ENPH 457 Final Report

A Neutron Calibration System for the Cryogenic Underground TEst facility (CUTE)

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Abstract

The SuperCDMS is an experiment that aims to probe the low mass region of the Dark Matter candidate called the WIMP. As a means for verification and testing of the technology used in SuperCDMS, the Cryogenic Underground TEst (CUTE) facility is being developed. Since the Germanium and Silicon detectors in the experimental setup rely on nuclear recoils of potential Dark Matter candidates, it is important to understand how the system will respond to nuclear recoils of known particles. For this reason, a neutron calibration system was designed. The novelty of the proposed design is that it allows for the neutron source to be contained within the experimental setup of CUTE, and remotely controlled to deploy the source. Modifications to a Monte Carlo simulation of the CUTE geometry were made such that different shielding designs could be coded into the simulation and tested for safety. The final design of the system contains a ^{252}Cf source which is double encapsulated on a source chain loop ensuring adequate knowledge of the source's location at all times. The shielded location of the source will be inside the water tank of CUTE, in the middle of a series of stacked polyethylene sheets where an S-curve is machined out of, so that the line-of-sight of the source to the outside of the water tank is minimized. Monte carlo simulations were performed using the proposed geometry verifying the safety of the source for all personnel working outside the experimental setup indicating the expected dose rate to be about 1 nSv/hr, adhering to SNOLAB's radiation protection program.

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Acknowledgements

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Chapter 1

Introduction

1.1 Problem Definition

The Cryogenic Underground TEst (CUTE) facility will be used to test detectors for the Super Cryogenic Dark Matter Search experiment (SuperCDMS) at SNOLAB, a low background underground laboratory located in Sudbury, Canada [1, 2]. SuperCDMS detectors are designed to identify the nuclear recoils from dark matter particles colliding with the detector via phonon and charge signals. They consist of disks of single Ge or Si crystals with thin metal films on their flat surfaces configured into sensors for phonon and electrical charges.

It is important to have a good understanding of the detector's response to interactions of different types to be able to interpret the data in terms of interactions with dark matter particles. This is accomplished by performing calibrations where the detectors are exposed to known types of particle interactions. For CUTE and many other dark matter experiments, this is done by introducing radioactive sources of known energy near the detector to generate dark matter-like events. For the CUTE/SuperCDMS collaboration the nuclear recoils from neutrons have been thoroughly investigated and it has been determined that calibrations with neutron sources is an important step in understanding the response of the detectors [3]. The task for this project is to model, and design the neutron calibration system for CUTE such that it can be built and implemented in SNOLAB. To model the CUTE facility with a neutron source, GEANT4, a particle simulator program developed by CERN, is to be used [4]. The simulations will inform design decisions about thickness of shielding and placement of the calibration system to limit the activity outside the experimental setup to a safe level in accordance with SNOLAB's radiation safety regulation [5].

1.2 Project Specifications and Constraints

Determining the required activity of the source is to be done by simulating the experimental setup with the neutron source in the anticipated calibration location, and interpreting the rate of neutrons in the detectors. The system also has a goal of being completely automated, so that the source can be permanently stored within the experimental setup, and moved into a calibration position with remote controls. The rate of events seen by the detector when the source is in the storage location should be minimal, not exceeding about one event per kg per day.

Since this system is to be installed in SNOLAB, all regulations set by SNOLAB in addition to the general safety considerations set by the Canadian Nuclear Safety Commission (CNSC) must be adhered to. These include, but are not limited to providing enough shielding to remain under 2.5 μSv/hr Dose emitted, ensuring that none of the personnel could possible be exposed to an annual radiation of more than 1 mSv, the limit for non-Nuclear-Energy-Workers (NEWs) personnel [5]. Due to the nature of neutrons giving a signal similar to that expected from Dark Matter, SNOLAB requires a laboratory simulation estimating how many particles will travel to lab area of nearby experiments. To alleviate the risk for potential contamination of sources from the manufacturer, SNOLAB requires all radioactive sources to be additionally doubly encapsulated upon delivery. Lastly, contingency plans should be made for the event of an accident or human error to minimize the risk to lab personnel.

Chapter 2

Background

2.1 Dark Matter

A problem has puzzled scientists for many years; accounting for all stars, and other light emitting mass, there are numerous examples where visible matter accounts for only a fraction of the total matter expected in a system.

The strongest observational evidence leading scientists to believe in the existence of the non-luminous matter (Dark Matter) is the rotation curves of galaxies. As early as 1906, Lord Kelvin first proposed a simple method to estimate the amount of matter in a system: treat each constituent as a gas particle and observe its orbit within the system in order to yield an estimate for the total mass [6]. This proved to be a good theory, and an astronomer named Fritz Zwicky was the first to notice at the galactic scale a discrepancy between the observed luminous matter and the predicted matter due to the velocities at varying orbits, called the rotation curve [7]. An example of a rotation curve is seen below in Figure 2.1.

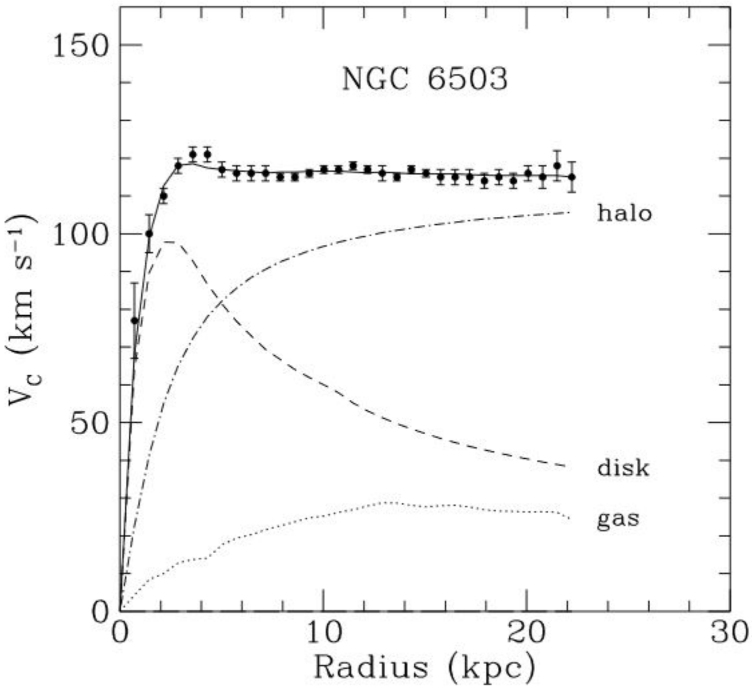

Figure 2.1: Rotation curve of the NGC 6503 galaxy. Shown are the expected velocities contributions from the disk and gas of the galaxy, the suspected Dark Matter halo, and the observed velocities of stars in the galaxy [8]

A second astronomical observation which leads to the suggestion of dark matter has come from certain cases of two clusters of galaxies colliding. The specific form of the galaxies is called a bullet cluster, which presents itself as two nodes after the merging of two galaxies passing through one another.

Figure 2.2: Astronomical image of the 1E 0657-56 galaxy cluster

In these bullet clusters, the visible mass is grouped in the center, since it interacts with other visible mass from the other galaxy seen in the image as the pink colour. We measure this via x-ray emission. The more violet colour, however, is where the center of masses of the galaxies are, based on gravitational lensing effects, supporting the idea that dark matter constitutes most of the mass [9].

There have been many suggested candidates for dark matter, ranging from super-massive black holes, to extremely light particles called axions [10]. The candidate with the most promise currently is the Weakly Interacting Massive Particle (WIMP), largely due to the "WIMP Miracle". One can predict the interaction cross section, effectively how likely a particle is to interact with other particles, for various massed and sized particles. Since it is known that everything was created from the big bang, and known how long ago that happened, a prediction about the abundance of a particle one would expect left in the universe for a given cross section can be made. The miracle of the WIMP is that for the approximate mass and cross section range, the same abundance value predicted there should be left in the universe is the same that the astronomical observations suggest.

Through the years, many experiments, employing different detection methods, have been performed with the goal of directly detecting WIMP interactions. The common interaction they are looking for is a nuclear scatter of a WIMP, where the nucleus' recoil can be detected. The two important parameters governing a WIMP's characteristic for detection are the mass and cross section. Experiments commonly plot an exclusion limit, the line corresponding to the threshold values at which the experiment would have been able to see a signal, had the WIMP parameters been above the line. An example of such a plot is given below in Figure 2.3.

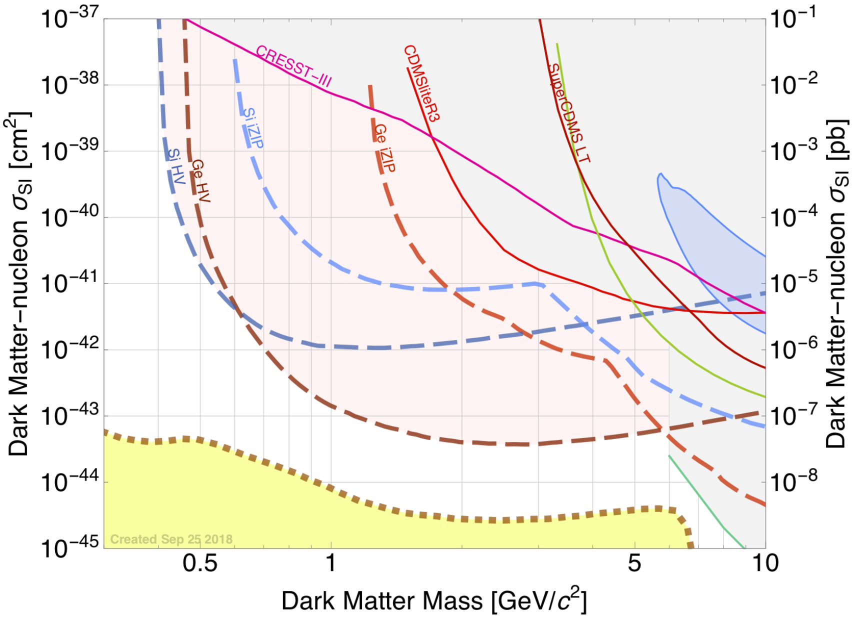

Figure 2.3: Current exclusion limit of Dark Matter mass and cross section, with expected sensitivity of SuperCDMS in its different operating modes shown as dashed lines. Shown specifically is the low mass region which SuperCDMS will be particularly sensitive to. Source: [11]

2.2 SuperCDMS

The Super Cryogenic Dark Matter Search (SuperCDMS) is a proposed experiment which will use germanium detectors at milliKelvin temperatures to detect small depositions of energy due to interactions with the electrons or nuclei in the crystal. The deposited energy is then carried through the crystal in the form of phonons (quantized vibrations) to the surface of the detector at which point Transition Edge Sensors (TES) convert the energy into a measurable electrical signal. The TES can be thought of as a highly sensitive thermometer, which, when a deposition of energy occurs, the experiences a dramatic change in its electrical resistance. This TES coupled with a sensitive electronics system transmits a signal out of the experiment proportional to the amount of original phonon energy. SuperCDMS detectors also have a second detection method which helps separate and classify interaction in the detectors. Energy deposited in the crystal can also ionize atoms, freeing electrons, which allow the detectors to record another signal by collecting charges on the top and bottom surfaces using an applied bias voltage. The experiment will be composed of 4 detector stacks, each holding 6 detectors, with the capability to hold up to 31 stacks.

Despite having a highly sensitive experiment which can discriminate between different interaction types, particle physics experiments cannot make scientific claims if the background event rate (events which might *look* like Dark Matter, but in fact are caused by regular particles) is too high. CDMS has run many test detectors and facilities in the United States to date, with the most advanced endeavour at Soudan lab in Minnesota, however even at over half a kilometer underground, there was still a notable background event rate from cosmic rays. For this reason, SuperCDMS is moving to SNOLAB in Sudbury, Canada for the SuperCDMS experiment to be installed in an even lower background facility.

2.3 CUTE

Before the CDMS experiment ran in Soudan, there were a few surface labs tasked with characterizing and testing each detector before they were to be sent underground. Once they arrived at Soudan, it was noted that the behaviour of detector performance was notably different in certain aspects when operating underground. Measurements on surface were hindered by the high rate of cosmic ray muons. It would be useful to the experiment to know whether the discrepancy between detector behaviour in the past was a function of location (surface vs. underground), or another unknown reason. Additionally, for SuperCDMS there are a number of hypothesized operation methods which have the potential to allow for a lower exclusion limit to be set, however these methods have not been tested in a full scale environment similar to SuperCDMS. Lastly, the characterization of detectors is extremely important in understanding the data from the experiment.

For the aforementioned reasons, the need for a test facility in conditions similar to that of SuperCDMS at SNOLAB. The Cryogenic Underground TEst facility (CUTE) will be a single stack facility whose role will be to understand the SNOLAB environment for a cryogenic experiment, characterize detectors to be installed in SuperCDMS, and act as a test facility for new technologies. We aim for CUTE to be installed and operational in SNOLAB by the summer of 2019, and have the potential to perform science data runs in early 2020. A diagram of CUTE is shown below in Figure 2.4.

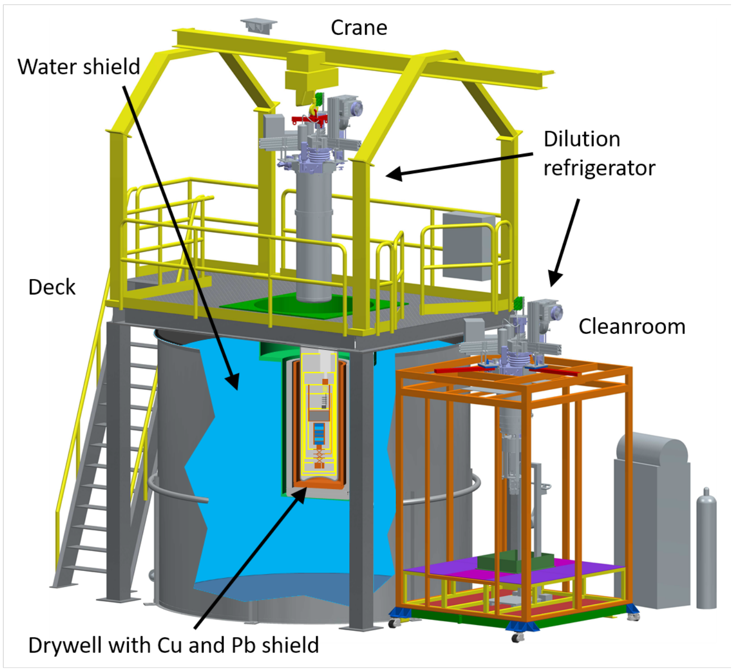

Figure 2.4: A CAD model of the CUTE facility. A monorail crane is used to lift the dilution refrigerator from the cleanroom into the shielded drywell in the water tank

2.4 Calibrations and Calibration Systems

Calibrations for experiments are performed by exposing detectors to regular matter particle interactions. For experiments which have different sensitivities corresponding to different particle types, multiple radioactive sources or particle beams will be used to probe the different particle type responses.

A common method of calibration is using radioactive sources inserted through the experiment's layers of shielding to expose itself to the detector. Understanding the source's location is important, for both correctly categorizing the energy reaching the detectors, as well as for health and safety of personnel operating the experiment. Some techniques experiments have used have been measuring the length of rope released by counting the corresponding number of rotation commands given to a stepper motor with Labview code, as proposed by the NEWS experiment, or a system 4 of 6 camera to monitor the source position on its journey into the detector as used in the PSUP Camera system in SNO+ [12, 13]. An example of such a calibration system is shown for CUTE's gamma source delivery method in Figure 2.5.

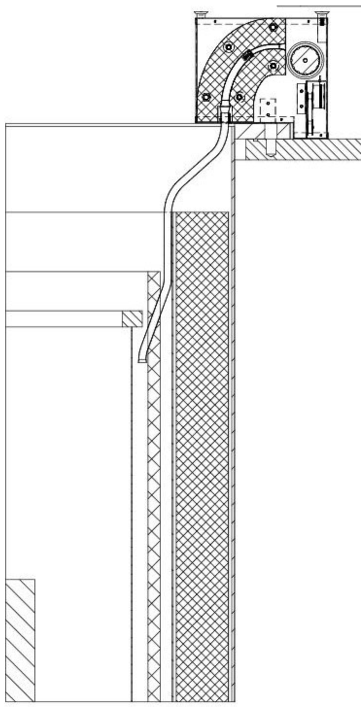

Figure 2.5: Gamma source for CUTE guided delivery system through shielding

For SuperCDMS detectors specifically, a gamma source calibration is required in order to probe how ionizing radiation is measured by the detectors via electron recoils. Gammas at high energies also allow for an understanding of how photoneutrons might look [14]. Nuclear recoils are also important, as WIMPs are expected to produce nuclear recoils. Using a neutron source is the most common method to achieve this calibration, which also gives the potential for a secondary calibration method [3]. ^{70}Ge is the most common stable isotope of Germanium, however when a neutron is absorbed by an atom to produce the ^{71}Ge isotope, this will further decay to ^{71}Ga via electron capture, which releases a characteristic photon or auger electron, or a mixture. This process is useful for calibration because it emits photons from within the detector, allowing for bulk Ge calibration in addition to the surface events which come from the external γ source.

Chapter 3

Simulations

3.1 Particle Physics Simulations

A common way in physics to predict the behaviour of a real system is through a simulated model using probability of events at incremented small steps sizes. The goal of this branch of physics, called Computational Physics is to build a system which statistically is representative of how a true system would behave. Monte Carlo simulations are the most common form of computational physics within particle physics, with many different programs being developed including GEANT4, FLUKA, PYTHIA, and MCNP [4, 15, 16, 17]. The commonality of all of these code packages is the ability to define geometries, set physics lists which defines the rules and probabilities of interactions occurring, and simulate particles in the program, the output of which can be used to make predictions. An example of a geometry which could be simulated is shown in Figure 3.1.

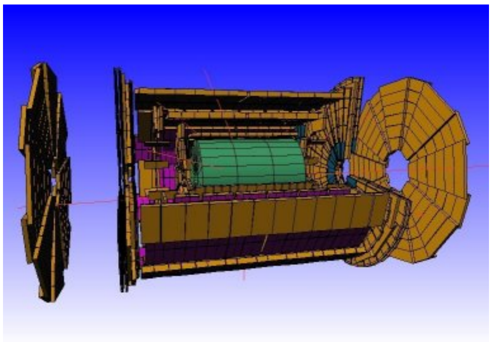

Figure 3.1: A GEANT4 simulation rendering of the ATLAS experiment [4]

3.2 SuperSim

Within the SuperCDMS collaboration, geometries and simulation parameters have been developed over the past 7 years into a package called SuperSim. This program ensures consistency among collaborators for simulation settings and allows for a common starting point for future geometries. The program is set up so that the user can define certain geometries to be *sensitive*, meaning that the particle parameters will be saved in a ROOT file when it interacts with said geometry. The ROOT files can then be analysed after simulation to extract the relevant information about particle tracks and interactions.

Chapter 4

Design

4.1 Initial Considerations

In the initial discussion for how to implement an autonomous system, it was suggested that keeping the source in the CUTE water tank away from the detector, and the outer walls of the tank would provide sufficient shielding to moderate the neutrons to achieve sufficient safety for humans. Water is good at attenuating fast neutrons, however to account for the possibility of the water tank being drained and the source being left in the tank during the draining accidentally, a secondary shielding method is required. The proposed solution is a polyethylene (PE) box, with a guide for a source tube machined into the middle of it, located at the bottom of the water tank. The source would be attached to a deployment chain and would be moved between the shielded and calibration locations by a stepper motor control system at the surface of the water tank. Since the source will be located in a location away from the control system, a detection method must be implemented to ensure the source was in the safe location, and did not get stuck in the guide tube along the way.

Neutron sources used for calibration usually fall into one of three categories; spontaneous fission, photoneutron sources, or alpha-decay induced neutrons. The latter works on the principle that the source is a mixture of an α source with a low-Z material, like Be, which occasionally when an interaction with an α occurs will emit a neutron as a product. An example of such a source, Americium Beryllium (AmBe), is given below:

$$^{241}Am \rightarrow \, ^{237}Np + \, \alpha + \gamma + 2e^-$$

$$^{4}\alpha + \, ^{9}Be \rightarrow \, ^{12}C^{2+} + \, n + \gamma$$

The disadvantage of using these types of sources is that most ^{241}Am decays do not result in a neutron, only about one in every 15000 α decays yields a neutron. For this reason, sources of this type require a high activity to yield a reasonable neutron rate [18].

Photoneutron sources are a combination of a low-Z isotope which, when a photon of sufficient energy is absorbed by the nucleus, will emit a neutron. Unfortunately, these sources have a similar problem to the α-n sources in that the probability of the decay happening is low, meaning a high activity source is required to achieve a reasonable neutron rate[18]. A common example of a source of this type is SbBe, which produces one neutron for approximately every 120,000 ^{124}Sb decays depending on geometry, and it follows the process below [18]:

$$^{124}Sb \rightarrow \,^{124}Te + \beta^{-} + \gamma(1.69MeV)$$

$$\gamma + \,^{9}Be \rightarrow \,^{8}Be + \,^{1}n$$

Spontaneous fission neutron sources are composed of a radioactive isotope which usually have a common decay mode, such as α decay, but will occasionally undergo 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 it's high neutron yield. ^{252}Cf undergoes fission in about 3% of all decays, with an average of 3.5 neutrons per fission making it the most efficient portable neutron source for calibration [18]. Considering that the intended use of the source is to stay contained in the water tank at all times, minimizing the overall activity limits the amount of energy introduced into the system. Additionally, a ^{252}Cf source gives a softer spectrum than a ^{241}AmBe source meaning the average neutron energy is lower which would yield a more comparable energy spectrum to a predicted WIMP spectrum. For all of the aforementioned reasons, a ^{252}Cf source was selected for this system.

4.2 Iterative Design

Sources are typically stored outside of the experimental setup, brought in from storage, and fed through a guide tube into the experiment usually relying on gravity for deployment. In the case of CUTE, since the source is to live permanently inside the water tank extra considerations will need to be made.

As mentioned, it is critical during the operation of a source to know where in the guide tube the source is. The importance lies in mitigating the potential for accidental exposure to either the detectors during a non-calibration period of time, or exposing personnel unknowingly. Since there is no easy method for visual confirmation of when the source is securely in the shielded location, different solutions were considered for ensuring the source arrived at the safety location in the PE Box correctly.

Multiple ideas such as a pressure pad, an electrical pad or a geared loop nested inside a larger guide tube with the source contained inside an inner source tube were suggested.

A simple circuit was proposed to detect when the source reached the bottom of the guide tube in the shielded location. Two nested conducting rings would be connected by the metallic source encapsulation when it is lowered onto the pad acting like a switch which completes the circuit. The pressure pad works on a similar principle, but rather than the encapsulation completing a circuit to give a signal, it would be the weight of the encapsulation resting on a sensor which produces the *safe* signal.

The disadvantage of the circuit and pressure pad ideas is that it only gives you a boolean signal when the source is back in the shielded location. In the event that the signal does not arrive when the user expects it (indicating a blockage), no more information is gained about the source's location. Also, deployment in these designs relied on gravity, meaning any snags in the tube would cause the chain to pile up and the source would stop. For these reasons, a geared loop of the string within the source tube was hypothesized as shown in Figure 4.1. The premise is that since the source would doubly connected, with a chain attached to the top and bottom of the encapsulation, deploying it and returning it to the storage location are both pulling actions, rather than relying on gravity. Any potential blockages would be immediately felt as resistance in the stepper motor, and the location can be tracked by counting the number of turns of the motor.

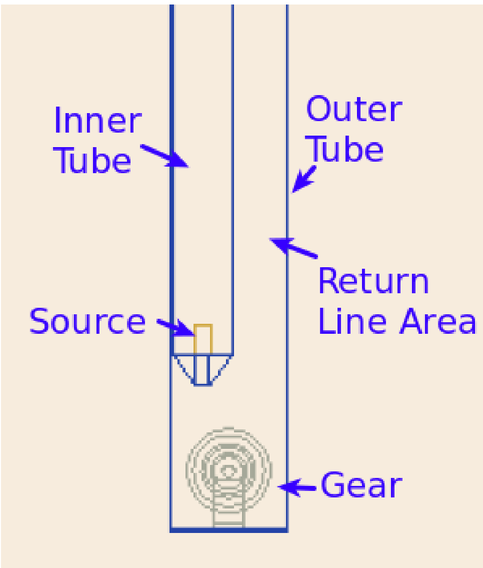

Figure 4.1: Sketch of gear system with nested source tubes

The issue with the geared solution is that it requires a large tube, and a number of finely machined pieces to be installed inside it. The best solution is to employ the advantages of the geared solution (a double ended source encapsulation) without having the return line be contained in the same section of tubing as the source deployment. A conceptual diagram of the different states of such a system are shown below in Figure 4.2.

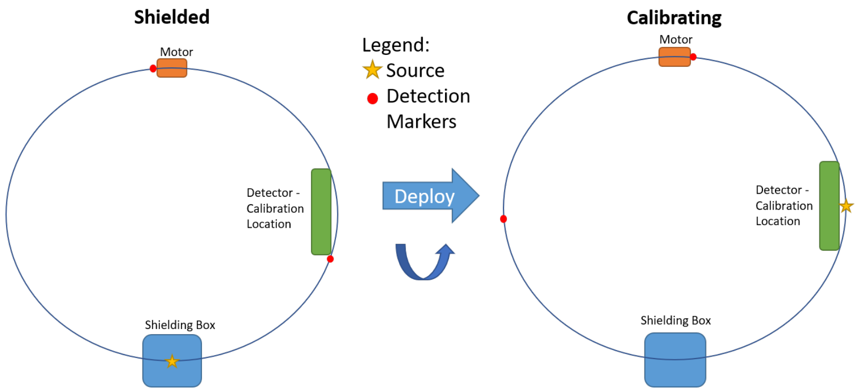

Figure 4.2: Block diagram of the full looped chain method for source deployment and location tracking. The arrow indicates the direction the loop would turn to deploy the source

As an added measure of ensuring the source's location, during installation two position marker beads will be installed on the chain so that when the source is at the two important locations in the system, the marker beads will be at the motor control box at the water tank surface. These marker beads would interact with an electrical sensor similar to the one proposed above giving an automated way of detecting the source position. This allows for a secondary security measure in addition to the source tracking performed by the stepper motor's rotation counting, and position recalibration in the event that the control system loses track of the source location.

4.2.1 Preliminary Box Design

The PE shielding box design was iteratively updated as the detection methods mentioned above advanced. The box design geometries were coded into the SuperSim framework and compared against each other based on the flux of particles leaving the box. An example of an early simple design is shown in Figure 4.3.

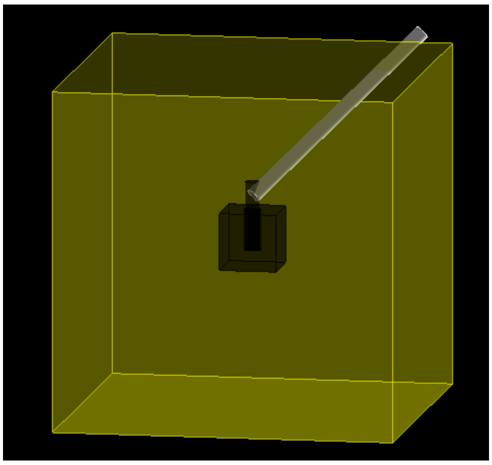

Figure 4.3: A simple PE Box design. In the center is a Lead Box core shown in brown, to shield from secondary gamma rays, Polyethylene shown in yellow, the source guide tube shown in white, and a hole for the source to fall into the lead box shown as black.

As the project progressed, more factors were considered in the design. Since the shielding box would be sitting on the floor of the water tank, and directly beneath the experiment is a concrete floor, there is no need to provide ample shielding below the source location. When shielding a source, a common phrase is to ensure there is no *line of sight*, which means that the design should ensure that there is no straight path from the source location to the outside environment; there should always be some level of shielding. For this reason, curves and turns are added to source paths. Additionally, the design of the source tube path inside the PE box had to consider the physical limitation of bend radius in order to ensure the source could pass through. Using simple geometry the following relationship was derived for the minimum inner radius of an arc the source tube can make such that the encapsulated source will not get stuck.

$$r = \frac{\frac{L^2}{4} + D^2 - ID^2}{2 * (ID - D)} + \frac{ID}{2} \tag{4.1}$$

Where the dimensions listed are shown in the following diagram:

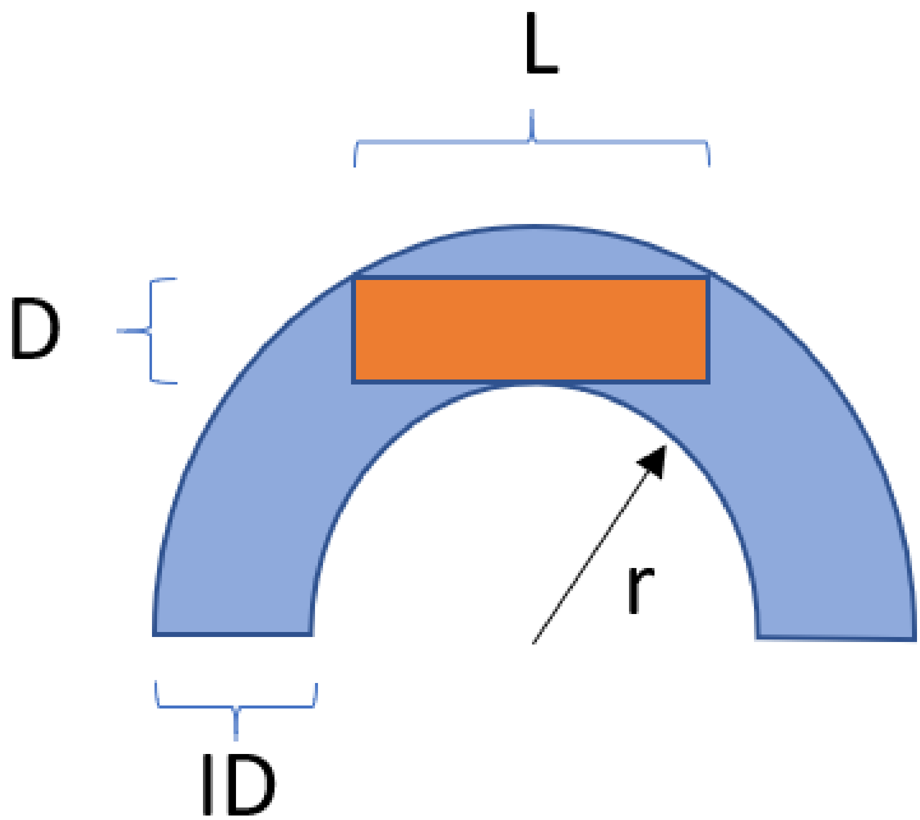

Figure 4.4: Labelled diagram of the encapsulated source inside the source tube under the limiting condition of the source getting stuck.

Lastly, the construction method in the water tank and how to assemble the PE box was an important factor in the final design. Polyethylene is typically sold in flat sheets with thickness ranging between 1/2" to 3", meaning that the box design should be compatible with a layered construction.

4.2.2 Source Design

To determine the activity required for the source, a simulation was run in SuperSim with the source location immediately outside the Drywell at the height of the detectors. Of the 500,000 neutrons simulated with the ^{252}Cf neutron energy spectrum, about 13,000 resulted in events in the six detectors. Assuming the desired rate of 5 events per second, per detector, the activity of the source was found using the following equation:

$$R = A_{source} * \mathrm{eff}_{SF} * \mathrm{nyield}_{SF} * n_{source}/n_{det} \tag{4.2}$$

Where R is the rate per second per detector, A_{source} is the activity of the source, eff_{SF} is the effective percentage of decays which are spontaneous fission, ≈3% in the case of ^{252}Cf, $nyield_{SF}$ is the neutron yield per fission, which is 3.7 neutrons for this source, n_{source}/n_{det} is the number of neutron events per detector for a given number of neutrons simulated [19]. Using the simulation results gives an approximate source activity of 11 kBq. A ^{252}Cf source of activity 18.5 kBq from Eckert and Ziegler's catalog was selected since it has enough activity to achieve the desired rate, and accounts for the short 2.5y halflife of ^{252}Cf [20]. Simulation testing suggests that the rate can be decreased, and the energy spectrum of neutrons arriving at the detectors can be softened (a more even energy distribution, and lower peak energy) by moving the source away from the dry well wall, allowing for more neutron attenuation by the water. This means that even though the activity will be higher than necessary when the source is first installed, control methods can be implemented to lower the rate to that which the detectors can handle.

The source encapsulation is based on the encapsulation design for the ^{133}Ba source for CUTE that has already been approved by SNOLAB [21]. The ^{252}Cf source from Eckert and Ziegler will come in their 3024 model cylindrical capsule with height 10 mm and diameter 6 mm [20]. This will then be placed inside two sets of copper encapsulations which will be sealed by soldering the halves together, encasing the source.

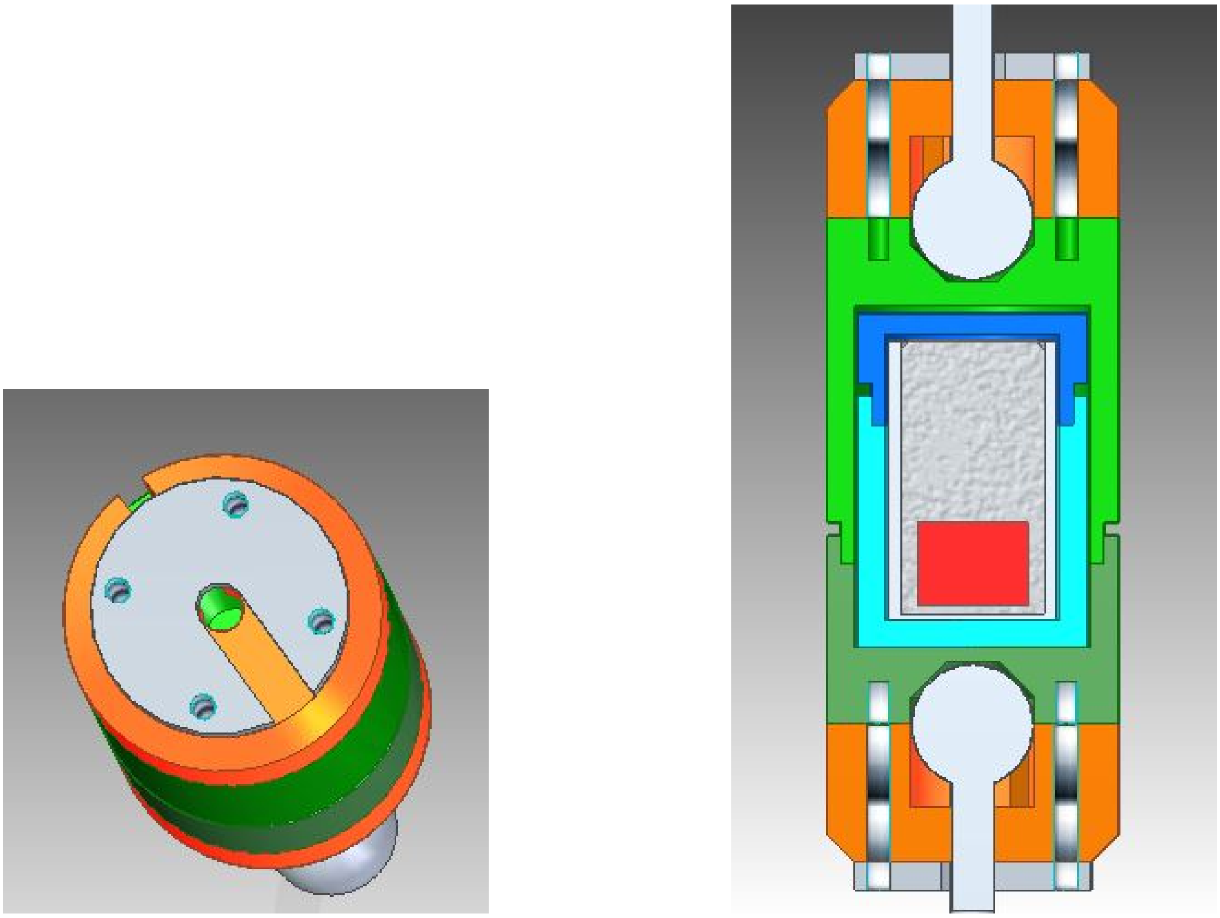

Figure 4.5: Source Encapsulation Design. Shown are the active volume (red), encapsulation from manufacturer (silver), first layer of encapsulation top and bottom (blue), second layer of encapsulation top and bottom (green), beaded chain (white), chain attachment (orange), and attachment washers (grey). Overall dimensions: 3cm length, 10.5 mm diameter

For ease of construction, the two lid pieces were designed to have a notch machined out of them so that the beaded chain could slide through the piece, and the lid pieces could screw into the encapsulation. The purpose of the washer is to prevent the the chain from sliding into the notch of the chain attachment piece and pulling the source at an angle.

4.2.3 Final Design

The final design of the shielding box is given in Figure 4.6. An S-curve was designed into the center of the box to reduce the line of sight for particles to get out of the water tank from the shielded position. The shielded location is at the center of a cylindrical heavymet (a tungsten alloy) block whose purpose is to reduce the gamma ray flux produced as a by-product of the other fission of ^{252}Cf. Lead bricks will be located directly above the source location to block the line of sight of gammas towards the top of the experimental setup. The radii of the arcs in the S-curve take into account Equation 4.1 which determine that the minimum inner radius assuming a 1/2" inner diameter tube was 46mm. The upper curve will be the primary track the source will travel through, with the lower curve acting only as a chain return line. This lower curve was designed to be able to pass the source through in the event that the chain breaks on the upper side of the source, the return line tube could be used as an emergency removal path.

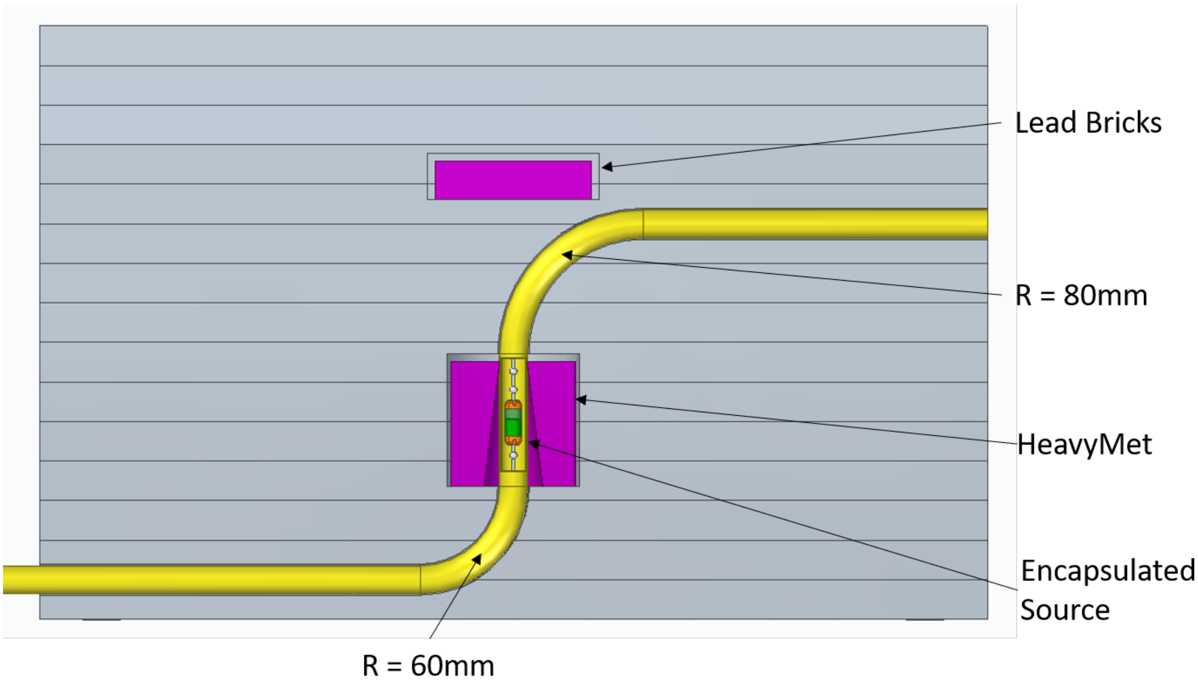

Figure 4.6: Cross Section of the PE shielding box, showing the γ shields (purple) and the source guide tube (yellow).

The base sheet, and all sheets above the S-curve will be full sheets (2'x2'x1") and all sheets will be held together by securing bars which go through the corners of each layer, with nuts attached to the bars at the top and bottom layer. The section of the box which contains the machined S-curve will be assembled by horizontal half sheet layers (1'x2'x1"). Figure 4.7 shows the assembled box, with the S-curve location left in as an internal sketch.

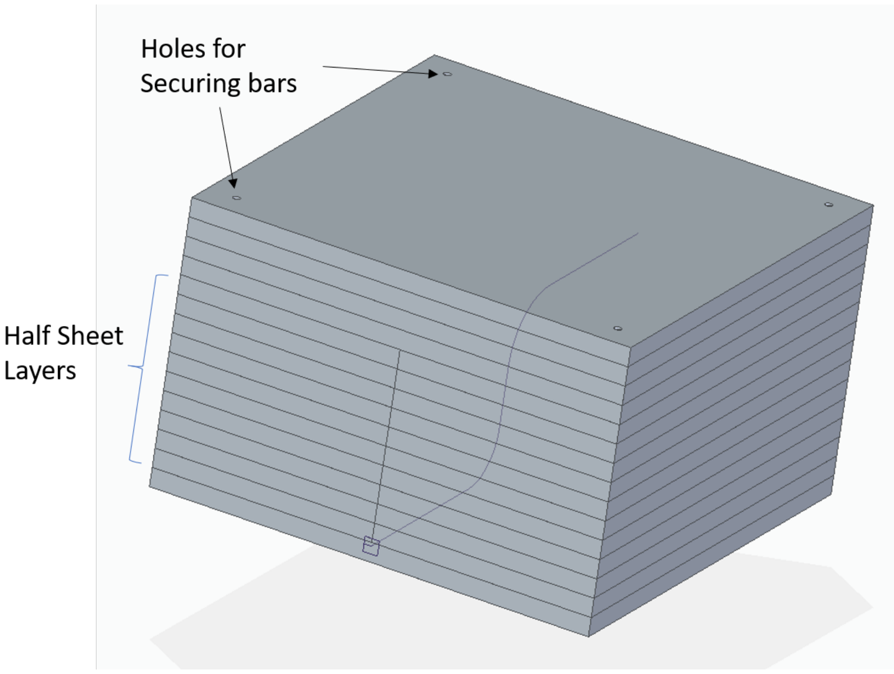

Figure 4.7: Assembled PE Box

4.2.4 Simulation Results

The entire design process relied on the SuperSim simulations to judge whether an idea was appropriate or not. The results of the simulation of final design show that the neutron source will be adequately shielded. The two areas of importance for personnel safety are shown in the SuperSim rendering found in Figure 4.8.

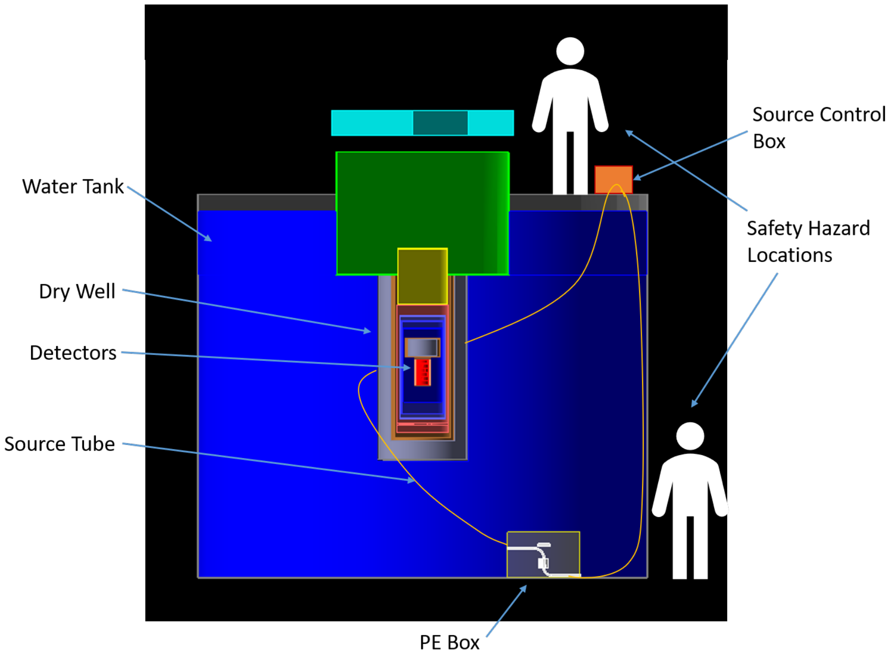

Figure 4.8: Rendering of the CUTE facility with stand-in figures showing the locations of potential hazard

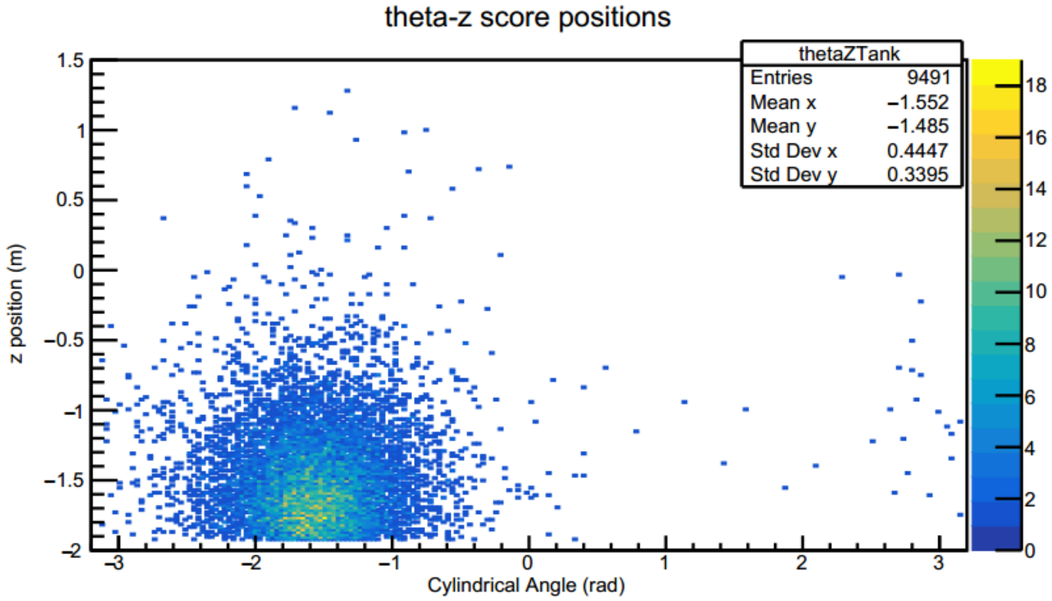

Figure 4.9: Flux map of particles leaving the water tank in a simulation of 500,000 neutrons, corresponding to 4.5 minutes of source time for an 18.5 kBq ^{252}Cf source. In the cylindrical angle, $\frac{-\pi}{2}$ is the radially biased direction of the shielding box, with π and 0 radians corresponding to the direction of the SuperCDMS and PICO experiments in the lab, respectively indicated in Figure 4.10.

The flux of particles leaving the water tank outer walls is shown in Figure 4.9. The particles shown are a mixture of neutrons and gammas produced as a by-product of nuclear collisions of the neutrons, with neutrons accounting for a minimal fraction of all particles shown. For the proof of safety, we will ignore the geometric reduction that a personnel standing nearby would have due to the fact that they could not normally be able to absorb all radiation emitted from the water tank, and instead assume that all particles are absorbed by a person with a cross-sectional area of A_{person} = 1m^2 with mass of m_{person} = 50kg. The resulting dose rate equation is:

$$H = Q_f * E_n * \frac{\#Particle}{time} * \frac{A_{person}}{m_{person}}$$

where H is the dose rate, Q_f is the quality factor associated with the particle type (20 for neutrons, 1 for gammas), and E_n is the mean energy of the particles. Accounting for the fact that only 3 neutrons came out of the water tank (the rest were gammas), and giving an upper estimate on the mean energy of particles of 2.5 MeV by assuming minimal energy loss of neutrons and gammas moderated through the water tank, the estimated dose rate is:

$$H = 1.04\frac{nSv}{hr} \tag{4.3}$$

In the same simulation, only 77 particles were emitted via the lid of the water tank, compared to the almost 10,000 emitted through the side walls, and there was no clear pattern associated with the clustering of the particles. For this reason it was also concluded that personnel on the top of the water tank are also safe when the source is in the storage location.

Additional simulations were conducted of the source in various potential calibration locations. As expected, the flux of neutrons from the side walls was reduced, but a significant increase in the number of particles emitted out the top was observed. The rate and density were such that the source would not pose a radioactive risk to personnel standing on top of the water tank, with similar calculations as those above yielding 9.7 nSv/hr. The issue with the calibration location is that it may be considered a background source for nearby experiments such as PICO and SuperCDMS. A simulation including the cavern space, shown in Figure 4.10 was performed, and over 2500 particles, 250 of which were neutrons hit the simulated wall in the direction of PICO.

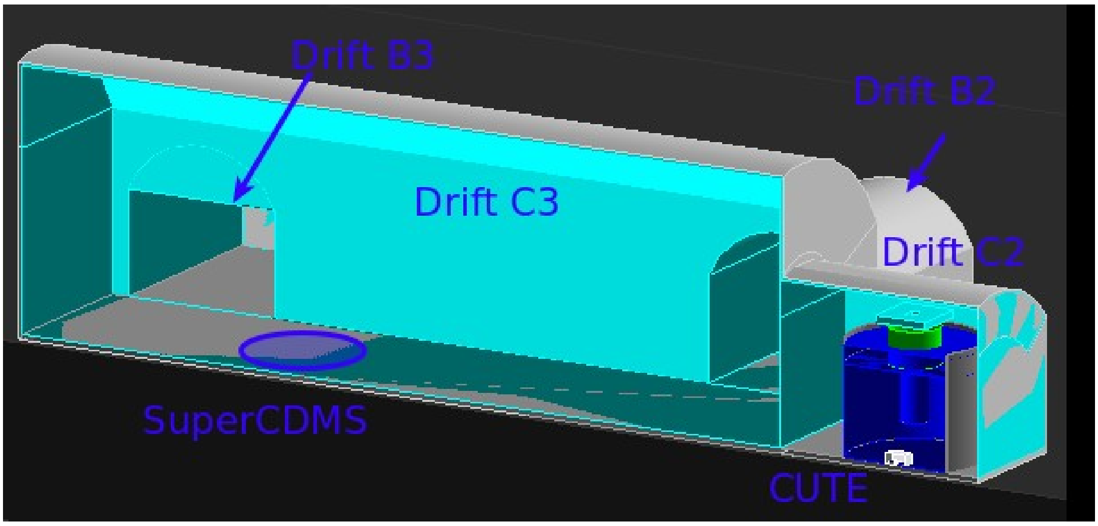

Figure 4.10: SuperSim simulation of CUTE with adjacent laboratory space included for purpose of tracking particles which may pose a risk to the science of other experiments. The SuperCDMS location is shown in the image; the PICO experiment is on the other side, roughly the same distance from CUTE as SuperCDMS, but this part of the cavern is not included in the simulation

All experiments require regular calibrations, so one potential solution to the issue of higher background to PICO and SuperCDMS whilst CUTE calibrates is to coordinate amongst the experiments to synchronize all calibrations on a regular schedule.

Chapter 5

Conclusion

A neutron calibration system for CUTE was designed and computationally tested. Based on simulations, the source activity was selected to produce an adequate rate in the detectors. The calibration system includes a shielding method against the radiation from the ^{252}Cf source such that the source does not impact the operation of the experiment, and safety of personnel not compromised. It is designed to be remotely controlled allowing for more flexibility from the experiment when performing calibrations. Potential faults have been identified and design decisions were made to mitigate the consequences of the hazards.

The server-based automation control system will be adapted from CUTE's ^{133}Ba gamma source control system. Physical testing of a mock source of similar dimensions has begun to verify the tube path dimensions ensuring the calculations on bend radius are accurate. Longevity and fatigue analysis of the source and chain system will also be performed simulating an equivalent of 500 calibration deployments. The ^{252}Cf source will be ordered from Eckert and Ziegler in the coming weeks, and while it is being shipped, construction of the PE box from multiple layers of PE sheets will begin.

Word Count: 4890

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