Design and construction of a cosmic ray detector array for undergraduate research at the City University of New York

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Abstract

Cosmic ray detectors are being built by undergraduate engineering and computer science research students, high school teachers, and college faculty, for a detector array at campuses of the City University of New York. One hundred surplus plastic scintillators were donated from the Fermi National Accelerator Laboratory, and 100 decommissioned photomultiplier tubes obtained from the Brookhaven National Laboratory for the detectors. This paper discusses the quality testing of photomultiplier tubes and the scintillator, the detector design, and cosmic ray measurements using the QuarkNet data acquisition board. Students are involved over the course of their undergraduate studies via research and scientific computing courses, and REU summer internships at the national laboratories. By involving students, teachers, faculty, and research scientists from eight different institutions a learning community has been established.

Keywords

Undergraduate research, cosmic rays, photomultiplier tube, scintillator, QuarkNet

Introduction

The City University of New York Cosmic Ray Detector Array project, CUNY-Cosmic, is a faculty led research education project involving the Queensborough Community College (QCC), York College, and Borough of Manhattan Community College (BMCC). Participants include students from QCC, Suffolk County Community College, and Stony Brook University via the U.S. Department of Energy's Community College Internship Program (DOE CCI) at the Brookhaven National Laboratory's Electronic Detector Group, the QCC Space Weather and Cosmic Ray Groups, and high school physics teachers in the NSF QuarkNet outreach program based at the University of Notre Dame and Fermi National Accelerator Laboratory (Fermilab).

PMT Dark Rate Measurements

The plan for the detector array includes 100 cosmic ray counters each comprised of a 1m x 0.3m x 0.02m plastic scintillator (Nuclear Enterprises 114), a photomultiplier tube (Hamamatsu R2083 in an H2431-50 assembly, or EMI 9954KB05), a low voltage DC to high voltage DC converter (XP EMCO G30); sets of counters in each school will use a QuarkNet data acquisition board [1] with a GPS antenna and receiver to time stamp cosmic ray events [2].

Each PMT generates noise; one type is thermionic emission of electrons from the photocathode which also occurs in the absence of incident light resulting in “dark pulses” of charge off the anode. This dark pulse rate increases with applied voltage. Dark rates were measured for 90 PMTs one at a time, in a dark box to isolate them from room lighting. To measure dark rate each PMT anode output was connected to a x10 amplifier followed by a discriminator, and its pulse count recorded on a scalar over gated time intervals of 8 seconds. The purpose of the discriminator was to convert each pulse of charge into a NIM standard -800 mV square wave so it could be counted by the scalar; the discriminator used requires a minimum input signal of 30 mV which implies a 3 mV lower limit for signal detection. The dark rates were measured to be typically between 100 Hz and 10 kHz. The measured dark rates as a function of high voltage are shown in Figure 1.

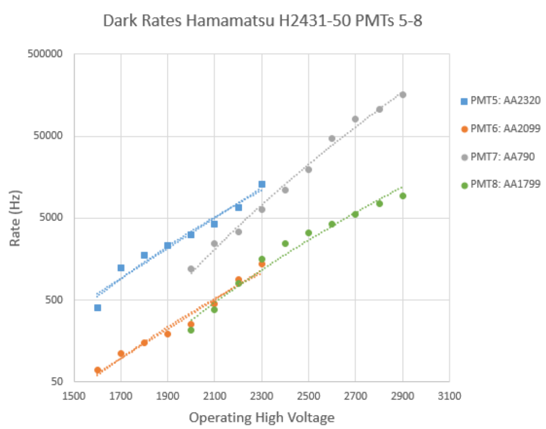

Figure 1: Measured dark rates for Hamamatsu H2431-50 PMTs

PMT Gain Measurements

To measure PMT gain a blue light LED was flashed on at 1.6V for 10ns, at a 10Hz rate, and distance of approximately 30 inches from the PMTs with the goal of limiting light on the photocathode to single photons. PMT pulses of charge were recorded on a Tektronix DPO4104 oscilloscope. The test setup is shown in Figure 2. A single photoelectron $\boldsymbol{e}$, of charge 1.6 x 10^{-19} C, emitted from the photocathode multiplied by the PMT gain $\boldsymbol{g}$, results in a pulse of total charge off the anode $Q_{\text{pulse}} = ge$. For the oscilloscope terminated in $50\,\Omega$ each point in the oscilloscope trace has voltage

$$V_i = I_i R = \frac{\Delta Q_i}{\Delta t_i} R,$$

where Δt_i is the oscilloscope time bin resolution; the 10-division horizontal display was set at 20 ns per division with 1000 points per trace thus $\Delta t_i = \frac{20\text{ ns/div } x \text{ 10 div/trace}}{1000\text{ points/trace}} = 0.2\text{ ns} \equiv \Delta t$.

The PMT pulse widths were measured at approximately $\Delta T = 16$ ns wide; each pulse has an area A near triangular in shape with an area determined by the amount of charge, and the rise and fall times of the PMT electronics. The expected peak voltage on the oscilloscope V_{peak} is calculated from

$$A = \frac{1}{2}\Delta T \cdot V_{\text{peak}} = \Sigma\, V_i \Delta t = \Sigma\, (I_i R)\Delta t = \Sigma\, \left(\frac{\Delta Q_i}{\Delta t_i} R\right) \Delta t = RQ_{\text{pulse}}.$$

For a single photoelectron off the cathode

$$V_{\text{peak}} = \frac{2R}{\Delta T} ge = \frac{2(50\Omega)}{16x10^{-9}\text{s}}\,(1.6x10^{-19}\text{C})g = 10^{-9} g\ \text{V}.$$

Thus our dark rate test setup having a 3 mV lower limit sensitivity should, in theory, see anode pulses from single photoelectrons while using a gain of $g = \frac{3mV}{10^{-9}} = 3x10^6$. The PMT manufacturer specified gain ranges over 10^6 to 10^7 at typical operating voltages which is consistent with our choice of test setup.

Figure 2: PMTs in dark box (left) and NIM electronics test setup (right)

To measure the gain the incident LED light was reduced until the PMT detection rate was about 10-20% (at the wavelength used the quantum efficiency specified by the PMT manufacturer is about 25%). The gain can be measured by integrating over the voltage

$$g = \frac{Q_{\text{pulse}}}{e} = \frac{1}{e}\,\Sigma\Delta Q_i = \frac{1}{Re}\Sigma\, V_i \Delta t = 2.5x10^7\ \Sigma\, V_i.$$

The oscilloscope traces were transferred to a computer with a LabView program as shown in Figure 3. From each trace a baseline was computed from points selected before the LED was turned on and after the PMT pulse position. A Python script was used to search for pulses by requiring the voltages for each of 5 consecutive trace points to be 3 standard deviations higher than the baseline mean. Waveform pulses were integrated after removing DC vertical offset, and noise, by subtracting the baseline mean from each point.

For a fixed LED driving voltage the PMT charge per pulse varies due to several factors including the number of photons emitted in each LED flash, the number hitting the cathode, and the PMT cathode's efficiency in converting photons to photoelectrons. Thus at each PMT operating voltage the charge in each of 20,000 pulses was measured $Q_{\text{pulse}} = \frac{\Delta t}{R}\Sigma\, V_i = 4x10^{-12}\Sigma\, V_i$; a charge distribution was filled from which the single photoelectron pulse charge was extracted from a fit (Figure 4). The fit function used was a Poisson distribution convolved with a Gaussian distribution which is a good approximation to the expected charge distribution [3]. The probability P that n photoelectrons would be collected by the first PMT dynode when μ is the average number collected by the first dynode is Poisson-distributed $P(n;\mu) = \frac{\mu^n e^{-\mu}}{n!}$.

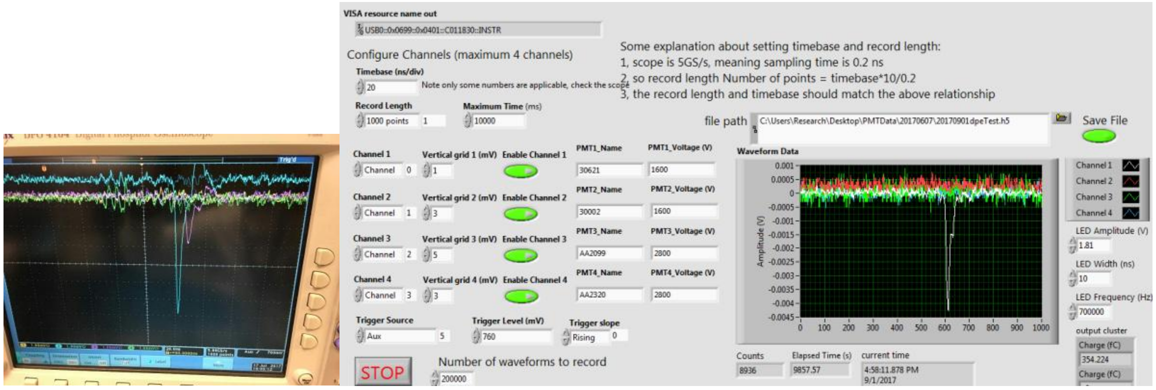

Figure 3: Oscilloscope trace with PMT pulse from LED flash (left); LabView interface to the oscilloscope (right)

The output pulse of the PMT is also dependent on the dynode chain which is assumed to be Gaussian-distributed

$$G(x; q_{\text{avg}}, \ \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-q_{\text{avg}})^2}{2\sigma^2}};$$

q_{avg} is the average charge output from the PMT when 1 photoelectron hits the first dynode, x is the variable charge, and σ is the single photoelectron charge distribution's standard deviation. The final fit function is

$$F(x) = P(n;\mu) \otimes G_n\big(x; q_{\text{avg}}, \ \sigma\big) = \sum_{n=1}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \frac{1}{\sigma\sqrt{2\pi n}} e^{-\frac{(x-nq_{\text{avg}})^2}{2n\sigma^2}};$$

q_{avg} and σ corresponding to the single photoelectron charge distribution are extracted from the fit. The gain was measured at different high voltages and a Gain vs. HV plot fitted to power law to measure the gain function (Figure 4).

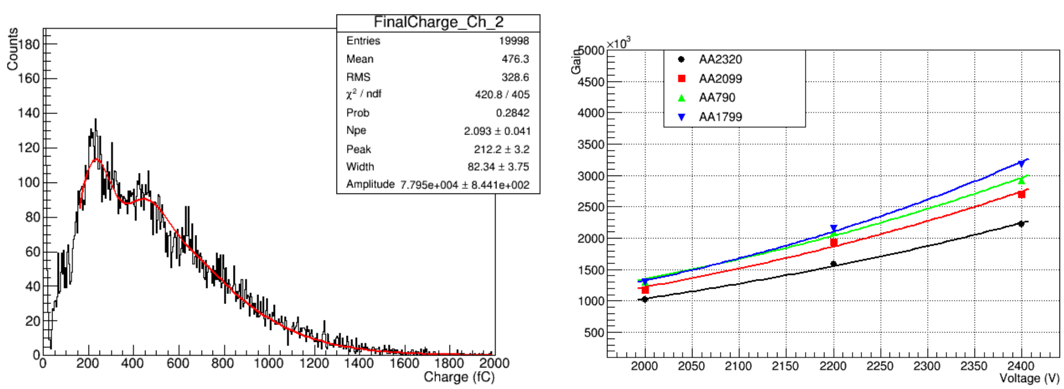

Figure 4: The Figure on the left is the fitted PMT charge distribution for 20,000 LED flashes; the parameters shown in the fit box corresponding to those defined in the fit F(x) are Npe ≡ μ, Peak ≡ q_{avg}, Width ≡ ***σ****. The gain vs. high voltage measured for four PMTs is shown in the right Figure where each gain curve is fitted to a power law function*

Scintillator Efficiency Measurements

The surplus scintillator had previously been rough cut into pieces approximately 1m long. The rough edges were cut, sanded, and polished clear for optimal light output. Different tools were used to cut the plastic to determine which resulted in the least amount of required sanding. The smoothest surface was obtained on a milling machine using a 4-fluted helical end mill. An OMAX 2652 abrasive waterjet cutting machine resulted in a rougher surface (the waterjet material setting was programmed to cut acrylic of 0.75" depth and Quality 5). A band saw with a dry metal blade, and a circular saw with a metal blade designed to cut plastics, both resulted in the roughest edges; these results are shown in Figure 5.

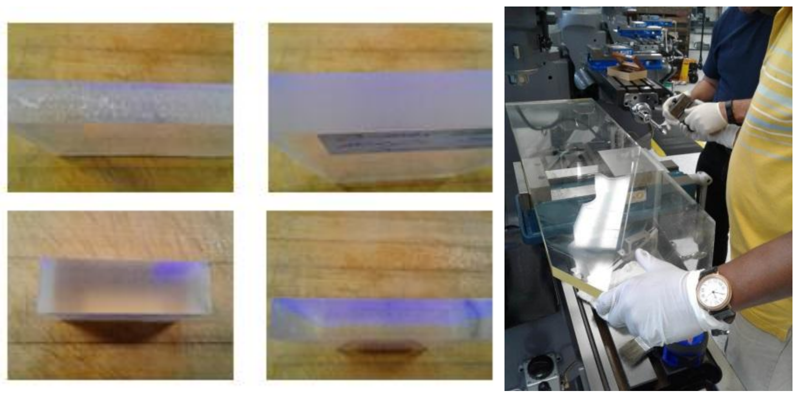

Figure 5: Pieces of scintillator after cut with different tools. Top left: band saw; top middle: waterjet; bottom left: milling machine; bottom middle: untouched piece from the manufacturer. Far right: scintillator being cut on the milling machine.

A NE-114 scintillator was wrapped in aluminum foil, mated to a H2431-50 PMT, and its efficiency in detecting cosmic ray muons incident at points far from the PMT was measured in a dark box. The efficiency was measured using a "muon telescope" consisting of two smaller paddle size detectors sandwiching the scintillator under test. The paddles were moved along the length of the scintillator and the ratio of the 3-fold coincidence rate to the 2-fold coincidence rate recorded

$$efficiency\ (\%) = \frac{coincidence\ event\ rate\ all\ 3\ counters}{coincidence\ event\ rate\ for\ paddles\ only}\ x\ 100\%.$$

The two paddle detectors are made from newer pieces of higher quality scintillator having larger light output, and only 1/3 as long. As with the dark rate measurements NIM electronics were used. The PMT output from each paddle detector was fed into a x10 amplifier followed by a discriminator, then into a 2-fold coincidence measuring unit connected to a gated scalar. The discriminator outputs from the two paddle detectors were also fanned into a separate coincidence unit to measure the 3-fold rate with the counter under test. The efficiency results are shown on the left hand side of Figure 6. When a 30 mV discriminator was used for all three counters the NE-114 counter's relative efficiency was 37% at a distance of 24 inches from the PMT. An 1/8" thick silicone optical interface pad was in between the PMT glass lens and scintillator, held in place with a support. The PMT lens will be glued directly to the scintillator with optical cement and the tests repeated.

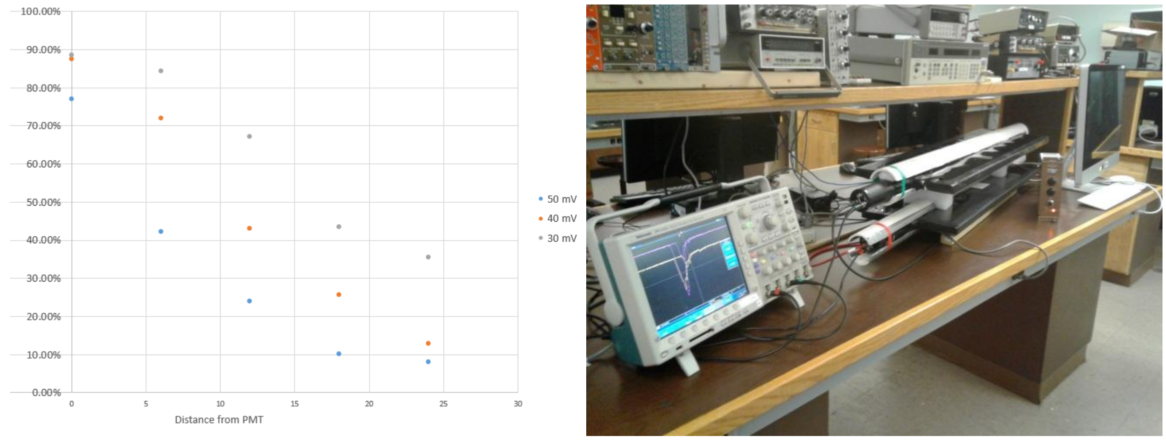

Figure 6: Left: scintillator efficiency measurements; the different color points correspond to different discriminator thresholds used for all three counters. Right: two NE-114 scintillators wrapped in aluminum foil and black paper, mated to H2431 PMTs, and recording cosmic ray muons on an oscilloscope.

Cosmic Ray Measurements

The CUNY Array detectors will use the compact Quarknet data acquisition electronics board (DAQ) which allows up to four PMT inputs per board, has on-board amplifiers, discriminators, coincidence logic, time gates, and scalars [1]. The board records each PMT pulse satisfying a user-defined criteria as an event; a 25 MHz clock outputs event information in 40 ns intervals and hexadecimal format. The DAQ board has additional on-board electronics which further resolves each event's leading and trailing pulse edges and time over threshold. A Python script was written to plot the DAQ output. The rate of cosmic ray muon flux incident on earth is known to be inversely correlated to atmospheric pressure. As a means to test our Python plotting script two QuarkNet scintillator detectors were used with the QuarkNet DAQ board to measure muon flux during winter storm "Stella" over three days in March of 2017; simultaneously the atmospheric pressure was measured with a barometer in the same lab; Figure 7 shows the results.

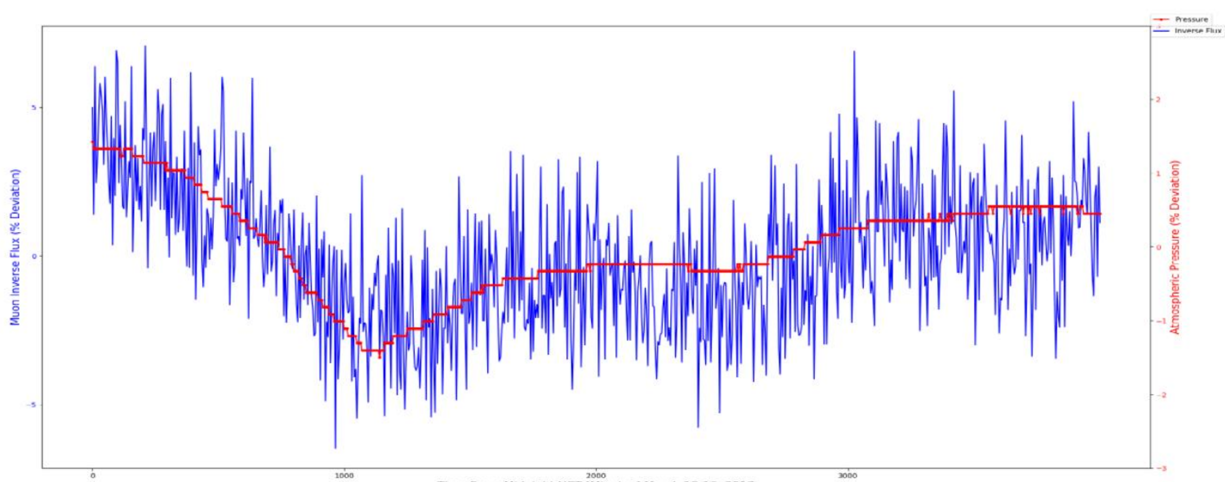

Figure 7: Inverse cosmic ray muon flux measurements (blue) overlaid with atmospheric pressure measurements (red);data recorded at Queensborough Community College using three QuarkNet detectors during winter storm "Stella" in March of 2017.

Conclusions

A cosmic ray detector array is being built for undergraduate research. One hundred 1m long surplus scintillators (1,500 pounds) were acquired from Fermi National Accelerator Laboratory and brought to the Queensborough Community College. Preliminary testing of the scintillator has begun. Ninety PMTs were characterized in their dark rate and gain from which seventy have been selected for the array. The Quarknet DAQ board has been tested and a computer program written to analyze the cosmic ray data. In the process of building the array, a learning community has been established involving students, teachers, and scientist mentors from several colleges, high schools, and national laboratories.

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References

1. Sten Hansen, Thomas Jordan, Terry Kiper, Dan Claes, Gregory Snow, Hans Berns, T. H. Burnett, Richard Gran, and R. Jeffrey Wilkes "Low-Cost Data Acquisition Card for School-Network Cosmic Ray Detectors," IEEE Transactions on Nuclear Science, Vol. 51, No. 3, June 2004, pp. 926-930.

2. Hans-Gerd Berns, Toby H. Burnett, Richard Gran, and R. Jeffrey Wilkes, "GPS Time Synchronization in School-Network Cosmic Ray Detectors," IEEE 0-7803-8257-9/04, Nuclear Science Symposium Conference Record, 2004, pp. 789-792.

3. E.H. Bellamy et. al., "Absolute calibration and monitoring of a spectrometric channel using a photomultiplier," Nuclear Instruments and Methods in Physics Research, section A, 339 (1994) 468-476.