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Data Analysis and Detector Troubleshooting for the Silicon Muon Scanner

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Abstract

Muon tomography is the calculation of the density distribution of a material from the probable angles of muon Coulomb scattering in a sampled object. This allows the probing of internal object structures that cannot otherwise be observed. It has many important applications for both national security and other fields, such as archaeology and geology. Its uses range from detecting radioactive material intended for nuclear weaponry to searching for hidden chambers in the Egyptian pyramids. In this project we intend to demonstrate the capability of a tomographic system which uses cosmic rays as the muon source and tracks each muon's initial and final trajectories to ascertain information about their scattering pattern. This method can be used to determine the structure or composition of an object, such as testing to see if a nuclear fuel cask is empty or full. We intend this as an early R&D exploration into the practicality of implementing silicon microstrip sensors in border scans for radioactive contraband, as an alternative to existing drift tube technology.

1. Introduction

One of they key advantages to muon tomography is the ability to probe matter at sufficiently accurate resolution with ambient particles that are constantly penetrating the sample under normal conditions, exposing it to no additional radiation. We can use muons present due to cosmic rays to image samples with no additional muon source necessary [1, 2]. Muons are able to penetrate long distances into matter, making what's already available from cosmic rays a superior choice over other methods like x-ray tomography, which require a source and exposure of the sample to additional radiation [1]. The Multiple Coulomb scattering (MCS) of muons within a sample can be probabilistically determined using the initial and final muon tracks to yield information such as elemental composition [1].

An experimental design to gain information about matter not directly accessible has potential applications in a wide variety of fields, many themselves completely unrelated to high-energy physics. Marteau *et al.* describe a project which used muon tomography to observe the internal structure of volcanoes [2]. Muon tomography is well suited to this as it is both long-range and non-invasive [2]. Scintillator-based detectors were used for this application [2]. This experiment was able to construct three-dimensional images of volcano structure and density distributions [2]. Another application was explored by Poulson *et* al., whose experiment demonstrates the capability of creating a detailed three-dimensional image of nuclear fuel casks by moving the detector around the cask, generating many two-dimensional images which can be reconstructed into three-dimensions [3]. Simulation played the main role in this, using the GEANT4 toolkit to perform simulations of muons passing through a Westinghouse MC-10 spent fuel cask [3]. In contrast to our experiment, two rings (initial and final) encircling the cask were used instead of planes [3]. Measurement of the muon scattering angles allows

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for the distinction between an empty and full fuel slot with a precision of 18 sigma [3]. Measuring particle transmission rates is less effective, as it is a parameter less sensitive to the fuel itself, creating a blurrier reconstructed image [3].

Muon tomography is already in current use in border security applications, but current systems use gas-based drift-tube systems [4]. These are too large and more expensive over time than silicon microstrip detectors on the scales used for scanning trucks crossing a border, and require much more maintenance than semiconductor detectors [4]. Additionally, silicon detectors have a much higher channel density, allowing for both a more compact detector and higher imaging resolution [4]. This project, funded by Mission Support and Test Services, LLC (MSTS), serves as a proof-of-concept that semiconductor detectors are a viable alternative and are worth further development for national security [4].

The structure of silicon microstrip sensors is a series of p-type doped silicon strips embedded into n-type silicon [4, 5]. A reverse-biasing high voltage is applied to increase the size of the depletion layer, the neutral region between the positive and negative regions [4, 5]. Charged particles are detected in this depletion region from the charge deposited in this neutral region, which is proportional to the energy possessed by the particle [4, 5].

The scanner structure is comprised of two chambers, each with four planes of detectors enclosed (see Figure A1 in Appendix A). The four planes come in two pairs, as each plane can only differentiate the position of a detected particle along one dimension. Two planes arranged perpendicularly to each other can take position data in both the x- and y- directions, providing a two-dimensional image. A second pair reveals the particle's position in another parallel plane along the z-axis, enabling the formation of three-dimensional position data. Each plane has an array of nine microstrip wafers. Every set of three wafers along the axis of measurement is connected to a High Density Interconnect (HDI) with six SKIROC2 chips for signal readout (see Fig. A2). The chips are coupled in pairs of two, called chains. Mounted on the top of the chamber are the lidboards, which hold the Cmod FPGA modules (see Figs. A2 and A3). Our current triggering method uses two scintillators atop the planes, separated by a steel sheet to filter out muons with insufficient energy to make it through all four planes. If both scintillators detect a muon, this is counted as an event and is saved for future analysis. Future designs plan to use a pair of larger scintillators, one above the scanner and one below, using the same triggering paradigm.

2. Progress

An early-project decision was made to use silicon detectors that were not deemed sufficiently functional to use for the construction of the outer tracker of CERN's Compact Muon Solenoid (CMS) detector at the Large Hadron Collider, and readout chips that were used in prototype testing for CMS's calorimeters. This was a more cost-effective purchase as they allowed the project to obtain components at a discount, but they proved to demonstrate more difficulties than were anticipated when they were selected. This summer, we ran many diagnostic tests to determine the cause of many issues, and whether or not repairs were possible or something we could spare the time and funding for, rather than developing a workaround.

The CERN-maintained data-processing software ROOT was used for histogram generation in data analysis. Analysis was performed on one of Fermilab's remote Scientific Linux servers, detsim. Software analysis often influenced hardware troubleshooting by facilitating more informed searches and hardware probes. The planes were tested using infrared LED pulses to check for dead channels and general response. Pulse tests included data sets from runs with and without the pulse, to allow for the subtraction of a constant offset from zero signal inherent to the system, called the pedestal. Initial troubleshooting this summer focused on pinpointing the extent and cause of an HDI with expected values that varied on a chip scale between values that were uniformly either much higher or lower than expected, if responsive at all (see Fig. 1). Due to the extremely consistent signal values, these were determined to be outputs indicating underflow and overflow errors due to specific signals being grounded. This was deemed irreparable under our project constraints, but as the issue was limited to this particular HDI, it was sufficient to ignore the signal from that HDI entirely.

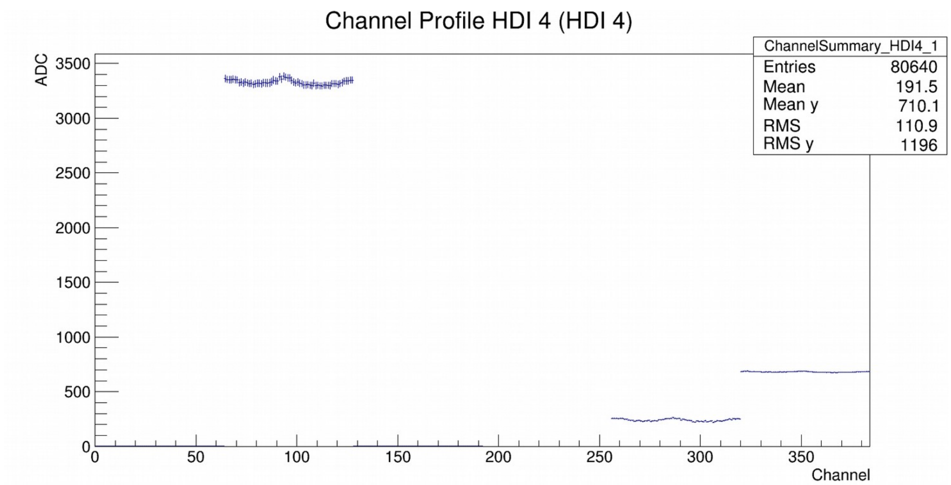

Fig. 1: A plot of the raw signal from the malfunctioning HDI.

Difficulties with a new lidboard were also resolved when it was discovered that the trigger signal was being inverted. Switching from an earlier configuration to the lidboards meant that the analysis-end geometry definitions swapped the positions of the first and third chip chains, which needed to be corrected for pulse data to not be transposed. We determined that pedestal height was not dependent on the trigger frequency, which was a crucial step in determining that no specialized trigger corrections were needed to take cosmic data, which has triggers at a rather irregular frequency.

The coding work we focused on was mostly analysis software. Masking methods needed to be developed for the many channels with readout issues that could not be determined or practically remedied, such as grounded signals or channels which showed expected pedestal values but never detected a signal above the pedestal. The amount of channels needing to be masked left us with what will result in a lower resolution going into the finished prototype, but we have enough channels left to us that imaging should still be feasible with longer cosmic ray exposure. A crucial step in the development of muon-tracking software is hit definition—that is, automating the procedure of discriminating a detected muon from fluctuations in the pedestal. The number of analog-to-digital converter (ADC) counts that indicates a muon event can fluctuate from around 15 to 90 ADC counts above pedestal, but they mostly remain significantly above the pedestal. Defining a cutoff of three sigma from pedestal-only signals is sufficient for most channels, though those less ideally functioning have a much lower standard deviation, making the cutoff value only 4 ADC counts above pedestal if defined in the typical manner. This is still within anticipated pedestal variance, and as such gives many false positives. A minimum cutoff is defined to fix this issue for channels like this which cannot use the typical custom definition, leaving suboptimal channels with the cutoff of 12 ADC counts above pedestal. This is lower than many cosmic events, but significantly higher than pedestal fluctuation, so it serves as a baseline minimum for event definition. These cutoff values serve as an analysis-end trigger to further classify events after the initial scintillator-based hardware trigger.

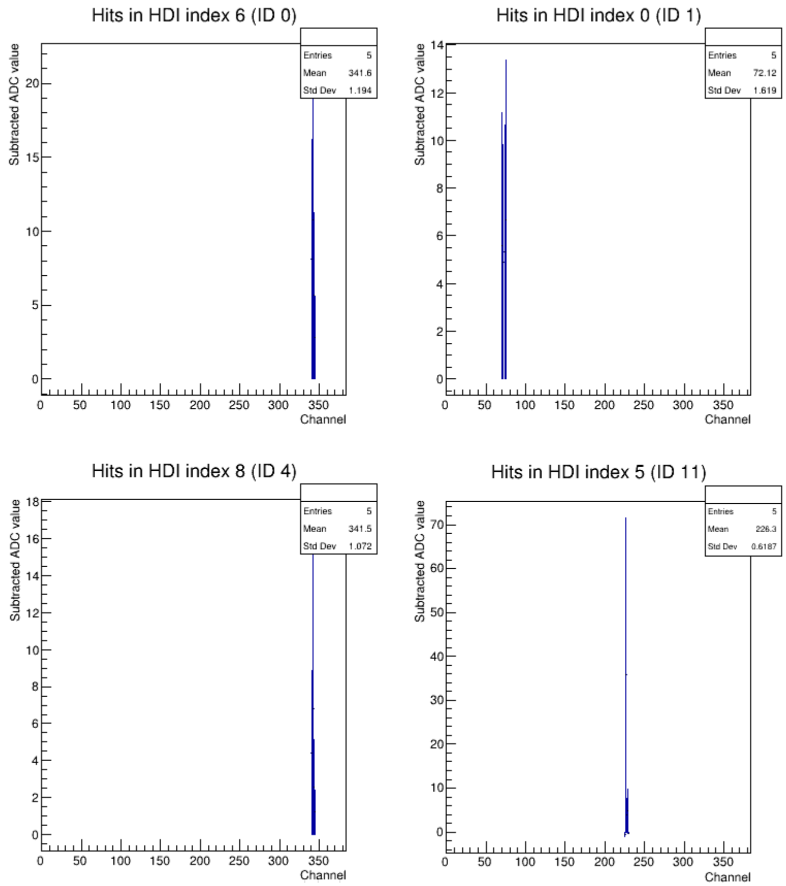

Fig. 2: A plot of an event in the relevant channels of HDIs on each plane.

3. Future Work

Beyond this point, we will focus on the construction of the remaining set of planes to detect outgoing muons. These also will need to be calibrated and screened for channels that require masking. New data will be taken with these and with the previous planes now inside the chamber. The next step after the existing analysis-end trigger refinement is the software construction of particle tracks through the detector, and then the calculation of the MCS through sample material. It is our hope that after the completion of the prototype, we will be able to begin further development with better-quality detectors, demonstrating the full potential of silicon microstrip sensors in muon tomography.

Our developing collaboration on other projects based on our circuit boards and other hardware solutions will also continue. We're currently working with a project at the Pacific Northwest National Laboratory (PNNL) which intends to use our existing plane and readout layout to identify the isotopes present in a sample of unstable gas, from the particles detected from the molecules as they decay. No other projects are currently in collaboration with ours, but the possibility for future projects to borrow techniques from our design remains open.

4. Impact

This project has the potential to greatly effect the implementation of tomographic muon detectors in homeland security screening. If, at the end of the fiscal year late this September, MSTS deems silicon microstrip detectors a favorable prospect in muon tomography technology, they will fund further projects to develop and refine our design for security use. These future projects may also require the aid and involvement of Fermilab. Another likely result is funding of further advances in semiconductor detector designs themselves, and any further advances are likely to be used in new accelerator detector upgrades, advancing the capabilities of future experiments in high-energy physics.

5. Conclusion

Over the course of this summer, we have addressed and worked around hardware issues present in the detectors and chips in use for our research. These remedies were both in the form of hardware solutions and analysis-side software compensation, such as channel masking. We were able to identify initial event candidates using a scintillator trigger and further refine the resulting data set with event-recognition software.

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References

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[2] J. Marteau *et al.*, *DIAPHANE: Muon tomography applied to volcanoes, civil engineering, archaelogy*, arXiv:1612.03905 [physics.geo-ph].

[3] D. Poulson *et al.*, *Cosmic ray muon computed tomography of spent nuclear fuel in dry storage casks*, arXiv:1604.08938 [physics.ins-det].

[4] J. A. Green *et al.*, *Silicon Strip Cosmic Muon Detectors for Homeland Security*, presentation at SORMA West, Berkeley, Ca., May 22, 2016.

[5] H. Spieler, *Semiconductor Detector Systems*, (Oxford University Press, 2005), pp. 8-10.

Appendix A: Images and Schematics

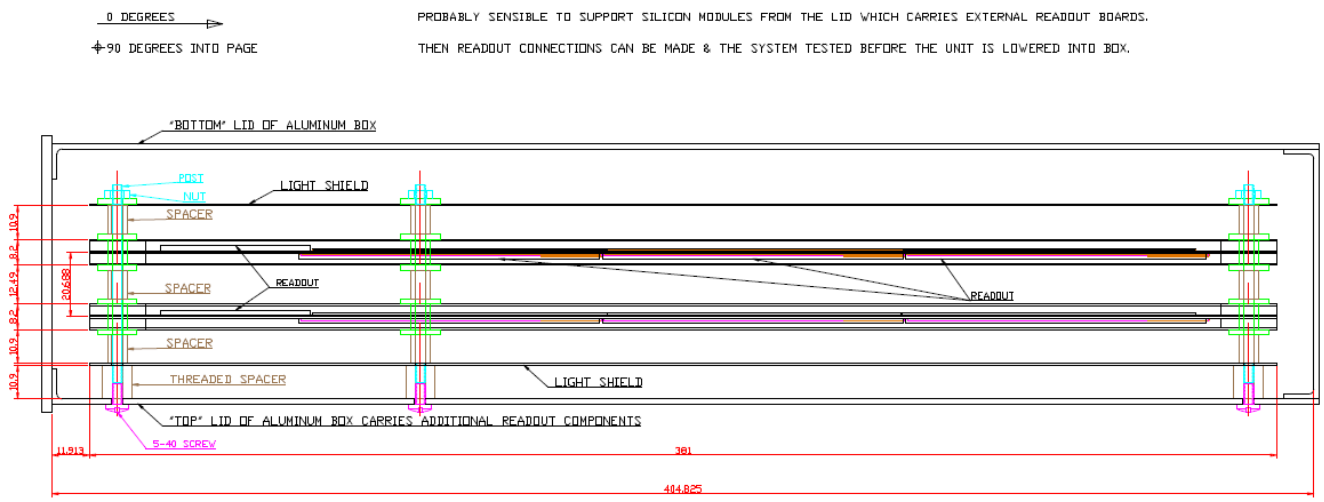

Fig. A1: Chamber configuration schematic.

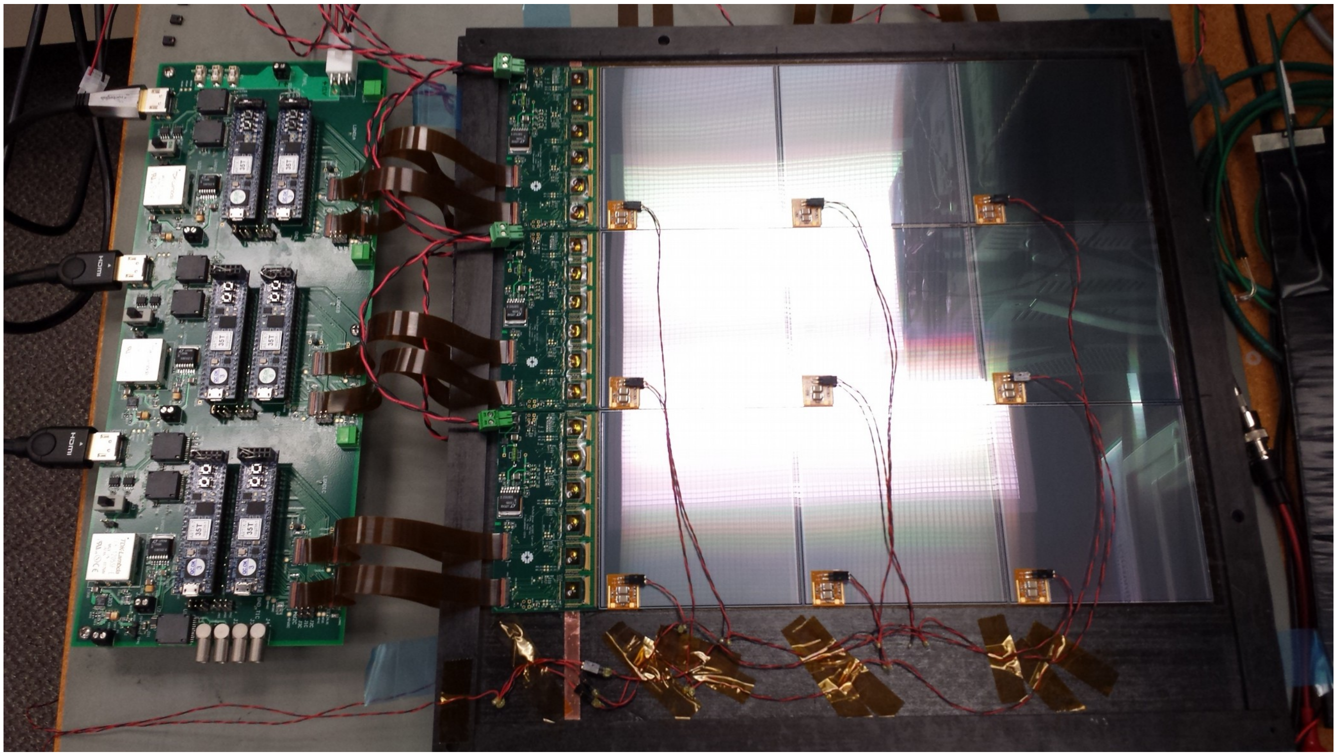
Fig. A2: Plane and HDIs, connected to lidboard.

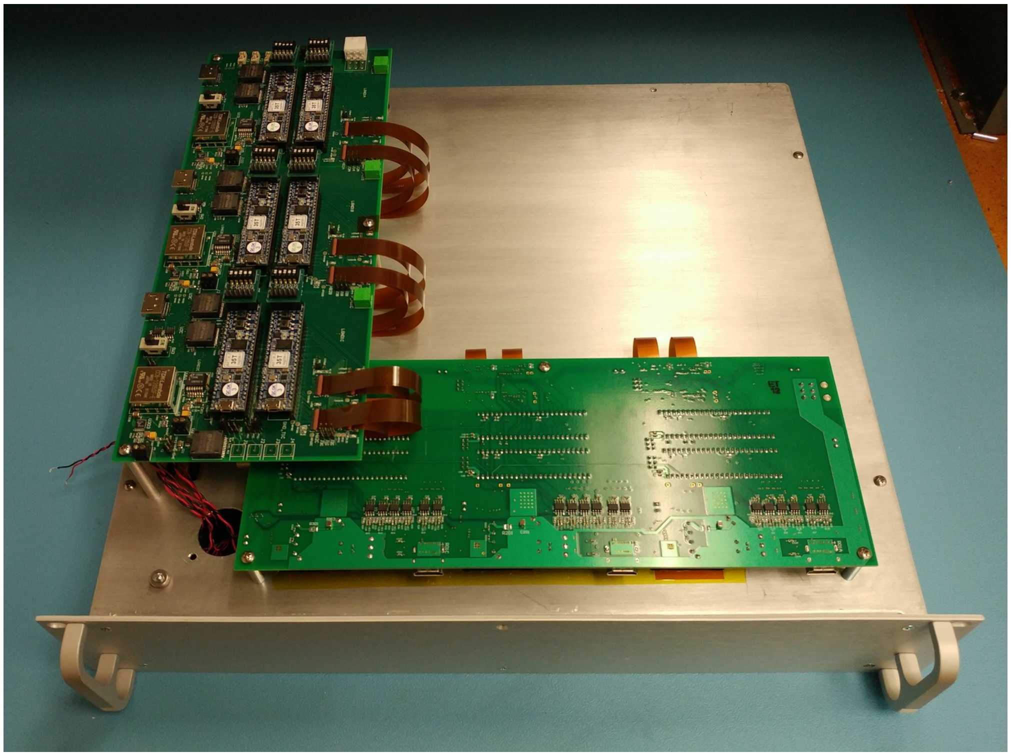
Fig. A3: Chamber with mounted lidboards.

Appendix B: Participants, Scientific Facilities, and Funding

Participants

J. Andrew Green, Mission Support and Test Services, LLC. Head of project, main analysis-end code developer.
Ron Lipton, Fermilab. Project mentor.
David Schwellenbach, Mission Support and Test Services, LLC.
Paul Rubinov, Fermilab.
Cristian Gingu, Fermilab.
Mike Utes, Fermilab.
Bill Cooper, Fermilab.
Johnny Green, Fermilab.
Bert Gonzalez, Fermilab.
Miguel Marchan, University of Illinois – Chicago. GEM intern, 2016 and 2017.
Rich Prokop, Northern Illinois University. Co-op student, 2018.
Martin Adams, College of San Mateo. CCI intern, 2016.
David Shi, Cañada College. CCI intern, 2017.

Facilities

The Fermilab Silicon Detector Facility (SiDet) was involved in the project in the assembly of most of the circuit boards used in the SMS, along with the construction of the scanner enclosure and mounting the sensors inside the enclosure.

Funding

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