Position calibration of cryogenic dark matter detectors

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Abstract

Preparations for a position calibration of cryogenic dark matter silicon and germanium crystal detectors were made. The use of a collimated particle beam from a radioactive source will be employed to create interactions at known locations on the detectors to allow for a calibration. This will be conducted using a radioactive source suspended on two piezoelectric motors mounted perpendicularly to allow both x and y motion. A mount was created for the piezoelectric motors and the radioactive source, and the parameters for the collimating apparatus were determined. A particle beam of .01 mm diameter is desired for accurate calibration. The piezoelectric motors were tested for affects on the temperature within the cryogenic fridge, and reaction time was measured.

1. Introduction

Dark matter is defined as a class of matter which does not interact electromagnetically, but rather influences other matter through the gravitational and weak forces. Dark matter is inferred to exist based on otherwise unexplained astronomical observations, and is thought to comprise most of the matter in the universe [1]. A particle theory is employed in order to describe dark matter as Weakly Interacting Massive Particles, or WIMPs. These particles are expected to have a mass range from 10 GeV to a few TeV and interact weakly with ordinary matter [1]. Their existence is predicted by the supersymmetry theory. The Cryogenic Dark Matter Search II (CDMS II) works towards the goal of directly detecting WIMPs in order to confirm the existence of dark matter in the universe [2, 3].

The CDMS II experiment measures the interactions between WIMPs and the nuclei of germanium and silicon crystal detectors. The experiment incorporates many collaborating laboratories, some of which are dedicated to ensuring that the detectors used are of the quality needed to detect WIMPs. The University of Florida CDMS II lab tests the detectors that have been or will be used in the CDMS II experiment in a cryogenic environment. The lab is one of many collaborating institutions which collects data and measures crucial parameters. These measurements are compared with those obtained by other testing facilities in order to ensure that the detectors are working properly.

Part of this testing process includes a position calibration of the detector. In order to prepare for this, a very fine scale piezoelectric motor has been tested and a mount has been created. This fine scale motor will hold a radioactive source above the detector, which will then be filtered into a small particle beam. This beam will allow for a position calibration of the detector by creating interactions in known locations.

2. CDMS II Direct Detection

The CDMS II detectors plan to record the presence of WIMPs by detecting the interactions of these WIMPs with the particles in the silicon or germanium crystal detectors. These interactions create a very small amount of energy, and as such, the experiment requires very specific conditions. The detector itself must be kept cold, at temperatures as low as 10 mK. This is the most critical requirement, because this condition makes it possible to distinguish the small amount of energy created by the desired interaction from other noise such as the thermal energy of the detectors' nuclei [3]. Thus, the detectors must be contained in a cryogenic environment. Many other measures are taken to isolate the experiment from further background noise which could create unwanted interactions on the detector surface. The current CDMS II experiment is located deep underground in the Soudan mines in Minnesota to allow for natural shielding from cosmic rays [3].

When an interaction occurs, vibrations called phonons are generated within the crystal lattice of the detector. CDMS uses phonon detection equipment to measure the energy transmitted to the nuclei of the detector through the collisions [3]. Some of the phonons created by the interaction vibrate to the surface of the detectors. At the surface, the phonons are absorbed by aluminum collector fins. There, the energy of the phonon is converted into quasi-particles, or electrons which were in a superconducting Cooper pair that was broken by the incoming energy of the phonons. The quasi-particle electron diffuses to a tungsten strip which is biased with an energy level just below that needed to transition from being superconducting to being normal. The addition of the energy from the quasi-particles causes the tungsten strip, which is attached to the aluminum fin, to undergo this transition. The transition from superconducting to normal significantly alters the resistance of the tungsten, which can be detected and amplified to create a pulse. Because of this, the tungsten strip is referred to as the transition edge sensor [3].

3. Calibration of Position Measurement

In order to calibrate the position signal from the detector when an interaction occurs, interactions must be created in known locations. To accomplish this, a radioactive source is placed directly behind a collimating apparatus. This produces a fine beam of particles with which to strike the detector and create interactions. This calibration provides data on the position readings of the raw interactions and the creation of phonons within the detector [4].

In this set up, a piezoelectric motor will mount a radioactive source and a collimating apparatus, the cross section of which can be seen in Figure 1. The motor will allow the operator to move the collimated particle beam to known locations over the detector, allowing for a calibration of the position measurement of interactions on the detector.

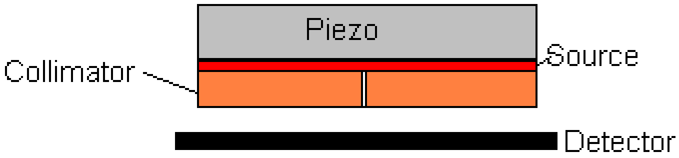

Figure 1 – Collimating apparatus cross section.

The piezoelectric motor operates based on an impact-drive mechanism. A voltage is applied to the piezoelectric actuator, and it is slowly extended, moving the clamped table with it as a result of the frictional force between them. When the piezoelectric actuator is rapidly contracted again, the inertial force on the clamped table overcomes the frictional force which attaches the table to the piezo, and the clamped table is left at the extended position. The principle also works in the opposite way, as seen in Figure 2, where the piezoelectric actuator is quickly expanded, without moving the clamped table, then slowly contracted, bringing the table along with it.

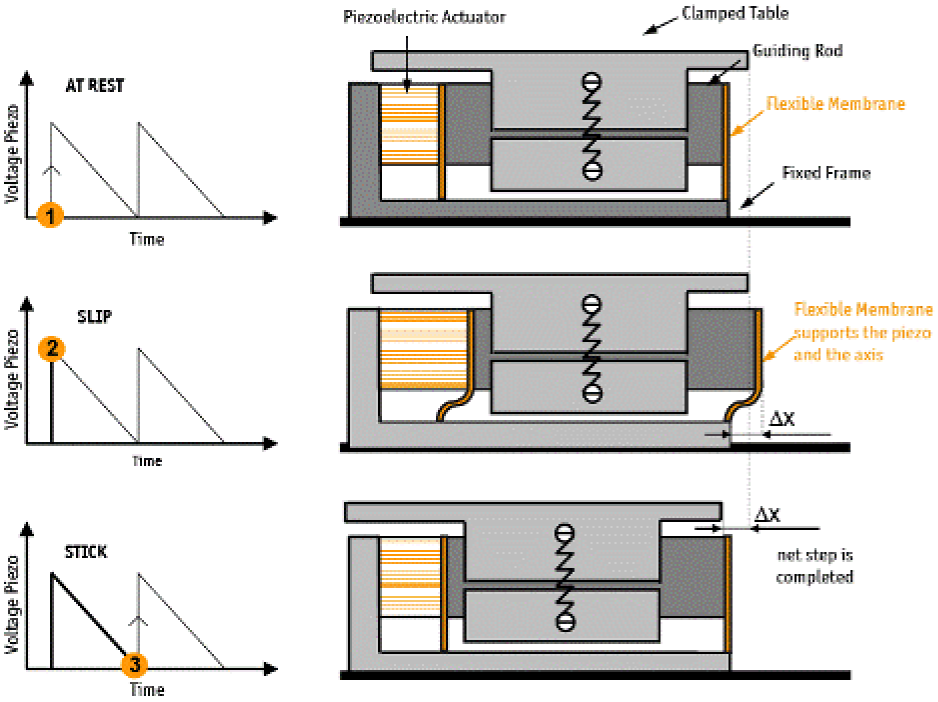

Figure 2 – Piezoelectric Motor Working Principles [5].

4. Piezoelectric Motor Mounting and Testing

An AttoCube Piezoelectric motor is used to mount the radioactive sample above the detector being calibrated. The positioner, shown in Figure 3, is capable of moving 10 mm in each direction from its absolute zero position. In order to allow an x-y range of motion for the sample, two motors are mounted perpendicularly atop one another. The motor works at temperatures as low as 10 mK and has step sizes ranging from 0.015-1.725 µm. The motor can withstand a maximum vertical load of up to 220g each, or 150g atop the two perpendicularly mounted

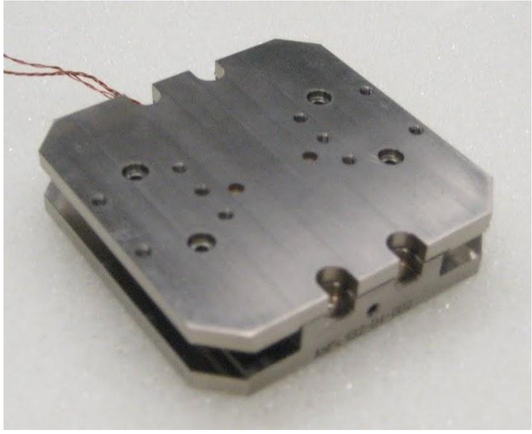

Figure 3 – AttoCube Motor.

motors. The motors require low resistance connecting wires because they require high currents to function properly (at low temperatures, a current of 0.5-1A is needed). However, due to the possibility of increased resistance in connecting cables used inside the cryogenic fridge, the motors were tested to have a maximum working resistance of 15 Ω with an input voltage of 70V. At these parameters, however, the minimum step size is 1.725 µm.

In order to mount the piezo motor and calibrating materials directly above the detector, a copper mount was designed and machined. The mount suspends the two motors directly above the open detector. A new detector 'lid' was also designed, as seen in Figures 4 and 5, in order to leave the detector open to the collimating beam.

For accurate and meaningful calibrations, it is important that the 'spot size' of the radioactive particle beam on the detector be as small as possible. From the setup, shown in Figure 1, it can be determined that the spot size is related to the diameter of the hole in the block, the thickness of the block itself, and the height of the setup above the detector as such:

$$s_s = d + (2dh)/t \qquad (1)$$

where s_s is the spot size, d is the diameter of the hole, t is the thickness of the block, and h is the height of the block above the detector. Thus, in order to minimize the size of the particle beam hitting the detector, the setup must minimize the diameter of the hole and the height of the block above the detector, while maximizing the thickness of the block. Table I shows the maximum thickness possible with the vertical load limitations of the piezoelectric motor, the corresponding minimum diameter for the hole through the block using machining methods, and the minimum spot size attainable with these parameters.

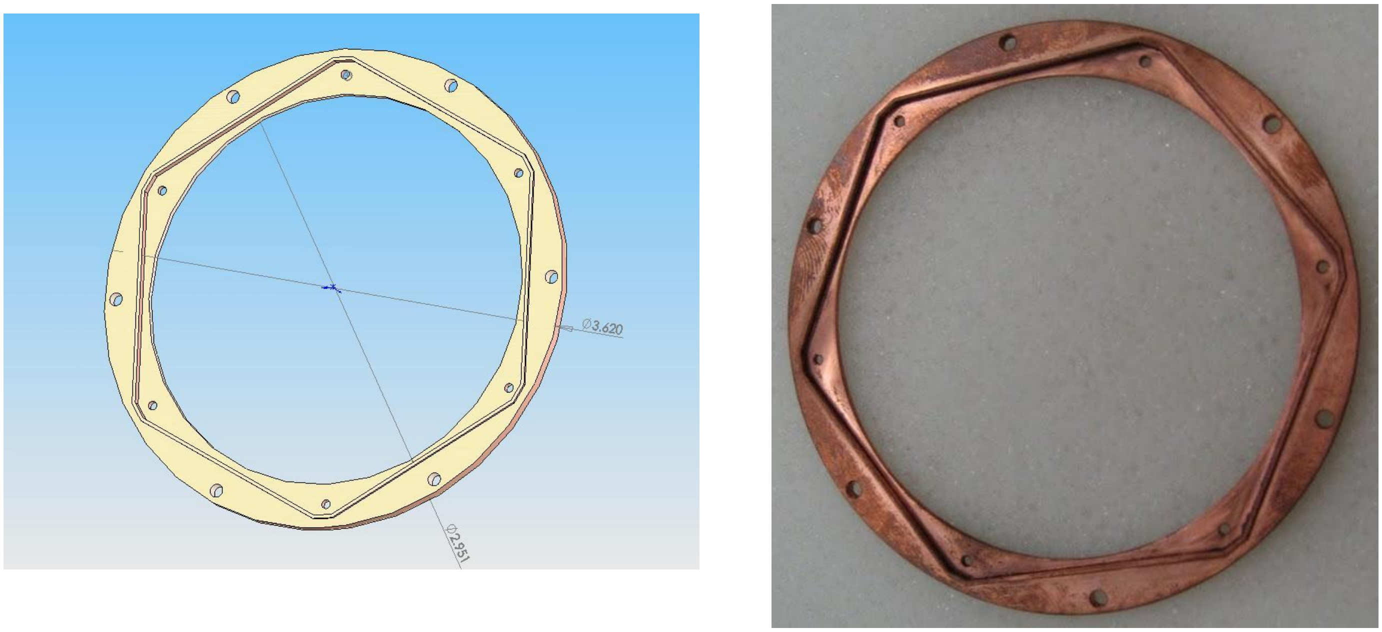

Figure 4 – Design for the open ‘lid’ of the detector (Left), machined lid (Right). The lip secures the detector and the inner screws mount the ‘lid’ to the detector. The outer screws secure the rods which suspend the piezoelectric motor above the detector.

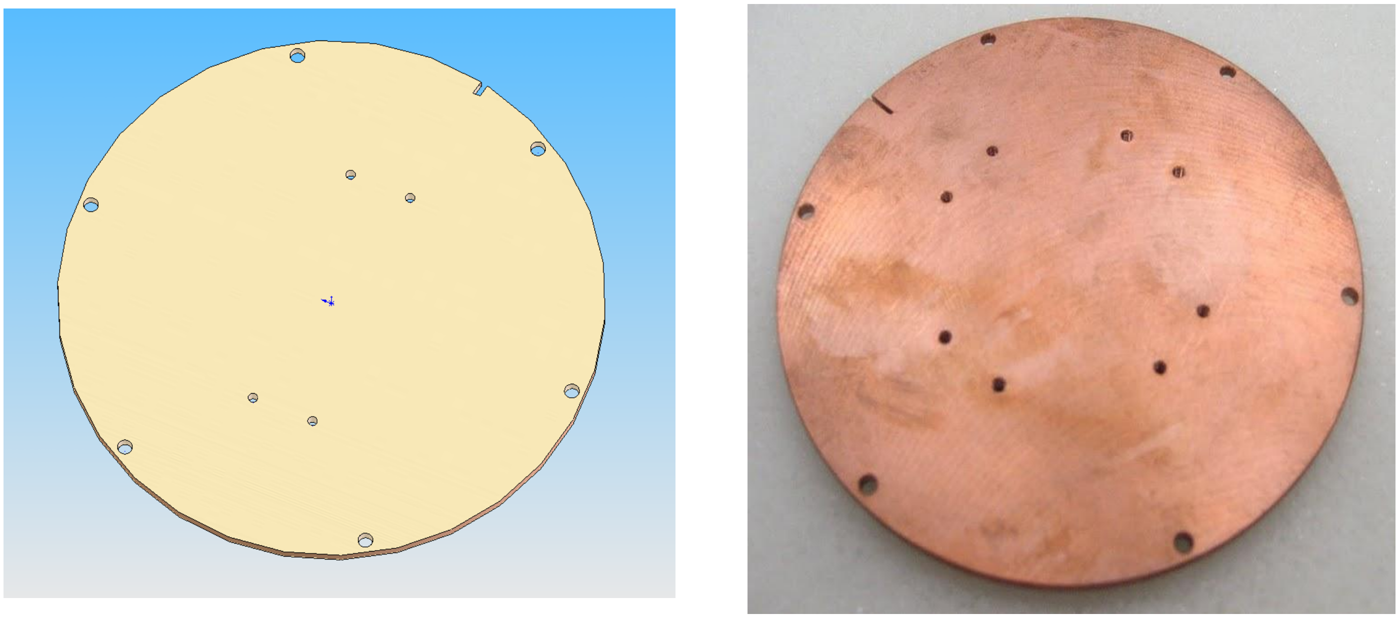

Figure 5 – Design for piezoelectric motor mount (Left), machined motor mount (Right). The four inner screws mount the bottom motor to the plate. The outer screws secure the rods which suspend the motor and collimating apparatus above the open detector.

Table I: Collimating apparatus parameters.

Copper [density = 8.94 g/cm3]

Resistance	Maximum Vertical Load	Thickness of Collimator	Minimum hole Diameter (Machining)	Height Above Detector	Minimum Spot Size
15 Ω	150 g	7.28 mm	0.508 mm	1.00 mm	0.65 mm
15 Ω	150 g	7.00 mm	0.508 mm	1.00 mm	0.65 mm

Aluminum [density = 2.7 g/cm3]

Resistance	Maximum Vertical Load	Thickness of Collimator	Minimum hole Diameter (Machining)	Height Above Detector	Minimum Spot Size
15 Ω	150 g	24.11 mm	0.508 mm	1.00 mm	0.55 mm
15 Ω	150 g	7.00 mm	0.254 mm	1.00 mm	0.33 mm

At maximum resistance, the maximum vertical load determines the maximum thickness of the collimator. The minimum diameter for the hole in the collimator is valid only for machining methods. The minimum spot size is above desired diameters.

With these parameters, however, the minimum diameter of the particle beam attainable with a copper block is approximately 0.65mm. This is significantly larger than the desired particle beam and will make an accurate calibration of the detector very difficult. In order to rectify this problem, a different method of creating the hole through the copper block must be employed. Currently, several methods are being considered that would allow for a much smaller hole to be drilled into the copper block of maximum thickness. The desired particle beam diameter is on the order of 10 µm. This type of diameter would require a hole through a block of 4mm thickness to be 0.01mm, or a hole through a block of 2mm of 0.005mm, which are dimensions that cannot be normally machined.

Before any calibration could begin, the piezoelectric motors needed to be tested within the cryogenic environment. It was important to determine how their motion would affect the temperature within the fridge, and how long it would take for this temperature change to be rectified. The motors were mounted inside the cryogenic refrigerator independently for testing, seen in Figure 6. When they were run, the motors introduced a large amount of heat into the system, the specific amount varying based on the input voltage, distance moved, and frequency of the motors. All temperature increases, however, would bring the temperature within the fridge above working limits when using a detector. An increase in temperature of 100 mK would prevent the detector from having the superconducting transition edge sensor, which is a necessary piece for the detection of interactions. So, in order to perform a position calibration with the current set up, the motors would have to be turned on and moved, then turned off long enough for the fridge to cool back to base temperature, at which point a calibration could be done.

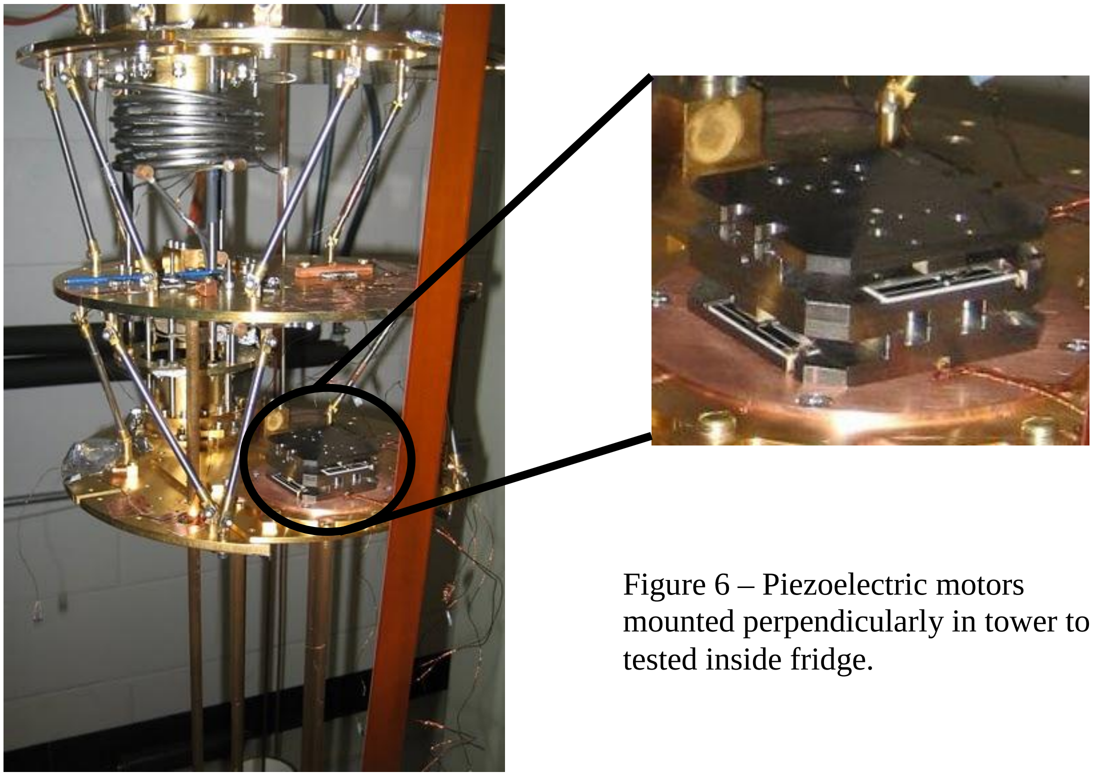

Figure 6 – Piezoelectric motors mounted perpendicularly in tower to be tested inside fridge.

5. Conclusion and Future Work

Thus, there are still a significant number of preparations to be made before a position calibration can be performed. A mounting system must be finalized and created which will satisfy the parameters necessary to produce a small particle beam with which to create interactions, and a process for moving the piezoelectric motors during the calibration must be determined. All of the preparations for these processed have been completed throughout the summer. The parameters of the piezoelectric motors have been characterized through an extensive series of tests, the calculations have been made for the desired collimating system, and the mounts for the motor have been machined. Finally, a program must be created to control the piezoelectric motors via LabView so that their control can be incorporated into the existing control programs.

6. Acknowledgments

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7. Documentation

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