SPT3g+ 100mK Bus Thermal Model

SPT3g+

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Overview

This document summarizes and provides details for the thermal model of the current 100mK raceway design and relevant 1K and 4K structures. The intention of this write-up is to document what has been done to assess the current subdesign of the SPT3g+ cryostat and allow internal vetting of the work. Feel free to reach out to me with questions and concerns stemming from the information in this write-up.

Geometry

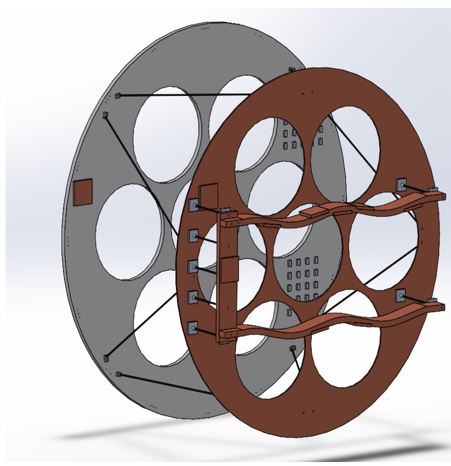

Figure 1: The above figure is the current proposal for the geometry of the 100mK thermal bus. The intention is to weave the copper thru the array of optics tubes prior to the focal plane. The copper squares are the heat strap footprints. The heat straps will route along the optical axis and around to connect to the back of the focal plane.

The raceway geometry under evaluation compromises between finding the shortest distance between the focal plane and the 100mK bus and maintaining a sufficient amount of readout real estate. The sine wave curvature is intended to weave thru the array of optics tubes. The curvature can then be mechanically faced off to give flat edges for the heat straps to attach.

Other geometries considered (pictured below) were a circular ring with a lip that extends to the center and a 'U' shaped, flat bus. The circular ring was thought to have too great a distance to the edge of the focal plane to curb thermal gradients, and the 'U' shaped bus needed to be too wide to accommodate readout infrastructure.

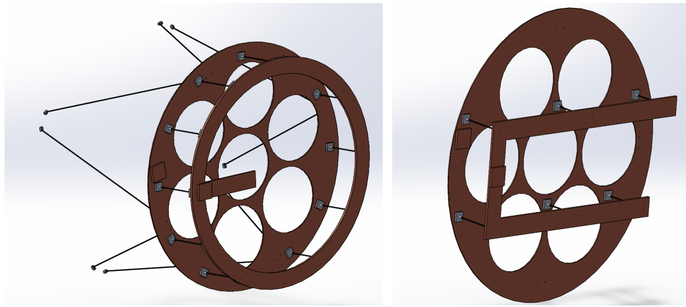

Figure 2: Other possible geometry choices for the 100mK thermal bus. The left ring shape prioritizes readout interface space while the right prioritizes simplicity and shortest distance.

Conduction

Going down the stack, the 4K plate will take a conductive load from the 50K shell that transfers thru the G10 support legs. This conductive load was calculated by hand to be 81.81 mW and is distributed across the face of the 4K plate on the opposite side to the above figure.

The 1K plate is supported by 8 carbon fiber legs, which should contribute some conductive load from 4K to 1K that I calculated to be about 6 μW. The Solidworks Finite Element Analysis (FEA) provides an independent calculation of this load, and the other conductive loads, to allow a sanity check on the simulation.

Analagously, the 100mK bus is supported by 7 carbon fiber legs that I calculated by hand to contribute a total of about 1.5 uW of conductive load from 1K to 100mK, which again is calculated independently by the FEA.

The data of thermal conductivity for carbon fiber below 4K originates from (Runyan Jones 2008). This temperature dependent curve is uploaded to Solidworks as a carbon fiber material property for the FEA to take into account.

The 1K and 100mK structures are made with OFHC copper for superior thermal conductivity properties to combat thermal gradients. Since the thermal conductivity does not change much in the realms of 1K and 100mK, I uploaded two average thermal conductivity of 286 W/m-K and 180 W/m-K for 1K and 100mK respectively. These numbers comes from the NIST curves on cryogenic materials for OFHC copper of RRR=100.

Temperature Boundary Conditions

The temperature boundary conditions are set by the heat strap connections. This simulation assumes there is no thermal gradient between the DR and PTC cold heads and the heat strap connections on the plates, though eventually this will change. The PTC connection and the DR connection to the cryostat are on the same side to be conservative with the temperature distribution. In reality, these connections would be on opposite sides of each other due to the geometry of the cryostat.

The heat strap connections are modeled by a 2" by 2" OFHC Copper footprint as pictured below. The placement is rudimentary and serves to define an early simulation environment and could change based on the results, particularly the temperature distribution.

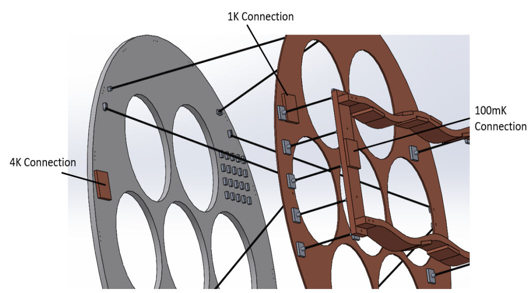

Figure 3: The heat strap footprints shown above are what defines the temperature boundary conditions for the simulation. These boundary conditions will change in the future depending on what the assumed thermal gradients are coming from the DR and PTC heads are. Also, the PTC and DR connections are on the same side (opposite the LNA's) to be conservative with the calculated temperature distribution. In reality, these would be on oppposite sides to each other.

Heat Powers Assumptions

The main heat power contribution that increases the conductive load between 4K and 100mK is the LNA power, which are electronics units mounted to the 4K plate. I assumed 45 LNA's distributed as shown in the figure below (a multiplexing factor of 6 per wafer and a few extra cause why not?). The distribution is such that the LNA's are grouped into two halves that are mounted in separate sections on the 4K plate as pictured below. Each LNA is assumed to contribute a power of 7.6 mW as given by the datasheet for the "Cryoelec 1MHz - 2GHz

Cryogenic LNA SN32", which I have a pdf of but cannot find online.

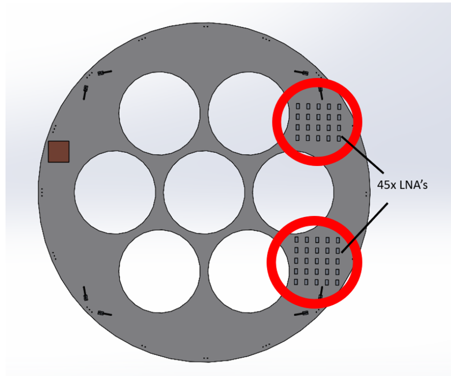

Figure 4: The LNA distribution on the 4K plate is shown above. This defines the thermal power that is dumped onto the 4K plate from the LNA operation. The LNA's are positioned opposite the 4K PTC connection to be conservative with the temperature distribution. There are also a few more than a 6x multiplexing factor.

The radiative load comes from the 4K enclosure and is calculated by hand to avoid long FEA computation times of geometric coefficients. I calculated the radiative load to be on the order of 0.5 uW, which is assumed for both 1K and 100mK surfaces. This is not the dominant contribution to the temperature distribution, but included for completeness.

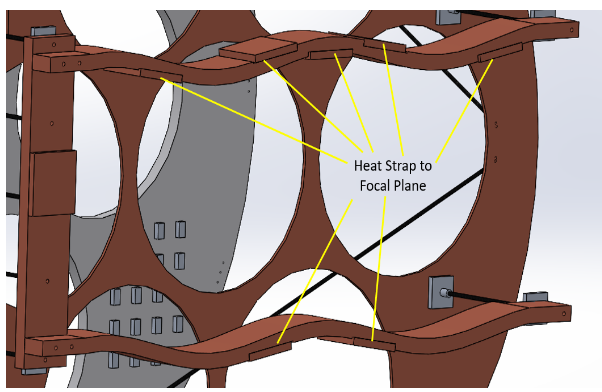

Figure 5: Each optics tube is assumed to contribute 25μW of operation power to the 100mK thermal bus. This heat power is deposited normal to these heat strap footprints pictures above.

Results

Temperature Distribution

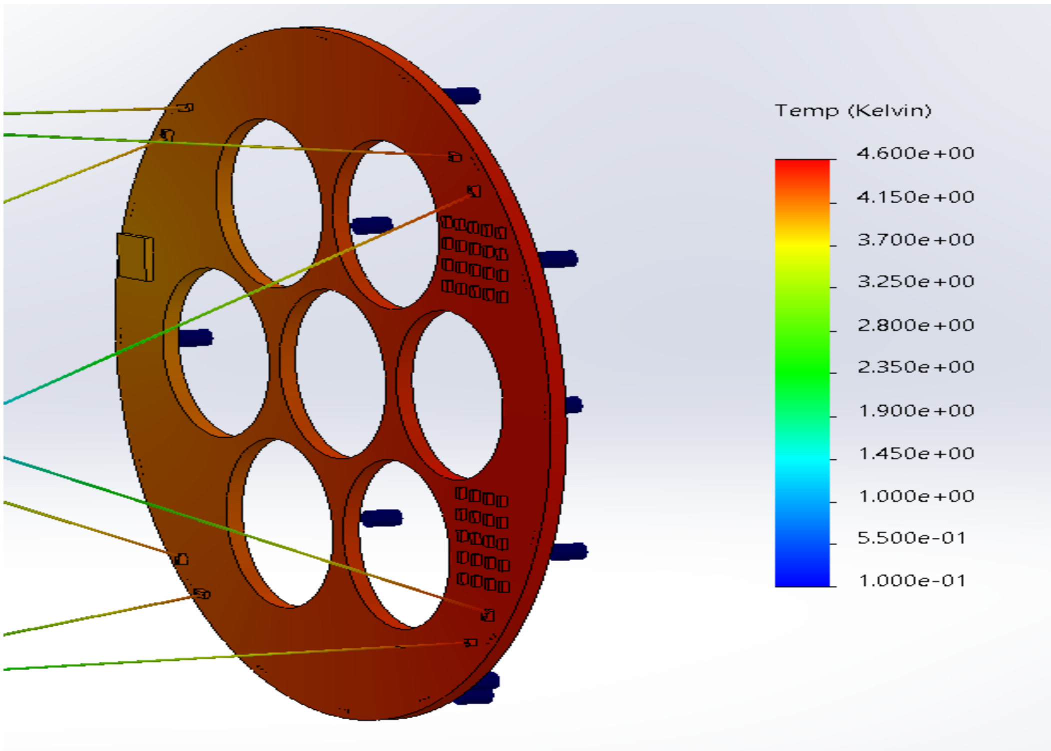

Figure 6: 4K Plate Temperature Distribution. This distribution has some profile that is hottest at the LNA distribution, which raises the temperature about 600mK from the 4K base temperature. As expected, this distribution smoothly transitions to 4K near the PTC head connection on the opposite side of the 4K plate.

Heat Flux Thru Heat Straps

The heat flux results are for heat flux in the direction of the global z-axis, which in this case is the optical axis. Since all the heat strap footprints line up with the optical axis this is ideal for assessing the heat flux flowing thru these connections in order to maintain that temperature boundary condition.

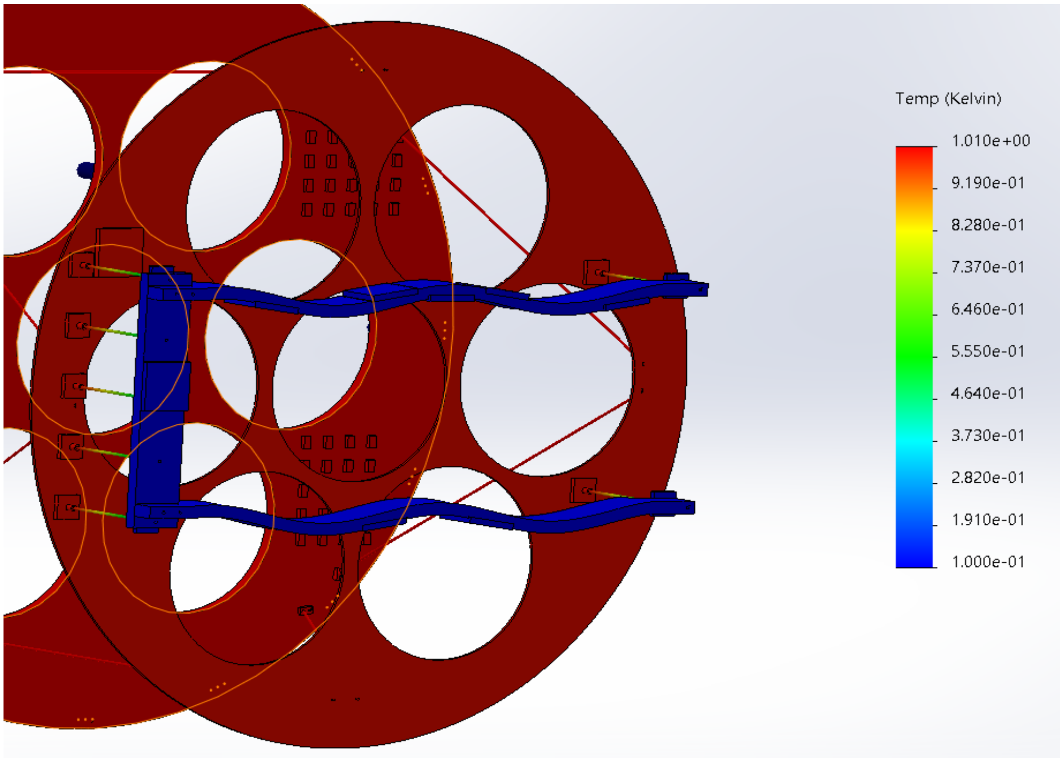

Figure 7: 1K Plate Temperature Distribution. This temperature distribution is very uniform. There seems to be a balancing between heat load coming in from the 4K plate and leaving to the 100mK thermal bus. This results in a uniform temperature distribution and a small heat flux for the 1K plate DR head to handle.

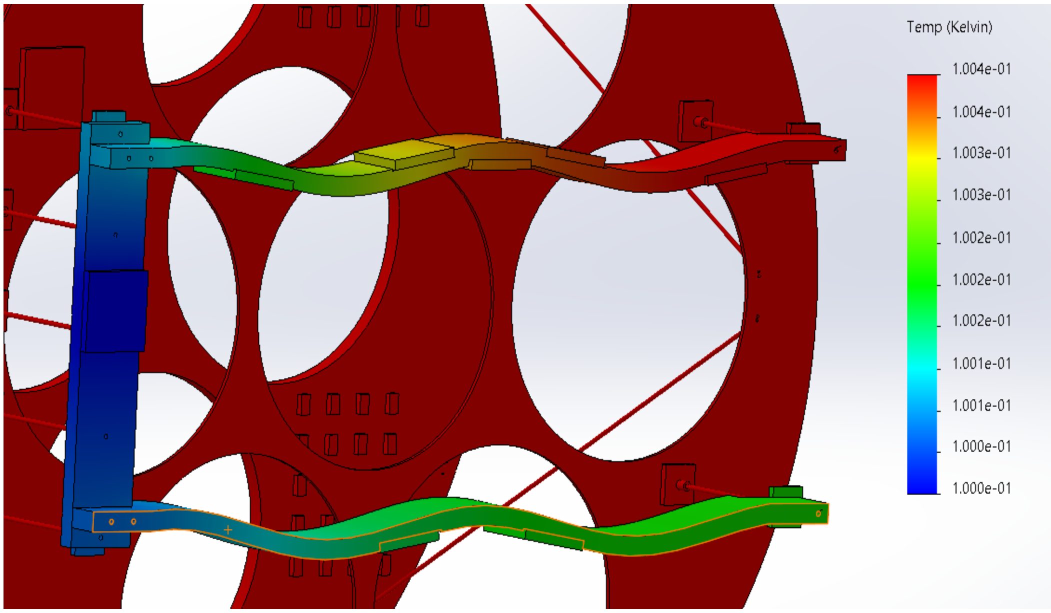

Figure 8: 100mK Thermal Bus Temperature Distribution. This temperature distribution is pretty uniform with a max temperature at the opposite end to the DR cold head connection 0.4mK above the 100mK baseline.

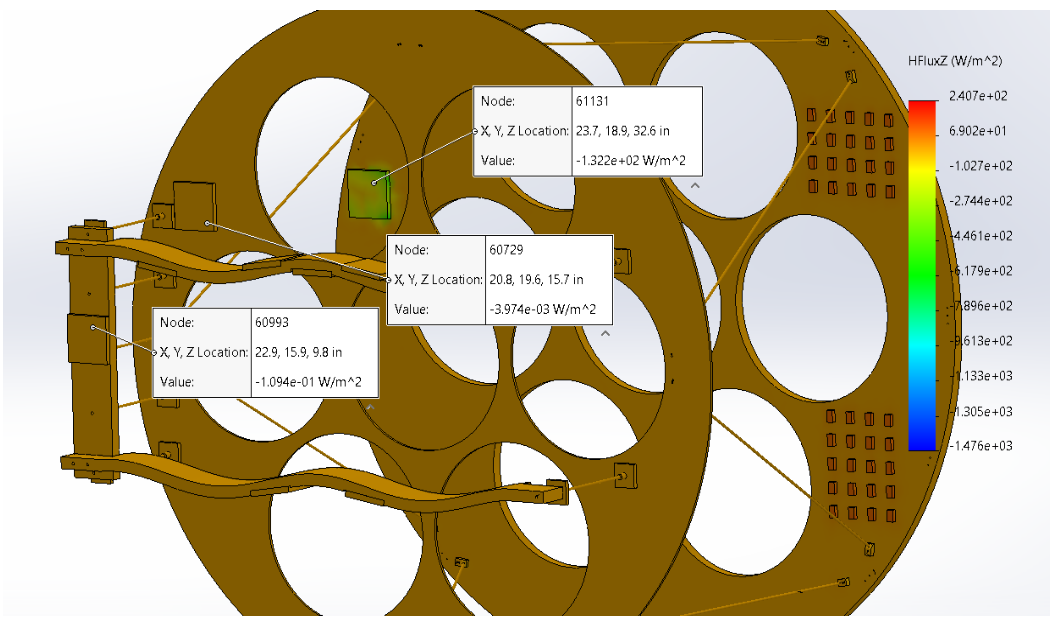

Figure 9: The heat strap footprint is 2" (0.0508 meters) on each side. The area can then be used to back out what the total heat power is flowing thru the normal direction to the footprint in order to maintain the temperature boundary condition. For 4K, 1K, and 100mK respectively, these heat powers are -340.6mW, -10.2μW, -258μW.