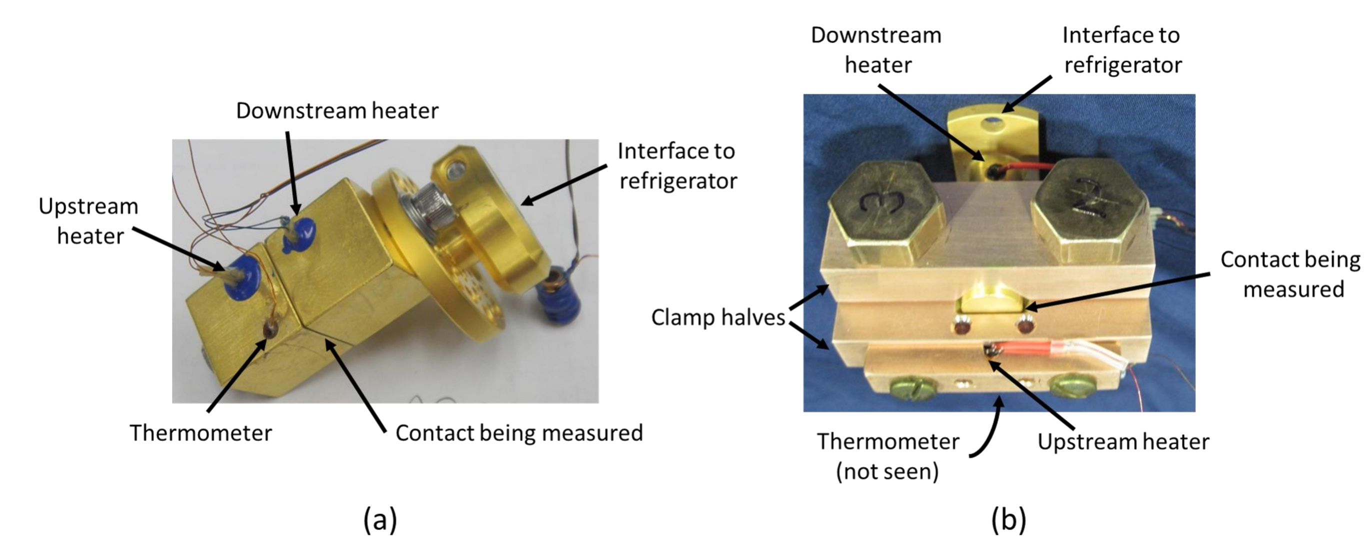
CAD rendering of the SuperCDMS-SNOLAB sub-Kelvin system showing the heat conduction elements- solid copper, bolted and clamped joints, and flexible straps

Stage	Specified tower temperature	Dilution fridge cooling budget	Calculated heat load [1]
MC	15 mK	5 μW @ 10 mK	1.6 μW
CP	250 mK	350 μW @ 230 mK	115 μW
ST	1000 mK	15 mW @ 800 mK	4.1 mW

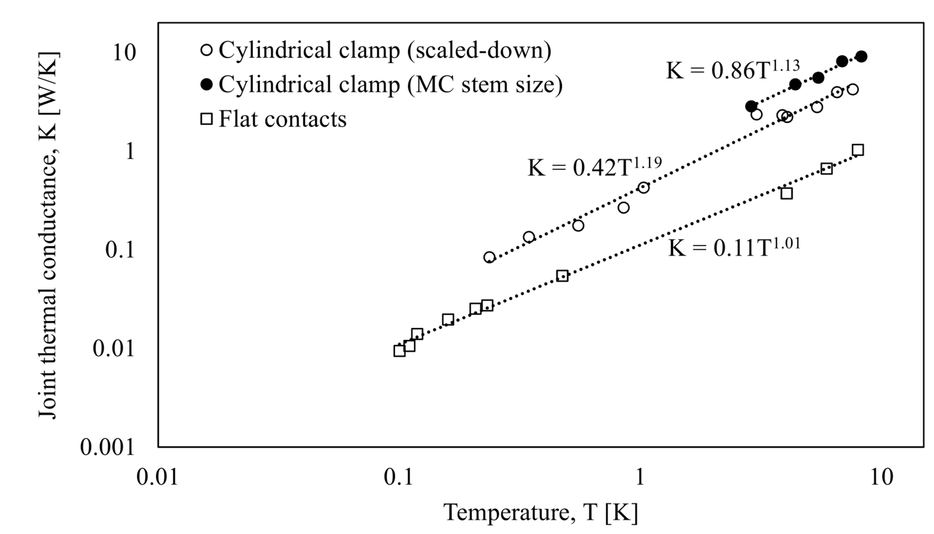
Table above lists the parameters governing the design of the sub-Kelvin system. The expected heat loads [1] are within the fridge cooling budget. The sub-Kelvin system must have enough thermal conductance between the fridge and enclosure so at to keep MC, CP, and ST layers below the specified temperatures. Conductance on each layer was therefore modeled. Conductance of joints and straps was measured and characterized.

Thermal conductance characterization

a) Bolted flat and cylindrical clamp joints

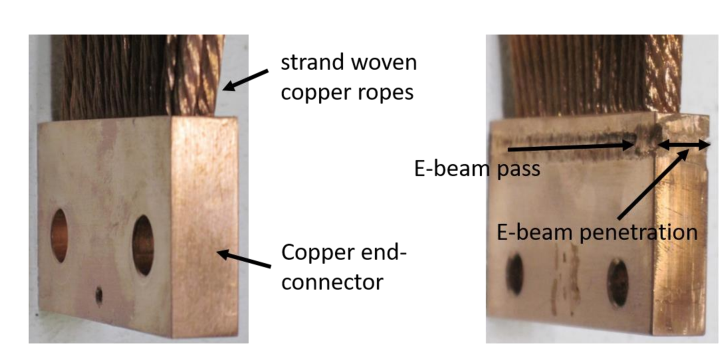


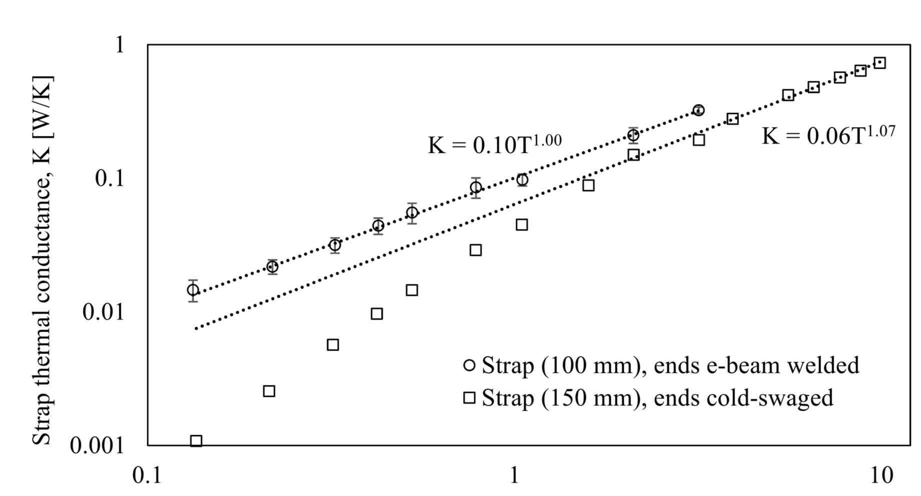
Prototype joints constructed for contact conductance measurement: (a) flat joint (b) clamped cylindrical joint. The contacting surfaces are gold plated.



Thermal conductance data of the pressed contacts. The variation with temperature is near-linear, which indicates electronic heat conduction being dominant across the contact.

b) Flexible thermal straps





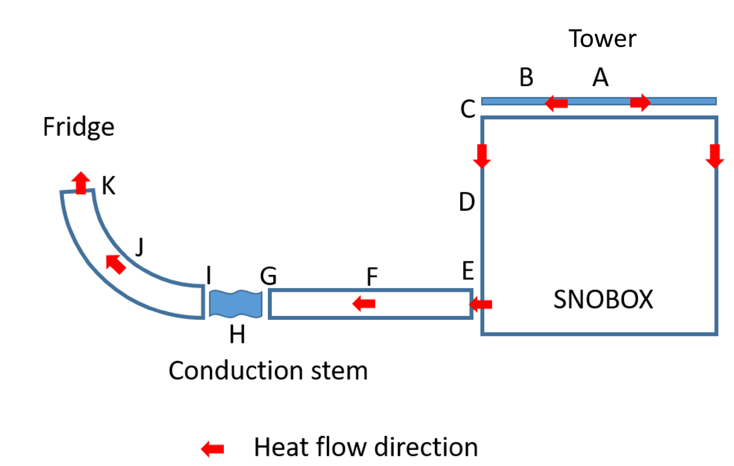
Thermal conductance data of the tested thermal straps. When conductance of off-the-shelf strap was inadequate below 1 K, the end-connectors were e-beam welded to the braid. The welded strap shows more than an order of magnitude improved conductance near 0.1 K.

c) Solid components

Solid components (rods/tubes/channels) will be made of C101 copper annealed to achieve RRR 150 as per Risegari's recipe [2].

Thermal modeling of the sub-Kelvin system

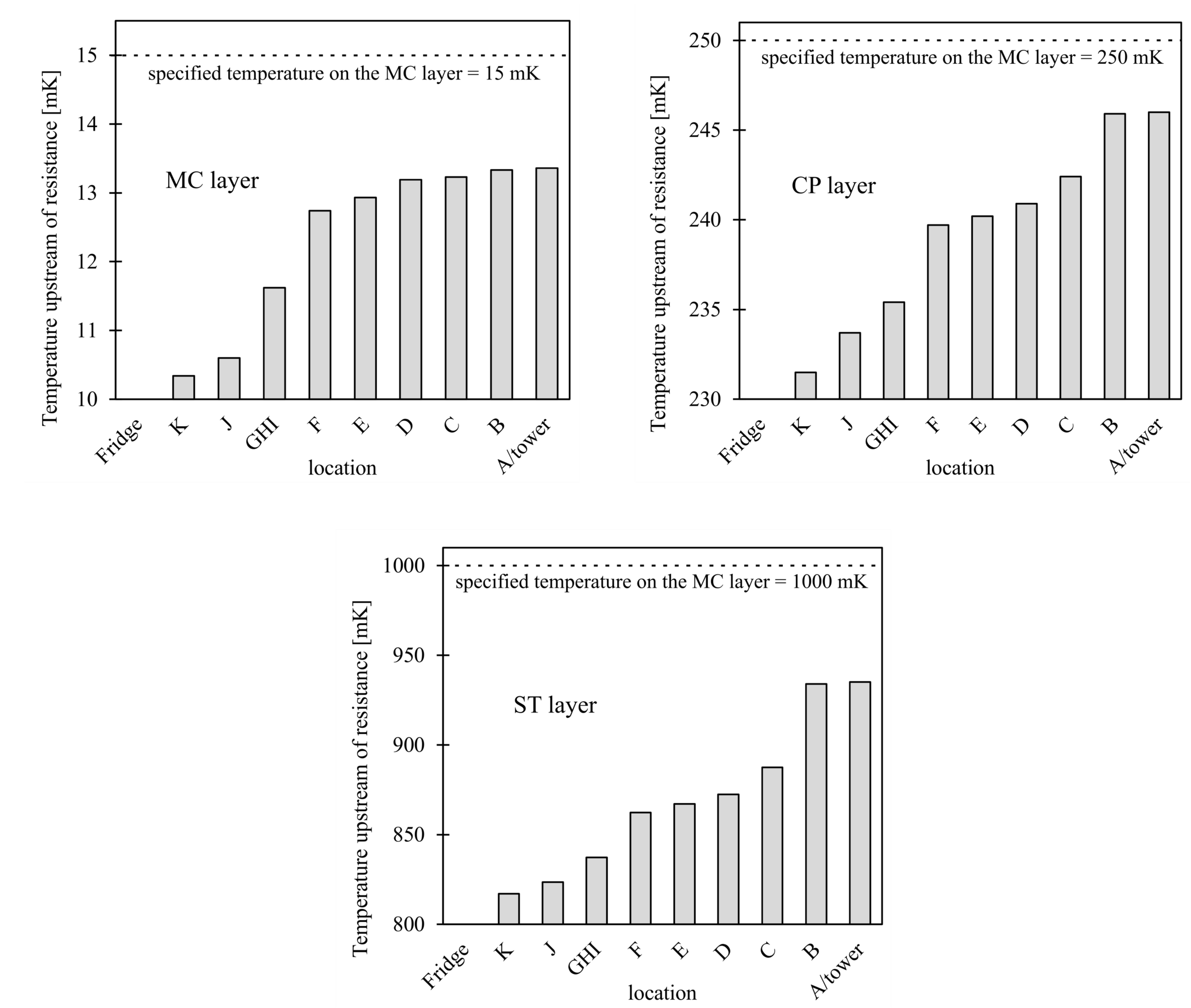
For conduction modeling, heat conduction path on each of the three layers was broken down in to a series of thermal resistances. These resistances going from 'K' at the fridge to 'A' at the towers are depicted in the figure below.



Label	Thermal resistance	Type
A	Tower to lid joint	Flat contact
B	Lid conduction	Solid
C	Lid to can joint	Flat contact/thermal strap
D	Can conduction	Solid
E	Can to stem joint	Clamped cylindrical contact
F	Round stem	Solid
G	Stem to flex joint	Flat contact
H	Flex	Thermal strap
I	Elbow to flex joint	Flat contact
J	Elbow conduction	Solid
K	Elbow to fridge joint	Flat contact

Thermal resistances on the conduction path between fridge and tower

Using known copper thermal conductivity and the measured contact resistances, we calculated temperature rise going from the fridge 'K' to the tower 'A'. The design for calculations uses commercially available component sizes.



Calculated temperature profiles on the MC, CP, and ST layers going from the fridge to the tower. On each layer, the detector tower is cooler than the specified temperature.

Summary

We have designed a sub-Kelvin conduction cooling system for the SuperCDMS-SNOLAB experiment. This thermal design would keep the detector towers below their specified temperatures.

Acknowledgement

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References

[1] SuperCDMS-SNOLAB: Preliminary design report
[2] Risegari L, Barucci M, Olivieri E, Pasca E and Ventura G 2004 *Cryogenics* **44** 875