Characterization of Sensors for Cryogenic Particle Detectors at the milli-Kelvin Scale

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July 28, 2022

Abstract

Cryogenic particle detectors are a useful tool in neutrino research, particularly neutrinoless double beta decay searches, due to their excellent energy resolution, potential to be made with high radiopurity and their high detection efficiency. To maximize energy resolution, such detectors are operated at extremely low temperatures ($\sim 10mK$), where the low heat capacity of the detector maximizes the intrinsic detector response to energy depositions. Such detectors require high-sensitivity thermometers that can operate in an ultra-low temperature environment. In this project we explore neutron transmutation doped germanium thermistors and superconducting tungsten thin films, both of which are expected to exhibit very strong resistance vs. temperature behavior. We also explore the resistance vs. temperature curve

of metal foil resistors to determine if they are suitable to use as reference heaters to monitor detector thermal response. In this report, we describe the design and construction of a sample holder, the cooldown process, and the analysis of the collected data.

Introduction

Neutrinoless double beta decay attempts to solve the mystery of why matter exists in the universe when in theory the matter and antimatter should have annihilated each other [Enss, 2005]. The theory is that when an isotope undergoes double beta decay, it emits two electrons and two antineutrinos. The antineutrinos annihilate each other, leaving two electrons behind, thus creating matter. This has not been proven, but is being searched for using a variety of techniques, one of which uses cryogenic particle detectors [Enss, 2005]. We tested our samples in a cryogenic refrigerator. Cryogenic refrigerators reach super low temperatures (less than 1K), and are used for various purposes, such as cooling superconductors and removing background noise from highly sensitive experiments [Balshaw, 1996]. In this experiment, we used a dilution refrigerator which functions by diluting ^{3}He in ^{4}He. When cooled to below 0.86K, the He3/He4 solution separates into 2 phases, one on top of the other: the concentrated phase, which is lighter and 100% ^{3}He, and the dilute phase, which is heavier and more He4 rich (only 6% ^{3}He) [Balshaw, 1996]. The cooling is done by evaporating ^{3}He out of the mixing chamber. It then condenses and is pumped back in as concentrated ^{3}He. As it returns to the mixing chamber it expands, cooling the system as it goes. the mixing chamber needs to be heated a little in order for the refrigerator to properly cool because if the ^{3}He gets too cold it becomes hard to evaporate, which slows the flow rate in dilution circuit [Balshaw, 1996]. Because of this, the still has a heater, which we set to 30mW to ensure the flow rate is adequate (approximately 1mmol./s). These refrigerators are complex machines, and in order to get them to function as efficiently as possible, we are in search of suitable components.

Process

The first step of this experiment was to make a box to hold the samples in the freezer. This box attaches to the mixing chamber plate and ensures the samples are thermally coupled to it so they cool down. The box is made of ultra-pure copper, which is electrically and thermally conductive, so ideally it should cool down to the same temperature as the plate. Using Fusion 360, we designed a box to fit around the sample holder (a flexible printed circuit board with copper pads and traces printed on it).

We made the sides relatively thin (3mm) so the box wouldn't be too heavy, as it takes more energy for the freezer to cool larger masses. We also put vent holes at the base of every threaded screw hole to ensure air wouldn't get trapped behind the screws, as it could leak out and disrupt the

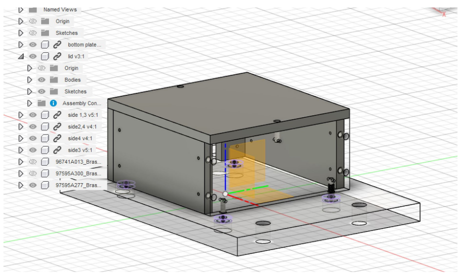
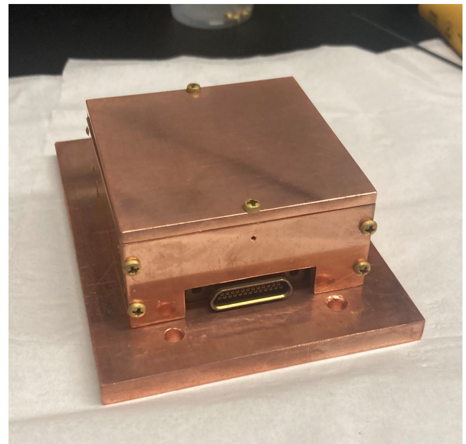



Figure 1. (left) 3D rendering of box in Fusion 360, and **Figure 2.** (right) Photo of the box

vacuum, which is necessary to avoid a thermal short from the outside. The parts were then machined to our specifications. Afterward, to ensure the copper was ultra clean, we wiped the pieces with ethyl alcohol, soaked them in citric acid overnight, and re-wiped them with ethyl alcohol. This reduces the chance of excess dirt or human oils in the freezer.

The next step was to prepare the samples for cooling. First, the sample holder was glued onto the 6mm copper plate using, GE low temperature varnish, a thermally conductive, electrically insulating epoxy. The samples were then attached to the holder using the same epoxy and allowed to dry. Next,as shown in Figure 3, the samples were wire bonded to the copper plates on the sample holder using a wirebonder and 25 μm gold wire.

The NTD was given 2 wires to each plate and the three heaters each had one wire connection per copper plate, due to their small size. The tungsten

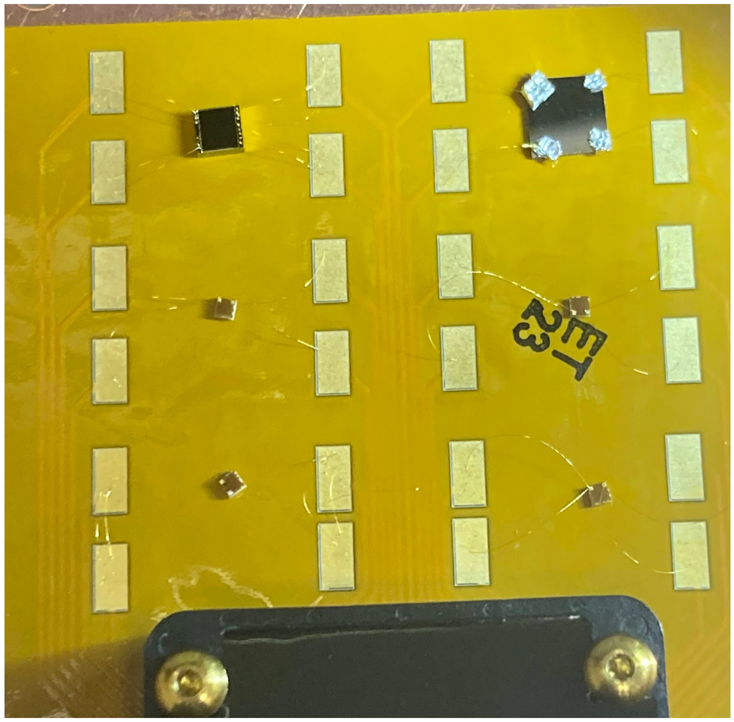


Figure 3. Samples in place on the holder.

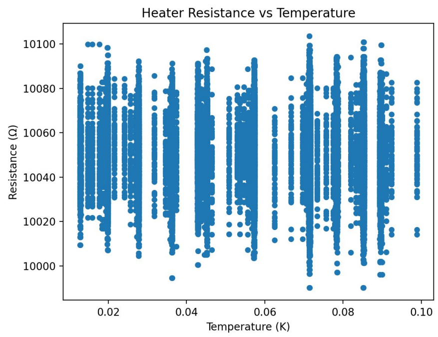
thin film would not bond with the gold wire, so we used indium to hold its wires in place (one wire per copper plate). Once all five samples had wire connections, the sides and lid of the box were affixed to the 6mm plate using brass M2 screws, as brass is thermally conductive but not as malleable as copper, so there is less risk of accidentally deforming the screws. After sealing up the box, we screwed it onto the cooling plate in the freezer and plugged it into readout line 2 of the fridge.

Next, we tested the resistances of each sample, discovering that one of the heaters had a short and did not work. We then closed the refrigerator and conducted a leak check, which involves spraying helium gas around the freezer's rubber o-ring seal and seeing if the leak detector senses any excess He in the system. The baseline leak rate was $2x10^{-10}$ mBar.l/s, and after spraying the helium it went up to $9x10^{-10}$ mBar.l/s, which means the seal is sufficiently tight enough for a cooldown. After the leak check, we started the cooldown. We checked the samples' resistances once the fridge was cool, noting that the NTD was not behaving properly and only one of the 3 heaters appeared to be working. This may have been caused by the wire bonds failing, as that is typically the weakest point. We then began collecting data for the heater at different power percentages each hour, which we matched up with the temperature data to make resistance vs temperature graphs. Then, we collected data for the tungsten film by changing the power every 30 minutes.

Results

Using a python script we wrote, we graphed the resistance vs temperature for the one functional heater and for the NTD. Our NTD was not working during this cooldown, but we had data for another NTD from a cooldown the previous week, so we used that data.

As seen in Figure 4, there is no evidence that the resistance exhibits a temperature dependence. Further analysis shows that the average resistance is $10050 \pm 14\Omega$, meaning the resistance is actually very stable, with only $\sim 0.1\%$ change overall due to noise.



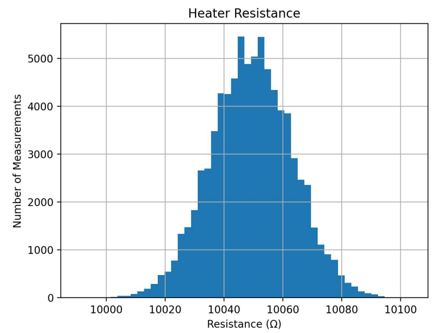


Figure 4. (left) and **Figure 5.** (right)

This can be seen in Figure 5, which shows that largest number of resistance measurements tend to be around 10050Ω. Thus these heaters may be used as a reference heater as they appear to have no temperature dependence. When graphing the ntd data, we used the formula $R = R_0 e^{(T_0/T)^{1/2}}$ [Enss, 2005]. This can be written as $ln(R/R_0) \sim (T_0/T)^{1/2}$, and simplified to $ln(R) \sim (1/\sqrt{T})$. Using this formula, we can graph the log of the resistance and the temperature as $1/\sqrt{T}$, in order to better see the relationship between temperature and resistance.

As seen in Figure 6, the NTD data shows a strong correlation between resistance and temperature, although it appears to lessen as the temperature decreases. This is likely because the samples were not actually at the temperature of the plate when it got that cold, which may have been caused by a variety of things, such as the electrons in the wires being excited by RF radiation, poor thermal contact with the cooling plate, parasitic heating of the NTD, etc. The tungsten film data was inconclusive, not showing a

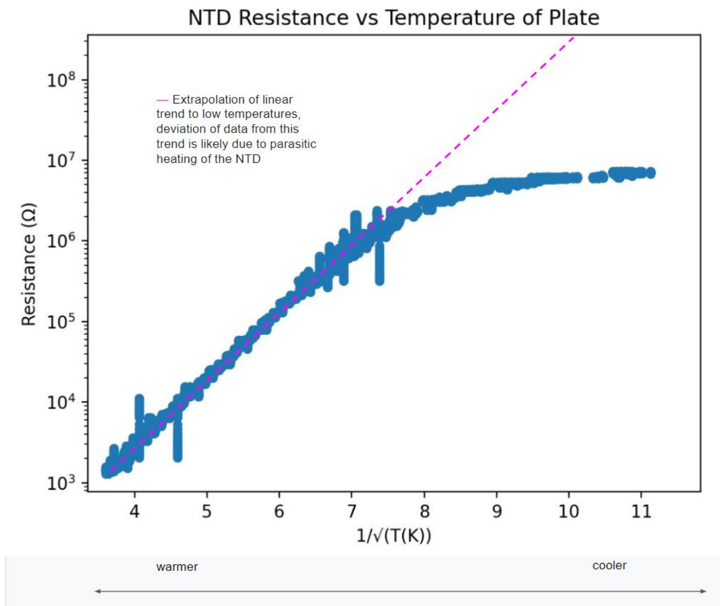


Figure 6. NTD resistance vs temperature graph.

typical superconducting transition. This should be re-tested, as it could have been the result of a number of variables, like our inability to wirebond to the sample or inconsistent temperature readings for the plate vs the sample.

Conclusion

Both the NTD and the heater show promising results, but they need to be researched further if they are to be used in a cryogenic particle detector, as there were a number of limitations on this experiment. Firstly, only one heater was able to be tested. It would be ideal if we had data from multiple heaters to ensure they are also unaffected by temperature. Also, the NTD in this experiment did not respond after the cooldown so it should be tested again. Additionally, the data shows decreased temperature dependence at colder temperatures, which would not make it an ideal thermometer. However, as mentioned earlier, this trend is likely due to discrepancies between the temperature of the plate and the sample, but more testing should be done to ensure this is the case. If we are able to show a strong temperature dependence at colder temperatures as well, these NTD's could be used as thermometers. Also, the tungsten films need to be re-tested, as we were unable to obtain conclusive data for the one we tested.

Acknowledgements

1. Professor Thomas O'Donnell, for helping every step or the way

2. Joe Camilleri, for making the sample holder and bottom plate of box

3. The people at the machine shop, for making the pieces of the box

4. We thank Prof. S. Emori (Virginia Tech Physics Department) for providing the tungsten film sample, the CUPID collaboration for providing the NTD samples and VPG Foil Resistors for providing the heater samples.

5. We acknowledge the outstanding support from the National Science Foundation, the Virginia Tech Physics Department and the Virginia

Tech Center for Neutrino Physics. This work was made possible by the National Science Foundation under grant No. PHY2149165.

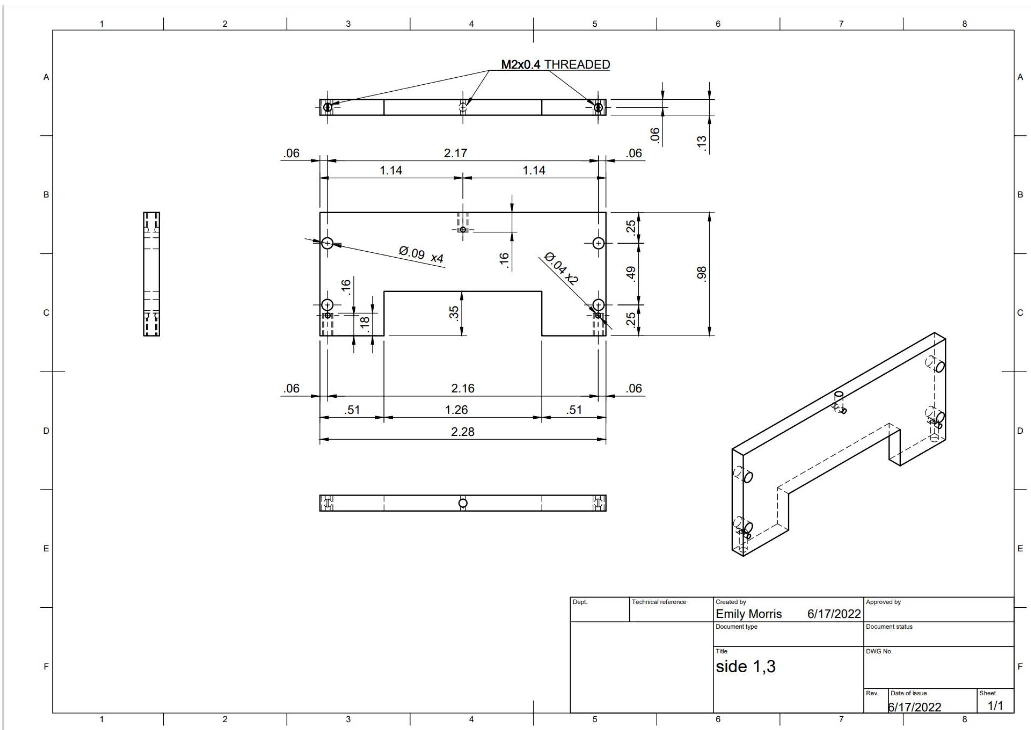
References

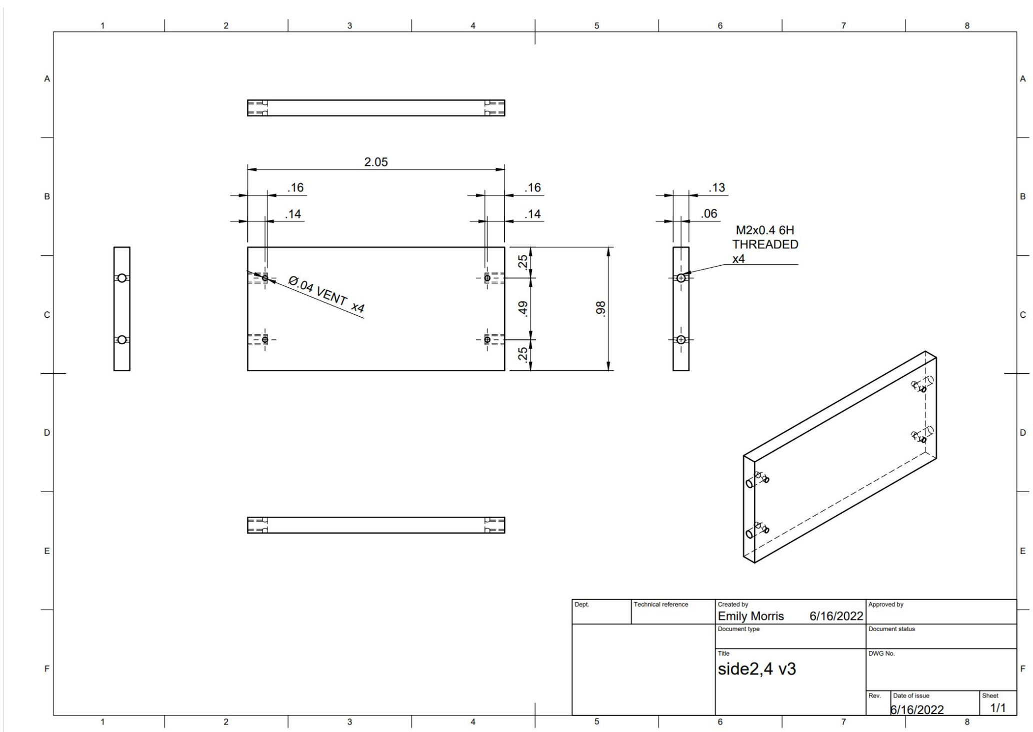
[Balshaw, 1996] Balshaw, N. H. (1996). *Practical cryogenics: An introduction to laboratory cryogenics*. Oxford Instruments, Scientific Research Division.

[Enss, 2005] Enss, C. (2005). *Cryogenic particle detection*. Springer.

A Appendix

This includes technical drawings for the box, as well as images of the machined pieces.





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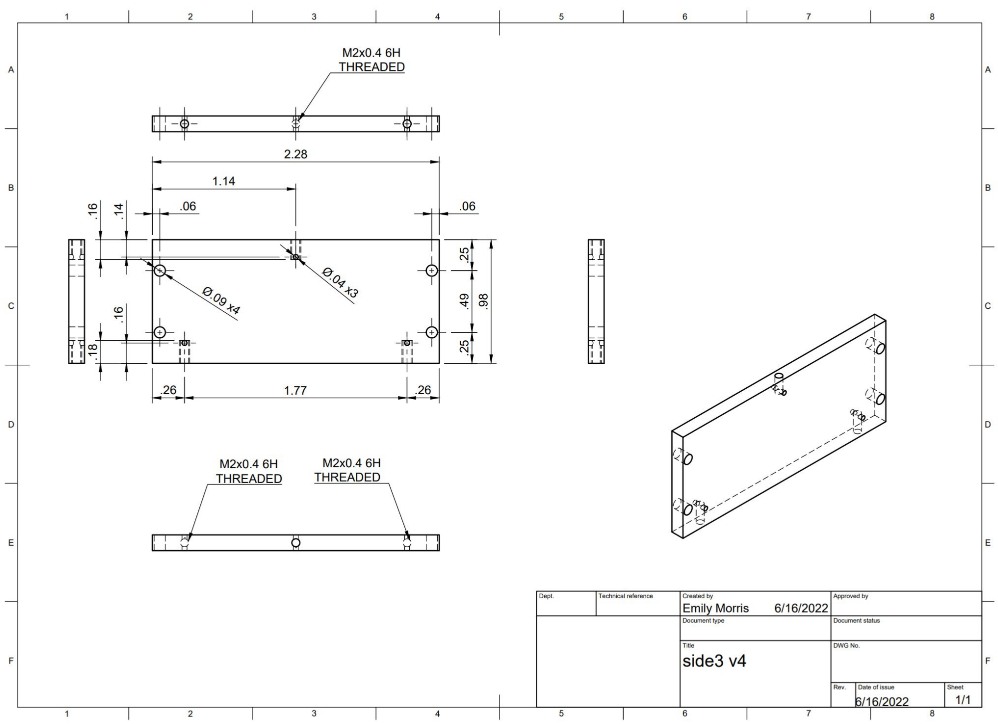
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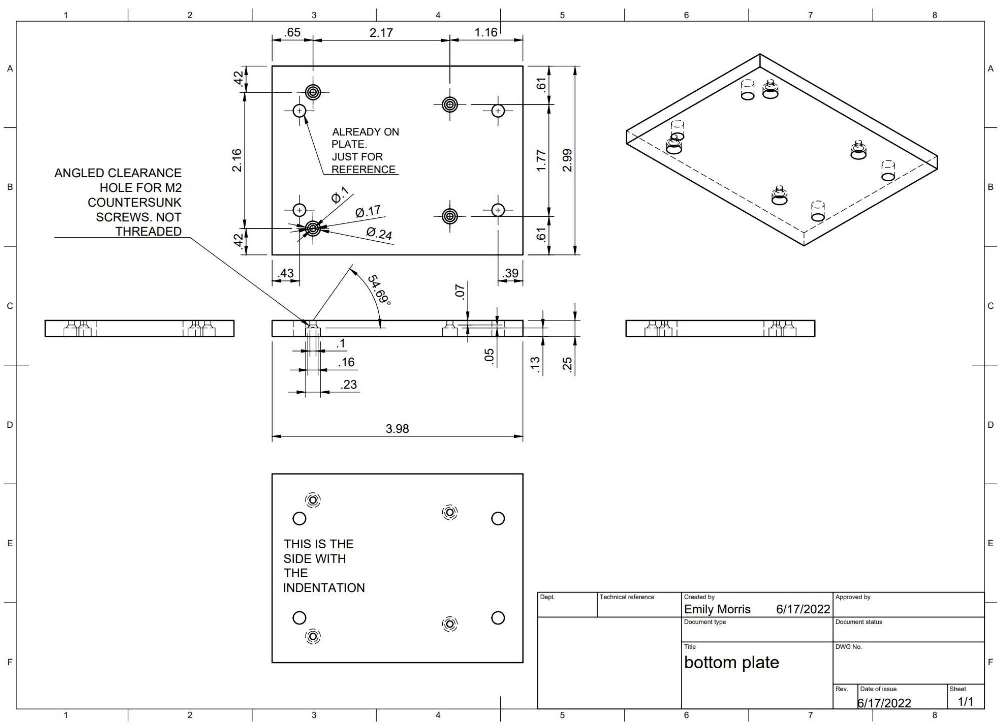
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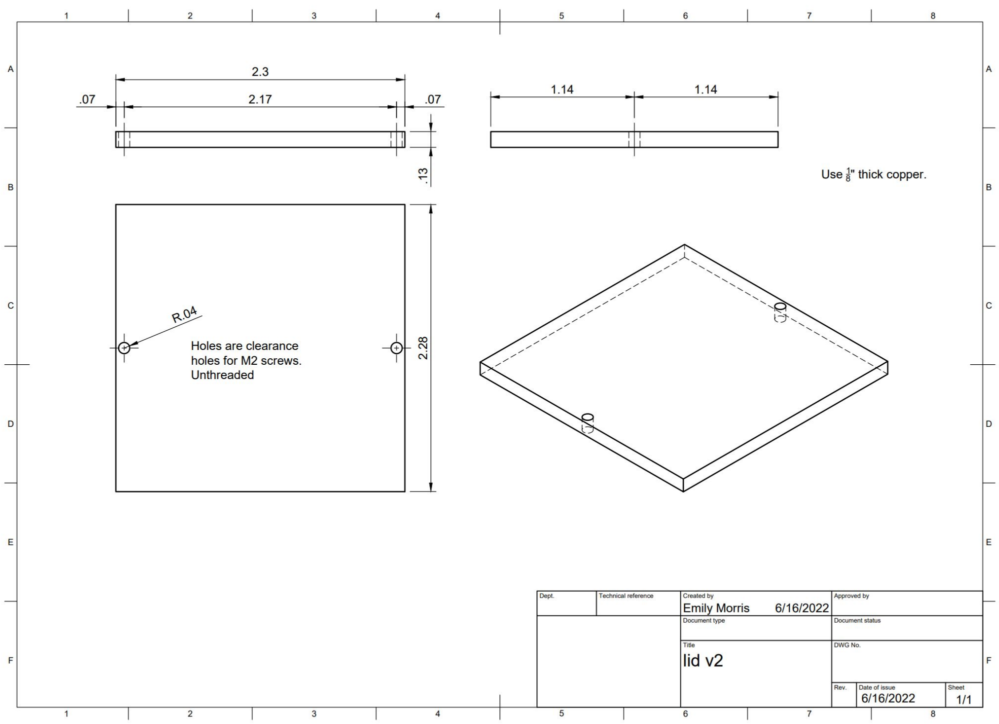
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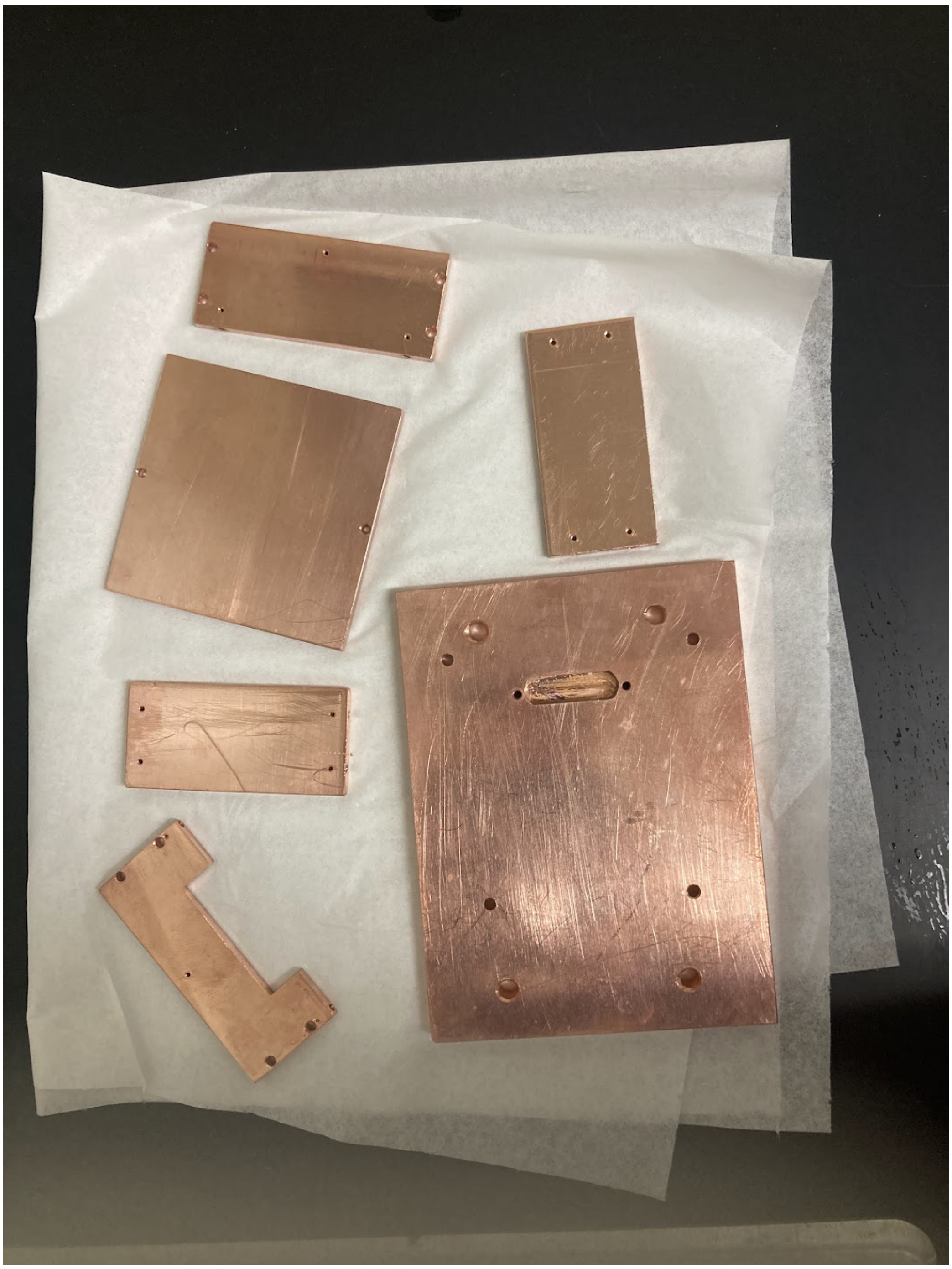

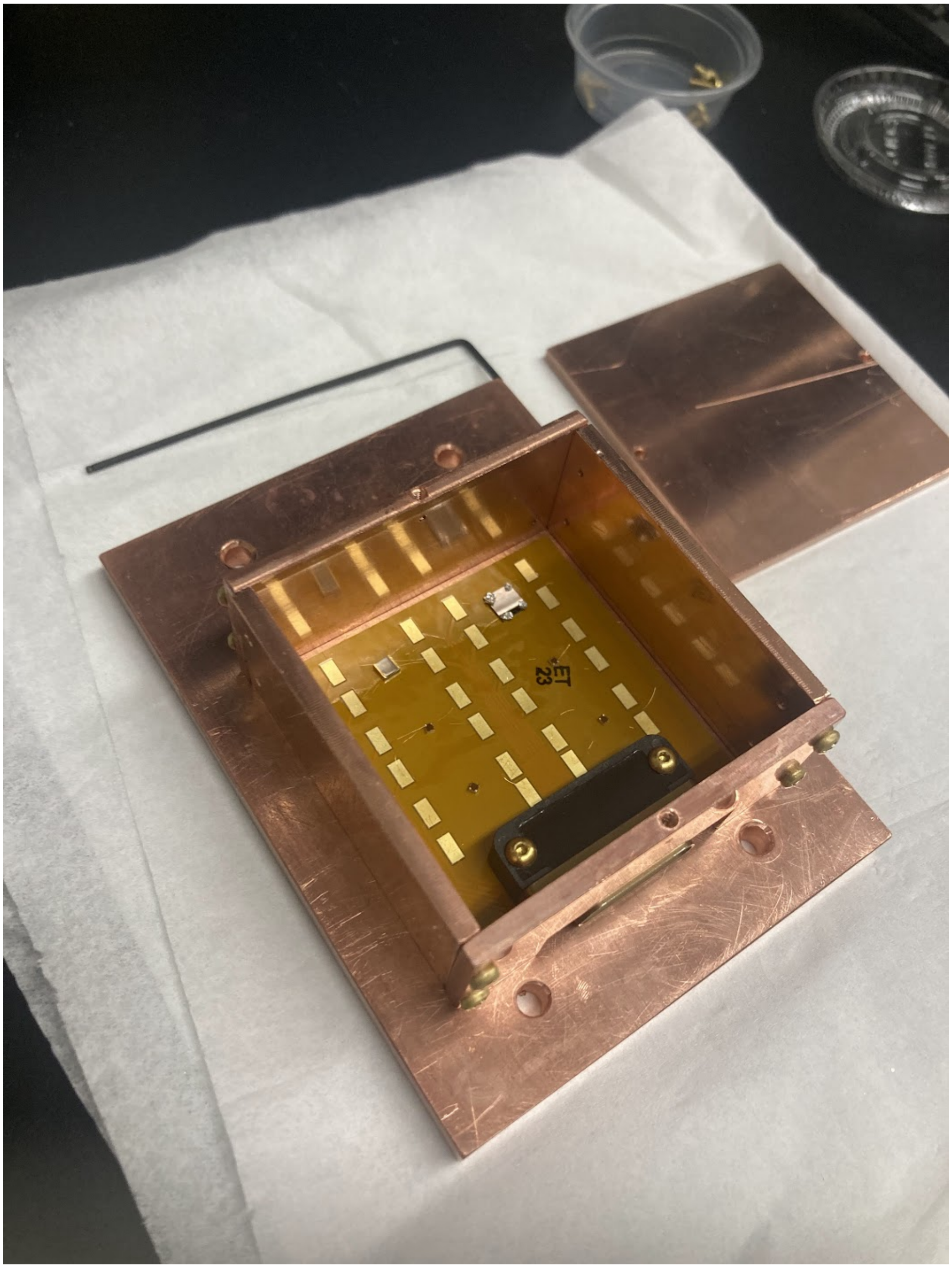
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