

NEUTRON CALIBRATION SYSTEM FOR THE CRYOGENIC UNDERGROUND TEST FACILITY (CUTE)

by

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Abstract

The mystery of Dark Matter in our universe has puzzled scientists over the past century, and a large number of experimental ventures have been conducted hoping to find an answer. The Weakly Interacting Massive Particle (WIMP) is a well motivated dark matter candidate with a number of direct detection experiments dedicated to finding WIMPs or excluding them from being the solution to the dark matter problem. SuperCDMS is a cryogenic dark matter experiment with semiconductor detectors currently being constructed in the underground low background laboratory SNOLAB, with plans to begin taking science data in 2023. The Cryogenic Underground TEst (CUTE) facility is presently operating at SNOLAB to test the detectors which will go in the SuperCDMS experiment, and perform preliminary science runs using SuperCDMS detectors in a low background, low noise environment. Calibrations of detectors is critical in order to understand and quantify the signals which they produce. The design, construction, and testing of the neutron calibration system planned to be installed in CUTE are highlighted, and an analysis of the collection efficiency of a detector was conducted by identifying the signal associated with ^{71}Ge decay. This thesis also discusses the contributions to the improved performance of CUTE through noise studies, and cooldown optimization.

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I would like to begin by acknowledging that this thesis could not have been possible without the support, patience, and guidance of my supervisor, Wolfgang Rau. It seems that Wolfgang's days must last at least 25 hours because he always managed to find time to support me academically and personally while balancing all of his other responsibilities. I am extremely grateful for the opportunities I had to work with you when you would visit Queen's or SNOLAB, and I hope our paths cross again professionally because there is much I can still learn from you.

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Statement of Originality

The work described in this thesis is largely my original work. In some cases contributions from others are described to provide the necessary context; those contributions are acknowledged in the text where they are mentioned. My work was performed in the context of the SuperCDMS experiment and the CUTE facility, and the extent of my work on CUTE extends beyond that covered in this thesis. I participated in and lead payload changes, shifts, and the training of personnel as well as the development of internal documents and procedures. I was frequently called upon to assist in the operations of CUTE and performing measurements, including those discussed in chapters 6 and 8. The work described in Chapter 5 (optimization of operating conditions for CUTE) was initiated and executed by myself. The noise study described in Chapter 6 was executed by me based on a plan developed jointly with the CUTE team. E. Fascione and R. Germond helped with the analysis and producing the plots. The ^{252}Cf calibration system described in Chapter 7 was designed, constructed, and tested by me, with the exception of the control box (design S. Crawford) and the location detection system, the design of which has yet to be completed. The work described in Chapter 8 is based on procedures developed by SuperCDMS collaborators. I implemented those procedures for detector T5Z2 operated in CUTE.

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Part I

Getting you up to Speed

Chapter 1

Dark Matter

Humans are curious creatures, and one quality that we have is that as a species we are constantly expanding our collective knowledge and try to understand and make sense of the world around us. An early theory by pre-Socratic philosophers stated that all matter was created from four principle elements; Earth, Water, Air, and Fire [1]. Centuries later philosophers like Plato suggested the difference between materials we experience is the shape of their fundamental particles; water is made of rounder icosohedron shaped particles, while metal is made of rigid cubes and fire from tetrahedrons[2]. Greek philosophers continued to refine the theories of their philosopher predecessors, and as the theories advanced, they began looking outwards for clues about the makeup of the earth and universe rather than solely inwards. As astronomy was included in the evidence for the make up of the universe, the geocentric theory became widely accepted; that the earth sits at the center of the universe with all other celestial bodies orbiting around it. The reason why this theory was so convincing was that by making complex models of how the planets in our solar systems orbit, it was able to predict with high accuracy the frequency of events such as transits or eclipses. Geocentricity lasted as the widely accepted model from 4th Century BC when Plato and Aristotle wrote their theory, to the Ptolemaic model which expanded the notion of other celestial bodies orbiting earth on nested spheres until the 16th and 17th centuries [3]. Renaissance mathematicians like Copernicus, Kepler, Galileo, and Newton presented a mathematical model based on concrete evidence about the motion of planets, primarily Mercury, in our solar system that showed that heliocentricity is in fact the correct theory of the solar system [4]. In heliocentricity the sun is the center

of our solar system, as opposed to the earth. Newton further explained this observation by introducing the concept of gravity, an attractive force proportional to the mass of the body in question.

Around the same time as Newton was doing his work looking out, other physicists were looking inward, attempting to understand the fundamental particles which make up everything in our universe. Theories evolved from the simple solid sphere describing an indecomposable particle (an atom) by the early greek philosophers and further refined by Dalton, to more complex models including the inner workings of an atom showing that they are composed of an electrons (Thomson) orbiting a nucleus (Rutherford) at defined energy levels, or orbitals (Bohr)[5]. In the 20th century, as further experiments probed the inner structure of the atom, and the other fundamental particles, pieces of a unifying theory of the universe and its components was beginning to form, but there were still many gaps and problems.

The problems were also presenting themselves at the same time in astronomy; Lord Kelvin proposed a procedure by which one can approximate the amount of mass in an orbiting system. By looking at the velocity of the particles at varying radii in a system, you can estimate the amount of mass contained since the gravitational force holding the object in orbital motion is proportional to the mass contained in the system. A few decades later Zwicky, a Swiss astronomer applied the virial theorem to a galaxy cluster to approximate the mass of the cluster and is credited as the first to propose the necessity of dark matter [6]. He found a large discrepancy between the accounted for mass emitting light and the calculated total mass of the cluster; the total mass was a factor of 400 higher than was accounted for by visible objects [7]. As telescope technology advanced, observations of the orbiting velocity of celestial objects within galaxies were able to be made with Rubin and Ford making an observation of the rotation curves of the Andromeda galaxy in 1970 [8]. Depending on the assumed shape of a galaxy, in this case a spiral galaxy, one can predict the velocity distribution of stars in the galaxy as a function of their distance from the center of the galaxy. The rotational velocity of an object in an orbit with radius r is

given by:

$$v = \sqrt{\frac{GM}{r}} \quad (1.1)$$

where G is the gravitational constant, and M is the mass contained in a sphere of radius r around the centre of mass of the system. For a galaxy with the majority of the mass contained at the center, one would expect the velocity to drop off as $r^{-1/2}$, but what Rubin and Ford found is that the velocity plateaus indicating a significant contribution of matter at greater distances from the center of the galaxy.

Shown in Figure 1.1 is a more recent measurement of a galactic rotation curve, but the conclusion is consistent with what Zwicky and Rubin had found; accounting for only the known mass in the system (the visible stars in the disk, and the calculated gas density based on star formation rate and size), a large fraction of mass is missing, and unaccounted for [9]. Zwicky coined the explanation for this anomaly as Dunkle Materie (DM), since he assumed there must be more mass present in the galaxy that we cannot see, hence calling it dark.

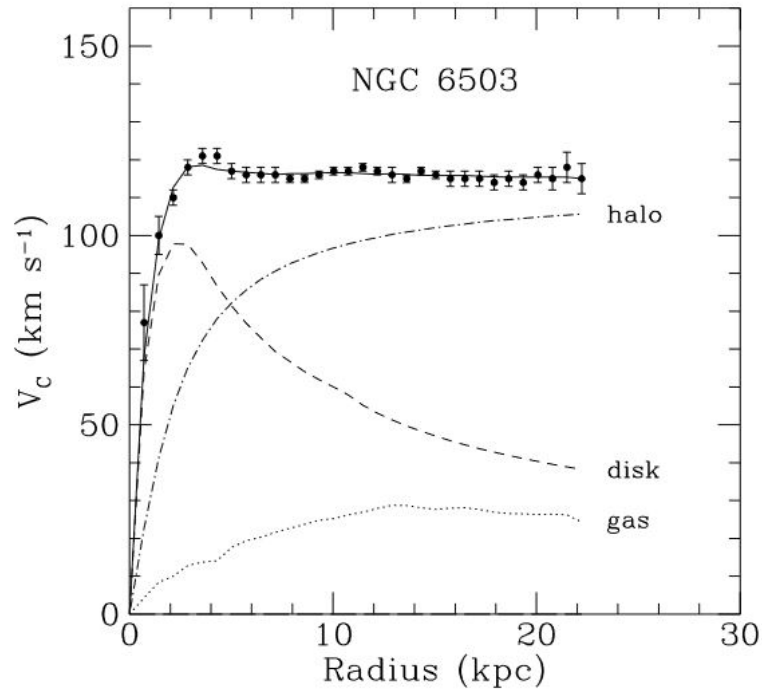


Figure 1.1: Rotation curve of the NGC 6503 galaxy. Shown are the expected velocity distributions if accounting for only the contributions from the disk and gas of the galaxy, the observed velocities of gas in the galaxy, and the suspected Dark Matter halo to account for the discrepancy between the anticipated and observed velocities of the galactic gas [9].

Having a single observation to support a new theory is insufficient, so researchers looked for other metrics which might be able to contradict this proposed *Dark Matter*, but instead what they found are more questions highlighting the shortcomings of the model without Dark Matter.

Gravitational lensing was predicted by Einstein's theory of general relativity [10]. Since massive objects curve space itself, when the emitter (distant galaxy) and the observer (earth) are co-linear with a large massive object, light that travels around the massive object and gets bent as it would in a lens. In ideal scenarios, the light originating from the source can be bent and observed on both sides of the central massive object, and in the perfect scenario an Einstein Ring can be formed where light travels around all sides of the massive object. Figure 1.2 shows the lensing effect and an observed example of such lensing. Scientists are able to calculate the mass of the foreground object and its relative location based on the magnitude of the lensing that occurs.

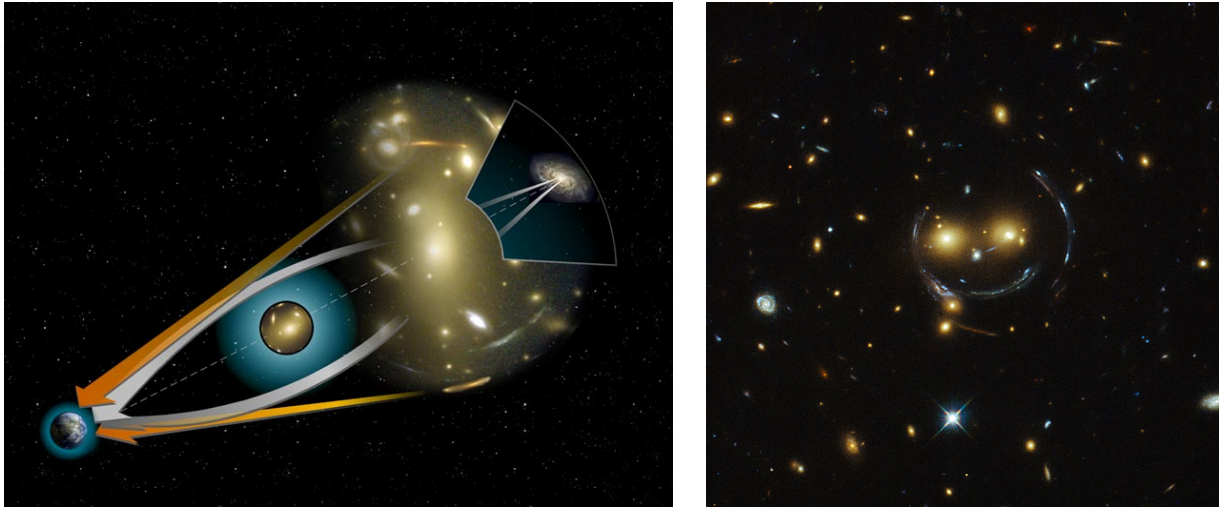


Figure 1.2: (Left) Diagram showing gravitational lensing where the orange lines show the perceived path of the light and point to the apparent location of the galaxy, but the white lines show how the light is bent around a massive object in the foreground such that light emitted from the same source can reach the receiver via two different paths. (Right) An Einstein ring observed of galaxy cluster SDSS J1038+4849 nicknamed the Cheshire Cat. Image sources:[11][12].

In some colliding galaxy clusters, which is the astronomical result of two clusters of galaxies colliding and passing through each other, interesting observations are made. Rather than the true center of mass of each galaxy being cocentric with the observable center of mass of the galaxies, they are further apart. The majority of mass of galaxies

comes from gas in the intermediate spots of the galaxy, and this gas can be observed by the x-ray emission from relaxation of the excited state of the atoms [13]. Here, as the two galaxies collided and pass through each other, since the dark matter is thought to be less interactive than “regular” matter, it passes through without much delay, whereas the gas undergoes more interactions and local effects from the other galaxies making their mass concentration closer to the center. The observation of a discrepancy between the centre of mass of baryonic matter and the centre of mass deduced from the lensing measurements is shown in Figure 1.3 of a galactic collision of two clusters named the Bullet Cluster. The gravitational lensing strength, shown as a purple hue, indicates where the effective centre of mass is located, whereas the center of mass determined by accounting for the visible mass and x-ray emission from the galactic gas in the two galaxies is closer to the center in the pink hued area [14].

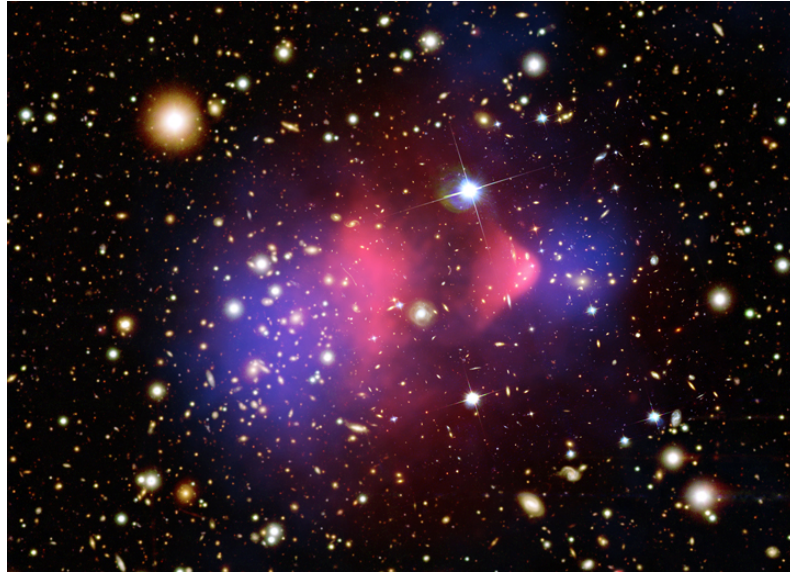


Figure 1.3: Bullet Cluster; Two galactic clusters 1E 0657-56 who recently collided. The dark matter passes through with minimal interaction and is concentrated in the purple areas, as determined by gravitational lensing. The visible “regular” matter remains closer to the center in the pink hued area with location determined by x-ray emission from gas Source: [15].

At the beginning of time in the early universe, all matter was contained in such a hot dense volume that matter was unable to form in any coherent small scale structure because the radiation present would immediately ionize and break down the structure. As the universe expanded and cooled, atoms formed as the photons from the blackbody thermal radiation decreased in energy to the point where they could no longer ionize and

break apart atoms and larger atomic structure [16]. The photons that remained after this threshold was reached where they could no longer interact and ionize the matter around them form the Cosmic Microwave Background (CMB) which we can still observe today. The photons have been red-shifted as the universe has continued to expand, to the point where the temperature associated with the photon blackbody spectra is 2.7260 ± 0.0013 K [17]. This background is primarily homogeneous, however looking at the fine differences in the photon spectra coming from different parts of the sky yields information about the composition of mass in the universe. Figure 1.4 shows the cosmic microwave background as measured by the Planck collaboration[18].

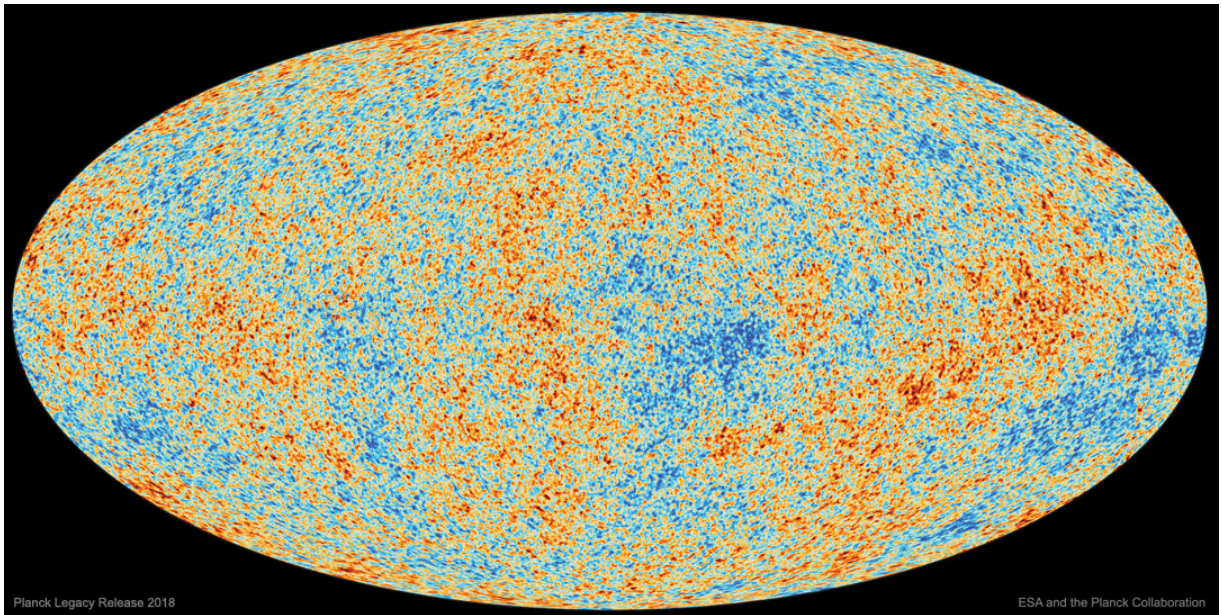


Figure 1.4: Cosmic Microwave Background measured by the Planck collaboration. Colour map shows the variance in temperature from different parts of the sky. [19]

At first glance, the CMB appears very complex, but calculating over what angular scales the difference in temperature variance is present, further conclusions can be reached. The Planck collaboration did just this, as shown in Figure 1.5: the first peak is related to the total contributions of both baryonic and non-baryonic matter to the calculation of the overall flatness of the universe which also requires knowledge of the amount of dark energy present in the universe. The second peak is related to the amount of baryonic matter present; if the peak was located at a higher multipole moment, this would suggest that the density of baryonic matter could have been higher. The problem with this is

that as the density increases, more interactions coming from the photons from the heat associated with being so dense will want to push the baryons apart. This “pressure” of the baryons pushing against each other reaches a point at which the baryonic matter could not sustain a high density, and therefore cannot exist at such a fine angular scale in the CMB. The third peak must be accounted for by a form of matter which does not interact as strongly with photons, since it did exist at higher multipole moments, indicating the “push-back” pressure from the heat associated with being incredibly dense has less of an effect as it did for baryonic matter [20].

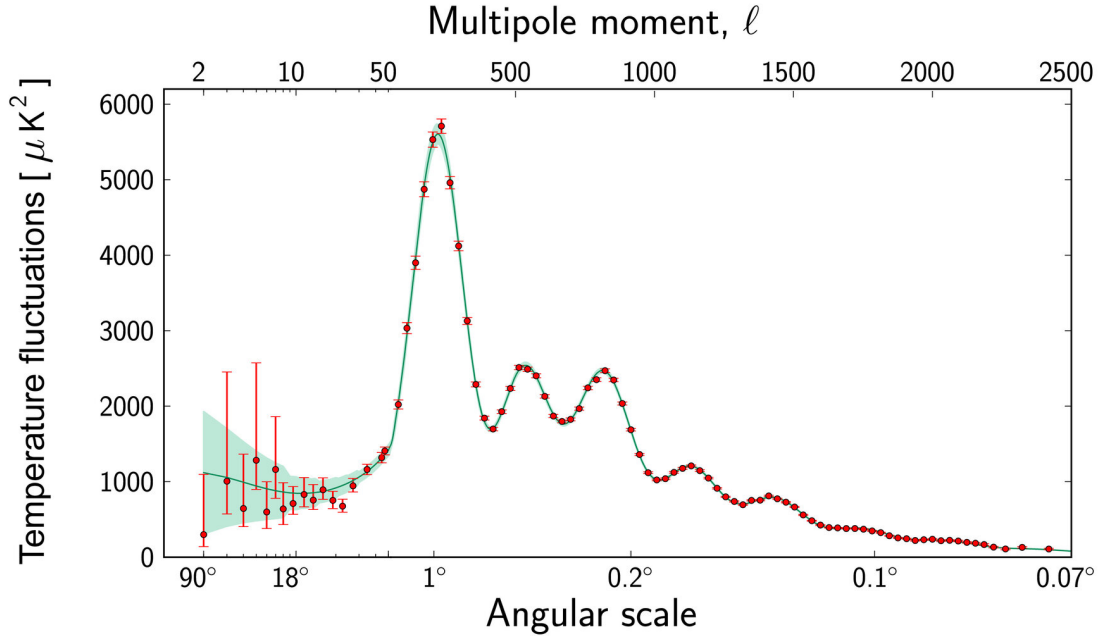


Figure 1.5: Variance in the temperature fluctuations of the CMB over different energy scales. The relative heights of the first three peaks can be used to calculate the abundance of dark matter and baryonic matter in our universe.

Analysing the relative heights of these three peaks, one can solve for the density of the baryonic and non-baryonic (assumed Dark Matter) present in the early universe. The results of the Planck collaboration yielded[18]:

$$\Omega_b h^2 = 0.0224 \pm 0.0001 \text{ and } \Omega_c h^2 = 0.120 \pm 0.001 \quad (1.2)$$

where Ω_b is the baryonic density, Ω_c is the dark matter density, both in units of critical

density and h is the reduced Hubble constant. This shows that the amount of Dark Matter present in the early universe was five times as much as the baryonic (regular) matter.

The first step after learning of the existence of matter should be to investigate whether it is actually one of the known forms of matter. The current unified theory of the fundamental particles in our universe which has been developed and appended over the past 70 years is called the Standard Model of Particle Physics [21]. Looking at the particle content of the standard model shown in Figure 1.6 we can immediately dismiss the quarks, since they are the components which make up baryonic matter which cannot be a dark matter candidate due to the issues that arose when looking at the CMB[18]. The non-neutrino leptons are not suitable candidates since they interact too strongly with electromagnetic fields, and studies have shown that the neutrinos are too light to account for all of the dark matter [22]. Of the remaining bosons the gluon and photon can be dismissed since they are massless, and the others are too short lived to be a viable candidate for dark matter.

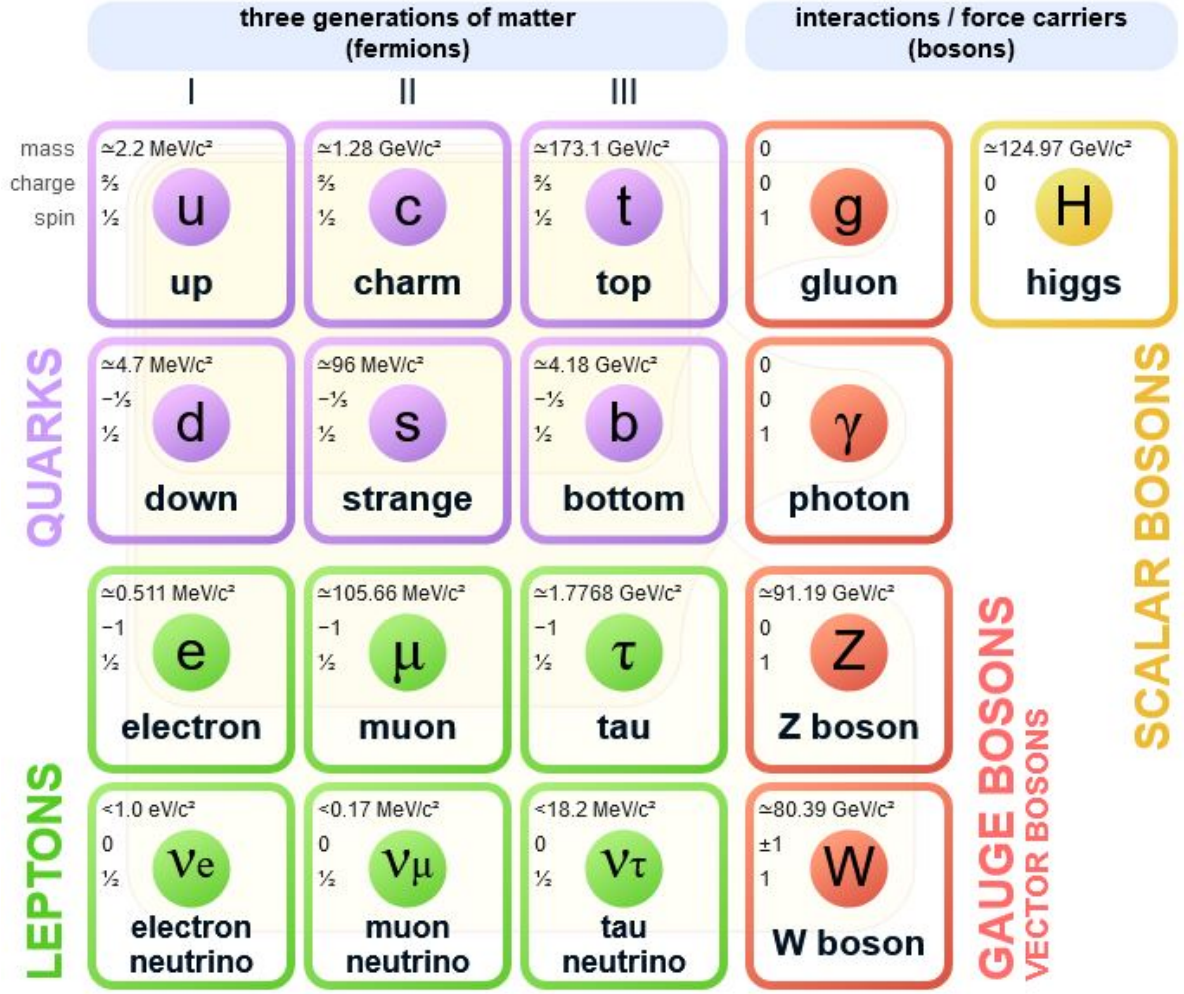


Figure 1.6: Standard model of particle physics showing the fundamental particles and their classes. Image source [23].

While a plethora of dark matter candidates have been proposed, I will only touch on the most common candidates where active experimental searches are presently being done.

The Weakly Interacting Massive Particle (WIMP) is a class of dark matter candidate which was originally highly motivated as a dark matter candidate due to the ‘WIMP Miracle’. All proposed candidates must have had a mechanism for their creation in the early universe, and some mechanism of interaction also will dictate how it may interact with regular matter, or annihilate. The WIMP miracle is that for the given cross section and mass of this proposed class of particle, the abundance we would expect in the universe at this point in time matches the abundance seen through astronomical scale observations. The WIMP would have a mass in the GeV/c^2 to TeV/c^2 range and would interact with the standard model weakly (hence the name), either through the weak interaction, or by

other forces not yet known which have even weaker coupling [24]. Some recent papers have suggested a Higgs-portal model whereby dark matter interacts with regular matter by the exchange of a Higgs boson[25].

Other dark matter candidates include the Massive Astrophysical Compact Halo Objects (MACHOs, large astronomical bodies that do not emit light), or the Dark Photon, and a second class of solutions to the DM problem instead look to find an explanation for the observations which would not rely on DM, like MOND or cosmic dust [26][27][28]. Each of these are motivated for different reasons and have collaborations around the world spending time to search for these candidates. Until people find evidence that their candidate is more favoured over others, many options will be pursued in parallel.

“The electron: may it never be of any use to anybody!” was a quote that J. J. Thomson, the physicist who discovered the existence of the electron and won the Nobel prize for his work in 1906 [29]. Such is the nature of advancing the collective human understanding of the universe and its components; striving to discover, without yet knowing its future purpose and use. The problem of Dark Matter is different than the advances in particle physics which came before; we know that DM must exist, but do not know in what form we will discover it.

Since the discovery of the form of dark matter is presently unknown, many experiments attempt to find it using different techniques, each providing strength in unique regions of where DM might be hiding. We know that all matter originated in the Big Bang, so there should be some form of interaction between DM and Standard Model (SM) particles. The initial breakdown of experiments hoping to find this interaction in WIMP-like candidates is into three primary classes which differ by the direction of the interaction they hope to observe; Production, Indirect detection, and Direct detection, nicknamed the “Make it, break it, or shake it” detection methods as summarized in Figure 1.7 [26].

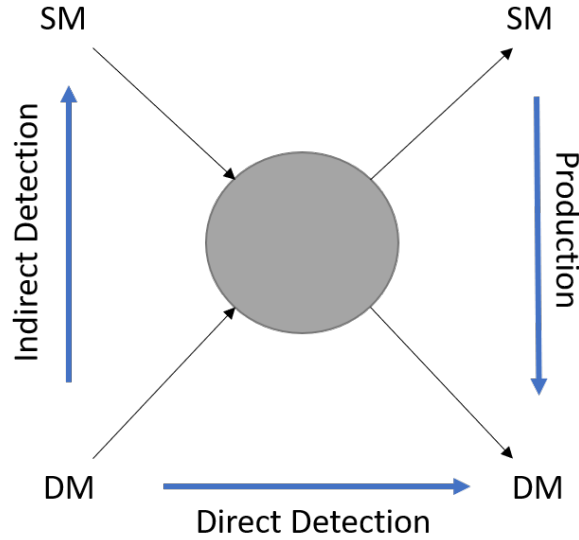


Figure 1.7: 3 classes of Dark Matter searches. Arrow direction indicates the direction of time in each method; Indirect has two DM particles turning into SM, Direct has an interaction between SM and DM resulting in SM and DM, and production where two SM particles turn into two DM particles.

The production, “make it”, method occurs with experiments who collide SM particles together in an attempt to create the DM. By setting up large detectors surrounding the collision site, which would be the location of DM creation, these collider collaborations measure all of the momentum of SM particles emitted from the collision and hope to find evidence of some unaccounted momentum which would be carried away by the DM particle. At the Centre European Recherche Nuclear (CERN) this work has been ongoing for many years, accelerating and colliding protons at center of mass energies on order of 10 TeV in the Large Hadron Collider (LHC). One class of dark matter candidates that CERN is looking for are the Super SYmmetric (SUSY) particles which are the partners to the SM bosons and fermions but much greater in mass, with the spin values differing as well (a selectron, the SUSY partner to the electron would be a boson for having an integer-valued spin rather than a half-integer-valued spin that fermions do)[30].

Indirect, “break it”, searches focus on finding when two dark matter particles interact with each other, possibly annihilating, releasing a SM signal which can be detected. If this interaction occurs, one would expect an excess of SM particles originating from areas of high density dark matter. Large scale experiments such as IceCube, or P-ONE use ice and ocean water as a medium to detect Cherenkov light coming from the leptons emitted

after high energy neutrinos interact, and are able to search for dark matter candidates in this fashion[31]. If an excess of neutrinos with a specific energy distribution is seen directionally from the center of the earth, or the sun, these experiments could infer this excess to be dark matter annihilating releasing the neutrinos that they detect. Telescopes sensitive to gamma ray bursts, like the Cherenkov Telescope Array (CTA), or balloon and satellite based experiments which can detect particles coming from space before they interact with our atmosphere are also able to set limits on Dark Matter candidates based on the signals they see (or rather, the signals they have not yet seen confirm what dark matter is *not*)[32].

Direct, “shake it”, detection requires a DM particle to interact with a SM particle in a controlled, detectable setting. Many factors contribute to whether a DM particle interacts or not, but the common two features generally used to compare results between experiments are the interaction cross section, and the DM particle mass. The DM particle mass (among other DM and detector characteristics) is important in determining the amount of energy deposited in the interaction, especially as the DM candidate mass which experiments search for gets lighter.

In the wide range of direct detection DM experiments, some have the strategy of pushing the interaction cross section lower, by building their experiments big - having an arrow hit a bullseye on a target from great range is difficult, but becomes easier if you have the ability to set up 1000x as many targets. LUX-ZEPLIN (LZ) collaboration is such an experiment taking this approach. Currently under construction to build a 10-tonne liquid xenon detector, when operational the experiment will be able to probe an order of magnitude lower into the WIMP-nucleon cross section than previous experiments with published data [33]. Other experiments aim to make their mark by lowering the threshold energy of detection of events by advancing the detection technology. SuperCDMS, collaboration takes this approach, using cryogenic temperature Ge and Si detectors which will have event thresholds lower than other technologies, opening the door to probing DM candidates with lower masses. Further discussion of this experiment will be highlighted in Chapter 3.

The technologies which collaborations utilize to build their experiments also differ to allow for the science community as a whole to search for different interaction specifics in parallel. Figure 1.8 shows a sketch summary of the main detection methods; phonons are generated proportional to the energy deposition causing vibrations, charge is the measurement of ionization of the detecting material by incoming particles and radiation, and light is the measurement of photons emitted as a result of an interaction. Further specialization is made by some experiments who purposely design their experiments around an interaction property not accounted for by others, so that if DM does interact using this special channel, those experiments will be able to detect it.

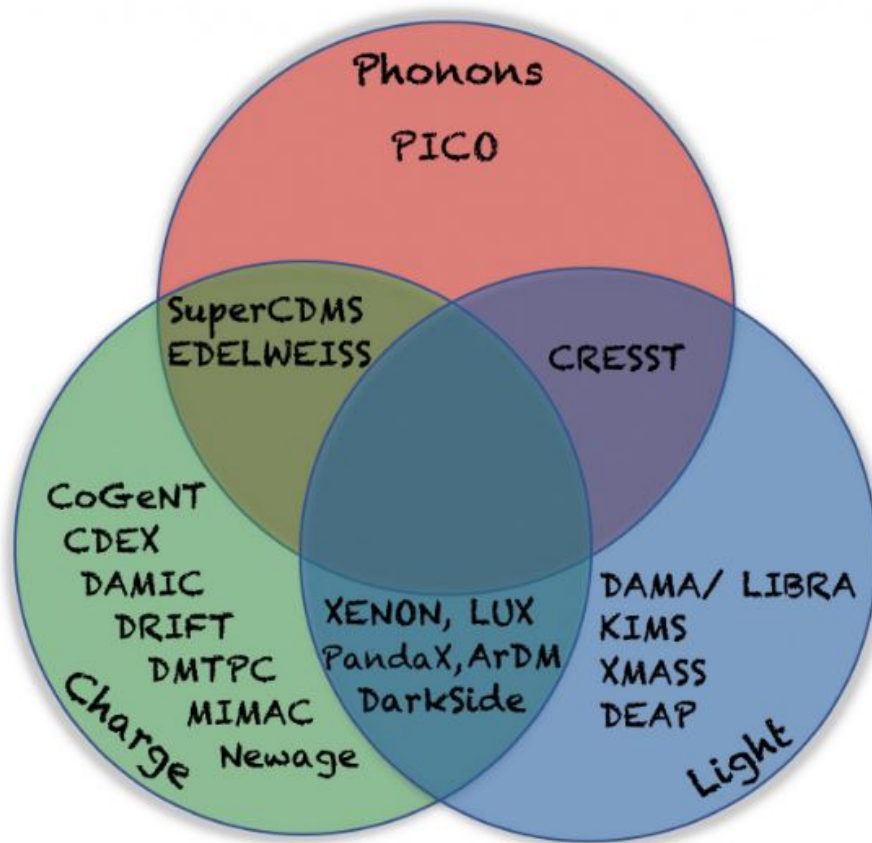


Figure 1.8: 3 classes of Direct detection Dark Matter searches. Phonon experiments measure the vibrations, and heat directly coming from the energy deposited in detectors. Charge experiments rely on the ionization of the detector material and collecting the charge to determine event energy. Light experiments measure the scintillation light coming from the detector material as it relaxes after an interaction. Image source: [34].

PICO is a bubble chamber experiment, where a fluid is superheated in a controlled environment such that the liquid is in a state where for the pressure and temperature

it should be in gaseous form, but first a small local volume of material in gaseous form, called a protobubble, is required. A small amount of energy needs to be deposited in a local area to push the fluid over a threshold where the surface tension of the growing bubble is overcome by the entropic desire for the fluid to be in gaseous form. What is special about PICO is that their fluid contains high levels of fluorine atoms which have an odd number of nucleons so the nucleus has a net spin [35]. If the DM interaction is spin-dependent, an experiment like PICO would be able to detect it.

If an experiment finds no evidence of dark matter, they will determine exclusion limits indicating the cross section and mass combinations of WIMP candidates which are not consistent with the experimental finding of an absence of a signal above the expected background. To compare the results of various experiments, the exclusion plots are compiled together, as in Figure 1.9 where published results appearing as solid lines, and anticipated limits from upcoming experiments in dashed lines. The general rule of thumb is that larger experiments can probe smaller cross sections, and experiments with lower event energy thresholds are able to probe lower mass limits.

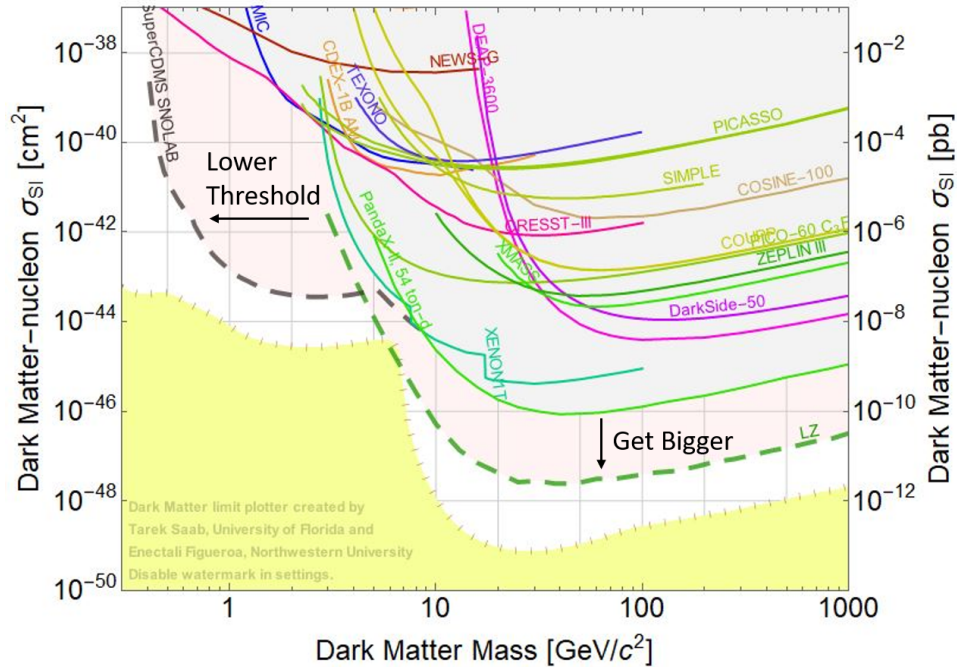


Figure 1.9: Exclusion plot of the most commonly proposed dark matter interaction method of various experiments. The anticipated limit of future experiments shown as a dashed line, and published results shown as solid lines. Image source: [36].

The search for DM is a team effort from the entire particle physics community. While it may seem like a race to find a DM signal, or rule out more parameter space where DM does not exist, having all of these different experiments allows the collective knowledge of them all to be combined to make big statements. As results are published, the vision and direction of the science community is updated to reflect the need to fill in our gaps of knowledge.

Chapter 2

Cryogenics Background

Cryogenics is defined as “the branch of physics dealing with the production and effects of very low temperatures” [37]. There are a number of different cooling principles which have been developed over the past century, each with unique strengths ranging from reliability, colder base temperature, ease of operation, and minimal noise for experiments. To get to temperatures below 500 mK there are two primary classes of refrigerators: Adiabatic Demagnetization Refrigerators (ADR) and Dilution refrigerators (DR). Both methods rely on understanding the entropy of the active cooling quantity and adjusting a secondary quantity such that the temperature of the material must compensate to maintain the entropy [38].

Both ADR and DR refrigerators typically will have two main cooling mechanisms. The first is responsible for getting the system from room temperature to liquid helium temperatures, while the second continues the cooling to base temperatures. *Wet fridges* accomplish the pre-cooling using liquid nitrogen followed by liquid helium to cool to those substances’ respective boiling points (70 K and 4 K).

An optional external recapture mechanism takes the boiled-off helium and liquefies it to be reused. *Dry fridges* use a cryocooler which performs an isentropic expansion of helium gas in a loop to cool to temperatures below ~ 3 K [39]. Temperature can be further reduced by exploiting the vapour pressure of helium; in a fridge, if a volume of liquid helium is present, by pumping off the evaporating helium above the liquid, helium from the liquid will evaporate to maintain the vapour pressure set by the entropy of the gas. Undergoing the phase transition to gaseous form requires energy which is drawn from

the surroundings, further cooling the helium bath at this stage. Under these conditions, fridges are able to achieve temperatures down to about 1 K.

2.1 Adiabatic Demagnetization Refrigerators

Adiabatic Demagnetization Refrigerators use an operating principle which leads to a sudden drop in temperature, and the experimental stage will be thermally isolated as much as possible once cold since the cooling provided is finite and will need to be reset. The experimental stage, and a magnetic refrigerant (ex. paramagnetic salts, or Nuclear Demagnetization materials such as Copper) are cooled from the pre-cool method using a heat switch, a mechanism in which you have control over whether it thermally conducts or not.

Heat switches are typically either a gas gap or superconducting heat switch. The gas gap has two closely placed thermal plates which are physically separated and in order to link the two thermally a gas (typically helium) must be present to act as a conductor. When it is time to isolate, the gas is pumped out, effectively switching off the thermal link [38]. Superconducting heat switches work on the principle that superconductors are poor thermal conductors, so implementing a link between two stages with a material which would typically be a superconductor thermally isolates them. If you want the two stages to be thermally linked, adding an external magnetic field of sufficient strength can force the superconductor normal.

Before the heat switch is turned off, a large external magnetic field is applied to the magnetic refrigerant, aligning the dipoles in the material (which is an exothermic process). The heat switch is then turned off once the stages have equilibrated with the pre-cool with the magnetic field on. The magnetic field is then turned off, allowing the aligned dipoles to relax. Since unaligned dipoles are more chaotic than aligned and the system wants to increase its entropy, a second parameter, temperature, must compensate for this. The energy to unalign the dipoles comes from the thermal energy of the surrounding material, including the experimental stage. The magnetic field can either be turned off all at once to achieve the lowest possible temperature, or gradually over time to maintain a stable base

temperature. The experiment stays cold until the magnetic field is exhausted and heating from various sources brings it above temperatures at which useful science can be done. At this point, the magnetic field can be turned back on, the heat switch can be reapplied, and the fridge can be reset to cool again. The advantage of ADRs is they can achieve ultra low temperatures especially when added onto an existing dilution refrigerator, are typically much cheaper than the only other alternative to achieve temperatures below 300 mK, and have less parts to maintain.

2.2 Dilution Refrigerators

^3He and ^4He have very different properties at low temperatures. Once a mixture of helium with both isotopes present has reached a temperature lower than the critical temperature of 870mK there is phase separation between concentrated ^3He and a mixture of ^3He and ^4He . In the latter helium liquid, there is a maximum concentration of ^3He at a given temperature and the mixture here is called the dilute phase. If the concentration of ^3He in the dilute phase of the mixture is reduced, ^3He will migrate across the phase boundary to rebalance the concentration. Since ^3He has a much higher vapour pressure than ^4He around 1 K, there is preferential evaporation of ^3He in the dilute mixture at the stage held at this temperature, called the still. This evaporated gas is then pumped away using a mixture turbo pump so that more ^3He can evaporate in an attempt to maintain vapour pressure. The heat required to evaporate the ^3He is taken from the still stage, cooling it. This reduction in concentration in the still will be accounted for at the interface of the $^3\text{He}/^4\text{He}$ liquids at a location called the mixing chamber. ^3He migrates across this interface, which is an endothermic process since the binding energy between ^3He - ^3He atoms is higher than between ^3He - ^4He but the entropy of ^3He in the dilute mixture is higher than in its concentrated form which drives the process. The heat required for this dilution to occur is taken from the experimental stage [38]. In some cases a low power heater will be applied at the still to promote greater evaporation of ^3He which would require more dilution at the Mixing Chamber to compensate, driving the temperature of the experimental stage lower.

To operate the dilution refrigerator continually, a mixture circulation loop cycles the removed ^3He from the still out to room temperature and eventually reintroduces it at the Mixing Chamber on the concentrated side. The mixture circulation loop of a dry dilution refrigerator can be summarized by looking at Figure 2.1. Beginning with warm ^3He gas, it filters through a cold trap to remove contamination, and enters the fridge at the injection line. The gas is precooled by some method depending on whether it is a dry or wet fridge. The gas passes through an impedance allowing the gas to expand and cool coming through the impedance orifice, and depending on the specific refrigerator this can occur before, between, or after the 60K and 4K stages. The gas is further cooled by helium returning from the mixing chamber through heat exchangers at various temperature stages, as it moves towards the concentrated phase of the mixing chamber. In the mixing chamber, the ^3He undergoes dilution as explained above, and begins its path back out of the fridge. The ^3He migrates in the dilute phase to the still where it evaporates and is pumped out by a room temperature turbo and scroll pump. The main advantage of this type of refrigerator over ADR is that it can maintain a constant temperature continually, whereas ADRs require the magnetic field to be cycled, typically daily.

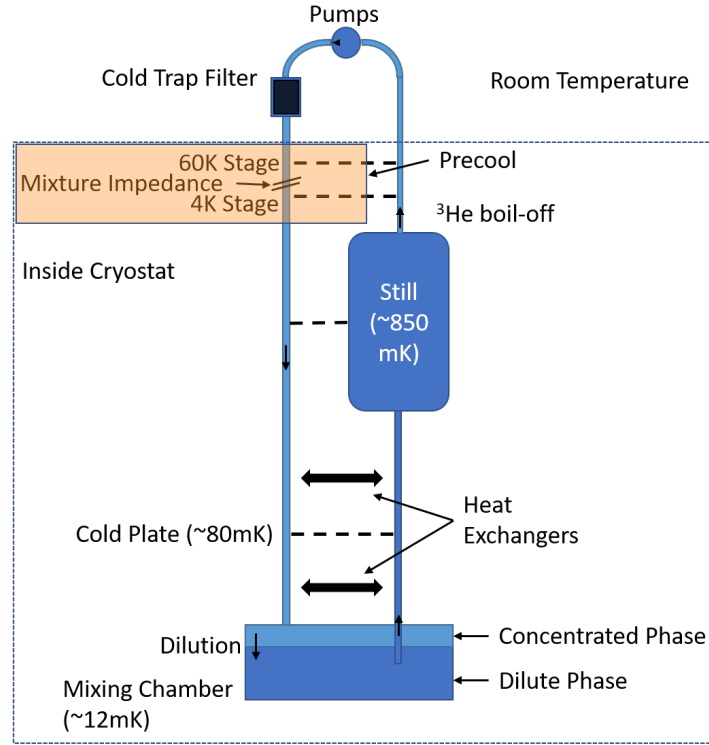


Figure 2.1: Schematic of the mixture circulation loop of the dilution refrigerator as used in CUTE. Warm He is cooled by cold outgoing gas through heat exchangers on its way into the refrigerator. After passing through a series of thermal stages, the ^3He reaches the mixing chamber where it transitions through the phase boundary to maintain ^3He concentration in the dilute phase, drawing heat from the thermal stage to do so. Gas migrates to the warmer still stage where ^3He evaporates due to the high vapour pressure and is pumped away by room temperature pumps.

2.3 Cryostats

The refrigerators by themselves can provide cooling power, but this is only useful if it can apply the cooling to an experiment. Cryostats are a series of nested thermal layers which are thermally linked to the various temperature stages of the refrigerator, and are rigidly attached together, but as thermally isolated as possible. The entire cryostat is held under vacuum to remove the ability for gas inside to act as a source of convective heating between stages. The purpose of having multiple stages is primarily because the rate of heating from blackbody radiation is proportional to the difference of the temperature to the fourth power of adjacent stages. By introducing more stages from room temperature to the coldest stage, less active cooling power is required to maintain the base temperature. To prevent this blackbody, Infrared (IR), heating, each nested thermal layer acts as an optical barrier for its neighbours so that higher energy photons emitted from the warmest

stages cannot reach the colder stages, since they are blocked by the next adjacent stage.

2.4 CUTE's cryogenics

CUTE operates using a dry dilution refrigerator, with a 2-stage pulse tube cooler implemented to cool the 60K and 4K stages. The cooling power is applied to the “cold head” in the fridge which is thermally linked to the 60K and 4K stages of the cryostat using the circulating helium mixture as a heat exchange gas. With present detector payloads, CUTE can cool from room temperature to a base temperature of $\sim 11\text{-}14\text{ mK}$ in 3-4 days and can maintain cryogenic operation at that base temperature for extended periods of time, with some cryogenic runs having lasted almost two months.

During the pre-cool, the period of the cooldown to take the cryostat from room temperature to temperatures at which condensation of helium can occur, the pulse tube cooler is the only source of cooling. As such, the mixture gas is routed differently than in Figure 2.1 to bypass the impedance on the way into the fridge, and uses a different route out of the fridge directly from the still through the “fast pumping” line. The purpose of this circulating mixture is to act as a heat link between the cold head side of the 4K and 60K stages with their cryostat temperature stages, and to deliver cold gas from the 4K stage to the lower temperature stages to remove heat from there. Chapter 5 will discuss this in greater detail.

Chapter 3

SuperCDMS

The Cryogenic Dark Matter Search (CDMS) originally started in the 1990's as an experiment utilizing cryogenic semi conductor crystals to search for WIMPs. In 2003 the experiment moved from its original location of Stanford Underground Facility (SUF) which acted as a proof-of-concept facility to develop the detectors and cryogenic systems to the Soudan Underground Laboratory in Minnesota. The primary reason for this move was to reduce the background coming from cosmic rays, since they had become the dominant background. The experiment had its name promoted to SuperCDMS in 2011 when the experiment underwent a major upgrade, increasing the active mass, and background rejection, providing more effective detection.

3.1 SuperCDMS SNOLAB

Once the experiment had run its course in Soudan, the collaboration looked for a new site to call home. SNOLAB, a laboratory operating as a class 2000 cleanroom 2 km underground in a Nickel mine outside of Sudbury, ON, Canada was selected to be the location for the next generation of the SuperCDMS experiment. SNOLAB was constructed after the success of the Sudbury Neutrino Observatory (SNO) experiment which began operation in the late 1990's and continued into the mid 2000's, provided evidence for the oscillation of neutrino flavour [40][41]. SNOLAB provides a location to house international experiments in a low background environment, such as PICO, DEAP, and SNO+; with 2 km of Canadian Shield overburden it makes SNOLAB one of the best locations in the

world for shielding cosmic rays, as shown by the reduction in muon flux in Figure 3.1. In addition to the scientific merit SNOLAB provides for the experiment, the laboratory infrastructure is already in place to provide operational support to experiments, and it is geographically convenient for travel from a number of the collaborating institutions.

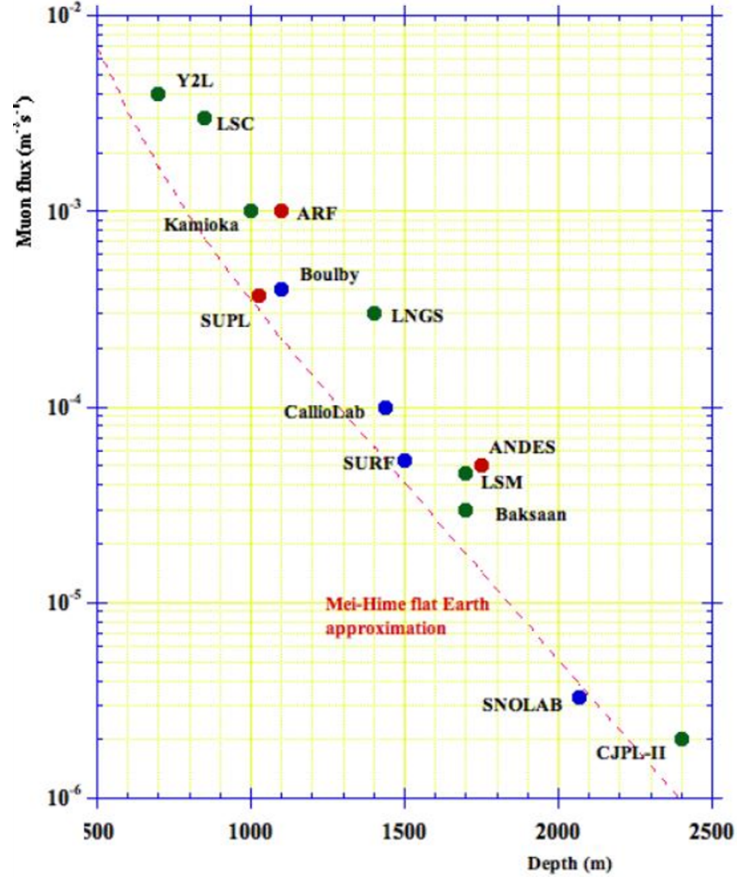


Figure 3.1: Muon flux measured at various underground laboratories around the world. Muons are a source of background in particle physics experiments, so lower flux implies more sensitive measurements can be performed as experiments will not be background limited. Image source: [42]

SuperCDMS SNOLAB was designed to hold larger detectors, with the mass of each Ge detector going from 600 g in SOUDAN to 1.4 kg at SNOLAB. The cryostat is designed to have the capacity to hold up to seven stacks of detectors, where six stacked detectors are called a tower. The first generation of operation at SNOLAB will have 4 towers yielding a total active mass of about 30 kg. The detectors used will be a mix of Silicon and Germanium semiconductor crystals and will also be a combination of two operating techniques which will be discussed in the next section: Interleaved Z-sensitive Ionization and Phonon detectors (iZIP) and High Voltage (HV) detectors. The advantage of iZIPs

is that they are useful at background discrimination and give the ability to determine whether an event was a nuclear or electron recoil (NR and ER) in the crystal, while HV detectors have a lower event threshold, meaning they can probe lower dark matter particle masses, but are not able to discriminate between NR and ER events.

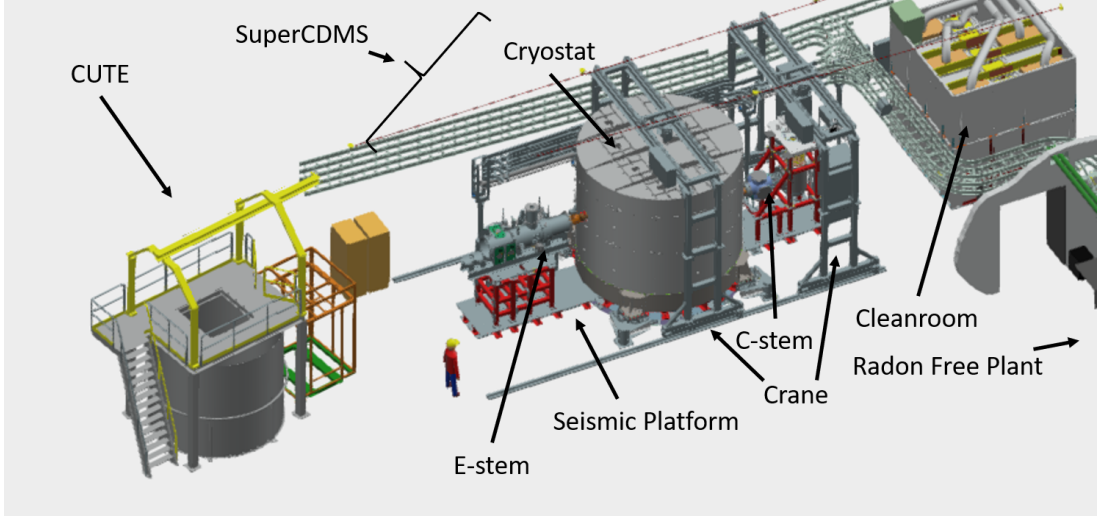


Figure 3.2: CAD rendering of the SuperCDMS facility with important features indicated. SuperCDMS sits in the SNOLAB cavern immediately adjacent to CUTE, so the proximity of the two facilities is also shown. Source: [43].

Like many large projects, SuperCDMS can be considered to be the assembly of a number of subsystems and components, each of which have their own purpose and reason for being included in the experiment. This is not only beneficial when trying to understand the entire complex project, but also allows for more efficient delegation and completion of work. Figure 3.2 shows the major subsystems designed to be included in SuperCDMS, which will be further discussed below.

Cryostat

The detectors are placed in the center of a series of concentric copper cylinders, similar to Russian Nesting Dolls. The advantage of having multiple cans is to reduce the amount of cooling power that is required at the coldest stage due to not having to remove as much heat to counteract the thermal radiation. Having multiple stages also allows for the cooling of the detector signal lines and cables, minimizing the heat conducted to the detectors.

SuperCDMS SNOLAB has been designed to have the dilution refrigerator located outside of the location where the detectors will be housed which is called the SNOBOX. This decision was made to achieve maximal shielding coverage of the detectors; the size of the shielding would need to be much greater if the refrigerator also needed to be contained inside. Also, some of the components in the refrigerator might have radioactive contamination deemed to be too high to be contained within the shielding, so having the fridge located outside the SNOBOX eliminates this issue. As seen in Figure 3.3 the SNOBOX has two feedthrough ports; the C-stem (Cryogenics Stem) and the E-Stem (Electronics Stem) are responsible for delivering the cooling power to the experiment, and transmitting detector data respectively.

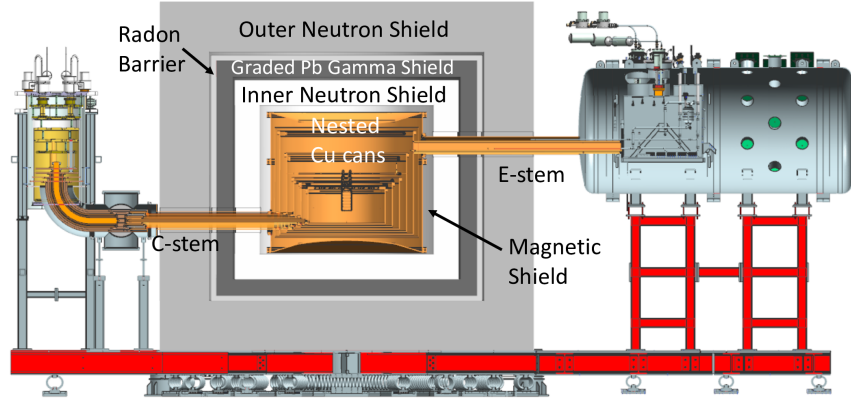


Figure 3.3: CAD rendering of the SuperCDMS Cryostat. A number of nested copper cans hold the detector towers with two stems protruding; the Cryogenic stem for cooling power to the detectors, and the Electronics stem for detector communication. Also shown are the shielding layers of neutron shields (water tank outer, polyethylene inner), radon purge layer, and lead gamma shielding. An updated smaller SNOBOX design is underway due to manufacturing limitations of the original large design shown here. Source: [44].

Shielding

SuperCDMS has three layers of shielding as seen in Figure 3.3. An outer layer of Polyethylene plastic and water both provide shielding from neutrons and some gammas which originate in the cavern walls. Also surrounding the SNOBOX are two layers of stacked lead bricks which provide shielding from high energy gamma radiation coming from the lab. These two layers have different levels of ^{210}Pb contamination, a radioactive isotope of lead with a 22 year halflife [45]. Particle Physics experiments are limited to the null hypothesis claims they can make by the background event rate. If the levels of radioactive

contamination like ^{210}Pb are not controlled in SuperCDMS, the scope to which SuperCDMS can perform science is impacted. An inner layer of polyethylene further shields from neutrons and gammas. The thicknesses required for the shielding were confirmed by simulations and existing knowledge of the radiation levels measured in SNOLAB, showing that the background events from known radioactive sources will be minimized to the level where SuperCDMS's scientific goals can still be achieved [46]. The background budget in SuperCDMS is dependent on detector type with the highest values of 370 and 0.003 events/kg/keV/yr for electron recoils and events in the nuclear recoil region respectively [47].

Calibrations

The calibration of detectors is required for all experiments. In some, calculations of the scaling factors as a signal goes through the series of electronics is sufficient, but in general in particle physics experiments radioactive sources are used. These sources emit particles with various energies and are measured by the detectors in order to understand the conversion from detector signal to event energy. Calibration sources used in SuperCDMS detectors also are used for Electron Recoil vs. Neutron Recoil discrimination, as will be discussed later in this chapter, and over the course of a run can be used to monitor detector stability. Detectors are deemed to be stable if the signal received from a calibration of a given energy at one point in time matches the signal received later. Understanding how detectors interact with “regular” matter at known energies can help to interpret data scientists think are evidence of interactions with Dark Matter [48].

Two calibration systems are planned for SuperCDMS. The first is a ^{133}Ba gamma source which emits photons with energies 302.9, 356.0, and 383.8 keV when the barium undergoes electron capture decaying to ^{133}Cs [49]. The gammas calibrate the detector for electron recoils and the source will deploy remotely using a steel cable through the shielding layers to the top of the SNOBOX [46]. A ^{252}Cf spontaneous fission neutron source will be deployed by hand through guiding tubes along the E and C-stems for nuclear recoil calibrations. Work has also been done recently to prove the feasibility of using LEDs at

cryogenic temperatures as a low energy photon source [34].

Crane

A 3-Ton Gantry crane is mounted on rails such that it has clearance above the assembled SuperCDMS experiment to aid in the installation of various heavy components in SuperCDMS including the seismic platform, shielding, and the SNOBOX cryostat.

Radon Filtration Plant

In addition to the contamination of ^{210}Pb in the shielding materials, ^{210}Pb is a daughter in the decay chain of ^{238}U which is found naturally in the Canadian Shield rock in which SNOLAB is situated. An intermediate isotope between the uranium and lead is ^{222}Rn , a radioactive gas with a relatively short halflife of 3.8 days which is emanated from the cavern walls in SNOLAB [45]. The natural radon level underground in SNOLAB is $\sim 130 \text{ Bq/m}^3$, which can be problematic for experiments that do not have controls implemented to minimize the exposure of sensitive equipment to lab air [50]. The issue is not only the decay of the gaseous radon itself, but also when the radon decays it deposits the radioactive daughter atom on nearby surfaces. A compressed air line which is sent from surface has a measured ^{222}Rn concentration of $5\text{-}10 \text{ Bq/m}^3$ [50]. Through background limit calculations, it was determined that having the detectors and copper housing exposed to this level of radon concentration for a moderate amount of time would be unacceptable for the target sensitivity limit SuperCDMS hopes to achieve. For this reason a Radon Filtration plant was designed and constructed for SuperCDMS which provides air with most of the radon removed to a level of $67 \mu\text{Bq/m}^3$ [51]. This radon filtration plant will supply the air to the SuperCDMS and CUTE cleanrooms.

Cleanroom

All detector work performed should be done in a clean environment. Not only is it a good idea to protect from dust found in the area from depositing on the detectors, but also to protect from the radioactive radon gas. The cleanroom will have a dedicated filtered

air supply with low radon concentration from the radon filtration plant to reduce the radioactivity inside. This cleanroom provides a good working area for work to be done, but it also gives a secure location for the radioactively sensitive equipment to be stored before it is installed in the experiment. The detectors will be assembled in the SNOBOX in the cleanroom, and then the assembly will be wheeled out of the cleanroom to a location on the floor where the crane can lift it onto the seismic platform in the experimental shielding.

Seismic Platform

Since this lab is located underground in an active mine, SNOLAB is frequently affected by minor seismic events. Even the vibrations which come as a result of lab personnel walking nearby the experiment have been seen in SuperCDMS detectors in other experiments when corrective action to isolate the experiment is not applied [52]. To account for this, the entire experiment sits on a seismic platform which acts as a damper for vibrations coming from the lab floor. The seismic platform is effectively a steel platform sitting on 64 stiff springs which can be seen in Figure 3.4, 3.2 and the bottom of Figure 3.3 [53].



Figure 3.4: SuperCDMS Seismic Platform under construction in SNOLAB, 90% completed. Also seen in the photo are the gantry crane, and foundation for the cleanroom. Image source: [44]

Data Acquisition and Readout Electronics

Once an event occurs in the detectors, the information about the event needs to be transmitted out to further electronics and computers to be recorded and saved for analysis.

The E-stem coming out of the SNOBOX contains the readout cables which both bias the detectors as necessary in order for them to be sensitive to events in the crystal, and transmit the signal of each detector out to the room temperature electronics. The end of the E-stem terminates at the Vacuum Interface Board (VIB), a board that interfaces electronic communication between the cryostat under vacuum and the room temperature, lab pressure electronics. The readout cable terminates on the vacuum side of the VIB and the signals are processed by Detector Control and Readout Cards (DCRCs) which plug in on the lab pressure side of the VIB. These DCRC boards are the “brains” of the detectors, setting and reading all the parameters for each detector, and each channel. The DCRCs contain the triggering information so that they constantly read in the signals and then determine when an event occurs and that the data needs to be saved. After the data are digitized by the DCRCs, they are sent via ethernet cable to a number of computers which are responsible for saving the data, categorizing it for further processing, and doing preliminary analysis. The preliminary analysis on certain parameters is performed so that experimentalists on shift can determine if the detectors are operating as expected.

3.2 SuperCDMS Detectors

To succinctly understand how the SuperCDMS detectors and readout system work, we begin by following the journey a potential dark matter particle would take from interaction in the detector to being saved as a recorded event.

For SuperCDMS, when a dark matter particle interacts with either the nuclei or electrons in the crystal, initial phonons, which are quantized vibrations, are produced and propagated through the crystal. There is also some charge that may be freed by this interaction which can travel through the crystal if the detector is operated with electric bias and be collected at the crystal surfaces.

In iZIP detectors, there is limited electric field present in the crystal, so the collected charges and phonons are indicative of what was initially released at the interaction of the particle with our detector atom. The reason why collecting the information on both charge and phonon amplitude is important, is that the ratio between the two indicates whether

the interaction occurred in the atom's nuclei, or with one of the electrons as shown in Figure 3.5. Being able to differentiate between these two allows for better sensitivity in the search for dark matter candidate events, and assuming an excess of events does occur, can give information on the nature of dark matter and how we can expect it to interact with regular matter.

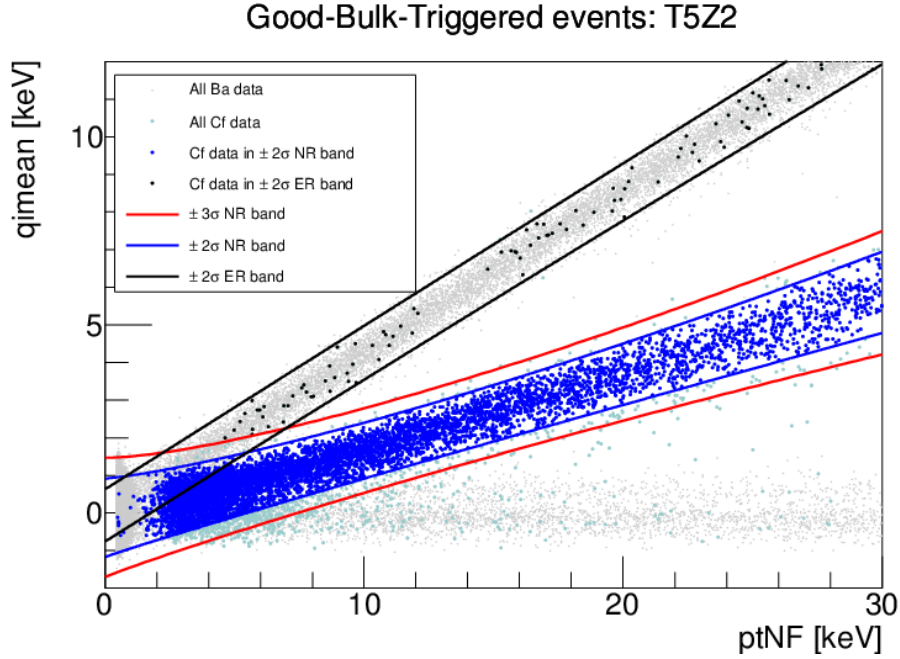


Figure 3.5: The ratio of ionization (y-axis) and phonon (x-axis) signal, here shown for a Soudan iZIP detector, differs between electron and nuclear recoil events. Shown in upper grey band are electron recoil events from a ^{133}Ba calibration, while the lower blue band are nuclear recoil events from ^{252}Cf neutron calibrations. Some ^{252}Cf events interacted through electron recoils (black), and some fall out of the bands of both classes (light blue). Image source: [54].

In HV detectors, a high voltage of $\sim 20\text{-}100\text{ V}$ is applied between the two faces of the crystal creating an electric field inside. After an interaction in the crystal, as in iZIP detectors, both phonons and charges are released, however in this case as the electrons and holes drift through the electric field, they emit Neganov-Trofimov Luke (NTL) phonons as shown in the schematic in Figure 3.6. The NTL effect is that as a charge accelerates through a crystal, phonons are emitted with a total energy equal to the electric potential energy of the charge in its original position [55] [56]. In the context of SuperCDMS detectors, the NTL effect amplifies a small charge signal into a large phonon signal. The total phonon energy, E_t is given by the following equation:

$$E_t = E_r + N_{eh}eV_b \quad (3.1)$$

where E_r is the phonon energy from the initial particle interaction, N_{eh} is the number of electron-hole pairs created in the interaction, e is the fundamental charge, and V_b is the bias voltage. N_{eh} is calculated from the recoil energy, based on the ionization yield and average energy required to create an electron-hole pair in the detector material. For a SuperCDMS Ge detector biased at 100 V, and events in the keV range this amplifies the ionization energy by 34 times. CDMS achieved a lower threshold than previously possible using this amplification technique obtaining an energy threshold of 56 eV for electron recoils using 24x NTL amplification in its CDMS Low Ionization Threshold Experiment (CDMSlite) [57].

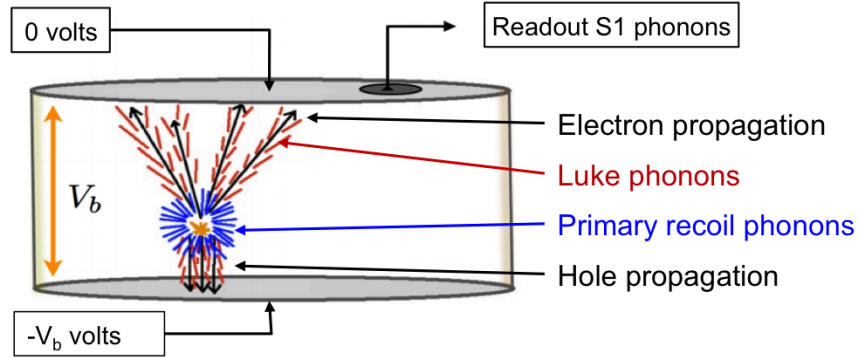


Figure 3.6: Schematic showing how NTL amplification works in detectors. When an interaction occurs in a detector, some energy goes into primary phonons, and some energy goes into creating electron-hole pairs. As the e-h pairs drift through the detector, they induce secondary (Luke) phonons proportional to the detector bias and initial ionization energy. Image source: [44].

When charges reach the surface of the detector, they are collected by two electrodes on each detector face. It is beneficial to have multiple phonon channels operating so that the difference in amplitude of the phonons and time of the initial phonons arriving at the sensor can be used to reconstruct the likely event location. Figure 3.7 shows the different channel masks used in SuperCDMS detectors, initially at Soudan, and the masks for SNOLAB detectors.

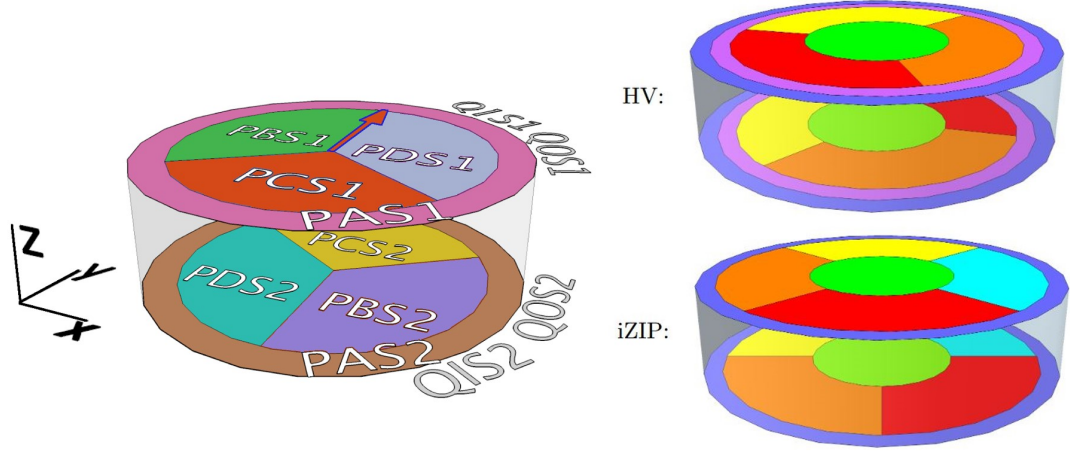


Figure 3.7: (Left) Channel masks on SuperCDMS Soudan iZIP detectors, with four phonon readouts and two charge channels per side. (Right) SuperCDMS SNOLAB HV and iZIP detector channel masks with six phonon readouts and two charge channels per side. Image source: [44][47].

The phonon energy gets collected by the detector and read out beginning with a Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor (QET), followed by a Superconducting QUantum Interference Device (SQUID). Figure 3.8 shows a schematic of the QET phonon readout device on a crystal surface. While this diagram is specific to an older detector generation, CDMS II, the same principle is employed in all SuperCDMS detectors.

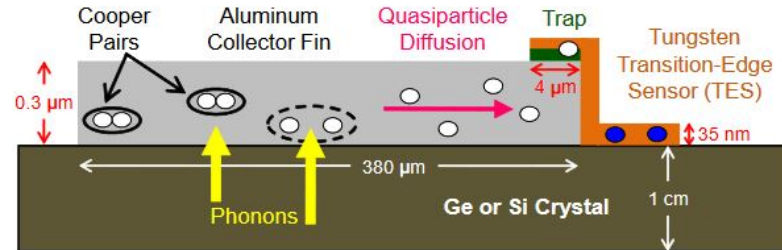


Figure 3.8: The QET diagram shows an aluminum substrate deposited on the detector crystal which absorbs phonon energy breaking apart Cooper pairs in the Al. The resulting quasiparticles diffuse through the Al to an interface where they are trapped in tungsten, unable to diffuse back into Al. In the tungsten the energy associated with these quasiparticles breaks more Cooper pairs, increasing the resistance of the W which produces a detectable signal in the QET electronic circuit. Image source: [58].

Deposited to the surface of the Ge and Si crystals are Aluminum (Al) collector fins. When phonons travel through the crystal and arrive at the surface they have a probability of entering the Al. In the Al they can break apart Cooper pairs creating electron

quasiparticles which cannot recombine into Cooper pairs in the superconducting material unless they find another quasiparticle with perfectly matching momenta [59]. The quasiparticles diffuse through the Al to a thin Tungsten film, with this overlap region called the Quasiparticle trap, and since the tungsten (W) has a smaller band gap than Al the quasiparticles migrate into the W, and cannot go back into the Al. The quasiparticles migrate into the bulk W volume at the Transition-Edge-Sensor (TES) where they break apart more Cooper pairs releasing energy in the form of heat. The TES is held at a critical point in transition between superconducting and normal state. By depositing energy into the electron system, originally from the phonons, the resistance of the tungsten increases. Operationally, we select the point in transition to give the maximum response (greatest $\frac{\Delta R}{\Delta P}$ where P is the power from the crystal heating the sensor). An example of a transition curve of a TES sensor is given in Figure 3.9 where it can be seen that a small deposition of energy resulting in a change in temperature of the TES would cause a measurable change in resistance of the tungsten.

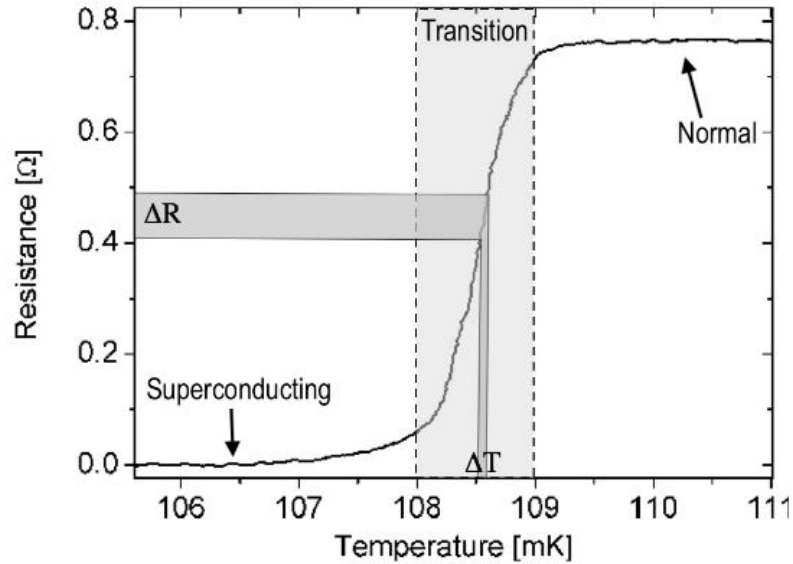


Figure 3.9: Transition curve showing that when Transition Edge Sensors are held at a defined temperature corresponding to the material being between its superconducting and normal state the resistance can change dramatically when a small amount of energy is deposited. Image source: [34].

The preamplifier circuit in the cryostat, or the “cold electronics” is shown in Figure 3.10 with R_{TES} being the TES resistance as described above which is where the signal

from the detector is introduced into the circuit. When the lefthand side of the circuit with the TES reacts to this change in resistance from an event, the change in current in the loop induces a change in magnetic field in the inductor. A Superconducting QUantum Interference Device (SQUID) is a superconducting loop with two Josephson junctions which is highly sensitive to changes in magnetic field. The rest of the SQUID electronics amplifies the current signal, provides a negative feedback magnetic field to the SQUID, and induces a voltage across the feedback resistor which gets read out and further amplified by the warm electronics.

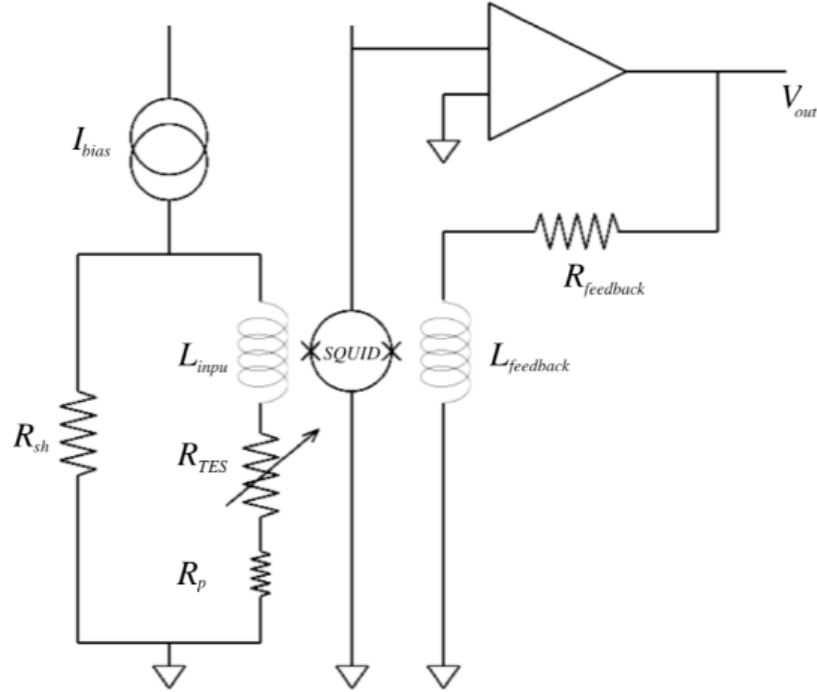


Figure 3.10: Circuit diagram of the cold electronics in SuperCDMS detector readout system. The left side is the QET electronics branch biasing the TES, the right side is the SQUID readout sensing and amplification electronics.

A number of electronic calibrations are performed on the readout system in order to get an understanding of their performance and limitations. The test relevant for this thesis is the $I_b I_s$ measurement which informs how the current going through the R_{TES} side of the QET circuit in Figure 3.10, I_s , changes as a function of the incoming bias current I_b . As the bias current increases from zero, the TES is superconducting and the resistance remains unchanged so the current through the TES side increases linearly. Once the bias

is sufficiently high, the sensor enters into transition and energy begins to be deposited by the current in the form of heat. At this point, the resistance increases (as seen from Figure 3.9) and the current through the TES decreases, since the parallel path through the shunt resistor will account for more of the bias current. When the bias current is large enough to put the TES in its normal state, the relationship between bias and response current becomes linear again. For this measurement, a sinusoidal signal is applied on top of the bias current so that there is a time varying I_b and the resulting time-varying I_s is measured. Figure 3.11 shows the result of one such calibration of a detector at CUTE.

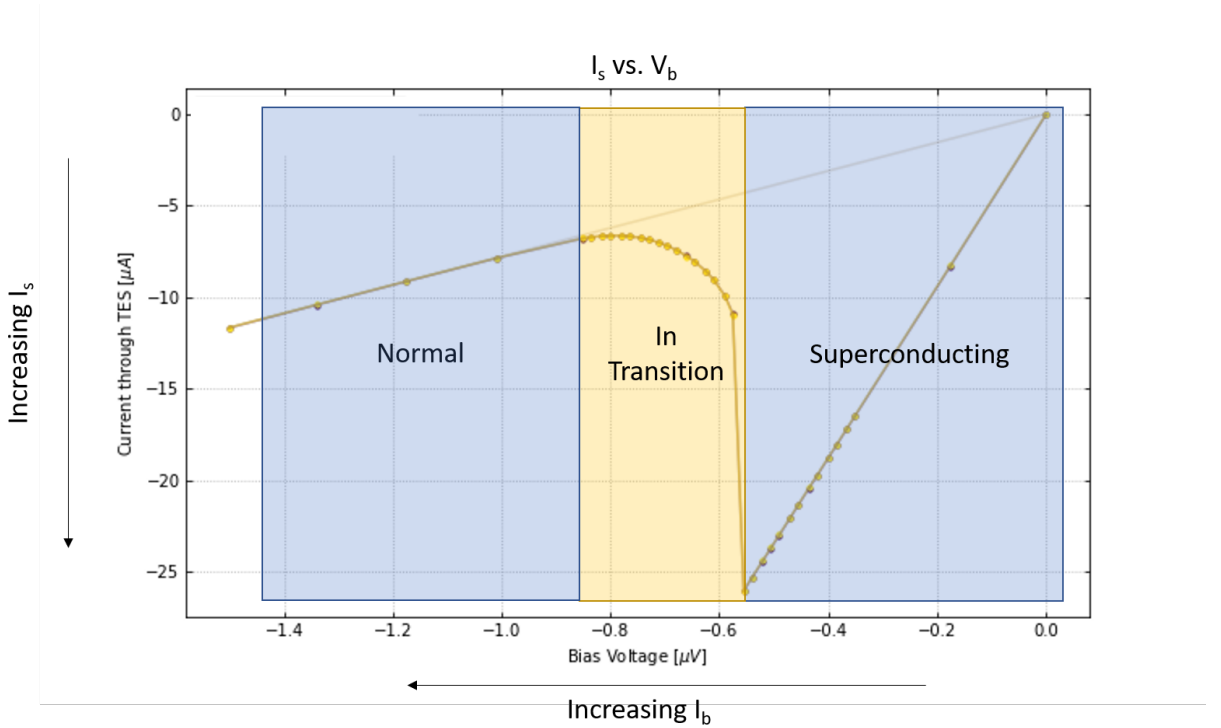


Figure 3.11: $I_b I_s$ calibration curve for a PD2 detector in CUTE. Bias voltage is directly proportional to bias current, but at CUTE it is a voltage source available, not a current source. Shown are the 3 regions in the TES response. Image modified from E. Fascione.

From this calibration, the experiment can determine at what point in transition detectors will be for various bias currents, which is important to know because the response of the TES can change for the same amount of energy collected depending on where in transition the sensor is. This allows us to convert an electronic amplitude associated with a readout to the true energy of the event in the crystal, which will be discussed later in Chapter 8.

Chapter 4

CUTE

With the increase in size, and lowering of energy threshold of the new SuperCDMS detectors, testing at surface facilities would most likely lead to constant pile-up. Surface facilities have much higher exposure to cosmic rays, which would induce too many events in the detectors for meaningful testing or science to be done. Additionally, due to the high purity of the detectors, limiting the exposure to radiation after production is critical to ensure minimal backgrounds from cosmogenic activation [59]. Beyond the necessary reasons why a low-background test facility is required for SuperCDMS, a number of opportunities arise if such a facility is available. The cosmogenic activation rate of tritium in silicon has yet to be measured for SuperCDMS detectors, which is expected to be the dominant background in the SuperCDMS experiment. SuperCDMS will still require at least a year of construction before being able to operate, but with a low-background test facility a dark matter search using the new detectors can be performed setting new limits on dark matter candidates in the meantime.

For the aforementioned reasons, there was a need for a low-background cryogenic test facility to provide conditions similar to that of SuperCDMS at SNOLAB. The Cryogenic Underground TEst facility (CUTE) is designed to test SuperCDMS detectors in a low background, low-noise cryogenic environment holding one full tower of SuperCDMS detectors. CUTE was installed and commissioned at SNOLAB in the summer of 2019, and has since been taking data, both to characterize the performance of the facility and to take preliminary low background science data using SuperCDMS detectors. Once SuperCDMS is operational and no longer has a need for detector testing, CUTE will be used for other

experiments that require a low background environment or will conduct small-scale rare event searches.

Chapter 2 discussed the operating principle of a dilution refrigerator, and began discussing how they are implemented in CUTE, but there are many more components and subsystems within CUTE which are important to note. CUTE faces similar challenges as SuperCDMS does relating to vibrations, shielding, and radioactivity and the details of how these challenges are overcome will be discussed in the following sections.

4.1 Systems at CUTE

Drywell and Shielding

In contrast to the shielding in SuperCDMS where the shield will need to be dismantled and rebuilt each time a payload change occurs, CUTE has a shielding system which can be moved out of the way quickly which allows the cryostat to be removed [60]. The CUTE cryostat sits in a stainless steel hollow, named the “drywell”, of a 3.6 m diameter water tank which provides shielding from neutrons and majority of gamma radiation. In the drywell two nested layers of lead with a low ^{210}Pb contamination level shield the detectors from high energy gamma radiation coming from below and beside. The shielding of the detectors from above comes from a 13 cm thick lead cylinder which is internally mounted in the CUTE cryostat, and a 20 cm thick Polyethylene slab mounted on wheels which can roll over the experiment allowing for 4π line-of-sight radiation protection, and the ability to quickly access the cryostat to move it away for payload changes and maintenance. In addition to the shielding required from radioactivity, a mu-metal shield is layered in between the inner and outer layers of lead to protect the SQUID electronics from static magnetic fields. The result of this shielding provides a low background environment for the detectors at a level of 2.87 events/keV/kg/day for events below 1 keV as projected by simulations [61]. Figure 4.1 shows the cross-section of the different passive shielding incorporated in CUTE.

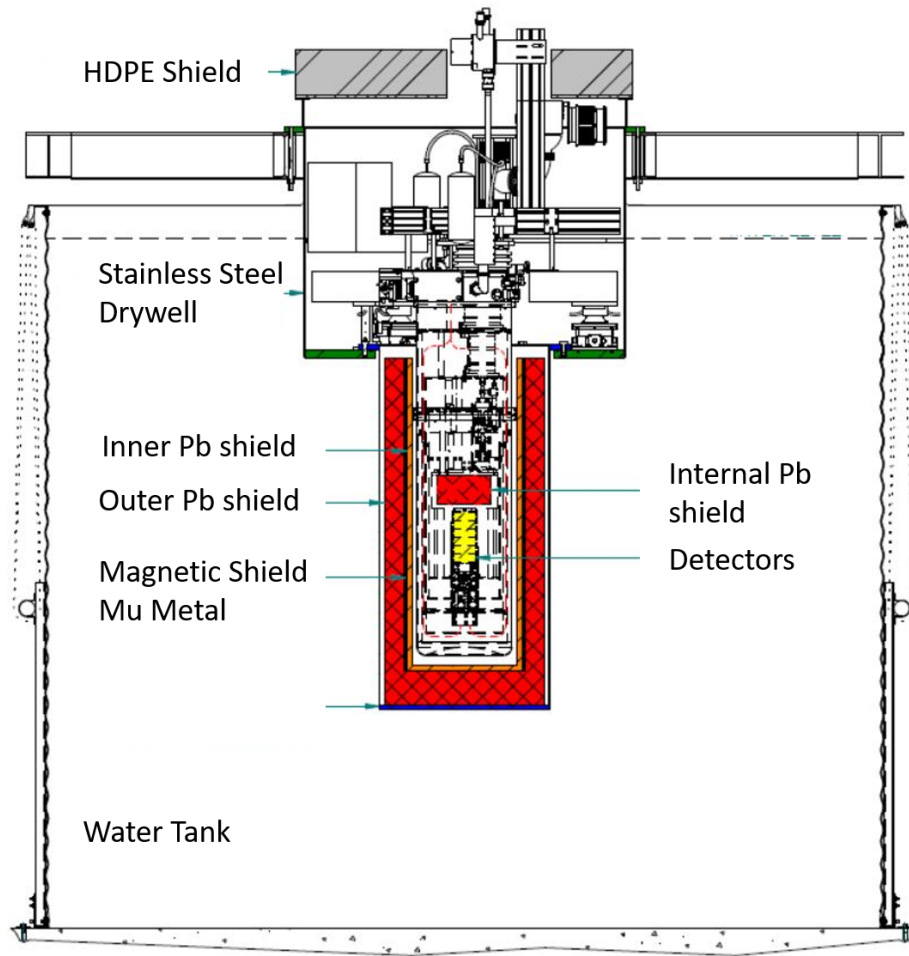


Figure 4.1: Schematic of the CUTE cryostat resting in the drywell showing the many layers and types of shielding. The water tank, and HDPE shield on top provide shielding against neutrons and some gammas, the 2 layers of lead shield in the drywell and lead block internal to the cryostat provide gamma shielding, and the μ metal provides shielding to external magnetic fields. Schematic from [62].

Cleanroom, Platform, and Crane

Due to the sensitivity and purity of the detector crystals, all work performed on the inner parts of the dilution refrigerator must be done in an environment which minimizes contamination both from the environment, and from personnel. The CUTE class 500 cleanroom was custom designed so that the dilution refrigerator could sit on top of the cleanroom, allowing the experimental stage to come through the ceiling. Rolling ceiling sliding collars wrap around the Outer Vacuum Can (OVC) to create a cleanroom seal allowing for maintenance and work to occur on the cryostat in a contained environment.

To move the cryostat between the cleanroom where payload changes and detector work occurs, to the shielded experimental location, and back as required, a 1-ton monorail crane

is mounted above to span both locations in CUTE as seen in Figure 4.2. A decked surface is installed above the water tank giving access to the experiment as it sits in the drywell to make all the necessary electrical and hose connections required. Figure 4.3 shows the general layout of the CUTE facility.



Figure 4.2: Photograph of the CUTE facility as seen from the ground level showing the close relation of the water tank and deck to the cleanroom where the cryostat can be moved to and from with the monorail crane mounted above.

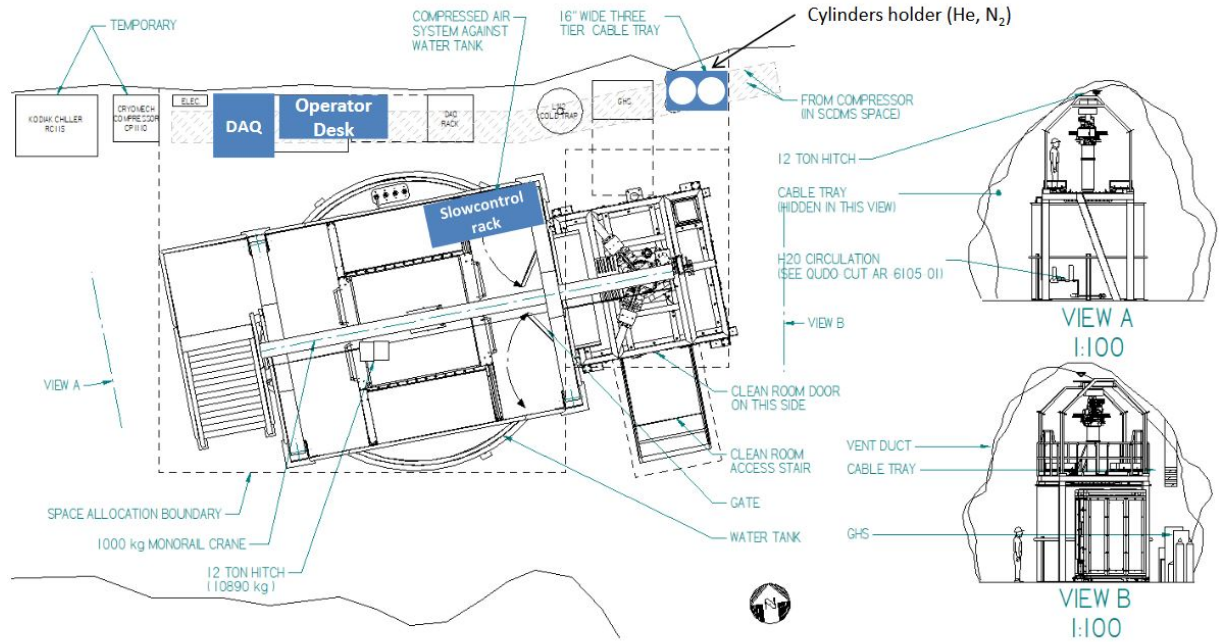


Figure 4.3: Marked up schematic of the CUTE facility in SNOLAB. Image source: [62].

Purge Gas

CUTE faces similar challenges as SuperCDMS does with radon mitigation mentioned in chapter 3; if we do not have controls in place to limit the amount of radon that can be in volumes which are close to operating detectors, the ^{210}Pb accumulation will introduce a significant background. In the drywell, the radon levels and subsequent ^{210}Pb build up are mitigated by having purge gas with low radon concentration from SNOLAB's compressed air supply pumped in to the bottom of the drywell below the OVC, which displaces air with high radon content which may have entered, and then continually prevents radon from entering the drywell by having constant flow out. The tube delivering the purge gas to a diffuser in the drywell can be seen in Figures 4.4 and 4.5. This low radon air is also supplied to the cleanroom reducing the exposure of the detectors to Rn during payload changes. Once the SuperCDMS radon filtration plant is operational, the air from that plant will replace the current supply to the cleanroom lowering the radon concentration from $5\text{-}10\text{ Bq/m}^3$ to below 1 Bq/m^3 [51].

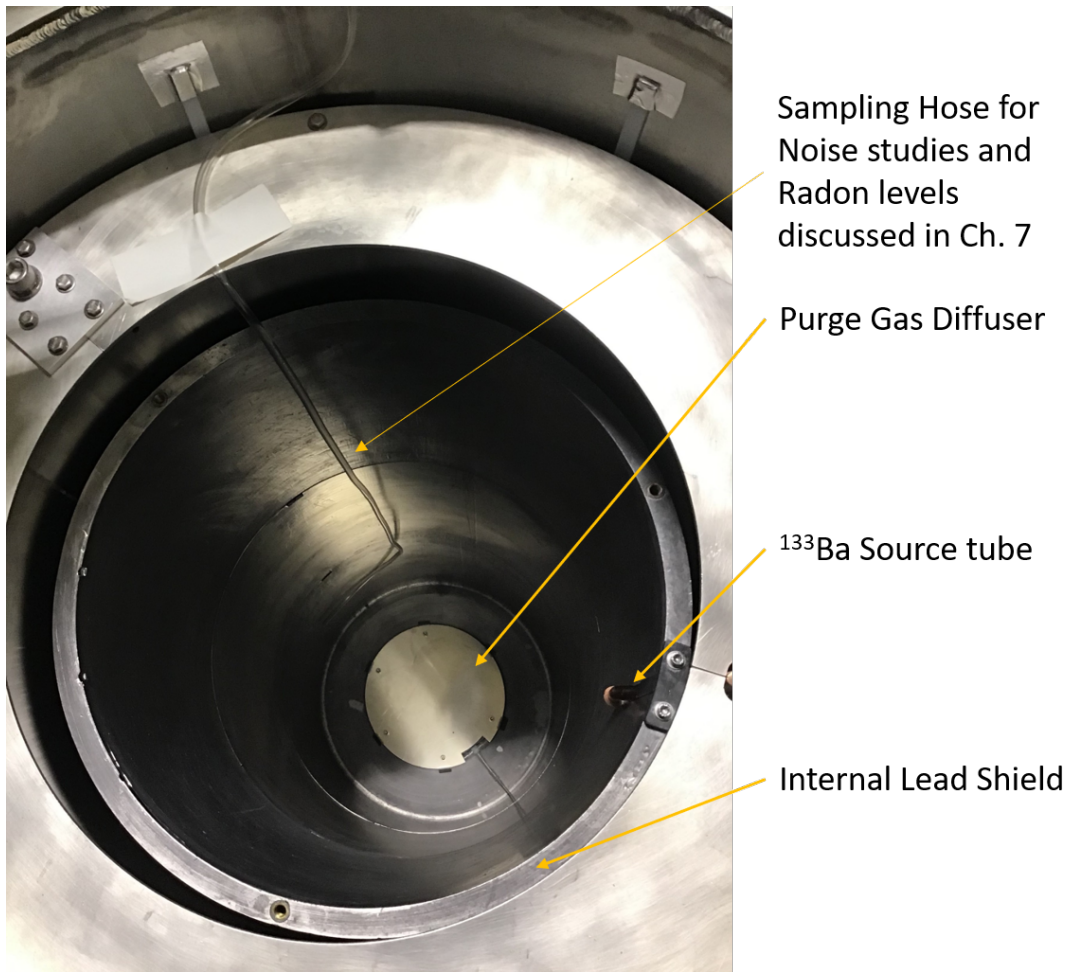


Figure 4.4: Lower part of the CUTE drywell showing the region in the lead shielding where the cryostat occupies. At the bottom of the drywell is the purge gas diffuser which distributes the low radon air.

Suspension System

Due to the high susceptibility of the detectors to vibrations and electromagnetic interference, the upper part of the refrigerator which contains the turbo pump, pulse tube, and electronic systems was designed to be vibrationally isolated from the lower part of the fridge. The vibrational decoupling inside the fridge is maintained by soft bellows, and the thermal contact between the pulse tube and the lower part of the fridge is achieved by circulating mixture so that no rigid connection links the upper 4K and 60K stages (directly connected to the pulse tube) to the lower 4K and 60K stages (which are rigidly connected to the copper cans). Since this lower section is held under vacuum, there is a net force due to the external lab pressure on the lower fridge in the upwards direction. This net force is compensated by adding masses to the lower section of the fridge, however

this force changes as lab pressure changes since it is proportional to the difference between lab pressure and vacuum.

To compensate for this changing force, this lower part of the cryostat sits on a suspension frame with actively controlled dampers in the drywell shown in Figure 4.5 which can be compressed or extended as needed. The dampers are required so that the coupling of vibrations which naturally occur in the drywell or the deck structure are greatly reduced to the cryostat components which rigidly hold the detectors. Using optical sensors the three mounting points of the suspension system can have their location measured with high precision (± 0.01 mm) and can then be lifted or lowered (± 1.00 mm) to ensure there is no tilt in the fridge. Since the mixture passes past the cold head with interlocking heatsinking fins, ensuring no tilt is highly important for the risk of the upper and lower fins touching, which could couple in vibrations from the pulse tube to the detectors. Changing the gap size between the upper and lower part of the fridge changes the cooling performance of the fridge since it can either inhibit or promote efficient mixture flow, and heat transfer. During the cooldown the suspension frame is lowered completely, and during detector operations the suspension system control unit maintains the suspension to sit at a set height with a tolerance of ± 0.05 mm to ensure consistent fridge performance.

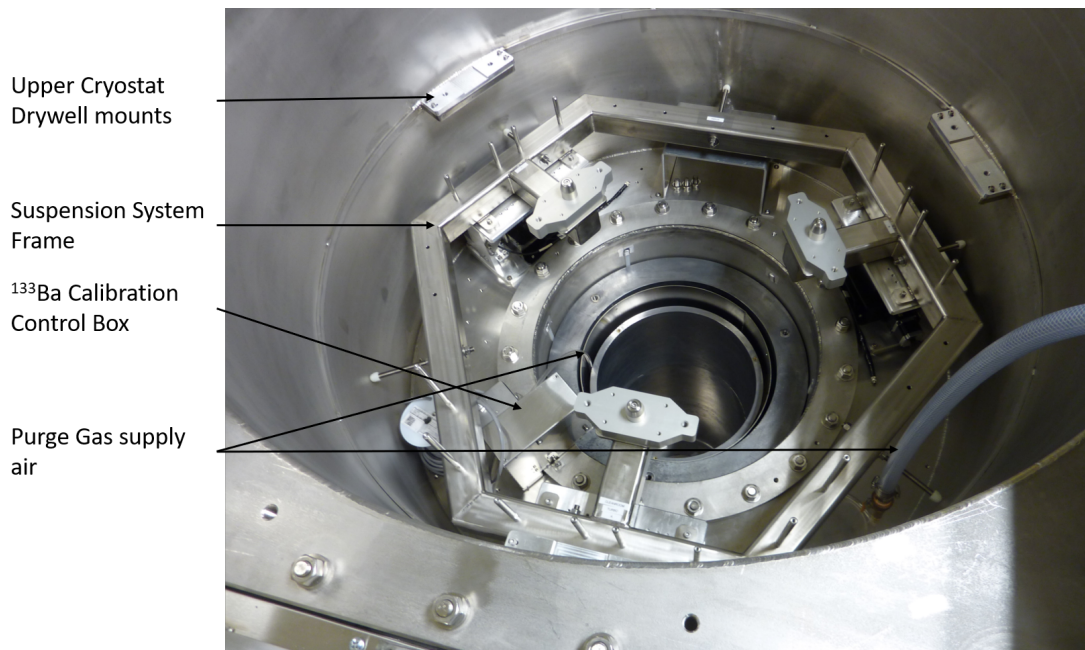


Figure 4.5: CUTE drywell with the suspension system upon which the lower fridge sits, the drywell ears to support the upper part of the cryostat, the Ba calibration system, the 2 layers of lead shielding and the μ metal, and the purge gas supply hoses.

Calibration System

CUTE contains a radioactive ^{133}Ba source which can be used for γ calibrations with the most prominent peak in the emission spectrum at 356 keV. This source is attached to a beaded chain which is wound around a sprocket attached to a stepper motor which can deploy the source from its storage location in a lead shielding block down into the drywell so that the source hangs adjacent to the detectors outside the cryostat, but within the lead shielding. Since this system is set up to be controlled from a stepper motor and lives permanently within the CUTE facility, CUTE has the flexibility to perform remote calibrations without requiring any lab personnel to be present at SNOLAB. Figure 4.6 shows how the calibration system was implemented in the CUTE facility, and the constructed subsystem can be seen in Figures 4.4 and 4.5.

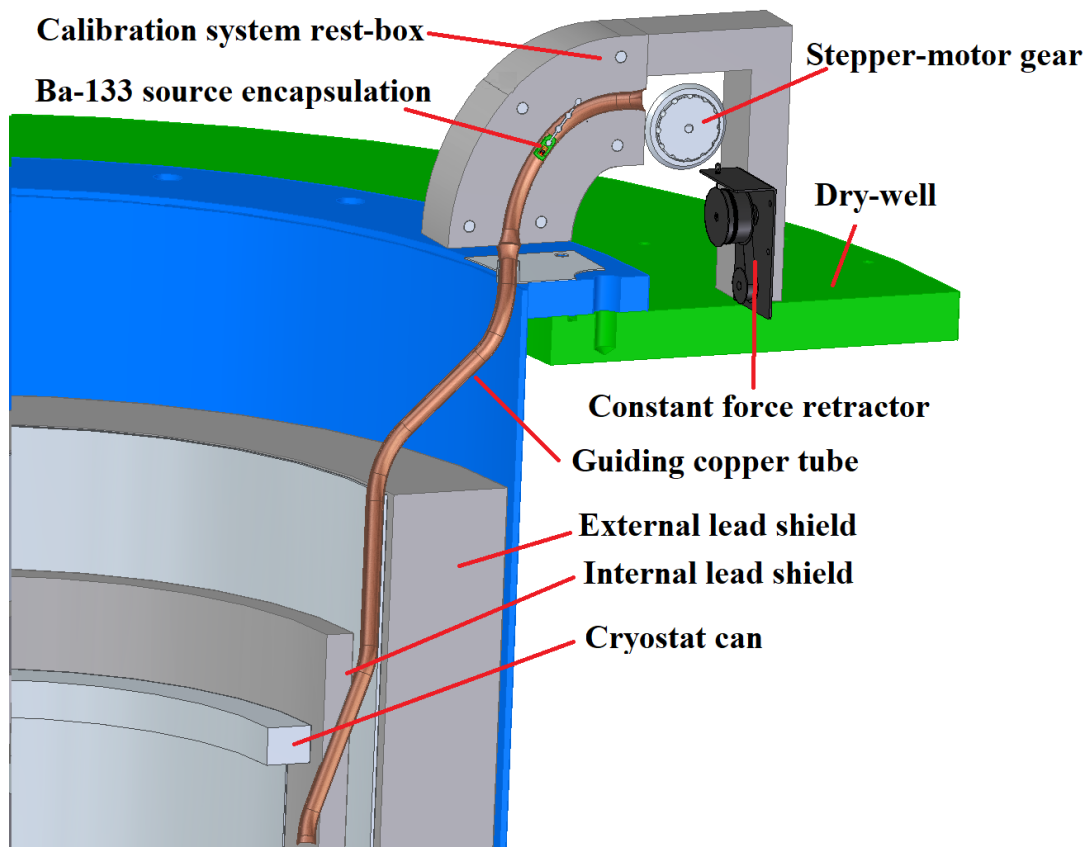


Figure 4.6: CAD rendering of the ^{133}Ba Calibration System. A control box containing a remote controllable stepper motor allows for deployment of the source from a shielded lead rest-box through shielding layers to an area adjacent to detectors for calibrations. Image source [63].

Peltier Cooler

The mixture turbo pump is vital to the operation of the dilution refrigerator because it removes the ^3He vapour which sits above the dilute mixture surface at the still as mentioned in Chapter 2. Since this pump is constantly on during operation it would naturally generate heat which needs to be removed. Our turbo pump is cooled with a thermo-electric (Peltier) cooler. This setup is easy to monitor and control and is more convenient than fluid-based cooling systems when the cryostat has to be moved to the cleanroom (and hence disconnected) for payload changes.

LN_2 Dewar and Cold Trap

Any contaminant in the helium mixture will freeze out inside the fridge in the circulation loop and hence bares the danger that it may block the thin lines. The mixture is routed through a liquid nitrogen cold trap to trap contaminants before the gas enters the fridge. The design of the cold trap bulb is such that the entering fluid must pass through the bottom of the bulb in order to exit via the hose leading to the fridge. The temperature of the charcoal bulb in the dewar is sufficiently low to precipitate out any gas contaminants which may have leaked into the lines before the mixture reaches the fridge [64]. By having all the mixture flow through the cold trap, the likelihood of unwanted contaminants going into the fridge is greatly reduced.



Figure 4.7: (Left) Schematic of a typical cold trap setup using cocentric tubes for the in/out flow with the transfer between the tubes occurring at the bottom bulb with activated charcoal which is submerged in Liquid Nitrogen, precipitating any contaminant in the gas into the charcoal. (Right) The Cold Trap used in CUTE resting on a side table for cleaning between runs.

Gas Handling System

The Gas Handling System (GHS) is the unit responsible for the automated control of the dilution refrigerator. It contains multiple pressure sensors, valves, scroll pumps, the mixture compressor, and a tank to store the helium mixture when it is not actively being used to cool the fridge. The many valves and tubing routes are needed for the different requirements during cooling down and operation, and to ensure the safety of the helium mixture.

Dilution Refrigerator

The Dilution Refrigerator consists of two main parts connected by soft bellows. The upper part has a pump, valves, and the pulse tube and is affixed to the drywell on stand-off ears shown in Figure 4.5. The lower part sits on the suspension frame isolating it from the upper part and the drywell and includes the experimental stage which holds the detectors and cold section of the readout electronics. The lower part also contains the dilution unit which provides the cooling to the colder stages of the cryostat. In CUTE there are 4 temperature stages which are completely enclosed in copper cans in the lower part

of the cryostat which are named for either their functionality, or the typical operating temperature: OVC (Outer Vacuum Can), 60K, 4K, and Still stage as seen in Figure 4.8. Colder than the still stage, there are also the cold plate and mixing chamber stages, but neither of these have a proper dedicated can; however, the experimental tower containing the detectors is enclosed by a custom built copper can nicknamed the “tophat”.

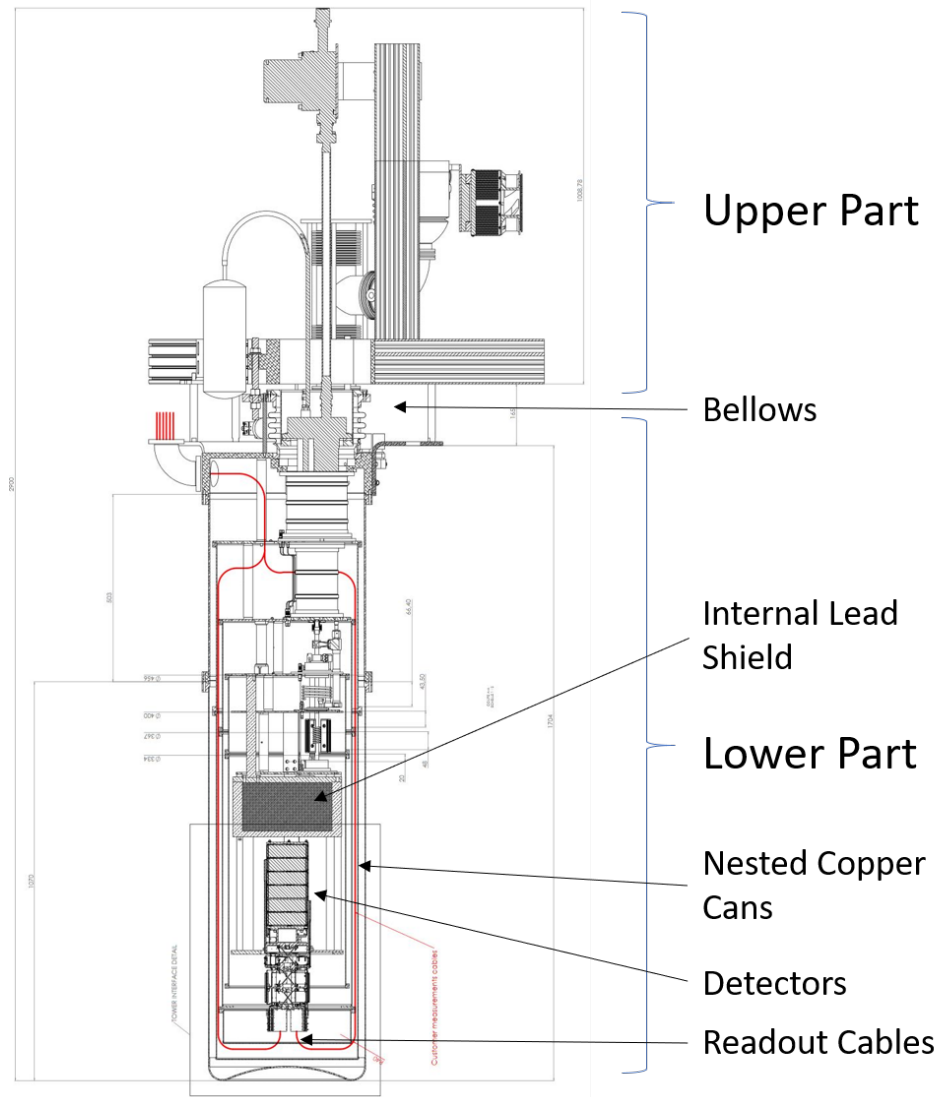


Figure 4.8: Engineering drawing of the CUTE cryostat highlighting the separation of upper and lower parts for vibration isolation of the part with the detectors from the upper part of the fridge. Lower part contains a series of nested thermal stages separated by copper cans, the red line shows the path of the detector readout cable from the 4K stage of the tower to room temperature.

Data Acquisition System and Software Management

When CUTE's time serving as a test facility for SuperCDMS is complete, and CUTE opens itself up to other collaborations to run low background cryogenic experiments, the data acquisition may change. In the meantime, CUTE is serving as a Data Challenge site for the full SuperCDMS data acquisition system. CUTE utilizes the prototypes of all the electronics readout systems and controls which will be produced for the large scale SuperCDMS experiment. Continuing the path of a detector signal from Chapter 3 from the cold electronics to the warm electronics, the SQUID signal is communicated via the Vacuum Interface Board (VIB) out of the cryostat to the Detector Control and Readout Card (DCRC) which then communicates via ethernet cable to a switch in the data acquisition rack. The Data Acquisition Personal Computer's (DAQ PC) job is to manage the run control, management of affiliated programs related to detector operation such as event triggering, random triggering, and LED control, and communicate with the DCRCs which execute the commands to operate the cold electronics. The DAQ PC also stores all of the meta data associated with each run and calibration (such as electronics parameters) for future reference. Once the DCRC has determined that an event has occurred by surpassing the trigger threshold, the raw event data is saved by the DAQ PC. After a pre-determined number of events occur, the DAQ PC bundles them together into a "dump" and sends the dump to the Data Quality Monitoring PC(DQM). Here, live time plots are created by performing preliminary analyses summarizing the main performance indicators coming from the detectors, so that offsite users can determine whether the quality of the data coming out of CUTE is sufficient, and if it is not corrective action can be taken.

After dumps are saved to the DQM, they are pushed to servers offsite for secondary storage. From these offsite servers, the data can then be processed using a variety of functions previously determined by the SuperCDMS collaboration to give useful parameters. The original and processed data are then available to be analyzed by individual users for specific analysis tasks by connecting to these offsite servers. The advantage of this analysis set up is the data and analysis remains in the offsite servers, so handling the

transmission of large volumes of data only needs to be considered between SNOLAB and the servers, rather than to each user as well. Figure 4.9 summarizes the flow of data and computing systems at CUTE.

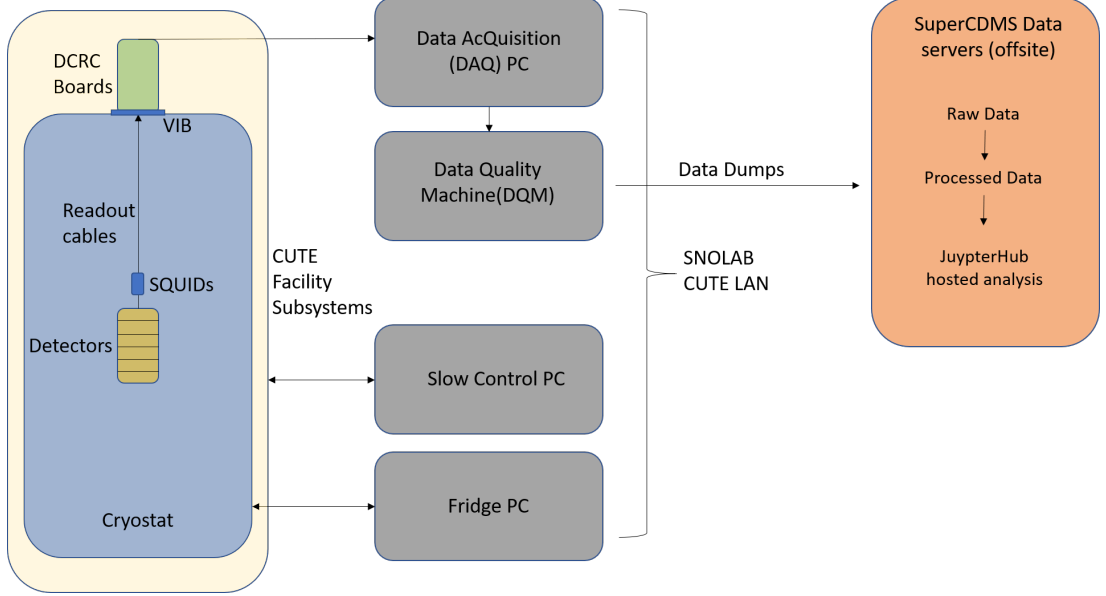


Figure 4.9: Schematic showing the communication and flow of data within the CUTE facility. Arrows represent the primary flow of data. Detectors are set up and read out by the DCRCs which communicate to the DAQ PC. The DQM monitors the incoming flow of data indicating the quality in real time and manages the data pushing to offsite servers. The offsite servers allow for the processing of data to extract a variety of parameters, store data, and host analyses of the data.

Two other computers are present at CUTE: the communication to the GHS and subsystems relating to the operation of the dilution refrigerator is handled by the Fridge PC, and the monitoring and control of the other facility subsystems like the suspension system, and calibration systems are managed by the MiniMac Slow Control PC. A third computer, the Noise Thermometer Laptop is currently present, but only as a temporary measure to monitor a few systems such as the Noise Thermometer, and the Peltier cooler which came with Windows OS software, but these systems will eventually be migrated to the MiniMac Slow Control PC.

4.2 Conclusion

CUTE has been operating for 18 months to date, with a brief delay due to COVID interruptions. The success of the facility is largely driven by the foresight of the sources

of noise that would be introduced in an underground environment. Work continues to improve the performance of the facility to further the quality of the data extracted from the detectors. At the conclusion of the testing of SuperCDMS detectors CUTE will be made available as a low background cryogenic facility for any research group worldwide on a proposal basis.

Part II

Work at CUTE

Chapter 5

Cryogenic Operation

The principle role of the CUTE facility is to allow for rapid payload changes of detectors, predictable and consistent cryogenic cooldowns, and to provide a stable, low-background environment for the detectors. By analysing the performance of the CUTE fridge over numerous cooldowns at SNOLAB I saw an opportunity for the fridge performance to be improved by modifying some of the operational parameters.

The pre-cool phase occurs as the experiment cools from room temperature to temperatures around 3 K at which point the other cooling methods discussed in chapter 2 take over to bring the refrigerator to base temperature. Mixture gas is circulated at varying pressures during the pre-cool in the mixture lines to act as a heat exchange gas between the stage with active cooling (4K and 60K) to all other stages. A higher mixture pressure allows for better heat transfer, but also acts as a greater load on the pulse tube cooled stages. Early on in the pre-cool this circulated mixture pressure can be quite high since the temperature difference between the 4K stage and the others is extreme (>100 K). As the temperature difference between the 4K stage and the lower stages is reduced, the fridge should reduce the mixture pressure to reduce the load on the 4K stage allowing it to reach lower temperatures. A compromise is required between obtaining the most effective heat transfer by having high circulating pressure, and allowing the cryostat to get colder by having a low circulation pressure.

The result of attempting to maintain this compromise is that the pre-cool will undergo multiple steps where the circulation pressure is adjusted. The automated control is simple; in up to ten stages, the circulation pressure is adjusted to a predefined value (with a defined

tolerance) set by the user when the mixing chamber (MC) reaches certain temperatures. It then ensures the circulation pressure is within a set tolerance of the target pressure for each pre-cool stage by either opening pneumatic valves to allow more mixture from the tank into circulation, or pumping mixture back into the tank if the pressure needs to be reduced.

To understand how effective the present pre-cool settings were, an analysis was executed using the historical cooldown data from previous runs at SNOLAB, with a simple running averaged numerical derivative of the MC temperature applied. Figure 5.1 shows the cooling of the MC (blue) as well as the control parameter which is the pressure in the circulation line (purple), the temperature of the 4K stage which has the active cooling from the pulse tube (red), and the MC temperature derivative (orange).

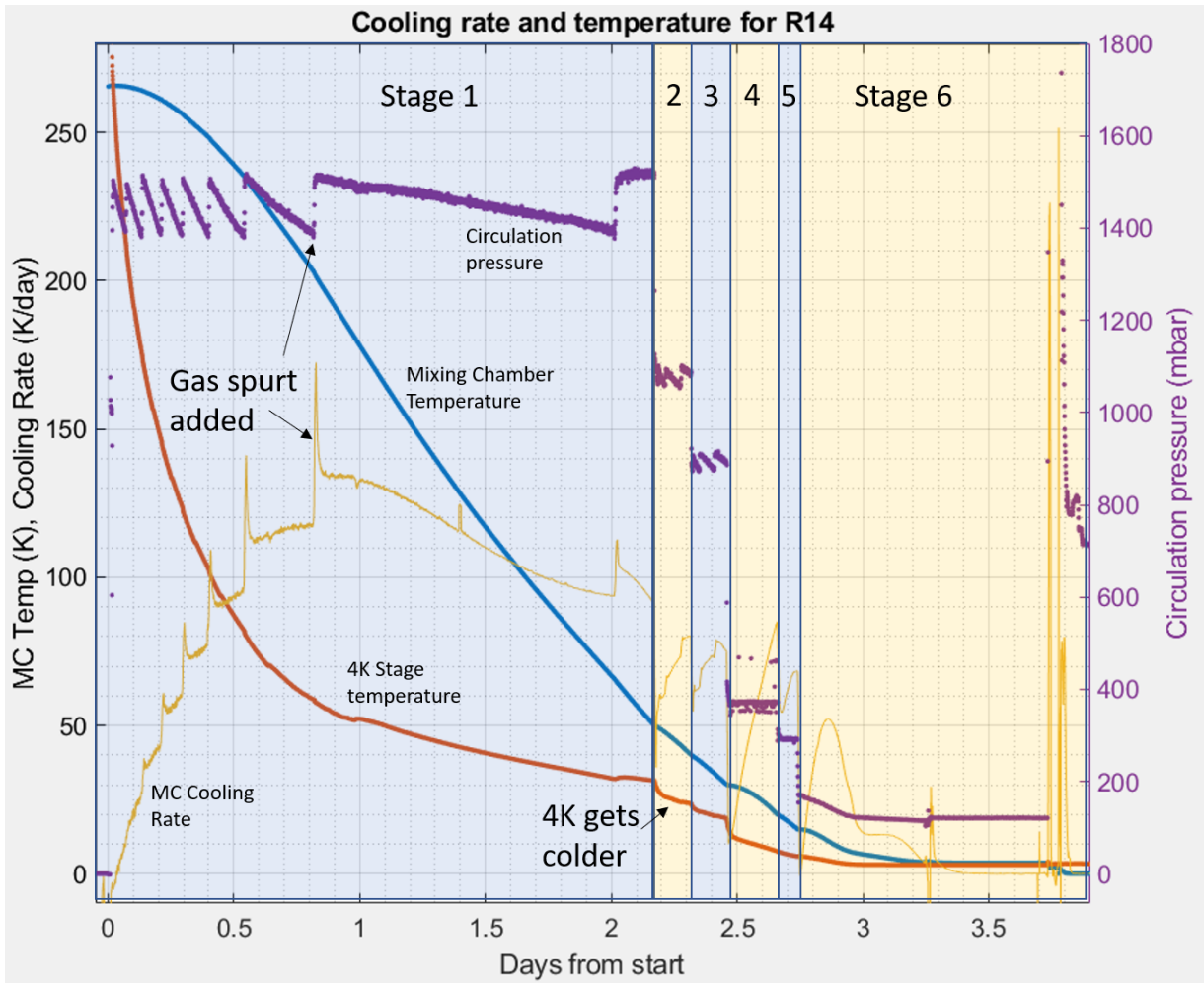


Figure 5.1: Cooling curves of CUTE Run14 utilizing factory-set cooldown parameters. MC temperature (blue line), 4K temperature (red line), cooling rate of MC (orange line), and circulation pressure (purple line). Shown are the different automated stages where circulation pressure is adjusted based on MC temperature (alternating blue/orange hues).

The corresponding stage transition temperatures, pressures, and pressure tolerance for automated pre-cool seen in Figure 5.1 are summarized in Table 5.1.

Table 5.1: Original pre-cool cooling parameters used in CUTE up to Run 18. Automation holds the circulating mixture pressure at the given pressure within the tolerance range until the MC reaches the end temperature indicated. This is a 6-stage cooldown since the final five stages have the same parameters.

Stage #	1	2	3	4	5	6	7	8	9	10
Pressure (mbar)	1500	1200	900	400	300	150	150	150	150	150
Tolerance (mbar)	120	50	30	30	10	50	50	50	50	50
Temp End (K)	50	40	30	20	15	3.7	3.7	3.7	3.7	3.7

To first order, the cooldown works as expected, with no apparent significant delays in the cooling of the MC, but looking at the derivative there are a few areas where improvement appears possible. The integral of the dT/dt curve represents the total change in temperature of the MC from room temperature to base temperature. The goal is to maximize the height of this derivative curve so that the time required to reach base temperature is minimized. In the first day of operation as the 4K stage cools down the rate of cooling of all other stages increases gradually as the thermal gradient increases. What we notice is that whenever the pressure of the circulation loops falls below its tolerance level (due to the average temperature of the gas going down in a fixed volume, resulting in a drop in pressure) it must give a small spurt of gas from the He dump tank. When this extra amount of gas is added the cooling rate goes up, with a sudden spike temporarily, but then the longer term behaviour of the cooling rate also displays signs of a higher cooling rate. We are limited to a maximum pressure of 1580 mbar circulating in the loop as is hard-coded into the software by the manufacturers, but another parameter we are able to control is the pressure tolerance level. Reducing the tolerance in the first stage of cooldown from ± 120 mbar to ± 30 mbar this removes periods of time where the circulating pressure is below 1470 mbar increasing the average cooling rate.

In the later stages of cooldown, the circulating pressure must be reduced in order to allow the 4K stage to get significantly colder. If this change does not occur, the cooling

power available to be transmitted to the experiment stage is significantly reduced. The control temperature of the MC at which these transitions occur can be adjusted, and so too can the set pressures that the system changes the circulating pressure to. Looking at the derivative curves, there is a sharp drop in cooling rate, followed by a period of recovery where the cooling rate is less than the anticipated cooling rate it would have had the transition not occurred. By reducing the set temperature at which the change in pressure occurs, the MC will follow the previous stage's cooling curve for longer which maximizes $|dT/dt|$.

Table 5.2: Proposed cooling parameters used for Run 19 CUTE cooldown.

Stage #	1	2	3	4	5	6	7	8	9	10
Pressure (mbar)	1500	1200	1000	600	400	300	160	150	150	150
Tolerance (mbar)	30	15	30	30	10	10	10	10	10	10
Temp End (K)	46	40	28	22	17	13	3.7	3.7	3.7	3.7

In Run 19 (R19) these two strategies of reducing the tolerance, and extending the periods of higher circulation pressure were employed to test how it affects the overall cooldown. Table 5.2 summarizes how the changes would be implemented. To investigate how effective the changes implemented for R19 were, the cooldown was compared to two other recent cooldowns using the old pre-cool parameters: R14, and R16. Unfortunately there were two delays over the course of the cooldown of R19. The first delay was encountered when the liquid nitrogen (LN) in the cold trap dewar ran low and could not be refilled for about 14 hours; to conserve the remaining LN, the circulation pressure was greatly reduced, in turn reducing the effective cooling power. The second delay was caused by a 2-hour power outage followed by a 2-hour communication blackout during which the fridge was able to warm up slightly. Run16 also experienced a worry of lack of liquid nitrogen, so its cooldown was also paused midway until the liquid nitrogen could be refilled, however rather than leaving the cryocompressor running with a small volume of gas circulating, everything was turned off.

A known issue at CUTE is a slow leak in the helium lines of the cryocompressor, indicating performance would deteriorate over time. In summer 2019 when CUTE was commissioned at SNOLAB the cryocompressor was filled to a pressure of 220 psi, after which point the pressure slowly reduced until February 2020 when it was measured to be 180 psi. The first cryogenic run in summer 2019 was Run 8 which was the fastest cooldown reaching the temperature at which point the helium tank empties after 3 days, 5 hours, 54 minutes. The cryogenic run in Feb 2020, R13, with a lower cryocompressor pressure took 3 days, 19 hours, 55 minutes to reach the same temperature, so cryocompressor pressure is a clear factor in cooldown performance. In all three runs R14, R16, and R19, the cryocompressor was refilled immediately before the run commenced to a pressure of 220-230 psi, so any significant improvements in R19 can be accredited to the pre-cool parameter changes, rather than a change in cryocompressor performance. There may be a long term deterioration of cryocompressor performance, because even though the pre-cool parameters were the same for runs 8-18, and in R14 and R16 the cryocompressor was refilled to the same level as R8, R14 and R16 cooled more slowly than R8.

For this reason, selecting more recent runs to compare R19 against and removing the deadtime of R19 and R16 gives a better picture of the effect the control changes had shown in Figure 5.2. R19 has a cooling advantage over R16 since the Pulse Tube was running during the first and second half of the second interruption, removing heat from the 60K and 4K stages and thus preparing for a more effective cooling when the circulation pressure was restored. This can be seen by the steep slope of MC temperature immediately following interruptions. In cases where the MC temperature was greater after the interruption, the resumption of the plot continues where the temperatures were equal. In the case when the MC cooled slightly during the interruption, a time gap was imposed equivalent to the time the MC would have required to make up the temperature difference had it continued cooling at the previous cooling rate before the interruption (e.g. between stage 1 and 2 of the R19 cooldown). R14 also incurred a delay due to a stalled MC temperature which will be discussed later in this chapter which slowed its cooldown by about 12 hours. After compensating for the cooling interruptions and delays, R19 reached

the ‘start of condensation’ step 12 and 14 hours faster than R14 and R16 respectively.

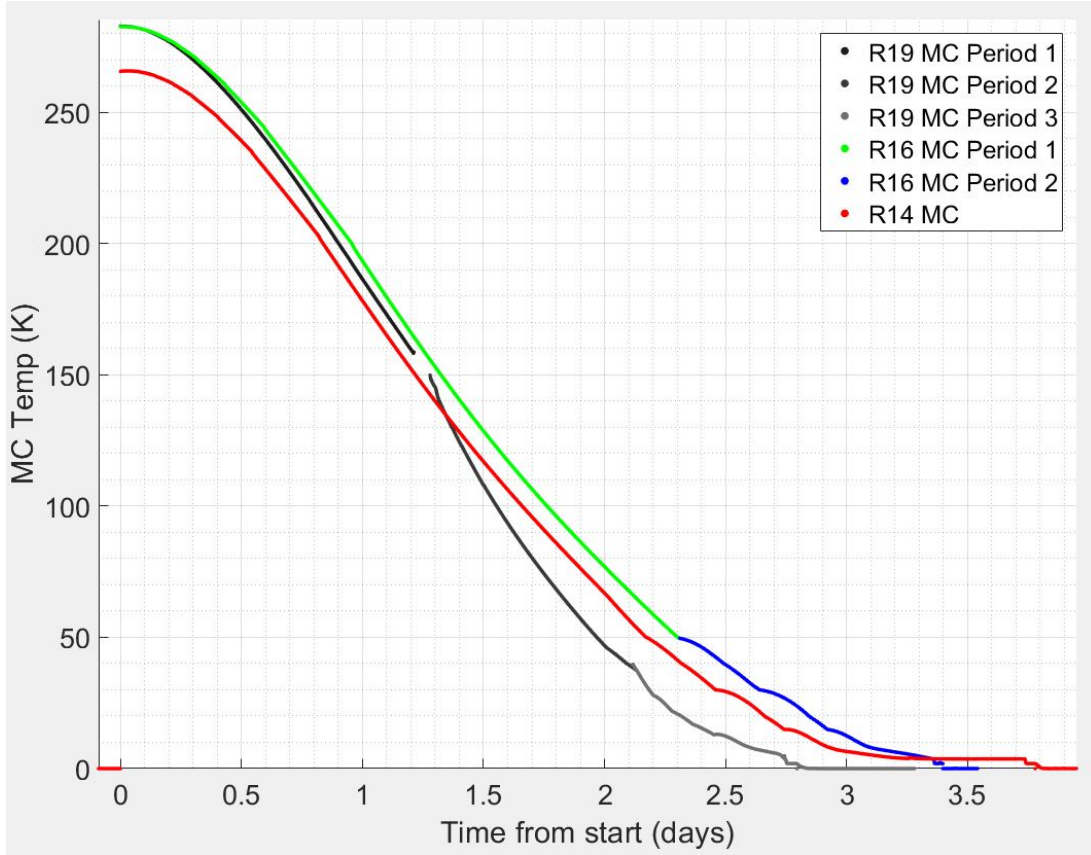


Figure 5.2: Cooling curve of Runs 14 (red), 16 (green and blue), and 19 (3 shades of gray) with periods of dead time removed. During R19, the cryocompressor continued to run when regular operation ceased allowing for an accelerated cooling rate immediately following the interruptions.

From the beginning of cooldown to the point when regular operation needed to be paused, the cooling rate of the MC was better in R19 with the adjustment than in previous runs. The effect of reducing the tolerance achieved the intended effect of making the average cooling rate higher up to the maximum cooling rate which occurs about 1 day into the cooldown of 140 K/day seen in Figure 5.3. At the point of stopping the regular operation the MC in R19 was 8.4 K colder than R16 after the same elapsed time, phrased another way, it reached 158 K 70 minutes before R16 reached that temperature. Run 14 began its cooldown at a lower temperature since that run began after R13 failed due to a blockage in the cryogenic lines demanding a warm up to the melting point of water to evaporate the blockage rather than beginning a run after a payload change. Comparing the change in temperature from where the two runs began to the temperature they were

at after the same elapsed time, R19 had cooled down 9.8 K more than R14 did in the same period of time.

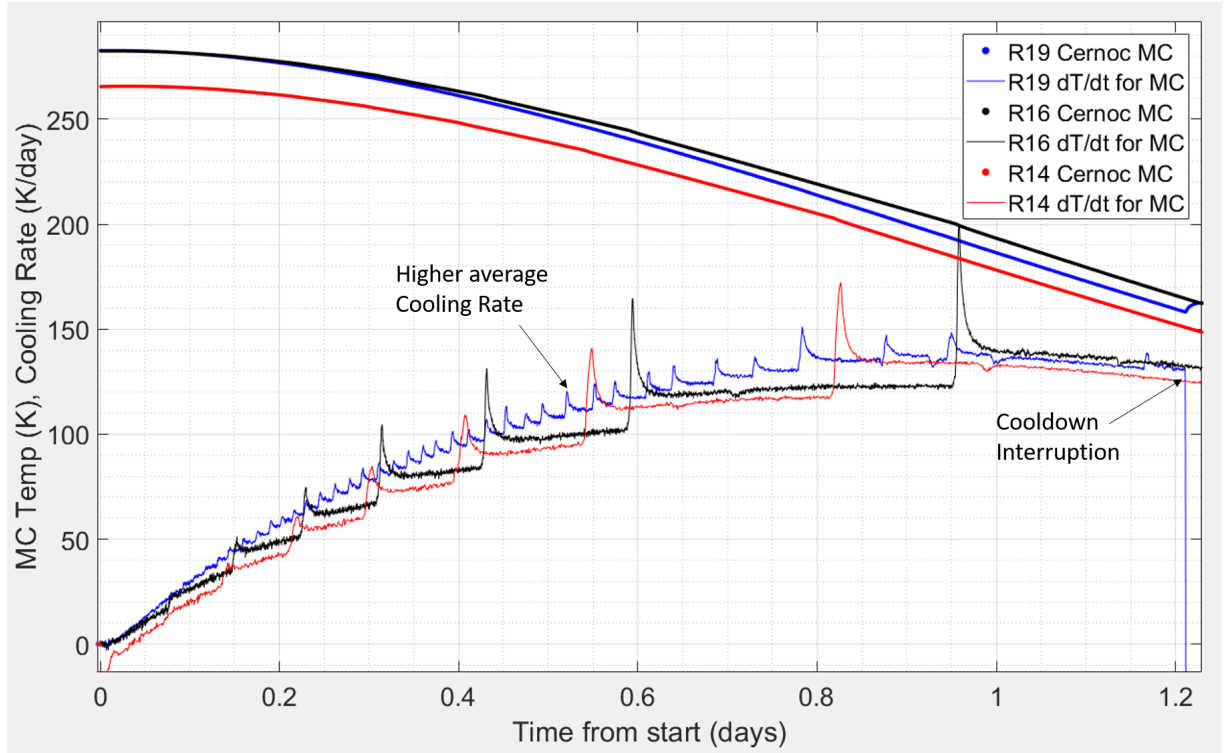


Figure 5.3: Cooling curve and cooling rate of Runs 14 (red), 16 (black), and 19 (blue) at beginning of run. Thick lines show the MC temperature, thin lines show the cooling rate. Due to the lower tolerance on circulation pressure the average cooling rate of R19 was higher in the early stages of cooling. R19 cooldown was interrupted 1.2 days in due to lack of Liquid Nitrogen to supply the cold trap.

In the time immediately following the cooldown pause once reliable liquid nitrogen supply was guaranteed, the MC cooled at an accelerated rate in R19 due to the fact that the other stages including the 60K and 4K stages were able to cool down significantly during the pause. By the end of the first stage, which originally occurred when the MC reaches 50 K, the rate of cooling in R19 was still slightly inflated compared to previous runs (immediate cooling rate was 100 K/day vs. 90 K/day for R14) due to the pause. To make the comparison between runs easier to view, the times of runs were aligned when each run reaches the same temperature. After the circulation pressure drops, the 4K stage is able to get colder, but there is a delay before the increase in cooling power to the MC stage because the immediate effect of reduced thermal conductance takes precedent until the thermal gradient is increased. This is why in both R14 and R19 there is a “step down” in cooling rate when the pressure is reduced. What is clearly displayed in Figure 5.4 is the

advantage of prolonging the time of high pressure circulation. By having the transition occur at 46 K rather than 50 K, the MC cooled an extra hour at a rate of 95 K/day rather than 60 K/day. This translated to an extra drop in temperature of 2 K in the same period of time, or conversely a time savings of 1:30. The cooldown interruption in R16 occurred just before the MC reached 50 K, so the cooling gradient was recovering during this period of time, so it does not contribute to the comparison at this stage of the cooldown, so it was omitted from Figure 5.4.

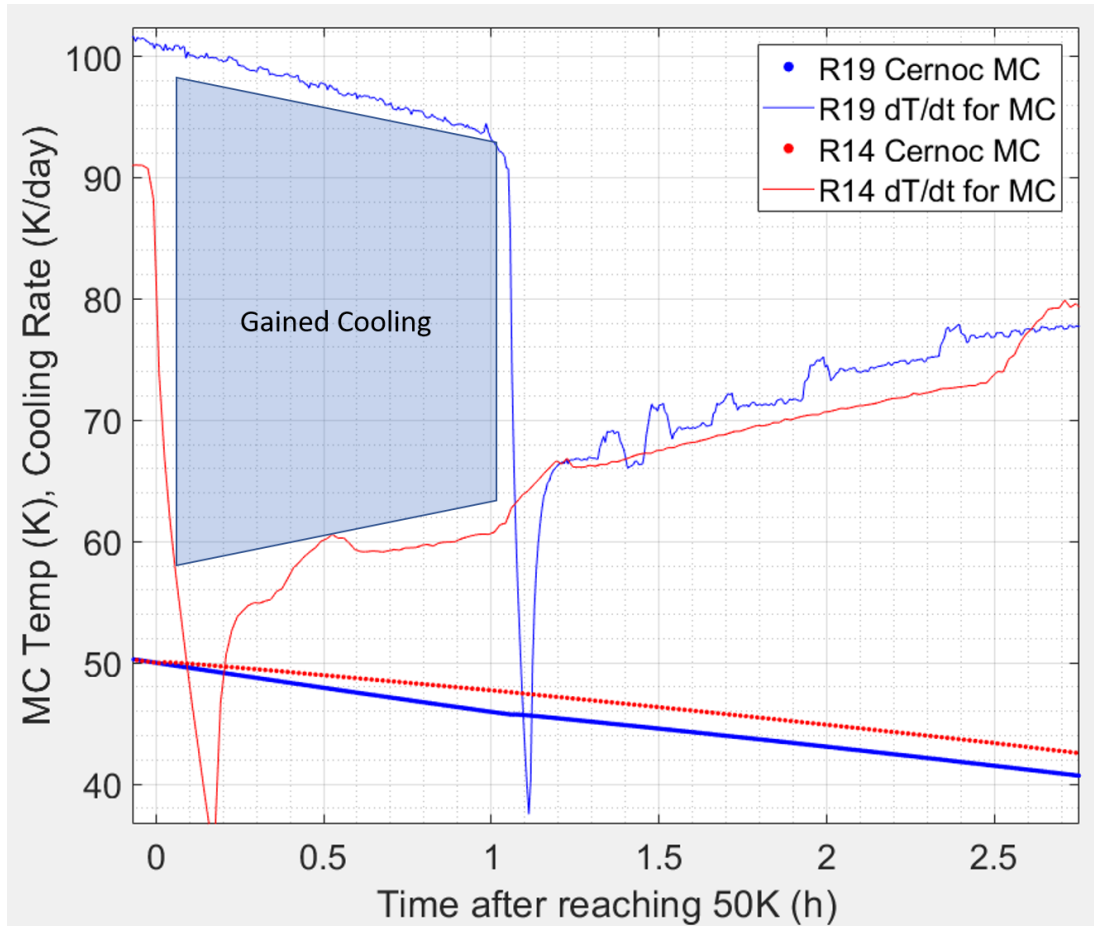


Figure 5.4: Cooling curve and cooling rate of Runs 14, and 19 with the time when each run reached 50 K aligned. Since R19 extended stage 1 to a lower temperature, it maintained a higher cooling rate for longer before reducing pressure. The gained cooling can be seen visually as the trapezoid representing the difference in the integral of R14 vs. R19 cooling rates. R14 appears as a dotted line due to the difference in sampling time of temperature measurements.

As the MC approaches the temperature of the 4K stage, the circulation pressure continues to need to be reduced in order for the 4K stage to get even colder until the point at which mixture can condense. For R19 I thought that rather than having a large drop in pressure, a more gradual “step down” with more transitions might be better. An extra

stage was added before the final stage beginning at 15 K (30K→20K→15K turned into 28K→22K→17K→13K). This modification ensured a greater amount of time at higher pressure, however it came at the cost of having an extra “step-down”. Figure 5.5 shows that this thought may not have been a good idea. For R20 the extra stage added was removed, but the pattern of riding each stage of higher pressure to a lower temperature was extended since in R19 by looking at the cooling rate curve, the period of high cooling rate from higher pressure was truncated too early. Both pressure reductions in Figure 5.5 have the MC cooling at a lower rate after the pressure reduction compared to what it was prior. Looking at the cooling rate soon after 28 K, in R19 the pressure was set to 600 mbar as opposed to 400 mbar which was a beneficial modification because the cooling rate climbed higher (to a peak of 100 K/day) and more quickly than the previous runs at the same temperature range.

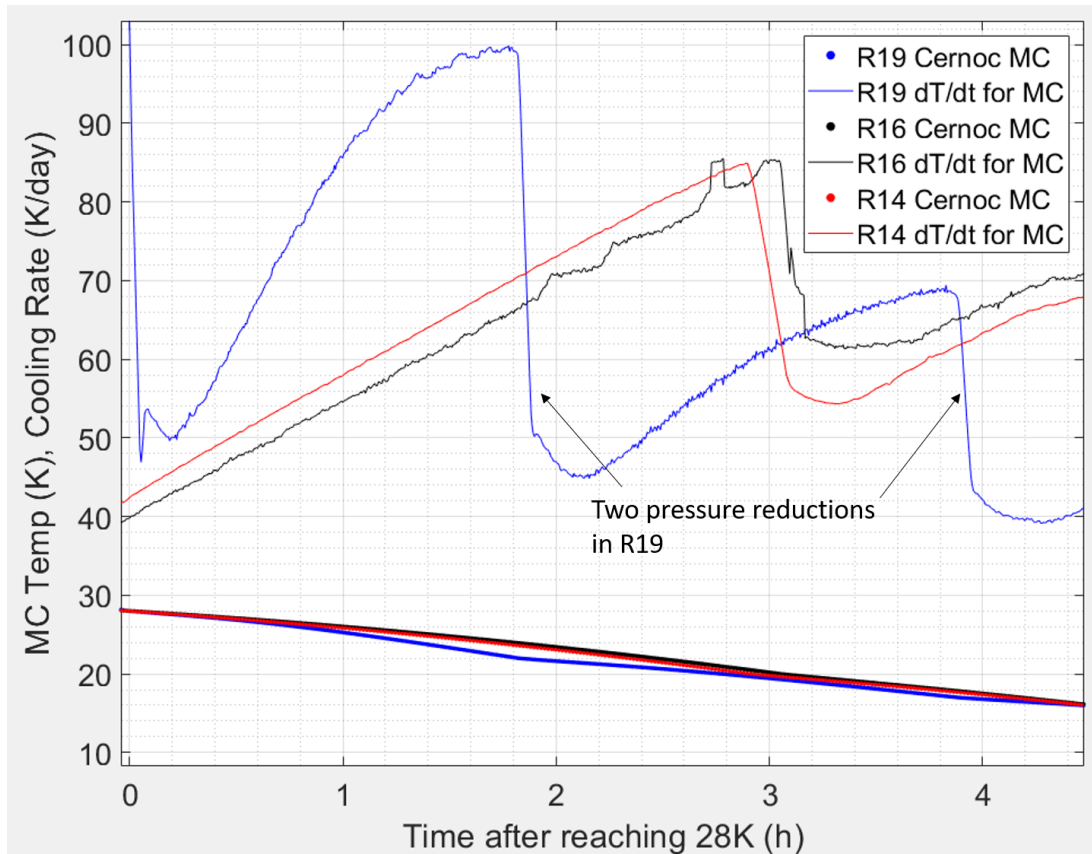


Figure 5.5: Cooling curve and cooling rate of Runs 14, 16, and 19 with the time when each run reached 28K aligned. R19 included an extra circulation pressure reduction requiring recovery time which negated the benefits from having a higher average circulation pressure.

The beginning of the final stage was initiated at different temperatures between runs

14 and 16, and run 19. In the former two runs this stage began when the MC passed 15 K, while in the latter it began at 13 K. While the MC benefited from the prolonged the higher rate of cooling in R19, the “step down” seen in the pressure transitions of Figure 5.5 also occurred at this final transition which negated the temperature gains by prolonging this stage. This adjustment did not make a significant impact in the overall cooling time.

When the MC reached a temperature slightly below 7 K in R19, a brief manual test was conducted by increasing the mixture pressure from 150 mbar to 160 mbar, leaving it for a period of time, then reducing the pressure to 140 mbar. At this point in the cooldown, the 4K stage had reached a temperature below the condensation point of Helium. What we believe is happening is the mixture is condensing on the 4K stage, continuing through the circulation loop as a liquid until it reaches a warmer stage, then drawing heat from the warmer stage to evaporate. While monitoring the 4K stage temperature, the mixture circulation pressure was increased gradually, giving a higher rate of liquid helium reaching the warm stages, increasing the cooling power. The pressure was increased until the 4K stage was unable to provide enough cooling power to manage the rate of condensation required by the circulating helium gas (which occurred when pressure was > 750 mbar). By finding the maximum circulation pressure at which the cooling power provided by the pulse tube would be completely used to condense the circulating helium, the time for the MC to cool from 7 K to < 4.2 K can be greatly reduced. As seen in Figure 5.6 once the test began and the circulation pressure was increased from 150, via 160, 200, 250, 275, 400, 500 to 750 mbar, the cooling rate became dramatically greater than previous cooldowns. After aligning the 7 K times, Run 19 reached the point in the cooldown where the full helium tank is emptied to be condensed in the fridge 2.5 hours ahead of Run16. One of the previous issues with the cooldowns at this stage was the high tolerance of the circulation pressure. In R14, the MC stalled at 3.6 K for over 12 hours, the reason at the time was thought to be a reduction in cooling power provided by the pulse tube due to leaking helium. Upon further inspection, the 4K stage temperature was at 2.9 K, and the mixture pressure was at 104 mbar which is within the set bounds of 150 ± 50 mbar. What happened during this cooldown was the cooling power provided to the 4K stage was adequate, but

the thermal link (circulation mixture) was insufficient to remove the heat from the MC stage. This evidence shows that in the final stages of the pre-cool the mixture circulation pressure needs to find a balance; you must provide sufficient mixture to deliver the cooling power from the pulse tube to the MC (> 100 mbar), but you should not provide too much mixture such that the pulse tube is overwhelmed and cannot condense all the mixture provided (< 750 mbar).

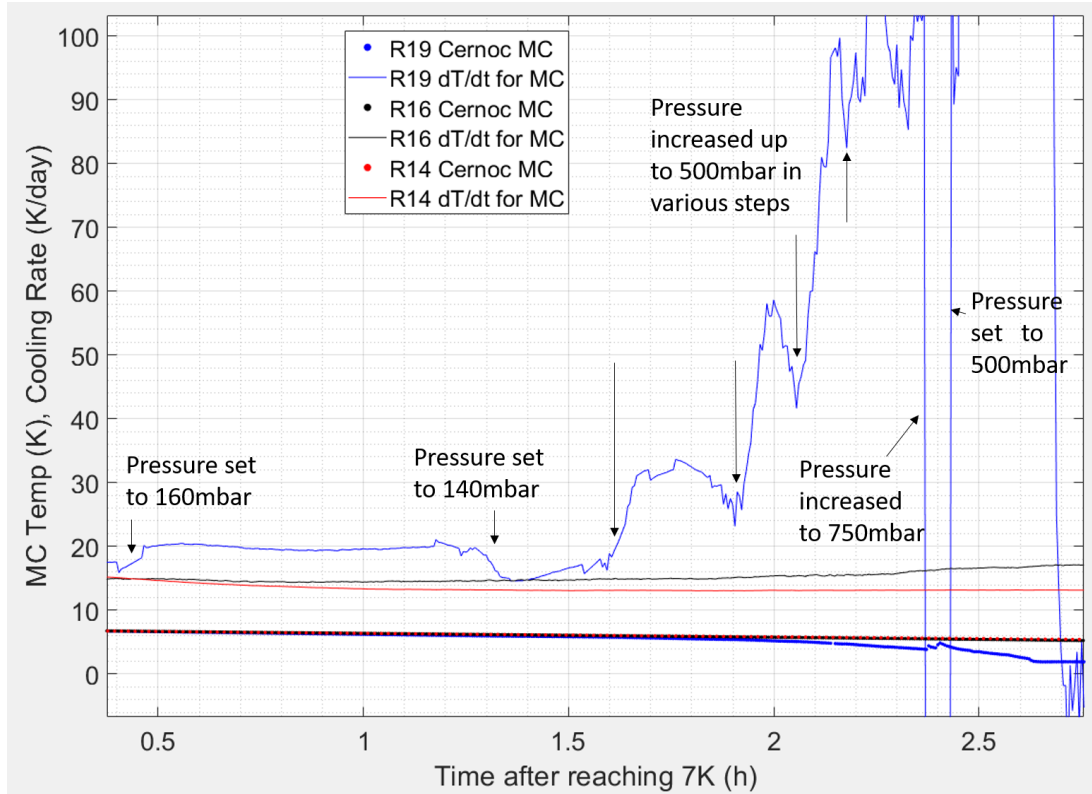


Figure 5.6: Cooling curve and cooling rate of Runs 14, 16, and 19 with the time when each run reached 7 K aligned. Tests adjusting the circulation pressure were conducted to show that increasing the amount of mixture increases the cooling rate once the 4K stage is sufficiently cold.

Run 19 acted as a proof of concept to test a few ideas of how to reduce the time needed to cool CUTE to base temperature and will be further improved upon in R20. Including 19 hours of delays which either fully ceased cooling, or forced R19 to cool at a reduced capacity, R19 reached the tank emptying temperature in 3 days, 11 hours, 17 minutes. R20 will continue the suggestion of extending periods of higher pressure circulation with lower tolerance, and will implement a planned late-cooldown increase in pressure to utilize the full cooling power of the pulse tube to condense circulating helium. The differences in cooling parameters are summarized in Tables 5.3 and 5.4.

Table 5.3: Actual cooling parameters used for Run 19 CUTE cooldown. Tolerances needed to be increased for the fifth and sixth stages during the run due to the control software having difficulties keeping the pressure within desired range.

Stage #	1	2	3	4	5	6	7	8	9	10
Pressure (mbar)	1500	1200	1000	600	400	300	160	150	150	150
Tolerance (mbar)	30	15	30	30	(10)25	(10)25	10	10	10	10
Temp End (K)	46	40	28	22	17	13	3.7	3.7	3.7	3.7

Table 5.4: Proposed cooling parameters used for Run 20 CUTE cooldown.

Stage #	1	2	3	4	5	6	7	8	9	10
Pressure (mbar)	1550	1200	1000	600	300	160	250	400	400	400
Tolerance (mbar)	25	15	30	30	25	15	25	50	50	50
Temp End (K)	44	40	26	18	11	6.5	5	3.7	3.7	3.7

5.1 New Findings from Run 20

Run 20 began on March 3, 2021 with the implemented modifications to the pre-cool parameters. Despite the cryocompressor not being refilled prior to the run, having a pressure of 200 psi in R20 compared to 225 psi in R19, R20 was the fastest cooldown to date reaching the temperature at which the helium tank empties in 3 days, 3 hours, 22 minutes. The greatest improvement over the changes made in R19 came from the first stage where the circulation pressure was increased to 1550 mbar. After one day, at which point R19 had its first interruption, R20 was ~50 minutes faster than R19, despite operating with a less efficient cryocompressor. R20 had a very brief interruption lasting about 15 minutes roughly 2 days into the cooldown, but the impact was not significant enough to influence the overall cooling performance.

During the intermediate stages of the pre-cool R20 cooled at about the same rate as R19, if not slightly worse due to the reduced pressure in the cryocompressor, however due to the interruptions in R19 discussed previously, it is difficult to compare. Nearing the end of the cooldown another manual adjustment was taken which proved to yield very

critical information. Since the 4K stage was already below 5 K, the circulation pressure was increased to promote more efficient heat transfer, cooling the MC stage faster. This occurred, but what was strange was that the MC passed the still temperature as seen in Figure 5.7. The path of the circulating mixture goes from the 4K stage with active cooling from the pulse tube, to the still, then the cold plate, *then* the MC stage, so you would expect the temperature to be increasing in the same order. Since the MC got colder than what was measured by the still thermometer, this indicates that at the still stage there is a temperature gradient between where the thermometer is mounted to where the heatsinking occurs from the mixture.

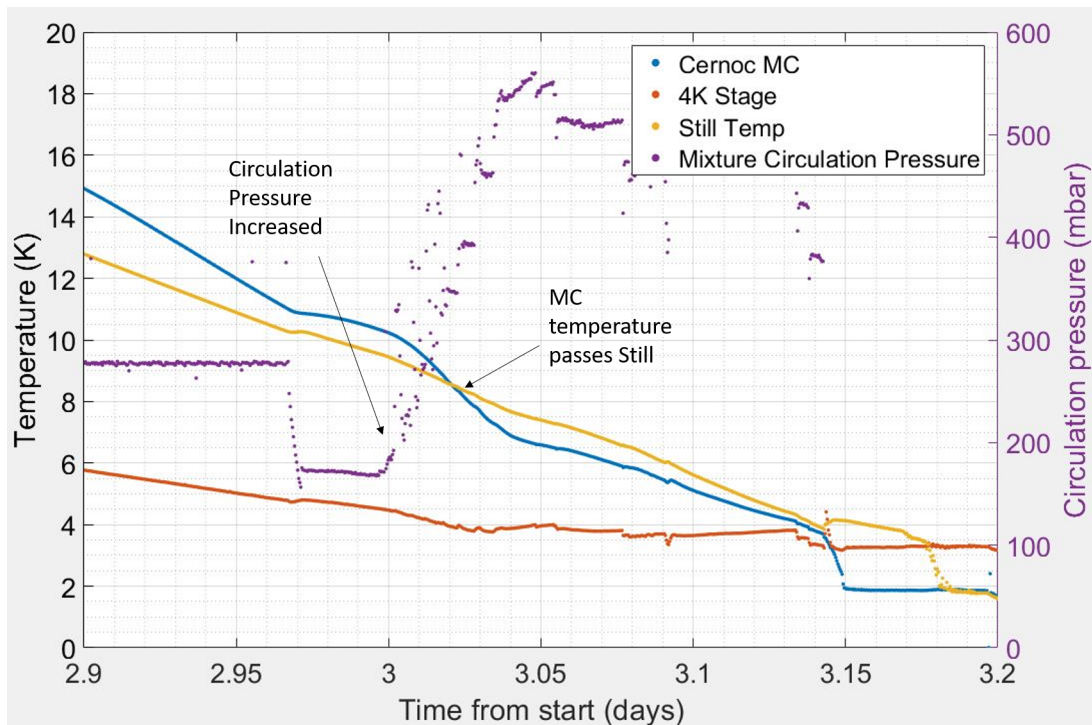


Figure 5.7: Cooling curve of MC (blue), 4K (red), and still (yellow) stages and circulation pressure (purple) at the end of R20 cooldwon. Increasing the circulation pressure allowed the MC to cool rapidly, surpassing the still temperature indicating the still stage is the dependent stage governing the speed of the entire cooldown and should instead be the optimized variable.

This gradient occurs because there is a large heat load on the still stage from the 63 kg of internal lead. The cooling of the still, at this stage of the cooldown is not limited by the temperature of the mixture delivered, or the ability of the mixture to remove heat; it is limited by the rate at which heat can migrate through the still stage. As shown in Figure 5.7 this also limits the overall cooldown time because there is a maximum rate at which the still can cool down.

The implication of this fact for cooldown optimization is that instead of optimizing to get the MC as cold as possible, as quickly as possible, the *still* should instead be optimized since it has the greatest heat load in the fridge. Once the still is sufficiently cold, mixture circulation pressure can increase which will rapidly force the MC to cool down similar to the fast cooling seen in Figure 5.7. Plotting the rate of cooling of the still over the course of the entire run shown in Figure 5.8, there are areas which can be improved, particularly when the still is in the temperature range of 50-30 K since the cooling rate of the still takes sharp positive jumps when pressure is reduced.

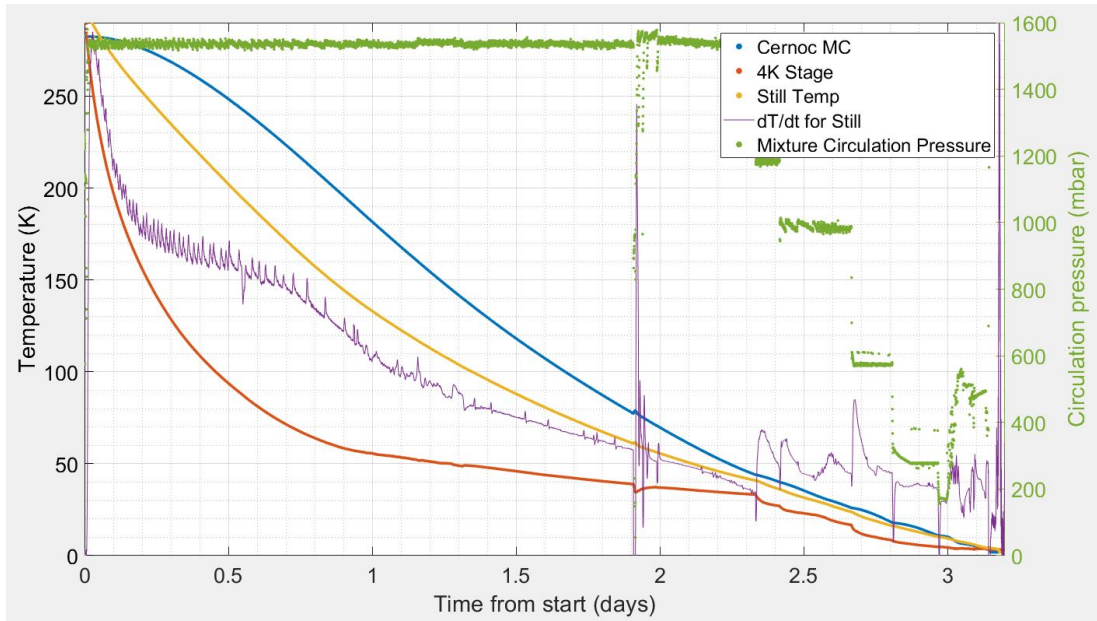


Figure 5.8: Temperature curve of MC (blue), 4K (red), and still (yellow) stages; cooling rate of the still (purple); and mixture circulation pressure (purple) throughout R20 cooldown. R20 optimized MC cooling rate, but as seen by the sharp rises in cooling rate when pressure was reduced, the still cooling rate is not optimized here.

5.2 Conclusion

By analysing the cooling rate of the mixing chamber during the cooldowns of CUTE, the time required to reach the end of the pre-cool phase was reduced to 3 days, 3 hours, 22 minutes in R20. The most recent complete cooldown with un-optimized parameters, R16, cooled in 3 days, 8 hours, 33 minutes after removing a delay incurred during that cooldown. From the lessons learned in R20, this pre-cool time could be further reduced by optimizing the circulation pressures for the best still temperature cooling rate.

Chapter 6

Noise at CUTE

After the initial commissioning of CUTE at SNOLAB and the verification that all the subsystems worked as intended, a noise study was performed in order to understand the facility performance. The two primary methods that noise can couple into detector readout is through mechanical noise (vibrations), and Electromagnetic (EM) noise. The suspension system and the μ metal in CUTE are designed to diminish a large portion of the vibrational noise sources introduced from the lab, and earth's static magnetic field. It is important to still test the limitations of the facility by investigating other potential sources of noise from the facility. Once the sources can be identified, efforts can be made to mitigate or reduce the impact on the measurements. Having a quiet environment allows for the detectors to operate in a more stable manner, better energy resolution, and in turn can allow for lower event energy thresholds to be achieved. While CUTE is testing SuperCDMS detectors, the 0-10 kHz frequency band is the most important region in which to have low noise because this coincides with the time scale of the detector signal. By monitoring the baseline noise in the expected signal frequency range of the detectors, and by using accelerometers rigidly connected to the lower part of the cryostat we can learn about the noise environment at CUTE.

6.1 Noise Study in CUTE

In order to assess the noise, various subsystems were turned off at different times and a Power Spectral Density (PSD) plot for each state was produced. The PSD shows which

frequencies carry the power coming from the electronic phonon signal, and by comparing states where only a single environmental variable has changed you can identify from where the noise is coming into the signal. Figure 6.1 shows the first few lines of the document used to organize the noise investigation campaign. As an example, between test 2 and 3 the suspension system was powered on but was not given the command to operate. All other variables remained in their constant state, so if a difference was noticed in the noise PSDs between the two tests, powering the suspension system could be ascribed with introducing the noise seen.

	Noise Measurement	Accelerator Measurement	PT	Purge	Damp	Lock	Susp	Susp M	Peltier	Calib	Calib M	Accelerometer	Data Series #
Switch calibration system off completely			x	x	x		x	x					
Switch off suspension system completely			x	x	x								
Prepare noise measurement			x	x	x								
Purge gas off			x		x								
Accelerometer measurement (AM) 1		1	x		x							x	
1. Take noise traces, slow control rack off	1		x		x								23200116_0834
1b. Slow control rack back on	1b		x		x								23200116_0841
2. Take noise traces and AM 2 at the same time * I had peltier cooler off by accident *	2	2	x		x							x	23200116_0847
Switch on suspension system, but keep active control off			x		x		x						
3. Take noise traces	3		x		x		x						23200116_0959
4. Move all motors down very slowly and immediately start noise traces (100 steps/sec)	4		x		x		x	x					23200116_1005
Stop noise traces just before the dampers bottom out			x		x		x	x					
Stop damper motors once bottom is reached			x				x						
AM 3		3	x				x					x	
5. Take noise traces as is	5		x				x						23200116_1022
6. Take noise trace while motors continue to move down (optical still 0, keep going down)	6		x				x	x					23200116_1030

Figure 6.1: A snapshot of the table which was used to organize the noise test campaign. In the first column it lists the action to be taken by the experimenter. The 'X' marks indicate which subsystems were on for each of the data sets acquired.

Some sources of noise identified could be easily mitigated, like the discovery that WiFi enabled devices, such as a laptop which is used for some control systems at CUTE, can cause interference in the detector readout as seen in Figure 6.2. For sources such as this, procedural controls were implemented to avoid the noise. In the case of WiFi interference, all network connections are wired and no wireless transmitters are allowed in the experimental area during data collection.

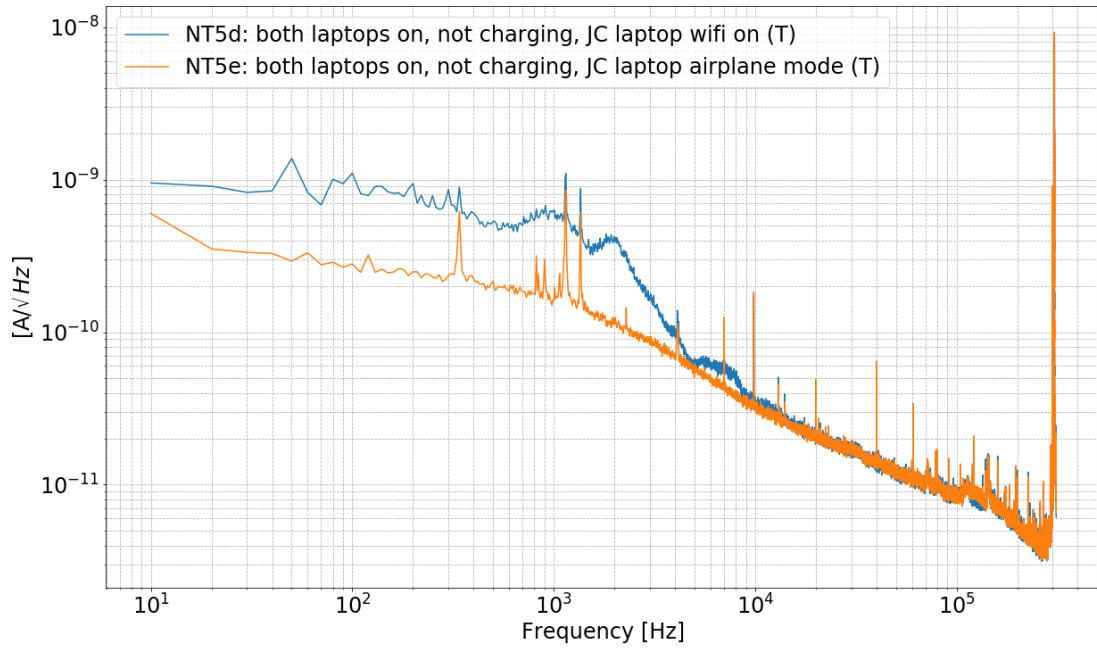


Figure 6.2: Noise introduced into one of the CUTE detectors by WiFi being enabled in a nearby laptop, with care taken to eliminate lurking variables such as laptop charging cables. The detector was set to be in transition, as it would be in regular operation. Figure adapted from code written by E. Fascione.

Other sources of noise cannot be eliminated from procedural controls and instead require design and engineering to reduce their impact or need to be substituted for an alternate solution which does not produce as much noise. A select number of subsystems where noise was identified and mitigated are discussed in the following sections.

6.2 Mitigated Noise Sources

6.2.1 Peltier Cooler Noise

A Peltier Cooler is used to cool the turbo pump that circulates the mixture for the dilution refrigerator. Upon original installation, the Peltier Cooler was left to run at full cooling power which led to ice build up on the heat sink surface. This is a concern because as the ice melts, water may drip onto the lead shield situated directly below inside the drywell and may lead to corrosion. Hence, a controller was installed that regulates the cooling power via a Pulse Width Modulated (PWM) power signal. A bin was installed under the cooler to catch any condensation drips as a short term solution until the controller was proven to eliminate the problem. Figure 6.3 shows the originally iced-up Peltier cooling

surface and the controller that was installed to overcome this problem.

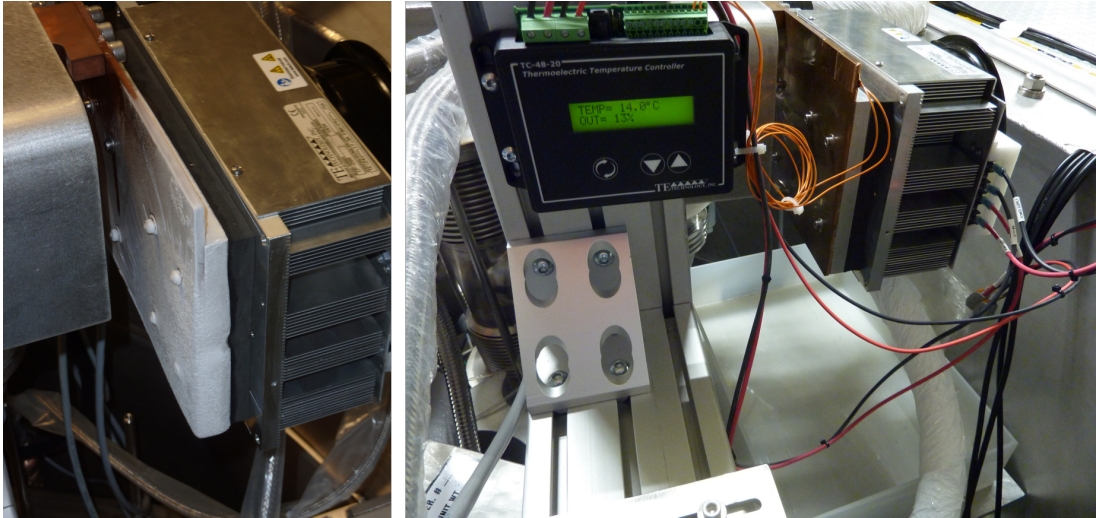


Figure 6.3: (Left) Peltier Cooler ice build up when left to operate at full power. The ice melts and water drips into the drywell when the Peltier cooler is switched off. (Right) Peltier Cooler controller with thermistor outputting a PWM signal for power control and a secondary condensation collection bin.

During the noise study a signal which matched the switching frequency (and harmonics) of the PWM control signal appeared in the PSDs when the Peltier Cooler was on, and disappeared when it was switched off as displayed in Figure 6.4. All other parameters remained constant between the two tests. A change in the noise contribution from a 60 Hz source and its harmonics was also noted, but this is most likely introduced due to ground loops in the facility reacting to the EM noise emitted by the high-power switching signal from the Peltier Cooler controller.

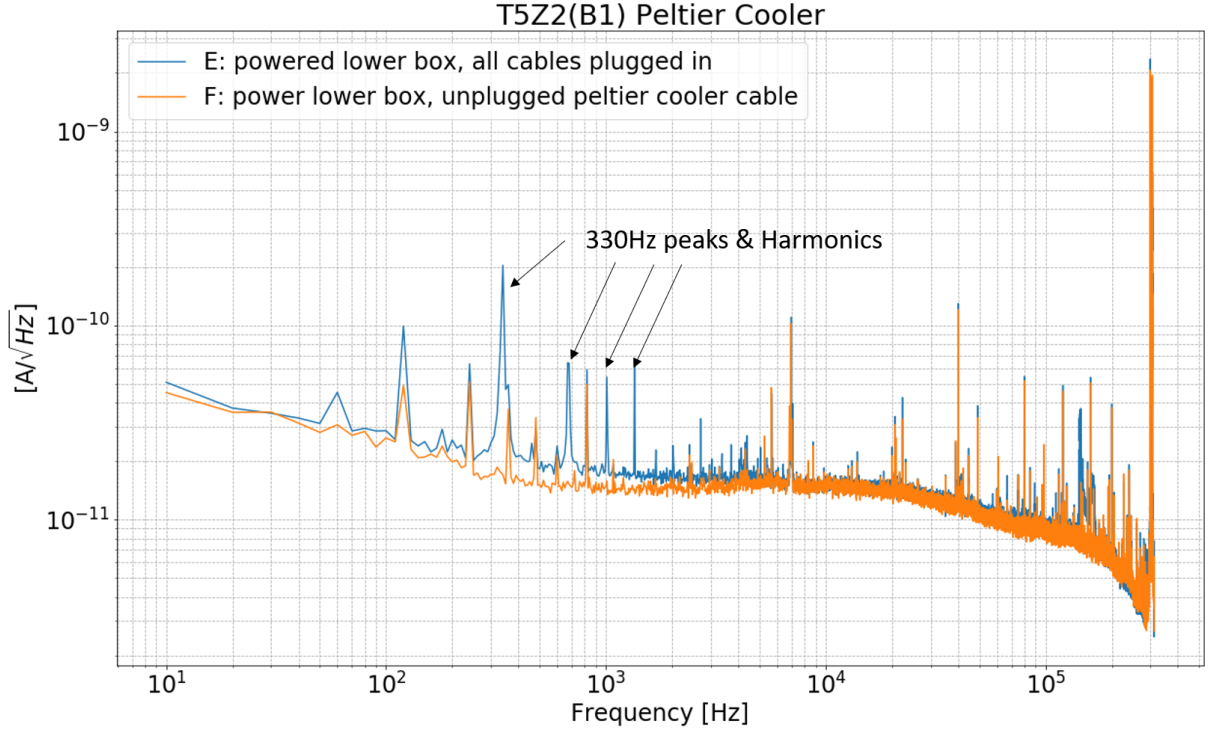


Figure 6.4: Noise introduced into one of the detector readout channels from the Peltier Cooler. The primary and harmonic frequency noise peak locations match that used by the peltier controller to modulate power output. Detector was set to be in transition, as it would be in regular operation. Figure adapted from code written by E. Fascione.

Attempts were made to further shield the peltier cooler from emitting EM radiation by wrapping the peltier power lines in grounded Aluminum tape. When this modification did not appear to make a significant difference on the noise, the controller was mounted outside the drywell with longer wires used to connect to the peltier cooler. Again this modification did not have a significant effect on the noise in the detectors. What did succeed in eliminating the 330 Hz and harmonics noise peaks was to control the peltier cooler with a switching power supply which switches at a much higher frequency outside our frequency range of interest, and has a filtered output to prevent the sudden changes in high current.

6.2.2 Electrical Isolation

The upper and lower parts of the fridge should be electrically isolated from each other so that any noise emitted from the numerous devices mounted to the upper half is decoupled from the detectors. For ease of operation, a connection plate was installed on the cryostat

so that the hoses which carry the helium mixture would not have to be connected and disconnected in difficult to reach locations each time the cryostat has to be moved to the cleanroom for payload changes. Dielectric breaks were installed on two of the mixture lines, but due to the fittings of the lines, these breaks could only be installed on the Gas Handling System side of the connection plate connection. Since the connection plate is metal with metal hoses which go to the lower fridge, this now acts as an electrical short between the upper and lower halves of the cryostat. This meant that electrical isolation had to be incorporated into the valve mounting to the connection plate so that the hose remained isolated from the upper fridge. Figure 6.5 shows the thin walled collars that were designed and fabricated to prevent the screws affixing the valves to the connection plate from coming in contact with the plate. An insulating plastic spacer was also placed between the connection plate and the valve. For the OVC pumping line and Mixture pumping line, on the fridge side of the connection plate, the metal KF25 connection was replaced with a machined plastic center ring to hold the o-ring, and a plastic C-clamp.

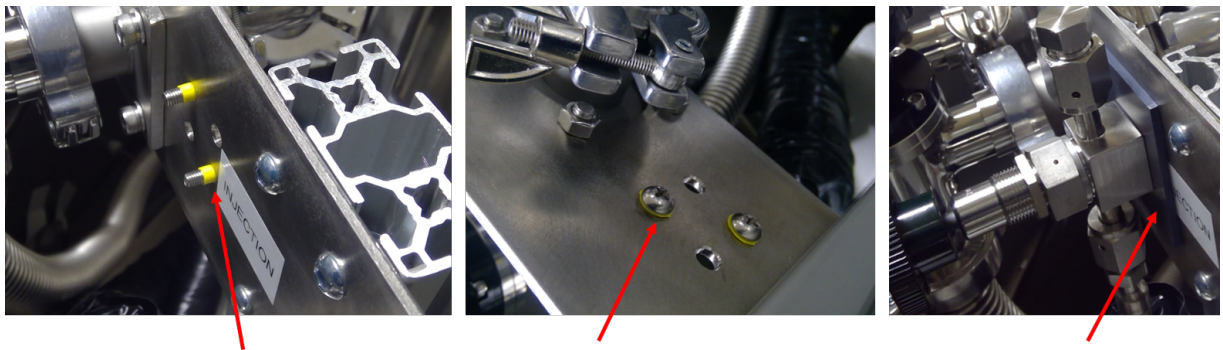


Figure 6.5: Plastic collars for the screws affixing the valves to the connection plate. The collars prevent the shaft of the screws (left), the heads of the screws (middle), and the plastic spacer prevents the valve surface (right) from touching the connection plate electrically isolating the valve and hoses from the upper fridge.

6.2.3 Purge Gas Noise

As a means to address the high Radon background experienced in the lab underground, low radon purge gas is forced into a diffuser located at the bottom of the drywell as mentioned in Chapter 4. To ensure sufficient flow to prevent Rn diffusing into the drywell the initial flow level of the purge gas was set to a relatively high level. This purge gas, set at a flow of 2 cubic feet per minute (cfm) introduces high frequency vibrational noise in a band of

frequencies of 3-10 kHz in the detectors as was determined during the noise campaign as shown by Figure 6.6. Later a second flow meter which could restrict the flow to lower values was installed at a time when the cryostat was not operating. Vibrations were measured by accelerometers mounted to the fridge with measurements in Figure 6.7 to determine the flow required to have the vibrational noise disappear. The vibrations coupling in to the cryostat is a feature of utilizing the suspension system, since it is “floating” it is more susceptible to vibrations from air currents. When the suspension system is driven down, coupling the lower cryostat to the drywell, the vibrations from the purge gas are greatly reduced (however vibrations from the lab, and drywell are introduced).

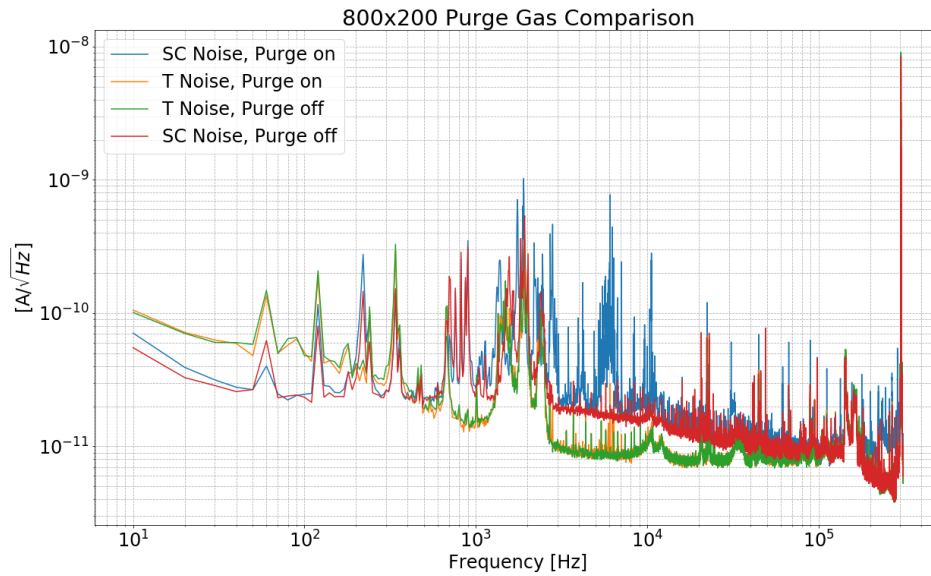


Figure 6.6: Noise introduced by vibrations caused by the purge gas as seen in a CUTE detector. In both Superconducting and Transition states of the detector, the noise in the detector is high in the kHz range as seen by the excess of Blue over Red, and Orange over Green curves. Flow rate was 2 cfm for the “on” trials. Figure adapted from code written by E. Fascione.

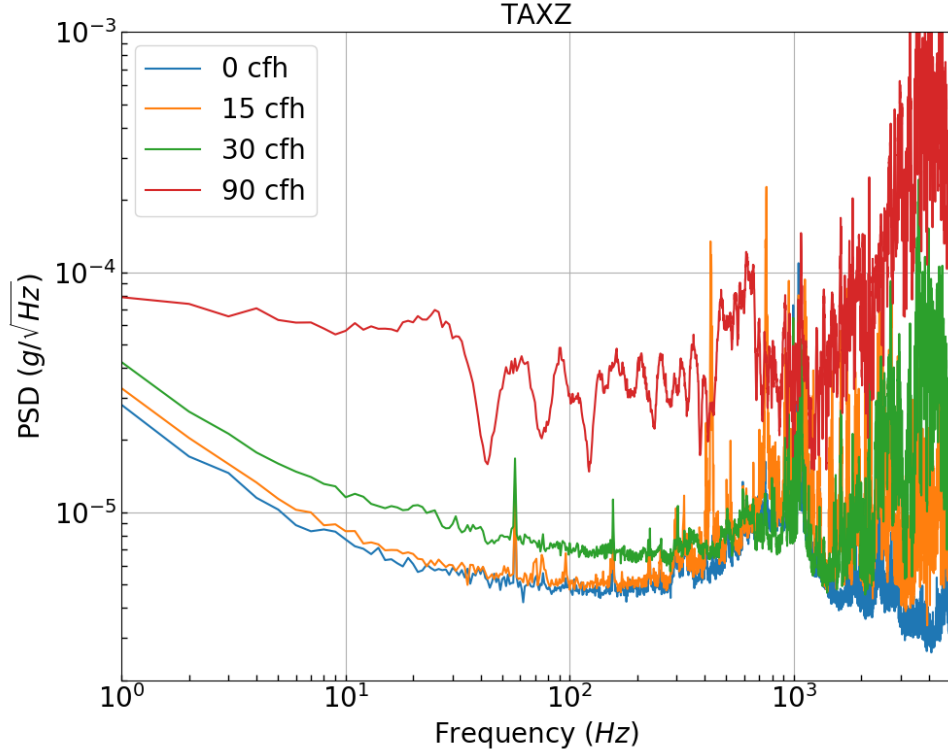


Figure 6.7: Vibrations measured by an accelerometer mounted of the lower part of the cryostat with varying amounts of purge gas flow levels using the low-flow meter. 90 cfh is equivalent to 1.5 cfm. Figure made by R. Germond.

To reduce the amount of purge gas required to prevent Rn diffusion, a low-flow collar which sits around the OVC of the cryostat was installed, and allows for a small gap between it and the drywell lead cover. To see what the requirements for the purge gas are from a radon mitigation point of view, a Rad7, a device which measures the radon concentration in air, was used [65]. A sampling tube was deployed at different depths in the drywell under changing facility conditions shown in Figure 6.8 at various purge gas flow rates. Table 6.1 shows the summary of the radon measurements from the Rad7 at different depths. The original flow meter had range of 84-120 cfm, a second flow meter with lower range was installed for tests 12-15 taken at the same time as the accelerometer measurements.

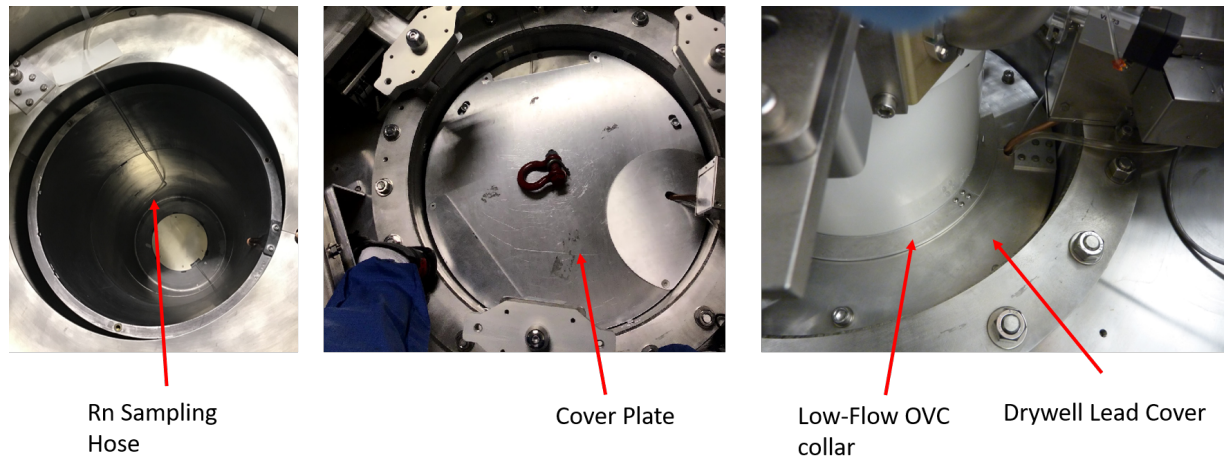


Figure 6.8: Sampling set up of the hose in different configurations. (Left) A test with the hose near the bottom of the drywell in the lead shielding with the fridge out and cover plate off. (Middle) Sampling hose fed under the cover plate with fridge out of drywell. (Right) Sampling hose being fed through an access hole in the drywell lead cover used for the calibration system into the drywell to test below the low flow collar.

Table 6.1: Summary of various Radon measurements in the drywell in 3 configurations; with the fridge removed and drywell open, fridge removed and the drywell Cover Plate (CP) on, with the fridge in the drywell. Low radon air purge gas had the flow rate, in units of cubic feet per hour (cfh), adjusted between various measurements. One measurement, #6, was taken attempting to measure the exhaust coming out between the Pb Cover (PbC) plate and the low-flow collar. The measurements thereafter were taken with the sniffing hose underneath the PbC measuring the volume between the shielding lead and cryostat. Measurements #1, #5 were test measurements to ensure the unit was working correctly and provided no informative measurements. Measurement #13 acted as a sanity check to verify radon can diffuse under the PbC if no flow is applied.

Rad7 Measurement #	Flow Rate (cfh)	Sampling Location	Drywell Status	Radon Level (Bq/m ³)
2	120	1' from bottom	No Fridge, CP on	12.5 +/- 2.1
3	120	10cm below CP		19.9 +/- 4.9
4	120	10cm below CP	No Fridge, CP off	60 +/- 15
6	120	Above PbC	Fridge in	35.8 +/- 3.2
7	120	115cm below PbC		0.8 +/- 1.6
8	84	115cm below PbC		1.9 +/- 1.0
9	84	100cm below PbC		3.3 +/- 2.7
10	84	50cm below PbC		2.3 +/- 1.2
11	120	50cm below PbC		2.26 +/- 0.7
12	40	50cm below PbC		1.45 +/- 0.92
13	0	30cm below PbC		89 +/- 24
14	40	30cm below PbC		4.3 +/- 0.6
15	15	30cm below PbC		3.7 +/- 0.47

One conclusion drawn from the measurements is that operationally the cover plate should always be installed when the cryostat is removed. The capacity of the purge gas,

even at full flow, is too low to prevent radon-rich lab air from getting into the drywell. Comparing Measurement #3 and #4, for the same sampling location and purge gas flow rate, only differing in the removal of the cover plate, a three-fold difference in radon concentration can be seen. Once the fridge was moved back to the drywell, a Rn sniffing test was done above the Pb Cover plate (PbC) at the gap between the low-flow collar and the PbC. This measurement showed the Rn levels were lower than regular lab levels, but since it was above the PbC where the low Rn air mixes with regular lab air, it was not indicative of the Rn levels under the PbC. Under the PbC with the fridge in, no significant change in Rn concentration was noted at varying depths shown in Measurements #7-12, so as a sanity check measurement #13 was taken with the purge gas off. This measurement saw a significant increase in Rn concentration confirming that the previous results of consistent low Rn levels were valid and the machine was working as expected.

Looking at measurement #15 which was taken with the low flow rate of 15 cubic feet per hour (cfh), the radon level near the top of the drywell under the PbC with the fridge in the drywell remained sufficiently low. 15 cfh could therefore be confidently selected to be the operational purge gas flow rate to limit both noise in the detectors, as shown from the accelerometer measurements, and radon in the drywell from the Rad7 measurements. The source of the purge gas to the drywell was adapted so that two new flow meters are installed in parallel. One high flow meter can be valved in when the drywell is empty with a cover plate on, so that the purge flow has higher range and provides as much purge as possible resembling conditions as Measurement #3. A flow meter with greater fine control of low range flow rates was installed in parallel to provide sufficient purge gas with minimum vibrational noise while the fridge sits in the drywell.

6.3 Conclusion

For CUTE to provide the best low noise conditions for the detectors which it houses, understanding of the noise limitations of the facility is critical. Four sources of noise which were discovered and controlled were discussed in this chapter. Any network communicating devices at CUTE will have their WiFi capability turned off and only wired ethernet

connection is permitted while CUTE is testing detectors. The power for the peltier cooler was modified to remove the 330 Hz noise from the previous PWM controller. Optimized purge gas flow was determined to limit the vibrations seen in the fridge, while maintaining sufficient gas flow to reduce the radon level in the drywell. Electrical isolation at CUTE is currently underway, with additional components which may introduce a connection between the upper and lower parts of the cryostat still being investigated. Ongoing efforts are being made to mitigate the sources of noise which can be reduced or eliminated.

Chapter 7

^{252}Cf Neutron Calibration System

7.1 Motivation and Considerations

For CUTE to act as a fully fledged test facility to test SuperCDMS detectors, as well as other experiments in the future, it should have the capacity to test and calibrate detectors. As mentioned in Chapter 3 Figure 3.5, iZIP detectors can distinguish between electronic and nuclear recoils from photons and neutrons by the ratio of charge and phonon amplitude. CUTE already has an automated ^{133}Ba calibration system installed to produce electron recoils. The need for a neutron calibration system in the facility is present so that controlled nuclear recoil events can be observed in the detectors. The desired neutron activity reaching the detectors is a balance of minimizing the pile up event rate while trying to maximize the overall event rate so that calibrations can be completed in a reasonable amount of time. A pile-up event is when a second event occurs in the detector within the same time period as the saved trace of an original event. For the current generation of detectors, the saved trace length per event is about 50 ms, we aim for a goal neutron rate of order of 6 Hz since that would be sufficient to provide ample neutrons for calibration while mitigating the risk of pileup events.

The initial considerations for the design of the neutron calibration system were driven by the intended use of the source. Since CUTE's purpose is to act as a test facility for detectors which will have multiple payload changes, frequent calibrations are anticipated. Due to SNOLAB restrictions regarding the movement of sources within the labs, if the calibration system design required manual deployment and movement of the source to

CUTE, the timescale and steps involved to calibrate would be burdensome [50]. The neutron calibration system should therefore permanently house the source, and provide adequate shielding for events in both our own detectors and the neighbouring experiments, and provide shielding from radiation for facility personnel. The list below summarizes the main considerations and requirements for the calibration system at CUTE which will be addressed later in this Chapter:

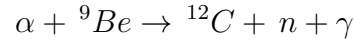
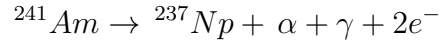
- House the source within CUTE to allow for efficient calibration operations
- Ensure that there is no radiological hazard to personnel working at or nearby to the facility in compliance with safety standards of less than $2.5 \mu\text{Sv/hr}$
- Ensure the background rate introduced from the source for neighbouring experiments is negligible, and will not hinder their science programs
- Provide a neutron event rate of order of 6 Hz in the SuperCDMS style Ge detectors during calibrations
- Allow for variation of shielding between the source and the detectors to moderate the neutron energy spectrum and rate seen by the detectors
- Maintain radiation safety of the system throughout all operations of the facility, even when the water tank is emptied
- Monitor the source position and have secondary detection methods to verify the location
- Ability to remove or replace the source from system without requiring a complete uninstallation

Considering all of the above, a system was designed and large fractions of it are constructed to deliver a ^{252}Cf source from a shielded location within the CUTE water tank, to an area adjacent to the detectors for calibration. The encapsulated source will be attached to a beaded chain inside a source tube which makes a loop through the water tank, and the source will be moved by a stepper motor which pulls the chain in each direction

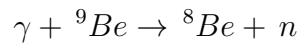
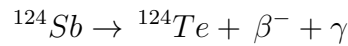
for calibration and return to storage. The sections below will describe how each component is implemented from the original idea to the final product to synthesize a coherent calibration system.

7.2 Source Selection

Neutron sources used for calibration usually fall into one of three categories: spontaneous fission, photoneutron sources, or alpha induced neutrons. (α,n) sources contain a radioactive alpha emitter, and a low-Z material that has a weakly bound neutron that can be released by an alpha particle interacting with the nucleus. An example of such a source, Americium Beryllium (AmBe), is given below:



Photoneutron sources are similar to (α,n) sources because they contain a combination of an isotope which emits high energy gammas, and a similar low-Z isotope with a weakly bound neutron which when a photon of sufficient energy is absorbed by the nucleus, will emit the neutron. A common example of a source of this type is SbBe, following the process below [66]:



The disadvantage of using both of these types of sources is that most ^{241}Am α s and ^{124}Sb gammas do not interact with the target Be nuclei. Only about one in every 15,000 ^{241}Am decays, and one in every 120,000 ^{124}Sb decays yield a neutron [66]. For this reason,

sources of this type require a high activity to achieve a reasonable neutron rate.

Spontaneous fission neutron sources consist of a radioactive isotope which undergo spontaneous fission where they release a number of products including some number of neutrons. ^{252}Cf is the most commonly used neutron source of this type, due to its high neutron yield. ^{252}Cf undergoes fission in about 3% of all decays, with an average of 3.7 neutrons per fission making it the most efficient portable neutron source for calibration [66][67]. Other radiation emitted by this source primarily come from the other decay method; ^{252}Cf undergoes α decay 97% of the time, whose α radiation can be effectively shielded with minimal shielding, however the subsequently emitted gammas need to be shielded. For spontaneous fission, gammas are also emitted with an average of 10.3 photons with a cumulative average energy of 8.2 MeV [68]. Compared to the alternative source options, this is relatively low gamma emission and will contribute minimal gamma background to the detectors. Considering that the intended use of the source is to stay contained in the water tank at all times, minimizing the overall activity reduces the amount of shielding required to safely store the source. Additionally, as shown in Figure 7.1, ^{252}Cf source gives a softer spectrum than an $^{241}\text{AmBe}$ source meaning the average neutron energy is lower which would yield a more comparable energy spectrum to a predicted recoil spectrum from a medium mass WIMP. Photoneutron sources, by comparison, typically have lower energy neutrons which, to first order, are mono-energetic. Sources of this nature allow for calibrations and understanding in a specific energy range, but do not allow for broad nuclear recoil calibration or neutron activation of Ge. ^{252}Cf has a reasonable half-life, $T_{1/2} = 2.64\text{ yr}$, such that the source can provide years of calibration before needing to be replaced [66]. For all of the aforementioned reasons, a ^{252}Cf source was selected for this system.

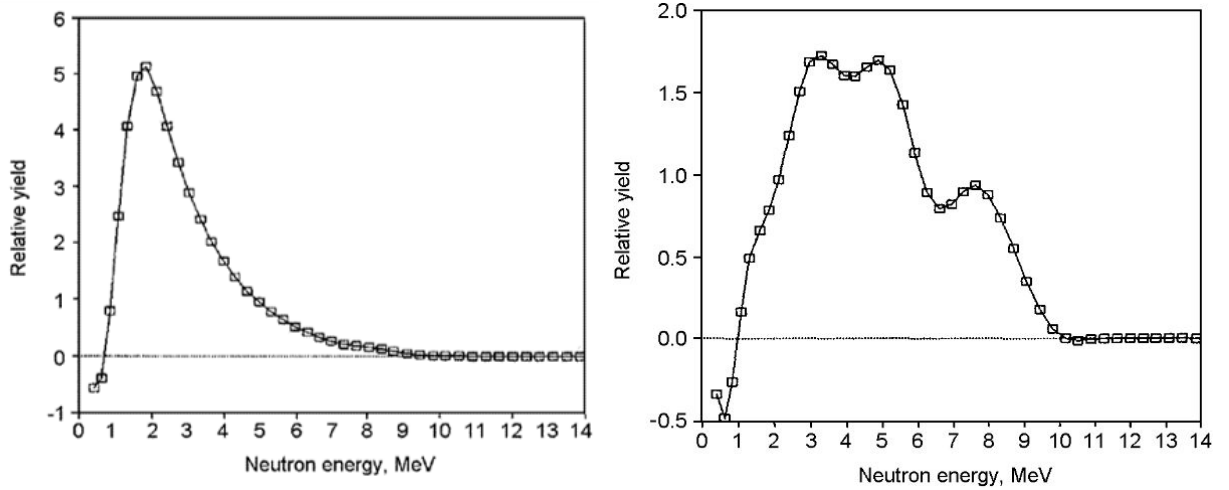


Figure 7.1: Spectrum of neutron energies emitted from ^{252}Cf in spontaneous fission events (left) and $^{241}\text{AmBe}$ source (right). Shown are the relative number of neutrons emitted at each energy for each source, and the low energy yields are negative due to electronic filtering of the scintillator detector at low bin values. Figure sources: [69].

7.3 Conceptual Design and Simulations

The method by which one shields from neutrons is to have the fast neutrons undergo nuclear scattering, reducing their energy until they thermalize in the material and are captured [70]. Materials with a high hydrogen content, such as plastics, or water, are favourable shielding since when the neutron scatters off of a particle with similar mass (neutrons and hydrogen atoms have about the same mass) the greatest amount of energy is transferred by the neutron. For example, a neutron with starting energy of 1MeV would need on average 18 collisions with hydrogen atoms to thermalize, whereas if the neutron is colliding with a larger atom such as Carbon, it may require over 100 collisions to thermalize [71]. To shield from gamma (photon) radiation, materials with high density, and high proton number are commonly used, such as Lead, or Tungsten. HeavyMet is a Tungsten based alloy, mixed with nickel, copper, and sometimes iron, which has a density of more than 1.5x that of lead making it a very effective gamma radiation shielding material [72][73].

The obvious choice for shielding the neutrons from the source within the CUTE facility is to utilize the water tank, whose purpose is to shield from the neutrons coming from cavern walls. It is foreseeable that the tank will need to be emptied from time to time, so

additional shielding should be incorporated into the design to continue to provide adequate shielding for personnel and the nearby experiments.

Through multiple iterations of design, followed by verification of the effectiveness of the shielding by Monte Carlo simulation, a conceptual design of the system was determined. This design includes a large plastic PolyEthylene (PE) box with an S-curve channel for the source tube to travel through, delivering the source to the center of the box. The S-curve is present to make sure there is no direct line of sight from the source to the outside world. At the resting location, a HeavyMet cylinder with a cone hollowed out of the center surrounds the source tube providing shielding against gamma radiation, while two lead bricks sit directly above the source. The HeavyMet and lead provide effective gamma shielding all around except towards the bottom where the radiation only hits the cavern floor.

Once the considerations of the shielding design were decided, the geometry was coded into SuperSim, the SuperCDMS specific package of GEANT4, a common particle physics simulator; a rendering of the setup can be seen in Figure 7.2. Multiple simulations were performed of the source under various facility conditions to investigate the anticipated rate in the detectors, the safety hazard to personnel working at CUTE, and the background this would introduce to neighbouring experiments. The variables which were adjusted and tested during these simulations were the PE thickness, location of the PE box in the water tank, shape of the source tube through the PE box, gamma shielding thickness, and water separation between the source and the drywell wall during calibrations. An upper bound on the event rate in the detectors was determined by setting the detector volume to record when a simulated particle originating from the calibration source passes through the volume. Dose rates for personnel standing *Beside* the water tank at ground level and *on Top* of the CUTE deck were determined by measuring the flux of particles emitted out the side walls and top of the water tank as shown by the figures in Figure 7.2. All particles emitted out of the side walls and top of the water tank were assumed to be absorbed by a human in the respective locations which acts as an upper limit on the dose rate since geometric reductions would greatly reduce the number of interactions the

particles would have with the human. Background event rate for neighbouring experiments were determined by setting a “net” five meters East of CUTE for SuperCDMS and twelve meters West for PICO, as measured from the center of the water tank, which accounted for all particles which pass through on their way to the neighbouring experimental zones.

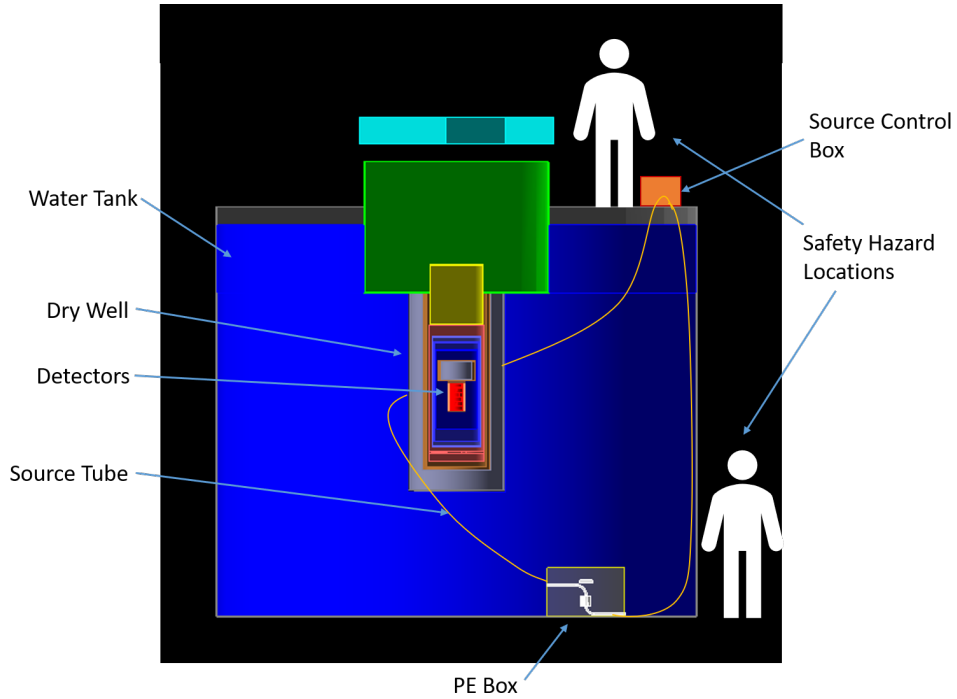


Figure 7.2: Rendering of the shielding in the CUTE facility highlighting the anticipated design of the neutron calibration system.

Table 7.1 summarizes the simulation conclusions of the source impact when it is located in the shielded location in the PE box, and when it is deployed for calibration adjacent to the detectors in the water tank. Contributions to background and dose received from natural sources in SNOLAB are given as reference for the level of background for which experiments must presently account [50]. The dose received by personnel is far below the limit dictated by the SNOLAB radiation program of $2.5\mu\text{Sv/hr}$, and well below the contribution users receive naturally from working in a Radon gas rich environment. The background rate for neighbouring experiments is about the same order of magnitude as the flux they would expect from the radiation emitted from cavern walls. Each of these experiments have their own shielding which was not taken into account in the simulation which would further reduce the rate of particles seen in their detectors. To merit the use of the additional shielding of the PE box, simulations were done with the source in its

storage location with the regular conditions, with the box present but all water removed, and as a control with no box and no water. The resulting dose rate received by personnel standing beside the water tank were 1, 50, and 2400 nSv/hr respectively, verifying the need for additional shielding in the case where the water tank is drained.

Table 7.1: Summary of the simulation results for a 40 kBq ²⁵²Cf source. Gamma backgrounds were taken to be high energy γ (>4.5 MeV) to compare to Table 2.4 in [50]. SNOLAB background dose rate is reported only for the contribution from high radon levels underground [74].

Source Location	Shielded	Calibration	SNOLAB Background
Health Hazard Beside (nSv/hr)	1	~0	862
Health Hazard on Top (nSv/hr)	~0	4	862
Gamma/Neutron Flux @ PICO (#/m ² /day)	45/<10	1300/1000	1000/4000
Gamma/Neutron Flux @ CDMS (#/m ² /day)	450/10	4000/3500	1000/4000

In addition to the quantitative expectations from the shielding system, a number of additional qualities of the system were laid out as an expectation. The first was the ability to vary the amount of water shielding between the source and the detectors. With more shielding, not only will the rate in the detectors decrease due to more neutrons being moderated by the water, but the neutrons which do reach the detector will have a softer spectrum, with the average energy of the incoming neutrons decreasing. The source will need to traverse through the system in a manner which must be able to be controlled remotely, and redundancy of source location detection methods must be included.

7.4 ²⁵²Cf Source

The previous section discussed why a ²⁵²Cf source was selected over other radioactive neutron sources. To determine the activity required for this source, a number of events were simulated with the source in the calibration location in the water tank in SuperSim, counting the number of neutrons reaching the detectors and interacting. Based on the relative detector counts to the total number of events simulated, and accounting for all reduction factors coming from the branching ratio of ²⁵²Cf, a minimum source activity of 18 kBq was determined to provide a rate of at least 6 Hz in each detector [75].

Due to the short half life of ²⁵²Cf, $T_{1/2} = 2.64 \text{ yr}$, the anticipated time scale between order and manufacturing of the source and installation, and the limitations of activity values guaranteed by the manufacturer, a 37.5kBq source, with encapsulation model 3024 from Eckert and Ziegler’s catalog was selected and purchased [66][76]. One of the design elements incorporated in the calibration system, which was further supported by simulation, is to be able to control the location of the source such that varying amount of water from the water tank is between the source and the drywell. The water attenuates neutrons, softening the energy spectrum, and reduces the overall rate of neutrons reaching the detectors. In the case where upon delivery and installation the 37.5kBq activity proves to be too great for the electronics readout system to handle, implementing these control methods to reduce the rate will allow for useful calibrations, and provide longevity of the system since the source will not need to be replaced as soon as it would have had it been of lower initial activity.

In accordance with SNOLAB’s policy to double encapsulate and verify the encapsulation is leak tight from releasing contaminants, the design for the ²⁵²Cf encapsulation was based on a method previously tested and approved by SNOLAB for the ¹³³Ba source at CUTE [50][63]. Both designs consist of nested copper cylinders with the source in the center, with the top and bottom parts of each cylinder layer soldered together. Tests showing the validity of this method of sealing were performed previously by enclosing Zeolite beads in the center of the encapsulation, and placing the encapsulated beads in a helium volume. If there had been a leak into the encapsulation, the beads would absorb the helium. After some period of time, the helium was evacuated from the container, and a helium sniffer was attached to the volume. The sniff rate of helium was monitored in the current state giving a baseline, then the sample was heated which activated the zeolite beads such that any trapped gas would be released [77]. Upon verification that the leak rate did not change significantly beyond the expected background level, this method of encapsulation was deemed to be adequate for SNOLAB standards of solid sources.

Based on the dimensions of the 3024 model encapsulation of the ²⁵²Cf source from Eckert and Ziegler, a cylinder 10 mm×Ø 6 mm, the design developed for the ¹³³Ba source

encapsulation was modified to accommodate this size. In the ^{133}Ba encapsulation the top had an attachment affixed with 000-120 screws to hold onto the final bead of the beaded chain, attaching the source to the chain. For the ^{252}Cf encapsulation, a second beaded chain attachment was added to the bottom of the source to match the intended design of the calibration system where the source will be moved through the tube by pulling it in one direction or another. Lastly, the dimensions of the source encapsulation were minimized to allow for maximum room inside the source tube [78]. The overall assembly of the double encapsulation with chain attachments to allow the source to be used in the system is shown in Figure 7.3 and is cylindrical in shape with dimensions $30\text{ mm} \times \varnothing 10.5\text{ mm}$. The washer was added on top to keep the chain aligned axially preventing the chain from sliding down the access slot in the chain attachment piece, which would potentially tilt the source within the tube.

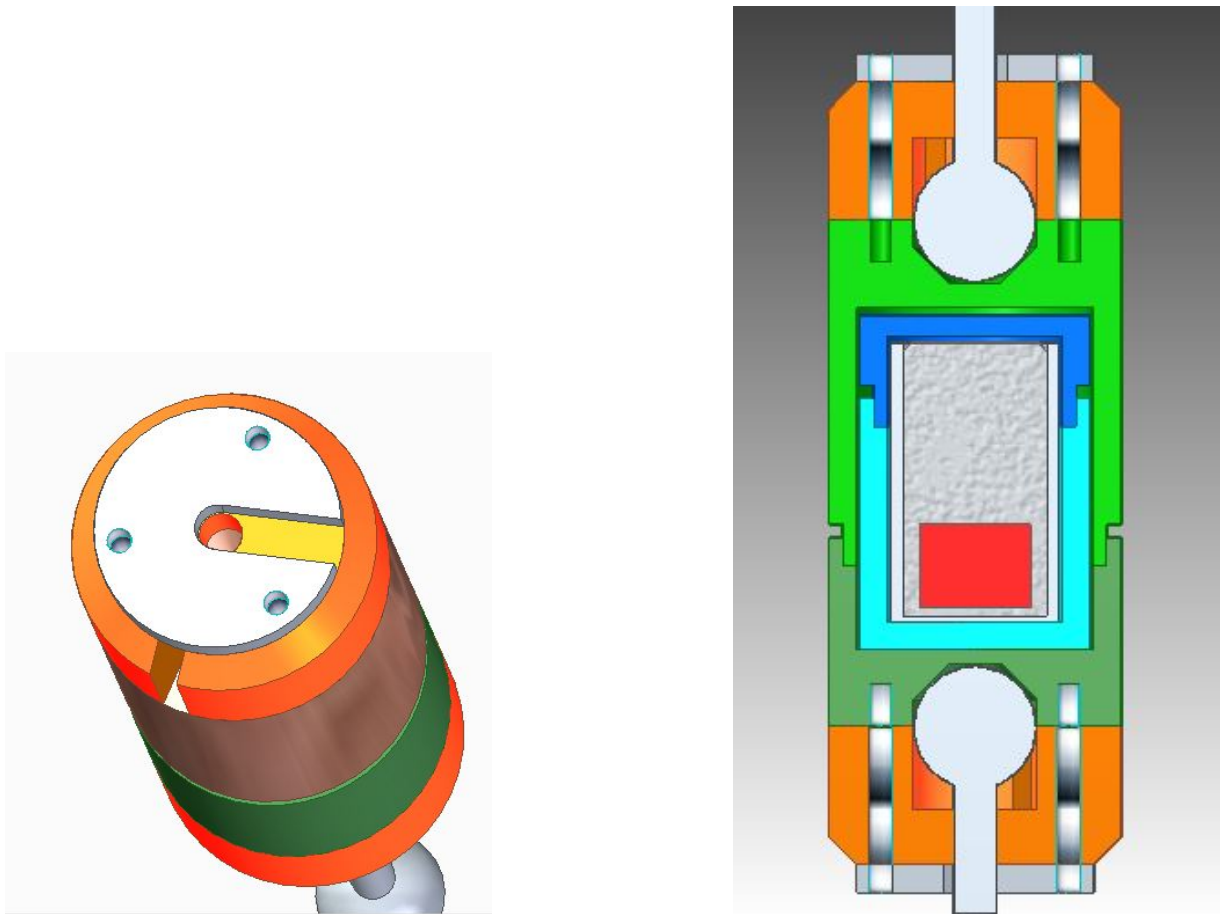


Figure 7.3: Source Encapsulation Design. Shown are the active volume (red), encapsulation from manufacturer (silver), first layer of encapsulation top and bottom (blue), second layer of encapsulation top and bottom (green), beaded chain (white), chain attachment (orange), and attachment washers (grey). Overall dimensions: 3 cm long, 10.5 mm diameter. Gaps in inner/outer encapsulation layers for soldering.

In addition to the encapsulation as a means to prevent contamination on the outside of the source interfering with the operation at SNOLAB, our ^{252}Cf also underwent multiple cleaning and testing cycles. Following a strict encapsulation procedure, at each stage in the encapsulation procedure, a wipe was used to wipe the outside of the volume, and the wipes were then sent to be counted on a High Purity Germanium radiation detector (HPGe) at Royal Military College (RMC). The result of these tests verified that not only did the source have no contamination upon delivery from Eckert and Ziegler, but the procedure of encapsulating and soldering did not introduce any other radioactive contaminants. All swipe tests showed that the contamination level was below the detection limit of the detector, meaning it is well within an acceptable range for use at SNOLAB [79].

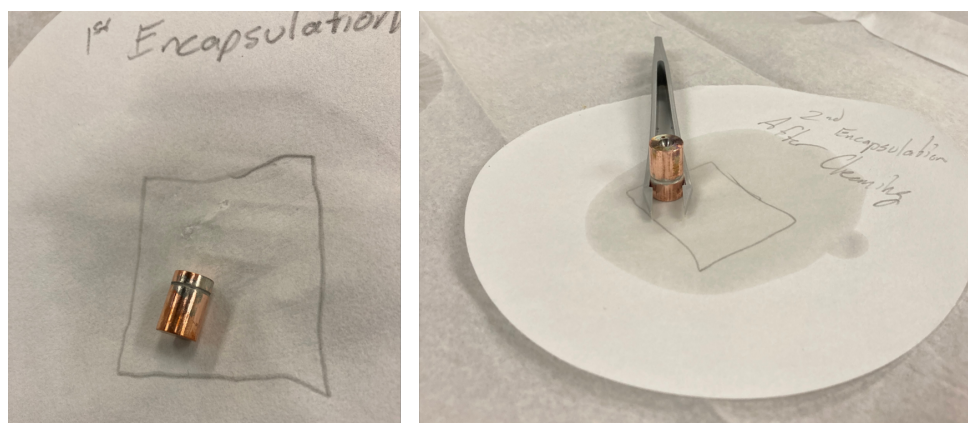


Figure 7.4: Photo of the encapsulated ^{252}Cf source as swipe tests are performed after the first (left) and second encapsulations (right). Tweezers were used to rub all encapsulation surfaces on a wetted wipe sample sheet.

The chain selected to be incorporated into the system is a plastic beaded chain commonly used in household curtain assemblies. The rationale for selecting this is for the wide availability of accessory pieces and due to its proven record of reliability with its typical use being to open and close blinds on daily basis, these chains would withstand heavy use. The beads spaced at regular intervals allow for efficient control of motion from a gear with matching spaced holes. Tubing selected to act as the source tube was Polyethylene Firm Tubing with 5/8" ID 3/4" OD. The tubing will be gently curved around the drywell with mostly straight sections otherwise, and one sharp S-bend inside the PE shielding, which will be discussed in section 7.9.

7.5 Calibration Spectrum Variation

As previously mentioned, the design of the neutron calibration system should have the ability to adjust the amount of shielding between the source and the detectors. With the source box's location in the water tank, there is ample water shielding to block most (through simulations greater than 1 part per 50 million) neutrons from reaching the detectors. The system must therefore be able to move the source closer to the drywell within the water tank, in a repeatable manner, so the tube must be affixed close to the drywell in the water tank - a smooth stainless steel surface with no available screw holes or standoffs for easy attachment. The solution for this is shown in Figure 7.5, a clamp which holds the source tube against the outside of the drywell in the water tank. The clamp has an elevated slot for a wormdrive band to pass through, which encircles the drywell and when tightened snugly holds the clamp in place. The clamp is shaped to hold the source tube immediately against the drywell, giving minimal water shielding from the source to detectors.

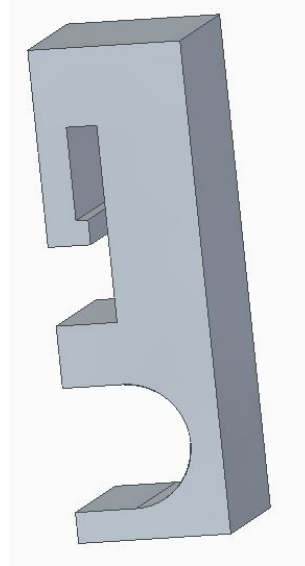


Figure 7.5: CAD model of the piece affixing the source tube to the drywell. Upper slot is for a 1/2" wide wormdrive band to pass through which surrounds the drywell, the lower semi-circle is where the source tube will pass through being pressed against the drywell surface. Dimensions of the clamp are 25×25×80 mm.

The second desired feature of the calibration scheme is the ability to vary the amount of water shielding to soften the neutron spectrum, and reduce the event rate in the detectors. For this task, a wedge was designed, shown in Figure 7.6, such that the inner mating

surface matched the curvature of the drywell, but the outer surface which the tube would attach to has a larger radius. A grooved slot with 3 sets of clamping holes keeps the tube in place on the outer wedge surface. Due to size limitations of the 3D printer selected to produce the wedge, it was produced in two parts, and through-holes in the center allow for the wedge pieces to be put together. The overall dimensions of the piece is a height of 20 cm, and an arc corresponding to a 25° angle on the outer surface of the drywell and the inside of the wedge area is hollow, so that water fills the volume. Adjusting the linear position of the source along the diagonal track in the wedge from 0 to 30 cm controls the amount of water available for neutron moderation from 15 to 90 mm. This wedge, similar to the clamp, has two slots for wormdrive bands to pass through which then surround the drywell holding fast the wedge to the drywell surface. Upon installation, the absolute distance along the source tube of the beginning of the wedge will be noted so that the control software can move the source to the wedge location, then finely control its location by up to 30 cm to adjust water moderation.

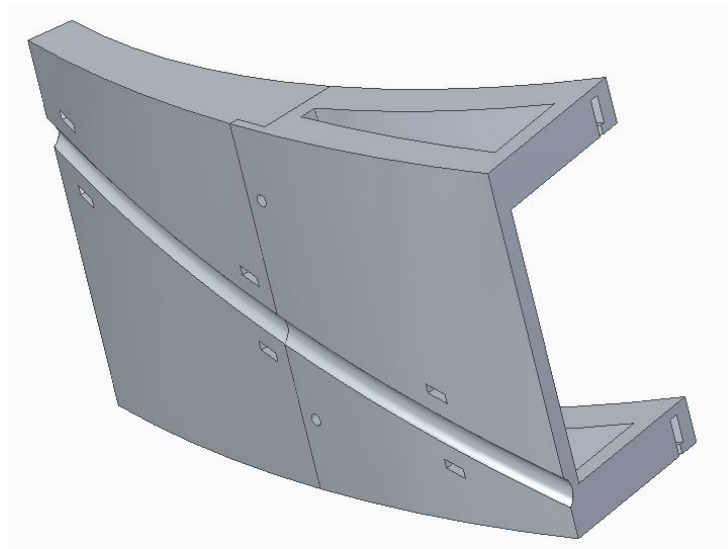


Figure 7.6: CAD model of the wedge which allows for controlled varying amount of water shielding between the source and the detectors. The inner curve of the wedge matches the curvature of the drywell, and the outer curve varies the spacing so that a thickness of 15-90 mm of water can be selected as shielding depending on where the source is located. Assembly constructed as two pieces due to machining limitations. There are two slots in the upper and lower legs for a wormdrive band to pass through which affixes the assembly to the drywell.

7.6 PE Shielding Box

The PolyEthylene (PE) box was constructed from 15 slabs of 5 cm thick milled PE, making an overall cuboid with dimensions of about $2' \times 2' \times 18''$. Figure 7.7 highlights the middle section of the box which holds 12 vertically stacked PE slabs and contains the S-curve. This orientation only requires the alignment of two slabs for the S-curve, whereas if the slabs were stacked horizontally, milling and alignment would need to be performed for each of the 12 slabs for the profile of the tubing at the respective height. Two $1/2''$ -20 threaded rods with lock-nuts at both ends go horizontally through opposite diagonal corners of the vertical slabs to compress the slabs rigidly holding them together. A single large horizontal slab sits below the vertical slabs, acting as a base, with the bottom of the return path of the S-curve also milled out of the slab.

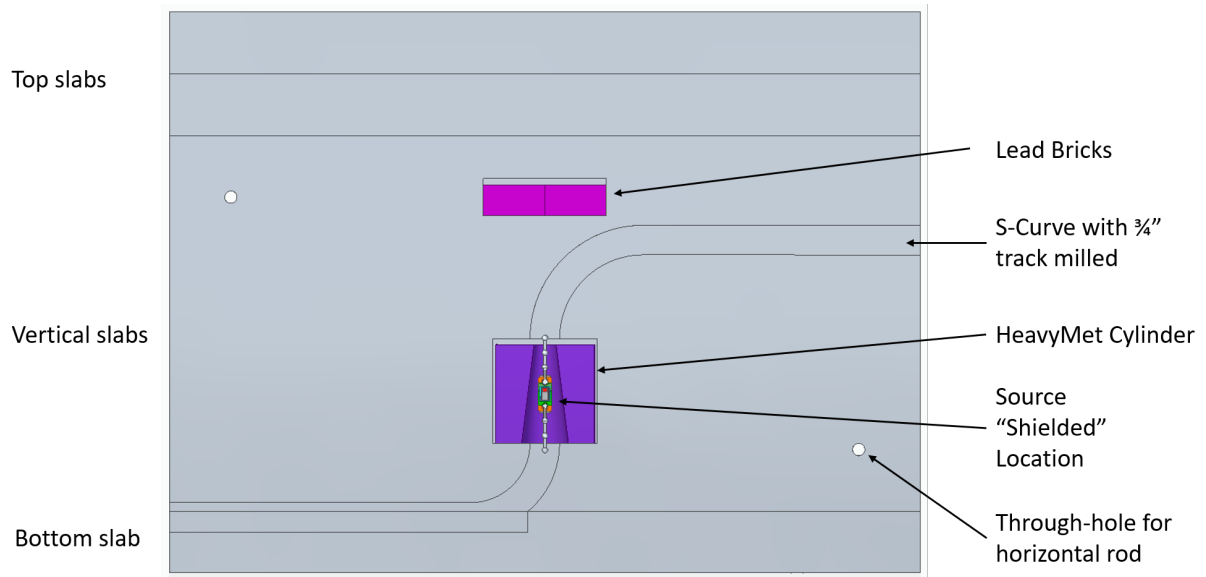


Figure 7.7: CAD rendering of the components in the middle of the PE shielding box. Shown are the PolyEthylene for neutron shielding (grey) and the gamma shielding components: lead bricks for gammas emitted with upward trajectory (pink) and cylindrical HeavyMet with a conical hole (purple). Horizontal through holes used to compress the vertically oriented slabs can also be seen.

Two horizontal slabs sit atop the vertical stacked slabs to provide sufficient shielding in the z-direction. The entire assembly was designed to be held together in the z-direction by four threaded rods which would travel through the corners of the horizontal slabs, and through the end vertical slabs as shown in Figure 7.8. The nuts for the vertical rods are hidden within the bottom slab using counterbored holes so that the bottom slab sits flush

on the floor.

After commencing the fabrication of the slabs, through discussion with the machinists it was determined that drilling a thru-hole vertically through the 1' tall vertical slabs would be difficult to do with precision. A design change was implemented where the vertical rods extend into the vertical slabs by 3", at which point a nut-access point is milled into the side of the slab. This access point is wide enough to place a nut inside in line with the vertical threaded rod, but narrow enough to prevent the nut from turning within the hole.

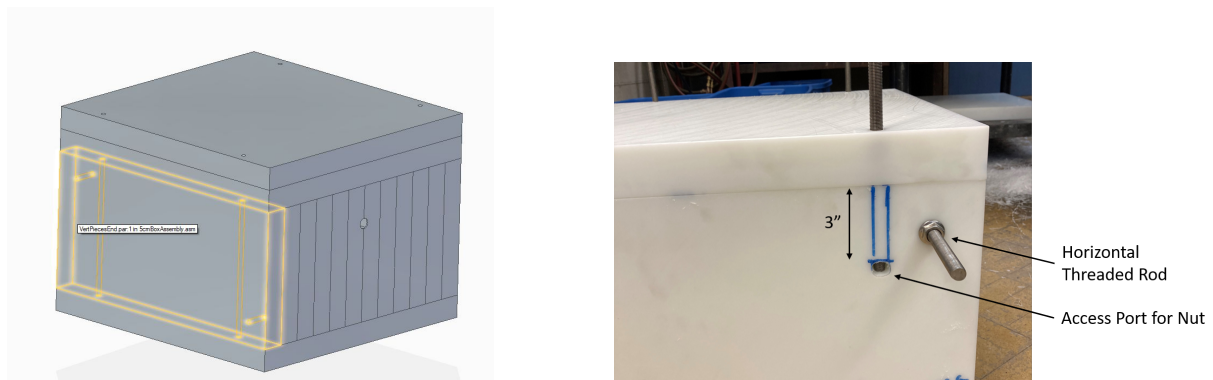


Figure 7.8: (Left) The original CAD design for how the PE box would be assembled, using six threaded rods going through slabs with locknuts at the ends to compress and hold it all together. Two rods horizontally through the 12 vertical slabs, and four rods vertically through the top sheets, end sheets, and bottom slab. The end slab is highlighted to see the internal holes. (Right) A slight modification during fabrication to extend the vertical rods only part way into the vertical slabs, with an access hole milled to insert a nut was made. After the box is assembled additional weights with a through hole will be added to the horizontal threaded rods.

The water tank in CUTE contains a large liner which cannot be penetrated for mounting or anchoring purposes. As such, a weight estimate was conducted of the assembly, to determine what action must be taken to ensure the box sits at the bottom of the water tank securely. If submerged in water the buoyant force almost compensates the weight of the PE box assembly, with only 20 N of net downward force. Therefore, additional weights will be attached to the horizontal threaded rods to achieve a total net weight in water of about 20 kg.

7.7 Control Box

The control system for this source is largely based on the control system for CUTE's ^{133}Ba calibration system, which itself was based on control software for SNO+. To move the source within the source tube, a stepper motor with a custom sprocket matching the bead spacing on the beaded chain rotates. The stepper motor is controlled by an AVR microcontroller which hosts a server so that users on the local network can view a webpage and control the actions of the motor. The AVR determines the source's location within the tube by counting the steps the motor takes, converting that to a rotational value, and then a linear motion value of the chain. This method of location determination mimics that used in the ^{133}Ba system, but for extra security a secondary system was designed to confirm and recalibrate the source's location. This location detection system is currently being designed with help of a SNOLAB engineer, Jasmine Gauthier, and consists of a limit switch where the chain passes through an extension of the switch arm. In specified locations along the chain marker beads which are larger than the typical beaded chain beads, are mounted on the chain, and will not pass through the limit switch hole. When the chain is moved to the point where the marker bead arrives triggering the limit switch, a signal is sent to the stepper motor to stop. These marker beads are installed a set distance away from the source during installation, so that a marker bead arrives at the limit switch when the source is deployed to the nominal calibration location, and in the other direction corresponding with the source being back in its storage location in the PE box. In order to prevent the chain from falling into the tube when the source is mounted onto or dismounted from the chain, a $\varnothing 1''$ chip which is larger than the opening of the tube can be attached to a bead of the chain. This chip slides in between adjacent chain beads, has a dimple in the center for one bead to rest, and sits on top of the tube opening as seen in Figure 7.9.

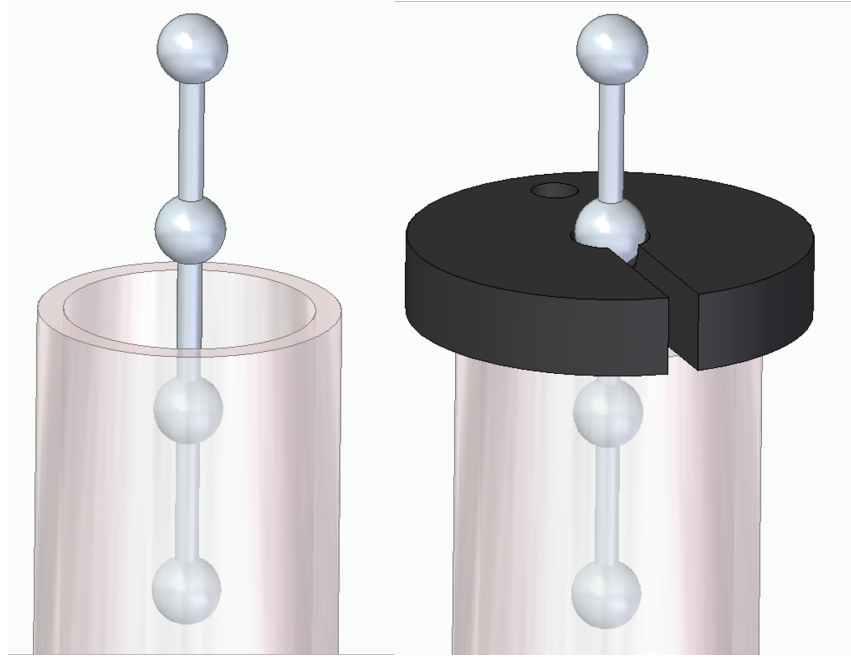


Figure 7.9: (Left) Without the chip, during mounting and dismounting of the source from the chain loop, the beaded chain could fall into the tube. (Right) A chip is installed between adjacent beads of the chain, holding the chain suspended, preventing it from falling into the tube.

All of the above mentioned components are designed to be contained or installed in a *control box*. The design for the box location and mounting was aided by Sean Crawford, a Queen's Junior Engineer and is summarized in Figure 7.10. A unistrut frame attaches to the CUTE deck I-beam and extends out above the pre-existing water tank access ports. Mounted on the frame is an aluminum control box which the stepper motor is attached to with the shaft of the stepper motor protruding inside the box. A secondary housing encompasses the bulk of the motor and protects the wiring with a strain relieved port to allow the cable going to the slow control rack where the AVR controller is located. Additionally inside the control box at the bottom is the a strain relief tube feedthrough for both ends of the source tube. Immediately above the feedthrough will be the limit switch for both directions of travel.

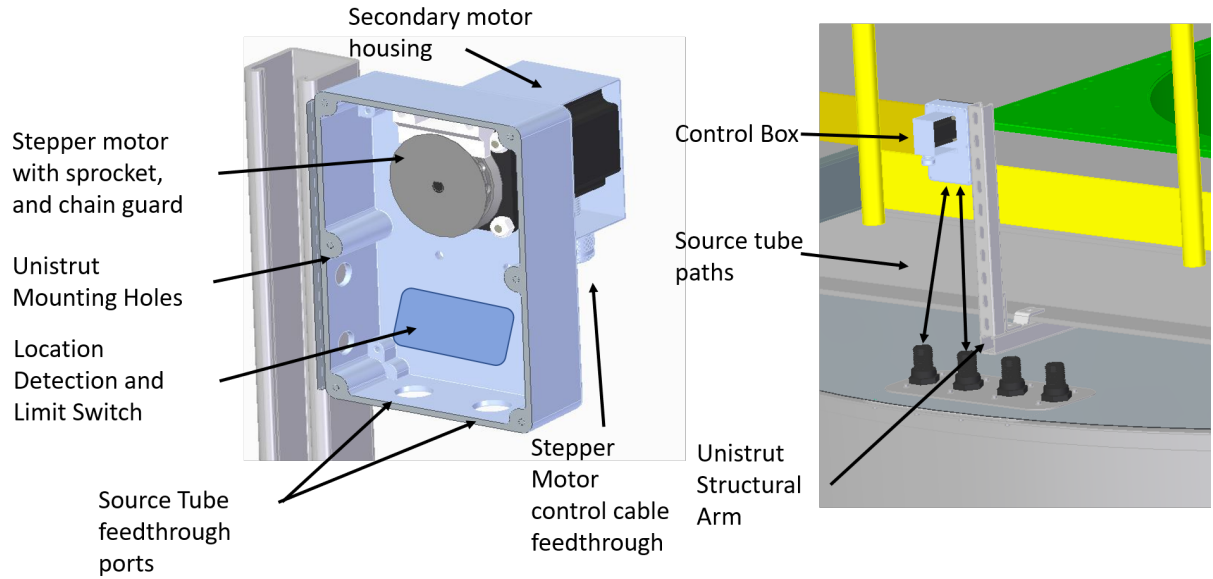


Figure 7.10: (Left) Control Box for the ^{252}Cf calibration system. A stepper motor is mounted to the back panel of a the control box. Inside, a custom sprocket with indents to match the beads of the chain, and a chain guide allow the rotations of the stepper motor to pull on the chain moving the source within the tube. Extra room was allocated below the motor for the design of the location detection mechanism, and a strain relief feedthrough for the plastic tubing. (Right) A Unistrut arm extends from the I-beam of the CUTE deck, to support the control box at a workable height above the water tank ports where the source guide tubes will emerge.

7.8 Software control

The stepper motor is controlled by an AVR microcontroller which relays commands and status to a server which hosts a webpage. This controller is responsible for both the ^{252}Cf source and the ^{133}Ba source, with only the control logic and specific pin wiring differing. The control as-is is rudimentary, and many of the unique software packages written for CUTE's subsystems are being reworked. To avoid duplication of work, for this thesis only a simplistic control was required. Modifications were made to the pre-existing ^{133}Ba software to allow for functionality with a second source control. Figure 7.11 summarizes the sequence of communication to access the stepper motor and control the deployment of the source.

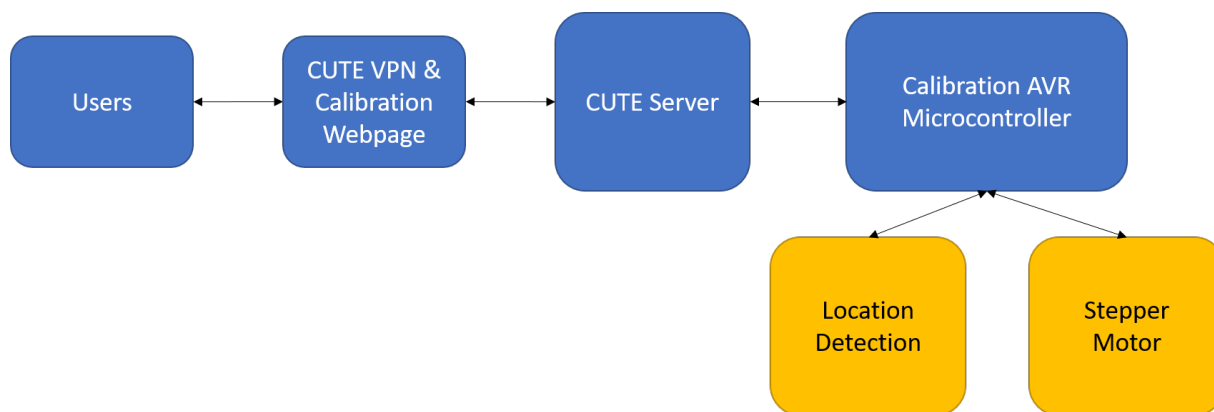


Figure 7.11: Summary schematic of the control system managing the calibration system. Users will communicate by a front end webpage which relays commands to the server and AVR for processing. The AVR sends the driving signal to the stepper motor to rotate, and monitors the signal from the location detection unit.

Once a user is connected to the CUTE local network, and they open the HTML webpage for the calibration system, a security check is implemented to ensure only approved users are able to control the source. The user can choose which source (Ba or Cf) to control, and a number of deployment options are made available. “Automatic Deployment” sends the source from the storage location to the pre-determined calibration location. “Send to Storage” directs the stepper motor to move the source back to its storage location in the PE box. The ability to manually drive the source is also made available by controlling the speed and direction at which the stepper motor turns. The AVR accepts the command coming from the server, parses it, and sends out a series of analog signals to the stepper motor to have it turn in a given direction at the requested number of steps. In all situations, the AVR monitors the signal coming from the limit switches and will stop the motor if one of them is triggered indicating the marker bead has arrived at the switch. Lastly, a dialog box is available for expert users to give commands directly to the motor for debugging purposes. Until the fully finished front end is, the current ^{133}Ba calibration system was modified as seen in Figure 7.12 so that the neutron source can be controlled by the dialog box directly.

CUTE Calibration System Log out

Automatic Calibration

Deploy for Calibration

Send to Storage

	Set	Act.
Speed (cm/s)	5	0
Position (cm)	-5	-5

Manual Calibration

Set Source Speed: 0 cm/s

Set Destination Source Position: -5.00 cm

Set Values

Submit

Select calibration type:

☐ Fixed Speed (STOP Manually, select direction)

☒ Fixed Position and Speed

Set Direction:

START

STOP

Logged in as: viewer

Active

Source Position (Depth from the edge of drywell in cm)

Rest Drywell Detectors

Source Speed (cm/s)

----- CUTE Cryostat Position Control v1.4 -----

(2 AVR's connected)

2021-03-21 23:03:50 [localhost] Connected

-5

comment:

Figure 7.12: Webpage for the calibration systems at CUTE. Presently the buttons for deployments and calibration control are relevant for the ^{133}Ba calibration system, however with the ^{252}Cf stepper motor attached to the AVR, it can be controlled from the dialog box below.

7.9 Testing and Validation

Prior to the full commitment to the design, a series of small proof-of-concept tests were performed to validate the project. A mock source, with similar outer dimensions, but constructed from solid aluminum rather than nested cylinders was created to investigate the feasibility of the S-curve bend using the beaded chain and stepper motor. An S-curve stand-in was made using milled aluminum plates, and using 7 m length tubing of similar dimension to that planned for the full scale project, a trial assembly was constructed. This test was to investigate the issue of friction of the chain within the tube, and whether the stepper motor would be powerful enough to pull the source through the tube in both directions. The test was successful, and the mock source could traverse the tube with ease, especially once the initial static friction was overcome. An observation made which further informed the design of other components was that the system worked more reliably when the tube was under tension - this was tested by adjusting the length of chain exposed between the breaks in tube, as shown in Figure 7.13. When the tube was not held in place firmly, as the chain began to be pulled by the motor, the static tension between the

chain and tube was too great and the tube would flex slightly in the same direction as the chain, rather than the chain moving inside relative to the tube.



Figure 7.13: Photo of the mock source in place in the testing set up. The chain was loaded in the plastic tube and was attached at both ends to the mock source. The exposed chain was then looped over the stepper motor gear and held in place to prevent skipping and using a protoboard, power supply, and function generator the stepper motor was driven moving the source within the tube.

Upon completion of the fabrication of the PE components of the box, a trial fit of the new source tube running through the box was performed. Although it was more difficult than originally anticipated to fit all the pieces together properly, the box could be completely assembled with the source tube, HeavyMet, and lead bricks inside. The AVR to be used for the control was already installed at CUTE to operate the Ba source, and no spare board was available for testing, an alternate driving method was used to test the stepper motor in the set up. A DC power supply, desktop function generator, and prototyping breadboard were used to drive the motor. Unfortunately, the friction of the chain was too great in the new tube which was longer at 50' in order to have excess which can be cut to the correct length during installation, and had more of a natural coil than the sample previously tested. The wedge and clamp to the drywell were tested using a garbage can, which has a smaller diameter than the drywell, but mimics an outer cylindrical face in which these pieces would be mounted in the water tank. Figure 7.14 shows how the pieces were supported around a cylinder, and effectively hold a sample tube in place.



Figure 7.14: Test conditions after the construction of various pieces in the Queen’s lab. (Left) Wormdrive band holding the drywell attachment piece which holds the source tube against the drywell with minimal water separation. (Right) Neutron energy spectrum variation wedge with a sample piece of tubing held in place on it, mounted to a test cylinder using a wormdrive band loop.

7.10 Conclusion and Recommendations

Much of the work for the ^{252}Cf calibration system has been completed. From the initial idea generation, design and refinement, to the proposal and approval process required by SNOLAB backed by simulation results. Construction of the shielding and many of the accessories of the full system is complete and various levels of testing have been performed. The design of the location detection method, software control front end, and the development of an installation procedure are currently underway such that the system can be fully implemented in SNOLAB in the coming months.

The issue of too much friction between the source chain inside the tube was discovered during the full scale tests with insufficient time for adequate mitigation to be implemented. Moving forward, a potential solution would be to attempt to cure the plastic tubing in such a way so that it holds more of a straight shape rather than a spiraling loop. This might reduce the area inside the tube that the plastic beads make contact with, and hence reduce the friction, allowing the stepper motor to pull the chain through. Another potential solution is to replace the plastic tubing with custom produced metal piping. The coefficient of friction between the metal and beaded chain may be less, but the primary

advantage is that the metal will hold its shape well, minimizing the bends and reducing the number of beads which make significant contact with the tube wall. Until the full system is available at CUTE, the source can still be used for calibrating detectors using the “old” SNOLAB calibration method of notifying at least 1 week in advance to all other experiments and deploying the neutron source manually.

Chapter 8

Calibrations and Analysis

8.1 Optimal Filter and Collected Energy

Chapter 3 summarized how SuperCDMS detectors go from a particle interacting in the detectors to it being read out by the electronics at the SQUIDS. In Chapter 4 I discussed how the signal goes from the cold electronics to being stored on offsite servers. The next step is the processing of the data where a large number of variables (“Reduced Quantities” or “RQs”) are calculated from the raw traces. The most important information about an event is the energy deposition, which is related to the amplitude of the pulse. By looking at the spectrum of deposited energies, trends will appear which can suggest a number of features of the detector, the facility, and possibly the new discovery of dark matter. The pulse amplitude is measured using an “optimal filter”, or OF. An OF is a template fit in frequency space where the contribution from different frequencies are weighted according to their contribution to the standard pulse shape and their prevalence in the noise spectrum.

The OF is optimal when the true pulse shape remains constant with only the noise contribution varying between pulses. The data points of the pulse trace are converted into frequency space by a fourier transformation, and here the optimal filter amplitude is found by minimizing the χ^2 between the pulse template in frequency space and each pulse [80]. The contribution of noise comes from a series of randomly triggered events at the beginning of each run called the “beginning-of-run-randoms”. In a typical case with constant pulse shape, a pulse trace, $P(t)$, can be described as the sum of the Noise $N(t)$

and a function describing the pulse shape (template) $A(t)$ multiplied by a scaling factor, a , accounting for the pulse amplitude:

$$P(t) = a * A(t) + N(t) \quad (8.1)$$

In SuperCDMS, we know that the location of the event within the detector can affect the shape of the pulse as it is received at the QETs, particularly the rise time of the pulse and the early pulse shape. The change in the relative contribution of the pulse shape from the rise time and decay time can be accounted for by adding a second pulse template to the model and extend the OF algorithm to finding a linear combination of the two templates that best describes the pulse. Figure 8.1 shows visually how the fitting of the raw trace can be described by the relative amplitudes of two templates. By following the signal back through all of the amplifications and signal modifications, the original cause of the pulse is a change in current through the TES line. As such, accounting for the scaling, the Optimal Filter Amplitude after processing is stated as a current by which the template would be multiplied by to represent the true change in current of the TES.

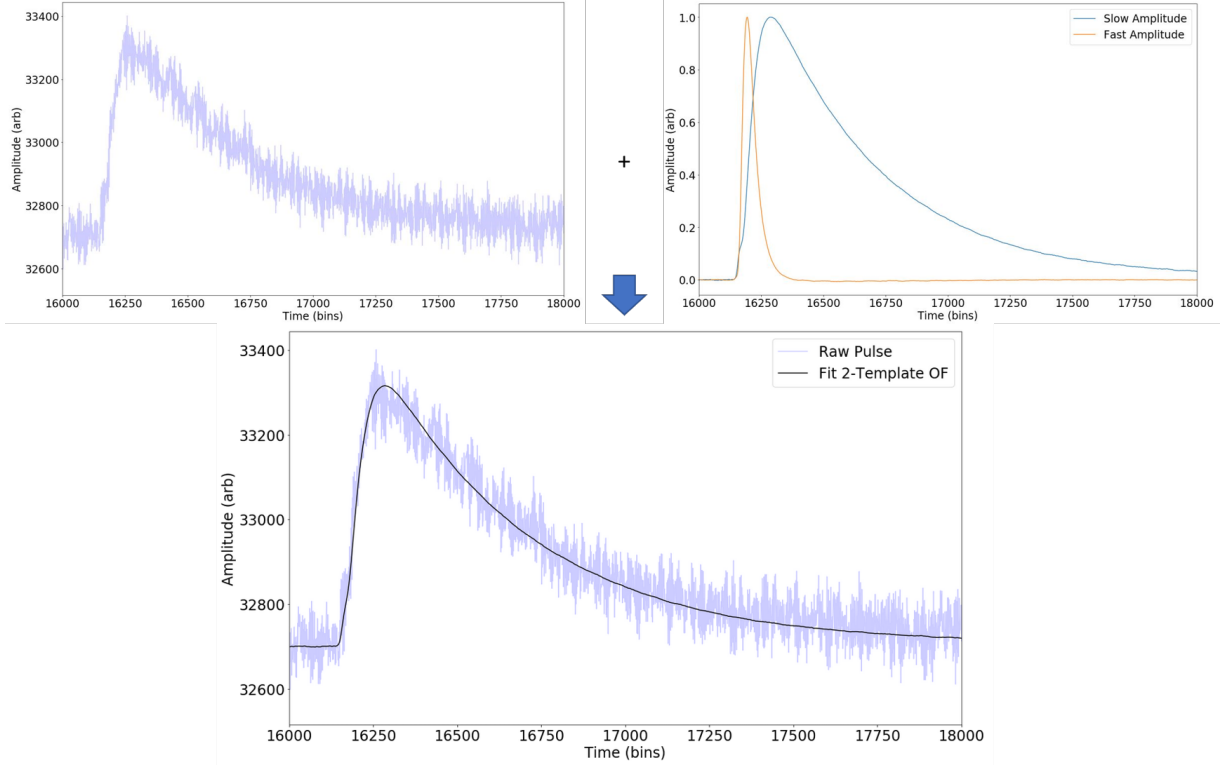


Figure 8.1: (Upper Left) Raw trace of an event in T5Z2 detector. (Upper Right) Fast and Slow templates used in the 2-Template Optimal Filter processing. (Bottom) Raw pulse with the 2-Template optimal filter fit associated with the pulse

Using the calibration files and the operating variables of the detector, this optimal filter amplitude (OFamp) can be directly converted into the deposited energy in the QET. Each detector and channel on the detector has a unique collection efficiency which states how much energy in the crystal lattice will be absorbed by the QET. Knowing the deposited energy in the QET, and the original event energy deposited in the detector, this collection efficiency can be calculated; or conversely knowing the deposited QET energy and the collection efficiency, the original event energy can be calculated.

To convert the value of the OFamp to collected energy, first we convert the current in the TES to power absorbed. This power is the rate that energy is absorbed by the sensor as the event occurs in the detectors, as the influx of quasiparticles heats the TES. While no events are occurring in the detector, the readout current which passes through the TES leads to a small amount of heating due to the TES's resistance from being in transition. This heating of the TES is what is referred to as the steady-state power, and is required to keep the TES in transition. The signal power, P can be expressed as the deviation away

from the steady-state power of the TES, P_0 , as determined by the instantaneous power from the TES, P_s :

$$P = P_0 - P_s \quad (8.2)$$

where

$$P_s = I_s V_{TES} = I_s V_R \quad (8.3)$$

Using the IbIs calibration curve for each detector channel, as an example shown in Chapter 3 Figure 3.11, we can infer how the instantaneous current through the TES, I_s , would adjust based on the external power applied. Figure 8.2 shows the cold electronics circuit displaying the branching of the bias current between the shunt resistor and the TES.

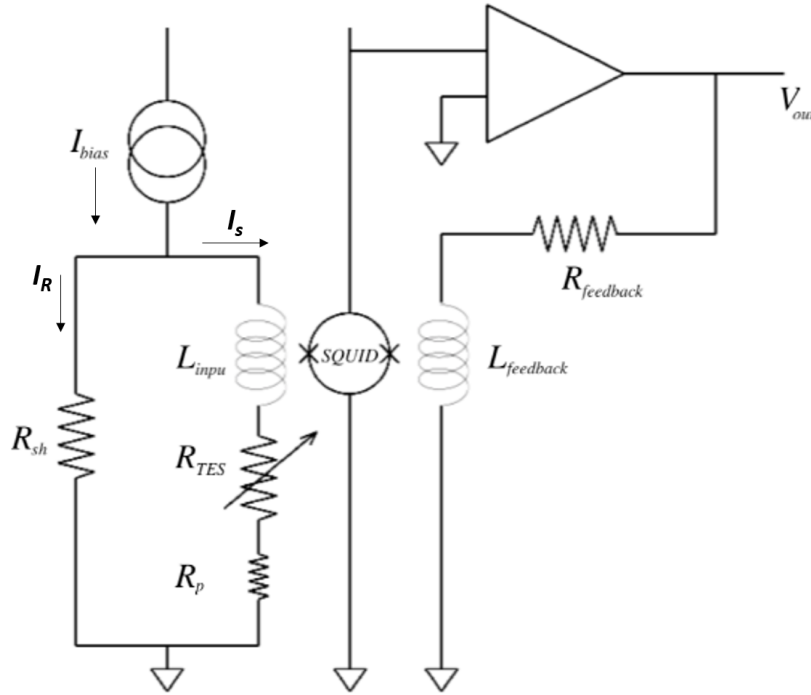


Figure 8.2: Cold electronics diagram showing the branching of the bias current into the TES channel I_s and into the shunt resistor I_R

Since the shunt resistor branch, R_{sh} , has a much lower resistance than the TES branch, most bias current goes through the R_{sh} resulting in a nearly constant voltage. A change in resistance of the TES slightly changes the proportion of bias current which goes into the TES channel, and therefore the overall voltage across both branches. The correction on the calculation of the bias across the TES resistor is given by Equation 8.4. For full

derivation of the absolute TES energy calibration see [81], but the main conclusion is that the instantaneous power is proportional to the operating current of the detector and the slope of how the TES current changes relative to bias current. The intermediate terms describing the branching between the shunt and TES channels end up cancelling when this correction is applied resulting in the following equation:

$$V_{corr} = -\frac{I_s/I_b}{dI_s/dI_b} * R_{shunt} * I_b \quad (8.4)$$

The sign of this correction is negative to account for the fact that the slope of dI_s/dI_b is negative. To get the power of the signal in the TES, this corrected bias, V_{corr} , is multiplied by the current going through the TES. To go from instantaneous power to energy, the power must be integrated. Instead of integrating the pulse itself, we integrate the OF fit template as this is much less noisy and describes the pulses well. This integrated template is multiplied by the pulse correction term above, and the OFamp value for each event yielding the energy collected by the TES sensor:

$$E_{collected} = OF_{amp} * \int Template * V_{corr} dt \quad (8.5)$$

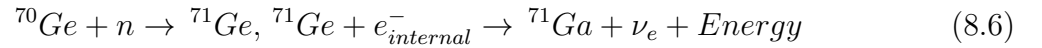
The integrated template and V_{corr} , called the “scale factor” are be different for each channel, and each series within a run if the operating conditions change, but will remain consistent from pulse to pulse within a series. If, over the course of the run, as the detector continues to cool and relax further from the initial cooldown, the IV calibration curve changes, the scale factor can be updated.

8.2 Collection Efficiency

Knowing the collected energy is useful, but for science searches we need to calibrate this energy and understand what the true event energy would have been to yield the collected energy at the sensor. The use of external radioactive sources in CUTE such as the ^{133}Ba source can calibrate at higher energies, since sources need to be strong enough to penetrate some shielding, but this energy scale is O(100 keV-1 MeV) typically. At lower energies we

must look for signals which would be present internally in the detectors.

Through neutron capture with a cross section of 3.05 ± 0.15 b, ^{70}Ge , a stable isotope adds a neutron to its nucleus becoming ^{71}Ge [49]. The ^{71}Ge decays with an 11.4 day half-life via electron capture; a proton and electron interact forming a neutron and an electron neutrino, turning the atom into ^{71}Ga . ^{68}Ge is another isotope which is cosmogenically produced, which also undergoes electron capture decay with a longer half-life of 270 days. In both of these isotopes, characteristic X-rays or Auger electrons are emitted associated with the binding energy of the electron in the atom which interacts with the proton. The characteristic X-rays can be emitted from the K, L, and M shells with energies of 10370, 1298, and 158 eV respectively but only the K-shell X-rays are considered in this analysis. The relative abundance of the other peaks are 10.3% and 1.7% respectively making them much less prevalent, and the energy scales at which they occur are close to or below the energy threshold in CUTE measurements [82]. Since this decay happens in the bulk of the detector, the X-ray interacts with other nearby Ge atoms and is converted to phonon energy of the crystal lattice. A summary of the two required reactions for this energy to be detected from a ^{71}Ge event is given below:



Using this 10.37 keV true energy peak as a calibration point, we can calculate the collection efficiency for each channel in the detector in order to reconcile the collected energy with the true energy. For future analyses, this collection efficiency can immediately be used, since collection efficiency is a property of the detector, QET masking, and TES for each channel.

This analysis used data taken during CUTE Run 11 from Dec 2019 - Jan 2020 on the T5Z2 detector. T5Z2 is an old CDMS Soudan Ge iZIP detector with a mass of 0.6 kg. This detector had been stored on surface for a number of years prior to its delivery to CUTE, and was expected to have a significant amount of ^{71}Ge and ^{68}Ge present. The generation of detectors from which T5Z2 was produced have 4 channels on each side of the detector, making 8 total as seen in Figure 3.7, however for this run only 4 channels

were wired up due to limited readout channel wire availability. During the run, one of the connected channels behaved erratically (issues with the SQUID) so it was decided to only take data with the three remaining detector channels: A2, C2, and B1 with the affiliated readout channel names PAS2, PBS2, and PFS2 respectively. Each of the three channels had the optimal filter processing done on their individual traces, but in addition the traces were summed together and then an optimum filter was applied on the sum. This summed OFamp is called PT (Phonon Total).

Figure 8.3 shows the initial spectrum of collected energy for one of the data series after the scaling to convert from OFamp to collected energy was applied. It can be difficult to discern where the 10.37 keV peak may be hiding, so a number of different avenues were pursued to attempt to isolate for the peak.

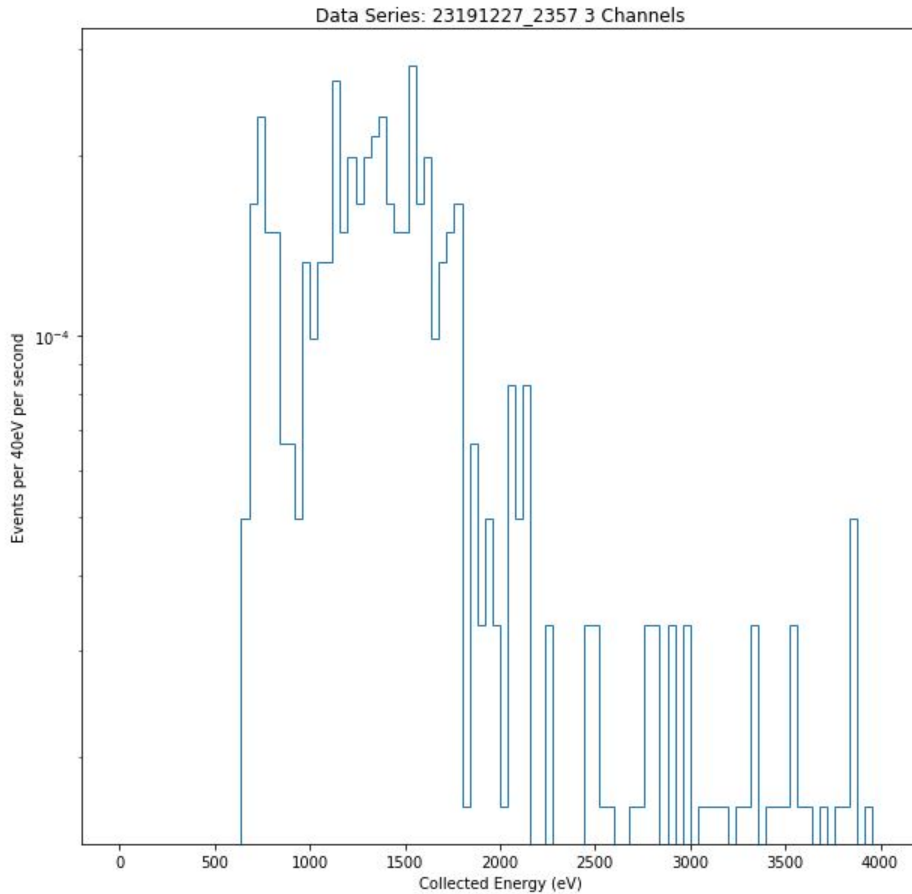


Figure 8.3: Collected energy summed over 3 channels of T5Z2 detector in CUTE for one data series in Run 11

Since the electron capture events have the same energy we would expect the shape of

the pulse in the trace to be very similar, differing only when events may occur in the crystal near a surface (surface effects can modify the observed pattern of absorbed phonons). The 2-Template Optimum Filter (2TOF) can be used to distinguish between the components of the pulse which are indicative of the event energy in the *slow* component, from the pulse component coming from the local effect of an event occurring close to a sensor or surface in the *fast* component.

Looking at the scatter plots in Figure 8.4 of the slow vs. fast template contributions to the overall pulse shape for the 3 channels individually, and the sum of the 3 channel traces, one channel in specific appears to have greater separation between the clusters of the 10.37 keV peak and the low energy background. A cut was applied on PFS2 channel for the collected event energies between 200-640 eV of the slow amplitude collected energy, and the events associated with that cut are then shown where they appear in the other channels in blue. Looking particularly at channel PAS2, there is great overlap between the low energy background and noise events with the ^{71}Ge events. Applying this cut selecting the events we know are ^{71}Ge from PFS2 allows us to analyse the other channels. The removed low energy events from PFS2 are highlighted in red in the other channels.

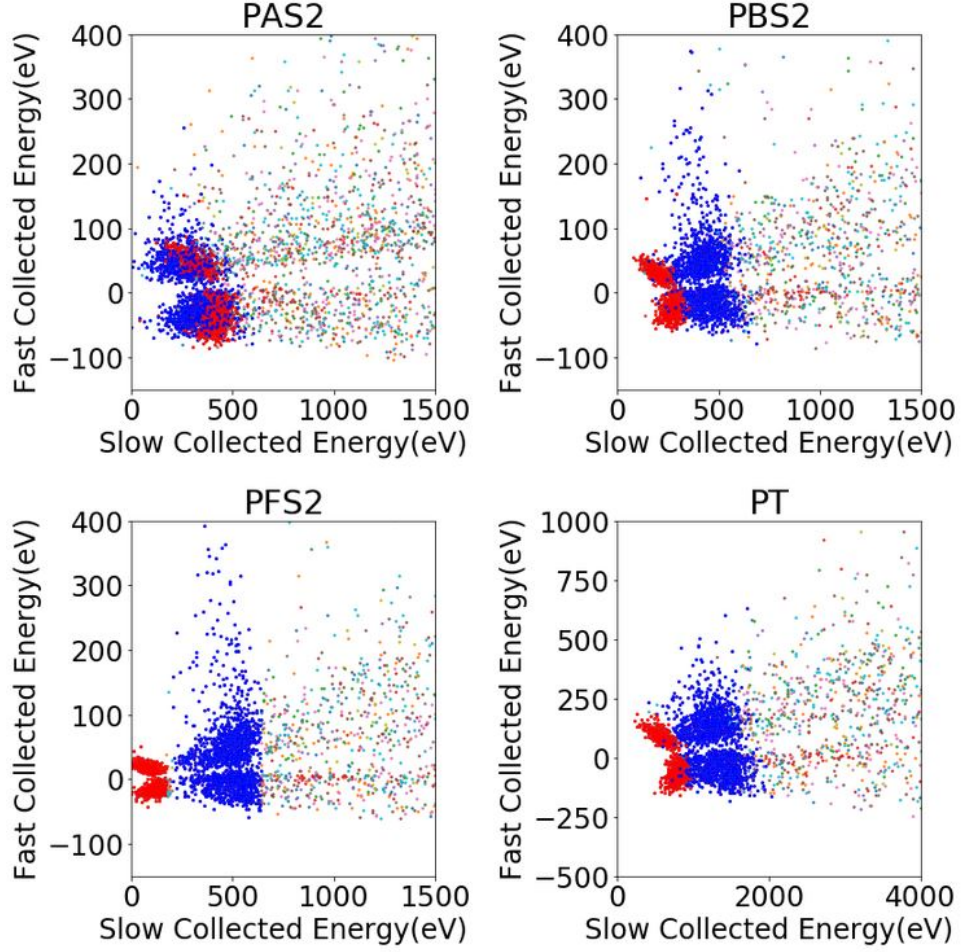


Figure 8.4: Scatter plot of the collected energy coming from the slow vs. fast optimum filter templates. PFS2 (bottom left) show the greatest separation between the events of interest and the low energy background events. The events in PFS2 between energies 200-640 eV are highlighted in blue in the other channel plots, while the low energy background events are shown in red

The good (blue) events were then subjected to a χ^2 cut, looking at how well the 2TOF fit the trace. Looking at Figure 8.5, of the already selected blue events, in channel PBS2 the pulses were most consistently fit with the majority being in a single band of χ^2 values. Events with an absolute χ^2 less than 35000 were kept, discarding those above that value. Since each pulse contains 2^{15} (32768) data points, this χ^2 band of events which pass the cut fit the model very well. Even though the events which failed the cut were in the acceptable energy range, they are more likely to have been caused by another source of random noise.

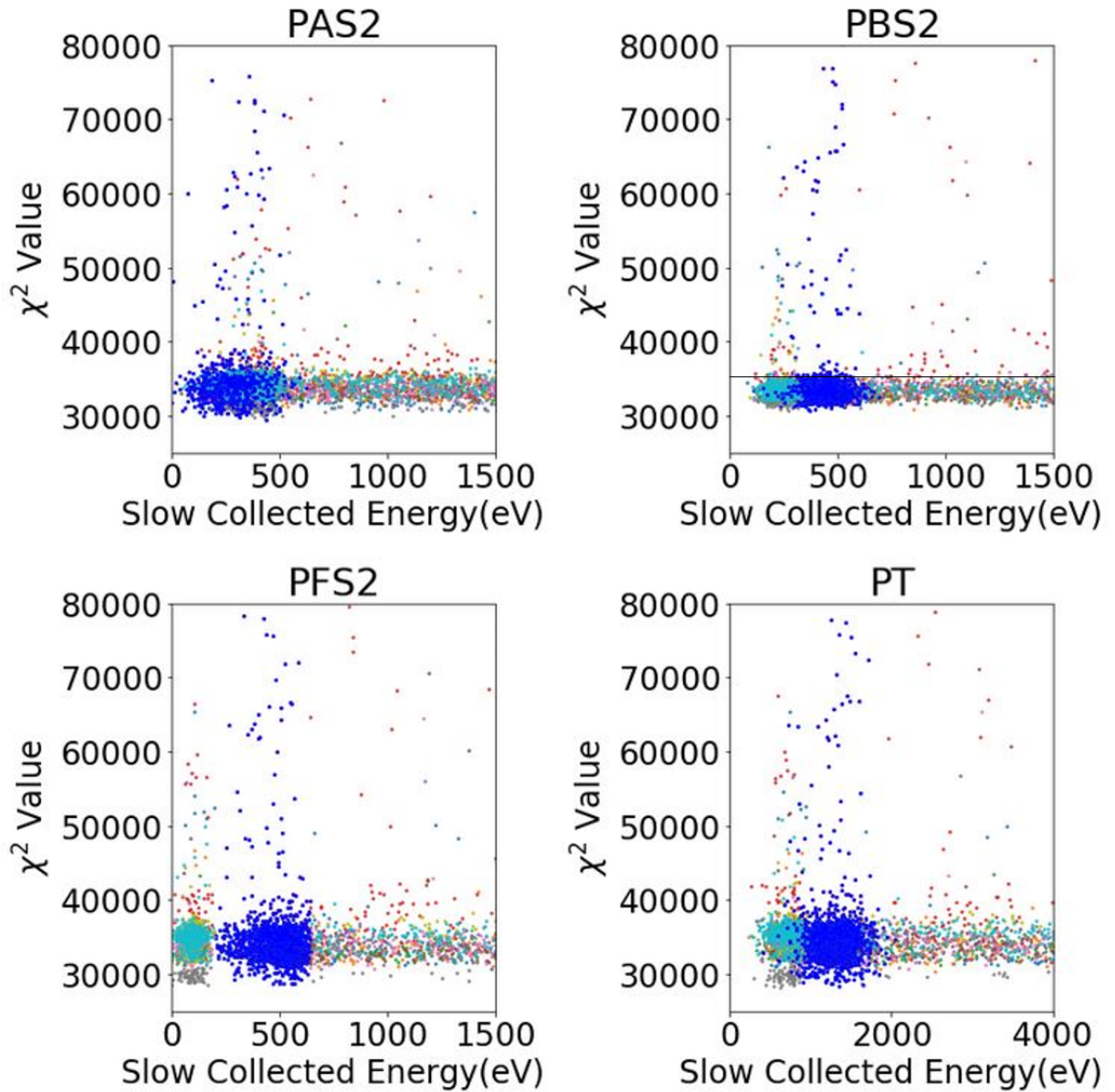


Figure 8.5: χ^2 values for each detector channel against event collected energy. Since channel PBS2 shows the most consistent band of χ^2 values, it was selected to be the channel with the cut removing events whose χ^2 value surpassed 35000 as indicated by the black line in the upper right plot, and this cut would apply for all channels

The remaining events of a single series were plotted for each channel on histograms shown in Figure 8.6. To find the mean collected energy of the Ge 10.37 keV peak for each channel, fitting this Gaussian distribution would be required.

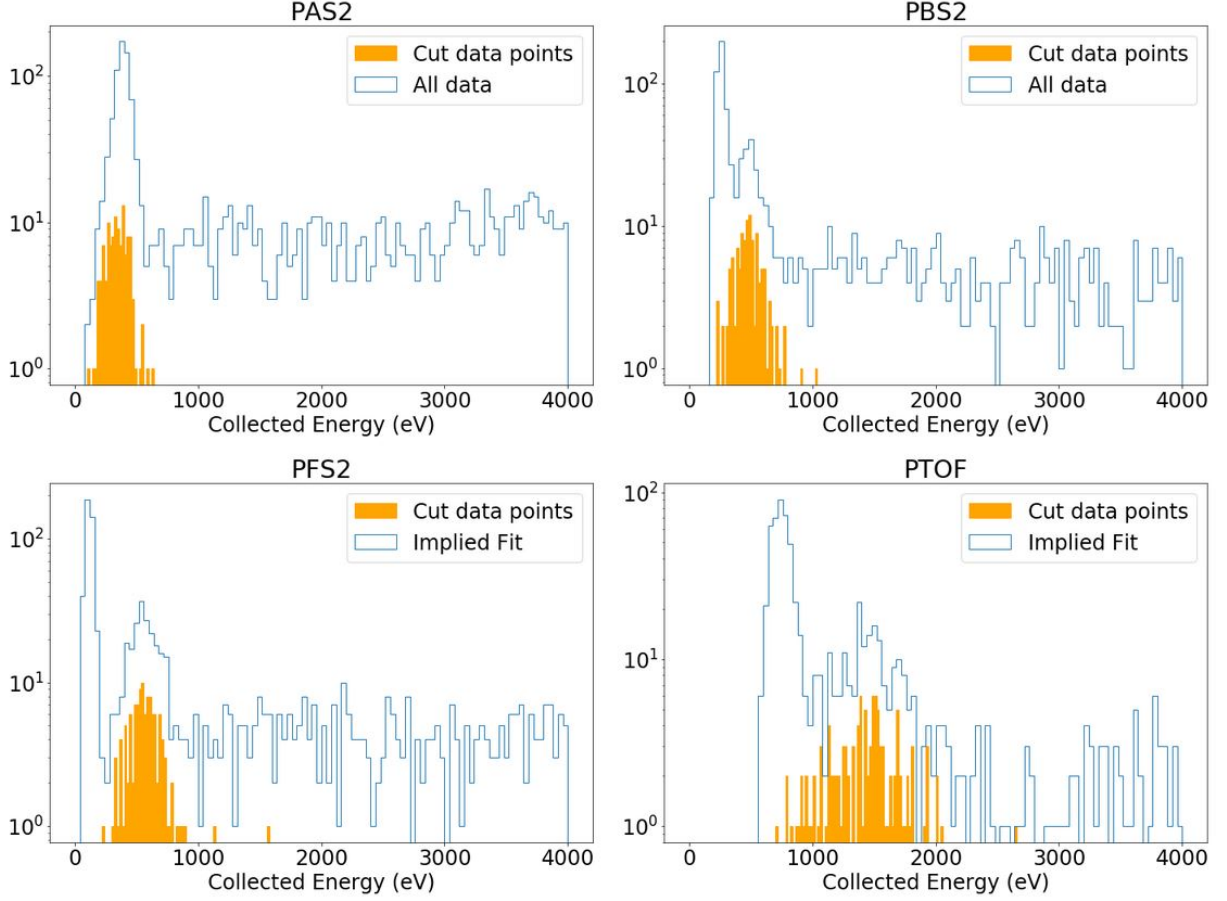


Figure 8.6: Histogram of each detector channel showing the counts per collected energy, and the cut data (orange) showing which of the data points belong to ^{71}Ge decay events standing out from events from others sources (blue)

Fitting a Gaussian function to binned data can lead to large uncertainties due to discretionary binning. To avoid the need for binning, a cumulative distribution was applied to the collected energy. Thus, instead of fitting a Gaussian to a binned distribution of the collected energy, I fit an error function (which is the integral of a Gaussian) to the cumulative distribution where the form used to fit the data is given by Equation 8.7.

$$y = A * \text{erf}((x - \mu)/\sigma) + d * x + e \quad (8.7)$$

Where A is a scaling factor corresponding to the number of data points in the distribution, μ is the mean location of the Gaussian, σ is the standard deviation of the peak, d is included acting as the constant background on the Gaussian data, and e is an offset for the error function to help with fitting (since error functions are centered vertically about zero this value is $A/2$). The associated Gaussian function using the same parameters is:

$$y = \frac{2 * A}{\sqrt{\pi} * \sigma} * e^{-(x-\mu)^2/\sigma^2} + d \quad (8.8)$$

Once the analysis was tested for each individual channel and data series, the fit was applied to all data series combined. Since the “scale factor” for each series was adjusted to account for slight differences in operating conditions between data series, the collected energy values across different series are consistent with each other. The cumulative function and error function fitting were applied to this collective data set and are shown in Figure 8.7. Taking the derivative of the fit error function yields a Gaussian fit for the summed cut data set which is shown in Figure 8.8.

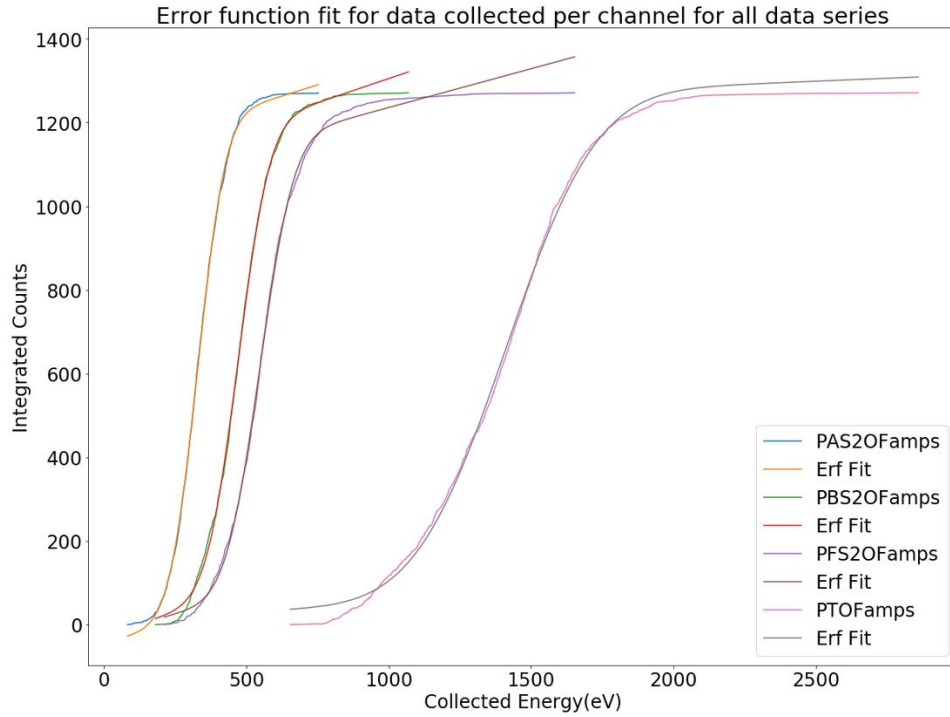


Figure 8.7: The collected energy for all data series shown after a cumulative function was applied, and the error function fit for that data

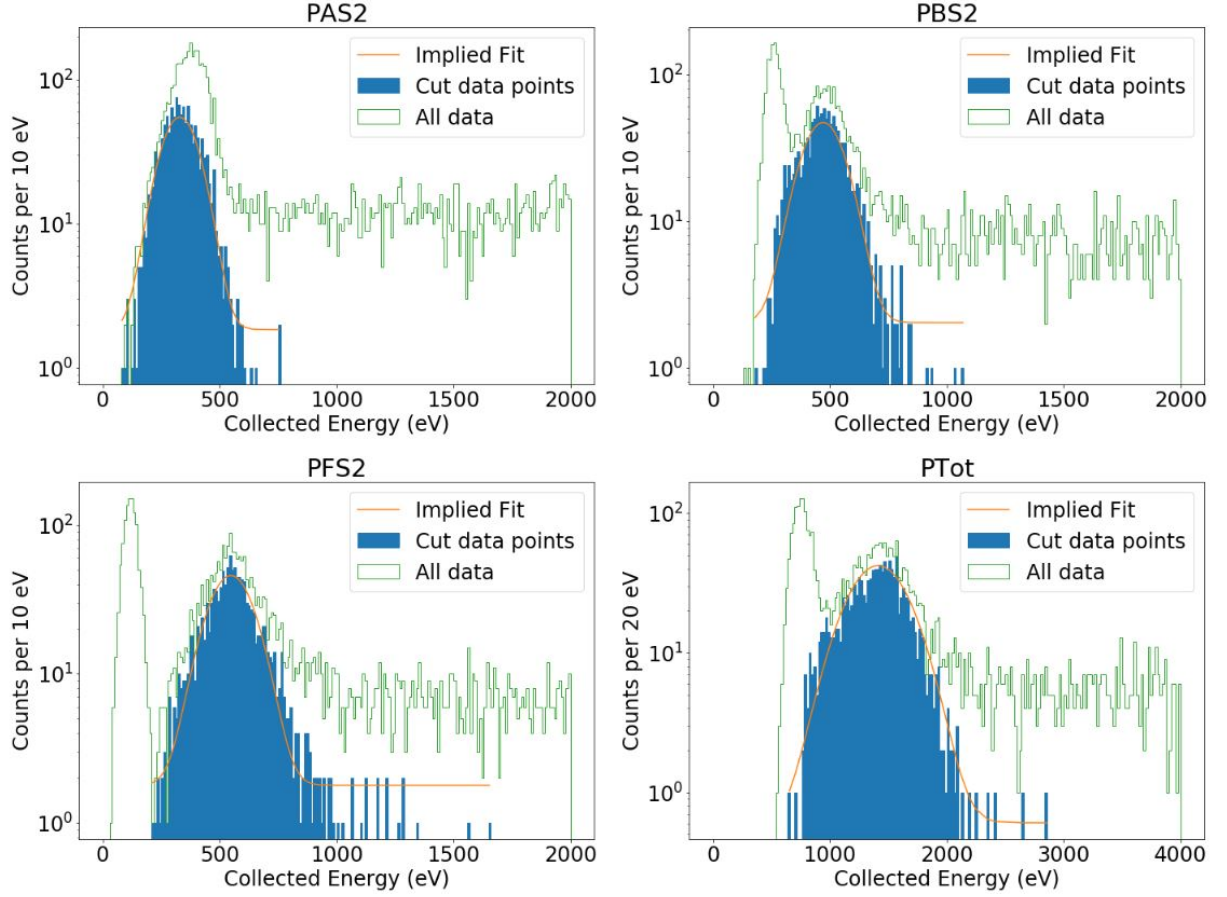


Figure 8.8: Fits of the differential of the error function (orange line) of the binned cut data (shown in blue) for each of the 3 channels with all R11 data series summed together. Distribution of the uncut data shown in green

Table 8.1 summarizes the means and standard deviations for each of the available channels in T5Z2 detector in Run 11. Despite only three channels being actively read out, the other five remaining would still collect phonons, meaning we know that not all event energy is collected. To first order, we can assume that the collection efficiency is about the same for all channels, so each channel's collected energy would be about $1/8^{th}$ of the event energy. We can estimate a total collected energy from the PT fit, multiplying it by $8/3$.

Table 8.1: Summary of the locations and widths to the 10.37 keV peaks, and implied collection efficiency in three channels of the T5Z2 detector and the sum of the three channels. The collection efficiency in the last column is calculated under the assumption that each of the eight phonon channels absorbs the same amount of phonon energy.

Detector Channel	Collected Energy mean (eV)	Collected Energy Standard Deviation (eV)	Collection Effi- ciency (%)
PAS2	329.6	108.4	25.4 ± 8.4
PBS2	471.8	122.8	36.4 ± 9.5
PFS2	548.3	132.5	42.3 ± 10.2
PTOT	1413.0	353.2	36.3 ± 9.1

The work done on this analysis was further continued by M. Baiocchi for ^{133}Ba calibrations on the T5Z2 detectors searching for the 356 keV peak associated with its decay [83]. This study was focused on finding the optimal deployment distance of the source for the best peak resolution. It utilized the framework from this analysis to convert the OFamp into collected energy, and further into event energy knowing the channel specific collection efficiency. It also used the Error Function and Gaussian fitting needed to quantify the peak location and width. Figure 8.9 aligned the 356 keV peaks and by looking at the associated parameters of the fits, 83 cm deployment height was determined to be the optimal position for energy resolution.

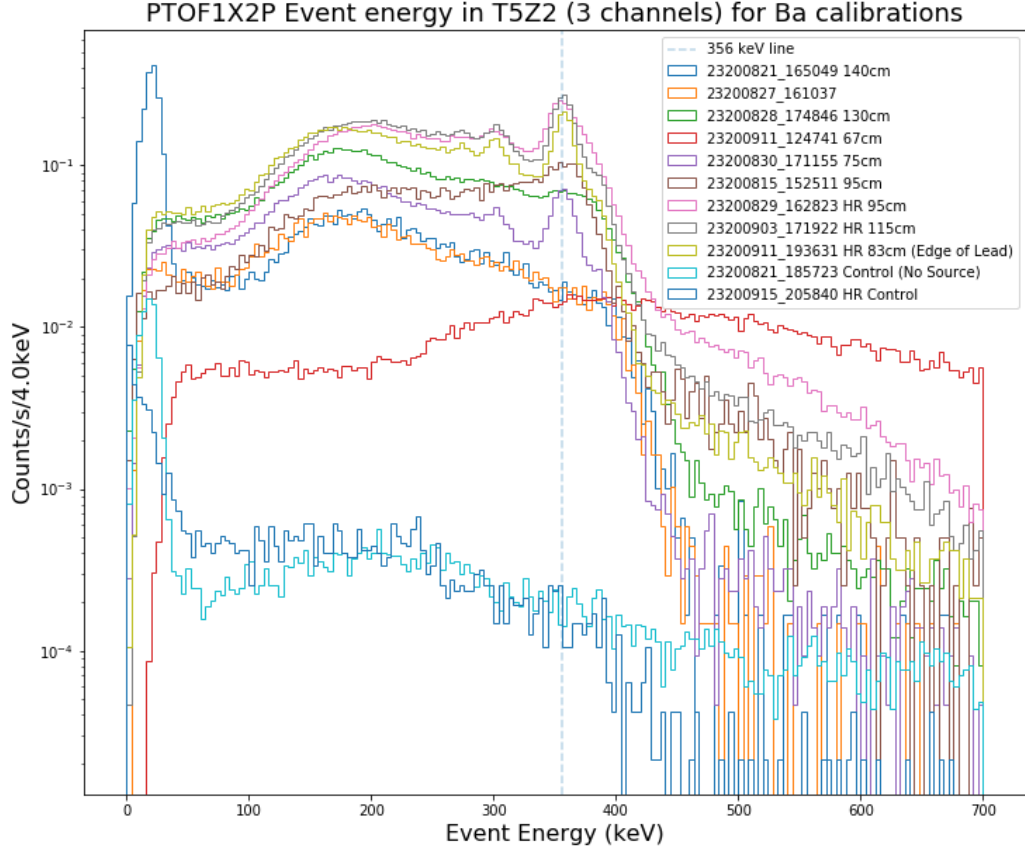


Figure 8.9: Various ^{133}Ba source locations with the 356 keV γ peak for each series aligned. From this study 83cm deployment position was determined to be the optimal calibration location for best event energy resolution. Figure provided by M. Baiocchi [83]

8.3 Conclusion

This analysis took the processed data of the T5Z2 Ge detector from Run 11, isolated and quantified the Ge 10.37 keV peak, and from it calculated the collection efficiency of three detector channels. To continue this work, the T5Z2 detector can be irradiated by a neutron source between cryogenic runs, such that it is activated for future analyses. From these analyses, finding the collection efficiency in the same manner can inform the longevity and consistency of the detectors and readout QET system. Furthermore, by searching through old CDMS Soudan data after detectors were radiated by neutrons, by extracting the collection efficiency from the detectors at that time and comparing to the collection efficiency found in this study, one can study if the collection efficiency changes

due to environmental conditions.

Chapter 9

Conclusion

The science community has been making good progress in the hunt for Dark matter, an elusive form of matter which through galactic scale observation we know exists, but have yet to detect its fundamental form. SuperCDMS, a dark matter search experiment with a specific focus on the low mass region of less than $10 \text{ GeV}/c^2$, is currently in the installation phase in SNOLAB, but a number of test facilities and institutions are working to understand the performance of the detectors and components which will go into the main experiment.

The Cryogenic Underground TEst (CUTE) facility is one such facility, with a cryogenic dilution refrigerator located also in SNOLAB in a low background, low noise environment. CUTE has been operating since Summer 2019, with work done to reduce the noise experienced by detectors in the facility, identify and understand the background associated with being in its location underground, and optimizing operations so that when the time comes for rapid testing and characterization of detector towers for SuperCDMS, the process will be fluid and reliable. This thesis discusses the contributions made to reduce the noise conditions of the facility by re-engineering subsystems as required. By optimizing the cooling procedure of CUTE, cooldowns are now more consistent and the time required to reach base temperature has reduced by 5 hours, with projections for future cooldowns to be even faster. In addition, many efforts were contributed to the general operation and maintenance of the facility, ranging from payload changes, cryogenic and detector operational shifts, developing and writing procedures, and training related to working in the facility to new members.

Analysis was performed to calibrate the T5Z2 detector in CUTE in the range of ~ 10 keV by identifying the 10.37 keV peak associated with electron capture on ^{71}Ge and ^{68}Ge . From this, the collection efficiency of three detector channels was determined, and a recommendation for future work is to repeat this calibration by activating the detector with a neutron source prior to a run, and repeating the analysis to determine the collection efficiency. This will inform how the detector performance may change over time in an underground environment.

The design work, construction, and preliminary testing of the neutron calibration system for CUTE has been completed at Queen's. The system will store a ^{252}Cf source inside a shielding box within the CUTE facility and allow for remote deployment to irradiate the detectors for calibration or activation. Through simulation it has been shown that the source does not contribute a significant background to CUTE or neighbouring experiments, and does not pose a health risk to personnel. The feature of being able to vary the level of shielding of the neutrons has been thoughtfully included to give the facility the ability to control the rate and spectrum of neutrons seen by the detectors. Future work to find a solution to mitigate the issue of friction within the source tube is needed before the system can be installed in SNOLAB.

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