Muon Scattering Tomography: Utilizing Silicon Photomultiplier Arrays to Trilaterate Muon Multiple-Coulomb Scattering Events

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Project Overview

What Is Muon Tomography?

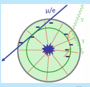
Muon tomography is a newly developed, passive imaging technique that utilizes the angle of scattering of muons through substances to determine elemental composition and density of said substance. This technique works by measuring the change in trajectory of an incoming muon due to multiple-Coulomb scattering through materials. The muon's exceptionally high attenuation length through various material cross sections coupled with its ability to undergo multiple-Coulomb scattering makes it an ideal candidate for tomographic imaging of mid- to high-Z materials.

Brief Project Synopsis

We invented a novel, cost efficient technique for conducting muon scattering tomography, which utilizes silicon photomultiplier arrays (SiPMs) placed by volumetric plastic scintillators to trilaterate muon ionization instances. Our method significantly decreases the costs of muon tomography while maintaining a similar voxel (volumetric pixel) resolution, accuracy, and scan time. Furthermore, a scaled up rendition of our device is far easier to maintain when compared to typical designs of muon tomographical devices.

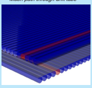
Conventional Designs

Drift Chambers: When the gas within the chamber is ionized, electron-ion pairs are formed which drift in the direction of the cathode and anode, respectively. Free electrons will furtherly ionize other gas molecules, creating a cascade effect that produces a measurable current in the vicinity of the particle incidence. This allows for extreme reliability and accuracy when determining particle positions. However, these drift tubes are exceedingly costly, require high maintenance, and use complex, costly readout electronics.



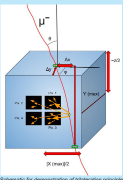
Muon path through drift tube[23]

Scintillating/Optical Fibres: Fibre optic cables cladded with scintillating material, when organized in a perpendicular lattice structure, sense particle instances through the coincidental emission of light at an intersecting node. Unfortunately, although the method is less expensive than drift tubes, this form of muon scattering tomography is still fairly expensive due to the implementation of fibre optics and photomultiplier channels allocated per each fibre. There is also a substantial loss of voxel resolution that arises from manufacturing limitations in the cross-sectional diameter of the fibres.



Scintillating fibre lattice[24]

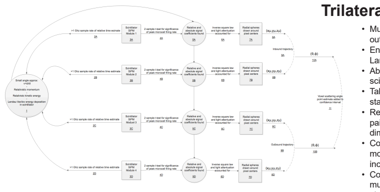
How Our Design Works



Schematic for demonstration of trilateration principle in scintillating prism

When a highly energized muon passes through a plastic scintillator, it ionizes, causing the plastic scintillator to transform the particles incidence into an optical signal with intensity relative to the amount of energy deposited within the sensing block. This is then sensed by a series of solid-state photomultiplying sensors placed upon the plastic to transform the optical signal to an electrical signal. The varying intensities allow for disparities in voltage in the final electrical signal; these disparities are quantitative inputs that may be construed (through trilateration) into spatial information regarding the position of the muon trajectory hypocenter. The discrete set of Cartesian coordinates collected from the four sensor modules enables the determination of an inbound and outbound trajectory from which a scattering angle may be derived as a three-dimensional reconstruction.

Trilateration



Flowchart visualization of trilateration algorithm

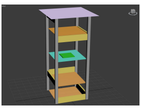
- Muon momentum is estimated using a timing system with a Schmitt trigger situated at the output of each photomultiplier array
- Energy deposition in scintillator is stochastically computed by using a Gaussian fit to the Landau-Vavilov distribution, and using the mode as a point estimate
- Absolute optical intensity: indicates depth of muon trajectory hypocenter into the volume of the scintillator, perpendicular from planar face of photomultiplier array
- Takes into account inverse square law of light sphere dispersion, attenuation effects in solid-state scintillator material, and empirical optical yield of the scintillator (Birks' Law)
- Relative optical intensity: discrepancy in Geiger discharge count between vertical and horizontal pairs of photomultiplier pixels indicates position of muon trajectory hypocenter along both dimensions of the planar surface where the photomultiplier array is placed
- Combining absolute and relative optical intensity measurements from all four scintillating modules enables the determination of an inbound and outbound trajectory for a singular muon incidence; multiple-Coulomb scattering angle ascertained
- Collusion between separate muon instances avoided due to low ambient flux of cosmic ray muons and partitioning of the scintillating material (where each partition has a respective photomultiplier array)

Engineering Process

Initial design [Nov 26 2016 - Dec 5 2016]

Using fibre optics cladded with scintillating material in a lattice structure with photodiodes on each individual strand would enable for muon scattering tomography to work.

- Significant size constraints for building a functioning prototype with a discernable results due to low voxel resolution
- Implausible to construct such a large prototype model with our limited resources and budget



Our initial scintillating fibre model for conducting muon scattering tomography

Revised and Finalized design [Dec 7 2016 - Feb 18 2017]

Using silicon photomultiplier (SiPM) arrays by volumetric scintillators to trilaterate particle instances would enable for muon scattering tomography to work.

- Plausible to build a scaled down prototype model with limited resources and still see significant results
- More simple and innovative design when compared to initial design
- Novel idea which has never been tested in this application
- More research was conducted for the creation of the device since there were no prior designs/examples to guide us
- Trilateration is an accurate way of discerning location of muon instance from disparity in quadrant signal strengths
- SiPM arrays are placed on the sides of scintillator, preventing its electric field from interfering with the muon's scattering
- 2 x 2 SiPM arrays allow for more accurate location of muon instance and less expensive than purchasing three individual SiPM's

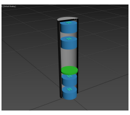


Diagram of second design utilizing volumetric scintillators

Type of Tomography	Drift Chambers	Initial Scintillating Fibre Lattice Design	Revised and Finalized Simple Trilateration Design	Further Modifications: Trilateration with increased PDE*
Overall Cost	Very Expensive	Very Expensive	Very Cheap	Cheap
Maintenance	Very High	Very High	Very Low	Low
Voxel Resolution	Very High	Low	Very High	Very High
Read-Out Electronics Cost	Very Expensive	Moderate	Very Cheap	Very Cheap
Timing Circuit	No	No	Yes	Yes

Chart visualizing the pro's and con's for various approaches to muon scattering tomography. Our novel design is seen on the right

Further modifications [Feb 22 - Present]

Increasing photon detection efficiency with the introduction of parabolic mirrors and lens. First form of efficient, scaled up version is designed.

Parabolic mirror

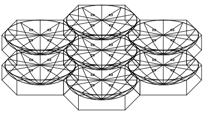
Light emitted away from the SiPM array will be redirected back to the sensor to enhance the signal received by the the SiPM's, thus increasing photon detection efficiency

Lens

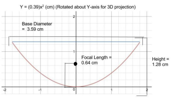
Allows for an increase in photon detection efficiency due an increase light being captured and redirected toward respective SiPM pixels

Scaled up implementation for finalized (increased PDE) design

- Large area scintillators with parabolic mirrors and lenses
- Individual pixels spaced across scintillator
- Stackable hexagon casings surround scintillator/parabolic mirror volume to allow for exchangeable layers



Scaled up design of parabolic, increased PDE approach. Hexagonal containers allow for easy assembly and maintenance



Dimensions of parabolic mirror

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