Rate-capability study of a four-gap phenolic RPC with a $^{137}$Cs source

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ABSTRACT: In this paper, we report on the systematic rate-capability study of four-gap phenolic resistive plate chambers (RPCs), with cosmic muons and gamma rays emitted from a $^{137}$Cs source. A prototype four-gap RPC with a gap thickness of 1.06 mm has been constructed with 2-mm thick phenolic high-pressure-laminated (HPL) plates. A 32-channel front-end-electronics board, which has been developed for the operation of the current double-gap RPCs in the CMS experiment, was used to digitize the detector signals of the prototype RPC, with charge thresholds of 80, 130, and 170 fC. The cosmic muons were reliably measured with efficiencies of higher than 95%, at a maximum gamma-hit rate of 5 kHz cm$^{-2}$. The present research confirms that the use of the current four-gap phenolic RPCs is advantageous to the high-$\eta$ triggers in CMS, by virtue of the high rate capability.

KEYWORDS: Resistive-plate chambers; Trigger detectors

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$^{1}$On behalf of the CMS collaboration.
1 Introduction

Resistive plate chambers (RPCs) of the Compact Muon Solenoid (CMS) detector have played an important role in the discovery of the Higgs boson in the Large Hadron Collider (LHC) experiment [1, 2]. In spite of the successful operation of the current CMS RPC system with a pseudorapidity coverage of $|\eta| < 1.6$, an extension of the RPC detection has been intensively addressed in the past years, which will enhance the muon trigger efficiency up to $|\eta| = 2.4$.

To achieve the desired muon-trigger performance in the LHC collision runs with a maximum luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$, the required rate capability of the present CMS double-gap RPCs was $1 \text{kHz cm}^{-2}$ [3]. However, in the future LHC experiment, when the luminosity of the LHC beam increases to a level of $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, the maximum background rate to be drawn in the RPCs at the ME1 station ($1.6 < |\eta| < 2.4$) would exceed $1 \text{kHz cm}^{-2}$ near the maximum $\eta$ division.

Furthermore, the detector current drawn in unit area of the present CMS double-gap RPCs is about $300 \mu\text{A m}^{-2}$ at a particle rate of $1 \text{kHz cm}^{-2}$, which far exceeds the practical limit that guarantees longevity in the detector operation [4, 5]. As discussed in the previous research [6], magnitude reduction of the avalanche pulses will be the best choice for the new high-$\eta$ trigger RPCs in the CMS experiment. In order to prove the detector performance of the four-gap RPC using a 32-channel front-end-electronics (FEE) board that has been developed for the operation of the current CMS RPCs, a prototype four-gap RPC was manufactured with phenolic high-pressure-laminated (HPL), and tested with cosmic muons and gamma rays emitted from a $^{137}$Cs gamma-ray source.

In section 2, we briefly describe the construction of the prototype four-gap RPC module in the present research. The digitizations of the RPC pulses in the FEE board, and the electronics setup to examine the prototype RPC are explained in section 3. The performances of the prototype RPC for the detection of cosmic muons with, and without, intensive gamma-ray hits, are described in detail in section 4. Finally, the conclusions for the performance of the phenolic four-gap RPC are summarized in section 5.
2 Construction of the prototype four-gap RPC

A four-gap RPC is composed of two bi-gaps and a strip panel, as described in the previous report [6]. For the present research, a new panel-shape four-gap RPC with an active area of $45 \times 45 \text{ cm}^2$ was manufactured with 2-mm-thick phenolic HPL. The thickness of the gaps supported by circular spacers was $1.06 \pm 0.15 \text{ mm}$. The signal plane laid between the two bi-gaps was composed of 32 copper strips with 14-mm pitches.

A few HPL samples of a size of $20 \times 20 \text{ cm}^2$ were cut out of the HPL panel to measure their bulk resistivity. The mean value of the bulk resistivity of the HPL samples was measured as $2.0 \times 10^{10} \Omega \cdot \text{cm}$ at $T = 20^\circ\text{C}$. The bulk resistivity of the resistive plates (here, HPL panels for phenolic RPCs) can also be obtained by measuring the total resistance of the RPC gaps by operating the RPC with high-rate gamma hits [7]. The effective high voltage across the RPC gaps becomes saturated and insensitive to the further increase of the applied high voltage as the gamma-hit rate approaches the rate capability limit of the detector. The saturation of the gap conductivity allows us to measure the resistance of the constituent HPL plates in the RPC. The valued bulk resistivity of the HPL normalized to $T = 20^\circ\text{C}$ was $2.67 \times 10^{10} \Omega \cdot \text{cm}$.

![Prototype four-gap RPC equipped with a 32-channel CMS FEE board.](image)

3 Experimental setup

Figure 2 shows the diagram for the electronics setup to examine the operational properties of the four-gap RPC, at gamma-hit rates ranging up to a maximum of $5 \text{ kHz cm}^{-2}$. As figure 1 shows, signals arising in 32 detector strips were transferred to a 32-channel FEE board, via 50-Ω coaxial cables. The low-voltage-digital-signal (LVDS) outputs of the FEE board were properly delayed, and transferred to a 64-channel multihit time-digital-converter (TDC), using 20-m-long 34-pin twist-pair cables, for a common-start-mode data acquisition. The maximum measurable time, the countable hits per channel, and the time resolution of the TDC were $64 \ \mu\text{s}$, 16 hits, and 1 ns, respectively.
Cosmic muons were triggered by a double coincidence of 10-cm-thick plastic scintillators each equipped with photomultipliers (Hamamatsu model H2431). The scintillator signals were digitized with a 30-mV voltage threshold, and fed into the TDC ‘Start’. Data for noises and gamma hits were selected for 16 µs, by 1-kHz clock trigger signals provided by a 2-GHz pulse generator.

Figure 2. Electronics setup to examine the prototype RPC with cosmic muons and gamma rays.

4 Results

The gas mixture to test the prototype four-gap RPC was composed of 95.2% C_2H_2F_4, 4.5% i-C_4H_{10}, 0.3% SF_6. Water vapour of approximately 0.3% (mass ratio) was added to the gas mixture, in order to maintain the constant bulk resistivity of the HPL used in the prototype RPC. The applied high-voltage (HV_{app}) values were converted to effective values (HV_{eff}), under the standard conditions, of P = 1013 hPa, and T = 293 K as explained in [6].

Firstly, the prototype RPC was horizontally placed and tested, to obtain the prime detection properties for muons. The digitization thresholds of 140, 195, and 220 mV for the input pulses of the FEE board correspond to charge thresholds of 80, 130, and 170 fC, respectively. The left-hand figure in figure 3 shows efficiencies (ε) and streamer probabilities (N_{st}) measured at digitization thresholds of 80 (full circles), 130 (open circles), and 170 fC (full triangles) as functions of HV_{eff}. N_{st} was defined as the ratio of the muon events with stripcluster sizes (C_s) of larger than 6 to the total number of the efficient events. As shown in the left-hand figure in figure 3, the HV_{eff} where ε reaches 0.95 for the data measured at 80, 130, and 170 fC are 11.24, 11.66, and 11.83 kV, respectively. The choice of the lower threshold is, therefore, fairly conducive to reduce the operational high voltage for the detection of muons. On the other hand, the increase of N_{st} with HV_{eff} for the data measured at 80 fC is significantly steeper than the one measured at 130 or at 170 fC. In the right-hand figure in figure 3, the mean strip-cluster sizes of the avalanche events for the muons, <C_s>, measured at the digitization thresholds of 80 (full circles), 130 (open circles), and 170 fC (full triangles) are shown together with the efficiencies as functions of HV_{eff}. <C_s> at ε = 0.95 for the data measured at 80 fC, 2.24, is significantly larger than the one measured at 130 (1.98) or 170 fC (1.94).
The detection properties of the prototype four-gap RPC at high background rates were examined by using a 200-mCi $^{137}$Cs gamma-ray source. The actual activity of the 12 year-old source was estimated as 154 mCi. In order to maximize the incident flux of the 661.7-keV gamma rays, the prototype RPC was vertically installed at a distance of 28 cm from the source position, as shown in the left-hand figure of figure 4. The mean incident angle of the muon tracks intersecting the prototype RPC was about $80^\circ$, with respect to the normal direction. Thus, the energy deposited by the single muon track is expected to be larger than the one for the previous measurement at the horizontal position (figure 3), by about a factor of 5. As the result, the position of the muon efficiency plateau in HV$_{\text{eff}}$ was about 300 V lower, than the one for the data shown in figure 3. Moreover, the strip-cluster sizes of the muon events were inevitably magnified, due to the same geometrical reason. The digitization threshold for muon and gamma pulses was set to 130 fC. The right-hand figure in figure 4 shows efficiencies ($\epsilon_{\mu}$) (circles) and mean strip-cluster sizes ($\langle C_s,\mu \rangle$) (triangles) for the muons measured with (open) and without (full) the gamma hits. The rate of the gamma hits measured at HV$_{\text{eff}} = 11.96$ kV was 2.97 kHz cm$^{-2}$. The data set measured with a gamma-hit rate of about 3 kHz cm$^{-2}$ (open symbols) is clearly shifted toward higher operating voltage with respected to the case of no irradiation (full symbols).

![Figure 3](image-url)

**Figure 3.** Efficiencies ($\epsilon$) and streamer probabilities ($N_{st}$) for muons measured at digitization thresholds of 80 (full circles), 130 (open circles), and 170 fC (full triangles) as functions of HV$_{\text{eff}}$ on the left and $\epsilon$ and mean strip-cluster sizes ($\langle C_s \rangle$) with the same notations in the right. The solid, dashed, and dot lines in both figures were drawn to guide the eye.

Figure 5 shows $N_{\text{d}}$ (left) and mean arrival times of signals ($t_{\text{mean}}$) (right) for muons marked by triangles and shown together with $\epsilon_{\mu}$ (circles) as functions of HV$_{\text{eff}}$. The comparison of the data measured with (open symbols) and without the gamma hits (full symbols) manifests the same trend that has been observed in figure 4.

In figure 6, the gamma-hit rate $N_{\gamma}$ (open circles) and the detector current $i$ (full triangles) are plotted with the muon efficiency $\epsilon_{\mu}$ (full circles) as functions of HV$_{\text{eff}}$. The maximum $N_{\gamma}$ for the 661.7-keV gamma rays predicted by a GEANT4 program was 5.7 kHz cm$^{-2}$ (indicated by a dash line). As figure 6 shows, the detector current induced by the gamma hits was measured at
Figure 4. Prototype four-gap RPC vertically installed at 28 cm from a $^{137}$Cs source (left) and $\varepsilon_{\mu}$’s (circles) and $<C_{s,\mu}>$’s (triangles) for muons measured with (open) and without (full) the gamma hits. The solid and dashed lines in the right figure were drawn to guide the eye.

Figure 5. $N_{st}$ (left) and mean arrival times of signals ($t_{mean}$) (right) for muons marked by triangles and shown together with the efficiencies (circles). The data marked by the open and full symbols were measured with and without the gamma hits, respectively. The solid and dashed lines were drawn to guide the eye.

12.17 kV, and at the rate of 3.60 kHz cm$^{-2}$, was 14 $\mu$A. The active area of producing the gamma hits was measured as 500 cm$^2$. Thus, the detector current drawn per unit detection area and per unit gamma-hit rate of kHz cm$^{-2}$, measured in the mid of the $\varepsilon_{\mu}$ plateau of the four-gap RPC (12.17 kV), is expected to be about 80 $\mu$A m$^{-2}$ (kHz cm$^{-2}$)$^{-1}$; this is about one third of that drawn in a typical double-gap RPC [6].
Figure 6. $N_\gamma$ (open circles) and the detector current $i$ (full triangles) plotted with the $\epsilon_\mu$ (full circles) as functions of $HV_{\text{eff}}$.

Figure 7. Distributions of strip-cluster sizes for muons and gamma hits, measured at $HV_{\text{eff}} = 11.76$ (left), and 12.17 kV (right).

Figure 7 shows the distributions of mean strip-cluster sizes for muons $<C_{s,\mu}>$ and for gamma hits $<C_{s,\gamma}>$ measured at 11.76 (left), and 12.17 kV (right). $<C_{s,\mu}>$ and $<C_{s,\gamma}>$ were 3.54 and 1.41 at 11.76 kV, and 4.16 and 1.55 at 12.17 kV, respectively. The large discrepancy in the strip-cluster sizes between the muons and the gamma hits, as observed in figure 7, can be understood by the following reason: while the high-energy muon tracks create signals in all the gaps laid in the
four-gap RPC, the 661.7-keV gamma rays induce Compton electron signals in the individual single gaps. The difference between the muons and the neutral particles implies that the digitization threshold for the present for-gap RPC can be properly ‘fine-tuned’ for an optimal detector performance, as well as for effective suppression of the neutral-particle background hits (bremsstrahlung photons and soft neutrons), in the RPC data.

5 Conclusions

In the present research, the rate capability of a four-gap phenolic RPC was tested using the FEE board standardly used in CMS/RPCs and a $^{137}$Cs gamma source. When in future the luminosity of the LHC beam will increase to a level of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, the use of RPCs constructed with an improved rate capability will be conducive for the RPC system in $|\eta| > 1.6$. We drew the following conclusions for the present four-gap RPC:

1. The usable size of the muon efficiency plateau for the four-gap RPCs, when digitized with the threshold of 130 fC, was about 800 V, which was relatively wider than that obtained in the previous tests [8]. The wider efficiency plateau is conducive to the reliable maintenance of detectors in the future CMS RPC system.

2. The shift of the overall detector characteristics in the effective high voltage due to gamma hits of about 3 kHz cm$^{-2}$, was measured as about 300 V.

3. The muon efficiency reliably exceeded 0.95 even when the gamma-hit rate present together with the muons reached 5 kHz cm$^{-2}$.

4. The detector current per unit area and per unit background rate of kHz cm$^{-2}$ drawn in the four-gap RPC, measured in the mid of the muon-efficiency plateau, was about 80 $\mu$A m$^{-2}$ (kHz cm$^{-2}$)$^{-1}$; this was about one third of that drawn in a double-gap RPC.

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