Offline Software of RPC Detector System in Daya Bay Reactor Neutrino Experiment

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Abstract: The Daya Bay Reactor Neutrino Experiment utilizes an RPC detector system to detect cosmic-ray muons for offline suppression of muon-induced backgrounds. This proceeding paper introduces the structure of the offline software of the RPC detector system, including simulation, detector calibration, and event reconstruction. In addition, preliminary analysis results based on the offline software are reported.

Keywords: RPC, offline software, simulation, calibration, reconstruction, muon flux

1 Introduction

The underground Daya Bay reactor antineutrino experiment aims at precise measurement of the last unknown neutrino mixing angle $\theta_{13}$. The first result of the Daya Bay Reactor Neutrino Experiment gave $\sin^2 \theta_{13} = 0.092 \pm 0.016 \text{(stat)} \pm 0.005 \text{(syst)}$, excluding a value of zero with a significance of 5.2 standard deviations [1]. There are two near sites (Daya Bay site and LingAo site) and one far site, which are called Experimental Halls 1, 2, and 3, respectively (EH1, EH2 and EH3). The near-far arrangement allows for a relative measurement by comparing the observed Inverse Beta Decay (IBD) event rates at various baselines. At each site, there is a detector complex consisting of Antineutrino Detectors (ADs), Water Cherenkov Pools (WPs) and an RPC (Resistive Plate Chamber) detector system, the latter two of which compose an anticoincidence detector to reduce the background from cosmic-rays [2].

The basic layout of the sub-detectors at one site is shown in Fig. 1. The ADs are deployed in a water pool which is covered by an array of RPC modules. The water pool is used to shield the background from radioactivity and to veto cosmic-rays, while the RPC module array is used to veto cosmic-rays and cross check the water pool.

Since its invention in early 1980s [3], RPC has been widely used in particle physics due to its simple structure and low cost, especially in large area applications, such as
B-factory experiments (BaBar [4], Belle [5]) and the experiments at LHC (ALICE [6], ATLAS [7], CMS [8]). Daya Bay Reactor Neutrino Experiment uses RPCs as an underground cosmic-ray muon detector [9,10,11]. These RPCs are developed by Institute of High Energy Physics, Chinese Academy of Sciences, who has studied Bakelite RPCs for many years [12] and has successfully applied them in BESIII as a muon identifier [13, 14, 15, 16].

![Fig. 1 Layout of the detectors in one site](image1)

2 RPC detector system

The RPC detector system includes the RPC Modules, Gas system, HV system and Readout system (electronics and DAQ), as shown in Fig. 2. A Detector Control System (DCS) has been setup for monitoring and controlling hardware. The HV system provides a working high voltage of 7.4 kV for RPCs, while the gas system supplies a
working gas mixture of Ar:R134a:i-C4H10:SF6 = 65.5 : 30.0 : 4.0 : 0.5. In the following sections, RPC modules and electronics are introduced in detail.

2.1 RPC modules

Both near sites (far site) contain an array of 9 × 6 (9 × 9) RPC modules and two telescope RPC modules. The two telescope modules are installed at two opposing banks of a water pool and 2.0 m above the top of RPC array, so the tracks of the muons passing through a telescope RPC module and the RPC array can be reconstructed with a position resolution, better than 10 cm [17].

![Fig. 3 Schematic inner structure of an RPC module](image)

![Fig. 4 Layout of RPC detectors (near site)](image)

The dimensions of an RPC module are 2.17 × 2.20 × 0.08 m³. As shown in Fig. 3, each module consists of 8 RPCs, forming 4 layers: X-strip layer, Y-strip layer, Y-strip layer and X-strip layers from bottom to top. Each layer has eight 26cm-width readout strips reading out the signals of two RPCs: one is bigger and the other one is smaller. Overlap
among layers (top right of Fig. 3) and modules (Fig. 4) is implemented to minimize dead space.

2.2 RPC Readout System

Each RPC module is read out by an FEC (Front-End Circuit) board with 32 discriminators (one for each readout strip). An FEC discriminates RPC signals, widens digital signals, then generates and buffers local triggers.

![Scheme of RPC Electronics](image)

A local trigger is formed if more than 3 layers in a module have hits simultaneously. The trigger signal is transferred to the RTM (Readout Trigger Module) through a ROT (ReadOut Transceiver) while the time and hit configuration data in the FEC is buffered in a FIFO register. The RTM generates a 400ns readout trigger based on local triggers and sends it back to the related FECs through the associated ROT. If there is more than one trigger within 200 ns from the same RPC module, the later triggers are ignored. With a tuned synchronization the buffered hit data is moved to the end of the FIFO register, when an FEC receives the corresponded readout trigger. The selected FEC hit data within 400 ns readout window, which spans 16 clock cycles, undergoes a bitwise OR operation across each clock cycle. The resulting data is transferred to an event buffer, and sent to the ROM (Readout Module) through an ROT, where the FEC data packages are buffered before the DAQ. In addition to locally generated triggers, a periodic forced trigger is mixed at the frequency of 10 Hz into normal data-taking runs to measure noise rates of the RPCs in real time.[18]

The DAQ reads out the data packages by the means of polling and sorts them online according to time stamps. [19]
3 RPC Offline Software

RPC offline software includes simulation, detector calibration and event reconstruction (Fig. 6). For simulation, muon samples in the experimental halls are generated using Geant4 with muons at sea level and surveyed mountain geometry as input. Then we simulate the detector readout mechanism to get a simulated data set. Experimental binary data are converted to physics events, which include event time, trigger type and a list of hits with coordinates. Physics events are used to calibrate detector performance (efficiency and noise rate) and reconstruct muon information (incident positions or/and tracks). Simulation results and analytical methods are validated and tuned by comparison with experimental data.

3.1 Simulation

3.1.1 Underground muon simulation

With a muon generator based on an improved Gaisser formula [20] and geometry from a Daya Bay mountain profile survey, muons in underground experimental halls are simulated using MUSIC [21]. The simulation shows the muon fluxes in the three experimental halls are, respectively, 0.88±0.09 Hz/m², 0.69±0.07 Hz/m², 0.039±0.004 Hz/m². Of course, the muon angular distributions in 3 experimental halls are also obtained. This work will be reported in detail in future publication.

3.1.2 Detector simulation

Simulation is based on Geant4 [22]. In order to simulate the detector performance accurately, all geometries are included in the detector description: onsite survey results...
of RPC arrays, layouts of RPC arrays, the structure of RPC modules and their internal
gallery (dead spaces of RPCs and overlap among layers in a module). The full
geometric description of RPC modules in experimental halls is achieved as shown in
Fig. 4.

Furthermore, a full electronics simulation chain including FEC, ROT, ROM and RTM,
follows the electronics readout mechanism as described in section 2.2. The simulation
is shown diagrammatically in Fig. 7.

3.2 Calibration

The calibration of RPC performance includes efficiency and noise rate of each layer in
an RPC module.

3.2.1 Layer efficiency

Calibration of RPC layer efficiency requires pure muons passing through the
investigated layer. 3-fold coincidences are not always caused by muons; i.e., they have
a contribution from noise accidentals and other backgrounds. Therefore, when we
calculate the efficiency of a layer, we require the water Cherenkov pool to have a muon
tag in addition to the other 3 layers of the module (the investigated layer excluded).
Furthermore, we require \( \leq 2 \) hits on each layer and if there are 2 hits on a layer, they
should be neighbors. Finally, the efficiency of the investigated layer in an RPC module
is obtained from the following formula.

\[
\varepsilon_i = \frac{N_{4\text{-fold},ijkl,WP}}{N_{3\text{-fold},jk1,WP}}
\]

When \( N \) is the number of events for a RPC module, the indices \( i, j, k \), and \( l \) represent
the four layers in a module and the subscript WP indicates that the water Cherenkov
pool tagged the muon at the same time.

The distribution of layer efficiency for all 3 halls is shown in the left plot of Fig. 8 and
the average layer efficiency for all 3 halls is summarized in Table 1. Further simulation and analysis indicate that the requirement that the water Cherenkov pool have a muon tag introduces muon angle selection bias, which causes a sub-percent bias on the efficiency calculation.

![Fig. 8 Distribution of calibrated RPC Performance (the first 3 runs since 3-sites data-taking)](image)

**Table 1 Average layer efficiency and noise rate for the 3 halls**

|          | EH1        | EH2        | EH3        |
|----------|------------|------------|------------|
| Average layer efficiency | 90.8%±0.4% | 87.1%±0.5% | 93.0%±0.3% |
| Average layer noise rate (kHz/m²) | 0.860±0.032 | 0.955±0.039 | 0.728±0.026 |

### 3.2.2 Layer noise rate

In order to measure the noise rate of RPCs in real time, a periodic forced trigger of 10 Hz is mixed into normal data-taking runs. In general, the hit data during a forced trigger is due to noise, however, the data with ≥3 layers having hits is rejected to prevent muon contamination. Considering that the typical width of a signal after discrimination and widening is ~150 ns, the sampling time of each forced trigger is 550 ns (= width of readout trigger + width of signal = 400 ns +150 ns). Finally, the noise rate is defined as the ratio of the number of noise hits in the investigated layer to the aggregated sampling time and area of the layer.

The distribution of layer noise rate for all the 3 halls is shown in the right plot of Fig. 8 and the average noise rate for all the 3 halls is summarized in Table 1.

### 3.3 Reconstruction

Due to relatively thin geometry of the RPC arrays and wide width of readout strips, only the incident positions of muons can be reconstructed using an RPC array. However, for muons passing through both the telescope RPC modules and RPC array, tracks can be reconstructed. Here, we introduce tags which correspond to the various detector combinations: array only, telescope only or both of them. Often, more than one RPC module is triggered in an event due to the overlap of modules and muon showers.
Accordingly, the reconstruction is processed following the procedures below.

1) **Clustering**: the algorithm of clustering is to group the RPC array modules with 3(4)-fold triggers in a single event into groups, in at least one of which, each module shares a common side or corner with one of the others. The two telescope RPC modules in each experimental hall are grouped into two independent clusters and do not participate in the clustering of RPC array modules.

Each cluster is labeled with an n-fold tag, which is the maximum number of layers with hits in any RPC module for all the modules in that cluster. This label helps choose pure muons for later analysis.

2) **Event type tag**: this tag labels the type of the reconstructed event (point, track or shower). The definitions are given below:

   - **Point**: only one cluster with ≤4 RPC modules from the RPC array or only one telescope RPC, with 3(4)-fold triggers.
   - **Track**: only one cluster (with ≤4 RPC modules) from the array and only one telescope RPC module, with 3(4)-fold triggers.
   - **Shower**: one cluster with >4 RPC modules, ≥2 RPC array clusters, or 2 telescope RPC modules, with 3(4)-fold triggers

3) **Incident position**: the incident position of each cluster is calculated by making use of Center-Of-Gravity algorithm.

4) **Tracks**: if the event satisfies the definition of ‘Track’, a track will be built by connecting the two incident points: one is on either of the telescope RPC modules and the other one on the RPC array.

In order to validate the reconstruction and geometry in data analysis, we extrapolate the RPC muon tracks to the horizontal plane of charge center in an AD, and compare the extrapolated coordinates \( (x_{\text{extrapolated}}, y_{\text{extrapolated}}) \) with those in the AD plane \( (x_{\text{Qcenter}}, y_{\text{Qcenter}}) \). The distributions of the differences \( dx = x_{\text{extrapolated}} - x_{\text{Qcenter}} \) and \( dy = y_{\text{extrapolated}} - y_{\text{Qcenter}} \) are shown in Fig. 9. The offsets in the x and y directions are approximately 80.6 mm and -79.6 mm, respectively. Considering the extrapolation distance, the AD muon spatial resolution and that the RPC spatial resolution of reconstructed tracks is around 8 cm per coordinate [17], the comparison shows that the reconstruction meets expectations. The ~40 cm variations are understandable, considering the spatial resolutions of AD and RPC. The EH2 and EH3 give similar results.
4 Data Analysis using RPC offline software

Within the framework of the RPC offline software, the following data analysis is performed based on the reconstructed data and calibrated performance. In this paper, the data taken from Dec. 24th, 2011 to Dec. 25th, 2011 is used for the analysis of RPC system efficiency and underground muons, while the data taken in EH1 from Dec. 24th, 2011 to Feb. 15th, 2012 is utilized for the preliminary analysis of fast neutrons.

4.1 RPC system efficiency

The system efficiency of an RPC array cannot be obtained directly from experimental data, considering the overlap among RPC layers and RPC modules, gaps between RPC modules and the spatial relationships between the RPC detectors, water Cherenkov pools and Antineutrino detectors.

Table 2 Comparison of RPC system efficiencies from tuning with simulation and selecting muons that pass through the inner half of a telescope RPC and a WP

|                  | EH1     | EH2     | EH3      |
|------------------|---------|---------|----------|
| MC with calibrated layer efficiency | 92.9%±0.4% | 88.7%±0.5% | 95.3%±0.7% |
| Cross-check with Telescope RPCs and WP | 93.5%±0.1% | 88.0%±0.2% | 95.8%     |

Therefore, the RPC system efficiency is estimated by simulating with real detector geometry and the calculated layer efficiencies. At the same time, we perform a cross-check estimation by selecting muons that pass through the inner half (closer to RPC array) of either of the two telescope RPC modules and a water pool (to make sure these muons pass through the RPC array). These two efficiencies are summarized in Table 2 for all 3 experimental halls and they are reasonably consistent, especially considering that the muon samples selected by the telescopes and WPs are only a portion of the total muons passing through the RPC array and that the detection efficiency is dependent on the incident positions and angles of muons.
4.2 Muon angular distribution

As mentioned in section 3.3, some muons can be reconstructed with tracks; therefore, we can obtain the angular distribution of muons in the experimental halls. In order to select very clean muons, an extra requirement that n-fold tags of the two clusters should be 4-fold coincidences is added. The angular distribution can be predicted by simulation as described in section 3.1.1. The comparison for EH1, shown in Fig. 10, exhibits a good consistency. EH2 and EH3 show are similarly consistent.

![Fig. 10 Comparison of angular distribution of muons from MC simulation and Data in EH1](image)

4.3 Muon Flux

In order to measure muon flux we need the rate of RPC tagged pure muons, so we only choose events in which all 4 layers of a module have hits. Corrections for accidental 4-fold coincidence from noise, dead time and efficiency are taken into account, when calculating the muon flux for each module. The muon flux in each near (far) hall is obtained by averaging over all 56(83) RPC modules.

|                | EH1     | EH2     | EH3     |
|----------------|---------|---------|---------|
| Simulation(Hz/m²) | 0.88±0.09 | 0.69±0.07 | 0.039±0.004 |
| Measured by RPC(Hz/m²) | 0.90±0.06 | 0.69±0.08 | 0.046±0.004 |

As mentioned in section 3.1.1, the muon fluxes in the experimental halls are predicted by simulation. They are summarized and compared with measurements in Table 3. Good agreement is seen for all 3 experimental halls. The detailed analysis and simulation will be reported in a future publication.

4.4 Muon-induced fast neutrons

Fast neutrons can be produced by the interaction of a muon with any material in an Experimental Hall, then slowed through collisions, and finally captured by a nucleus.
Recoil protons produced by neutrons slowing inside an AD can generate IBD-like prompt signals, and the subsequent capture of the neutrons in the AD produce IBD-like delayed signals. Fast neutrons are an important background for the selection of IBD events.

With the RPC detector system, we can study this kind of background events when either the RPCs or WPs have a muon tag. We have selected and analyzed this kind of event according to time relation. In the preliminary analysis, we required either the WP or RPCs to have a muon tag. The energy spectra of prompt signals and delayed signals attributed to fast neutrons for AD1 in EH1 from Dec. 24th, 2011 to Feb. 15th, 2012 are shown in Fig. 11. They preliminarily indicate that the IBD-like event rate from fast neutrons induced by tagged muons is 99.8±1.4 events/day for AD1 in EH1. We are planning to study this further to minimize the uncertainty on the background from muon-induced fast neutrons.

5 Summary

The offline software of the RPC detector system in Daya Bay Reactor Neutrino Experiment has been functionally achieved, including simulation, calibration and reconstruction. Data analysis has been performed in the framework of the software and it shows good agreement with data. Further improvement and study is under development.

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