Developments for the DarkSide-20k Project, a WIMP Dark Matter Detector

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The existence of dark matter is one of the most central open questions in modern physics, to account for the discrepancy in the amount of matter we can observe in the universe and the mass we would expect to see based on gravitational effects. One model explaining this is the existence of Weakly Interacting Massive Particles (WIMPs), a dark matter candidate. However, no such particle has been definitively observed yet. The DarkSide-20k experiment is a dual-phase Time Projection Chamber that proposes to use 20 tons (fiducial volume) of Liquid Argon over a ten-year detection period, expecting a "5σ discovery significance for a 1 TeV/c^2 WIMP" [1], to either detect WIMPs or significantly constrain their parameter space. At Virginia Tech, we are contributing to two key components of the experiment: the wire grid and the Anode Deformation Monitoring System. The wire grid, composed of 1236 tensioned wires held at -5.2 kV, enables the drifted ionization electrons from an event (S1) to induce secondary scintillation (S2) in a gaseous argon region, providing X-Y positional information for 3D event reconstruction (with the Z-component determined by the S1–S2 time difference). We have also developed an autonomous, contact-free method of measuring wire tension, as well as methods to manufacture springs in-house with consistency in spring constant and preload tension. Simultaneously, we have been developing the Anode Deformation Monitoring System to detect nonuniformity in the anode due to gravitational sag. In this paper, I present our technical developments and current progress in these areas.

INTRODUCTION

The existence of dark matter is our current theory to account for the discrepancy between the mass observable through electromagnetic radiation and the mass we would expect based on galactic rotation curves, gravitational lensing, and the anisotropy of the cosmic microwave background [1].

The DarkSide-20k detector is a dual-phase Liquid Argon (LAr) Time Projection Chamber (TPC) dark matter detector. It aims to detect Weakly Interacting Massive Particles (WIMPs), with a "5σ discovery significance for a 1 TeV/c^2 WIMP", for a 10-year detection time. The detector, filled with 20 tons (fiducial volume) of Liquid Argon, will be housed underground at Laboratori Nazionali del Gran Sasso, in Italy.

The detector uses argon as its target material, and relies on argon's scintillation properties to produce the initial signal (S1). This signal is the release of photons upon the recombination of ionized argon molecules following an interaction.

As the interaction also releases ionization electrons, we use an electric field to drift these electrons upwards, and further accelerate them using a secondary field through the boundary between liquid argon and gaseous argon. This secondary field is produced between the wire grid, a series of 1236 tensioned wires held at -5.2 kV, and the anode. With enough energy, these electrons can cross the boundary and interact with the gaseous argon, causing electroluminescence. This releases further photons, which are detected as the secondary (S2) signal. Photons from S1 and S2 are collected by Silicon Photomultipliers (SiPMs) housed at either end of the detector [1].

A fundamental concept this detector relies on is *planarity*. For accurate 3D reconstruction of events to occur, both the anode and the wire grid must be completely flat (to within 100 μm). This, alongside the time difference between S1 and S2, allows for accurate 3D reconstruction of the X, Y, and Z coordinates, which is integral in determining whether an event that was detected may be dark matter or not.

At Virginia Tech, we are primarily responsible for building the wire grid and the Anode Deflection Monitoring System (ADMS), alongside quality assurance and radiopurity. Hence, much of the focus of this paper will be on how we maintain planarity in the wire grid and the anode.

METHODOLOGY AND RESULTS

Measuring Tension on a Wire

Motivations and Constraints

Our wires that comprise the cross-grid section of the DarkSide-20k detector are required to be at a specific tension of 7 N. This value was chosen as the sweet spot to allow the wire-grid to run at up to -6 kV with electrostatic stability and prevent wires from "running away" to maintain planarity. Alongside a cross-wire setup, we minimize the risk of wire instability [2].

For all practical purposes, there are a number of ways to measure the tension on a string. However, our particular use case required that certain constraints were met. Namely:

- No object must make direct contact with the wires, to ensure uniformity of the wire grid.
- Must not permanently deform wires.
- Must be able to accurately measure tension to at least ±0.2 N.
- Must be able to measure wires spaced out 3mm apart.
- Ideally able to automate the tension measurements for 1236 wires to save time.

Derivation

To this end, multiple methods were explored that focused on inducing oscillations in the wire. For the fundamental harmonic of a standing wave, we observe:

$$\lambda_1 = 2L \quad (1)$$
$$v = f\lambda \quad (2)$$
$$v_1 = 2Lf_1 \quad (3)$$

Where v is the wave speed, λ_1 is the wavelength of the fundamental harmonic, and L is the string length.

The wave speed in a string is given by:

$$v = \sqrt{\frac{T}{\mu}} \quad (4)$$

Where T is the string's tension and μ is the linear mass density.

Equating these expressions gives us the equation for tension:

$$T = 4L^2 f_1^2 \mu \quad (5)$$

Where f_1 is the fundamental frequency of oscillation.

Experimental Setup

To prototype our tension measurement, I opted to use a photodiode and laser setup. The wire would block a certain amount of light from the laser, and when the wire was excited, its oscillation would be detectable as a change in voltage intensity from the photodiode.

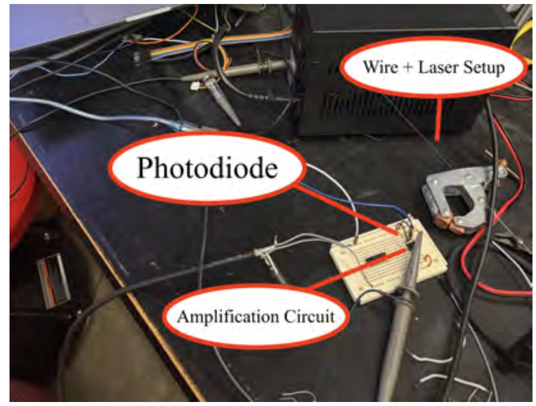

FIG. 1. Experimental method for measuring wire tension, the laser, omitted for clarity, is incident on the tensioned wire. Exciting the wire allows an oscillation to occur, from which tension can be calculated.

We set up the photodetector in a transimpedance amplifying circuit, which uses the photodiode in a reverse bias setup, improving response times and voltage swing, to generate a photocurrent. The op-amp adjusts its output to maintain a 0 V difference between both inputs, which flows through the feedback resistor (whose magnitude determines the gain). This brings the output voltage to a value compatible with our microcontroller (0-5 V), an Arduino UNO. To deal with high-frequency extraneous noise sources, we devised a low-pass filter to attenuate signals beyond ≈ 100 Hz. The diagram below shows the circuit setup for this component.

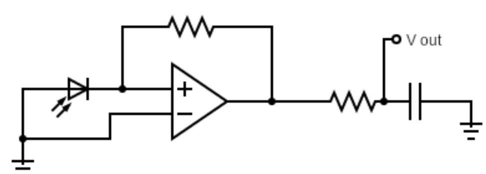

FIG. 2. Transimpedance Amplification Circuit - current to voltage converter with gain proportional to feedback resistor. There is a low-pass filter between the output of the op amp and the V out (Arduino readout), which helps reduce high-frequency noise sources.

Once we have aligned the laser to the photodetector and ensured the wire is blocking some of the light between the two, we are ready to begin data collection. We induced an oscillation through two main ways, firstly through a manual excitation (i.e. a pluck), and subsequently through a pulse of gas to aid our automation of tension measurements. After recording the signal received from the microcontroller (∼ 10 s), we then perform a Fast Fourier Transform (FFT) of the data, and conduct some manipulation to determine the fundamental frequency of oscillations. Then, we use Eq. (5) to calculate tension.

Data Collected

As we can see from Table I below, we were able to get within ± 0.2 N of the expected tension in the wire.

Weight, N	**f_1, Hz**	**Tension, N**	**Discrepancy, %**
5	16.2	5.07	1.40
7	19.1	7.13	1.86
9	21.8	9.20	2.22
11	23.8	10.99	0.09

TABLE I. Table of calculated data and discrepancy

Conclusions and Further Improvements

Although this method was successful in determining tension, we deemed it too inconvenient to create a system that would allow the laser to be moved opposite to the wire grid in sync with the photodetector circuit. Hence, we explored an alternative method to measure the light *reflected from* the wire as the laser was incident onto it. This had the benefit of allowing all parts of the system to operate from the same side, so we could eventually have a small system on e.g. a cart, that could traverse the entire wire grid and take individual tension measurements of each wire.

This proved to be successful, though requiring additional changes as the intensity of the reflected light was far less than that of the direct laser, as the wires reflected diffusely rather than specularly. Nevertheless, we were able to obtain successful tension measurements through this process, and opted to continue on with this method as our prime focus.

Consistency of Spring Constants

Spring Requirements

Our wire grid setup involved attaching the tensioned wires described previously to two springs, one at either end, which are then connected to the TPC's frame. This allows for tension to remain consistent "in the presence of small horizontal deformations of the frame" **(Design Review B)**, as well as to compensate for "the anticipated early wire contraction compared to the frame during cool-down", as the grid will be submerged in liquid argon at cryogenic temperatures. Among other things, these primary reasons necessitated the creation of in-house springs that met our specific requirements.

As we intended to make over 2000 springs in total for the wire grid setup, one of our biggest challenges was ensuring that each spring was manufactured consistently. Though we used a significant amount of automation in manufacturing springs, small variations in, e.g., the twisting of the wire as it was coiled, could lead to significant changes in preload tension and spring constants. These are both important, as the pretension affects how the spring responds to a force as it essentially ensures the spring is always stretching, and the spring constant directly influences how much the spring will extend for an applied force.

Experimental Setup

To measure spring constants, we created a simple setup to test Hooke's Law; that is:

$$F = -k\Delta x \tag{6}$$

Where F is the tension force applied to the spring, Δx is the change in extension, and k is the value of interest, the spring constant. With pretension in the spring, this becomes:

$$F = -k\Delta x + F_0 \tag{7}$$

Where F_0 represents the pretension.

Iterative Design Changes

In order to account for the more rapid cooling of the wires compared to the overall frame as they are immersed in the Liquid Argon, the springs will need to stretch an average of 0.5 cm on either end (though specific stretching will depend on spring constants). To ensure our string lengths and pretension were such that extension would not be too long at 7 N (the operating tension of our wires), we manufactured springs with varying amounts of twisting and winding (which correspond to different pretension). Our initial designs proved to be inconsistent in both spring constant and pretension, which we attributed to the compounding effect of non-standardization across multiple steps in the production process. We also found that springs of higher pretension tended to be more consistent, which we took into account for our future batches.

Eventually, we determined the "sweet spot" of windings, which offered consistent spring constants and extended just far enough at 7 N as not to touch the Faraday cage and other components of the detector. Then, we decided to do a mini production run of 22 springs.

Mini Production Run Results

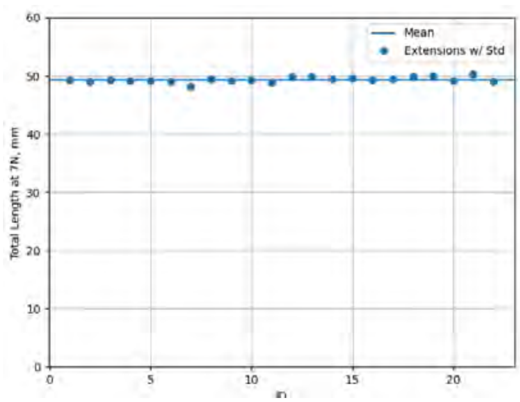

FIG. 3. The extension of 22 springs at 7 N of applied force, measured three times per spring using vernier calipers. For all springs, the length at 7 N was $l = 49.36 \pm 0.44$ mm

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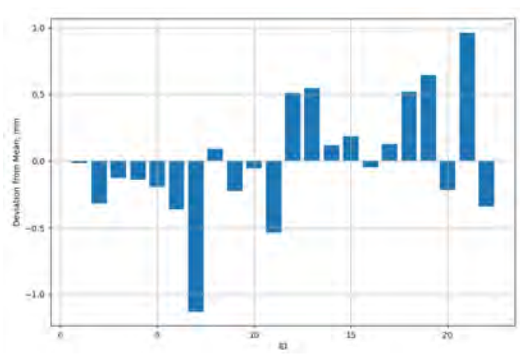

FIG. 4. The deviation of each spring from the mean, represented by $y = 0$. The largest deviations $+0.96$ mm and -1.13 mm.

Overall, our springs at target tension 7 N had an extension of $l = 49.36 \pm 0.44$ mm. This gives us a sub-1 % variability in our springs, which is far more consistent than we expected.

Anode Deformation Monitoring System

The anode responsible for accelerating electrons between the liquid to gaseous Argon boundary is essentially a charged planar structure. However, the presence of various forces that interact with the anode, including gravity, may induce sag that disrupts planarity. As mentioned previously, planarity is necessary to accurately create a 3D reconstruction of events, and hence it is imperative for us to be able to measure any deformation of the anode throughout the data collection process ($t \approx 10$ yr). We now introduce the anode deformation monitoring system, designed to measure within ~ 100 μm the planarity of the anode.

Subject to future change, our current designs involve a series of six evenly spaced quartz rods that rest atop the anode at various intervals across the entire plane. Any deformation of the anode should manifest as a vertical displacement of the quartz rods, which we can measure in various ways.

Although initially, Virginia Tech would be responsible for a system to adjust the anode alongside measuring deformation, the Anode Adjustment System is now under the purview of Queens University and the University of Alberta [3].

Requirements

Our anode deflection system should be able to, upon activation, automatically measure the displacement of the anode via the vertical position of the quartz rods. Any method used must:

- Withstand the cryogenic temperatures of the environment
- Avoid introducing noise into the detector (i.e. no light)
- Be reliable for 10 years of continuous data collection
- Be accurate to 100 μm

Prototypes and Initial Designs

Throughout our initial design phase, we considered many potential options to measure small deviations in displacement. This included reflectors of light/sound, and small piezo actuators. To achieve our necessary resolution without introducing background signal, and to have a system that is as reliable as possible (to be left inaccessible for > 10 years), we opted to use a stepper motor. As it is brushless, there is less potential for mechanical wear over time.

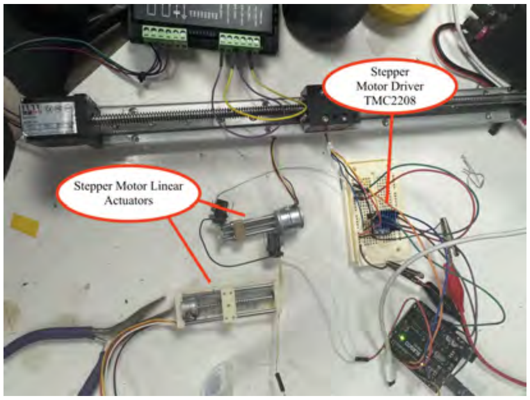

FIG. 5. A series of stepper motors of varying sizes, stroke length, and pitch. Pictured is the stepper motor driver we are using for this project, the TMC 2208. In general, reducing stroke length and decreasing screw pitch will increase the accuracy of our measurement system, as well as having a motor with more steps per revolution and with microstepping.

As a proof of concept, I devised a stepper-motor linear actuator measurement system using an actuator of stroke length 45 mm. With this, I was able to attain precision on the order of $\sim 10\ \mu$m. This could be further improved using microstepping.

One barrier we had to address early on was the cryogenic liquid in which the actuator would be immersed. To simulate this, I opted to test using Liquid Nitrogen ($T = 77$ K, vs LAr $T = 87$ K).

Cryogenic Testing

To test, I initially immersed my first linear actuator, made of metal with plastic housing, into the nitrogen while it was oscillating back and forth to determine if it would remain operable. As expected, the plastic housing quickly cracked. The motor, interestingly, continued to operate for a brief moment before it seized as it cooled down closer to Liquid Nitrogen temperatures.

Next, I opted to use an actuator that was primarily metal to determine if it would fare better. However, after immersing even the end opposite the motor, it still seized very quickly. I theorized this could be due to thermal contraction of the bearings housed at both ends of the motor, presumably for alignment of the rotor. On my most recent cryogenic testing, I seem to have damaged the motor or driver by increasing the voltage up to the maximum of 9 V, and given the time constraints this marks the end of my work with this project at the Vogelaar Lab.

CONCLUSIONS AND NEXT STEPS

Throughout these ten weeks, we have made substantial progress towards many components of the DarkSide-20k Dark Matter detector. We have determined a suitable method of autonomous and contact-free tension measurement, a method of ensuring consistent spring production, and begun testing of our Anode Deformation Measurement System.

We now need to finalize our automation process for our tension measurements, with the end goal of having a "one-button" press to measure tension across all 1236 wires. We are currently in the process of purchasing and assembling the relevant components, and will eventually have a cart that houses all the electronics and uses a belt drive to move across the entirety of the detector.

Simultaneously, we will begin our mass production of over 2500 springs, which will take around 2 months. This will mark the completion of one of the most time-intensive parts of this detector.

Finally, development of the Anode Deformation Monitoring System will be taken over by my successors over at the Vogelaar Lab. We are currently exploring alternative options such as purpose-built cryogenic-compatible linear actuators, which we have hitherto avoided due to their significant cost. If possible, we would like to develop in-house cryogenic-compatible actuators, which would not only be a more economic option but also be usable for future projects that make extensive use of cryogenic conditions.

These components are all integral to DarkSide-20k, and play a critical role in position reconstruction and background rejection. We expect to begin data collection in the next two years, and following ten years of detector operation, we hope to finally detect the elusive WIMP, or at least constrain its parameters down to the neutrino floor.

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[1] C. Galbiati (2024), unpublished proposal submitted to the National Science Foundation.

[2] P. Agnes, M. Angiolilli, E. Augustine, B. Bottino, J. Brandt, A. Caminata, M. Caravati, M. Carlini, G. Darbo, S. D. Cecco, G. Dolganov, A. Elersich, T. Erjavec, D. Fleming, B. Freeman, A. Guirguis, A. Hallin, A. Jamil, M. Kuzniak, M. Kuzwa, J. Monroe, N. A. Moss, E. Pantic, G. Plante, A. Pocar, S. Pordes, M. Rescigno, D. Rogowski, J. Runge, P. Skensved, K. Thieme, J. Thomas, B. Vogelaar, A. Wong, and T. Zhu, .

[3] P. Agnes, M. Angiolilli, E. Augustine, B. Bottino, J. Brandt, A. Caminata, M. Caravati, M. Carlini, G. Darbo, S. D. Cecco, G. Dolganov, B. Freeman, L. Grandi, A. Guirguis, A. Hallin, M. Kuzniak, M. Kuzwa, J. Monroe, N. A. Moss, E. Pantic, S. Perricone, G. Plante, A. Pocar, M. Rescigno, D. Rogowski, J. Runge, P. Skensved, B. Stillwell, K. Thieme, J. Thomas, A. Wong, and T. Zhu, (2024).