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The mass production and quality control of RPCs for the Daya Bay experiment

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ABSTRACT

Resistive plate chambers will be used in the Daya Bay reactor neutrino experiment to help veto backgrounds created by cosmic-ray muons. The mass production of RPCs began in 2008 and by the end of 2009, 1600 RPCs (3500 m^2) had been produced and tested. This paper describes the production and quality control procedures, and quality assurance using cosmic-ray testing.

1. Introduction

The Daya Bay reactor neutrino experiment [1] is designed to determine the last unknown neutrino mixing angle, θ_{13}, with a sensitivity of $\sin^2 2\theta_{13} < 0.01$ at a 90% confidence level. The main backgrounds at Daya Bay are caused by cosmic-ray muons, which are suppressed by locating the detectors underground. Though this background at Daya Bay is less than 1% of the antineutrino signal [1], efficient muon rejection is vital for a high sensitivity measurement. To accomplish this, the neutrino detectors are submerged in water pools where they are shielded from muon-induced neutrons and gammas by at least 2.5 m of water. Muons will be tracked through the water pools, which are outfitted with PMTs to detect Cherenkov light, and through arrays of resistive plate chambers (RPCs) above the pools.

RPCs are gaseous particle detectors first developed by Santonico et al. [2], in the early 1980s. Due to their simple structure and low cost, they are well-suited for use over large areas. Therefore, RPCs have been an important component in many particle physics experiments such as BaBar [3], BELLE [4], OPERA [5], and those at the LHC [6–8]. A new type of bakelite RPC, which does not use the commonly-applied linseed oil, was developed by the Institute of High Energy Physics (IHEP) in Beijing, and is being used in BESIII [9]. Its performance has been shown to be more than satisfactory for the BESIII muon subsystem [10,11]. The Daya Bay experiment has also chosen to use these RPCs and operate them in streamer mode to detect muons.

The mass production of Daya Bay RPCs began in 2008, and a total of 1600 RPCs (3500 m^2) were finished in 2009. The testing of individual RPCs using cosmic muons was finished at IHEP in 2009. This paper describes the processes of RPC production and quality control, and quality assurance using cosmic ray testing.

2. RPC structure

The Daya Bay experiment will use 1560 RPCs (3330 m^2). All RPCs will be assembled into $2.20 \times 2.17 \times 0.08\ m^3$ aluminum boxes as detector modules. A module contains 4 layers of RPCs, each of which consists of one smaller and one larger RPC ($1 \times 2.10\ m^2$ and $1.10 \times 2.10\ m^2$). The dead-space between each

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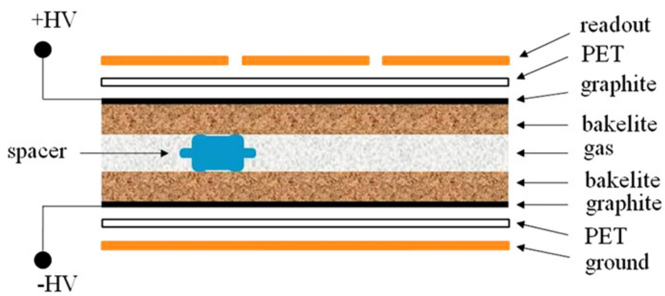

Fig. 1. Basic structure and configuration of an RPC.

larger and smaller RPC is staggered between layers so that the dead-spaces are not vertically aligned. There will be 189 modules, each weighing about 210 kg, divided among three detector sites: 54 at both of the near sites and 81 at the far site.

The basic structure and configuration of a Daya Bay RPC is shown in Fig. 1. Two bakelite plates of thickness 2 mm sandwich a single gas gap of 2 mm. The gas gap size is maintained by polycarbonate button spacers, glued in a $10 \times 10\,cm^2$ grid. These spacers have a disk-shaped mid-section of 12 mm diameter to increase the surface current path-length (see Fig. 1). Including the mid-section width, the button spacers occupy not more than 1% of the total area of an RPC. Excluding the mid-section, a more accurate estimate of effective dead-area is less than 0.5%. A graphite layer is sprayed on the outer surface of each bakelite plate for the application of high voltage. A 100 μm polyethylene terephthalate (PET) film covers the graphite layer to protect the surface and insulate the readout strips and ground plane from the graphite layer. The readout strips and ground plane are made from sheets of copper-clad FR-4. Signals are picked up on positive side.

3. RPC mass production and quality control

The mass production and quality control of the RPCs consists of bakelite plate production and bulk resistivity measurements, bakelite plate preparation and graphite surface resistivity measurements, RPC assembly and leak testing, and RPC training. After assembly, RPCs are sent to IHEP for training and quality assurance using cosmic-ray testing. The characteristics and performance of all bakelite plates, RPCs and RPC modules are recorded, and have been used to accept or reject RPCs. These data are archived in a MYSQL [12] database accessible through the internet. A unique identification number is associated with each RPC, which will allow tracking long-term behavior.

3.1. Bakelite plate production and bulk resistivity measurements

The bakelite plates are produced at the Li Shen Wood Product Inc. factory in Xinji City. The thickness of the plates is controlled to 2.00 ± 0.02 mm, and the length (width) is about 230 cm (120 cm). The basic material components of the bakelite plates are paper with phenolic and melaminic two-step resins. The proportions of phenol and melamine are controlled to select the bulk resistivity of the bakelite. The paper laminates are heated and compressed between stainless steel plates after being coated with the resin solution. The smoothness of the bakelite plate surfaces is ensured by the outer laminates, which are differently paper coated in a differently-proportioned resin. In addition, new stainless steel press plates were purchased and used for Daya Bay bakelite production to maximize surface smoothness.

After production, bakelite plates are sent to IHEP for measurement of their bulk resistivity. For each plate, the bulk resistivity is measured at nine uniformly spaced regions. A region is covered by two electrodes of 5 cm diameter to which a voltage difference of 4 kV is applied. The current is recorded (as well as temperature and humidity) and used to determine the resistivity. Since the measurements are done in a room that is not temperature-controlled, they are corrected to 20 °C according to the following formula:

$$\rho_{20} = \rho_T 10^{0.06(T-20)} \tag{1}$$

where T is the recorded room temperature in degree Celsius, ρ_T is the average bulk resistivity measured at temperature T, and 0.06 is an empirical parameter taken from a dedicated study performed at IHEP. A bakelite plate is accepted only if the resistivity of each measured region is in the range of $0.5–2.5 \times 10^{12}\,\Omega\,cm$ at 20 °C. Fig. 2(a) shows the distribution of the temperature-corrected average bulk resistivity for all measured bakelite plates. Out of 3625 measured plates, 358 (9.9%) were rejected. Fig. 2(b) shows the distribution of the RMS deviation of the 9 measured regions. The average deviation is 6.7% of the average bulk resistivity and 4.4% of the range of acceptance.

Generally, higher resistivity yields lower current and noise rate, but it also implies a longer charge recovery time, which can reduce efficiency, particularly at higher rates. Since the rate at Daya Bay is low, it is sensible to use a higher resistivity, but not so high as to significantly reduce the efficiency. The ranges of bulk and surface (see Section 3.2) resistivities are essentially inherited from RPC development done for BESIII [13].

3.2. Bakelite plate preparation and surface resistivity measurements

The bakelite plates that satisfy the bulk resistivity requirement are sent to Gaonengkedi Ltd. Co. (GNKD) in Beijing, for the assembly of RPCs. Before assembly, all bakelite plates are cut to the dimensions of $1 \times 2.10\,m^2$ ($1.10 \times 2.10\,m^2$) for smaller (bigger) RPCs. The size of a bakelite plate is ensured by the positioning pin of the cutting machine, which can make an error less than 0.1%.

After cutting and careful cleaning with ethanol, a layer of special graphite paint is uniformly coated on one side of each bakelite plate using an airbrush, leaving a 1 cm uncoated perimeter. The surface resistivity of the graphite coating is measured about 1 day after painting. The graphite surface resistivity is taken as the mean value of two measured regions. Both of the measured values are required to be in the range of 400–1000 kΩ/□.

After the graphite resistivity measurements, a $1 \times 10\,cm^2$ strip of copper tape is applied to the graphite near one of its corners for the high voltage connection. Then, a 100 μm PET film coated with a hot-melt glue is applied to the graphite side of the bakelite plate using a laminator.

3.3. RPC assembly and leak testing

RPCs are assembled in a temperature-controlled clean room at GNKD. At the beginning of the assembly, one bakelite plate is put on a platform and cleaned with ethanol. Segments of edge spacers made of ABS, each with a width of 10 mm and thickness of 2 mm, are glued along the perimeter of the bakelite plate. Two gas feed-throughs made of ABS are embedded at both of the shorter sides of the plate, diagonally across from each other. Polycarbonate button spacers, with a mid-section diameter of 12 mm and thickness of 2 mm, are glued onto the plate every $10 \times 10\,cm^2$. Then, a second bakelite plate is glued to the tops of the edge spacers and button spacers. Finally, the RPC perimeter and regions around the gas feed-throughs are glued externally. For the first 2 h after gluing, the RPC is vacuumed to about 8% atmospheric pressure by a vacuum pump, after which it is sealed. This process is to prevent the gas gap from expanding beyond the height of the spacers.

After 2 days of curing, the gas-tightness of the RPC is tested by applying an over-pressure of 300 mm of water (30 mbar) to the