Report on PET Chiller Studies

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1 Introduction

The TPPT PET scanners, both the in laboratory scanner (e.g. Mini PET) and the MD Anderson scanner, utilize the PETsys Silicon Photomultiplier front-end readout modules (FEM) with 128 SiPM channels. The 128 channel FEM consists of four components, two FEB/A_v2 boards, the FEB/S board, and the FEB/I (Figure 1). The FEB/S connects the SiPM arrays to the FEB/A_v2 boards and has two temperature sensors in order to record the temperature of an attached PCB. Connected to each FEB/A_v2 board is a TOFPET2 ASIC as well as a temperature sensor near the ASIC. These temperature sensors located on the FEMs are used to monitor the temperature of the electronics during data acquisition. The FEMs are placed into copper "ribs" to form the overall geometry of the PET scanners (Figure 2).

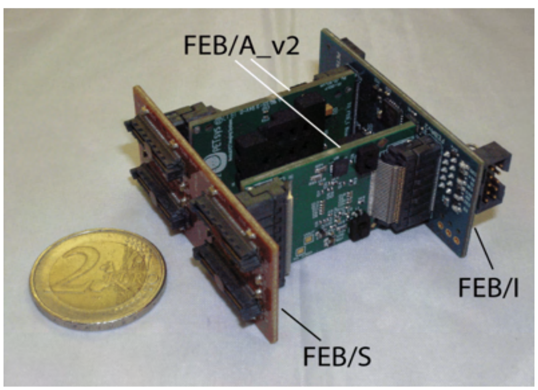

Figure 1: The 128 channel FEM, image sourced from the PETsys website.

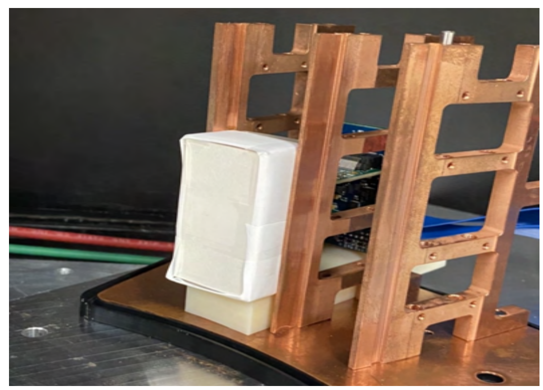

Figure 2: A crystal array and FEM placed inside one of the Mini PET ribs.

The PCB and SiPM channels are known to minimally heat, however, the ASICs heat up significantly and result in convection heating of the PCBs. The performance of SiPM channels' photo detection capabilities are partly dependent on low, stable temperature conditions and thus an effective cooling system is necessary for proper data acquisition in the PET scanners. The current understanding of cooling TPPT scanners is that the temperature of the SiPM channels should be between 16 - 18 °C and kept within a maximum temperature deviation of 1 °C during data acquisition. The final objective of these studies is to develop a cooling system aimed at lowering and stabilizing the temperature of the ASICs, which in turn will stablize that of the PCBs and their corresponding SiPM channels.

The cooling system chosen for the TPPT PET scanners was the Yamato Close Cooling Water Circulator Neocool Circulator, model CF302L-A. The rationale for using a water circulating chiller is that a network of acrylic tubing stemming from the chiller can pass over all the ASICs on the FEMs, effectively cooling the components through thermal contact as water flows. In a scanner, once the tubing reaches the copper ribs where the FEMs are held, the water flows from the acrylic tubing into two, tubed copper pieces that are positioned between the FEB/A_v2 boards for each FEM. These copper pieces are pressed up against the ASICs such that water flowing through the copper pieces makes good thermal contact with the ASICs and cools them down (Figure 3). The

CF302L-A chiller has the following specifications relevant to cooling PET scanners: a maximum flow rate of 10 LPM and a temperature fluctuation trend of ± 3.0 °C. The known temperature fluctuations of the chiller are a cause for concern due to the need for temperature stability in the SiPM channels and became a key focus of many of our studies. The chiller also has a given temperature setting range of -20 °C to 30 °C, however, below 10 °C, the chiller must be used with antifreeze solutions instead of water.

Figure 3: Parallel copper pieces as they would be placed in an FEM for Mini PET.

2 Methods

Throughout the following studies resistors were attached to the copper pieces to replicate ASICs. The ASICs are known to dissipate approximately 1 watt of power each. Therefore, for all the cooling geometries tested, the resistors were configured into circuits such that each resistor dissipated 1 watt of power as to appropriately match the joule heating of ASICs. The temperature data was recorded using thermocouples connected to a digital thermometer; a thermal camera was used in some of the preliminary studies as well. For all of the following studies, the chiller only circulated water. However, it was observed that after extended periods of time (2+ hours of water circulation) ice would build up in the chiller's reservoir. For this reason deliberations are currently being conducted to find non-toxic antifreeze solutions to use instead.

3 Results & Discussion

Various studies have been conducted to test the effectiveness of the chiller for ASIC and SiPM cooling. Below is a table of contents detailing the studies in order of which they will be discussed in this report.

Subsection	Study
3.1	Small Copper Piece Preliminary
3.2	Mock Mini PET Geometry
3.3	Long Copper Preliminary/ Buffer Volume
3.4	Mock PCB Study 1
3.5	Mock PCB Study 2/ MD Anderson Geometry

Table 1: Table of contents of the various chiller studies.

3.1 Small Copper Piece Preliminary Study

The first chiller study conducted was with a single, small copper piece (Mini PET copper piece) with two resistors attached (Figure 4 and 5), which replicates the number of ASICs each copper piece would be in contact with in the Mini PET geometry. The base line flow rate of this configuration was determined to be 3 liters per minute. The first two tests were done with the chiller's water set to 15 °C and 10 °C. The results of these tests are detailed in Figures 6 and 7 which display the temperature verses time plots from the point of thermal equilibrium of the heated resistors before water flows and after chilled water begins to flow. The temperature data in these plots was collected by hand via both a thermal camera (Cam) and thermocouples (TC) as indicated by the legends. Both the temperatures of the copper and one of the resistors were measured labeled as Cu and R, respectively, in the legends. The thermal camera seemed to measure temperatures approximately the same as the thermocouples. For this reason, the thermal camera was no longer used after this study and all data was gathered from the thermocouples and thermometer.

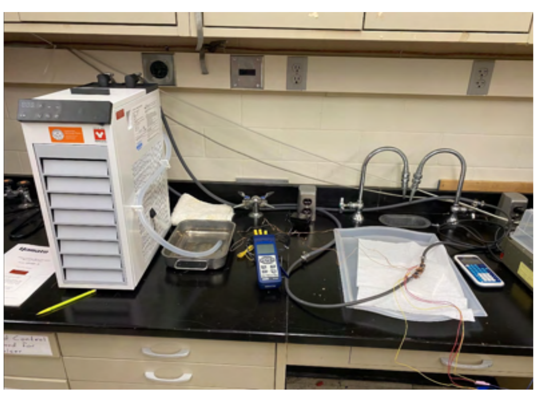

Figure 4: The single copper piece cooling configuration.

Figure 5: The single copper piece with 2 resistors.

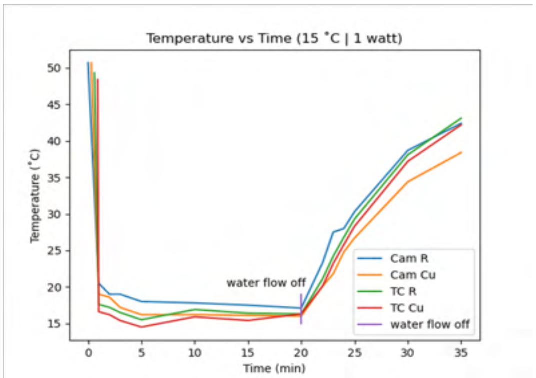

Figure 6: Temperature verses time for the single copper piece cooling configuration with the chiller set to 15 °C.

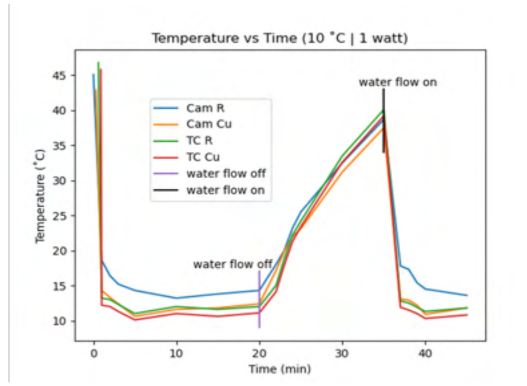

Figure 7: Temperature verses time for the single copper piece cooling configuration with the chiller set to 10 °C.

The results shown in the figures above demonstrate that the chiller can indeed sufficiently lower the temperatures of the resistors and copper within 1 °C of the chiller's set temperature. As noted in the background section, the objective is to get the PCBs to temperatures between 16 - 18 °C which is clearly achieved. Thus, these studies suggest the chiller may be effective enough to properly cool at least one 128 channel FEM.

The next question addressed was if the flow rate of the water had any effect on the cooling efficiency of the chiller. Since the chiller does not come with any adjustable flow rate settings, a flow meter was installed into the configuration. However, due to the restrictive nature of this single copper configuration the addition of the flow meter did not allow us to significantly adjust the flow rate from the base line flow of 3 LPM. Figures 8 and 9 display the results of a 10 °C runs at 2 and 2.5 LPM, respectively. The results from these runs suggest that the flow rate does not noticeably impact the cooling efficiency of the chiller.

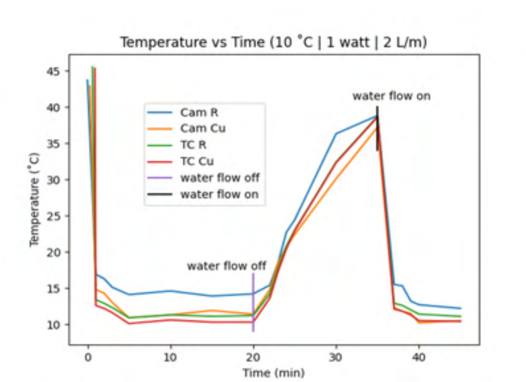

Figure 8: Temperature verses time for the single copper piece cooling configuration with the chiller set to 10 °C at a flow rate of 2 LPM.

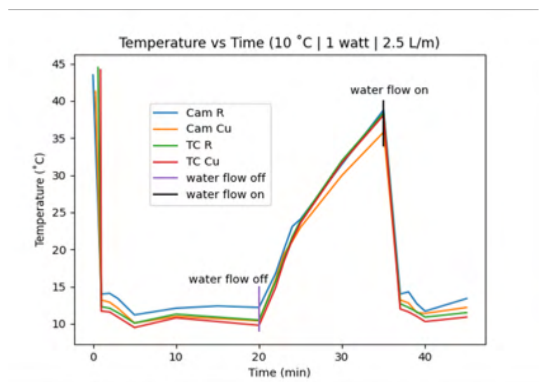

Figure 9: Temperature verses time for the single copper piece cooling configuration with the chiller set to 10 °C at a flow rate of 2.5 LPM.

3.2 Mock Mini PET Geometry Study

Once the the chiller was proven to effectively cool at least one copper piece, a mock set up replicating the geometry of Mini PET was configured. The full geometry of Mini PET consists of 4 FEMs (4 PCBS and 8 crystal arrays) on each set of opposing ribs, for a total of 8 ASICs on each side. In a fully functioning Mini PET with the chiller added as the primary source of cooling, each copper piece can cool 2 ASICs. Therefore, in the real Mini PET geometry a total of 8 copper pieces would be ingrained into the tubing network of the chiller. Figures 10 and 12 show the mock Mini PET cooling geometry. Notice that there are only 7 branches/copper pieces, however it was argued that if the chiller can cool 7 pieces then the results will be sufficient to prove it can also cool 8 pieces for the real Mini PET geometry.

As done in the Small Copper Piece Preliminary Study, the water was allowed to flow and temperatures of both the copper and Resistors were recorded. Starting in this study, the temperatures were no longer recorded by hand but rather were recorded every 10 seconds by the thermometer's automatic datalogger. The temperature data at 10 °C with the flow rate at 5 LPM was recorded and the results are displayed in Figures 11 and 13. Both the outer and inner branches of the 7 branch geometry were measured in order to ensure temperature uniformity across all cooled copper pieces.

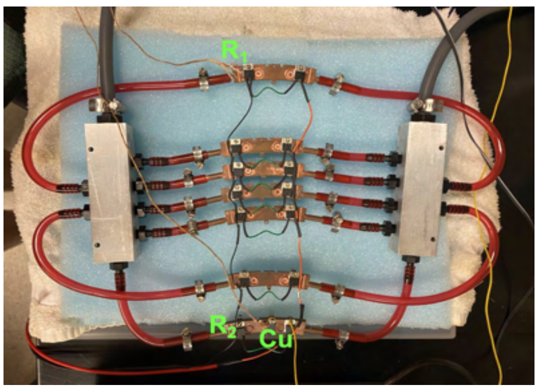

Figure 10: The Mock Mini PET geometry with thermocouples attached to the outer branches.

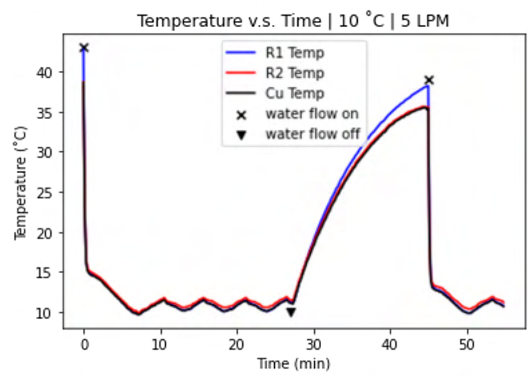

Figure 11: Temperature verses time for the outer branch run.

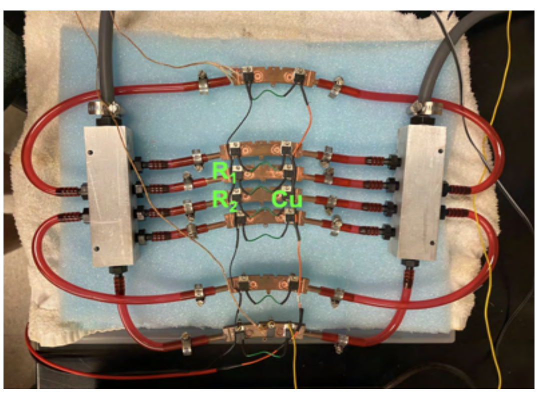

Figure 12: The Mock Mini PET geometry with thermocouples attached to the inner branches.

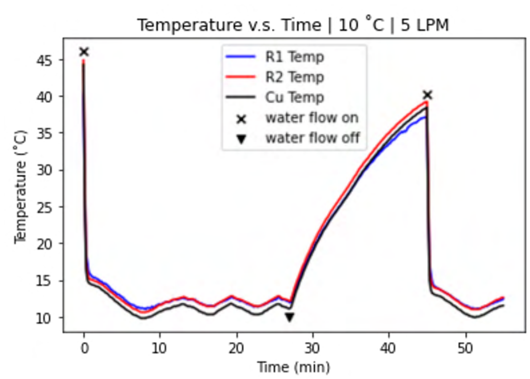

Figure 13: Temperature verses time for the inner branch run.

The plots above demonstrate that the chiller can effectively and uniformly cool multiple heated components (Resistors or ASICs) in thermal contact with multiple copper pieces. However, the use of the automatic datalogger also revealed a previously unseen problem, fluctuations of the resistor and copper temperatures which can be seen between the 10 minute and 30 minute marks on Figures 11 and 13. As stated in the Introduction, the known temperature fluctuations of the chiller itself is ± 3 °C, however, it was not apparent before that the resistors and copper pieces were following the chiller's oscillation trend. Figures 14 and 15 take a closer look at the temperature fluctuations shown in Figure 13. From these plots, we can see that temperature fluctuations occur approximately in a period of 10 minutes and have a total range (trough to peak) of 1.4 °C. This is cause for concern as the goal is to keep the temperature of ASICs and more importantly the SiPM channels in a scanner within a 1 °C range during data acquisition. The last study conducted with the Mini PET setup was a 2 hour cooling run in order to test if the fluctuations would subdue after an extended period of time. Figure 16 shows the fluctuations do not seem to reduce in frequency or range over an extended period of time.

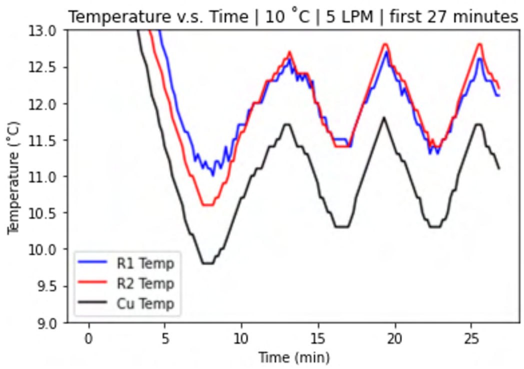

Figure 14: A close up of the temperature fluctuations from Figure 13.

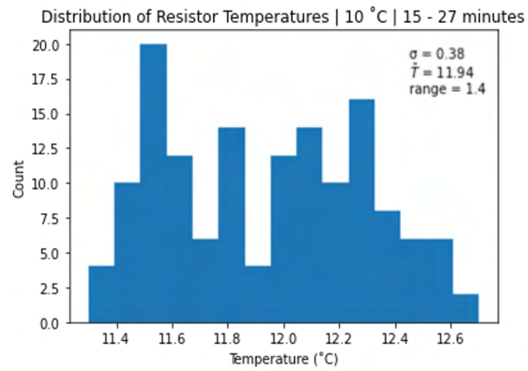

Figure 15: The distribution of temperatures from Figure 13 from 15-27 minutes.

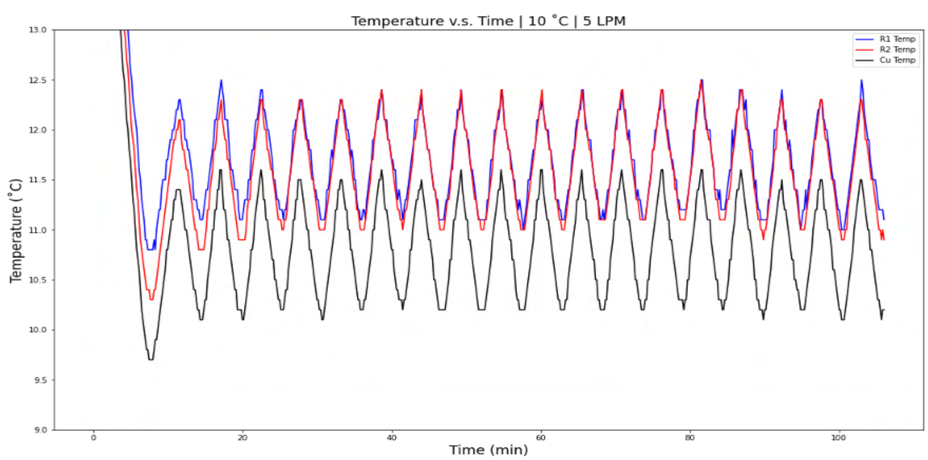

Figure 16: The temperature verses time plot for a 2 hour+ cooling run.

3.3 Long Copper Preliminary/ Buffer Volume Study

By this point in the studies, it has become clear that the chiller is fully capable of reducing the temperature of multiple resistors and/or ASICs in thermal contact with the copper pieces. However, the ability of the chiller to stablize temperature is a more pressing question. The next configuration studied was with the long copper pieces, which are those that will be used in the "half moon" modules for the MD Anderson Scanner. A single long piece was set up with 10 resistors (Figure 17) each dissipating 1 watt of power (in the real MD Anderson scanner 12 ASICs total would make thermal contact with each long piece). The base line flow rate through the long copper piece was measured to be 3 LPM. The results from a 10 °C run followed almost identical temperature verse time patterns as the Mock Mini PET configuration as shown in Figure 19 (see Figure 14 as reference).

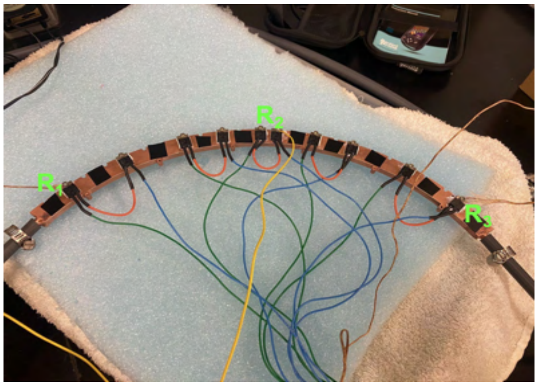

Figure 17: The resistor configuration on the long copper piece.

Figure 18: A long copper piece (top) compared with a small piece.

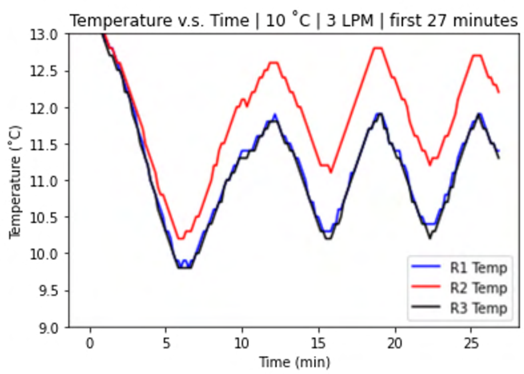

Figure 19: The temperature fluctuations exhibited by the long copper piece.

Next, the original long piece configuration was modified to add a 3.5 L buffer volume into the tubing network stemming from the chiller (Figure 20 and 21). The buffer volume was our first attempt at reducing the temperature fluctuations with the intention that the additional thermal volume would help provide thermal inertia to the system and reduce the fluctuation trend. The results of a 10 °C run are shown in Figures 22 and 23. The buffer volume did indeed help to elongate the fluctuations with a temperature increase period of each cycle being about 8 minutes long and a decrease period of 3 minutes. This is in contrast to cooling before the buffer volume, which had symmetric temperature cycles (see Figure 19 above). The overall range of these fluctuations was an average of 1.4 °C, which is still outside of 1 °C range necessary for proper PET data acquisition.

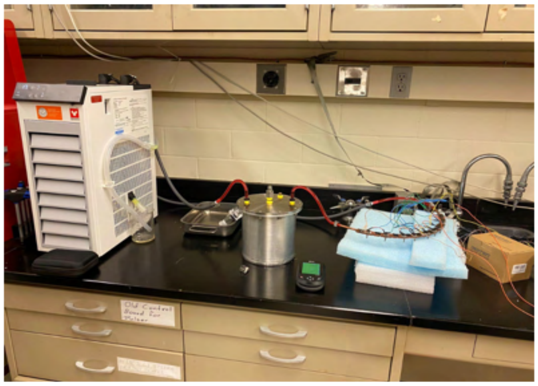

Figure 20: The long copper piece configuration with the added buffer volume.

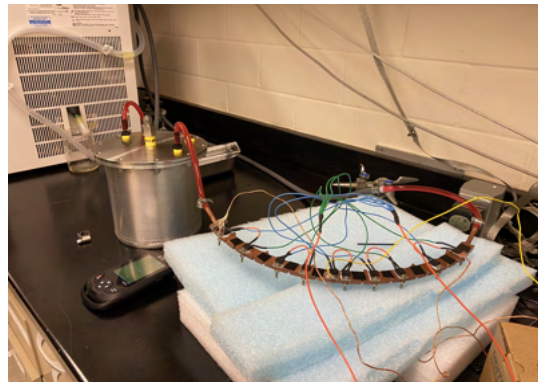

Figure 21: The buffer volume configuration from a different angle.

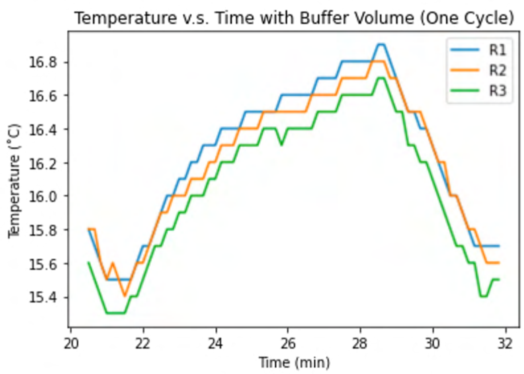

Figure 22: One cycle of a temperature fluctuation from the long copper piece, buffer volume run.

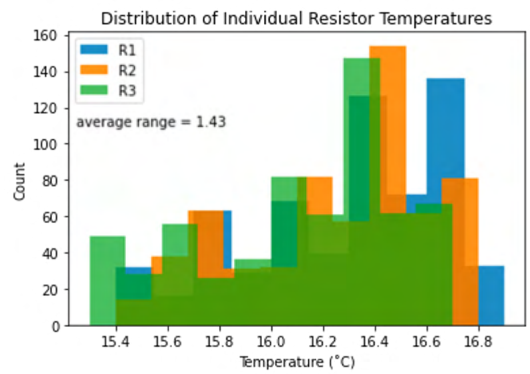

Figure 23: The distributions of the individual resistor temperatures from the long copper piece, buffer volume run.

3.4 Long Copper Preliminary/ Buffer Volume Study

It became clear that the temperature fluctuations are difficult or impossible to completely subdue. However, the fluctuation trends observed have been for the resistor temperatures, which ultimately mimic the ASICs. The temperature stability of the ASICs is not nearly as important as the stability of the SiPM channels. Therefore, the studies shifted focus to observing if a PCB would follow the same temperature fluctuation trends as the cooled resistors/ASICs. In order to simulate the ASIC-SiPM relationship, the previous buffer volume setup was modified such that an independent, small copper piece was placed 1 inch away from the long copper piece, similar to the actual distance between the ASICs and SiPM arrays (Figure 25). The small copper piece was meant to mimic a PCB in this study such that it was not heated or cooled through thermal contact only convectively from the resistors on the long copper piece. The area around the buffer volume and copper pieces was insulated with Styrofoam as shown in Figure 24.

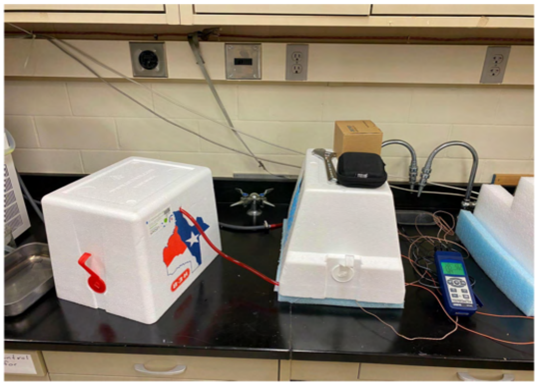

Figure 24: The insulated mock PCB configuration.

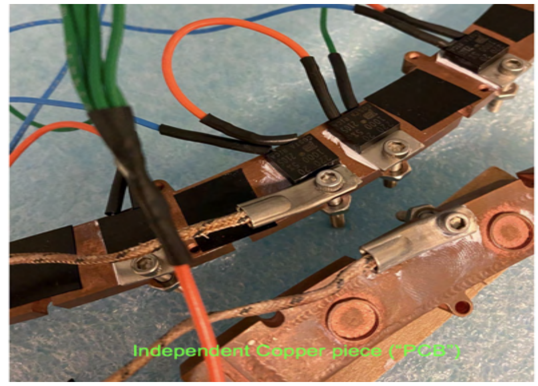

Figure 25: An image of the mock PCB (Cu) next to the long copper piece.

The results from a 10 °C run displayed a very promising result as shown in Figures 26 and 227: the independent, small copper piece did not follow the temperature fluctuation trend of the cooled resistors. In fact, from the 1 hour to 2 hour mark shown on the below figures, the small copper piece had a temperature range of 0.4 °C. This value falls well within the 1 °C temperature range goals as needed for SiPM temperature stabilization for data acquisition. The results suggest that the chiller is fully capable of stabilizing the temperature of a PCB.

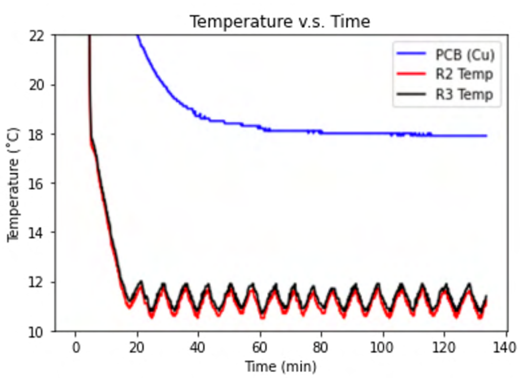

Figure 26: The temperature verses time plot for the 10 °C mock PCB run.

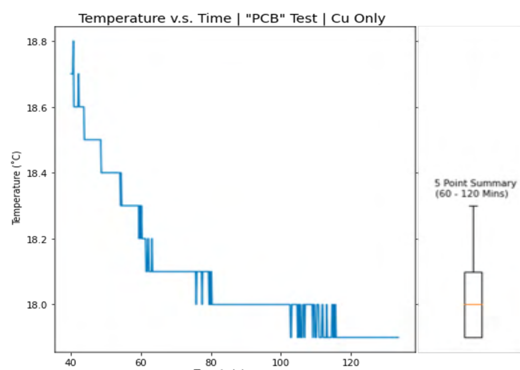

Figure 27: A close up of the temperature function of the mock PCB from Figure 26.

3.5 Mock PCB Study 2/ MD Anderson Geometry Study

The final studies conducted with the chiller was cooling tests within the MD Anderson half-moon copper ribs. A thermocouple was attached to a decommissioned PCB and placed into the ribs in order to study how an actual PCB will convection cool. The initial configuration had one long piece placed into the ribs with the 10 resistors attached as before. The entire setup was then placed into a partially insulated box (see Figures 28 and 29 below). The ambient temperature within the box was recorded throughout the cooling run as well.

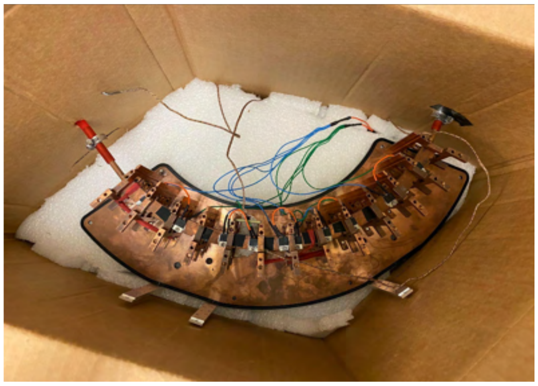

Figure 28: An above image of the MD Anderson ribs cooling configuration inside the partially insulated box.

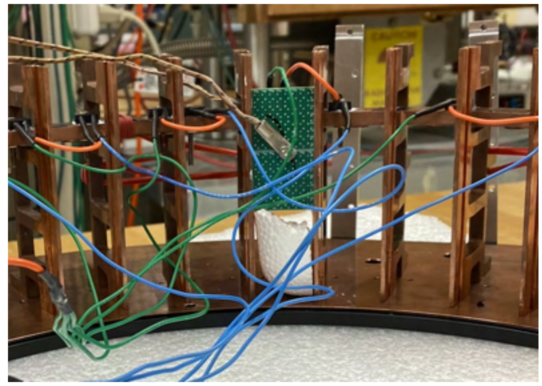

Figure 29: A close up image of the decommissioned PCB with the attached thermocouple.

The results from a 10 °C run show very similar results to that of the independent, small copper piece from the subsection above (Figure 30). However, the time needed for the temperature of the PCB to stablize is much longer than that of the small copper piece, which is more than likely a result of PCB being less thermal conductive than the copper. As shown in Figure 31, the temperature of the PCB decreases by 1.8 °C from the 1 to 2 hour mark and 0.3 °C from the 2 to 3 hour mark. Thus, if this was the temperature trend during a TPPT PET scanner run, the chiller would have to be running and cooling the ASICs for at least 2 hours before data acquisition as to meet the 1 °C threshold range for proper data collection. Despite the long cooling period, the results of this temperature data reinforce the chiller's ability to sufficiently reduce and stablize the temperature of the PCBs in a PET scanner.

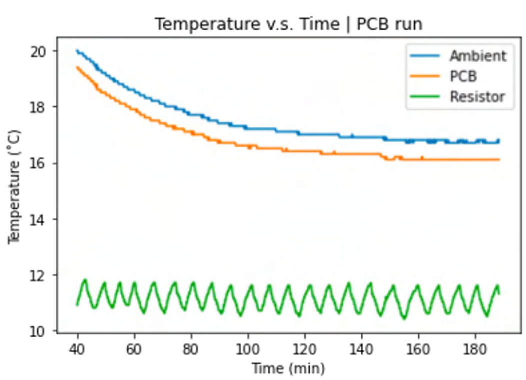

Figure 30: The temperature verses time plot for the 10 °C MD Anderson geometry run.

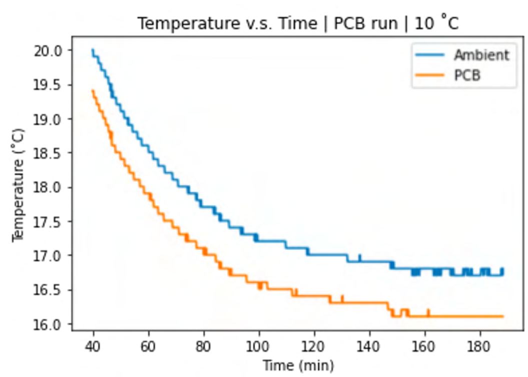

Figure 31: A close up of the Ambient and PCB temperature functions from Figure 30.

A second configuration was setup with the MD Anderson ribs with 4 long copper pieces placed into the ribs, all of which were connected to the chiller and had water flowing through them. No additional resistors were added to the setup, so only the original 10 resistor copper piece was joule heating (Figure 32 and 33). The true geometry of MD Anderson will consist of 4 long pieces cooling 48 ASICs per half-moon module. Along with the PCB, the temperature of the copper ribs was also measured. Figures 34 displays the temperature verses time plot of this configuration with the chiller set to 10 °C and Table 2 displays relevant statistics of the temperature data. The data presented in Table 2 demonstrates that the addition of three more long copper pieces allowed for a faster cooling period compared to the run with a single long copper piece above. Prior, the configuration with a single long copper piece required a period of 2 hours before the PCB temperature was properly stabilized. The four long copper piece run required only a 40 minute period. From this, we may conclude that when the chiller is employed into the real scanner, the chiller should run for at least 1 hour before the SiPMs will have an appropriately stabilized temperature for data acquisition.

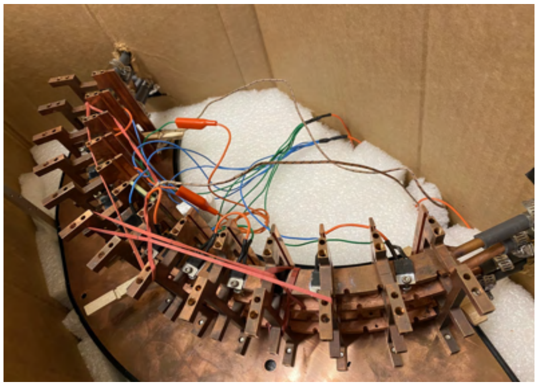

Figure 32: An above image of the MD Anderson ribs with four copper pieces.

Figure 33: The four long copper pieces inside the MD Anderson ribs.

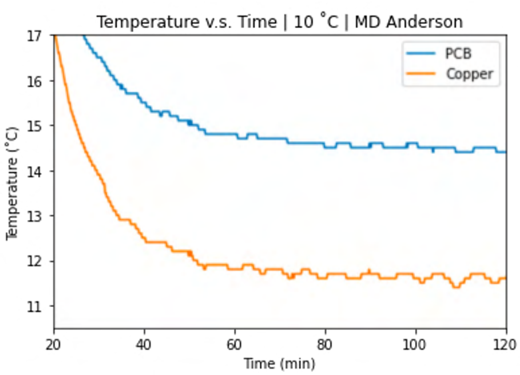

Figure 34: The temperature verses of time plot for a 10 °C MD Anderson Geometry Run with four copper pieces.

Time (min)	**PCB** (°C)	**Cu Ribs** (°C)
0 - 20	Range = 10.5 $\sigma = 3.76$	Range = 9.3 $\sigma = 3.22$
20 - 40	Range = 4.1 $\sigma = 1.12$	Range = 4.7 $\sigma = 1.32$
40 - 60	Range = 0.70 $\sigma = 0.22$	Range = 0.70 $\sigma = 0.22$
60 - 80	Range = 0.20 $\sigma = 0.070$	Range = 0.30 $\sigma = 0.085$
80 - 100	Range = 0.10 $\sigma = 0.049$	Range = 0.20 $\sigma = 0.051$
100 - 120	Range = 0.20 $\sigma = 0.052$	Range = 0.30 $\sigma = 0.090$

Table 2: Temperature data statistics from Figure 34.

4 Conclusion

The chiller was found to effectively reduce the temperature of the resistors (and presumably ASICs) and the surrounding copper in these studies within 1 °C of the water's temperature in just a few minutes for both Mini PET and MD Anderson geometry studies. The mock PCB studies demonstrated that PCBs do not follow the fluctuations of the chiller and resistors but rather have temperatures that stabilize within the necessary 1 °C range after being cooled for 1 - 2 hours. Overall, the results suggest that the chiller is fully capable of achieving the appropriate cooling parameters necessary to cool the TPPT PET scanners. The next steps will be to find and test the chiller with antifreeze solutions instead of water and to test the chiller with functioning SiPM arrays and ASICs.