Design and Construction of a 100mK Cryostat for Testing Cosmic Microwave Background Detectors

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***Abstract*— We investigated possible designs for a cryostat requiring a final stage that reaches 100mK and can support a wafer, lenslet and readout assembly in order to test detectors. Achieving extreme cold temperatures requires proper design and construction of the cryostat. We successfully designed and built a four stage cryostat that achieves vacuum. Experimentally we proved that we can cool down the first two stages. Mathematically we proved that we can reach the base temperature of 100mK for the final stage.**

I. INTRODUCTION

The cosmic microwave background (CMB) has been the focus of much research and study since the late 1900's. Since then, the field has seen much growth in observation techniques and theoretical understanding. The CMB is the edge of the detectable universe. It is the oldest, and farthest light in our universe that we can observe. What we see today in the CMB is the thermal radiation remnant from the recombination era in the Big Bang theory. The recombination era occurred approximately half a million years after the Big Bang is proposed to have happened. The radiation from the CMB is almost uniform across the sky, except for very small scale fluctuations.[1] The CMB is the best example of a perfect blackbody spectrum, and its spectrum matches identically with that of a blackbody at a temperature of about 3K.[1] Any theory or model for our universe, its construction and evolution, must predict and result in the CMB. This allows scientists to test their theoretical models. The CMB gives strong support and evidence for the Big Bang model that has an inflationary period of our universe early in its history. The focus of the research group at Lawrence Berkeley National Laboratory (LBNL) is detecting and measuring the polarization of the magnetic and electric fields in the CMB. Although the CMB is relatively uniform across the entire sky, it is the smaller scale anisotropies in its polarization that can provide evidence and support for many dark physics.[2] Such things as neutrinos, dark matter, dark energy and gravitational waves, among other things, can be learned from studying the CMB.[2] In order for the CMB to properly be studied, very precise and intricate equipment must be designed and developed. The CMB radiation is very faint, therefore, It is important for detectors to limit any sources of noise in the observations. The primary strategy in mitigating the noise is to cool the detectors. The lower the temperature of the detectors, the less thermal noise there is in the observations, and the more clear and precise the data is. The goal of this group is to design and construct a sub-Kelvin cryostat that reaches 100 mK to be used for research and development of detectors for CMB observation. The cryostat will consist of four stages, 50K, 4K, 1K and 100mK. A helium gas pulse tube refrigerator (PTR) will cool the 50 and 4 Kelvin stages, and then an adiabatic demagnetization refrigerator (ADR) will cool the 1K and 100mK stages. Since no liquid cryogenics will be used in this setup, this cryostat is dubbed a dry dewar.

II. METHODOLOGY

The construction of the cryostat started with its 3-D computer model. We used SolidWorks 3-D software to create the computer model of the cryostat, and test its components for stength, heating, mass, and fit. Once a part was fully designed and implemented in the SolidWorks assembly, then we would create a drawing of the part and send it to be ordered. There were two main methods to purchase products, eMachineshop's free CAD software to order parts online, or through the Berkeley Laboratory's connections with third party manufacturers. Many parts ordered through eMachineshop required further, small remachines to finalize the part. The remachines to the parts were drawn in SolidWorks and then given to an on site machinist to complete. As parts were finished and acquired, they were added to the cryostat. Due to long lead times on some of the parts, especially the 50K and 4K shells, the entire cryostat was not able to built.

III. MATERIALS

The design of the cryostat called for various materials to be used throughout for differing purposes. Our design used either a metal or a non-thermally conductive material. The metals included stainless steel, aluminum and copper, while the non-thermally conductive material included G10 plastic, carbon fiber and Kevlar string.

- Stainless Steel was used for the construction of the 300K stage. It is a strong and sturdy metal that is able to hold large amounts of weight well. Since the 300 K stage is the outermost stage, it must support the greatest mass, thus the reason for building it out of stainless steel. Also, since the 300K stage is not cooled down, it does not need high thermal conductivity.
- Aluminum was mainly used for the 50 K stage. Two types of aluminum were used, the 6000 series and 1000 series. Aluminum 6000 is an aluminum alloy that offers

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excellent machinebility and weldability at a low cost for the material, while also providing good structural strength. Most of the 50 K stage, and various parts on other stages, were machined with Aluminum 6000 to minimize costs, while maintaining structural integrity. Aluminum 1000 is high purity aluminum and it offers increased thermal conductivity to that of Aluminum 6000 along with good machinability; however, it is not considered structurally sound and was not used for any parts that were required to hold much mass.

- Oxygen Free High Conductivity (OFHC) Copper was used for all parts where thermal conductivity was important. This amounted to almost the entire 4K, 1K and 100mK stages, along with the heat strapping for the 50K stage. OFHC Copper offers excellent thermal conductivity, as well as a relatively low thermal mass.
- G10 plastic is a commonly used plastic in cryogenic environments. It offers low thermal conductivity, low thermal expansion/compression, and solid structural strength. G10 was used to thermally isolate the 50K stage from the 300K stage, and also to connect our pulley system for the 1K and 100mK stages.
- Carbon Fiber was used for struts to thermally isolate the 4K stage from the 50K stage. It offers a tensile strength greater than that of Aluminum or steel, while also being lighter than both. Most importantly, it has low thermal conductivity and expansion/compression.
- Kevlar string was the material used for thermally isolating the 1K and 100mK stages. The design for these stages was for a pulley system that used a string to suspend the subsequent stages of the pulley, via tension in the string, from the previous stages. This design called for a material that is thermally inductive, along with a high tensile strength, that can be made into a string. Thus, Kevlar was used.
- Other materials used in the construction process included titanium, epoxy, and mylar. Some of the parts required various finishing, such as gold plating, to decrease the thermal radiative loading.

IV. Design

The design and construction of the cryostat had three main focuses, thermal isolation, thermal shielding and thermal mass. Thermal isolation is making sure that each stage of the cryostat is not touching any other stage with material that is thermally conductive. Thermal shielding refers to creating a protective barrier between stages such that successive stages are enclosed inside the previous stage so that thermal and light radiation cannot transfer from one stage to the next. Lastly, thermal mass alludes to designing stages that are low enough in heat capacity and mass such that the cold heads for each stage have enough cooling capacity to reach the target temperature.

A. Thermal Isolation

The first strategy for thermal isolation, occurring between the 300 K plate and 50 K stage, used G10 struts to prevent conduction.

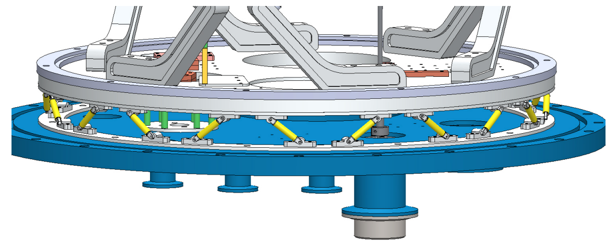

Fig. 1. G10 Struts (yellow) between 50K and 300K plates (SolidWorks Model)

The G10 struts are used because G10 has a low thermal conductivity and low thermal expansion. Thus, the G10 is equipped to provide strong support for the weight while not being warped or conductive at cryogenic temperatures. The alternating diagonal pattern utilizes kinetic mounting to limit the degrees of freedom of movement in the struts to improve structural integrity. Kinetic mounting means constraining all six degrees of freedom (three translation and three rotation). In our design, the G10 struts limit all six movements because they are angled in alternating directions, and connect around the whole circle of the 50K plate. Attempting to move or rotate the 50K plate in any direction will be prevented by the G10 supports.

The second strategy for thermal isolation was using carbon fiber struts between the 50K and 4K stage.

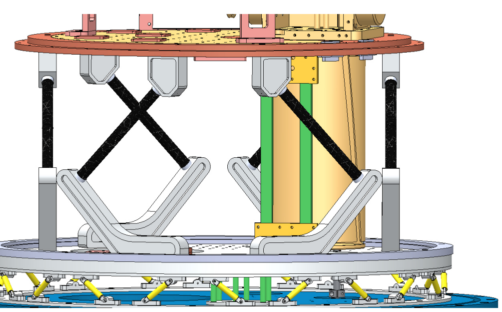

Fig. 2. Carbon Fiber Struts (black) between 4K and 50K plates (SolidWorks Model)

Once again, kinetic mounting was used in the alternating angle and fully circular placements of the struts. The switch to carbon fiber was because the 4K plate needs to be a minimum distance above the 50K plate to allow room for the ADR to sit. While the G10 is strong enough to hold the 50K plate at the small separation (1.25) shown between the 300K and 50K plates, it would not be able to handle the now large separation of the 50K and 4K plates. Carbon fiber is stronger than G10, while still having the needed properties of being a thermal insulator and lacking significant thermal expansion.

The final strategy for thermal isolation is from the 4K plate to both the 1K and 100mK rings. Here, we used Kevlar strings to isolate the stages.

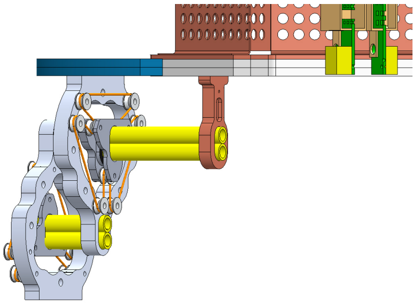

Fig. 3. Kevlar suspension for 1 K and 100 mK stages (SolidWorks Model)

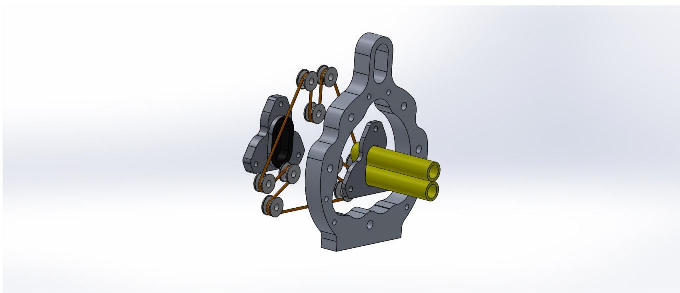

Fig. 4. Exploded view of the Kevlar suspension (SolidWorks Model)

As seen in the picture above, there is a two stage design for the Kevlar suspension isolation. Kevlar string has very high tensile strength and once again has low thermal conductivity. The design of three, equidistant suspension point on a circular plane eliminates any translational movement in the planar direction, and the tautness of the Kevlar strings suspending the parts prevents any rotational movement and normal translational movement.

B. Thermal Shielding

The concept of thermal shielding ties in with the other requirements of thermal loading and thermal isolation. Stefan-Boltzmann law states that the energy emitted by an object is directly proportional to temperature, in Kelvin, to the fourth power. This is why it is so pivotal to have the successive stages setup. The 50K stage acts as a buffer, to prevent the 300K stage from radiating heat onto the 4K stage. Therefore, when the 4K stage is attempting to cooldown, it only has to deal with radiative heating from 50K and not from 300K. This creates a difference in magnitude of energy of radiative heating of 1,000 Watts per square meter. Multi layer insulation is also added to the outside of the 50K stage to help reflect the radiative heating of the 300K stage onto the 50K stage. This same concept is why a 4K shell is needed in between the 50K and 1K/100mK stages. The difference in magnitude of energy of radiative heating for 50K to 4K is 10,000 Watts per square meter.

C. Thermal Mass

Thermal capacity refers to the amount of energy required to cool material from one temperature to another temperature. The equation for energy of heat transfer is

Fig. 5. Multi Layer Insulation applied between 300 K and 50 K

$$Q = m \times c\Delta T \tag{1}$$

The important thing to note in thermal capacity is whether the thermal capacity is less than the cooling capacity of the refrigerators. The cooling capacity of the first two stages (50K and 4K) was so large that this was not an issue. However, the cooling capacity of the last two stages (1K and 100mK) was small, and much thought and foresight was required in designing these two stages. The cooling capacity of the 1K stage is 1.2J, and the cooling capacity of the 100mK stage is 112mJ. From equation 1, we can see that the heat transfer energy is proportional to specific heat capacity, change in temperature and mass. Since the specific heat capacity and temperature change are fixed (we have to cool down from 4K to 1K or 100mK, and OFHC copper is the material we need to use due to thermal conduction and known properties for heat capacity), only the mass can be changed. Therefore, the goal was to minimize the mass such that our thermal capacity of a stage was well below its respective cooling capacity. When performing standard heat transfer energy equations, the specific heat capacity is assumed to be constant throughout the change in temperature. At subKelvin temperatures, this is not true for copper. Therefore the differential equation for heat transfer was used instead:

$$\delta Q = m \times c(T)\delta T \tag{2}$$

To calculate c(T), we gathered data from a pdf on NIST's website for the value of copper's specific heat capacity at various subKelvin temperatures and fit a curve to the data.[3]

As seen in the above graph, the fit seems to have two different sections. From 100mK to 1K c(T) is linear, and from 1K to 4K it is roughly a second order polynomial. The differential energy transfer equation can be simplified to:

$$Q = m \int c(T)dT \tag{3}$$

Finally, we graphed the cooling capacity divided by thermal capacity, Q, versus mass for both the 1K and 100mK stage to determine how much mass we had to work with for each stage.

With the information about how mass relates to the ratio of cooling to thermal capacity, we were able to get requirements

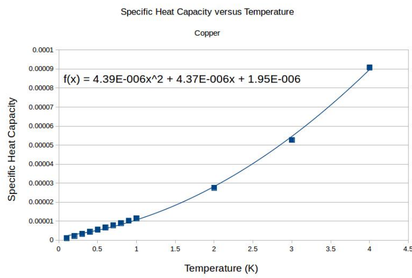

Fig. 6. Graph of specific heat capacity of copper versus temperature with a second order polynomial curve fit

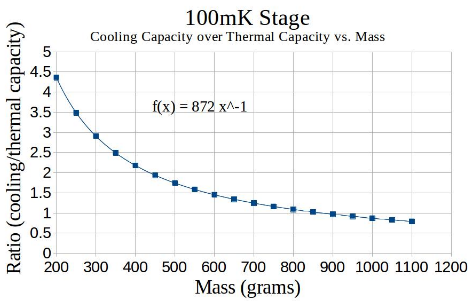

Fig. 7. Graph of ratio of cooling capacity over thermal mass versus mass for copper

for the mass allowed for each stage. The 1K stage had no issues with design, but the milliKelvin stage was more difficult. Our initial plan of another cylindrical spool shell had to be scrapped due to mass and cost requirement. Eventually, we came up with the following design:

Fig. 8. SolidWorks model of final 100 mK design

The design is to have the hexagonal shell of the milliKelvin stage be purchased as a flat piece of sheet metal 1/64 thick. Then, the sheet will be folded into the neccesary hexagonal pattern such that it fits our wafer assembly and pulley system design. This greatly reduces the cost and allows for a much thinner piece of copper to be used. The many hole cutouts were added to also reduce the mass of the material, but the holes had to remain small enough to keep the structural integrity of the shell and serve as a Faraday cage for radio frequency shielding.

V. Results

A. Design and Construction

The 3-D model of the system was finished, as well as the ordering of all parts. Not all parts had arrived by the end of the project date, therefore, not all of the parts were remachined and finalized. Construction of the cryostat was completed partially up to the 4K stage. The 300K stage and 50K stages were completely finished, and the majority, but not all of the 4K stage was completed. The construction of the 1K and 100mK stage still has most left to be done, once the parts arrive.

B. Vacuum

Initial vacuum testing of the cryostat proved to be a success. Leak checks on the flange ports of the 300K stage successfully demonstrated that there were no leaks with the parts. The initial vacuum pumping on the system was able to reach the milliTorr range, which is within the range of minimum vacuum for the compressor and pulse tube to be used. A vacuum sensor was hooked up to the cryostat, and the pressure within was graphed versus time.

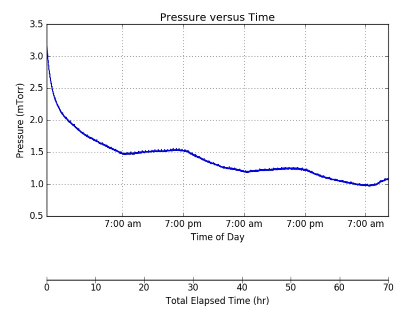

Fig. 9. Graph of pressure of cryostat while on turbo pump

Initially, the increases in pressure of the cryostat led us to think that there may have been a leak. However, after further study of the pressure, it became apparent that the increases in pressure coincided with the time of the day. This suggests that outgassing is occuring within the cryostat, and that the temperature of the day effects the rate of outgassing. As the sun comes up at 7:00 am, the temperature outside increases drastically, which causes the increase in outgassing. Pumping on the system for a longer duration, as well as possibly baking the system will help limit the amount of out gassing occurring. By the third and fourth vacuum pumps, the system would reach to around 0.3 milliTorr.

C. Cool Down

Without the 4K and 50K shells, a full cool down of the pulse tube refrigeration is not achievable due to the thermal loading of the 300K stage onto the first two stages. And without a full cool down to 4K, the ADR cannot be switched on. Instead, a preliminary cool down was performed, sans the 50K and 4K shells, and we were able to reach a temperature of roughly 120K for the first stage, and 140K for the second stage.

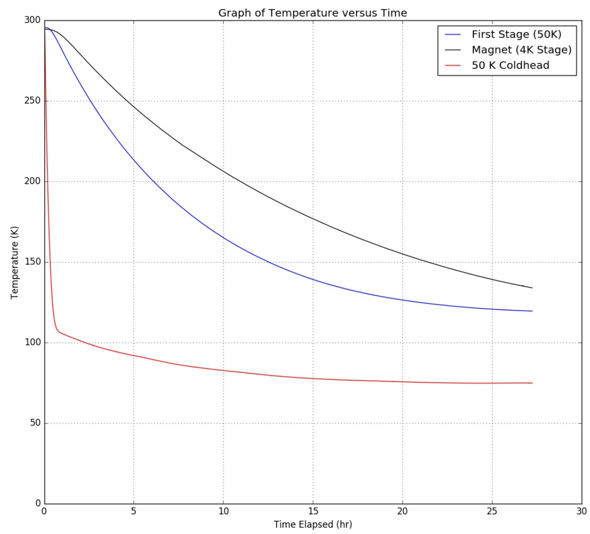

Fig. 10. Graph of temperature versus elapsed time for cryostat

Once the shells to the two stages are installed, another cool down can be run and should result in the necessary cool down of 50K and 4K for the first two stages.

VI. Conclusion

We were able to successfully design a 100mK cryostat to be used as a future testbed for detectors of the cosmic microwave background. The design meets all requirements and construction was finished up to 4K stage. The preliminary vacuum test and cooldown prove that the cryostat and pulse tube work as expected. Once further installation of parts can be completed, the ADR and 100mK stage can also be tested.

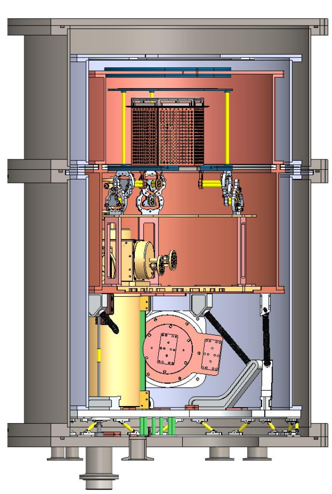

Fig. 11. Finished SolidWorks model of 100mK cryostat

VII. Acknowledgment

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