Digital Photomultiplier Tube Bases and Preparation for the Chicagoland Underground Observatory for Particle Physics' Muon Veto Dark Matter Detector

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ABSTRACT

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The Chicagoland Underground Observatory for Particle Physics (COUPP) is preparing to commission a muon veto weakly interacting massive particle (WIMP) dark matter detector consisting of a 30-liter, 66-kg, heavy-liquid bubble chamber, amidst a one-ton water Cerenkov light cosmic ray detector, by the end of 2009. The water Cerenkov light detector will use 19 Hamamatsu photomultiplier tubes (PMT). New digital bases were designed and created for these PMTs, allowing 20 PMTs to be connected to a controller card, which is in turn connected and controlled by a single computer. Due to the revolutionary design of these bases, before they could be implemented in the detector, they required testing and debugging to ensure their proper operation, which was performed without incident. Following the debugging of the bases, a 55-gallon water Cerenkov light detector utilizing one PMT was set up, and measurements were taken using a scale proxy of the 66-kg bubble chamber to determine to what extent the bubble chamber will affect the light properties of the one-ton Cerenkov light detector, and how much of the bubble chamber would be required to be covered in white Tyvek to ensure good light characteristics.

INTRODUCTION

While gravitational effects of dark matter have been detected, actual detection of dark matter has remained elusive. A prominent theory is that dark matter is composed of WIMP's, massive particles that have a gravitational field, but only interact with other particles through the weak forces. Based on this theory, COUPP is currently in the process of commissioning a muon veto dark matter detector. The detector consists of two parts: a central bubble chamber, which is surrounded by a water Cerenkov light detector. Bubble chambers were the primary detectors used in particle physics until newer technologies replaced them in the 1970s. A bubble chamber works by using metastable superheated liquids. When an accelerated particle passes through this liquid, the heat deposited by the ionizing radiation of the particle generates a local nucleation. The nucleation leads to the formation of bubbles along the particles' paths, which are photographed, and the chamber is then reset by fast recompression of the liquid to its stable liquid phase, and then decompressing it again to bellow the vapor pressure, making the liquid metastable again and sensitive to accelerated particles. In the past, uncontrollable bubbling on porous materials such as gaskets and metallic surfaces meant that the liquid would only remain in its sensitive state for a small amount of time (~seconds) which was acceptable for measuring the bunched arrival of an accelerator beam, which takes only a couple of milliseconds [1]. Yet, precautions can be taken to prevent this from occurring and allow for indefinitely long periods of sensitivity, which is required for WIMP detection [2]. The benefit of using a bubble chamber for WIMP detection is that they are sensitive to both spin-dependent and spin-independent WIMP couplings, as well as being able to be made insensitive to the minimum-ionizing backgrounds that have hampered other WIMP searches [3]. In order to discriminate against muons, the bubble chamber is situated inside a one-ton Cerenkov light water chamber, which detects the

Cerenkov light produced by accelerated cosmic rays traveling through the water. The light is measured by PMTs, and muon interactions can then be detected and discriminated against. To aid in this, special digital bases were designed and created for these PMTs. These bases contain numerous inbuilt features such as: high voltage (HV) power supply, signal integrator data acquisition (DAQ), and the ability to work with synchronized timing with a total of 20 bases. Due to the new design of these bases, they needed to be tested and debugged to ensure their usability. The inside of the Cerenkov light detector is covered in white Tyvek, a water proof form of paper such as that used for envelopes, in order to increase the reflectivity of the inside of the detector, allowing for greater light detection by the PMTs. The outside sides and bottom of the bubble chamber are also covered in Tyvek for the same reason, however, the top of the bubble chamber contains numerous piping, and it needed to be determined whether it would be worth the effort of placing Tyvek on the top of the bubble chamber as well. This was tested using scale models of the Cerenkov water chamber and the bubble chamber.

MATERIALS AND METHODS

i. Digital PMT Bases

In preparation for the COUPP muon veto detector, new digital bases were designed and built for the PMTs (see Figure 1) [4]. The base is powered by a standard 24 V “calculator style” power source, which provides a low voltage (LV) source to a DC-DC converter. An intermediate voltage is then generated by a transformer secondary, which is then used by a Cockcroft-Walton multiplier to generate the HV needed by the PMT. This eliminates the safety problem associated with HV distribution. This 24 V power supply is also enough to operate up to 20 bases.

Each base consists of an anode signal-processing chip. The anode signal is attached to an integrator, which has a decay time constant on the order of 250 ns. The integrator is attached to a 40 msps analog-to-digital converter (ADC). The ADC sample rate is subdivided into 16 parts. The ADC is connected to a field programmable gate array (FPGA), which is in turn connected to a synchronous dynamic random access memory (SDRAM) allowing for an arbitrary length of ADC data record to be read. A differentiator takes the integrator output and sends a clipped signal to a time to digital converter (TDC), which operates at 1/16 of an ADC sample (~1.56 ns per count).

A selected sequence of data words are copied to an event buffer, where it awaits a query asking if any trigger conditions have been met. The base then responds with a list of trigger times, which are stored in a buffer that can store on the order of 300 ms of un-zero-suppressed ADC and TDC data. This is then accessible by a computer through a universal serial bus (USB) port. The bases also contain two RJ-45 connectors which are compatible with standard Cat-5 cables. These allow the bases to be used in chains of up to five, with information, timing, and power being transmitted through the Cat-5 cables (see Figure 2).

A controller card has also been designed, and is still in the process of being built, which would allow four chains of five bases each, to be linked together. The controller card has the same type of power distribution system as the bases, and is designed for the 24 V power source to be plugged into it, and can then distribute power to all the bases through the Cat-5 cables. The controller card contains a variable crystal oscillator (VXO), and uses geographic addressing to synchronize all the bases. It also contains a microcontroller and an FPGA, allowing for software triggering, readout, control, and monitoring, as well as LEMOs for frequency references, triggering, test pulses, and synchronization (see Figure 3). When queried, the controller card will send out its own query to all the bases if the set trigger conditions have been met. If so, then the bases will sequentially send the controller card their ADC and TDC data, which is then stored on the controller card's own SDRAM, which can then be read by a computer through an Ethernet cable connection. As a result, these new bases, in conjunction with the use of a single controller card, eliminate the need for an external HV power supply, discriminator and DAQ, which are needed when using previous PMT base designs.

ii. Debugging Setup

Currently, only prototype boards of these new digital PMT bases have been produced; thus, testing is required before they can be implemented in the dark matter detector. To this end, two RCA 2454 PMT's were attached to a single piece of solid scintillator, and made light-tight using electrical tape (see Figure 4). One of the new digital bases was attached to each PMT, and a LabVIEW v8.5 program was written to interface with the bases. After the LabVIEW program was written, data was taken using various settings of the threshold, sample length, and pedestal length, and the results were compared with previously measured ranges of the PMTs.

iii. Cerenkov Light Water Chamber

In addition to ensuring the usability of these new digital PMT bases, knowledge of the light qualities of the Cerenkov water chamber would be desirable. A smaller, 55-gallon Cerenkov water chamber was set up, with a single R5912 PMT set floating on the water on a raft of Styrofoam. The inside of the 55-gallon barrel was lined with Tyvek, and two scintillator paddles were placed on top of each other below the water tank, and were used as a trigger so that data would only be taken when an actual muon stream was detected with the paddles [5]. A proxy detector was then built using a piece of pipe that would be roughly to scale for the bubble chamber inside the one-ton Cerenkov water chamber (see Figure 5). Measurements of the Cerenkov light were then taken without the proxy detector, with the proxy detector without any Tyvek, with Tyvek just on the sides and bottom, and completely covered in Tyvek. Measurements were taken of each case with the PMT at 1400 V, 1500 V, and 1600 V.

RESULTS

i. Digital PMT Bases

The results for the debugging of the new digital bases were largely qualitative in nature. The two primary parameters to determine were: to ensure that the bases worked properly with the LabVIEW program such that it read back the correct changes when the various settings were altered, and that the data read fell into the range of previously measured values. Traces and histograms were taken, and were visually compared to see if they fell within the appropriate ranges.

ii. Cerenkov Light Water Chamber

The resulting voltages from the ADC used with the PMT were graphed in a histogram, with the value of the pedestal subtracted from all the values. A Gaussian was fit to each histogram, and the average and root mean square (RMS) were calculated (see Figure 6). At all voltages, the same consistent trend was seen. The amount of received light, as determined by the resulting ADC signal, decreased when the proxy detector was added to the water chamber by ~10%.

When just the sides and bottom of the proxy detector were covered in Tyvek, the average again decreased by another ~10%. When the entire proxy detector was covered in Tyvek, the average was increased to ~95% the amount of light that was received without the proxy detector in the water chamber.

DISCUSSION AND CONCLUSION

i. Digital PMT Bases

While there were a few issues with being able to set the threshold properly and resetting the buffer memory all issues involving the bases working with the LabVIEW program were overcome, and no modification is required of either the base or the program. Similarly, all the measured values appeared to be consistent with what would be expected for the PMTs. Thus, the bases are now continuing to be produced and finished in preparation for their implementation in the dark matter detector.

ii. Cerenkov Light Water Chamber

As would be expected, the amount of light received by the PMT decreased when the proxy detector was placed in the water chamber. What was not expected is that adding Tyvek to the sides and bottom of the proxy detector appeared to have further decreased the amount of light received, instead of actually increasing it. However, when the top was also covered, the PMT received significantly more light, over 90% of the light that was received when the water chamber did not contain the proxy detector at all. It is possible that the Tyvek was not securely attached to the sides of the proxy detector, and that light managed to get trapped in between the layer of Tyvek and the proxy detector. When the top was also covered, this could have covered up the gap between the proxy detector and the layer of Tyvek, preventing light from getting trapped there. If the same is true for the actual bubble chamber in the one-ton water chamber, then its top should also be covered in Tyvek. However, the proxy detector had a flat top, while the actual bubble chamber has numerous hoses coming out of its top (see Figure 5), so covering the top of the bubble chamber should not increase the amount of light received by the PMTs by the same ratio that covering the proxy detector increased it by, and would prove difficult to implement.

FUTURE WORK

By the end of 2009, it is expected that the COUPP muon veto dark matter detector will be commissioned. Currently being done are: characterization of the PMTs, building of the PMT bases, and finishing construction of the bubble and water chambers, all of which should be completed by late August 2009. Designing of the controller card for the PMT bases has just been finished, and the card should be assembled by early September 2009. Once the entire detector is finished, it will take some measurements to ensure the functionality of all its systems before it is moved ~350 feet underground to the Neutrinos at the Main Injector (NuMI) tunnel at Fermi National Accelerator Laboratory.

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[3] W. J. Bolte *et al*., Kavli Institute for Cosmological Physics at the University of Chicago, “WIMP detectors: Low-background detectors—neutrinos, axions, WIMPs,” July 24, 2009, June 25, 2006, http://collargroup.uchicago.edu/projects/wimp/index.html.

[4] The bases were designed and built by Sten Hansen (Hansen@fnal.gov), Fermi National Accelerator Laboratory.

[5] The purpose for placing the paddles directly on top of each other instead of telescoping them so as to know the direction of the muon stream is for expediency of data collection, and that the results require only comparisons between data sets.

FIGURES

Figure 1: A picture of the newly designed digital PMT base to be used in the Cerenkov water chamber part of the COUPP muon veto dark matter detector, along with the 24 V power source that can be used to power up to 20 PMTs and their bases.

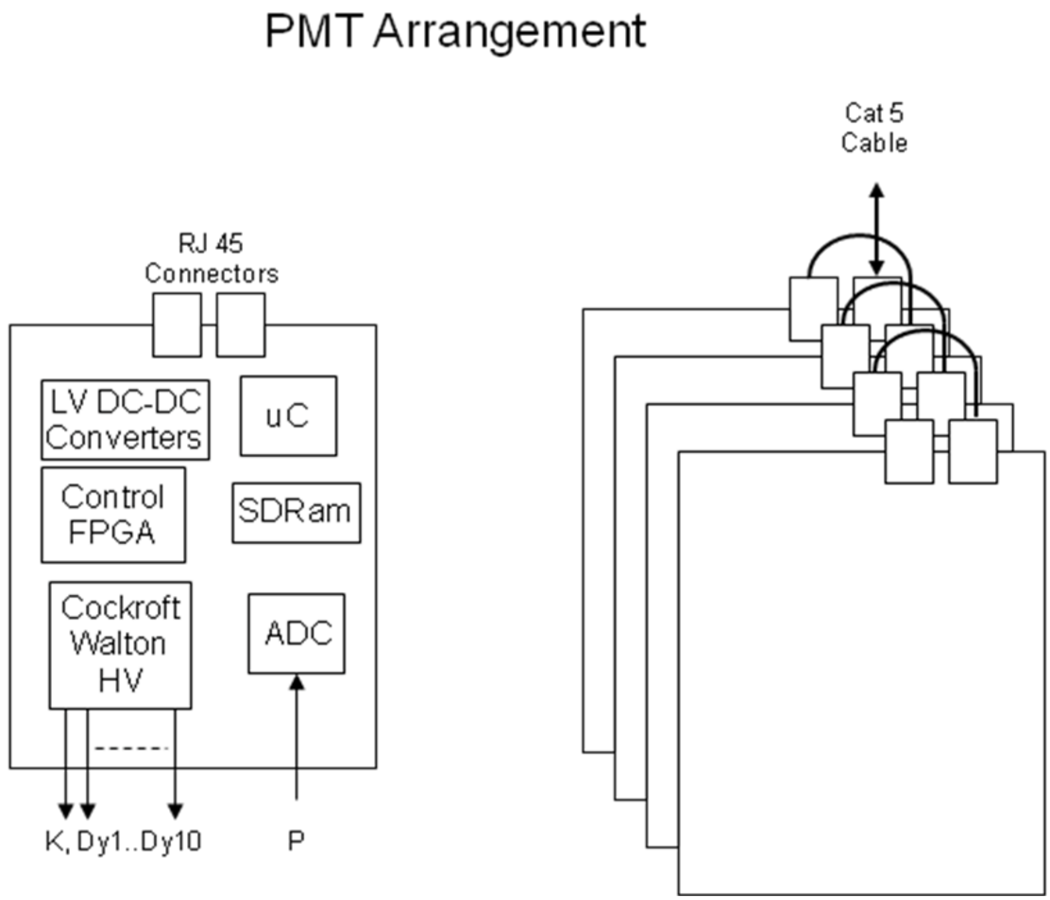

Figure 2: Left: shows a block diagram of the various components on the bottom half of the PMT base. Right: an example of how multiple PMT bases can be chained together.

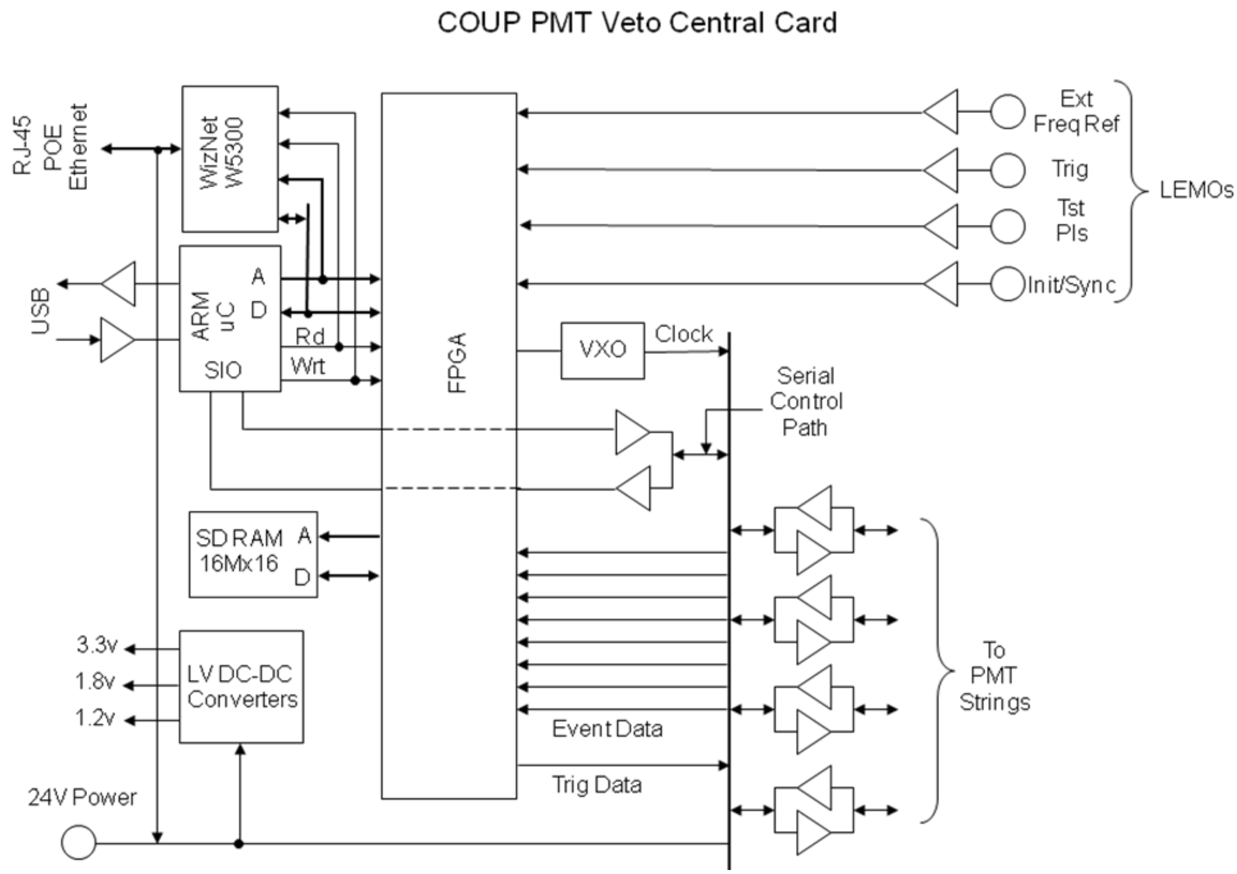

Figure 3: A block diagram of the controller card.

Figure 4: The setup that was used to ensure the usability of the new digital PMT bases, consisting of two Hamamatsu RCA 2454 PMTs with the new digital bases, attached to a single piece of solid scintillator. In the lower right is the 24-V power source, which is plugged to one base, with power running to the second base through the Cat-5 cable connecting them at the back. The two USB cords run directly to a computer with LabVIEW.

Figure 5: Left: the 66-kg bubble chamber sitting in the 1-ton Cerenkov water chamber. Right: the scale proxy detector covered in Tyvek in the 55-gallon water chamber.

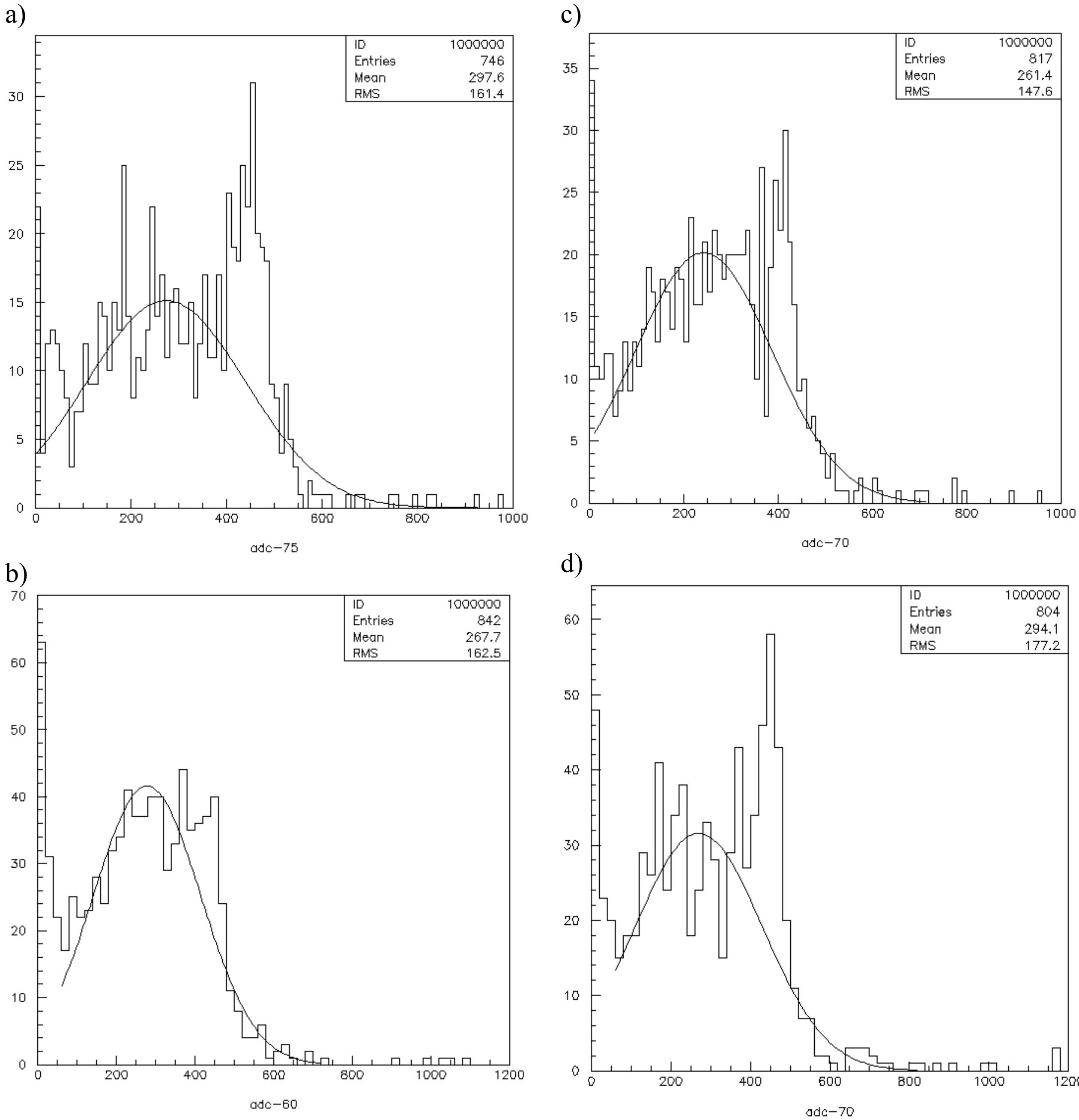

Figure 6: Set of histograms with the PMT set to 1500 V of the ADC data with the pedestal subtracted (as indicated by the negative number following ADC on the x axis). These follow the same trend as the data taken with the PMT at both 1400 V and 1600 V. A Gaussian has been applied to the graphs with the mean and RMS calculated. a) Histogram of the water chamber without the proxy detector in it. b) Histogram with the proxy detector in the water chamber without any Tyvek. c) Histogram with the sides and bottom of the proxy detector covered in Tyvek. d) Histogram with the entire proxy detector covered in Tyvek.