Calibration of a Three-dimensional Muon Detector Based on Scintillator Binary Optical Encoding

Team Dawson Technicolor

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INTRODUCTION

At any given moment, there are muons raining down on us at a rate of approximately 1 muon per square centimeter per minute [1–4]. Traditionally, spark chambers or wire chambers allow the tracking of muon trajectories. However, building a high voltage chamber is a technical challenge, especially for high school students and for their mentors worrying about safety. We wanted to create a simple, safe and easily reproducible way of observing muons, which is what led us to develop our three-dimensional scintillator-based detector, a.k.a. The Scintillating Chamber.

DESIGN

The general working principle of our detector is simple: polyvinyl toluene (PVT) scintillator rods are arranged in the detector, and when a muon passes through a rod, photons emitted are then detected by a Silicon Photomultiplier (SiPM). The collected data is then transferred to a computer where the data is processed and rendered to display the possible paths of the muon. Our design strays from conventional detectors when it comes to the arrangement of the scintillator rods. While typical detectors use a grid design, we opted for a design inspired by binary encoding (see figure 1).

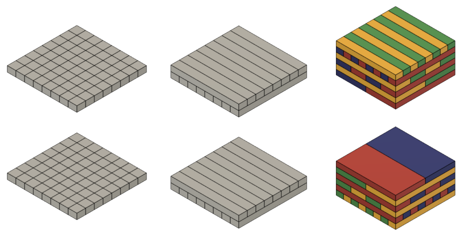

FIG. 1. Comparison of three scintillator placement methods: n being the number of scintillators on the side of one of the extreme layers. **Left:** One layer grid design. Number of sensors scale as $2n^2$. **Middle:** Two layer grid design, scales as $4n$. **Right:** Binary encoding arrangement, number of required sensors scales as $8log_2(n)$. In each layer, identically coloured scintillators are optically linked to the same SiPM by WLS fiber.

This has two main benefits. First, it reduces the number of sensors needed, as only two sensors are necessary per layer. As such, the number of sensors needed for the detector increases logarithmically. Our design also allows for easy encoding of the detector's state. With each layer only having two sensors, its state can be represented with a single bit, and because each layer is more specific than the previous, it narrows down the possible paths of the particle through the detector. Each set of signals therefore encodes for a specific pattern. This is analogous to the system used in the Apollo Guidance Computer's rope core memory, with each bit representing an inhibit wire pair[5].

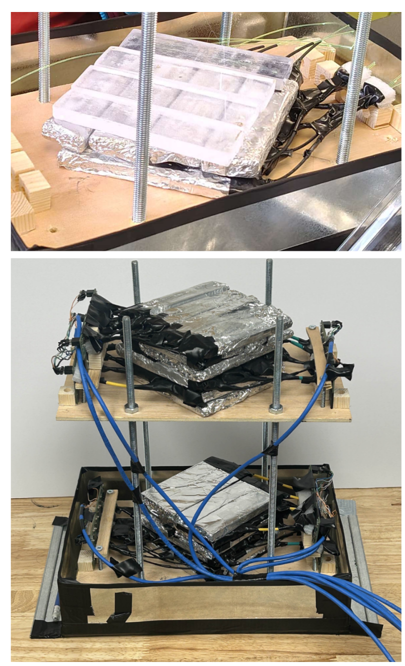

FIG. 2. Isometric view of physical detector. WLS fiber is encased within dark tubing toward the SiPM boards. Four threaded rods elevate the top platform: nuts allow for relative parallelism adjustment. Top and bottom scintillator packs permit the encoding of XY positioning; both combined, 3D trajectory tracking. A total of 12 layers $\times$ 2 SiPMs/layer = 24 SiPMs.

In greater detail, each rod is optically isolated from its neighbors with aluminium foil and connected to a remote SiPM through wavelength shifting fiber (WLS fiber)[6] . We opted for WLS fiber, as is common among scintillation detectors, because it is more efficient at capturing the photons emitted by the scintillators than clear fibers. The output of the SiPMs being too weak, we use op-amp transimpedance amplifiers to amplify the signal. After being amplified, the signals are digitized before entering an FPGA circuit for fast acquisition [7]. An Arduino then filters the signal before it is sent to a computer for processing.

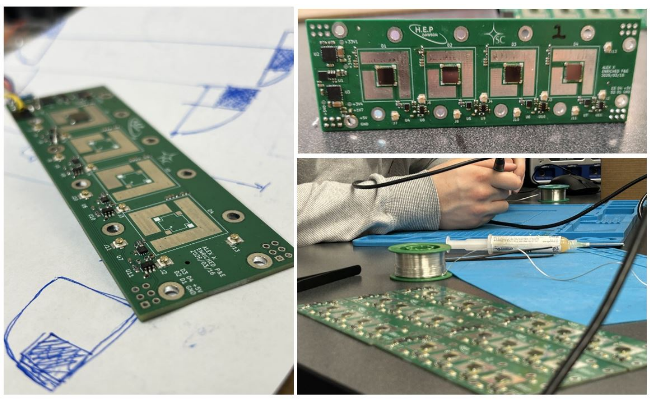

FIG. 3. Student-designed SiPM printed-circuit boards. Each PCB has four channels; a total of six PCBs are used in our detector. SiPMs and other components are manually populated onto the PCB.

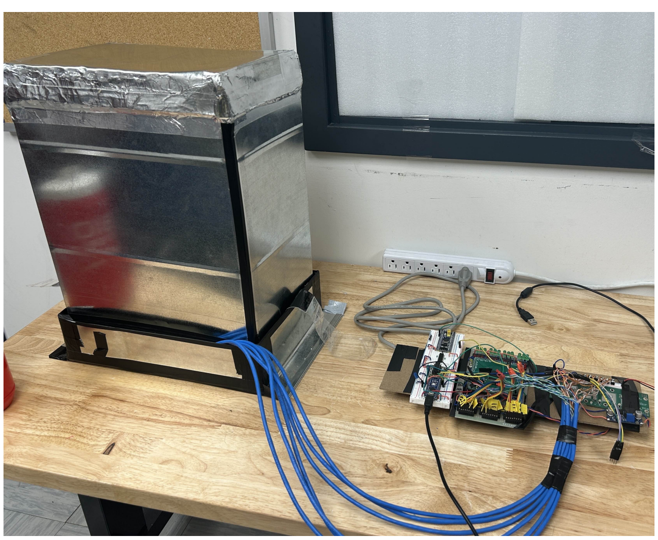

FIG. 4. Binary optical encoding scintillation detector in its final form. **Left:** Light-tight faraday cage containing the detector made of HVAC conduit—decreasing light contamination and electrical noise. **Right:** Acquisition circuit linked with data cables.

The trajectory volume—the possible volume of muon trajectory—is calculated in O(n) using Python code[8] by splitting the detector into two side-projections. The code calculates the trajectory volume projection for each side view by iterating over two levels at a time and conserving the tightest projection, first combining the center levels and finally the uppermost and lowermost levels. The volume trajectory projections are combined into the volume trajectory. Future updates will include : adapting to situations where the muon passed between two rods of the same level and taking advantage of situations where muons had to pass in between same level rods.

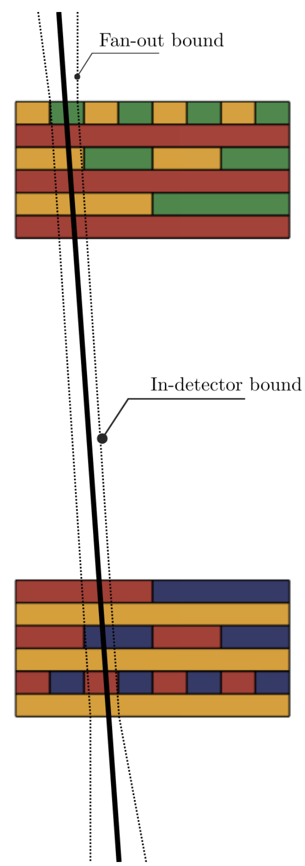

FIG. 5. Representation of a possible muon trajectory and the calculated trajectory volume projection. Black line a possible muon path. Black dotted line is the side muon volume projection: boundaries for all possible muon paths.

The display is written in Python, using GLFW to create the display window, PyOpenGL to turn the coordinates from the muon volume trajectory into coordinates relevant to the computer, as well as to create the shaders, vertex arrays, and vertex buffers which are needed to render the scintillator structure and trajectory volume to the computer, and ImGui to create the text box that gives information to users.

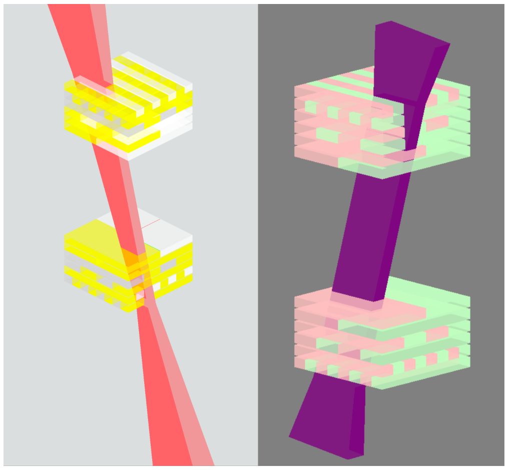

FIG. 6. Two experimental instances of isometric views of binary positional decoding by our software from real data. **Left:** Signals sent to the computer are interpreted visually. ***Yellow:*** Triggered scintillators. ***White:*** Untriggered scintillators. ***Red:*** Volume of possible muon trajectory resulting from binary elimination of trajectories. **Right:** More efficient render without signal interpretation. ***Purple:*** Volume of possible muon trajectories.

RESULTS

After initial testing, we recorded several detections. The results were not affected by the intensity of light in the room, suggesting that the detector was successfully optically sealed.

The muon flux detected is around 2.5 hits/minute, lower than in theory. We believe that this is due to our conservative data filtering, and small field of view: we wanted to reduce the chances of introducing noise as much as possible. As such, the calibration of our detector is crucial to capture accurate trajectories.

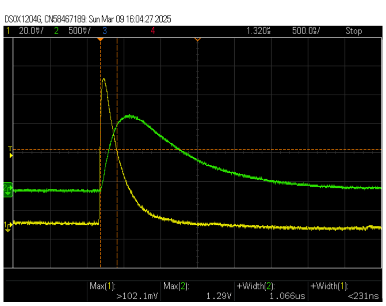

FIG. 7. Initial amplification testing with OnSemi C-Series SiPM (41% photon detection efficiency (PDE), 420 nm peak wavelength). **Yellow:** voltage across $49.9\,\Omega \pm 1\%$ shunt resistor on reverse-biased diode anode. **Green:** non-inverting op-amp configuration (LT1807) output. Light output measured from BC408 PVT scintillator.

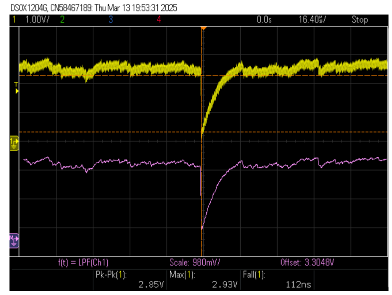

FIG. 8. Initial transimpedance amplifier testing. Gain of $2.26 \times 10^5 \pm 1\%$. **Yellow:** inverting op-amp output. **Pink:** low-pass filter, 940 kHz bandwidth.

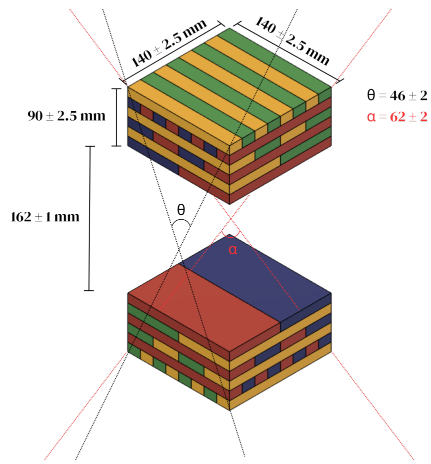

FIG. 9. Cosmic ray capturing field of view: $46 \pm 2°$ minimum (on X and Y axes side projection), $62 \pm 2°$ maximum (on diagonal). Top and bottom scintillator stacks are $140 \times 140 \times 90 \pm 2.5$ mm—separated by an air-gap of 162 ± 1 mm. The minimum trajectory volume cross-section is 15×15 mm : 225 mm^2.

EXPERIMENTAL PROPOSAL

Our muon tracker is currently producing experimental results, but we have no way of confirming their validity. As such, we propose using CERN's high-energy Proton Synchrotron as a source of a controlled muon beam and use this experiment to compare our detector tracking results with the known trajectory of the Proton Synchrotron muon beam.

The evaluation of XY translational accuracy will be assessed by aiming the detector's Z axis toward the beamline and iterating through different XY positions; the evaluation of XYZ rotational accuracy will be done by iterating through diverse altitude and azimuth angles. As the position is encoded to an 8×8 grid, a minimum of 64 different translations and 64 rotations will confirm the correct triggering of all SiPMs and the faithfulness of the trajectory volume computation with the actual trajectories.

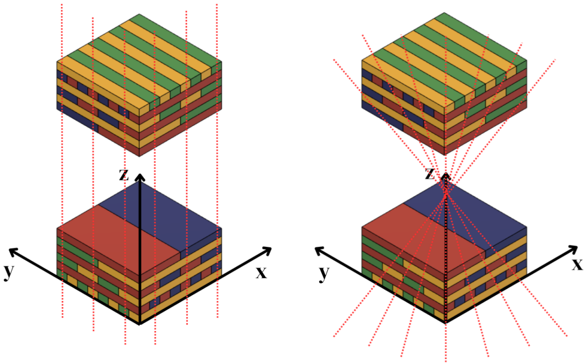

FIG. 10. Experimental proposal axes reference frame. **Left:** Example XY translational testing beamlines. **Right:** Example XYZ rotational testing beamlines.

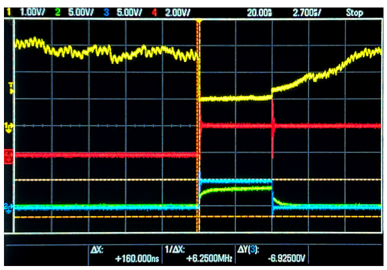

FIG. 11. Digitizer circuit signals from acquisition hardware. **Yellow:** analog output from trans-impedance amplifier connected to comparator inverting input. **Red:** latching FPGA register for acquisition. **Blue:** comparator output. **Green:** level-shifted comparator output. Adjustable comparator threshold voltage: 1.133V ± 0.1%.

OUTLOOK

We have fully developed the detector's software and hardware components on our own. Therefore, precise calibration would require exposure to a controlled muon beam. Further, a controlled muon beam would permit us to test out features we are currently developing such as measuring the detection time and using a time-over-threshold system to find the energy of muons passing through the detector. Access to CERN's facilities would allow us to validate our detector's performance and refine its accuracy.

The confirmation of the viability at CERN of our safety-oriented detector design allows for open-sourcing, along with physics classroom outreach—projects with which we align. We believe that getting this detector ready for research will inspire more students to design their own particle physics experiments.

COMMUNITY OUTREACH

Women, though largely unrecognized, have played a great role in the development of modern science. Marie Curie, Ada Lovelace, Katherine Johnson, and many others have been role models for generations of scientists. Our team at Dawson TECHNICOLOR firmly believes that part of promoting science education is promoting the inclusion of women and other marginalized groups. As such, we are currently working with Dawson STEMM FEM, a local club, to create talks and participate in events that will hopefully encourage many young women to join the beautiful field of physics and of science as a whole.

Furthermore, The Scintillating Chamber is set to be presented in May at Dawson's ScienceFest. This event consists of a fair where a myriad of scientific projects are introduced to the student body. This opportunity will allow us to make particle physics more accessible and easier to grasp while sharing our unwavering passion.

ACKNOWLEDGMENTS

We would like to sincerely thank Dr. Manuel Toharia for his dedication to the High Energy Particle Physics group at Dawson, for his captivating lectures and for his guidance throughout our project. We are incredibly grateful to McGill University Professor Dr. David Hanna for his invaluable advice and for graciously letting us use his scintillator block as well as McGill University Professor Dr. François Corriveau for his guidance. We express our sincere appreciation to Université de Montréal technician Dr. Nikolai Starinsky for his scintillator cutting advice. This project would not have been possible without the Dawson Foundation's Student Academic Growth and Enrichment Fund, whose grant provided money with which we bought power tools, safety equipment, and electronics. Finally, we would like to express our gratitude to Dawson College for offering us a wonderful learning environment that allowed us to flourish and engage in science activities that we are passionate about.

APPENDICES

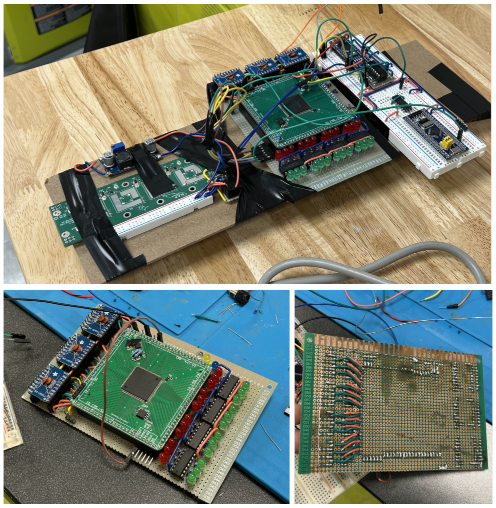

FIG. 12. **Top:** Signal acquisition circuit. ***Left:*** Low-noise 5 V power supply for all SiPM PCB boards (TPS7A470, 4 μV_{RMS}). ***Middle:*** 24-channel digital signal reader with FPGA (ICE40HX1K), 5 V to 3.3 V level shifters, and indicator LEDs associated with each SiPM sensor. ***Right:*** Breadboard: Arduino Nano for serial data communication over USB to the computer, and STM32F103C for clock signal generation. **Bottom left:** Work in progress FPGA detector module. **Bottom right:** Manual soldering of individual wires for the 24 LED indicators.

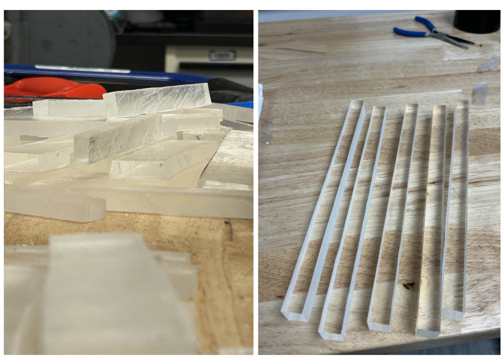

FIG. 13. Scintillator rods cut with a bandsaw from a larger scintillator block. Two 500 × 250 × 30 mm BC408 PVT scintillators were graciously offered to us by McGill Professor Dr. David Hanna—which we then proceeded to cut and polish manually.

* Teacher

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[7] All circuits and PCBs are custom-made. Access the documentation here.

[8] All code can be found in our GitHub repository.