A Focus on Cryogenic Engineering for the Primordial Inflation Polarization Explorer (PIPER) Mission

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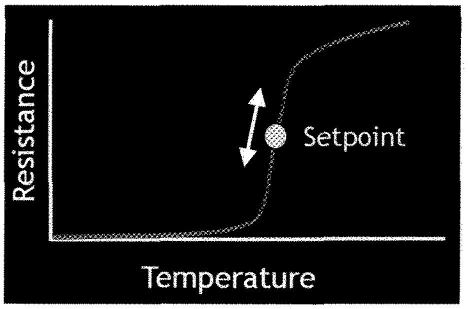
Abstract. *Cryogenic engineering involves design and modification of equipment that is used under boiling point of nitrogen which is 77 K. The focus of this paper will be on the design of hardware for cryogenic use and a retrofit that was done to the main laboratory cryostat used to test flight components for the Primordial Inflation Polarization Explorer balloon-borne mission. Data from prior tests showed that there was a superfluid helium leak and a total disassemble of the cryostat was conducted in order to localize and fix the leak. To improve efficiency new fill tubes and clamps with modifications were added to the helium tank. Upon removal of the tank, corrosion was found on the flange face that connects to the helium cold plate and therefore had to be fully replaced and copper plated to prevent future corrosion. Indium seals were also replaced for the four fill tubes, a helium level sensor, and the nitrogen and helium tanks. Four additional shielded twisted pairs of cryogenic wire and a wire harness for the Superconducting Quantum Interference Devices (SQUIDs) were added. Finally, there was also design work done for multiple pieces that went inside the cryostat and a separate probe used to test the SQUIDs. Upon successful completion of the cryostat upgrade, tests were run to check the effectiveness and stability of the upgrades. The post-retrofit tests showed minor leaks were still present and due to this, superfluidity has still not been attained. As such there could still be a possibility of a superfluid leak appearing in the future. Regardless, the copper plating on the helium tank has elongated the need to service it by three to five years.*

I. Introduction

Strong evidence for the "Big Bang" has been presented by several NASA missions such as COBE and WMAP. Naturally, the next step would be to find out what exactly happened afterwards. Current theory stipulates that there was a small time period where all matter expanded very rapidly. This inflationary epoch has not seen any concrete evidence of its existence and is therefore one of the main goals of the PIPER mission.

PIPER is a balloon-borne mission with a 5000 liter bucket dewar that will do a series of flights over New Mexico and Australia in order to capture remnant gravity waves that could present solid evidence that inflation did happen. The bucket dewar will cryogenically house twin telescopes that need to be kept at 1.5 K to reduce photon shot noise, an array of 5120 transition-edge sensor (TES) bolometers with backshort-under-grid (BUG) architecture, and 128 SQUID arrays each containing 100 chips in series.

The BUG arrays need to be held at 130 mK due to their very high sensitivity. Figure 1 shows the relationship of resistance versus temperature for the bolometers. The setpoint signifies the ideal temperature to capture incoming radiation. Its sensitivity is so high that when an incoming photon is captured the temperature rises, which then causes an exponential change in the resistance of the bolometer. This



Versus Resistance of

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change in resistance is recorded and useful information may be extracted from the data.

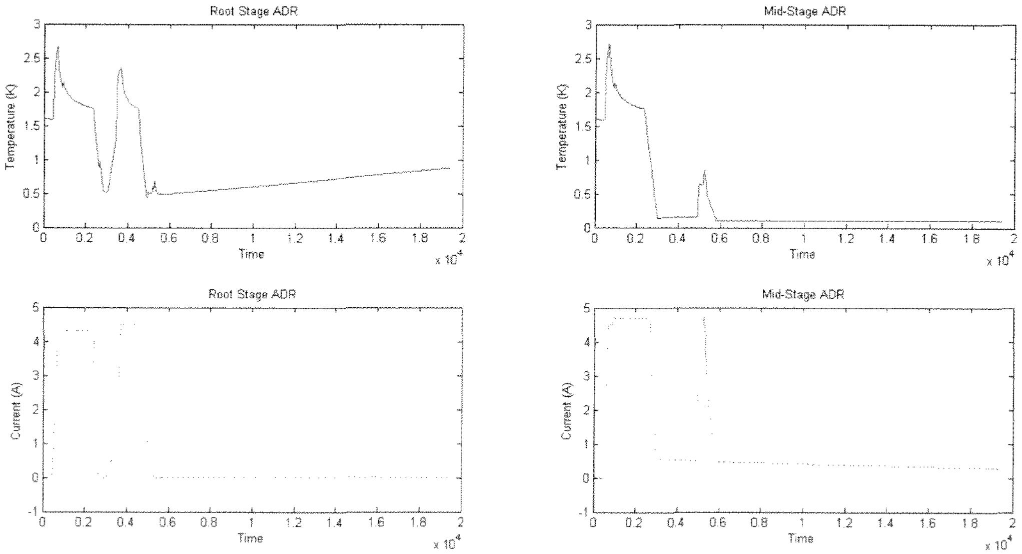
TES arrays are normally connected by extracting leads from every pixel. Having 5120 bolometers proves this to be difficult, so a way to get around having such a large number of leads is by multiplexing the arrays directly onto the SQUIDs using bump-bond technology. Additionally, because the signal that is being captured is so weak, a need for thousands of SQUIDs is necessary to amplify the signal in order to achieve a better reading. To ensure proper working condition of each individual SQUID, a dip probe was proposed to be built to test up to four SQUID arrays at a time.

In order to test all of these flight components an external laboratory cryostat must be used. The primary cooling technology utilized is adiabatic demagnetization refrigeration, which has the ability to cool to as much as 62 mK. The cryostat is composed of a liquid nitrogen tank and a liquid helium tank both of which are connected to their own individual cold plates made out of gold plated copper 101. Prior to the upgrades the cryostat was pre-cooled with nitrogen to 77 K and with helium to 4 K. Then, the helium tank was pumped to a lower pressure which resulted in the transition to superfluid helium at about 1.5 K. At this point the precooled ADR system kicks in with the root stage bringing the temperature down to 600 mK. The last stage then brings down the final temperature to at least 100 mK.

II. Laboratory Cryostat

A. Leak Discovery

To have a better understanding of the leak discovery it may be necessary to acquire a very broad knowledge of how an ADR system operates. As mentioned before, in order to achieve millikelvin temperatures, ADRs are used in conjunction with conventional liquid helium and nitrogen cooling. ADRs harness magnetic fields to control the entropy of paramagnetic salts. When current is ramped up this causes the magnetic field to increase and the salts are aligned in such a way that their entropy is reduced. This then builds up heat that is transferred to a liquid helium bath. Slowly the magnetic field is decreased and energy is retrieved from a source, in this case it is the cold plate. This lack of energy in the cold plate then reduces the temperature. A normal run with the relationship between magnetic field and temperature can be seen in Figure 2. The one drawback from this system is that there is a need for the helium to go superfluid. With its lack of viscosity it is able to pass through even the finest pours. As such, extra maintenance and care must be taken wherever there is a mate.



'00 mK) can be

For two and a half years the cryostat worked properly without needing disassembly. Upon pumping to superfluid helium on a routine test day it was discovered that there was a sharp increase in temperature as soon as the helium went through its phase transition. Usually, this increase in temperature is normal because the magnetic field is ramped up and the paramagnetic salts gather heat and what follows is a much larger decrease in temperature caused by the ADRs. It can be seen from Figure 3 however, that there was a very sharp increase at 100 seconds of about six Kelvin. It is worth noting that the increase in current and the increase in temperature were both coincidental.

Further troubleshooting was done and it was witnessed that the same increase in temperature would happen anytime that the helium would transition into superfluid. As the superfluid helium found its way into the vacuum, energy transferred into the cold bath thus increasing the temperature and causing rapid convection. This posed two problems. The first was that the temperature could no longer be maintained in order to go to 100 mK. The second is that since helium becomes a liquid at 4 K, this added energy aids in converting the liquid into gas, which in turn pressurizes the vessel. After troubleshooting it was deemed necessary to totally dismantle the cryostat in order to localize and fix the leak.

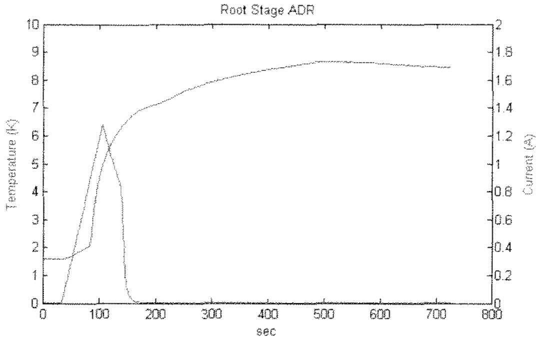


Figure 3. Data that showed discovery of a leak.

Wherever there are two surfaces that are connected in a cryostat, there is a leak risk. There are usually two types of material that are used to seal surfaces: rubber o-rings and indium. The rubber o-rings are used in areas where only a vacuum is needed and no cryogenic fluid is passing through. The indium seals on the other hand, are used in critical areas where cryogenic temperatures are reached. Indium is a very malleable material and provides an essential metal to metal contact since at such low temperatures rubber o-rings would freeze. In this cryostat there are a total of six seals. There is one for the helium level sensor, two for the helium fill tubes, two for the nitrogen fill tubes, and one each for the helium and nitrogen to cold plate surfaces. If there is a superfluid helium leak then the most probable area is in the indium seals that are related to the transfer of helium.

Upon removal of the mate between the helium tank and the cold plate, it was noticed that the seals were very weak. The nitrogen tank took some effort to remove, which showed that a good seal was present. The surfaces of the helium were closely scrutinized due to this lack of effort for removal. It was discovered that there was a large build up of corrosion on both, the tank and the cold plate which can be seen in Figure 4.

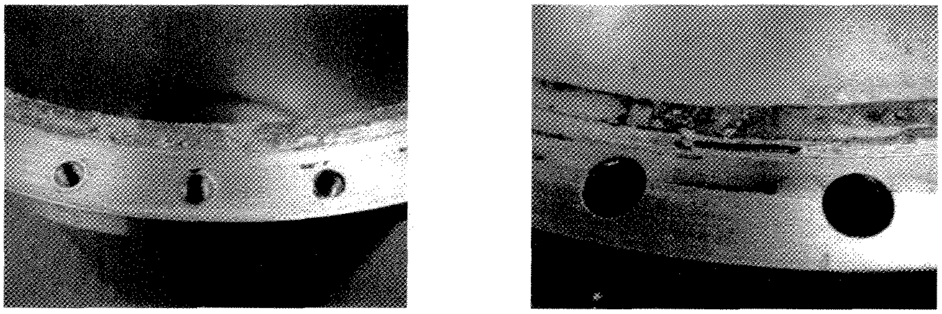


Figure 4. Corrosion on the helium tank (left) and cold plate (right).

The nitrogen and helium reservoirs are always exposed to the outside atmosphere, with the exception of when the helium tank is depressurized to convert it to superfluid. As the tanks gets filled up, the air is replaced by its respective liquid gas and therefore leaves traces of oxygen and water. They both act as oxidizers and therefore leave corrosion residue on the surfaces. The helium tank was also constructed out of aluminum, which is a material that is highly reactive to oxidation.

B. Repairs and Upgrades

Now with concrete evidence of where the leak was located it was time to fix it and take measures to prevent it from happening again. Since the cryostat is rarely taken apart, it was also decided that there be improvements in order to better its functionality, ease of use, and prolong the amount of time required before another tear down. All of these will be discussed with greater detail as follows.

Before any improvements could be made, the superfluid leak had to be addressed. As mentioned earlier, there was a copious amount of oxidation all over the two helium surfaces. The first technique used for removal was ordinary sand paper. A moderate sized grit was used first in order to remove the bigger conglomerations and with each successive pass the grit size was decreased. This worked to a certain extent. The majority of the oxidation was removed except for very deep areas. It was considered to insert the tank onto a lathe in order to face off the flange surface. This proved to be very risky though, because the wall thickness was very thin and putting it into a lathe meant the possibility of crushing the tank with the vice. Instead it was decided to copper plate the tank in order to cover up the blemishes. By copper plating, it eliminated the risk of having aluminum oxidize because of the homogeneous material. Unfortunately, after plating it was discovered that the pits of oxidation were still there. At this point it was deemed that the tank was unrecoverable and instead it was decided to manufacture a new one. The same specifications were used, including the copper plating. The new tank and mating surface can be seen in Figure 5. It is estimated that this has increased the need for service from two to three years to about five.

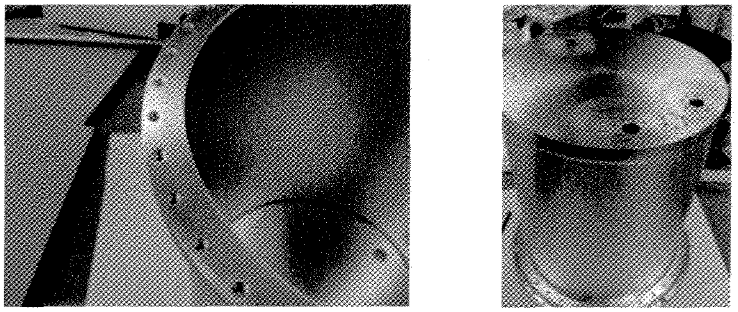


Figure 5. Newly manufactured helium tank.

Other upgrades performed on the cryostat included longer fill tubes that made it easier to transfer fluid and reduce o-ring freeze. New mounting clamps with separate o-rings that prevent water from seeping in and the ability to mount heaters to prevent fill tubes from frosting. New wire ways were also cut into the helium cold plate in order to better route harnesses as well as co-axial cabling was added for SQUID connectivity. Additionally, all individual components were leak tested to make certain that they were ready for final assembly.

C. Results After Assembly

Initial tests showed positive results. All vacuums were kept constant and the transfer of cryogens went smoothly. At the point of thermalizing the system to 4 Kelvin however, there was a problem encountered. Leaving the helium overnight led to a discovery of an additional leak and zero helium left in the tank the next day (See Figure 6). Upon hooking up the leak checker it was discovered that the vacuum jacket was filled with helium. Extensive testing over the next few days resulted in a hermetic connector having a bad ceramic to metal bond and very residual amount of corrosion left on the cold plate, resulting in a bad indium seal. The hermetic feed through was replaced and the rest of the corrosion was cleaned up with a dremel tool and under a microscope.

At the time of this writing, leaks were still present and further tests were underway to determine where they could be located. Unfortunately, the main turbomolecular pump also failed when the tests were about to start, so a backup pump will be used. This may introduce new difficulties because it is a much older pump and less reliable. There is also the pertaining issue of a superfluid leak. The lowest temperature that has been reached with all these additions has been 4 Kelvin so there is still a possibility that a superfluid leak may be present.

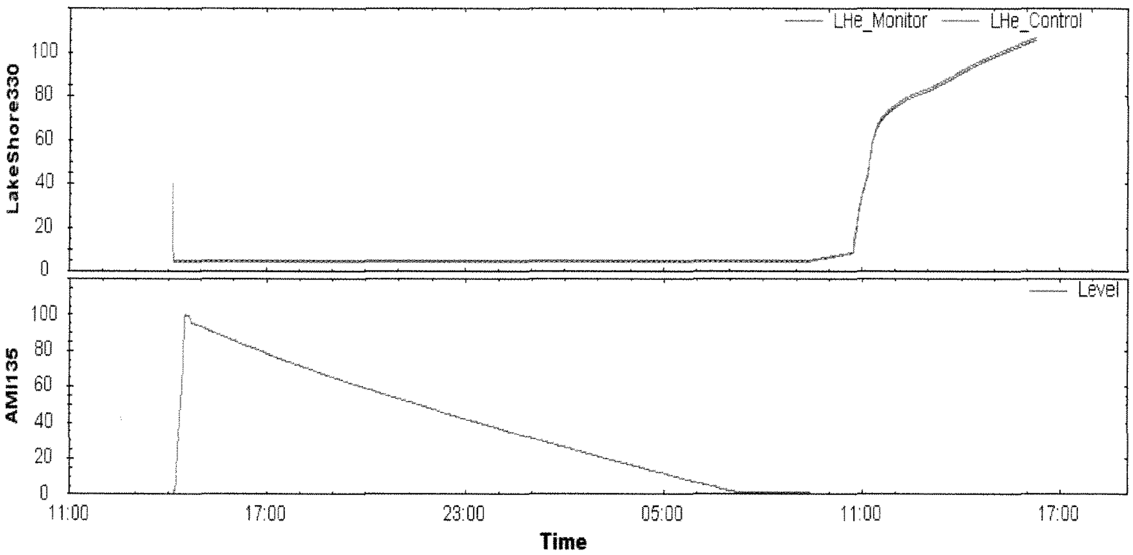


Figure 6. Overnight test of cryostat at 4 Kelvin.

III. SQUID Design Work

Cryogenic design presents a whole new set of challenges that have to be taken into consideration because the properties of matter change drastically at close to absolute zero temperatures. Unlike at room temperature, the coefficient of thermal expansion is greatly taken into account. Any type of coefficient mismatch could cause slippage or damage due to extreme pinching. Similarly these same mismatches can be used to one's advantage. Real-estate in the cryostat is also a big issue since everything must be compacted into a cold plate with limited diameter. And finally the designer should always be aware about how much material should go into a part. The more material that is on a part the longer and more energy it takes to bring all the temperatures down to an equilibrium state.

A. Niobium Shield Holder

The use of SQUID devices in PIPER is essential for mission success. They act to amplify a very weak signal so it could be read and interpreted. The main SQUIDs that will be used in the payload are currently being developed by the National Institute of Standards and Technology (NIST) and until they are finalized an alternate system is being used that is manufactured by STAR Cryoelectronics. The model (SA632) is a series SQUID array containing 32 detectors enclosed in a niobium can to shield it from external magnetic noise. Most of the design revolved around the mounting holes that were provided on the can, the constraint of real estate in the cryostat, and the ½" hole pattern on the cold plate. All materials were copper in order to thermalize the SQUIDs to their proper temperature.

The first design contained a clamping mechanism that would pinch the top of the cylinder while having a 1.5" end-to-end hole mounting (Figure 7a). The main problem with this initial design was the real-estate. A 1.5" hole distance would take up too much room from the already exhausted cold plate space. Additionally, because of the clamping mechanism there would be no guarantee that the 1.5" hole spacing would be consistent. As a result the mounting to the cold plate should be independent of the clamping.

For the redesign all of these issues were addressed. A mounting plate was created to only fit a ½" pattern as well as to mount it diagonally. There are no real-estate issues when building upward, so this mounting only requires an area of 1.5"x1" instead of the previous 2"x1". The clamping is also independent of the cold plate mounting, which makes it more reliable (Figure 7b).

The third and final design was changed once the actual niobium can was acquired. The real dimensions and mounting hole pattern were known and an independent bracket was designed. This bracket would sit at the top of two attachments that were the length of the niobium can plus the thickness of a 4-40 screw head. There were also two tapped holes to accommodate a copper ribbon that is directly connected to the SQUIDs array and a wire harness that contains feedback signals. There were also holes drilled perpendicular to the mounting holes in order to vent trapped gas. A side-by-side view of the solid model with the real-life component can be seen in Figure 7c and 7d.

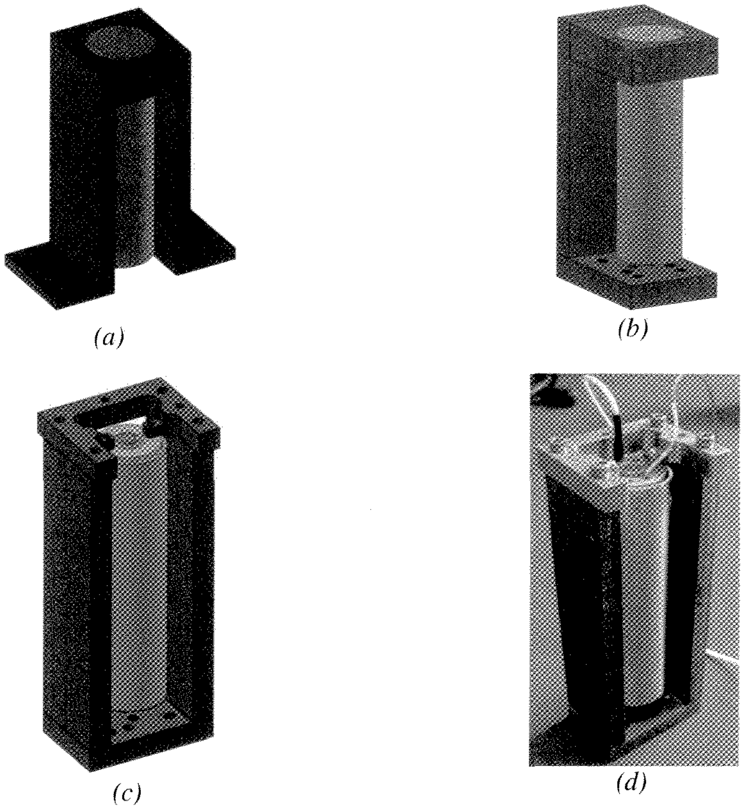


Figure 7. The evolution of the niobium shield design.

B. SQUIDs Dip Probe

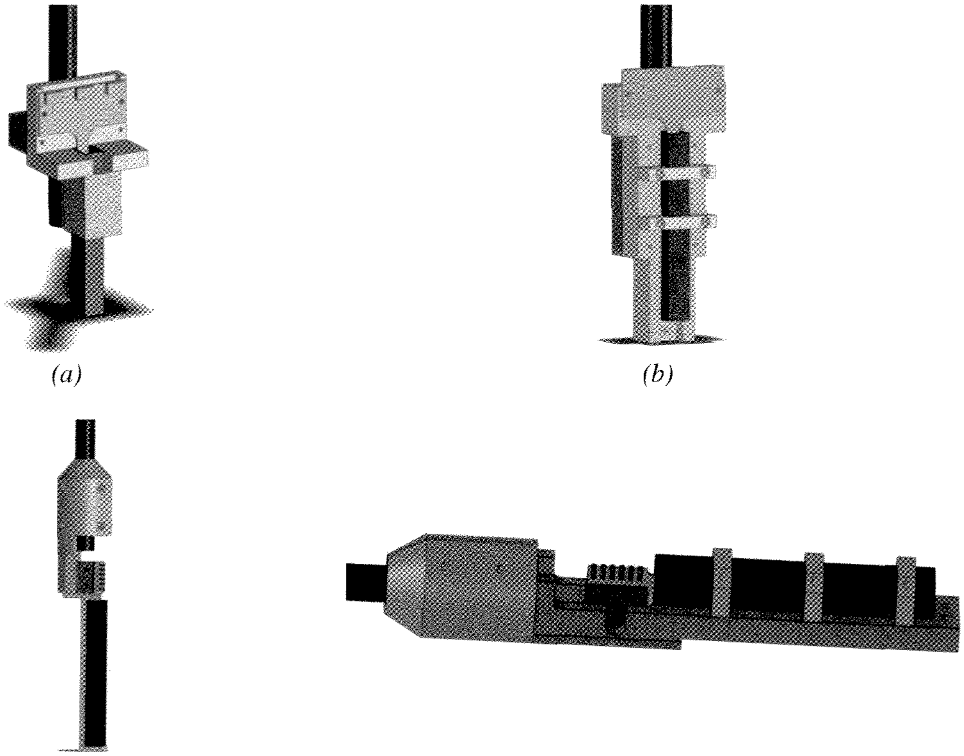
For the NIST developed SQUIDs a very simple but effective test was developed in order to make sure that each manufactured detector actually works and that it reads what it is supposed to read. It consists of a probe that houses four electronic boards that are used to test one SQUID array of 100 chips each. This probe is then dunked into a dewar of liquid helium that has an open aperture of 1.4 inches. Since the SQUIDs are niobium based their superconductivity is reached at 9 K, which makes the 4 K helium temperature plenty in order to test them. Since these are custom made boards the dip probe must be tailored specifically to hold these parts and must be able to do it easily to test 128 boards.

For the first phase of the design a "T" shaped board was presented that would only hold one of the SQUID arrays. That is the design that can be seen in Figure 8a. The most important requirement was the safe retrieval of the SQUID board because there is high risk that a poorly designed mechanism could fall into the dewar, possibly damaging the chip. This part uses two clamp mechanisms, one for the stainless steel five foot rod that will be used to lower the probe, and another to hold the niobium box that is used to reduce all background magnetic noise. It is planned to create two dip probes to be able to test seamlessly. The total number of manufactured pieces for this design would be five, which isn't ideal because there is a longer machining setup time. The best design is one that requires minimal effort for the machinist to make.

Design two (Figure 8b) was much simpler and required the machinist to only set up three times. There is also a much more efficient design when it came to the clamping mechanism. It is all done via the main middle base. The two yellow clamps hold down the niobium box while a roll pin or screw prevents the box from sliding downward. The back part clamps down the stainless steel pipe.

The third iteration (Figure 8c) included a major change in the SQUID array board design. A copper block was provided to hold four SQUID series arrays with different board shapes at once in order to cut the testing time. The amount of parts was once again reduced to only two. A taper was integrated at the top of the probe in order to aid in removal from the aperture. This way there is less risk of the part coming loose from an impact on the top edges. There was still a problem this design however. It was decided that the copper block and the portion that holds the niobium box should be on the same piece in order to interchange the test components much easier. This way the teal clamp can stay on the stainless steel pipe and all the testing components stay on one carriage.

With that said, the fourth and final design (Figure 8d) made the testing carriage into one robust attachable bracket. The four SQUID boards will have leads coming out so there was ample room to route the wiring through the pipe. Brackets were once again added to add a strong hold as well as two roll pin holes to prevent slippage. This model is currently in production as of the time of this writing. All parts for the SQUID dip probe were being manufactured out of 6061-T6 aluminum.



(a) *(b)*

(c) *(d)*

Figure 8. The evolution of the SQUID dip probe design.

IV. Conclusions

Since the cryostat was still producing very minor leaks, mostly caused by o-rings, there is an effort underway to localize all the leaks in order to cool to sub-Kelvin temperatures. The ADRs are installed and are awaiting a cool down via superfluid helium. This can also present another superfluid leak in the near future. When major additions are added to a cryostat there is always difficulty getting the system back to 100% on the first try, so it is no surprise that it has taken more effort than it was first predicted.

Similarly, it takes time to evolve a design from pure concept to reality. After multiple iterations only the niobium shield holder was manufactured during the author's stay. The SQUID dip probe is currently in the process of being manufactured. Actual feedback from use of these designed parts will be awaited in the future.

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