SPT4 Cryostat Thermal Budget

SPT4

Alec Hryciuk

April 22, 2022

Overview

This document presents the thermal budget along with details on where the projections come from. The budget is broken down by thermal stage. Cumulative loading should be compared to the total cooling power supplied to that stage at that temperature.

50K Stage

The 50K Stage will be cooled by the attached PTC. The PTC420 is used as a reference on cooling power, for which the estimated value at 50K is 55W. A summary of the projections and cumulative load is shown in the table below.

Table 1: This table summarizes a breakdown of the expected loading on the 50K stage. Further details of which are expounded upon following the table.

Loading Source	Heat Load to 50K (W)
G10 Supports	1.59
IR Radiation	8.6
BB Radiation from Shell	8.14
BB Radiation from End Caps	4.2
Wiring	0.0068
RF Shielding	0.05
Total	22.587

0.1 G10 Supports:

The conduction through the G10 support structure from the 300K vacuum plate and the 50K shell is modeled as a plane area conduction problem with a thermal conductivity dependent on the position along the optical axis. The fourier law conduction problem is numerically solved assuming 300K and 50K boundary conditions, discretizing the axis of conduction into 1000 steps, 16 G10 tabs (w,t,h: 48mm x 2.54mm x 127mm), and a best guess of the conductive load to begin the iterative calculation.

0.2 Blackbody Radiation From 300K:

The radiative load from the 300K shell is derived from a simple concentric shell model for radiative transfer such that the view factor is assumed to be unity using the equation below.

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{\epsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\epsilon_2}{\epsilon_2 A_2}}$$

This projection is then broken down into the curved face calculation and the two end caps calculation. The emissivities are taken to be that of nickel-plated aluminum at 300K (0.05) and a 50K shield wrapped in MLI (0.01) (cite). These assumptions are made to maximize heat transfer so as to be conservative but this calculation does not take into account thermal gradients, which could increase the loading.

0.3 IR Radiation Through Window:

IR Radiation through the window is taken into account by extrapolating the measured IR power from SPT3g and scaling by the ratio of the areas between the focal planes. Namely, the SPT3g focal plane is 600mm in diameter and sees the range 5-10W of IR power (cite), meaning this 7 210mm diameter optics tube cryostat would see $7 * (\frac{210}{600})^2 * (5 - 10[W]) = 4.3 - 8.6[W]$.

0.4 Wiring:

Each coax line on the input and output of the 50K shell is assumed to be stainless steel, which for an approximate distance of 0.45 meters between 300K and 50K, gives a loading per coax line of 0.04 mW. Taking into account 7 optics tubes and a target number of channels per optics tube of 6, the cumulative loading to the 50K shell from the coax lines is about 6.8 mW.

0.5 RF Shielding:

Assuming the RF Shielding can be modelled as a thin film, the conduction via this shielding can be estimated using Wiedemann-Franz. The conduction length is the distance between the shells, which is 0.0477 m. The average circumference of the interface is then found by the average of the two diameters, and comes out to 2.67 m. Assuming the aluminum is 15 nm thick, and the resistivity is that of aluminum at 300K, the resistance can be found to be $R = \frac{\rho l}{tc} = \frac{(2.65*10^{-8})(0.0477)}{(1.5*10^{-8})(2.67)} = 0.032\Omega$. The estimated power to the 50K stage is then estimated by

$$P = 2.44 * 10^{-8}[\frac{W\Omega}{K^2}]\frac{\Delta T^2}{R} = 2.44 * 10^{-8}\frac{(300-50)^2}{0.032} = 0.048W$$

4K Stage

Equivalent to the 50K stage, the 4K stage is cooled by the mounted PTC, for which an example Cryomech PT420 has 2W of cooling power at 4K. The projections for loading on the 4K stage as well as the cumulative load is shown in the table below.

Table 2: This table summarizes a breakdown of the expected loading on the 50K stage. Further details of which are expounded upon following the table.

Loading Source	Heat Load to 4K (mW)
G10 Supports	81.81
IR Radiation	0
BB Radiation from Shell	4.54
BB Radiation from End Caps	2.92
RF Shielding	2
Wiring	2.5
LNA's	(540, 1075)
Total	(656.81, 1191)

0.6 G10 Supports:

The G10 supports from 50K to 4K are bipods with an inner radius cutout ($r_{outer} = 0.5$", $r_{inner} = 0.26$", $l = 6.1778$", $N = 16$). The problem is solved the same as previous, just a different geometry.

0.7 Blackbody Radiation from 50K:

The radiative load from the 50K shell is again modeled as concentric shells with end caps as in the previous section. Again, the assumptions are thought to be conservative but do not take thermal gradients into account.

0.8 RF Shielding:

Similar to the 50K Stage, the 4K stage can be estimated as follows. The conduction length is 0.039 m between 50K and 4K shells. The average circumference is 2.52 m. So the resistance is 0.027 Ω. The power is thus

$$P = 2.44 * 10^{-8} \frac{(50 - 4)^2}{0.027} = 1.91mW$$

0.9 Wiring:

The heat load due to wiring (separate from the LNA's) is estimated as in the previous section by calculating the conductive power from the 50K to the 4K stage due to the cumulative sum of the input and output coax lines. The approximate heat load per coax line to the 4K stage is 0.03 mW. For 6 channels per optics tube and 7 optics tubes, the cumulative sum comes out to about 2.5 mW of heat load from the 50K to the 4K stage due to the coax lines.

0.10 LNA's

The LNA's attached to the 4K end cap will dissipate heat energy to the 4K shell at a rate $P = V_{bias} I_{bias} = (1.6V)(8mA) = 13mW$ per LNA. The target number of channels per optics tube (wafer) being 6 by deployment, which is represented by the lower bound in the table. The upper bound is representative of the **worst case scenario** and should be taken lightly, but is included for completeness. Either way, the LNA's contribute a large fraction of the heat load to the 4K stage.

1K Stage

The 1K stage derives it's structural integrity from the 4K plate through a carbon fiber member network.

0.11 Support Structure Conduction

0.12 RF Shielding

Using the Wiedemann-Franz Law, the approximate thermal load via aluminized mylar (15nm thick aluminum) is $P = 2.44 * 10^{-8} \frac{\Delta T^2}{R}$, where $R = \frac{\rho l}{tc}$. t being the thickness of aluminum, l being the linear distance between the temperature stages, and c being the average circumference between the two thermal stages. The inner diameter of the 4K stage is 0.7823 m, the 1K diameter is not set yet, but could be thought to be about 0.77 m in diameter. The rest of the parameters can be found and thus the thermal load from RF shielding is approximately 24.4 uW.

0.13 Wiring:

The heat load due to the wiring is estimated the same as in the previous sections, and is taken for NbTi coax cables, though other materials are being explored such as Cupronickel. For a distance of 5.53 inches between the 4K and 1K interfaces, the heat load per coax line for a NbTi cable is 1 uW, or a cumulative load of 35 uW. The analagous number for Cupronickel is 15 uW per coax line for a cumulative load of 525 uW.

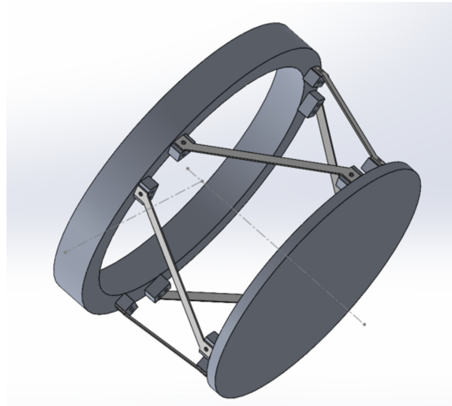

Figure 1: The hexapod titanium 15-3-3-3 support structure between 1K and the 100mK detector wafer mount.

100mK Stage

Table 3: This table summarizes a breakdown of the expected loading on the 100mK stage. Further details of which are expounded upon following the table.

Loading Source	Heat Load to 100mK (uW)
Ti Supports	3.5
Carbon Fiber Supports	1.5
IR Radiation	0
BB Radiation from Shell	0.1
BB Radiation from End Caps	0.1
Wiring	37
Detectors	TBD
Total	42.2 + TBD

0.14 Titanium Support Structure

The hexapod support structure is made of Ti 15-3-3-3, a cryogenic titanium alloy. The material properties for this alloy are found in the NIST cryogenic materials database. The support structure is shown below in figure 2.

The dimensions of which yield a cumulative conductive load of 0.5 uW per optics tube, or

3.5 uW total conductive load onto the 100mK stage.

0.15 Carbon Fiber Support Structure

There is also a structure that provides support for the 100mK thermal bus line. This will originate at the 1K plate in a similar manner to other support structures. This will provide an additional conductive load. For 7 carbon fiber legs of diameter 3mm, the additional conductive load is estimated to be 1.5 μW total assuming Runyan-Jones cryogenic thermal conductivity of carbon fiber.

0.16 Wiring

As in the previous section, the conductive load of the wiring is the sum of the inbound and outbound wires. The outbound coax lines for this analysis are chosen to be NbTi for superconducting properties. This gives a load per coax line of about 0.87 uW, or a cumulative load of 37 uW to the 100mK stage.

0.17 Detectors

0.18 Radiation

The radiative load onto the detector wafer from the 1K background is quite small. The loading can be estimated by the radiative heat transfer equation from previous sections and is estimated to be about 0.1 uW, which is virtually negligible.