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Design and preliminary test results of Daya Bay RPC modules*

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Abstract: Resistive Plate Chamber (RPC) modules will be used as one part of the cosmic muon veto system in the Daya Bay reactor neutrino experiment. A total of 189 RPC modules will cover the three water pools in the experiment. To achieve track reconstruction and high efficiency, each module consists of 4 layers, each of which contains two sizes of bare chambers. The placement of bare chambers is reversed in different layers to reduce the overlapping dead areas. The module efficiency and patch efficiency were studied both in simulation and test of the data analysis. 143 modules have been constructed and tested. The preliminary study shows that the module and patch 3 out of 4 layers efficiency reaches about 98%.

Key words: RPC, RPC modules, module efficiency, dead area, Daya Bay neutrino experiment

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1 Introduction

The Daya Bay reactor neutrino experiment is a high sensitivity experiment designed to determine the unknown neutrino mixing angle θ_{13} [1]. The primary sources of background are neutrons generated from muons interacting with rock and other materials. Neutrons that reach the fiducial volume have a finite probability of mimicking neutrino signals. Therefore, to reach the planned sensitivity, the cosmic muon background must be efficiently and accurately measured. This will be achieved with the arrays of RPC modules positioned above three two-zone water Cherenkov pools in three underground experimental halls. The primary information about the cosmic ray background will come from the photomultiplier tubes in the water pools (sec. 7.2 of Ref. [1]). The RPC system is designed to increase the muon detection efficiency and to enhance the tracking capability. The combined muon tagging efficiency of the RPC system and water Cherenkov system is designed to be 99.5% with an uncertainty of 0.25%.

RPCs are tracking detectors that are attractive for economically instrumenting large areas. They have been used in many particle physics experiments such as BABAR [2], BELLE [3], OPERA [4], BESIII [5],

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experiment stations in LHC [6–8] and also first used in ARGO-YBJ experiment [9] for cosmic ray measurement in large area. They can be easily stacked in many layers which can give not only very high efficiency for detecting particles, but also very low noise rate by taking signals from several layers in coincidence. At Daya Bay, about 3330 m^2 of bare chambers will cover more than 750 m^2. All Daya Bay bare chambers are produced by GNKD Company (Gaonengkedi Science and Technology Company in Beijing), which also produced the BESIII bare chambers [10]. This paper describes the design principle and preliminary performance of 143 tested modules to be used at Daya Bay.

2 RPC module design and structure

The average efficiency of bare chambers had been tested to be about 96.05%[1]. This meets the Daya Bay RPC system requirement (90%–95%) [1]. However, compared with a muon rate of 1.27 Hz/m^2 at Daya Bay near site, the typical 1 kHz/m^2 noise level of bare chambers is too high. High noise level will greatly increase neutrino detection dead time. To increase the signal-to-noise ratio (S/N) and to reduce the dead time, we choose a multi-layer design of RPC modules working in the coincidence mode. Table 1 shows the effects of different trigger modes assuming the noise pulse width of 100 ns, the layer size of $\sim$2.1 m×2.1 m and modules number of 54 at near site.

From this table, we can see the 3 out of 4 (3/4) trigger mode greatly reduces the noise rate, thus improving the signal-to-noise level and reducing the dead time. We select a 4-layer design with a 3/4 trigger mode, which also provides redundancy to the system, i.e., when one layer in a module is dead, we can still use 3 layers to do analysis in 2/3 trigger mode and the dead time ratio increases a little, 11.67% /54$\sim$0.2%.

Table 1. The noise level in different trigger modes.

trigger mode	2/3	2/4	3/4
noise rate/(Hz/m^2)	2.55	5.09	0.0022
S/N	0.50	0.25	587.86
dead time ratio(%)	11.67	23.33	0.0099

Based on the 4-layer design, a Daya Bay RPC module is designed as an aluminum box containing 8 bare chambers in four layers separated by insulating materials, support panels, read-out strips and ground planes (Fig. 1). The size of a module is 2.17 m×2.20 m with a thickness of 8 cm. A bare chamber is composed of two bakelite sheets of 2 mm in thickness and a single 2 mm gas gap. Each layer in a module contains two different sizes of bare chambers: one is larger (1.1 m×2.1 m) and one is smaller (1.0 m×2.1 m). The placement of bare chambers is reversed between adjacent layers (Fig. 2(b)) to reduce the overlapping dead area.

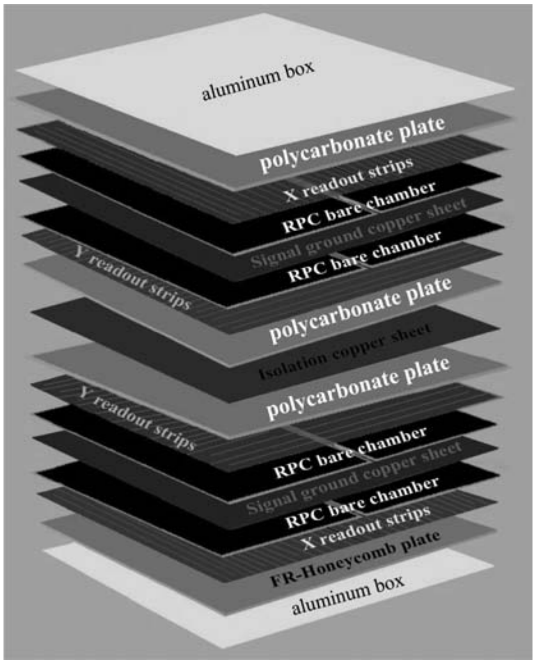

Fig. 1. The RPC module inner structure. Each module contains 4 layers of bare chambers, 4 layers of read-out strips, 3 layers of polycarbonate plates, 1 layer FR-4 honeycomb plate and 2 signal grounds and 1 isolation ground. The outer aluminum box is also an isolation ground.

Each layer has one read-out plane which consists of 8 read-out strips of copper-clad FR-4. The dimensions of a strip are 2.10 m×26 cm, the same length as a bare chamber and one eighth the width of a layer. The read-out strips are oriented like $X\ Y\ Y\ X$, as seen in Fig. 1. When viewed from above, this configuration divides a module into 64 26 cm×26 cm patches. Thus, the position resolution along X/Y direction can reach about 26 cm / $\sqrt{12} \approx$ 7.5 cm. However, the strips are of a zigzag design such that they turn three times: once at one of the 26 cm sides and twice at the other (Fig. 3). This produces the same effect as a strip that is 6.5 cm wide and 8.4 m long. Since the muon event rate of the RPC modules at Daya Bay will be quite low, the effect of the

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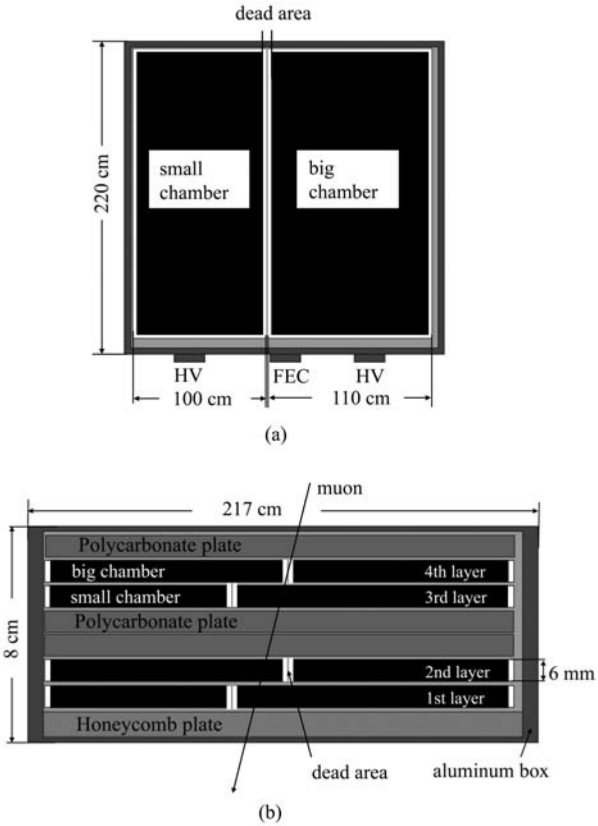
[1] The bare chambers have been tested by Liehua Ma et al. and the paper “The Mass Production and Quality Control of RPCs for the Daya Bay Experiment” will be submitted to NIM.

longer strips is negligible. One strip corresponds to one electronic read-out channel and each module has 32 read-out channels.



(a)

(b)

Fig. 2. The schematic of module structure and dead area. Top view of module (a) and cross sectional view (b). The figures are not to scale.

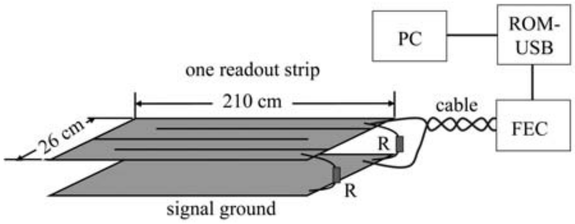


Fig. 3. The RPC electrical schematic. Signal travels along the read-out strip and is read out by the front-end card (FEC), the USB readout module (ROM-USB) and then the raw data are stored on a computer (PC).

A copper isolation plane in the middle of the module divides the module into two symmetric halves (Fig. 1). It provides an isolation ground and electrically separates the second and third layers of bare chambers and their read-outs. The two copper-clad read-out planes in each upper and lower half are connected through resistors to a single copper ground plane which serves as both the signal ground and the electrical isolation between different chamber layers. Thus, each read-out plane is between two ground planes. Signals are read out from twisted pair cables connected to each read-out strip. The read-out strips are connected to their nearest ground plane by two 27 Ω resistors: one at each "end" of the strip (Fig. 3). The 2.0 cm thick FR-4 fiber glass honeycomb plate at the bottom of the module has high rigidity to prevent module deformation. It also provides electric insulation from the aluminum box. The three 1.0 cm twin-wall polycarbonate plates provide similar functionality as they separate and insulate the copper-clad read-out strips. No significant cross-talk is observed in this configuration.

The gas-flow route through a module is illustrated in Fig. 4. The upper and lower halves of a module are supplied by two independent gas channels. Thus, 4 bare chambers are connected in series. In this configuration, if one gas channel fails, the other one will still provide one X and one Y read-out. In addition, each layer of bare chambers has its own high voltage channel. In this configuration, if one of the 4 high voltage channels fails, the other three layers will still provide a non-zero module efficiency.

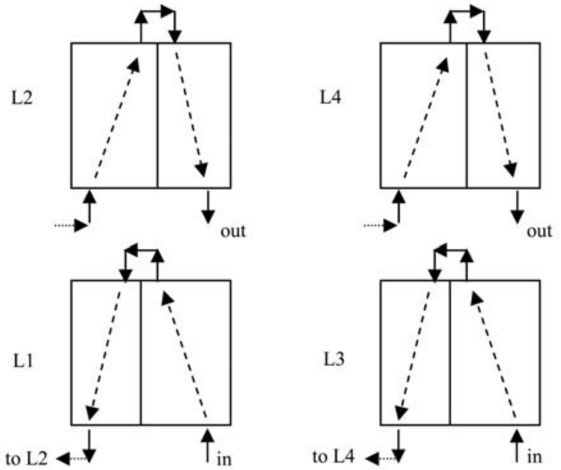


Fig. 4. The layer-by-layer gas flow schematic of one module.

3 Module efficiency calculation and simulation

The function of the Daya Bay RPC system is to help veto the false neutrino events induced by muons. Thus, the muon detection efficiency and its uncertainty are the most important parameters to test. The muon detection efficiency of the RPC system is most finely represented by the 64 patch efficiencies of each RPC module. The variance among all of these patches is indicative of the uncertainty in muon detection efficiency of the RPC system. All bare chambers chosen for use in modules have had their efficiency, dark current and singles counting rate tested and recorded in a bare chamber test. With 4 layers of bare chambers in each module, a 3/4 trigger mode will be used in offline data analysis, but for more physics information keeping, a 2/4 trigger mode will be used in online data acquisition. So, the efficiencies of 2/4 and 3/4 trigger modes are both analyzed in this paper.

Assuming all bare chambers have the same uniform efficiency (f), module efficiency and patch efficiency (ϵ) in these trigger modes, which can both be calculated by the following equations:

$$\epsilon_{2/4}=\sum_{i=2}^{4}C_4^i f^i(1-f)^{4-i}. \qquad (1)$$

$$\epsilon_{3/4}=\sum_{i=3}^{4}C_4^i f^i(1-f)^{4-i}. \qquad (2)$$

where $C_4^i = 4!/(i!(4-i)!)$ is the binomial coefficient. Supposing the efficiency of each bare chamber is 96.00%, formulas 1 and 2 give 99.97% and 99.09% for a module's 2/4 and 3/4 efficiencies, respectively.

In reality, the RPC modules and bare chambers both have dead areas. The gas gaps of bare chambers are sealed by 1.0 cm wide edge spacers around the chamber perimeter. To reduce the overlap of these dead areas in modules, the bare chambers are not stacked identically between layers (Fig. 2). Of course, the chamber perimeters that coincide with the module perimeter all overlap. To mitigate the effects of these overlapping dead areas at Daya Bay, adjacent modules will overlap each other by 10 cm so that the sensitive region of one module will cover the dead area in the other one. This does not, however, avoid the 2.4 cm by 2.1 m dead area in the central region of a module (labeled as 'dead area' in Fig. 2). So, this dead area does decrease the module efficiency and some patches' efficiencies. Fig. 5 shows a schematic of the 64 patches in 8 columns and 8 rows. The central dead area is within the fourth and fifth columns. So, the efficiencies of patches in columns 3 and 4 will be lower than the others.

These dead area patches have been simulated using Geant4 [11] software and 10 million atmospheric muons are generated from the modified Gaisser formula [12]. Table 2 gives the efficiency of a patch in Column 3 or 4, where there is a dead area. We can see that if the bare chamber efficiency is 96.00%, the patch efficiency is about 99.57% in 2/4 mode and 93.44% in 3/4 mode. By comparing with Eqs. (1) and (2) calculation, we would expect 2/4 efficiencies of patches in Column 3 and 4 will not be obviously lower than other patches, but that their 3/4 efficiencies should be 5% lower than other patches.

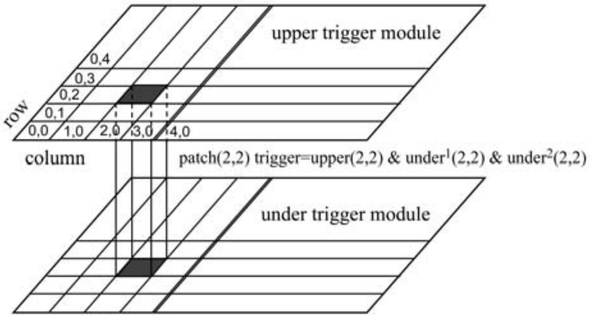


Fig. 5. The scheme of the 64 module trigger patches. (2,1) means Column 2, Row 1.

Table 2. The middle patch efficiency (having dead area) for different bare chamber efficiencies from Monte Carlo simulation.

chamber eff.(%)	92	94	96	98	100
patch 2/4 eff.	98.93	99.28	99.57	99.80	100.00
patch 3/4 eff.	90.21	91.97	93.44	94.58	95.38

Table 3 gives the total module efficiencies from simulation under different bare chamber efficiencies. We can see that if the bare chamber efficiency is 96.00%, 2/4 efficiency is about 99.89% and 3/4 efficiency is about 97.79%.

Table 3. The efficiency of real module geometry for different bare chamber efficiencies from Monte Carlo simulation.

chamber eff.(%)	92	94	96	98	100
module 2/4 eff.	99.61	99.77	99.89	99.95	100.00
module 3/4 eff.	95.11	96.66	97.79	98.57	98.93

Lastly, it is noted that the bare chambers have dead areas due to polycarbonate spacers located every 10 cm×10 cm, giving a dead area of about 0.5%. From simulation, it is determined that their contribution to 2/4 and 3/4 inefficiencies is ~0.1% and ~0.3%, respectively.

4 Module performance

4.1 Experimental setup and test conditions

The RPC module testing shelves, read-out electronics and gas system are shown in Fig. 6.

The edges of the 8 modules are all vertically aligned. Five modules (No. 3–7) are tested at one time. The 3 modules nearest to each module under test are used to provide a coincidence trigger. For example, when testing Module 5, Module 3, 4 and 6 act as trigger modules. Each trigger module is required to have at least one X plane hit and one Y plane hit, which forms one patch hit. The test lasts for more than 24 hours to record at least 100000 signals in each 26 cm×26 cm patch. The gas mixture is argon: R134a:isobutane:SF$_6$=65.5:30:4:0.5. Before testing, all modules are flushed with 5 module volumes of the gas mixture, which takes about one day. We use the Daya Bay gas system components to control the gas fractions and monitor the gas flow rate of each gas channel (Fig. 7). The 4 gas components are mixed in a static gas pipe before going through the last mass flow meter (MFM) and then distributed among 16 channels going to 8 modules. Each channel has a digital bubble monitor to monitor the gas flow rate. We use the Daya Bay RPC front-end electronics cards [13] to test the modules ('FEC' in Fig. 3). During testing, air conditioning is used to control the temperature to about 20.0±2.5 ℃.

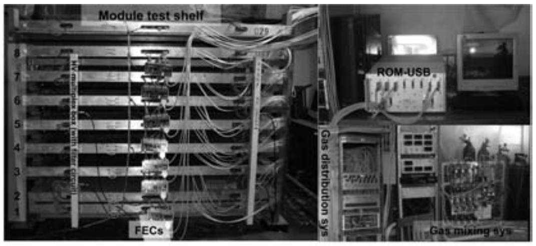


Fig. 6. The RPC module testing setup. One batch of 5 modules to be tested on the test shelf and the topmost module is not connected to FEC (the left part). The right part shows the gas system, ROM-USB and computer in data acquirement.

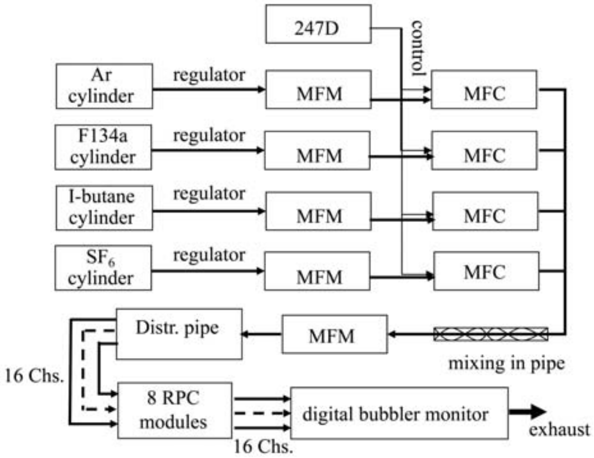


Fig. 7. The gas system scheme. MFM represents the mass flow meter and MFC for the mass flow controller. 247D is a crate to control MFCs. All components are made by MKS, except the pipe connection made by Swagelog.

Figure 8(a) shows 3/4 efficiency versus high voltage for three modules at a 30 mV threshold. The efficiency nearly reaches plateau at 7200 V. Fig. 8(b) shows 3/4 efficiency versus threshold at 7600 V. The efficiency begins to drop sharply around 50 mV. We choose 7600 V and 30 mV as the testing voltage and threshold, respectively.

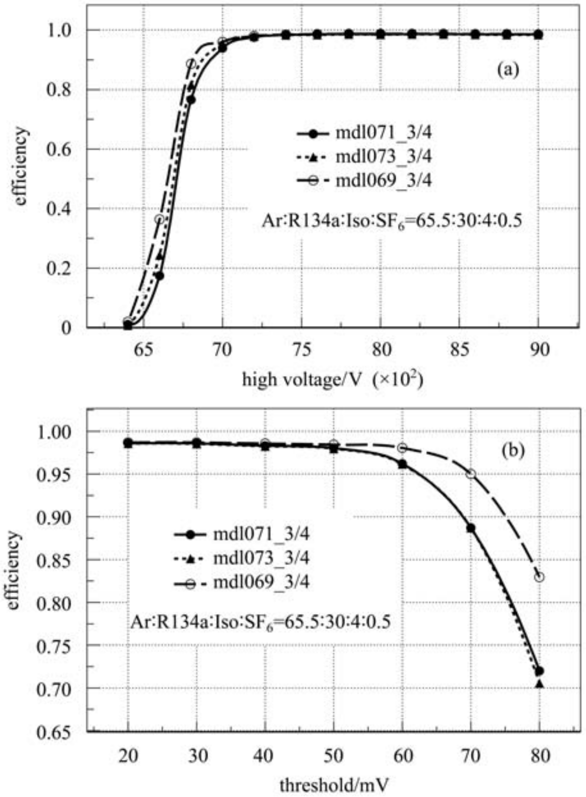


Fig. 8. The 3/4 efficiency versus voltage (a) and the 3/4 efficiency versus threshold (b), for three modules.

4.2 Patch efficiency

The Daya Bay experiment will need high muon detection efficiency over all areas covered by the RPC module; so, the efficiency of the 64 patches is of primary concern for testing. Analyzing raw data for RPC module 005, its patch efficiency performance is as shown in Fig. 9. Patch numbers 0–7 correspond to the first column in Fig. 5. Patch numbers 8–15 correspond to the second column and so on. Patch efficiencies vary with their location in a module because of the dead areas. In Fig. 9, the 3/4 efficiencies of the middle patches 24 to 39 are lower (about 94%) than the other patches (about 99%) due to the dead area in Fig. 2. This drop in 3/4 efficiencies for the middle patches agrees with the simulation results in Tables 2 and 3. The 2/4 efficiency is not largely affected by this dead area. We can also see a reduction on the order of 0.1% efficiency for patches along an edge of the module, namely the first and last group of 8 patches (0–7 and 56–63) plus the other 12 patches along the module perimeter. Correspondingly, the efficiencies of the four corner patches are even lower (patches 0, 7, 56 and 63).

Figure 10 shows the patch efficiency distributions of all 143 accepted modules. The average 2/4 patch efficiency is about 99.8% with RMS below 0.2%. The patch 3/4 efficiency is about 98.0% with a portion centered near 94% caused by the dead areas in the patches of Column 3 and 4. Excluding the lower portion of the distribution, it has an average efficiency of about 99.3% with the RMS of about 0.3%.

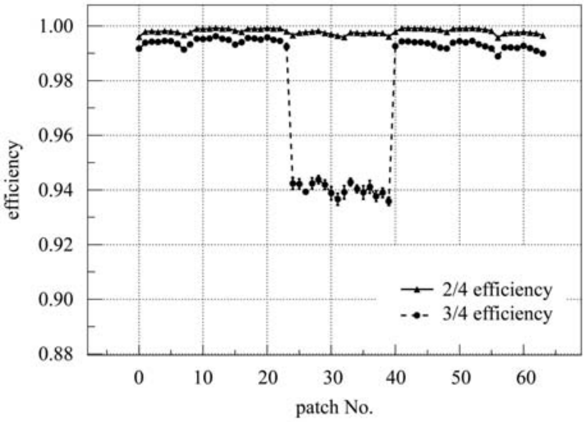


Fig. 9. The patch efficiencies of one RPC module (RPC module number 005).

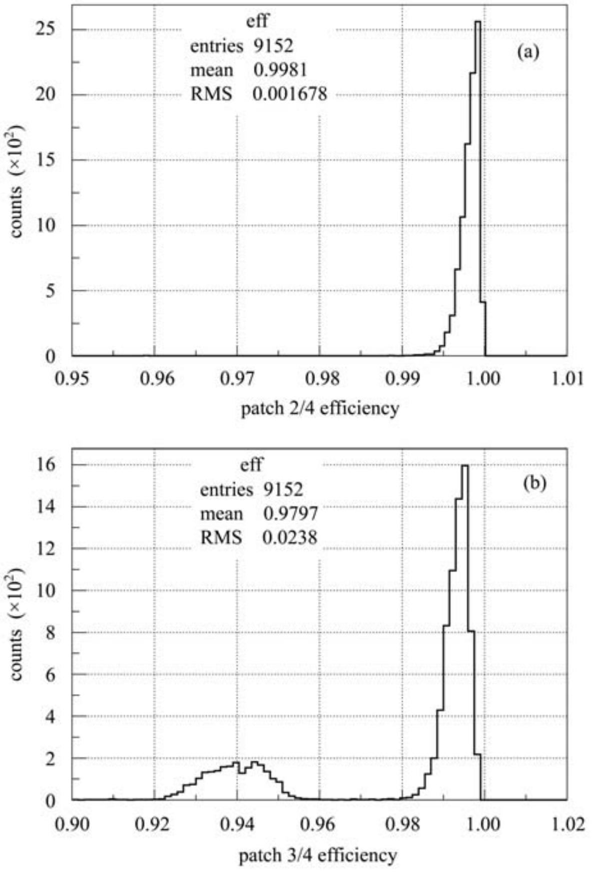


Fig. 10. The patch efficiency in 2/4 and 3/4 modes of all modules.

We note the acceptance criteria of module testing: for each patch, in the 4th and 5th columns, the 3/4 efficiency should be greater than 92%, while that of the other patches should be greater than 95%.

4.3 Module efficiency statistics

Up to now, 143 modules have been tested and passed. Fig. 11 shows the module efficiencies. The 2/4 efficiency is about 99.8% with the RMS of about 0.05% and the 3/4 efficiency is about 97.9% with the RMS of about 0.24%. This agrees well with the simulated module 3/4 efficiency (see Table 3) under a measured bare chamber efficiency of 96.05%. Using a bare chamber efficiency of 96%, further simulation of the full array of RPC modules at Daya Bay, arranged as described in Section 3, gives a total system 3/4 efficiency of 97%, which is beyond the design requirement (90%–95%) [1].

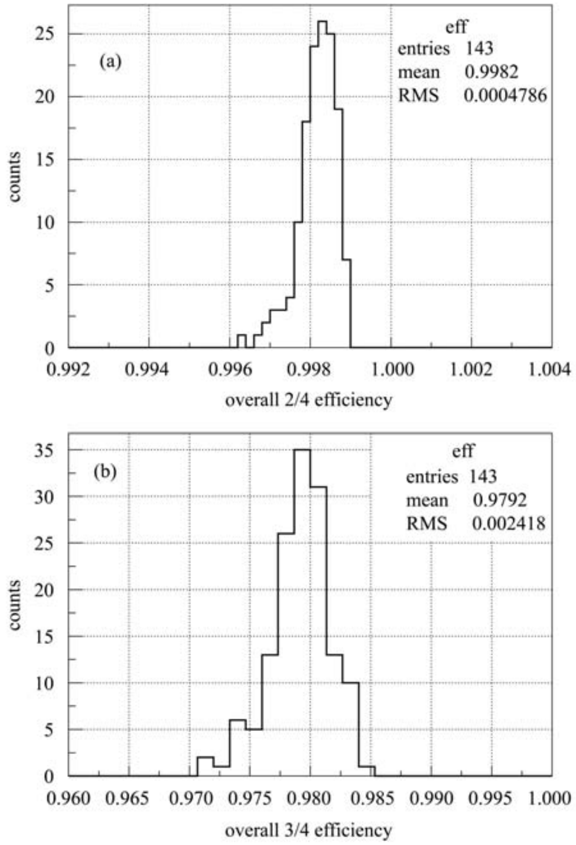


Fig. 11. The module efficiency in 2/4 and 3/4 modes.

5 Conclusions

The 4-layer design of the Daya Bay RPC modules and use of 3/4 trigger mode give an negligible noise rate and the noise-induced dead time. Modules of 4 layers of bare chambers have been constructed. Simulation studies of module efficiencies agree with the bare chamber test results. The reversed placement of two-sized chambers in different layers to overlap dead area is well understood in 2/4 and 3/4 trigger modes. Preliminary test results of RPC modules show that the average module and patch efficiency is high and uniform. The 3/4 trigger mode reduces noise rate greatly and keeps the required detection efficiency. Thus we will use the 3/4 mode in the Daya Bay Data analysis. All components (gas system, electronics, modules and so on) of the testing system reported here are working as designed. This work provides us with the experience for the Daya Bay RPC detector commission.

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