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Plastic scintillator-based hodoscope for the characterization of large-area resistive plate chambers

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Abstract. A scintillator-based hodoscope is fully operational at Nuclear Physics Division, Bhabha Atomic Research Centre (NPD-BARC). It was used for characterizing the resistive plate chambers (RPCs) assembled for the RE4 upgrade for the compact muon solenoid (CMS) experiment, installed during the long shut-down (LS1) using cosmic muons. It has now been employed for R & D related to gas mixtures and glass RPCs for the India-based neutrino observatory (INO) and muon tomography studies. The hodoscope is equipped with gas flow lines, LV, HV and VME-based DAQ with multihit TDCs. CERN-based software was adapted, implemented and along with the cosmic trigger, was used to evaluate the functional parameters for the RPCs, such as efficiency, cluster size etc.

Keywords. Plastic scintillators; resistive plate chambers.

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1. Introduction

Resistive plate chambers (RPCs) [1] are gaseous detectors having resistive electrodes usually made of bakelite or glass. Particles are detected when they ionize the gas mixture. Depending on the gas composition and mode of operation, signals are induced on the read-out strips by the generation of avalanche or streamers after ionization in the presence of a high electric field. The geometry, shape and configuration of RPCs depend on the application and requirement. RPCs are fast detectors possessing excellent timing properties. They are inexpensive, have good position resolution and can cover large area. They are used for trigger, tracking and timing purposes in many high-energy physics experiments.

There are around 1000 RPCs in the CMS detector [2] including the end-cap and barrel regions and the proposed iron calorimeter (ICAL) detector at INO [3] would require approximately 30000 RPCs of $\sim$4 m^2 area. These experiments are built underground and operating over long periods of time. If detectors develop problems when these experiments are running, it is not possible to service or replace them. Therefore, RPCs need to be tested thoroughly before being employed. The dimension and the number of RPCs needed for these experiments, requires a set-up which can characterize each RPC in a reasonable amount of time for functional parameters such as efficiency, cluster size, strip profile and noise rate. A cosmic muon hodoscope is a suitable option.

Hodoscope is an instrument which is used to detect the path of a particle. The hodoscope at NPD-BARC was constructed to characterize RPCs with cosmic muons, both for the RE4 (4th RPC end-cap disk) upgrade for the CMS experiment during the long shut-down (LS1) and also for the R & D related to glass RPCs for INO, muon tomography and related experiments. India had been mandated to build and characterize 50 RE4/2 (2 refers to the inner ring of the end-cap disk) RPCs for the RE4 upgrade which was done during the long shut-down LS1 (2013–2014). The hodoscope contains 16 large-area scintillators for characterizing RPCs using cosmic muons as triggers. These large-area scintillators have been fabricated to fully

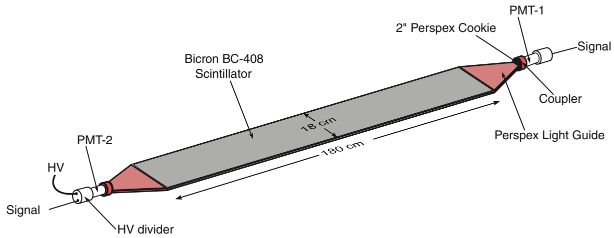

Figure 1. Schematic of a long scintillator paddle.

characterize RPCs in one go covering the entire active area. At the surface of the Earth, the average energy of muon is 3–4 GeV with an average flux of 1 cm^{-2} min^{-1}.

The scintillators are arranged in two layers, each consisting of eight scintillators. The two layers are separated by a vertical distance of 210 cm between which RPCs can be stacked in seperate shelves for characterization. Each of the scintillator (Bicron BC-408) measuring 180 cm × 18 cm × 1 cm, were cut and polished (up to 10 μm levels) in the Centre for Design and Manufacture, BARC. Each of these scintillators is coupled to a separate photomultiplier tube (PMT) at each end. The PMTs were procured from Electron Tubes (ET-9814B, 51 mm diameter, QE ∼30% and gain $\sim 10^6$). As these scintillators are quite long, it was decided to have two PMTs at either end, so that the efficiency of the scintillator is not compromised, over its length. Figure 1 shows the schematic of the scintillator, light guide, cookies, PMT and the HV divider. The whole assembly was then wrapped by a reflector in the inside and doubly wrapped with black PVC tape on the outside.

The hodoscope is shown in figure 2a. Figure 2b shows eight scintillators lined side by side in the top layer shelf #9 of the cosmic stand in the RPC Lab. The bottom layer of scintillators is configured similarly in shelf #2.

To localize the region of the RPC while characterizing them, two portable scintillator paddles of smaller dimension (40 cm × 18 cm × 1 cm) with a single PMT at one end were also fabricated using the same scintillator sheets in a similar way as the long paddle.

The coincidence of these scintillator signals will provide us the cosmic trigger to evaluate the performance characteristics of the RPCs. The hodoscope along with RPCs will also be very helpful for the proposed muon tomography programme. Bakelite and glass RPCs characterized using the hodoscope discussed in this paper are operated in the 'avalanche' mode.

2. DAQ and trigger

The signals of the PMTs are brought to the electronics through 10.5 m cables to ensure equal delay (∼50 ns).

Electronics is composed of both NIM and VME standards. The VME controller is CAEN Mod. V2718. It communicates to the PC through an optical link bridge. It can generate a clock of 20 MHz and is used to synchronize the TDCs. The TDC (multihit) we are using is CAEN Mod. V1190A having 128 Channels. Its maximum resolution is 100 ps (with 40 MHz clock). It accepts either ECL or LVDS (low voltage differential signaling) signals only. The V1190A is being operated in the so-called 'straddling' mode [4] where the trigger window is straddled around the trigger, so that events occurring both before and after the trigger are recorded, provided they are within the window width. The trigger matching mode can be decided by setting different programmable parameters [4].

In the CMS RE4/2 RPC, the front-end board provides LVDS signals from the strips. No level translation is needed and the signals are taken to the TDCs through flat cables.

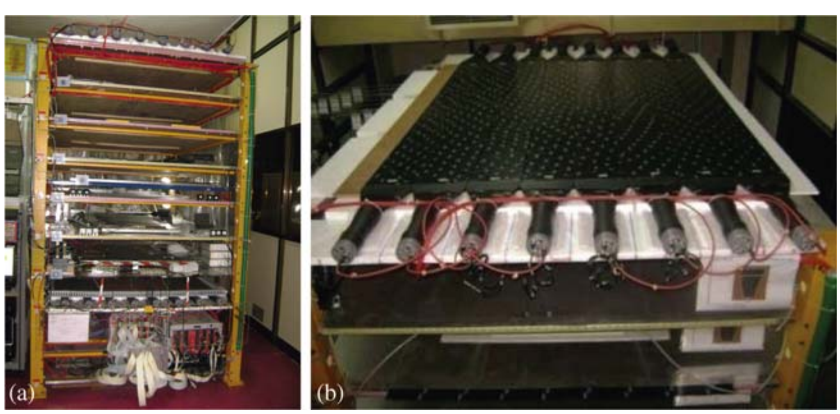

Figure 2. (**a**) The hodoscope and (**b**) the top plane having eight scintillators.

In the case of the glass RPC, the signals from strips are first amplified using 8 channel hybrid microcircuit (HMC) based preamplifier boards, discriminated using commercial NIM leading edge discriminators and fed to NIM-ECL translators. The ECL output is then fed to the TDC. The HMCs of the preamplifier board (BMC-1513, BMC-1595, BMC-1597) have been developed by Electronics Division, BARC. Signals of the scintillators coming from the NIM electronics are converted to ECL signals using ECL to NIM translators as well.

The way the trigger is generated is illustrated in figure 3. Each scintillator is coupled to two photomultipliers. The logical OR of the two photomultiplier signals after discrimination forms the scintillator signal. We shall have eight such signals from both top and bottom planes. Eight-fold logical OR of the signals in one plane forms the plane signal. Therefore, we shall have two signals: one from the bottom plane and the other from the top plane. The coincidence pattern of the top and bottom plane scintillators observed for 100 000 events is shown in figure 4. The pattern peaks along the diagonal. This is expected as the cosmic muon flux is not uniform over the zenith angles. Small scintillator paddles described in §1 are used to localize the region of the RPC during characterization. By employing the paddle in coincidence with the top and bottom plane scintillators, the geometrical coverage of the hodoscope can be constrained to particular sections of an RPC (illustrated in the next section).

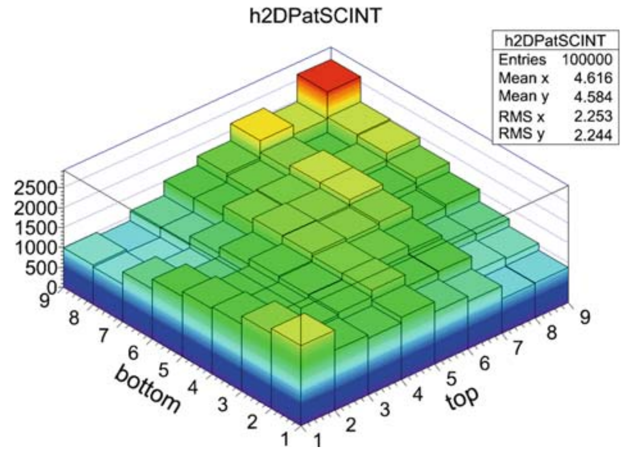

Figure 4. Coincidence plot of the top and bottom plane scintillators. Top 1–8 and bottom 1–8 are the numbers corresponding to the scintillators in the top and bottom planes of the hodoscope.

Due to the trapezoidal shape of the RE4/2 RPC, using four scintillators in each plane (top and bottom) ensures proper geometrical coverage. Therefore, we use only the middle four scintillators in both planes during RPC characterization. Other scintillators are turned off. The logical AND of top and bottom plane signals in coincidence with the paddle signal forms the trigger. Trigger, individual top and bottom plane scintillator signals and paddle signals are also fed to the TDCs after translation to ECL. Software developed at CERN for DAQ which stores data in the ROOT format [5] has been adapted to the hodoscope.

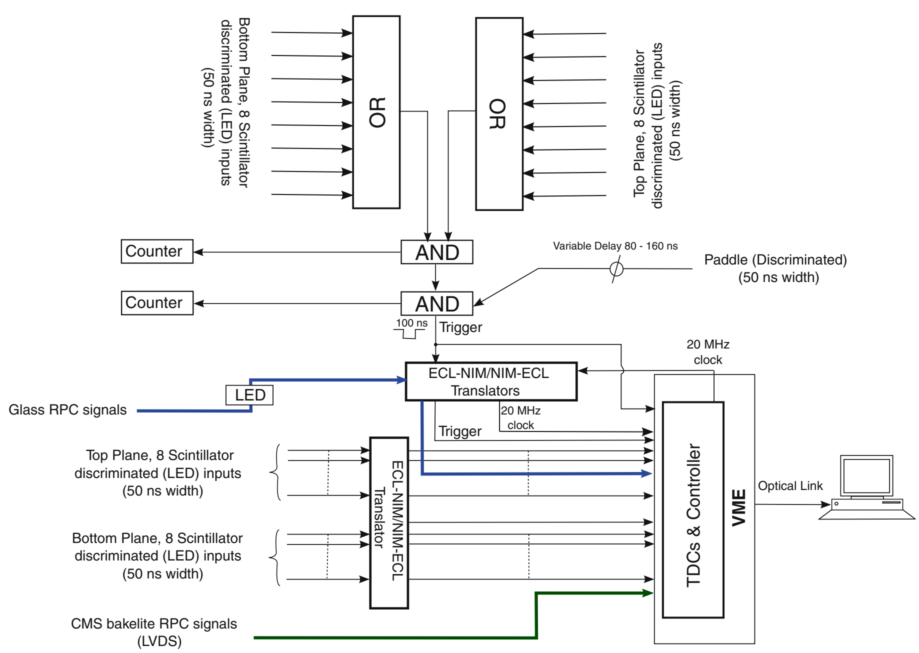

Figure 3. Block diagram of the hodoscope set-up.

3. Characterization of RPCs

3.1 *Bakelite RPCs*

RPCs of the CMS end-cap are trapezoidal in shape. Schematic of an RE4/2 RPC is shown in figure 5. It has two layers of bakelite gas gaps. Bakelite electrodes of the gas gaps are 2 mm thick and the electrode spacing is 2 mm. The surface resistivity of the conductive graphite coating is ∼100–250 kΩ/square. The length of the active area of the RPC is ∼1.6 m and width is ∼0.9 m on the wide side and ∼0.6 m on the narrow side. The read-out has a total of 96 strips from three sections (32 strips in each section). The sections are denoted as $\eta =$ A, B and C corresponding to the different pseudorapidity [5a] regions covered by the RPC when employed in the end-cap of the CMS detector [2]. The bottom layer has a large gas gap called the BOTTOM gap (covers all sections) and the top layer has two smaller gaps called TOP WIDE (covers only section A) and TOP NARROW (covers sections B and C). The read-out, which is also segmented according to the sections, has 32 copper strips in each section longitudinal to the length of the trapezoid. It is sandwiched between the two layers of gas gaps. The trigger geometry is confined to each section by keeping a paddle over the required section using a movable stand (figure 6). Three RPCs stacked below the paddle in consecutive shelves are to be characterized simultaneously.

The gas mixture is composed of freon-R134a: 95.2%, I-butane: 4.5%, SF_6: 0.3%, with ∼40% RH (relative humidity).

Sample efficiency plot for the RPC for $\eta =$ A section using the paddle is shown in figure 7. Efficiency is the number of counts registered in the RPC section divided by the number of triggers. Trigger filtering is done at the time of analysis neglecting shower events. If more than one scintillator in the top or bottom plane fires for an event, the event is not considered. The number of triggers shown in figure 7 is the hardware trigger. Since the RPC is composed of two layers of gas gaps, efficiency TOP, BOTTOM and DOUBLE correspond to the efficiency of the RPC when the TOP, BOTTOM and both TOP and BOTTOM layers of gaps are powered respectively. A sigmoid function [6,7] of the form

$$f(x) = \frac{a}{1+\exp[b(c-x)]} \tag{1}$$

is used to fit the data where a is the maximum efficiency, b is the slope and c is the voltage at 50% efficiency. High voltage applied to the RPCs is scaled to a reference pressure and temperature using environmental conditions in the lab. This is done so that the measurements become independent of the site. The scaling relation [6,7] is

$$HV_{\text{eff}} = HV_{\text{applied}} \times \frac{P_0}{P} \times \frac{T}{T_0}, \tag{2}$$

where P, T are the ambient pressure, temperature and $P_0 = 990$ mbar, $T_0 = 293$ K are the reference pressure and temperature respectively. The reference values can be arbitrary, but it would be preferrable to have typical values corresponding to the site where the detectors would be employed. While temperature in the lab is maintained at the reference temperature, pressure is slightly more (between 1000 and 1015 mbar).

Strip profile and cluster size plots are shown in figure 8. They are for the DOUBLE configuration. In figure 8a, the strip channel from 0–31 corresponds to the section A, 32–63: B and 64–91: C respectively. When we keep the paddle on section A, we observe all counts in that section. Cluster size shown in figure 8b shows that at a voltage of 9400 V, two strips fire on an average, for a muon event. The variation of the mean cluster size with voltage is shown in figure 8c.

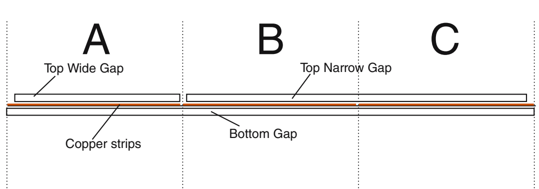

Figure 5. Side view of the RE4/2 RPC illustrating double layered gas gaps.

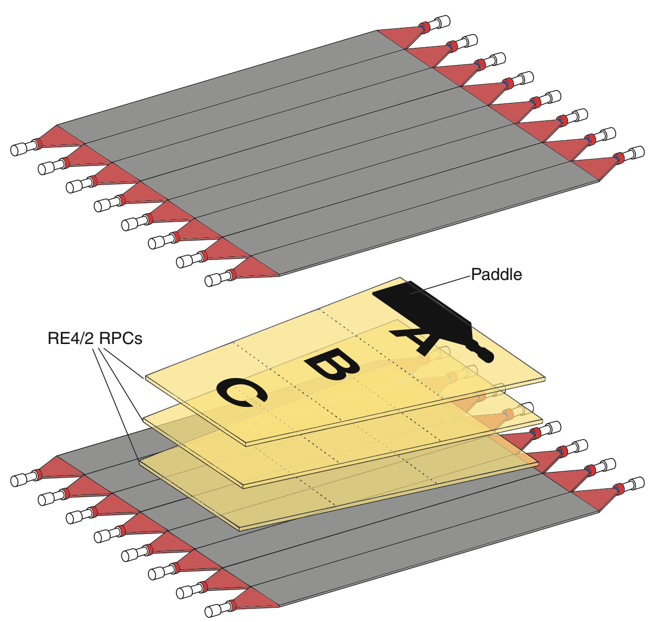

Figure 6. Geometry for the RE4/2 RPC.

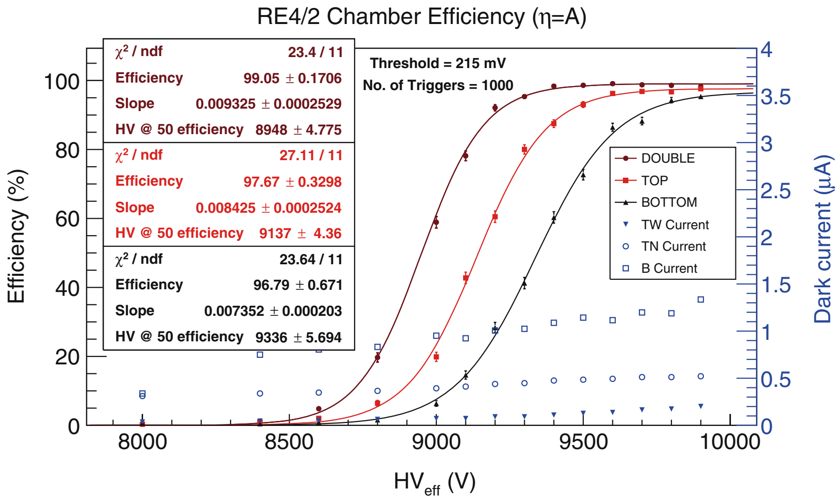

Figure 7. Sample efficiency plot for an RE4/2 RPC using the paddle covering the A section (η = A), for the DOUBLE, TOP and BOTTOM configurations.

Figure 8d shows the distribution of time of the signals from the 12th strip of the CMS RE4/2 RPC in section A with respect to the time of the trigger. The value of sigma is ∼1.7 ns. From figure 9, we can see different regions corresponding to the signals. An interval which spans the RPC signal region is chosen and the hits occurring outside the interval are considered as noise for that particular strip or channel. Noise rate is expressed per unit area of the RPC and is typically <1 Hz/cm^2 at an effective voltage of 9.4 kV.

All the CMS RPCs assembled and characterized show similar behaviour in terms of efficiency, cluster size, strip profile and noise rate. More information regarding the QC protocols and chamber performance statistics is given in ref. [7].

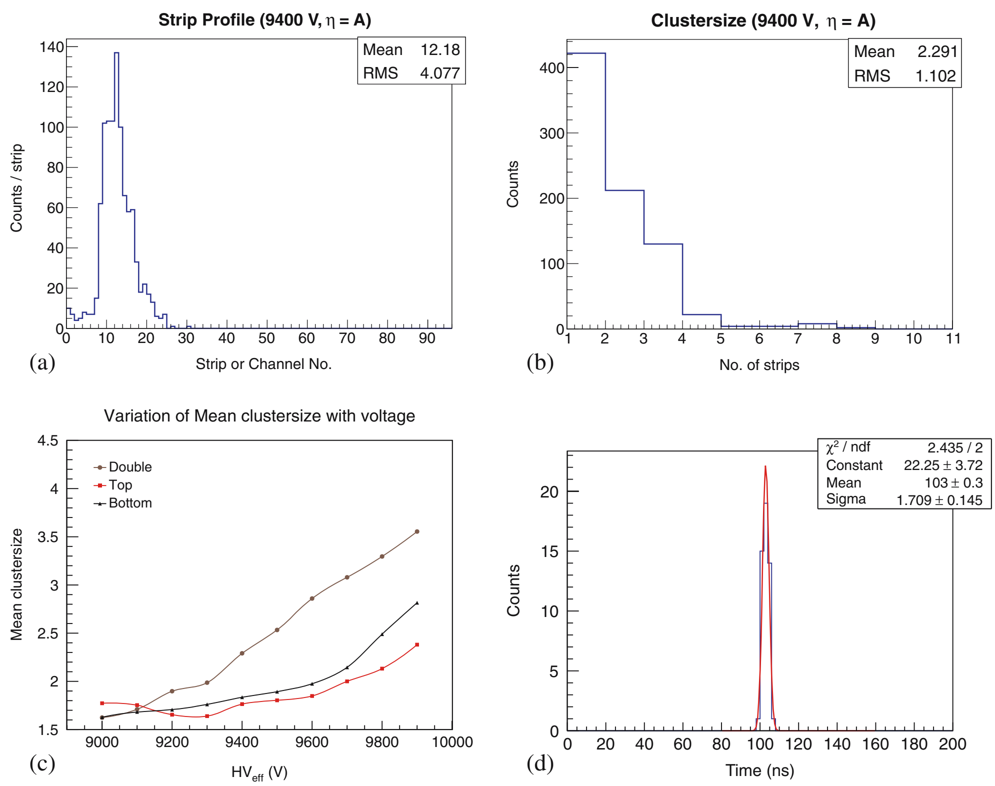

Figure 8. (**a**) Strip profile for the RPC at 9400 V (η = A, DOUBLE), (**b**) cluster size for the RPC at 9400 V (η = A, DOUBLE), (**c**) variation of mean cluster size with voltage and (**d**) distribution of the time interval between the signal of the 12th strip and the trigger. Plots shown are for η = A and DOUBLE configurations.

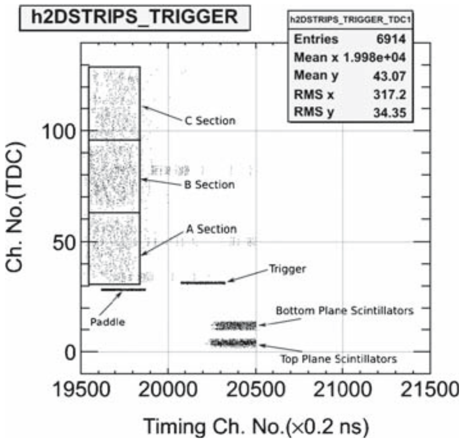

Figure 9. Timing distribution of signals.

3.2 *Glass RPC*

The glass RPC is for the R & D towards INO, muon tomography and related experiments. The gas gap is square in shape, is of 1 m^2 area and procured from KODEL, South Korea. Glass electrode is 3 mm thick and the electrode spacing is 2 mm. The surface resistance of the conductive graphite coating is 1 MΩ/square. It has two square read-outs made of G10 fabricated by a local company in Mumbai, with 32 strips of copper each 2.8 cm wide and 1 m long. The gap is sandwiched between the read-outs. The read-outs are placed orthogonal to each other so that one can have position information as XY coordinates. Gas composition is the same as in RE4/2 RPC, with the absence of relative humidity component. Illustration of the set-up is shown in figure 10.

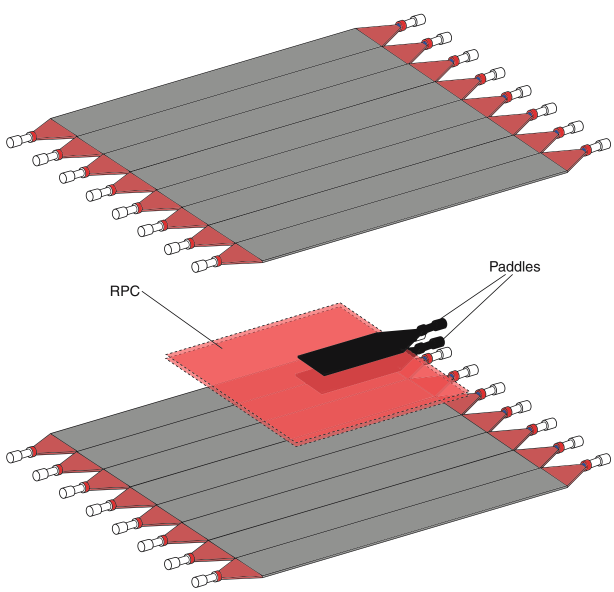

Figure 10. Glass RPC in the hodoscope.

The bulk of electronics, especially commercial NIM discriminators and translators needed for a stack of six such RPCs = 6 × 64 = 384 channels, will be too much. So, an application-specific integrated circuit (ASIC)-based front-end solution is being developed indegenously by Electronics Division, BARC, which will amplify, discriminate and provide output from the RPC directly in the LVDS or ECL format.

Preamplifier boards described in §2 have an input impedance of 50 Ω. Theoretical estimate of the impedance of the read-out strip yields a value of ∼5 Ω. Using 5 and 50 Ω resistance combinations, the impedance of the strips were matched to that of the preamplifier. Threshold was set at 30 mV and the gain was ∼80.

Four middle scintillators of the top and bottom planes are used in coincidence with two small scintillator paddles for the trigger. Paddles were placed one above and the other below the RPC. We chose this configuration (4-fold) to do a preliminary measurement of

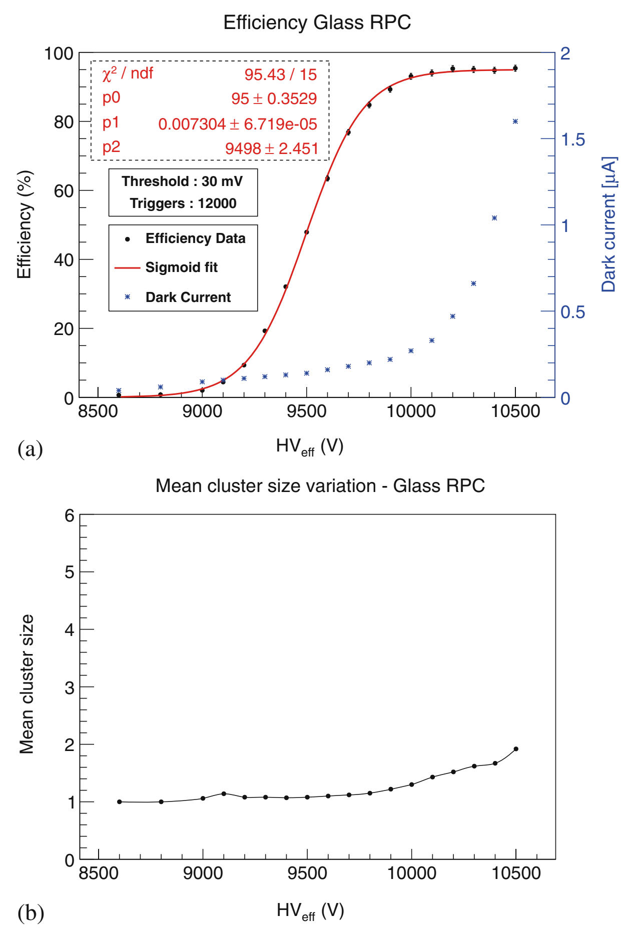

Figure 11. (**a**) Efficiency of the glass RPC at a threshold of 30 mV and (**b**) variation of mean cluster size of the glass RPC with voltage.

the efficiency and cluster size of the glass RPC. As the paddle width is only 18 cm, inclusion of a second paddle of the same dimension constrains the geometry to only six strips.

Efficiency and cluster size plots for the glass RPC are shown in figures 11a and 11b respectively. From figure 11a, we can notice that the plateau occurs at the knee region of the rising dark current which is expected. Efficiency of 95% is obtained. Mean cluster size remains below 2.

4. Conclusions

The hodoscope composed of 16 scintillators with double PMTs is fully operational. VME DAQ system was implemented by adapting the CERN-based software and CMS-RE4/2 RPCs were assembled, characterized and dispatched to CERN, where they were installed and commissioned in the 4th end-caps in 2014. During the ongoing $p-p$ collisions (Run 2) at 13 TeV, they are crucial in providing the trigger for the CMS experiment with increased efficiency. Good preliminary results have been obtained from glass RPC.

The CMS bakelite RPCs show better efficiency compared to glass RPC in the double configuration. This is because it has two layers of gas gaps sandwiching the read-out. Signals from both layers add to give a better signal. For a given event, if a gap in one layer does not produce a signal, the other layer will compensate for it. The probability of both layers not producing a signal is very small. Glass RPC having a single gas gap is expected to show slightly lesser efficiency.

From our experience with bakelite RPCs of the CMS end-cap, we see that handling, assembly and transportation of bakelite RPCs is far superior compared to glass. Keeping these things in mind, we have ordered 1 m $\times$ 2 m bakelite gaps from General Tecnica, Italy for benchmarking and will be simultaneously developing 1 m $\times$ 2 m bakelite gaps and RPCs in India.

Until now the hodoscope was being used only for RPC characterization. Now that we have sufficient TDC channels (728) and ASIC-based front-end is being developed, by assembling more RPCs, we plan to perform studies on gas mixture, timing and muon tracking for R & D towards INO, muon tomography and related experiments.

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