DOE-HOUSTON-41518

Final Report

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Summary

This report describes progress made by the University of Houston (UH) high energy physics group for the DOE Grant: DE-FG02-07ER41518 with emphasis on the last 3-year budget cycle. The grant started out as an award to Professor Kwong Lau in August 15, 2007 to work on Daya Bay. Professor Kwong Lau joined the Mu2e collaboration in 2010 and submitted a joint proposal with Professor Ed Hungerford at the University of Houston to apply for fund from DOE to work on Mu2e. The Mu2e award was merged with the Daya Bay grant in fiscal year 2011. Professor Kwong Lau was supported at 75% FTE in the joint DOE grant to work on Daya Bay with the balance support (25%) in Mu2e.

To align with the new funding cycle after Comparative Review, the grant was extended for 7 more months in the last 3-year cycle with a supplement to March 14, 2014.

The report includes activities and accomplishments of the Daya Bay and Mu2e projects for the funding period from August 15, 2007 to March 14, 2014, with emphasis on the last three years.

The subsequent sections describe the achievements of the 2 main tasks: Daya Bay and Mu2e. The publications and invited talks are listed in the Appendix.

Daya Bay

Faculty: Kwong Lau, Postdocs: Xiaobo Huang, Dawei Liu, Students: Logan Lebanowski, Shih-Kai Lin

Daya Bay is a nuclear reactor based neutrino experiment located in Daya Bay, China, aimed at measuring the third, presumably last, neutrino mixing angle θ_{13} to a sensitivity for $\sin^2 2\theta_{13}$ better than 0.01 [1]. This goal is about a factor of 10 improvement over the combined global precision in 2010 [2].

There are 3 nuclear reactors in the Daya Bay reactor complex: Daya Bay, Ling Ao I and II, each with 2 cores, corresponding to a total thermal power of about 17.4 GW. The basic design of the Daya Bay experiment is to use the antineutrino detectors (ADs) at the two near experimental halls, both located at a distance of about 400-600 meters from the nearest reactor, to measure the neutrino flux from the reactors, and compare the interaction rate at the far hall, located at about 2 km from the reactors, to those at the near halls. The 8 ADs are 20-ton target-mass Gd(Gadolinium)-doped liquid scintillator (GdLS) modules, built as 4 identical pairs, to minimize detector systematic errors. Two modules are deployed at each near hall, and 4 modules at the far hall, in the so-called (2, 2, 4) configuration. The neutrino interactions are identified by the so-called inverse beta decay (IBD) reaction in the GdLS:

$$\bar{\nu}_e + p \rightarrow e^+ + n,$$

where a coincidence of the prompt positron annihilation signal and the delayed neutron capture signal offers high background rejection. The statistical error in the far hall in three years of running is about 0.002, making a sensitive search for $\sin^2 2\theta_{13}$ below 0.01 possible in 3 years if the systematic error can be controlled to 0.002 or less. Technical details of the experiment can be found in the Daya Bay proposal [1].

The Daya Bay experiment made tremendous physics progress in 2012. The data showed that the ADs are functionally identical, with performance exceeding our requirements [3]. Using partial data with 3 ADs in the far hall, Daya Bay discovered that θ_{13} is large. The result was announced and submitted for publication in March, 2012 [4,5]. Using additional data with 6 ADs, we measured the spectra at the far and near sites, and found agreement with 3-neutrino oscillation hypothesis [6]. For the first time, Daya Bay simultaneously measured $\sin^2 2\theta_{13}$ and one of the mass differences of the neutrinos using electron-type neutrinos. After running for about 400 days with 8 ADs completed in 2012, we reached a sensitivity of about 5% for $\sin^2 2\theta_{13}$ and Δm^2 with a total of about 620 days of data. The latest (preliminary) result for the 8 AD period (about 400 days) is shown in the figure below,

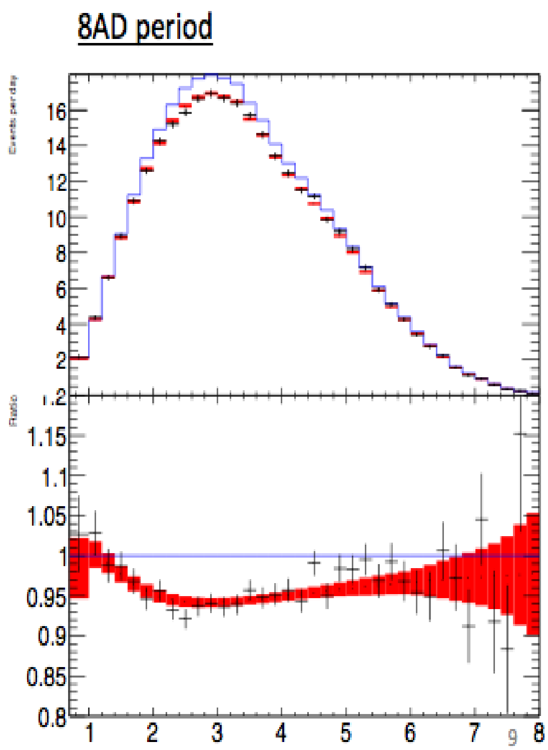

Figure 1. Top panel: A comparison of the spectrum at the far site (data points) to that of the near site (histogram). Bottom panel: a fit of the spectral difference to the 3-flavor neutrino oscillation model to obtain $\sin^2 2\theta_{13}$ and Δm^2. The data were taken with 4 ADs in the far hall for about 400 days.

where the fitted value for $\sin^2 2\theta_{13}$ and Δm^2 are

$$\sin^2 2\theta_{13} = 0.078 \pm 0.005$$
$$\Delta m^2_{ee} = 2.52 \pm 0.12 \times 10^{-3}\ \text{eV}^2$$

Daya Bay's long-term plan is to continue data taking until 2017. This will more than triple our current statistics. The projected errors for $\sin^2 2\theta_{13}$ and Δm^2 are about 2% if the errors are still dominated by statistics.

To reach the ultimate sensitivity of about 2% in the overall error of $\sin^2 2\theta_{13}$ and Δm^2, we need to understand all sources of systematic uncertainties. One main component is the background related to muon-induced neutrons. The accidental coincidence of neutron interactions and gammas from ambient radioactivity interacting in the AD is the dominant background in the current analysis, and this background fortunately can be measured in-situ with negligible uncertainty. Fast (energetic) neutrons can also mimic neutrino interactions by having an elastic collision with nuclei creating a prompt signal followed by their capture. The main source of neutrons comes from the interaction of surviving muons in the rock around the ADs. For the present analyses, the neutron-like singles rates are determined empirically. The error assigned to the fast neutron background is 30%, one of the largest uncertainties in the analysis. The muon system is designed to measure the muon flux and neutron yield by cosmic muons with high efficiency, aimed at quantifying this background precisely.

The muon system consists of a water pool surrounding the neutrino detectors to attenuate neutrons and gammas from surrounding rocks and two independent active muon detectors: resistive plate chambers (RPCs) on top of the pool and a water Cerenkov detector by instrumenting the pool with photomultiplier tubes (PMTs) to track muons. The Houston group contributed to the RPC component of the muon system, and the writing of a collaboration muon system paper [7]. Most of the neutron-induced background events produced by muons are tagged by the active detectors, and are removed from the IBD sample. The combined detection efficiency of the muon system exceeds 99.5%. The small amount of untagged background events produced by muons entering the surrounding rock will be estimated by Monte Carlo simulation based on a measurement of the muon flux and associated background, and are subtracted statistically from the IBD sample. The production of neutrons by muons and its contribution to IBD background will be studied extensively to get a more precise estimate. The production of neutrons by cosmic muons in liquid scintillator is the subject of one of the students' thesis at UH.

The DOE grant supported the scientific personnel at UH to contribute to the Daya Bay Experiment. Professor Kwong Lau, the PI of the Daya Bay task at UH, served as the inaugural Chair of the Institutional Board (IB) until February 2011. He is also L3 for RPC QC/QA and Chair of the RPC Committee. He was supported by the DOE grant for his summer salaries and travels. The DOE base grant also supported on average 1 postdoc and 2 graduate students.

The Houston group is responsible for the quality control and assurance (QC/QA) of the RPCs. Extensive bench tests of 6 full-size RPCs were conducted at UH to investigate their performance. One postdoc (Dr. Guanghua Xu) was supported by project fund to lead the studies. The studies included gas mixtures and readout strip geometry [8,9]. The Houston group participated in the QC/QA work of the RPCs: Cullen Newson, a technician supported by project fund, was stationed at IHEP for about a year to participate in RPC QC work. Two graduate students, Logan Lebanowski and Shih-Kai Lin, took part in the RPC QC work at IHEP for varying periods of time. The QC/QA work for the bare RPCs and RPC module production is published as two refereed papers [10,11]. Both graduate students worked on site at Daya Bay, and took part in the commissioning the RPCs [12]. They also contributed to the pressure-testing of some 150 PMTs for the water Cerenkov. Logan was appointed the US coordinator of RPC commissioning. He worked on the online monitoring of the RPCs [13]. He also contributed to the $\sin^2 2\theta_{13}$ analysis by studying the linearity of PMT electronics [14,15].

Graduate student Shih-Kai Lin worked on RPC muon reconstruction software [16]. He used the reconstructed muons to study the performance and long-term stability of the RPCs. Figure 2 below shows a study of the efficiencies of a row of 8 RPC modules over a period of some 20 days since official data taking. The plot shows that the efficiency of each module is basically constant over the period studied. However, there are variations over time and among modules. The variations are above the statistical errors, and being monitored.

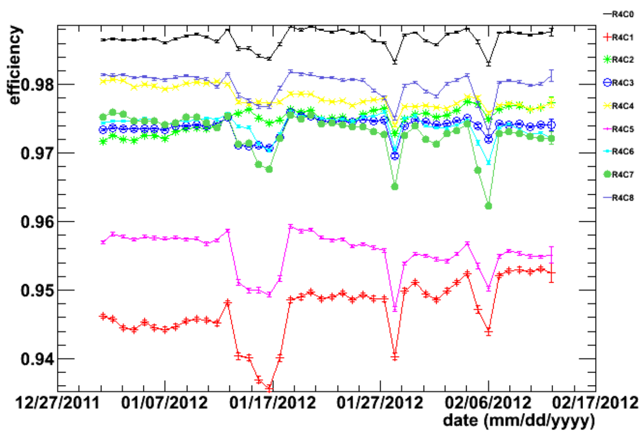

Figure 2. The efficiencies of a row of 8 RPCs in EH1 (there are 7 rows of RPCs in EH1) for about 20 days since data taking. The efficiency of each RPC module is determined by requiring at least three out of four possible layers fired for a muon defined by the water pool and AD going through a RPC.

The Houston group is also responsible for monitoring the RPC gas in situ with a set of small RPCs: the so-called M-chambers. These chambers, 4 in each site, will sample two branches of the some 20 gas input and their returns at each site. The currents of the M-chambers will be monitored by the Daya Bay slow control (DSC) system. Any contamination of the gas supply or deviations from the standard mixing ratio will likely create anomalous current in the M-chambers which will alert the experimenters on shift. Two of the exhaust branches will also be monitored to detect early signs of aging. Supported by project fund, we completed the system, and shipped the M-chambers to Daya Bay in 2011.

The grant initially supported 50% FTE postdoc in Daya Bay. Dr. Xiaobo Huang joined Daya Bay project as a postdoc in September, 2011. Xiaobo split his time equally between Daya Bay and Mu2e. Xiaobo's Mu2e activities will be described under the Mu2e task. For Daya Bay, he worked on data analysis related to RPCs. He installed NuWa, the official Daya Bay data analysis software, at UH which allowed us to process some raw data in our local desktops. This sped up the turn-around time for small analysis jobs. Xiaobo also investigated the tracking capability of RPCs by utilizing the water pool PMT information. Xiaobo left the group in June, 2012.

The grant was augmented in 2012 to support 2 postdocs, one for Da Bay and one for Mue2. Dr. Dawei Liu was hired as a full-time Daya Bay postdoc in October, 2012. Dawei was a member of Daya Bay since 2005, and had worked on the water PMT system while at LBNL and UIUC. He continued his work in PMT in Houston. He was also tasked to maintain the RPCs.

Shih-Kai Lin started working on his thesis project after his return to UH in 2012. He decided to examine the production of neutrons by cosmic muons in liquid scintillator for its obvious relevance to the IBD background. He devised a novel methodology by measuring the neutron yield on a track-by-track basis. He selected tracks whose 1-m-radius cylindrical fiducial volume around the track lies within the AD. In this way, he was able to measure the radial distance distribution of the neutrons from the track, as well as energy deposition associated with the production of neutrons. The preliminary radial distribution results are shown in Figure 3. Some earlier results were presented in an APS meeting [17]. He is close to completing his thesis, and plans to defend it by the end of 2014.

Logan completed his MS program in spring 2012, and decided to continue his PhD work in Tsinghua University.

For the future, we proposed and received support to continue the Daya Bay activities. We plan to continue our role in data-taking and maintenance of hardware we have expertise in, and contribute to data analysis. Kwong Lau will attend requisite Daya Bay administrative meetings, and mentor students and postdocs in the research on background studies. He will ramp up his involvement in Mu2e in the next 2 years. He has recruited 1 PhD student to work on straws for the electron tracker in Mu2e. It is envisioned that this student will contribute to the construction and testing of the straw tracker, but will write his thesis using Daya Bay data. The postdoc and his replacement will contribute to maintain the RPCs and study their long-term stability.

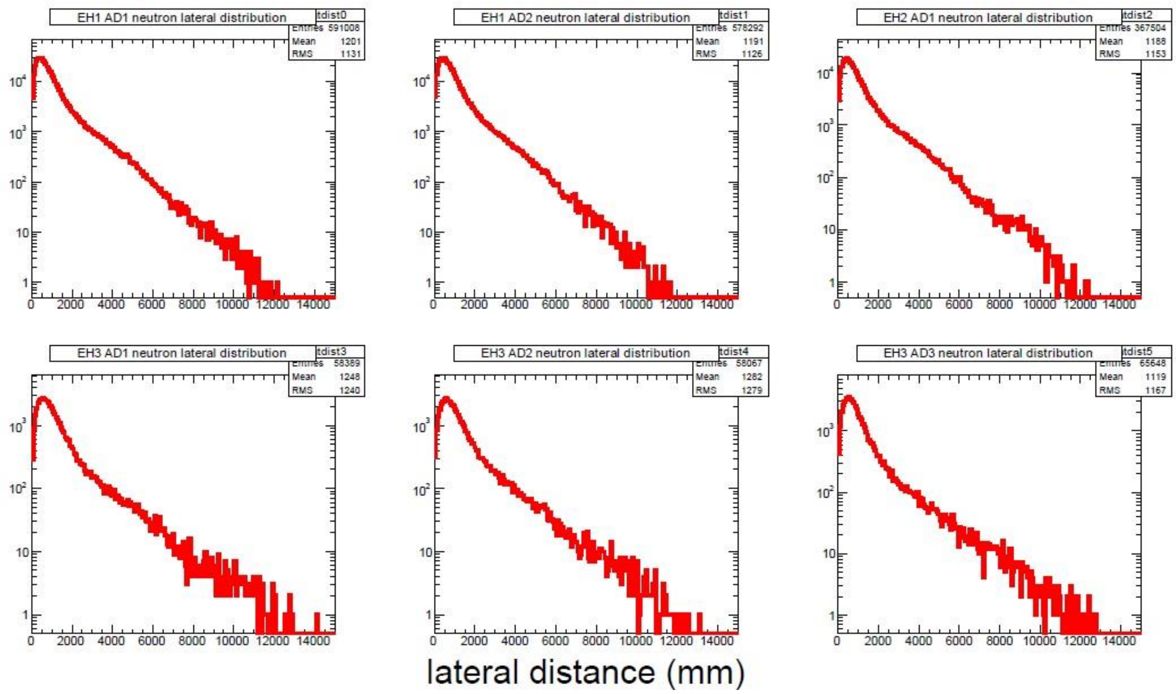

Figure 3. The radial distributions of neutrons produced by comic muons in liquid scintillator and captured by the AD in the near (top panels) and far (bottom panel) halls. The distributions are fitted to a 2-D Gaussian with the standard deviation as a fitting parameter. The acceptance for neutrons with radial distances less than 1 m can be determined by the fit.

Mu2e

<u>Summary</u> - Charged Lepton Flavor Violation (Mu2E)

This report describes progress made by the University of Houston (UH) high energy physics group on Task B of the DOE award for the years 2010-2013. The present Task B group consists of Ed Hungerford (Faculty), Kwong Lau (Faculty), Aji Daniel (Postdoc), Daniel Alexander (Grad. Student), and Jonathan Miller (Undergrad student). Kwong Lau joined the Mu2e collaboration in 2010, and was supported at 25% FTE for the 3 year grant period.

Group activities were begun in 2010, and a postdoctoral student, Xiabo Hunag, devoted 50% Mu2e and 50% to Daya Bay for about 6 months beginning September of 2011. The graduate student began working part time till summer 2012 and then has been100% on Mu2e onward. One mechanical tech was used part-time for 12 months beginning Spring of 2011, and a full time postdoc (Aji Daniel) was added 100% to Mu2E in September 2012. Presently, Professor Ed Hungerford is 50% committed to Mu2e and 50% to a dark matter search, Darkside, funded by the NSF. Professor Lau is 10% committed to Mu2e and 90% committed to Daya Bay.

Activities

The University of Houston (UH) group has chosen to undertake a program of R&D for, and construction of, the Mu2e electron tracking detector. The group is fully capable of performing the proposed tasks, as the PI (Hungerford) was responsible for the electron tracker design, construction, and readout of the similar MECO tracker [18]. For Mu2e, it is expected that detector construction for example, will take advantage of a synergistic interaction with the particle physics group at Rice University (Marjorie Corcoran PI). The activities involve **short** and **long-term** programs of research.

Short Term Activity

The group is involved in a measurement of the rate and spectrum of particle emission after μ capture on Al and Ti targets at the Paul Scherrer Institute in Switzerland (PSI) [19]. An initial component of the experiment ran in November 2013, and a second run pending results of the first, would begin in 2015. Proton emission dominates the single hit rates in the tracking chambers, and particularly in the front planes and inner straws of the tracker. In addition to large event rates which introduce multiplicity in the straw hits and saturation in the electronics, there is potential radiation damage and ageing of the straw detectors. A proton absorber is to be placed between the stopping target and the electron tracker to reduce the proton flux, but this degrades the energy resolution and the ability to track electrons back to their primary source. MC studies are attempting to optimize the thickness and position of the absorber but these need experimental data for calibration. In addition to the charged particle spectrum, the UH group has the particular responsibility of measuring the rate and spectrum of neutron emission after μ capture. Neutron rates cause significant background problems in the calorimeter and after diffusing through the shielding, in the cosmic ray veto. The rates can blind the Ge detector used to monitor the muon stopping rate, and also cause event upsets in the electronics. Low energy neutron emission depends on the nuclear physics of the target, so it is important to measure the rates and spectra for Mu2E targets of interest, Al and Ti. The only available spectrum of low energy neutrons comes from medium-to-heavy nuclei, and a neutron spectrum, typical for an Al target, can be approximated from experimental data [20].

The group developed a Fluka simulation to understand expected rates, efficiencies, backgrounds, and the potential spectrum, and spent 2 weeks at the University of Washington

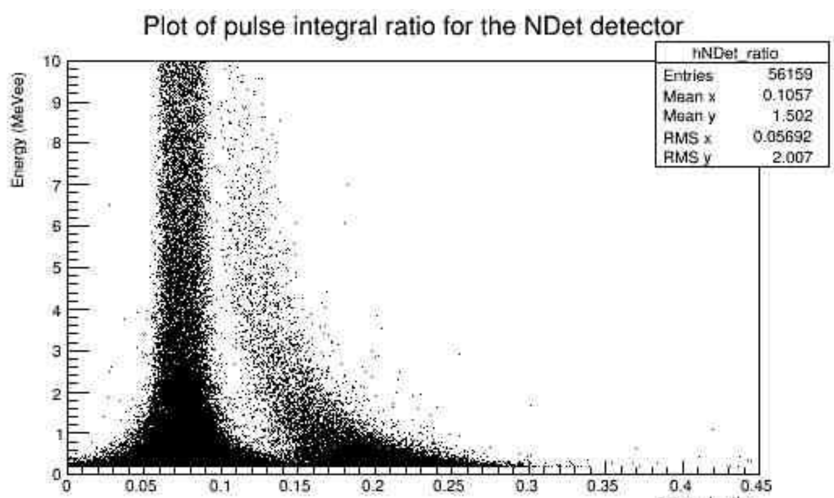

Figure 1. Pulse shape discrimination between neutrons and gamma events from a 50 mg Al target. Separation along the horizontal axis as a function of energy in MeVee plotted vertically. The intense, near vertical line are gammas, the curved line to the right are neutrons. For

reference, 1 MeVee (vertical) corresponds to approximately 2 MeV neutrons. The signals are processed with a delayed time cut between 300 to 1000 ns after the muon beam pulse.

prior to the PSI run developing the data acquisition and detection systems. The experiment ran for 4 weeks in November–December 2013 at PSI. Data collected in the first run are presently under analysis. An example of the present status of analysis of the neutron data is illustrated in Figure 1 which shows the neutron-gamma separation using the shape of the waveform from the neutron detector. Further work is needed to better determine the energy calibration, but we anticipate the ability to determine rates for neutrons with energies between approximately 2 to 15 MeV.

Previously the constructed a full scale support ring for the tracker and examined its deformation under the tension which would be applied to it by the straws and wires [21]. Figure 2 shows the out-of-plane deformations which were observed. These lie outside accepted tolerances. The UH machine shop will construct component for a prototype tracker panel (1/3 of a ring) to be used in a full panel readout test scheduled for February 2015.

Long Term Activity and Planning

Using past MECO experience, the PI of the UH group is managing a FNAL engineering team developing an electronic readout controller (R0C) which connects the waveform digitizing front end of the straw detector to the triggerless data acquisition system placed outside the vacuum wall of detector solenoid. The group meets weekly via conference call and approximately bi-monthly at FNAL. In essence the ROC is a local computer using an FPGA to interface, organize, buffer, transmit, and control the operation of its adjacent 96 wires [22], Figure 3. The front end electronics includes an anode preamplifier which feeds a digitizer providing wave sampling and timing from each straw end. This information after zero suppression, is passed in clocked sequence to the ROC which buffers, sets the address of the straw, completes the time stamp, and streams the information on optical fiber to an event builder in the DAQ. The ROC also controls activities of the front end via an SPI control buss, and collects status information of the front end system which it also passes to the DAQ. For example the ROC can inject test pulses to the straw front ends, set/change the gain of each individual preamplifier, and select the channel through which the high voltage from an inoperative wire can be remotely removed.

Depending on the number of planes, the Mu2e tracker has a nominal 216 ROCs. The Digitizer receives signals from both ends of 4 (or 8) straws and multiplexes 4 of these into one output buffer before sending a packet of data to the ROC on 1 (or 2) LVDS lines. Digitized data transmission from the output buffer to the ROC is clocked at 200 MHz. Every 1695ns during a super-cycle, each ROC sends to its Digitizers a signal indicating the start of a μ−spill and a 200 MHz clock. These are used by the digitizer to synchronize event time with respect to the μ−spill start. The ROC also sends to the Digitizer the lowest 4 bits of the μ−spill number and a programmable gate which starts and ends data digitization during a μ−spill. Both the μ−spill number and the gate follow the μ−spill start on the same LVDS line. Nominally a μ−spill start occurs every 1695 ns for 54ms, and the data gate follows after a nominal latency of 670 ns. Thus hit data is digitized for a period of some 1025ns. This data is stored in a local FIFO output buffer at the digitizer before being sent to the ROC. Transfer from the output buffer begins as soon as data appears in the buffer and continues until all data collected during a μ−spill has been transferred. Data transmission is then latent for at least one clock pulse before data transfer from the next μ–spill begins. After inserting the data collected for a μ–spill in the buffer, the digitizer inserts an end-of-μ–spill data packet. This allows data transfer from the FIFO buffer to be

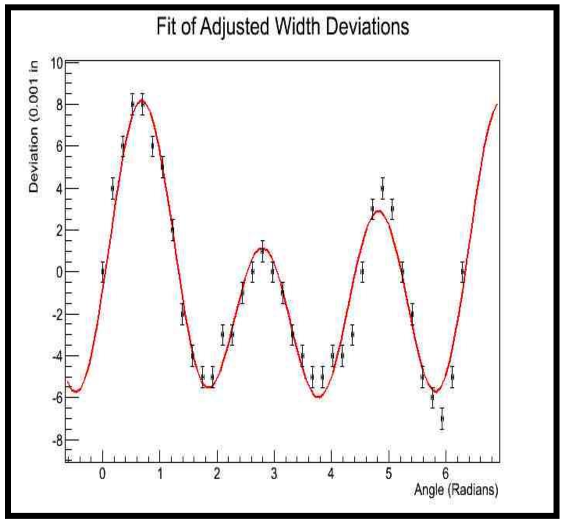

Figure 2. Out of plane deflections of a prototype Ring showing deflection (mils) as a function of angle.

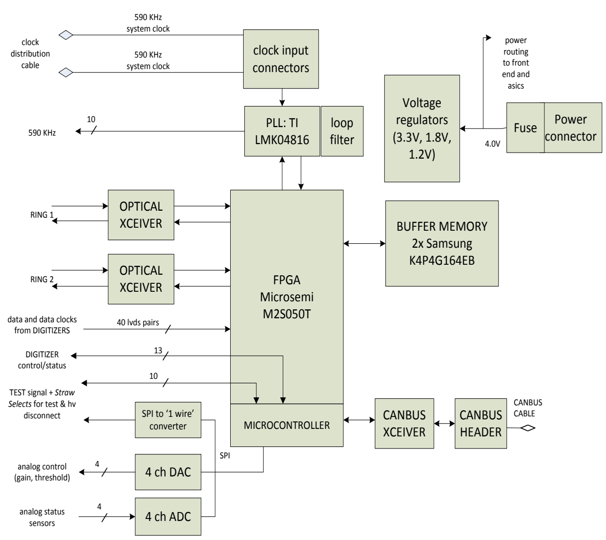

Figure 3. A block diagram of the ROC electronics. Input Data is processed by the FPGA and transmitted by optical fiber tot eh DAQ. Slow control occurs through th eon-board microprocessor.

transferred without loss of synchronization even if the transfer continues beyond a μ–spill. The amount of data collected during a μ–spill is determined by the single event rates of the straws, and the output buffer must have sufficient depth to provide an average data transfer from the 4 multiplexed straws during a super-cycle.
The work is presently focused on a integration test in July-August 2014 involving the transfer of data from the front end to the DAQ and a full data panel test in February 2015.

Information on specific testing, performance, and history of each ROC and associated electronics will be inserted in the tracker data base in a way that it can be retrieved and updated. Just how this data is recorded depends on the mechanical structure of the electronics on a panel. However, each panel and motherboard will be identified as well as each mezzanine card (if the ROC is separated from the motherboard). There will be a test and performance data sheet which will be completed as each system is tested and operated. This sheet will be entered in to the data base at regular intervals.

Plans for future activities involve working with Rice University to produce, assemble, and provide QA of the straw tracking panels. Straws, previously leak tested at York University, will be inserted and tensioned in panels containing 96 straws in two layers in Houston. The sense wires will also be inserted, tensioned, and a high voltage with output signal tests performed. Before shipping the panels to Duke University for measurement of the sense wire position via x-ray, QA will be completed on the panels with results documented. Tentatively the division of the activities between UH and Rice, assumes Rice will mount the straws and wires, and UH will complete the electronic tests and the QA documentation for each of the approximately 225 panels. QA involves measuring and recording for each wire and panel, the straw and wire batch numbers and tensions, epoxies, and electronic test results. QA management will be handled by a project technician/post-doc at UH. The test work will be completed by graduate students and 8 undergraduate students working approximately 4 hour shifts. It is estimated that the complete QA and testing would last approximately 12 months.

References

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2 G.L. Fogli, et al., *Evidence $\theta_{13} > 0$ from global neutrino data analysis,* Phys. Rev. D84:053007, 2011. e-Print: arXiv:1106.6028

3 F.P. An et al., (Daya Bay Collaboration), *A side-by-side comparison of Daya Bay antineutrino detectors*, Feb 2012. 24pp. E-Print: arXiv:1202.6181

4 F. P. An et al., (Daya Bay Collaboration), *Observation of electron-antineutrino disappearance at Daya Bay*, Phys. Rev. Lett. 108 (2012)171803.

5 Kwong Lau, *Observation of electron-antineutrino disappearance at Daya Bay,* Special seminar at UH, March 8, 2012.

6 F. P. An et al., (Daya Bay Collaboration), *Spectral Measurement of Electron Antineutrino Oscillation Amplitude and Frequency at Daya Bay,* Phys. Rev. Lett. 112 (2014), 061801.

7 F. P. An et al., (Daya Bay Collaboration), *The Daya Bay Muon System*. Submitted to NIM, May 2014.

8 See Daya Bay Internal Reports, DocDB#1126*, Study of 1% isobutane RPCgas mixture.*

9 See Daya Bay Internal Reports, DocDB#1484, Study of a new Zig-Zag strip.

10 L. Ma *et al.*, *The mass production and quality control of RPCs for the Daya Bay experiment*, Nucl. Instrum. Meth. A659, 154-160, 2011

11 J. Xu *et al.* Design and preliminary test results of Daya Bay RPC modules, Chin.Phys.C35, 844-850,2011.

12 Ning et al, *Calibration algorithms of RPC detectors at Daya Bay Neutrino Experiment*, JINST 8 (2013) T03007.

13 See Daya Bay Internal Reports, DocDB#6128. The Daya Bay Internal reports cited in this report are available in http://uhhep.phys.uh.edu/~logan/UHDocDB/

14 See Daya Bay Internal Reports, DocDB#7408.

15 See Daya Bay Internal Reports, DocDB#7611.

16 Talk presented to the Daya Bay Analysis Workshop in Houston, Sep 19-23, 2011. See also Daya Bay Internal Reports, DocDB#7611.

17 Shih-Kai Lin, *Cosmic muon induced neutrons at Daya Bay*, Session G9: Neutrino Mass and Oscillation Experiments, APS meeting, Denver, Colorado, April 13–16, 2013.

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Appendix1: Publications and Reports

Daya Bay

1. F.P. An et al., (Daya Bay Collaboration), *A side-by-side comparison of Daya Bay antineutrino detectors*, Feb 2012. 24pp. E-Print: arXiv:1202.6181.

2. F. P. An et al., (Daya Bay Collaboration), *Observation of electron-antineutrino disappearance at Daya Bay*, Phys. Rev. Lett. 108 (2012) 171803.

3. F. P. An et al., (Daya Bay Collaboration), *Improved measurement of electron antineutrino disappearance at Daya Bay*, Chin. Phys. C37 (2013) 011001.

4. F. P. An et al., (Daya Bay Collaboration), *Spectral Measurement of Electron Antineutrino Oscillation Amplitude and Frequency at Daya Bay*, Phys. Rev. Lett. 112 (2014), 061801.

5. L. Ma *et al.*, *The mass production and quality control of RPCs for the Daya Bay experiment*, Nucl. Instrum. Meth. A659, 154-160, 2011.

6. J. Xu *et al. Design and preliminary test results of Daya Bay RPC modules*, Chin.Phys.C35, 844-850, 2011.

7. Ning et al, *Calibration algorithms of RPC detectors at Daya Bay Neutrino Experiment*, JINST 8 (2013) T03007.

8. F. P. An et al., (Daya Bay Collaboration), *The Daya Bay Muon System*. Submitted to NIM, May 2014.

Mu2e

Publications (17 internal reports) Examples

1. Mu2E Doc-db 1961 ‘Report of the WBS 6-9 Cost review Committee’ January 2012
2. Mu2e Doc-db 2597 ‘ROC Architectural Specification’ December 2012
3. Mu2e Doc-db 2706 ‘Notional tracker test plan’ February 2013
4. Mu2e Doc-db 3568 ‘AlCap Experimental review’ November 2013
5. Mu2e Doc-db 3973-V4 ‘Tracker ROC Specifications’ April 2014.

Presentations

1. Seminar Sam Houston State University Mar 2012
2. NuFact Conference July 2012
3. Seminar Fudan University June 2014