Nuclear Instruments and Methods in Physics Research A 794 (2015) 25–32

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Waterproofed photomultiplier tube assemblies for the Daya Bay reactor neutrino experiment

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ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form
26 April 2015
Accepted 4 May 2015
Available online 11 May 2015

Keywords:
Daya Bay
Reactor
Anti-neutrino
Waterproof
Photomultiplier tube
MACRO

ABSTRACT

In the Daya Bay Reactor Neutrino Experiment 960 20-cm-diameter waterproof photomultiplier tubes are used to instrument three water pools as Cherenkov detectors for detecting cosmic-ray muons. Of these 960 photomultiplier tubes, 341 are recycled from the MACRO experiment. A systematic program was undertaken to refurbish them as waterproof assemblies. In the context of passing the water leakage check, a success rate better than 97% was achieved. Details of the design, fabrication, testing, operation, and performance of these waterproofed photomultiplier-tube assemblies are presented.

1. Introduction

The Daya Bay Reactor Neutrino Experiment is designed to measure the neutrino-mixing angle θ_{13} with high precision [1]. To reach this goal, the experiment utilizes detectors located in one far and two near underground experimental sites at different distances from three pairs of reactors. At each site multiple detectors filled with 0.1% Gd-loaded liquid scintillator are used to detect electron anti-neutrinos from the reactors. Each site is shielded by significant overburden to reduce the flux of cosmic-ray muons, and each anti-neutrino detector (AD) is submerged in a water pool to suppress ambient gamma-ray and neutron backgrounds. Except at the top, each water pool is segmented into two optically isolated zones that are instrumented with 20-cm-diameter photomultiplier tubes (PMTs) as independent water Cherenkov detectors for detecting muons [2].

In each of the two near sites (EH1 and EH2), the water pool is approximately 16 m × 10 m × 10 m, and is instrumented with 288 20-cm waterproof PMTs. In the far site (EH3), the water pool is approximately 16 m × 16 m × 10 m, and is populated with 384 20-cm PMTs. Of the 960 PMTs, 619 are new Hamamatsu R5912 PMTs [3] custom-built as waterproof assemblies for Daya Bay. Since the PMTs in the water pools are used only for tagging incoming muons, we decided to recycle a number of PMTs that had been used in the MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) experiment in Italy [4]. We succeeded in waterproofing about 400 MACRO PMTs that passed a pressure test in water, and selected 341 of them to instrument the water pools of the Daya Bay experiment.

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http://dx.doi.org/10.1016/j.nima.2015.05.002
0168-9002/

In Section 2, we discuss the design of the waterproof PMT assemblies, which includes the MACRO PMT, voltage divider, potting shell, and studies of potting materials. In Section 3 we describe the potting procedure in detail, including the pressure test used to verify that the potted assemblies were waterproof. Based on the initial pressure test results, the fabrication procedure was improved and the mass production of all ~400 waterproofed PMTs was completed successfully. The waterproofed assemblies that passed the pressure test and a subsequent electrical test were installed into the water pools. Their performance in the water pools during data taking is presented. Section 4 is the summary.

2. Design of the waterproof PMT assembly

2.1. MACRO PMT

The MACRO PMTs we used are EMI (now Electron Tubes) models 9350 KA, and D642 KB [5]. They have a 20-cm-diameter hemispherical glass window with a blue-green sensitive bialkali photocathode. Each has 11 high-gain SbCs dynodes and 3 BeCu dynodes of linear-focused design for good linearity and timing. Since their structure, geometry and light detection features are similar to those of the newly purchased Hamamatsu R5912, the 9350 KA and D642 KB are viable candidates for instrumenting the Cherenkov detectors of the Daya Bay experiment. However, in the MACRO experiment, these PMTs were immersed in mineral oil and their bases were not sealed, whereas, at Daya Bay, they are submerged in ultra-pure water and subject to greater pressures. Thus, it was necessary to encapsulate the electrical components in the bases with epoxy to make them waterproof, and ensure they could withstand sufficient pressure before installing them in the water pools at Daya Bay.

2.2. Design of voltage divider

In the MACRO experiment, two cables were utilized to operate a PMT, one carrying negative high-voltage (HV) and the other one carrying the signal. However, in the Daya Bay experiment, a single cable carries both positive HV and signal from the base to a decoupler, which isolates the signals from the applied HV and directs them to the front-end electronics. Thus, we designed and fabricated new bases for the MACRO PMTs. Several operational characteristics of the PMTs are sensitive to the base design, such as the working HV at a particular gain, rise and fall times, linearity and collection efficiency. Generally, the specifications of the MACRO PMTs are similar to those of the Hamamatsu R5912s; for example, a maximum gain of 3×10^{7} at a HV of less than 2 kV, and linearity better than $\pm5\%$ at 60 mA peak anode-current.

In our design of the circuit as shown in Fig. 1, the values of the resistors follow the recommendation of the manufacturer of the EMI 9350KA. In particular, the resistor between the photocathode and first dynode provides a potential difference of around 450 V at our nominal operating voltage. Our tests have shown that similar performance is achieved for the EMI D642 KB PMTs with the same circuit design. Based on the evaluation of a few prototypes, we found that the combination of a 50-Ω terminating resistor (R30) and no damping resistor (R31) at the output of the anode provided an optimal waveform, i.e., it minimized both the recovery time after the overshoot and the ratio of the overshoot amplitude to the signal amplitude. The circuit was carefully laid out to reduce potential electromagnetic interference between components.

2.3. Design of potting shell

To ensure that the refurbished MACRO PMTs work in water, their bases must be well sealed. To achieve this goal, the potting shell has to have minimal contact between the epoxy and water. Our design shown in the left picture of Fig. 2 also needs to satisfy the constraint that the potted tube geometry and PMT mounts be compatible with those for the purchased Hamamatsu waterproof assemblies. To achieve this, the profiles of a few MACRO PMTs were scanned and modeled by a coordinate measuring machine (CMM). The tube length, socket diameter and dome diameter of all 400 MACRO PMTs were then measured. The variations of the parameters were within tolerance for mounting the potted PMTs on support frames for installation. The drawing on the right of Fig. 2 is a vertical cross-section of the two-piece potting shell. One piece is the acrylic base that sits on the cone-shaped glass envelope of the PMT and holds the plastic socket with the connecting pins. The voltage-divider board plugs onto the socket. The other piece is the acrylic cap, which joins with the acrylic base. The top of the acrylic cap has a crossing rib design that strengthens the potting shell. The side wall of the acrylic cap has an opening that allows the coaxial cable to exit the base. Another opening in the top of the acrylic cap (labeled as 'filling hole' in Fig. 2) is for pouring epoxy into the volume between the two acrylic pieces to seal the PMT base. At the narrow end of the acrylic base, there are four layers of protection from inside to outside: epoxy, sealant, mastic tape and sealant. At the acrylic cap, the coaxial cable also has four layers of protection: epoxy, sealing plug, sealing acrylic cap and mastic tape. The acrylic base and acrylic cap are sealed together with acrylic cement. The filling hole in the top of the acrylic cap is closed by a smaller acrylic cap and sealed with the same acrylic cement. Thus, whichever side of the potting shell is seen by water, there are multiple layers of

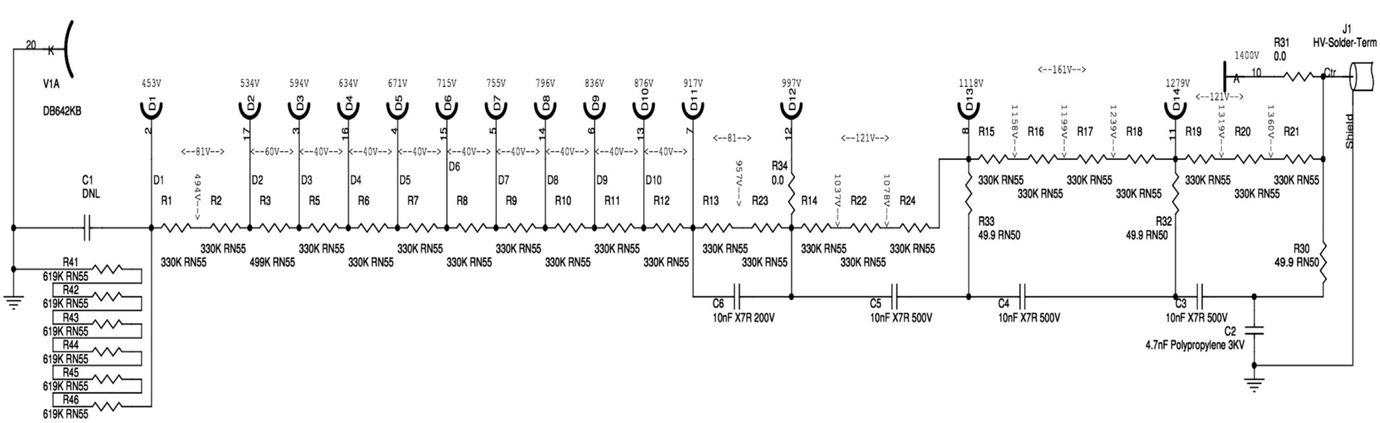

Fig. 1. Schematic diagram of the voltage divider for operating EMI 9350KA or D642KB photomultiplier tube with positive high voltage.