Designing Data Read Out Electronics for the CHANDLER Neutrino Detector

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July 28, 2021

Abstract

CHANDLER is a reactor neutrino detector technology with potential applications in nuclear security, nuclear instrumentation, and basic science. In 2017 a prototype of CHANDLER named MiniCHANDLER was deployed at North Anna Nuclear Generating Station, where it demonstrated the detection of reactor neutrinos. Since this deployment, the CHANDLER collaboration has been working to make improvements. One of the many improvements that are being made to MiniCHANDLER is the readout electronics. The old electronics were based on a shaper circuit, single-ended input of the photomultiplier tubes (PMT) signals, and a digitizer with a 12-bit analog to digital converter (ADC). The old electronics were not able to effectively measure higher energy neutron proton recoils, there was cross-talk between neighboring channels, and high energy pulses would lead to a large oscillation of the baseline. In the new electronics, there is improved dynamic range and no cross-talk. The new electronics consist of a custom all-in-one base that will digitize and process the PMTs signals as well as provide the high voltage. This all-in-one base is based on a field programmable gate array, which allows coding capabilities that were not present in the previous electronics. This summer, to improve the trigger algorithm, a new running baseline code was made. This running baseline takes an average of previous ADC counts and accounts for baseline fluctuations. Having this new baseline potentially allows for a more precise online separation of neutrons and gammas in the FPGA. Once these electronics are fully assembled testing will take place.

1 Introduction

CHANDLER (Carbon Hydrogen Antineutrino Detector with a Lithium Enhanced Raghavan optical lattice) is a reactor neutrino detector technology. The CHANDLER technology consists of layers of wavelength shifting plastic scintillator cubes separated by thin sheets of lithium-6 (^{6}Li) loaded zinc sulfide. Currently, there are two prototypes of CHANDLER, these are MiniCHANDLER and MicroCHANDLER. The size of MiniCHANDLER is 8x8x5 cubes and the size of MicroCHANDLER is 3x3x3 cubes. There is a plan to make the third iteration of CHANDLER called full CHANDLER. Full CHANDLER will be 20x20x26 cubes.

^{6}Li is used to capture a neutron, which is how CHANDLER technology is able to detect antineutrinos. In inverse beta decay, when an electron antineutrino scatters off a proton, it creates a positron and a neutron [1].

$$\bar{\nu}_e + p \to n + e^+ \tag{1}$$

When this reaction occurs, the positron acquires most of the energy from the antineutrino. Next, the positron energy is deposited into the scintillator cubes, which produces light proportional to the energy of the antineutrino. The light that is produced by the scintillator cubes is then guided to the PMTs by total internal reflection. The neutron is captured on a ^{6}Li nucleus in the zinc sulfide sheet which emit light into the scintillator cube above and below the interaction [5]. This allows for 3D spatial reconstruction, because not only can the length and width of the reaction be detected, but also the approximate sheet. Once the light is captured by the PMTs, information is then reported back to the computer.

Most nuclear power plants use four main fissile isotopes for power. These fissile isotopes are ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu. The ^{239}Pu is produced by neutron capture on ^{238}U followed by two beta decays. Most nuclear power plants will produce large amounts of ^{239}Pu, which is not a problem if it is contained within the reactor. This becomes a problem when the ^{239}Pu is extracted from the other fuel. A country or group may want to do this because Plutonium with over 90 percent of ^{239}Pu is weapons-grade plutonium. When enough ^{239}Pu is obtained it can be used for nuclear weapons. The neutrino spectrum from a detector is dependent on the reactor power and the isotopic composition [4]. Each type of fissile isotope used in the detector will have a slightly different neutrino spectrum. There are several applications for CHANDLER technology. Fuel composition can be observed without having to do traditional monitoring methods. This could be a viable option over traditional monitoring methods because they can be costly and detrimental to the operations at the nuclear plant. CHANDLER technology could also be used after a nuclear accident to detect criticality in the reactor core. Other implications for CHANDLER technology include fuel consumption monitoring and power monitoring.

On June 15, 2017, MiniCHANDLER was taken into the Mobile Neutrino Lab and deployed at North Anna Nuclear Generating Station, where it stayed for four months detecting antinuetrinos (See figure 1). The Mobile Neutrino Lab sat 25 meters away from the center of the reactor core and detected about 100 neutrino interactions per day [3]. Though this deployment was successful and proved the effectiveness of CHANDLER technology, it was also apparent that MiniCHANDLER could be much more effective. The electronics faced complications because of its range, dynamic range, oscillating baseline, and inability to do complex sequences. To improve the CHANDLER technology significant upgrades are taking place. These upgrades include light guides on the PMTs, half cubes, and electronics. The light guides will be attached to the PMTs so that the PMTs can collect light over a greater surface area on the scintillator cube, which enables it detect about 64 percent more light. Half cubes are being implemented to increase the ^{6}Li neutron capture efficiency. Instead of the traditional setup, the scintillator cubes will be half as high and the PMTs will span two cube layers, staggered on opposite sides of the detector. This means that one PMT will see above and below a zinc sulfide sheet. Perhaps the most important upgrade is to the electronics.

Figure 1: Mobile Neutrino Lab at North Anna Generating Station

2 Old Electronics

The old electronics for MiniCHANDLER consisted of a shaper, CAEN digitizer with a 12-bit ADC (See figure 2). The 12-bit ADC was not able to effectively measure higher energy neutron proton recoils, because they exceeded the range. Another problem with the old electronics was that there was cross-talk between neighboring channels, due to the channels of PMT signals being so close together [4]. Moreover, the pattern recognition could fail under high energy pulses, as it would cause large oscillations in the baseline. This oscillation distorts the delta-time histogram as shown in figure 3. These oscillations caused retriggers and at times the inability to read low pulse height neutron signals. If the trigger threshold was set to the level required for maximal neutron detection efficiency, the digitizer would send too much information, using too much bandwidth. To compensate the trigger threshold was raised, which led to missing vital information.

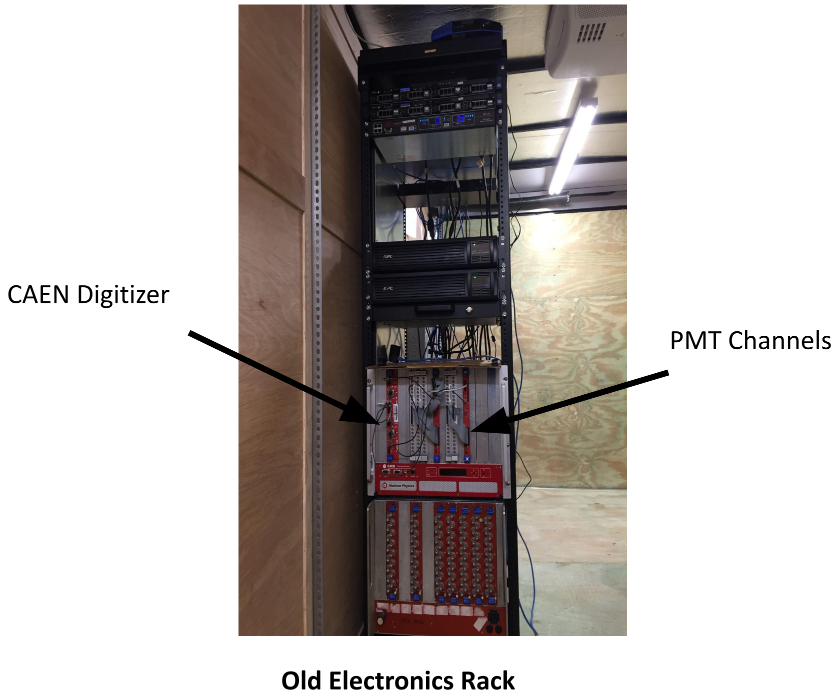

Figure 2: Old Electronics Rack

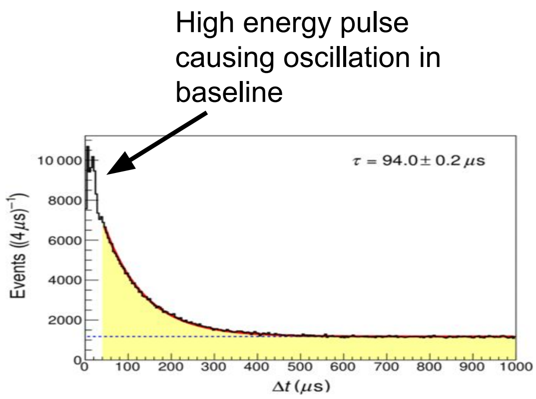

Figure 3: Delta-time histogram of gamma and neutron events

3 New Electronics

The development of the new electronics is geared toward eliminating the failings of the old electronics. The new electronics will have no crosstalk, better dynamic range, no oscillating after effects, take up less space, and be less expensive. The custom all-in-one base will consist of three circuit boards that will be placed on each PMT, which will replace the old electronics rack (See figure 4). These circuit boards will be the photomultiplier tube interface board, the high-voltage board, and the logic board. The high-voltage board takes a low voltage and ramps it up through a Cockcroft-Walton multiplier. The photomultiplier tube interface board digitizes the PMT signals at the PMT base, which is a solution to the crosstalk of the old electronics. Lastly, the logic board houses the microcontroller, RAM, and the FPGA. The FPGA is an addition to the new electronics that adds coding flexibility. FPGAs allow for more complex codes to be used, which can fix some of the problems with the old electronics. Two problems that are going to be improved because of the FPGA are the trigger algorithm and the running baseline. To improve on the issue of not being able to effectively measure higher energy neutron proton recoils, the 12-bit ADC was upgraded to a 14-bit ADC. This improves the range from 4096 ADC counts to 16384 ADC counts, which increases the range, and dynamic range. The baseline is never set to zero so that it is possible to observe baseline dips.

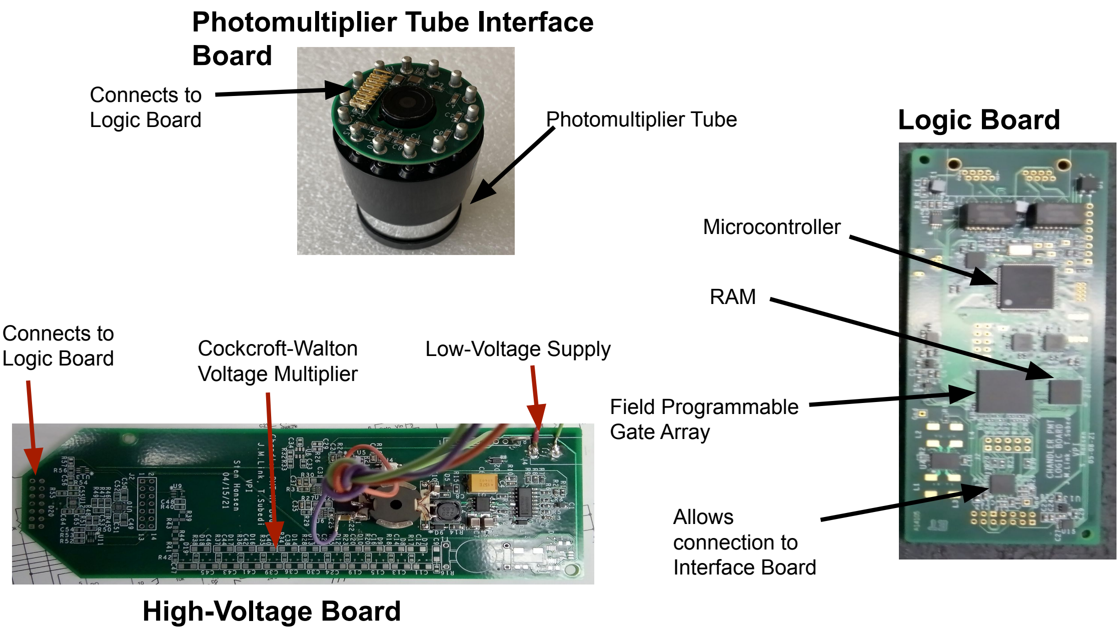

Figure 4: New Circuit Boards

4 Readout Firmware

The FPGA uses VHDL as the coding firmware. The running baseline code characterizes the baseline allowing the pretrigger window to be analyzed. The running baseline will send out the sum of the ADC counts, moving average, ADC values squared, sum of ADC squared, and moving average squared. These all could be used as important indicators to compensate for the running baseline not being perfectly flat. Preceding an event trigger two types of pretrigger patterns are expected, which are a relatively flat baseline and exponential decay. The figures below display the ADC counts and sums for a relatively flat baseline going into a small neutron hit, and exponential decay of a neutron (See figures 5 and 6).

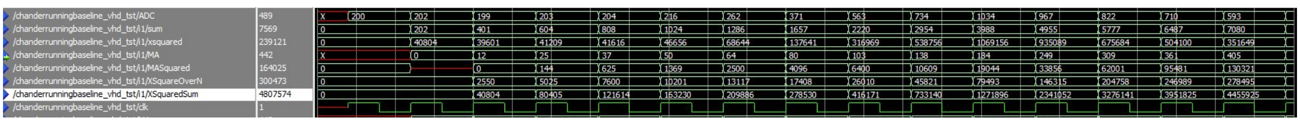

Figure 5: Simulation of flat baseline leading into small neutron hit

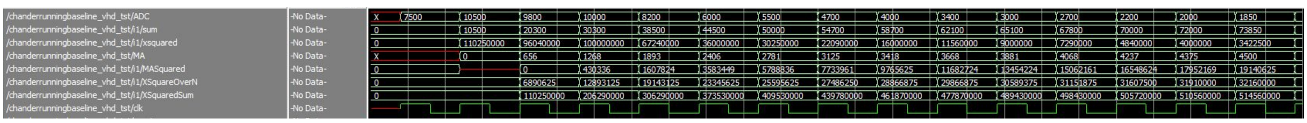

Figure 6: Simulation of neutron decay

Implementing the running baseline code allows neutrons detected in rapid succession to a preceding position to be analyzed better. Without the running baseline code, once the ADC counts cross a threshold, a neutron candidate is recorded. With the running baseline code, an average can be taken at all times, and the trigger can be adjusted accordingly. Furthermore, the running baseline also sends out additional information that can be used for analysis. In addition to the moving average of the ADC counts, the running baseline code calculates and sends different sums including, but not limited to the most recent ADC value, the oldest ADC value, the ADC value squared, and the difference of the last two ADC values squared. The purpose of sending out these sums is to send enough information to the computer for proper analysis of the behavior of the baseline. Although some division operations can be performed in the FPGA, they should be avoided because of accuracy and resource consumption. Division in FPGAs takes a lot of resources, to get around this you can divide vectors by powers of two by taking bits off the end. Taking off one bit is the equivalent of diving by two, taking off two bits is equivalent to dividing by four, every time you take off a bit it divides by additional power of two. This is an effective method and is a workaround for division, but it is not completely accurate because it truncates. This means it only gives the whole number, and does not round up. The truncation from taking bits off the end of the vector in question causes problems when you have to do division multiple times. For example when calculating the root mean square the values can be very inaccurate, so instead of calculating the root mean square in the FPGA we can send the sums that are needed to calculate the root mean square to the computer so the calculation can be performed there.

In the future we are considering adding another workaround for the truncation, these are look-up tables (LUTs). LUTs have stored values that can be called upon when needed. The reciprocals of values that need to be used for division will be stored in the LUTs. Another future plan for the running baseline code is to not have it continuously send all of the information it obtains. A study will be done of what “sums” will be good indicators that nothing unusual is occurring in the baseline, then those sums will be the only data sent out. If those sums are not in their normal range then all of the information will be sent out so that the baseline can be analyzed and the problem can be solved.

5 Conclusion

The old electronics for MiniCHANDLER were effective, but had many problems. This summer, an effort was made to improve the electronics in the form of the running baseline code. The running baseline code sends out information of the pretrigger window, which is important for baseline analyzation. Future work includes adding LUTs and only sending the necessary sums. The LUTs will allow more for more accurate division and sending less sums will conserve bandwidth for other information. This code has been tested in the Quartus simulation tool ModelSim, but official testing in the FPGA will take place once the electronics are fully assembled.

Acknowledgements

This work was funded and supported by the National Science Foundation grant number IIP-1941238. Thank you to, Prof. Jonathan Link, Tulasi Subedi, Sten Hansen, and the CHANDLER collaboration for guiding me through my summer research. Thanks to Prof. Camillo Mariani, and Betty Wilkins for handling the logistics of my research at Virginia Tech.

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