Construction

How can we build a functioning prototype to conduct muon scattering tomography with a $1,200 budget?

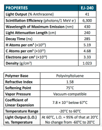
The entirety of this project was designed, constructed, and calibrated by us. The model consists of four sensing apparatus layers, an outer frame, metal shielding, and electrical circuitry. All materials not found at home were purchased out of pocket with the help of part-time jobs and prize money.

Sensing Apparatus Layers

Consists of: four scintillating cubes, four SiPM arrays, and metal holding brackets

Scintillating cubes

- Organic polyvinyltoluene based scintillator
- Peak emission wavelength of 430 nm
- Long decay time of EJ-240 (285 ns) enables the use of slower, cheaper electronics
- The differential optical flux is measured on the diamond-milled face of the scintillator while machine finished sides are glued to perpendicular metal shafts

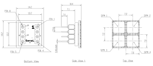


PROPERTIES	EJ-240
Light Output (% Anthracene)	41
Scintillation Efficiency (photons/1 MeV e⁻)	6,300
Wavelength of Maximum Emission (nm)	430
Light Attenuation Length (cm)	240
Decay Time (ns)	285
H Atoms per cm³ ($\times10^{22}$)	5.19
C Atoms per cm³ ($\times10^{22}$)	4.68
Electrons per cm³ ($\times10^{23}$)	3.33
Density (g/cm³)	1.023

Polymer Base	Polyvinyltoluene
Refractive Index	1.58
Softening Point	75°C
Vapor Pressure	Vacuum-compatible
Coefficient of Linear Expansion	7.8×10^{-5} below 67°C
Temperature Range	-20°C to 60°C
Light Output (L.O.) vs. Temperature	At 60°C, L.O. = 95% of that at 20°C No change from -60°C to 20°C

Properties of EJ-240 [2]

SiPM Arrays



Schematics for the ArrayC-60035-4P-EVB [1]

ArrayC-60035-4P-EVB [1]

- Silicon photomultiplier array incorporates four distinct pixels (CMOS microcell matrices) with independent outputs
- These SiPMs have a peak detection wavelength of 420 nm to couple with the polyvinyltoluene's peak emission wavelength
- The manufacturer specified an overvoltage of 2.5V to be applied with a reverse bias of 24.5V, allowing the sensors to function at 27V

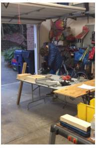
Epoxy drying after used on scintillators

- Machine finished sides of scintillator were epoxied to rough, sanded acrylic which was situated between two metal brackets that acted as holding shafts
- Shafts are placed at four different altitudes upon 80/20 rows so that the polyvinyltoluene cubes are in the center of the prototype
- Shafts are adjustable for calibrating purposes

Outer Frame

Consists of: 80/20 aluminum, various metal beams, metal brackets, wood, and fasteners

- Cut 80/20 aluminum used in the prototype skeleton into appropriate segments with a Dremel tool, handheld metal saw, and sander
- Fastened 80/20 segments together with perpendicular angle brackets
- Created hollow wooden rectangular prism to act as a base for the machine; electrical components are stored inside
- Attached metal beams as supporting columns with counterpart locking mechanism in order to secure prototype with wooden hood



Sawing 80/20 with other construction materials on table

Metal Shielding

Consists of: weldable steel

- Weldable steel was professionally TIG welded together corner to corner by a local metal fabricator

Electronics

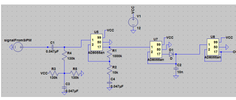
All electronics were designed, tested, soldered, and built by us. Aid was only received by an electrical engineer for general signal processing knowledge of our SiPM's. Electronics not shown: homemade evaluation board for each SiPM

The following images are illustrated using LTSpice. Simulations are generated to visualize signal processing system only.

The output each individual quadrant of the SiPM arrays consists of a steady voltage near ground with a fluctuation in voltage due to noise. The lowest energy muon of 800 MeV to pass through our scintillator will deposit enough energy to produce light that will fire an average of 24 microcells in each SiPM pixel. These microcells will produce a cumulative current of around 63μA, which is 20mV when flowing through the SiPM circuitry. Therefore, we have constructed circuitry to process voltages well below the minimum so that all expected muons are measured and accounted for.

Stage 1: Signal Isolation

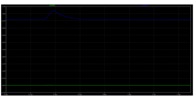
- Isolates raw signal from noise using capacitors
- Removes direct current using coupling capacitor
- Matches impedance using voltage follower made from AD9055A



LTSpice circuit diagram of signal processing. Image lacks first voltage follower, Schmitt trigger, and BJT for they are not necessary for visualizing signal processing system

Stage 2: Voltage Amplification

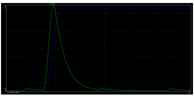
- AD8055A op-amps used to amplify signal for easier data analysis
- Processed signal from Stage 1 receives DC voltage of ~6V to carry away from ground
- AD8055A has a maximum gain of 35dB (55 times amplification) for expected frequency of signal (5.26MHz)
- Voltage disparity jumps from 20 mV to ~1V



Visualization of Stage 2

Stage 3: Timing

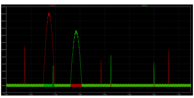
- Timing system is imperative for trilateration
- Schmitt trigger is used to detect rising voltage edges
- Disparate scintillation events allow for relative timestamp registering during reconstructive phase of data acquisition
- Total time estimate for muon transience is calculated



Visualization of Stage 4

Stage 4: Sample and Hold Circuit

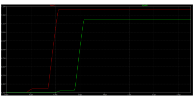
- "Sample and hold"-type circuit is constructed to solely detect utmost voltage peak of signal
- Extends signal until naturally droops or is reset by microcontroller



Simulation of two muon instances. Thermal noise, cross-talk, and other varieties of noise are taken into account.

Stage 5: Analog to Digital Conversion and Analysis

- Built-in A/D converters inside of various Arduino-based microcontrollers convert analog voltage to legible digital values
- Values are fed into main microcontroller (Raspberry Pi B2 or Arduino UNO), our data acquisition system



Expected outputs once signal is processed from image above

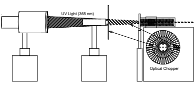
Calibration

Calibration of the proposed design consists of a dark count test, a UV LED to simulate signal in scintillator, and an optical chopper coupled with the UV LED for producing oscillations to observe rise/fall times.

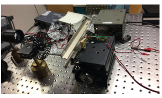
- Dark count test was conducted to evaluate microcell Geiger activation rates by thermally-induced noise in order to conclude significance thresholds for muon point detection

- UV LED allowed for the observation of fluctuations in the analog signal from modulating total energy deposited in the scintillator, and the differential signal generated in each "pixel" of the silicon photomultiplier arrays as the beam coordinates, pitch, and yaw were manipulated
- This data was compiled to develop an algorithm for beam trilateration and calculation of trajectory

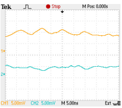
- An optical chopper was employed to model the SiPM output when two different microcell ring equilibria were alternated in a short timer interval
- Analyzing the analog signal amplitude and rise/fall times allowed us to determine optimal values for: bit resolution, gain requirement of op-amp setup for signal amplification trigger threshold for sample-and-hold circuit, and delay parameter for the BJT controlling the release of the peak detection phase



Calibration procedure of SiPM arrays when dividing UV light into various segments with optical chopper and directing it through 1.8 mm diameter aperture



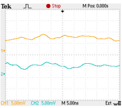
Our calibration set-up for a day's worth of testing



UV LED projected in upper left quadrant of scintillator (closer to SiPM 1 (Ch. 1))

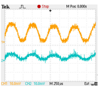
These oscilloscope outputs depict calibration testing for our trilateration algorithm. SiPM Pixels 1 and 4 were tested to see the differences between their signals when projecting the UV LED at various positions on the polyvinyltoluene scintillator.

On the images, Channel 1 (orange) indicates Pixel 1 and Channel 2 (blue) indicates Pixel 4. Signals were measured in diagonally positioned SiPM quadrants in order to maximize the disparity in the fluorescence detected by these pixels.



UV LED projected in lower right quadrant of scintillator (closer to SiPM 4 (Ch. 2))

As seen with the testing, the closer the LED beam was to the corresponding pixel, a higher voltage signal was supplied to the oscilloscope. This lower-energy simulation is more characteristic of a muonic signal because the photomultipliers are removed from their nonlinear saturation interval. This testing also helped mimic energy loss through a scintillator because there was consistently a higher voltage supplied by Pixel 1 due to the UV LED scattering directly when entering the plastic scintillator, emitting less intense light to Pixel 4.



Chopper output at 1 revolution per ~24,150 μs

In order to determine the bit resolution to design a readout circuit for analog to digital conversion, testing with a laser pulse segmented by an optical chopper was conducted at various chopper speeds. The signal output was measured with a high frequency oscilloscope where Channel 1 represents Pixel 1 on our array and Channel 2 represents Pixel 4.