SPT4 Cryostat Temperature Gradient Characterization

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Motivation

The finite and sensitive cryogenic environment requires accurate accounting of thermal loadings and residual temperature gradients. These two forces go hand-in-hand with each other: high temperature gradients producing excess thermal load onto lower temperature stages, and excess thermal loadings from hot sources or wiring producing higher thermal gradients. Real systems with finite thermal properties will always present resistance to heat transfer, and thus thermal gradients, making precise modeling necessary to limit redesigns of the system in the lab assembly stage of the cryostat and identify hot spots in the design.

For this, I employ two types of thermal calculations to estimate the thermal gradients under the spec'd loading conditions the cryostat will be subjected to. These calculations have been done and are tabulated in another wiki post, the results of which are only quoted as loading conditions for the systems. The first type of calculation is a 1D heat conduction problem that would be analogous to a linear A/l calculation had it not be for the exceedingly large changes in thermal conductivity over the temperature ranges for OFHC copper (a multiplicative factor of a couple). The second, I corroborate the previous calculation with Finite Element Analyses, which is more robust to boundary and loading conditions.

Input picture of skeleton of thermal connections for 50K and 4K

Summary of Thermal Gradients

50K (1D)	50K (FEA)	4K (1D)	4K (FEA)	OT Spread (alum1100 4K Plate)	OT Spread (OFHC Cu 4K Plate)
19.7 K	18.115 K	4.141 K	4.608 K	1.881 K	0.242 K

50K Heat Straps

1D Numerical Calculation:

This calculation reduces the geometry of the problem to 1 dimension. This makes it simple to code a model using Fourier's law of conduction under the assumption that the azimuthal temperature gradient will be small along the length of the heat strap. The equation for this is shown below

$$\dot{q} = -kA\nabla T$$

To which in 1D and constant cross sectional area this reduces to

$$\dot{q} = -kA\frac{dT}{dx}$$

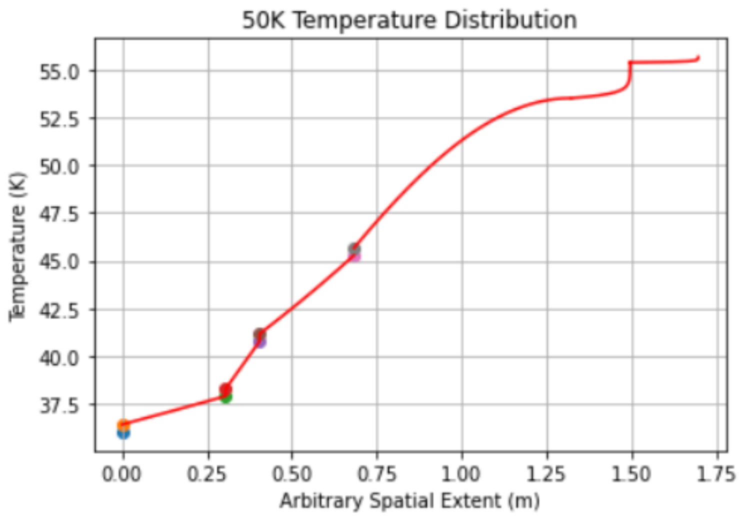
Since the thermal conductivity of OFHC Copper changes drastically in these temperature ranges, I employ numerical modeling to calculate the temperature distributions across these elements, the fundamental assumption being in making the step size very very small compared to the spatial extent of the problem. Numerical modeling represents the derivatives in the infinitessimal limit as in the forward-differenced example below

$$\frac{dT}{dx} \rightarrow \frac{T[i+1]-T[i]}{\Delta x}$$

Solving for T[i] with a known heat load, geometry, and thermal conductivity, the equation above yields

$$T[i] = -\frac{\dot{q}\Delta x}{k[i+1]A} + T[i+1]$$

I use this model for each section of constant geometry. For the heat straps I pulled numbers from SPT3g braided heat (1"x1" footprint) straps that spec from (here)[1] (https://pole.uchicago.edu/spt3g/images/2015_01_30_SPT3G_Cryostat_CDR.pdf), which give about a 3K gradient (at 25 W of load) when taking into account contact resistance (0.3875K for 2 braided heat straps which I spec from (here)[2] (https://www-sciencedirect-com.proxy.uchicago.edu/science/article/pii/S1359431122013424) at a nominal pressure of 1MPa). Stitching together all of the geometry gives the temperature distribution below



The spatial extent can for the most part be ignored, instead of accurately representing the circular elements and the heat paths involved I stitched the longest possible heat path onto here for readability (the actual shortest heat path is about 1.3m which is still pretty long).

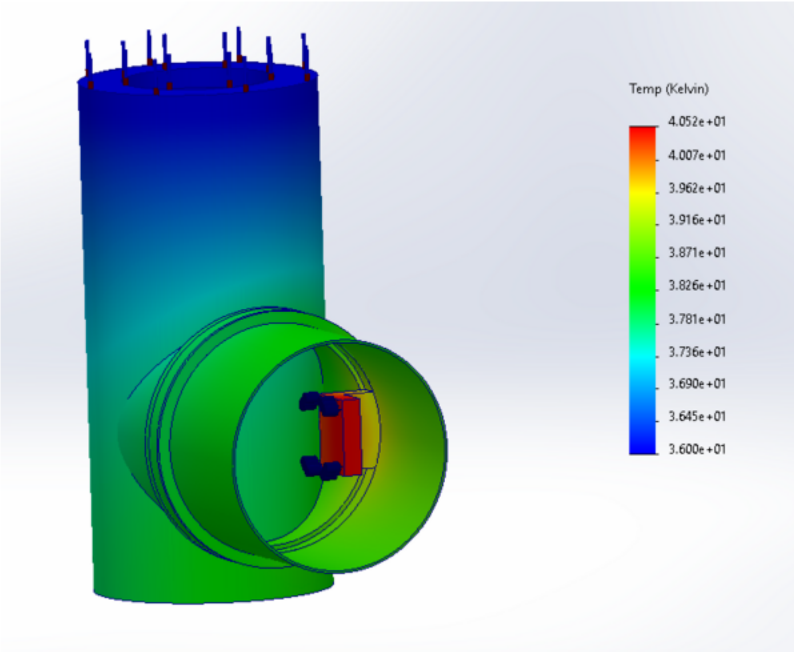
The total temperature gradient estimated with this model is 19.7K

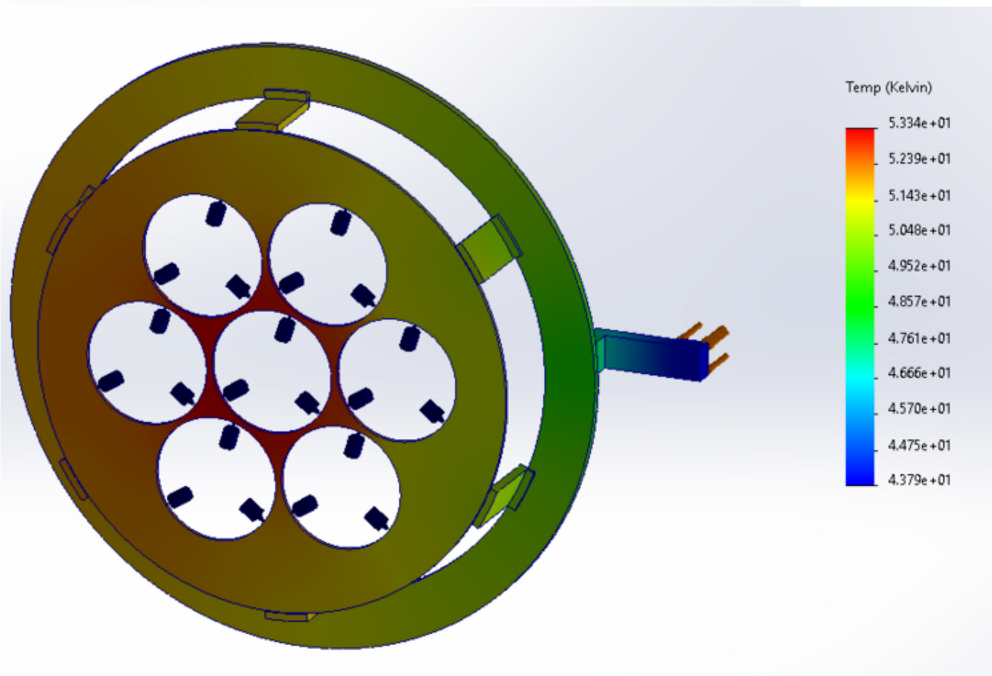
Finite Element Model:

The finite element model discretizes the solution in a similar way to the 1D model, but allows for an independent 2D calculation of the problem, at least on the pretense that the proper boundary conditions and loading have been applied to match the 1D calculation. The setup for this model is quite simple: a relevant Solidworks assembly is created with superfluous features such as bolt holes suppressed, boundary conditions and loading defined on faces, a mesh is generated, and solve.

The problem here is split into two parts at the confluence of the braided heat straps, which are modeled as in the 1D calculation and added as an offset to the boundary condition of the second portion. That is to say the first section (the section connected to the Pulse Tube Cooler) is calculated with 25 W of loading and a Cryomech PT420 spec for the head temperature at this loading magnitude (36K). The results of this FEA are used in the second section, which are the internal component of the cryostat body along with the alumina filter stack, the boundary conditions of which are chosen to be the highest temperature of the first section plus 3.27K (the temperature gradient for 2 braided heat straps of 1"x1" footprint with contact resistance). The total thermal gradient for this model is then 17.34K, though there are a few missing contact resistances compared to the 1D. These are the connections from the PTC head to the copper shield and the copper shield and the heat strap ring (the red block in the left picture below). This adds an additional 0.775K offset.

The total thermal gradient for the FEA model is then 18.115K





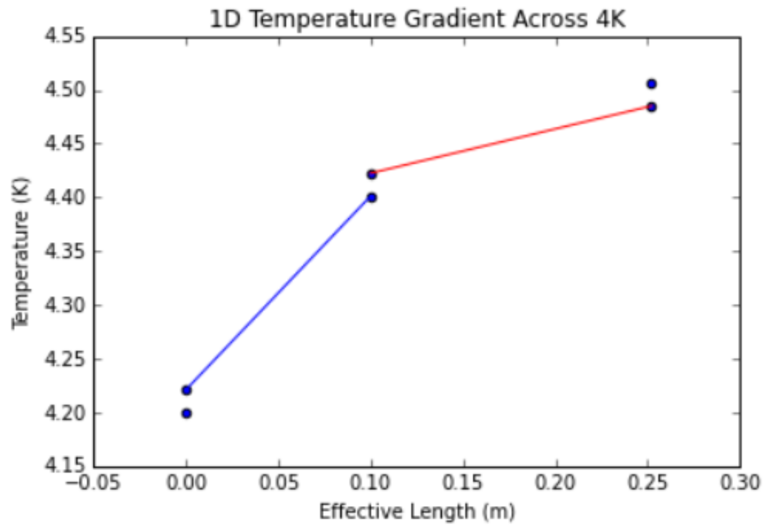
The colorbars out of Solidworks simulation are nonlinear so be careful. The astute observer will draw their attention to the center of the alumina filter stack on the right plot which is a concentrated hot spot in this model due to the small cross sectional area for the heat to flow.

The peak temperature is at the center alumina filter (~54K) which should be sufficient for operation specs provided contact resistance is not significantly worse (which gold plating would be an option to combat).

4K Heat Straps

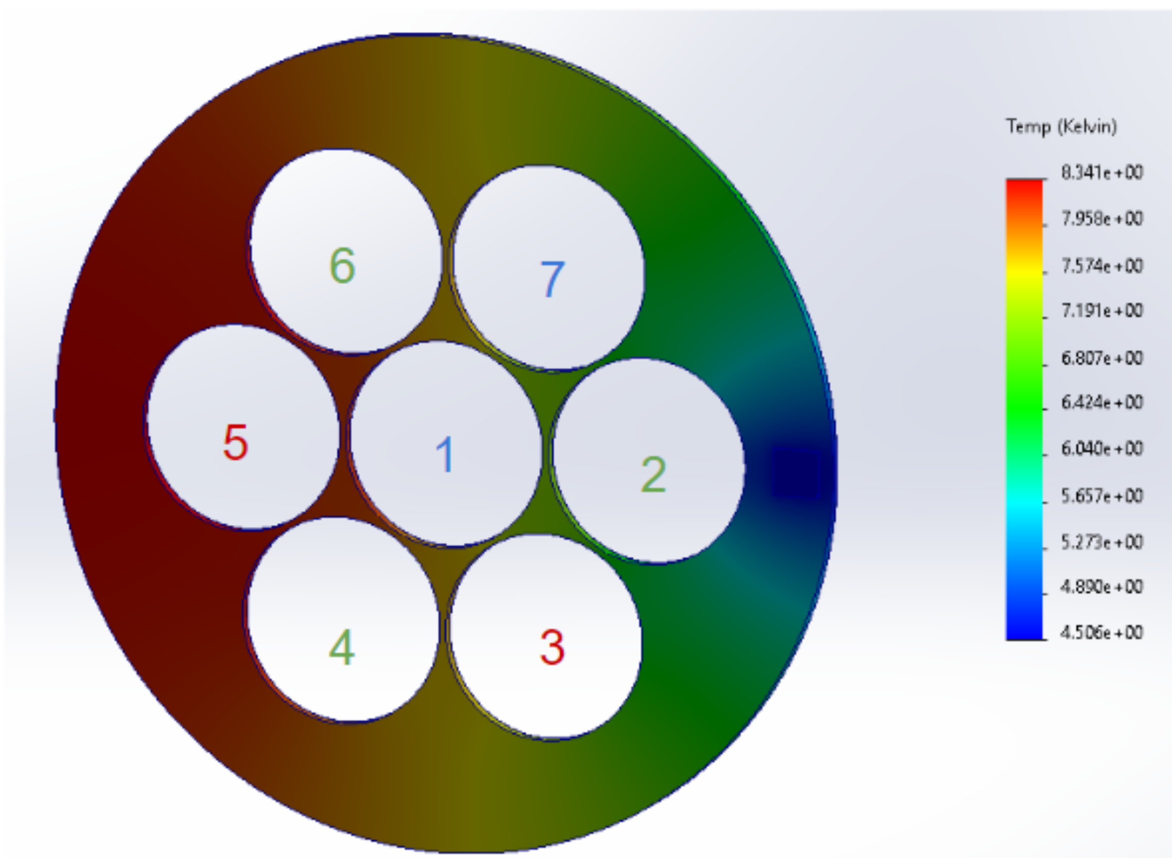
1D Numerical Calculation:

The 1D numerical model was done in the same manner as the 50K. The PTC head temperature is spec'd at 4.2K for 1.8W of loading (which is about the magnitude of load we predict).



The 4K plate that serves as the structure for the optics tube array then has a temperature gradient across it. The loading situation is fairly uniform across the plate due to the LNA's that will be mounted to the back. This gradient is important because it will set the boundary conditions for the optics tubes, the optical elements of which are sensitive to temperature specs.

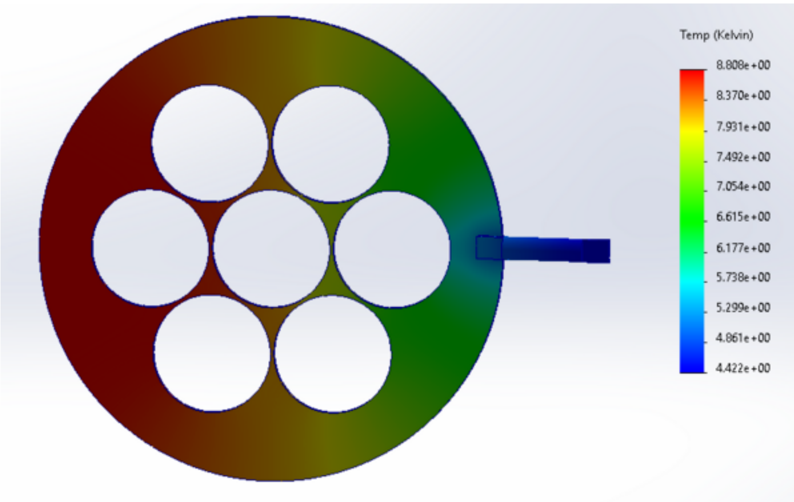
Below is an FEA of the 4K plate with 1.79W distributed across the plate and 30mW per optics tube that sets these boundaries for the later optics tubes, which are expounded upon in the next section. The temperature boundary condition at the right end of the plot (blue splotch) is set by the end of the previous 1D calculation.



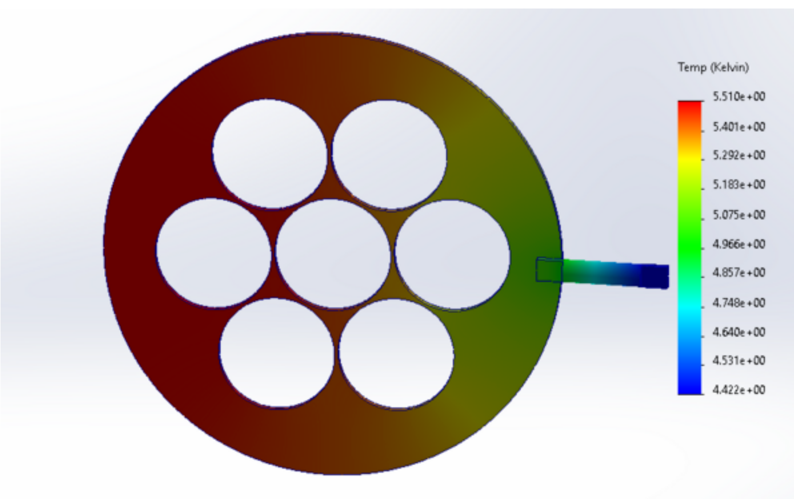
The numbers indicate the indexing for the optics tube section, **red = 220GHz, green = 285GHz, blue = 345GHz**. The far right blue section (~4.8K) is where the braided heat strap will mount that concentrates heat flow to the PTC head. The temperature ranges from 4.506K here to a maximum of 8.341K at the opposite end.

Finite Element Model:

This calculation has the same boundary conditions as the previous FEA but with the heat strap connection, so I would expect the two results to be very close. Namely, the loading is a 1.79W distributed heat load and 30mW per optics tube on the radial connection interfaces. The extended end of the copper bar is set to 4.442K, which takes the braided heat straps into account from the 4.2K PTC head.



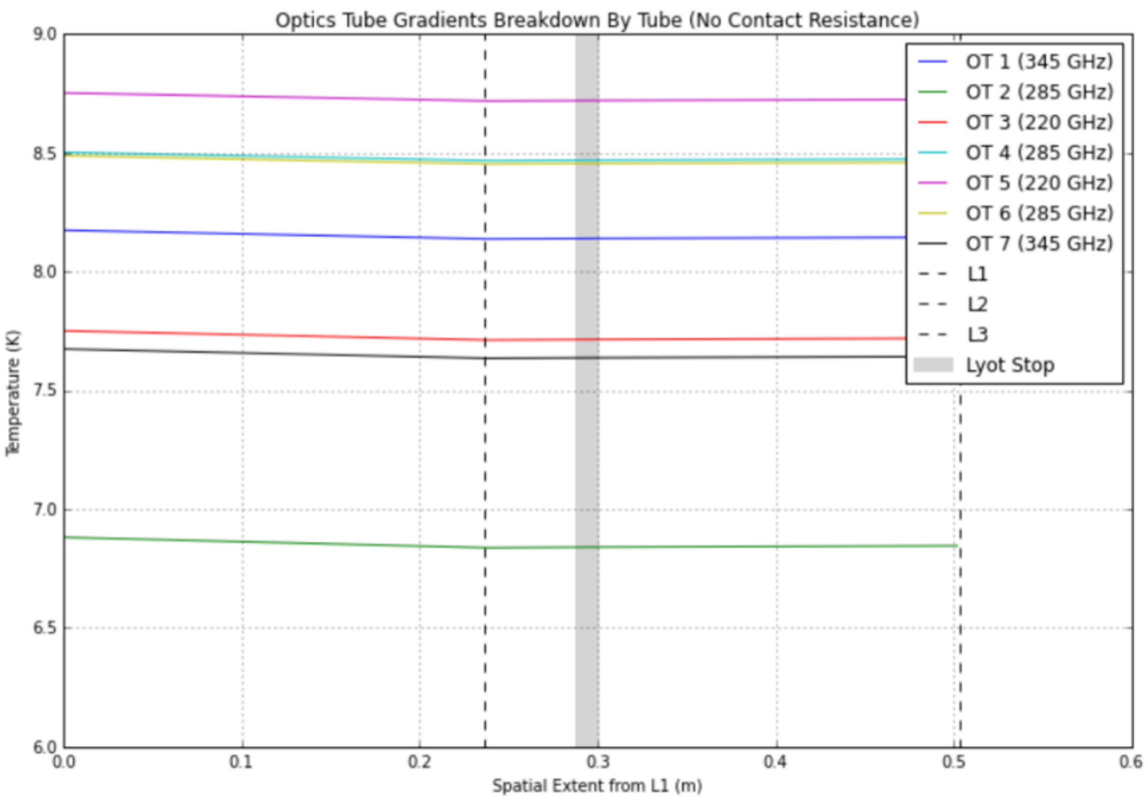
We could save a few Kelvin if we made the 4K Plate OFHC Copper. We would give us 60% more stiffness and 50% more yield strength, but is of course quite expensive



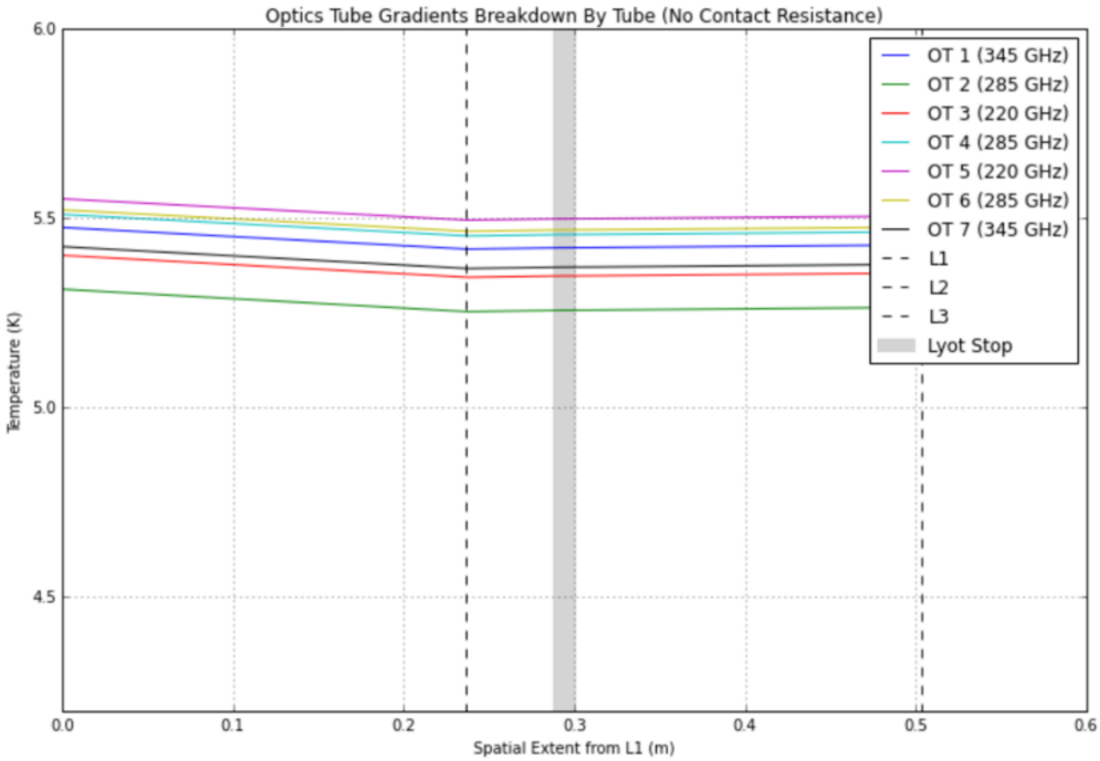
Optics Tube Gradients:

There are parts of this model I am not done with yet and don't have an FEA of the system. Below is what I have done so far, which is modeling the OT's as segments of metal in 1D with varying BCs from the 4K Plate FEA

Without contact resistance or the conduction through the silicon and with an Alum1100 4K Plate, the spread in optics tube boundary conditions is below



And if the 4K Plate was made completely of OFHC Copper the spread in optics tube boundary conditions is below



Update: I can't find any information on the cryogenic thermal conductivity of Silicon, but using the 300K value (148 W/m-K) and keeping in mind the thickness of the lenses is ~10mm, the temperature gradients across the lenses would be on the order of 1mK, which for all intents and purposes is negligible at the 1K level. This graduates to ~10mK if we relax the thermal conductivity to sub-percent of the 300K value, which is still negligible. Contact resistance should be in similar estimations that could be reduced with gold plated if that becomes necessary.

Next Steps

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- This page was last edited on 27 February 2024, at 10:54.