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Studies on the DAQ System of GRINCH detector

A thesis submitted in partial fulfillment of the requirement for the degree of Bachelor of Science in Physics from The College of William and Mary

by

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Studies on the DAQ System of GRINCH detector

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April 15, 2016

Abstract

The A_n^1 experiment at Jefferson Lab Hall A is designed to precisely measure the virtual photon asymmetry of neutrons in the Deep Inelastic Scattering (DIS) region using Hall A polarized ${}^{3}He$ target and BigBite spectrometers. Even though both electrons and pions will be scattered, the BigBite spectrometer is designed to measure electrons only. Thus the Gas Ring Imaging Cherenkov (GRINCH) detector is vital, given its capacity to reject pions. The standard Fastbus Data Acquisition (DAQ) system used at Hall A lacks efficiency facing the increasing beam intensity. Thus it is impossible to generate directly a trigger for GRINCH that can be integrated into the BigBite trigger. Now a faster DAQ system is required. One proposal is the VXS-based Electron Trigger and Readout Card (VETROC), a FPGA-based digital board that contains not only a high-rate pipelining Time-to-Digital Converter (TDC), but also a programmable cluster-finding desired trigger. VETROC will be tested on a GRINCH prototype detector, a simplified version of GRINCH. This thesis is meant to prepare for VETROC tests by setting up a fully functional Fastbus DAQ system. This Fastbus DAQ, whose timing resolution ranges from 6 ns to 15 ns, is able to record Photomultiplier tube (PMT) firing patterns. A red LED is used to replace the Cherenkov light as the event source for the Fastbus tests.

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1 Introduction

GRINCH is the key to pion rejection in the ongoing A_n^1 experiment in Hall A, which eventually will give information about the spin carries by the quarks [1]. Photomultiplier tubes in GRINCH are expected to take in a maximum rate of 140 kHz per tube for less than 5 kHz of single electron rate from the calorimeters in BigBite and HRS [2]. However Fastbus TDC could only handle 5 kHz event rate with a 25% dead time [3]. The major candidate to replace Fastbus is VXS-based Electron Trigger and Readout Card (VETROC). There are two key features of the board. One is that it has a built-in high-rate pipelining Time-to-Digital Converter (TDC) with 128 channels whose preliminary resolution is 20 ps [4]. The other is that it is FPGA-based and thus allows a programmable cluster-finding trigger. The built-in trigger is unprecedented. For now the data of Gas Cherenkov detectors could only be used for off-line analysis because in such a high-rate environment it is practically impossible to produce a detector trigger signal that can be integrated into BigBite trigger[5]. The success of VETROC would also make huge contribution to other projects because at Jefferson Lab people have been long concerned by the low-rate problems due to various reasons [6]. This thesis means to prepare for future VETROC tests on a GRINCH prototype built in 2012. A Fastbus DAQ will be set up and tested, which is ought to be capable of capturing PMT firing patterns. Such patterns will be crucial for the cluster-finding algorithm design in the future. No cosmic ray is needed for DAQ functionality tests, so a red LED is used to replace the Cherenkov light as the event source. However, make no mistake, the GRINCH prototype is fully able to detect Cherenkov light, as tested back in 2012.

1.1 Theories of Gas Ring Imaging Cherenkov Detector



Figure 1.1: GRINCH top layout from W&M-Jlab wiki. The red line represents the incoming window, the green line represents the PMT arrays, the yellow line represents the exit window, and the orange shape is the mirror. The particles scattered bt the target will enter from the red line and exit from the yellow line. The Cherenkov light waves will be reflected by the mirror towards the PMT arrays (510 PMTs totally). The radius of curvature is 130 cm.

GRINCH detector was designed at The College of William and Mary, in collaboration with North Carolina Agricultural and Technical State University and James Madison University, to be used in the upgrade of the BigBite spectrometer for the A_n^1 experiment [7]. Its

main objective is pion effective rejection. Like other Cherenkov detectors, GRINCH utilizes gas Cherenkov radiation, an electromagnetic shock wave produced when a charged particle passes through a medium (gas here) with a speed higher than that of light in the medium. The Cherenkov angle θ in figure 1.2 depends on the speed of particles in the medium. Because of the mass difference between electrons and pions, with the same momentum the two particles will travel with different speeds. Hence the emitted light waves will have different patterns. The light waves will be reflected by the concave mirror inside GRINCH towards the Photomultiplier Tubes (PMT), which converts light into measurable electric current through the photoelectric effect. Photoelectrons generated from photocathode will be multiplied upon impact on each Dynode. Then with the help of an external counter like a TDC, the patterns of light waves can be studied through the PMT firing patterns. In this way, pions can be identified and rejected from the hodge-podge.



Figure 1.2: Cherenkov Cone [8]. The angle θ is the Chenrekov angle. The particle is moving to the right.



Figure 1.3: Diagram of a PMT [9]. Photoelectrons are multiplied on each Dynode.



Figure 1.4: Uncompleted GRINCH vessel at Jefferson Lab. In the future, other parts like the mirror will be installed.

1.2 GRINCH prototype

To run preliminary tests a simplified prototype was constructed in 2012. Unlike the actual GRINCH embedded with 510 Photomultiplier Tubes (PMT), the prototype possesses only 81 PMTs. Also the prototype has a much smaller mirror and internal volume. However for my experiment, the prototype was modified. More details are in section 2.



Figure 1.5: GRINCH prototype. The black arrow through the window indicates the direction of incoming light, and the arrow from the mirror indicates the direction of the reflected light to the PMT arrays on the left. The mirror used here shares the same curvature with GRINCH.

1.3 Fastbus DAQ



Figure 1.6: Fastbus crate. The modules on the left are ADCs and those in the middle are TDCs. The CPU is the silver module on the right.

The signal output from PMTs will flow into the Fastbus DAQ system. Fastbus is made of crates. Each crate contains a central CPU and a combination of LeCroy 1877 Time-to-Digital converter (TDC) modules and LeCroy 1881M Analog-to-Digital converter (ADC) modules. LeCroy TDC modules take in only Emitter-coupled logic (ECL) signals and the ADC modules only take in analog signals. Both a TDC and an ADC require a trigger to function. Luckily every TDC and ADC shares one trigger inputted to the whole Fastbus crate. TDCs basically convert electric signals into digital representations of the time they occurred. Once triggered, TDCs start to work from "start", which is the input ECL signal, to "stop", which is usually a delayed ECL signal. ADCs provide the amount of charge integrated from the signals within a selected timing window called the gate. To cope with difference inputs, the analog signal outputs from PMTs go into NINO cards first. The NINO cards are made by collaborators from University of Glasgow. Each card contains a 16-channel amplifier/discriminator based on CERN NINO chip [10]. The NINO threshold is set via external DC voltage. A 2.0 V DC supply would generate a maximum NINO threshold, while a 1.6V DC supply generates a minimum. The amplified analog signal eventually goes into ADCs and the Low-voltage differential signaling (LVDS) outputs are converted into ECL signals and enter TDCs. Because these LeCroy modules are seriously outdated, Fastbus TDC could only handle 5 kHz event rate with a 25% dead time [3].



Figure 1.7: The two NINO cars used in my experiment. The black ribbon cable is for analog signals and the colorful ones are for digital signals. The golden LEMO connectors on the bottom of the figure take signals from PMTs. The blue wires on the top power the NINO card on the right, while the black and red wires provide external thresholds.

1.4 VETROC



Figure 1.8: VETROC board/vfTDC [4]

The VETROC board refers to the vfTDC, an electronic board based on the VXS-based Electron Trigger and Readout Card (VETROC). VETROC was originally designed for the Jlab Hall A Compton polarimeter [11]. The board contains a high-rate pipelining TDC with a crate trigger processor (CTP) which could self-trigger. The TDC words have a Dynamic Range of 32 bits and each board has 128 channels for input. Up to 17 boards may be used with a single CTP [12]. Meanwhile, the board accepts any kind of differential input, including ECI, LVDS,etc from 100 mV to 4V. The price for each board is below \$2000 [12]. The preliminary resolution is 20 ps [4]. It indicates that VETROC is able to recognize events with an unprecedentedly high resolution. The newly tested result by Scott Barcus shows that the two-hit resolution, which measures how close two signals can be shown together while not distinguished by the TDC as two separate events, is about 8.8 ns. [12] Also VETROC tends to

completely fail only above rates of about 520 kHz per input channel and introduces zero dead time for hit multiplicity five (five times the number of pulses per second) up to about 166 kHz [12], which is much higher than the expected 140 kHz rate per tube. Thus VETROC is more than enough for GRINCH. However VETROC can only function if installed in a VME crate.



Figure 1.9: VME crate for VETROC

The trigger algorithm was originally written in Verilog by me, and later corrected and translated into VHDL by Scott Barcus. It is able to search patterns— a cluster of 2/3/4 adjacent and simultaneous hits for the whole PMT arrays in GRINCH. It was successfully tested on a Altera board with cyclone II. This thesis helps identify the kinds of possible patterns. Since my algorithm covers at most any hit patterns within a 4x4 squire, the final version of the trigger algorithm will be a sheer deduction from mine.



Figure 1.10: VETROC trigger algorithm demonstration

2 Experiment setup

2.1 Prototype Detector Modification

I made several modifications on the prototype for experimental purposes. Firstly I replaced its original flat mirror with a concave mirror whose radius of curvature is 130 cm just as that of the mirror in the actual GRINCH detector. Secondly I installed a red LED, powered by a function generator, from the aluminum window into the detector. Its purpose is to "simulate" a light source and substitute cosmic rays for early stages because cosmic rays have a much lower rate compared to an adjustable LED. Also with a LED, no gas is needed since Cherenkov radiation is not utilized. The LED is held in a customized container that induces a light cone with a 3 ° variance in each degree of freedom. Then with the help of the concave mirror, a cluster of light should appear on the PMT arrays. Thirdly Bogdan suggested a small circular observation hole right besides the LED on the window, which is sealed but could be open if necessary. Fourthly the noise background for TDC measurements was created by an external UV LED installed through the observation hole. It serves to simulate real scenarios. Finally the shop made a new stainless-steel stand to hold the detector in different orientations so that it will fit the cosmic ray tests in the future.

The critical part is to ensure the cluster generation. Figure 2.2 shows the actual cluster of red light on the PMT arrays. The green background is caused by the laser for illumination. A scalar is used to measure the count rate of each individual PMT. The LED is powered by a function generator. The function generator is set at a period of 250 μ s, a width of 20 ns and a peak-peak voltage of 5 V. However the actual output only provides 3.12 V for unknown reason. Because the LED works fine with a voltage between 1.8V and 6V, the discrepancy in the output is acceptable. The bias voltage of each PMT is based on the previous gain match result done in 2012. The data is represented by color in figure 2.3. From it we can see that the clusters vertically spread along the cluster center in figure 2.2, since the the count rate



Figure 2.1: A rough scratch of prototype detector (top view)



Figure 2.2: View of cluster from the observation hole. The green background is caused by a green laser for better visibility. The red area is the reflected LED light.

of the PMTs are proportional to the intensity of light. Thus our experimental result matches our expectation for the setup.



Figure 2.3: PMT count rate map

2.2 Fastbus DAQ

2.2.1 ADC Gain Match

In my experiment, the core thing I care about is the timing of signals, which could only been learned from TDCs. Therefore ADCs only serve as a tool to match the overall amplification factor (gain) of the 81 PMTs in the prototype. The gain of a PMT is linearly supply-voltage dependent. Usually a higher voltage means a larger gain. The gain-match is crucial because any unexpected variable produced by "improper" supply voltages to PMTs would significantly damage my experimental results. Due to limitation on the cable supply, only 16 channels out of 81 channels of PMTs were to be examined by the ADC a time.

The experimental setup is demonstrated in figure 2.4. The TDC setup was only a check to see whether the TDC module functions. There is actually one huge mistake in this setup: the output from the function generator is not inverted before entering the discriminator, which only accept signals with negative voltages. However I was so lucky that the output from the function generator was not a perfect square wave with a positive amplitude. One small part of it was periodically negative, whose value was higher than the minimum threshold of the discriminator! Since the discriminator output has the same amplitude as long as it is triggered and the negative part of the square wave is in perfectly phase with the rest (positive parts), neither the gate signal nor the Fastbus trigger signal is affected! The setup also demonstrates why a LED was chosen in the first place: the whole crate can be simply trigger by the function generator that powers the LED! If I were to use cosmic ray, I would have to set up a muon hodoscope and have the crate triggered by the coincidence. The biggest challenge here is to select the amount of time to delay so that the analog signal sits exactly in the gate. Figure 2.5 demonstrates a successful signal-gate match. The gate in the figure is about 100 ns wide, but the width was increased to 120 ns to the right when taking ADC

data.



Figure 2.4: ADC Gain Match setup



Figure 2.5: Delayed signals

For each PMT, three set of data was taken. The supply voltages for initial test were selected from the gain-match report from 2012, and for every new set of data, they were increased by 100 V. Note: the PMTs here feed on positive voltages only. However all ADCs introduce a large peak called pedestal on the very left of the horizontal axis in the histogram. It is irrelevant to the PMT signals and thus has to be removed. The positions of pedestals are only ADC-dependent, so they were measured by having the power of PMTs cut. Then in the histogram, a cut around the position of the pedestal was introduced. Everything on the left side of the cut was abandoned. Because the samples in figure 2.6 and 2.7 show two different tubes with different supply voltages and therefore they do not share a peak position.



Figure 2.6: Sample ADC histograms with pedestals



Figure 2.7: Sample fitted ADC histogram with pedestals removed

Once all the pedestals were removed, I was able to apply gaussian fit on each individual peak. A gaussian fit sample is shown in figure 2.7. Then the three peak positions corresponding to three different voltages for each tube was plotted with a linear fit. Using the linear fit formula and a chosen peak value of 300, a new supply voltage was calculated for each tube. Figure 2.9 shows the peak positions for all the channels after applying calculated voltages. Besides several channels, most channels peak at around 300. So the gain-match was successful. I believe the discrepancies were caused the imperfect PMT power supply, which could not give out a 100% desired voltage.



Figure 2.8: Sample linear fit of peak positions for PMT channel 10



Figure 2.9: Peak positions for all 81 channels in one plot

2.2.2 Single Event Display



Figure 2.10: Single Event Display setup

Once all PMTs were gain matched, the experimental setup was redone. The ADC was disconnected because it would have contributed nothing to my timing measurement. This time a inverter was correctly installed. The noise UV LED powered by a random pulse generator was used to simulate the noisy background in a real experiment. It was expected that the standard deviation of the gaussian fit for the peaks would increase due to the noisy background. Because in order for the TDC to function, the start signal has to come in before the stop signal, we chose a 389 ns delay to create enough timing difference. Note: my setup could only measure 32 channels a time. Multiple sets of data were taken with different NINO thresholds.

The singal event display is highly useful because it tells which tubes are firing within a common TDC stop, like a screen shot in time. At each screen shot, patterns are recognized, which will provide vital intels for VETROC trigger development. To ensure the quality of TDC histograms, 32 PMTs in the area with highest intensities of light were chosen, as figure 2.11 described. The blue numbers are irrelevant in this case. DO NOT confuse the blue numbers here with those in other similar signle event display plots in section 3. In section 3, all blue numbers indicate the TDC value corresponding to each PMT within a common stop.



Figure 2.11: Layout of chosen PMTs

2.2.3 TDC Calibration

However before doing analysis, all TDC histograms have to be calibrated, by moving the peaks to the origin. The reason is that singal event displays require a precise cut around the peak position, and parameters are much easier to input if the peak is at the origin. The location of the peak was found through gaussian fits. In both figures below the mean value

denotes the peak position, and the standard deviation gives the resolution. One special modification in my TDC histograms is the "customized" unit of the horizontal x-axis. Originally one unit in x-axis equals 2 ns, while in my histograms, it represents 1 ns. That is to say for example the peak in figure 2.12 is at 336.4 ns, NOT half of that!



Figure 2.12: TDC histogram of channel 15 with noise



Figure 2.13: Calibrated TDC histogram of channel 15 with noise

To make sure what I did was valid, I took another set of data that covers all the PMTs without noisy background (UV LED off). My result showed that the peaks did not move much. The difference between the two peaks for each of the 32 channels is less than 4%. Note: The red squares represent data without noise. Also TDC channel-1 does not represent PMT-channel 1 because of the layout in figure 2.11.



Figure 2.14: Peak positions for the chosen 32 PMTs with and without noise

Another test is about the rate limit for the TDC system. Both the NINO thresholds and the period of function generator output were modified, in order to find the highest rate the system could handle.

3 Data Analysis



3.1 Fastbus DAQ Resolution and limit

Figure 3.1: Peak standard deviations for the chosen 32 PMTs with and without noise

The resolution of the TDC is given by the standard deviation of the peak fit. Here the red squares represent data without noise. Clearly a noisy background (1000 kHz) does introduce a higher value of standard deviation, because it forces PMTs to take in photons randomly and more frequently. Except for the high value in channel 0, others remain pretty consistent, ranging from 6 ns to 15 ns. The lowest standard deviation with noise is about 6.003 ns and it comes from channel 15.



Figure 3.2: Calibrated TDC histogram of channel 15 with noise

Meanwhile, I found that the TDC system started to crash given the maximum NINO thresholds and a period of 125 us for the source red LED. That is to say that my Fastbus DAQ system cannot handle a rate higher than 8 kHz. By saying "crash", I mean the failure to respond of the data-taking software CODA. However, no dead time measurements were done. It is highly possible that the upper limit can be improved by switching the current CPU in the Fastbus crate.

3.2 Single Event Display

The most important part about single event display is the cut — a chosen area within the histogram that contains the peak only. If no cut is applied, all PMTs will be firing all the time due to the high frequency noisy background (100 kHz). Then a single event display will be useless. The cut is determined from figure 3.2 to be +/- 20 ns around the origin. That is only the piece of data within x=-20 and x=20 is analyzed. Such cut covers almost the whole peak. Also because of the TDC calibration, all peaks should be around this range with different width though.



Figure 3.3: Single event display at the fourth common stop with a 20ns cut.



Figure 3.4: Single event display at the fourth common stop with no cut.



Figure 3.5: Single event display at the seventh common stop with a 20ns cut.



Figure 3.6: Single event display at the seventh common stop with no cut.



Figure 3.7: Single event display at the twenty first common stop with a 20ns cut.



Figure 3.8: Single event display at the twenty first common stop with no cut.



Figure 3.9: Single event display at the twenty seventh common stop with a 20ns cut.



Figure 3.10: Single event display at the twenty seventh common stop with no cut.

The four sets of single event displays show that without any cut, no pattern is tractable since all the tubes are always firing. But with a 20ns cut, patterns are clear. The blue numbers represent the corresponding TDC values, which indicate the time, with respect to the TDC start within a common stop, when a PMT fires. For example, a "0" means that at t=0 a PMT fires. All valid hits should occur around 0 since all the peaks in the TDC histograms are shifted to the origin. Hits with much larger TDC values are highly likely coming from the noisy background. All the four plots with a 20ns cut demonstrate hits from the red LED source around t=0, while the four plots with no cut show background noises at large t along with source hits around t=0. The dominant pattern in the with-cut plots is a cluster of 2/3/4 hits. This result is highly promising since my Verilog algorithm is fully capable of handling such kind of pattern.

4 Conclusion and Future work

My tests demonstrate that the Fastbus TDC system for GRINCH prototype is fully operational. It is able to capture patterns of incoming light waves and thus it provides vital intel for the VETROC trigger algorithm development in the future. The dominant pattern is a cluster of 2/3/4 hits, which can be easily handled with my Verilog trigger algorithm. However as expected, such a DAQ system is only able to maintain its efficiency in a low rate environment (below 8 kHz). Also the best resolution the Fastbus TDC achieved is around 6 ns.

In the future there are many more to accomplish. Firstly, a VME VETROC crate will be set up in the ESB building at Jefferson Lab. The same 32 chosen PMTs for the single event display will be used. This time VETROC will be the one to find hit patterns. Also my trigger algorithm will be tested. Secondly, future Fastbus and VETROC tests are to be done with cosmic rays. Because the red LED I used in my experiment supplied both source signals and trigger signals, it cannot represent reality, where people could only work with random coincidence triggers. Also a pattern caused by a LED is not a reliable one for triggering since it does not concern any Cherenkov light in the first place. The figure 4.1 shows the draft setup. The Lucite inside works like a scintillator.



Figure 4.1: A rough scratch of prototype detector (top view)

Moving on, more data need to be taken with real Cherenkov radiations. The box will be filled with gas and resealed. Finally with enough information, the trigger algorithm can be improved and help prepare VETROC for the actual GRINCH detector in the near future.

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