Charge distribution dependency on gap thickness of CMS endcap RPC

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ABSTRACT: We report on the results of a systematic study for the charge distribution dependency of CMS Resistive Plate Chamber (RPC) on the gap thickness. Prototypes of the double-gap RPCs with six different gap thicknesses ranging from 1.0 to 2.0 mm in 0.2 mm steps were built with 2 mm-thick phenolic high-pressure-laminated (HPL) plates. The efficiencies of the six gaps were measured as a function of the effective high voltages. We report that the strength of the electric field of the gap decreased as the gap thickness increased. The charge distribution in the six gaps was measured, and the space charge effect is seen in the charge distribution at high voltages near 95% efficiency. The logistic function is used to fit the charge distribution data, and smaller charges than charges within the current 2.0 mm gap are produced within smaller gas gaps. The digitization threshold should also be lowered to utilize these smaller charges.

KEYWORDS: Gaseous detectors; Resistive-plate chambers; Trigger detectors

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1 Introduction

The resistive plate chambers (RPCs) used as muon trigger detectors in CMS experiment have been demonstrated to have good trigger performance in LHC environments. The CMS RPC trigger system can be divided into two parts according to the RPC locations: the barrel region with six trigger stations and the forward Endcap region (RE) with four stations, called RE1–RE4 [1].

Within each RE station, there are three concentric sections that divide the RE in terms of the pseudorapidities. Until now RE1/2, RE1/3, RE2/2, RE2/3, RE3/2, RE3/3, RE4/2 and RE4/3 have been installed to comprise the RPC trigger system with pseudorapidity coverage of the RPC trigger up to $|\eta| < 1.6$ [2, 3].

The plan within the CMS Phase II Upgrade is to install all remaining RE1/1, RE2/1, RE3/1 and RE4/1 for full trigger coverage. The current CMS plan is to use GEM technology for RE1/1, but the conventional RPC technology seems applicable to the remaining sections of the CMS RPCs. Current R&D on CMS RPCs is to find a detector solution especially for RE3/1 and RE4/1, covering $1.6 < |\eta| < 2.1$ [4].

RE3/1 and RE4/1 need to have a rate capability of about 2 kHz/cm$^2$ in an expected background rate of 0.6 kHz/cm$^2$. The lower resistivity about $10^{10}$ Ωcm of the electrode allows to achieve a higher rate capability since the rate capability is inversely proportional to the value of the resistivity of the electrodes. Charge reduction is also a key to improve the higher rate capability. One way to obtain smaller charges is to reduce the gas gap thickness. The smaller charges also reduce the probability of aging due to the high-rate background, guaranteeing the longevity of the RPCs. However, the many advantages of smaller charges can only be achieved if a lower digitization threshold can be used [5].

The main theme of this paper is to show that both the smaller thickness of the RPC gaps and a low digitization threshold are required to utilize the advantages of smaller avalanche charges. However, lowering the digitization threshold requires new development of front-end electronics that are more sensitive than the current ones used for CMS-RPC operation. Therefore, we concentrate on investigating the dependency of the charge distribution on the gap thickness.
2 Efficiency in variation of gap thickness

Six RPCs with different gap thickness varying in 0.2 mm steps from 1.0 to 2.0 mm were built to study dependency of the charge on the gap thickness, as shown in figure 1. For the six RPCs with six different gap thicknesses, we measured the efficiencies and cluster sizes of cosmic muons as a function of the high voltages. The gas composition used in this work is 95.2% C$_2$H$_2$F$_4$ + 4.5% i-C$_4$H$_{10}$ + 0.3% SF$_6$.

The efficiencies of the gaps are measured with TDC, the charges of the gaps are measured with flash ADC, and the readout strip pitch is 20.0 mm. A simplified schematic view of the DAQ is shown in figure 2.

The applied high voltages are converted to the effective high voltages (HV) under standard conditions of $P = 1013$ hPa and $T = 293$ K. Figure 3 shows the efficiencies of the cosmic muons that were measured for the 2.0 mm-thick (right) and 1.0 mm-thick (left) double-gap RPCs as a function of the HV. The HV values yielding efficiencies of 95% and 50% measured for the six different RPCs are summarized in table 1.

As we reduce the gap thickness from 2.0 mm, which has been the standard CMS gap thickness, to 1.0 mm in steps of 0.2 mm, the values of HV at 95% and 50% of efficiencies decreased slower than of a linear rate, as shown in figure 4. However, the relationship between the gap thickness and the effective high voltages is expected to be linear.

We assumed a gap-thickness-dependent high voltage, $HV = Kg^\gamma$ for the effect of the gap thickness on the HV. Here, $g$ is the gap thickness while $K$ and $\gamma$ are the fitting parameters. For the values of two $K$ and $\gamma$, we fit the data shown in table 1 with the function shown in figure 4 [6].

$\gamma$ would have a value of 1 if the relationship between the gap thickness and the HV were linear, but we obtained a value of $\gamma$ of 0.73 and 0.78 for 95% and 50% efficiency, respectively. When we plot the electric field of the gap in terms of the gap thickness, it becomes more obvious that the

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**Table 1.** HVs measured at efficiencies of 95% and 50% for the six different RPCs. The error is 0.01 kV.

| Gap thickness (mm) | 1.0   | 1.2   | 1.4   | 1.6   | 1.8   | 2.0   |
|-------------------|-------|-------|-------|-------|-------|-------|
| $HV_{\varepsilon=0.95}$ (kV) | 5.38  | 6.16  | 6.94  | 7.71  | 8.47  | 9.17  |
| $HV_{\varepsilon=0.50}$ (kV) | 5.66  | 6.50  | 7.21  | 7.99  | 8.78  | 9.39  |
We understand it in terms of the first Townsend coefficient, where the avalanche amplification grows by the factor $e^{\alpha g}$ with $\alpha$ as the first Townsend coefficient and $g$ as the gap thickness. Our operation mode is the avalanche mode in which our signal size is above the threshold and below the streamer signal. This means that our gas amplification is fixed within these ranges. As $g$ increases, $\alpha$ should decrease, and the strength of the electric field should also decrease, as shown in figure 5.
3 Charge distribution for the variation in gap thickness

We also measured the charge pulse distribution in six different gap thicknesses. Figure 6 plots charge measurements for the 2.0 mm and 1.0 mm gap thicknesses at various HV. For the 2.0 mm gap, at the lower HV of 8.96 kV in figure 6, the charge distribution is mostly populated near zero. As HV increases, the small charge distribution that had been mostly populated around zero moves to higher values with its distribution shape remaining intact, as shown for 10.02 kV in figure 6. These small charges are difficult to find at higher voltages. Since small charges are produced near the
Figure 6. Charge distributions at various HVs of 1.0 (2.0) mm gap in the two right (left) columns.

anode, this means that at higher voltages, the space charges have an effect near the anode, preventing smaller charges from being produced.

These trends can also be found in the charge distribution of the 1.0 mm gap. The charge distribution for the 1.0 mm gap is presented in the two right-hand columns in figure 6. As in the case of the 2.0 mm gap, the charge distribution is most popular near the zero at the HV of 5.27 kV. However, the smaller charges near zero at 6.14 kV diminish significantly. Four other remaining gaps also show the same trend as that of the charge distribution seen from the 2.0 mm and 1.0 mm gaps. From these observations, we can conclude that the smaller charges are not produced due to the space charge effect near the anode at higher voltages.

We also plot the mean charge together with the efficiency curve in terms of the HV in figure 7. The charges plotted with the logarithm show that the amount of induced charge collected by the pickup strip is proportional to the HV. However, the proportionality slope changes from a faster rise to a slower rise at around 9.4 (5.4) kV for 2.0 (1.0) mm gap thickness, as shown in figure 7.

The charge distributions from all six gaps follows this pattern and are similar to each other. However, one noticeable pattern is that the transition from a faster rising slope to a slower rising slope occurs at around the HV of the 95% efficiency for the 2.0 mm gap, but the transition started earlier at about 300 volts below the HV of 95% efficiency for the 1.0 mm gap. The transition from faster rising to slower rising at higher voltage, shown in figure 7, and the space charge effect near the anode, shown in figure 6 at the higher voltages, lead us to think about the charge saturation near the anode.

4 Charge distribution models

The mean values of the charge distributions for the six gas gaps at various HVs are plotted in figure 8. The avalanche models of the exponential charge growth don’t consider the presence of space charges, and this intuitive exponential growth cannot explain our charge distribution data. Therefore, we need the appropriate models to understand these charge distributions for the different
gaps. At least, there are some models to consider: the effect of the space charges on the shape of the charge spectra [7], a first principles simulation of the charge development from the [8], the charge saturation described within a logistic model [9] and a comprehensive treatment of the charge development in RPC [10].

The logistic function provides simple forms to fit the charge distributions. The mean charge distributions for the six gaps are fitted with the logistic function, and the fit results for the 2.0 mm gap and 1.0 mm gap are plotted in figure 9, where $v_0$ is the H.V at the half of the saturation value, $\alpha$ is a growth rate, $K$ is the saturation value and $v$ is the HV.

The logistic function describes the overall mean charge distribution as a function of HV reasonably well, as shown in figure 9. We noticed in the results of the fit summarized in table 2 that
Figure 9. The mean charge distribution of the 1.0 mm gap (left) and 2.0 mm gap (right) are fitted with the logistic function’s cumulative results.

Table 2. Summary of mean charge of six gaps as a function of HV.

| Gap (mm) | HV 95% (kV) | <q> (pC) | $V_0$(kV) in a logistic function |
|---------|-------------|---------|-------------------------------|
| 2.0     | 9.39        | 1.658 ± 0.108 | 9.36                        |
| 1.8     | 8.77        | 1.621 ± 0.072  | 8.80                        |
| 1.6     | 7.99        | 1.607 ± 0.080  | 7.91                        |
| 1.4     | 7.21        | 1.473 ± 0.069  | 7.05                        |
| 1.2     | 6.50        | 1.448 ± 0.049  | 6.36                        |
| 1.0     | 5.66        | 1.423 ± 0.079  | 5.62                        |

$v_0$ in the logistic function is very close to the beginning of 95% of efficiency, at which it is already saturated with space charges.

The transition points from faster rising to slower rising for all six gaps are related to the saturation due to space charges near the anode. However, the logistic model does not tell us where the transition point occurs. In the future, a more comprehensive model can describe not only the mean charge distribution, but also the location of the saturation due to the space charge.

5 Digitization threshold limiting the charge distribution

When the gap thickness is reduced from 2.0 mm to 1.0 mm, the amount of charge reduced is 18% of the 1.66 pC, as shown in table 2. This is because the digitization threshold value was set too high to utilize smaller charges produced in the smaller gas gaps. One scenario is that if the digitization threshold values could have been lowered much below the current value, we might have obtained a much smaller charge of around 0.5 pC than the 1.42 pC obtained with the threshold value of 1.0 mV. The charge distributions for the 2.0 mm gap and 1.0 mm gap in figure 7 support this scenario.
6 Conclusions

A systematic study investigated the dependency of the charge distribution on the gap thickness. The efficiencies of the six gaps are measured as a function of the HV, and the strength of the electric fields of the six gaps decreased as the gap thickness increased.

The distributions of the charges in the six gaps were measured and the space charge effect is seen in the charge distribution at higher voltages. The logistic function is used to fit the charge distribution of the six gaps.

As the gap thickness decreases, the amount of the pickup charge decreases. However, the reduction of the charge is not so much as expected due to the higher digitization threshold. A smaller avalanche charge can be utilized only by the combination of a smaller gap thickness and lower digitization threshold.

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