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Vallary Bhopatkar, Marcus Hohlmann, Aiwu Zhang

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Measurement of the Charge Induced on the Readout Strips of a GE1/1 Detector Prototype for the CMS Muon Endcap GEM Upgrade

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March 30, 2017

Abstract

Early in the second phase of the LHC program, Gas Electron Multiplier (GEM) technology will be implemented in the GE1/1 muon chambers for the region $1.6 <| \eta |< 2.2$ of the CMS muon endcap. A VFAT3 front-end chip is being designed to read out the GE1/1 detector that will provide binary hit output. The charge that is induced on the GE1/1 readout strips by minimum-ionizing particles is an important parameter that informs the design of the amplifier-shaper input stage of the VFAT3 chip. We have measured this charge distribution directly with a GE1/1-III prototype chamber read out with the pulse-height-sensitive APV25 chip and exposed to a mixed-hadron beam at Fermilab. When operating 50 V above the start of the efficiency plateau in an Ar/CO_2 70:30 gas mixture, i.e. with 3250 V applied to the drift electrode, the most probable value, mean value, and 99^{th} percentile value of the Landau distribution of the charge induced on a single strip are found to be 4 fC, 11 fC, and 115 fC, respectively. Measurements with a more economical readout structure with 128 zigzag strips per η-sector instead of the 384 strips per η-sector in the GE1/1 are also analyzed. When equipping the same GE1/1 chamber with a readout board that features such zigzag strips and operating the chamber in the same way as before, the corresponding measured values for most probable and mean values are 7 fC and 16 fC, respectively.

1 Introduction

One-meter-long GE1/1 triple-GEM[1] detectors will be installed in the $1.6 <| \eta |< 2.2$ region of the muon endcap in early in phase II of the LHC program, i.e. during the second long shutdown of the LHC. This installation will provide precise tracking and trigger information of the system due to the high spatial resolution of the detectors. GEM and Cathode Strip Chambers (CSC) together can discriminate lower p_T muon from higher p_T muons as they provide accurate measurements of the muon bending angle. As a result, the GEM plus CSC system will help to reduce soft muon rate at trigger-1 level substantially. For this detector system, the CMS experiment proposes VFAT3 readout electronics[2] which produces binary hit output for each readout strip. The VFAT3 chip has 128 channels which read out the analog signals from radial strips in the GEM detector. The chip provides "fast OR" fixed-latency trigger information and full granularity tracking information[3]. The matching of the dynamic range of the induced charge to the dynamic range of the chip input

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determines the quality with which the signal is read from each strip. Consequently, it is important to optimize the dynamic range of the chip with respect to the expected input charge. In the following sections, we present measurements of the most probable and mean strip charges and cluster charges as well as the 99^{th} percentile of the charge distributions to determine the requirement on the dynamic range of the input charge for the VFAT electronics.

2 Test chamber and measurement setup

We constructed a one-meter-long GE1/1 triple-GEM prototype detector (generation III) at Florida Tech and tested its performance at the Fermilab test beam facility in 2013. Details on the test setup and on the measured detector performance can be found in Refs.[4] and [5]. Here we briefly describe the main features of the prototype detector. It has 3,072 radial strips arranged along the azimuthal direction and distributed over eight η-sectors. Each sector has three standard Panasonic connectors connected to 384 strips. Overall, 24 APV25 hybrids[6] are used to read the analog signals from all readout strips using the RD51 Scalable Readout System as shown in Figure 1. The system gives pulse height information in terms of ADC counts. The prototype detector was operated with an Ar/CO_2 70:30 gas mixture at the test beam.

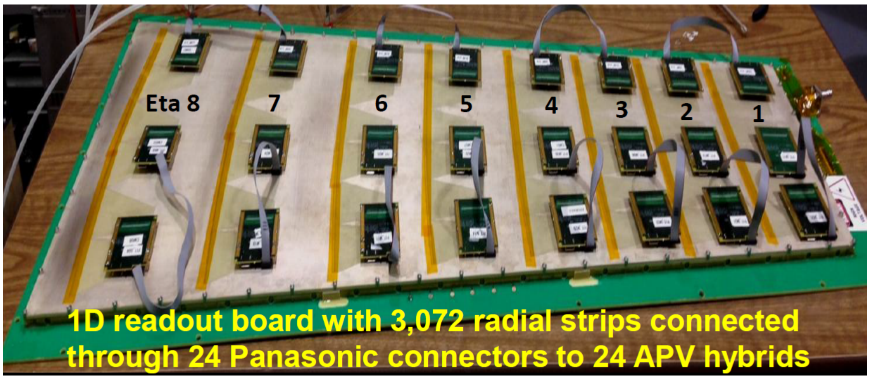


Figure 1: A GE1/1-III triple-GEM prototype detector with 24 APV25 hybrids connected to 24 Panasonic connectors.

3 Charge conversion from ADC to fC

Like the VFAT3 chip, the APV25 chip features 128 channels. Since we need to calculate the dynamic range for VFAT electronics, we need to convert charge from ADC counts to femtocoulombs (fC). For the precise conversion from ADC to fC, we use APV25 calibration data shown in Figure 2[7]. The APV25 shows linear charge response up to 800 ADC counts and for higher ADC counts the response becomes exponential. It is important to apply the non-linear correction for higher ADC counts ($\geq$800) for precise conversion.

Figure 3 shows how the calibration data are split into two parts; one for the linear correction for lower ADC counts ($<$800) and the other for the non-linear correction for higher ADC counts ($\geq$800). From linear and exponential fit parameters, the ADC-to-fC conversions can be expressed as follows:

$$Q \text{ (in fC)} = 0.03719 \times ADC \qquad \text{for ADC} < 800 \tag{1}$$

$$Q \text{ (in fC)} = \exp[1.8 + (0.0018 \times ADC)] \qquad \text{for ADC} \geq 800 \tag{2}$$

These factors give precise conversion values. We use these factors in the following charge distribution studies to express charge in both raw ADC counts and fC units.

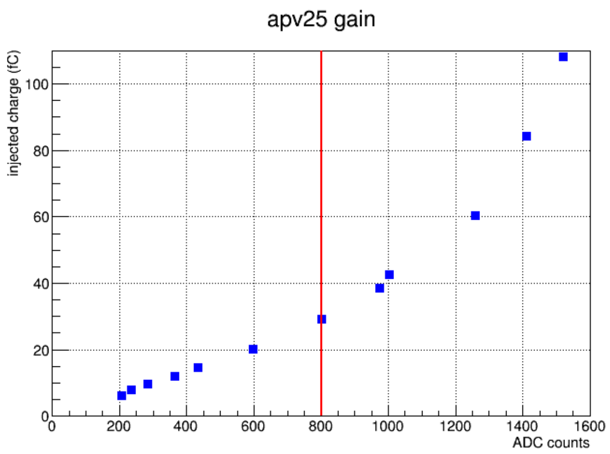
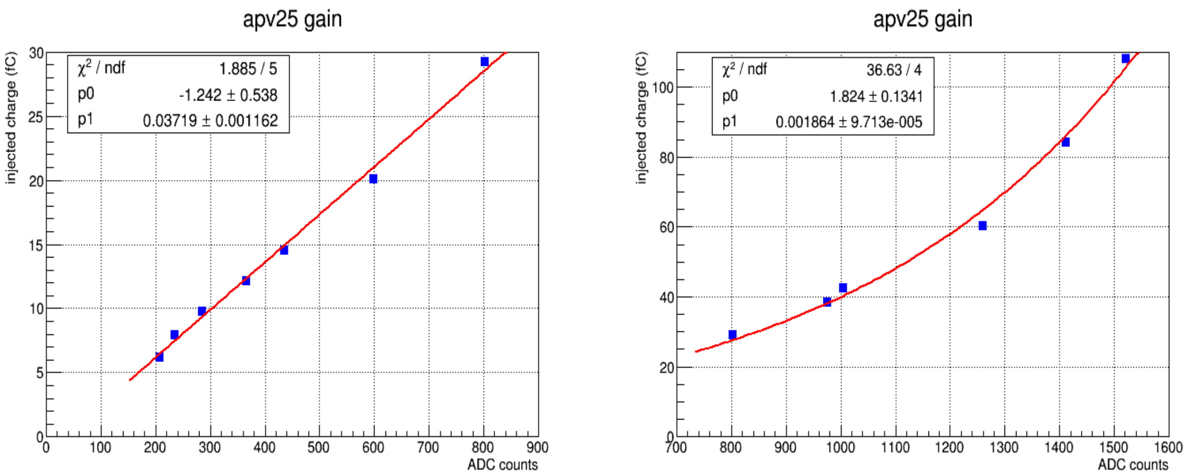


Figure 2: Charge to ADC count relation using APV25 calibration data[7].



(a) (b)

Figure 3: (a) ADC to fC conversion for lower ADC counts with linear fit. (b) ADC to fC conversion for higher ADC counts with exponential fit.

4 Charge Distribution Measurement for GE1/1 Detector

Performance characteristics of the GE1/1 detector were studied using Fermilab test beam data. Details on the setup and measurement program can be found in [4]. High voltage scan data are used for the charge distribution studies discussed here. For each voltage from 2900V to 3350V, the charge distribution is plotted and fitted with a Landau function. Fit parameters such as Most Probable Value (MPV), mean, and sigma are used for determining the range of the charges. The charge distribution is plotted for two cases, individual strip charge and total cluster charge. The following strip multiplicity of clusters were selected to compare the strip charge distribution: all strip clusters, $\geq$2-strip, 4-strip, 3-strip, 2-strip, and 1-strip only. Similarly, for total cluster charge all strip clusters, $\geq$2-strip clusters, and 1-strip clusters were used for plotting the distribution. Finally, the 99^{th} percentile of the maximum charge of the strip charge distribution is plotted to determine the required full dynamic input charge range for the VFAT electronics.

The cluster charge distribution is studied for this large-area triple GEM detector with two different readout designs, one with radial straight-strip readout as mentioned in section 3 and the other with radial zigzag strips. A radial zigzag strip readout board for a one-meter-long GEM detector was designed by Florida Tech[5]. We replaced the readout board of the GE1/1-III detector with this radial zigzag strip readout and tested its performance in the Fermilab beam test in Oct 2013. As seen in

Figure 4, this readout board has 1,072 radial zigzag strips distributed along the eight η-sectors and the signal can be read out from the entire chamber using only 8 APV25 hybrids. This readout board design is cost-effective because it reduces the number of channels for the readout electronics by a factor or three.

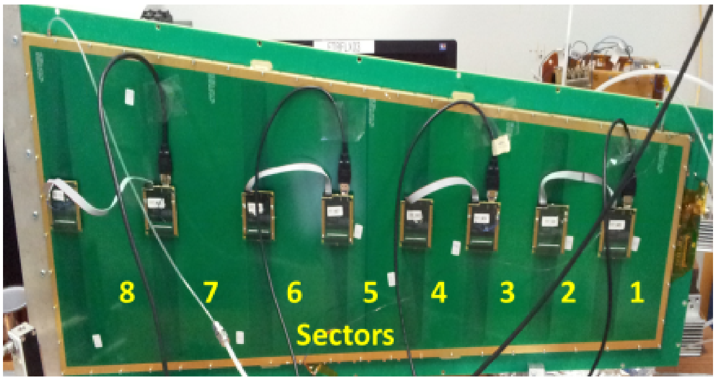
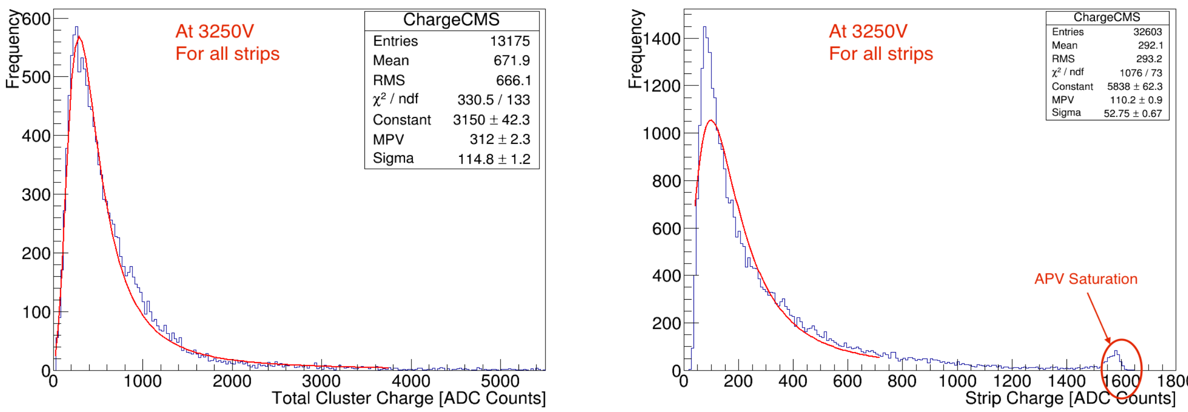


Figure 4: A large-area GEM detector with radial zigzag strips read out with 8 APV hybrids connected to 8 η-sectors through Panasonic connectors.

4.1 Charge Distribution Measurements

In the GEM detector, electron/ion pairs are produced due to ionization by traversing charged particles. Electrons produced in these pairs are called primary electrons. The total number of electrons produced in the ionization process follows the Landau distribution and the total charge produced in the detector can be characterized using its distribution parameters.

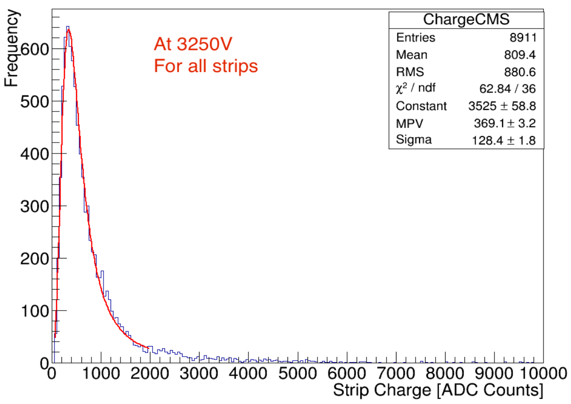


(a) (b)

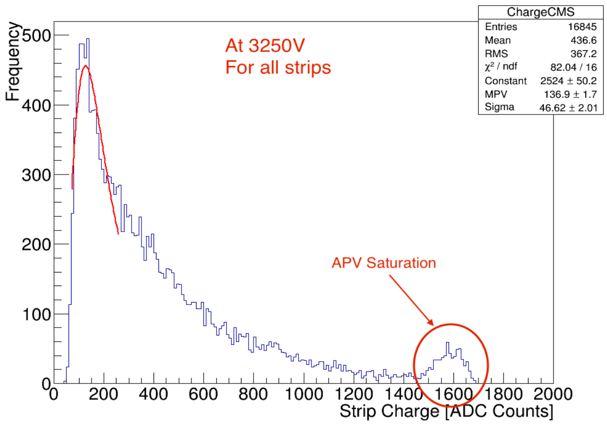
Figure 5: Charge distribution measured with GE1/1-III detector: (a) Total cluster charge distribution fitted with Landau function. (b) Individual strip charge distribution fitted with Landau function.

Figure 5 (a) shows the total strip cluster charge distribution for all strip clusters at the operating voltage of the detector, i.e. at 3250V. The distribution is fitted with a Landau function. The mean charge value is 671.9 ADC, which is equivalent to 25 fC. For Ar/CO_2 70:30 gas, the total mean number of primary electrons in the 3 mm drift gap is $< N_{tot} >$ = 29 electrons. This prototype detector was operated at a gain of around 8000. The expected mean charge is then $< N_{tot} > \times$ Gain = 232,000 e = 37 fC = 964 ADC counts. The measured mean cluster charge is within 27% of the calculated value.

The individual strip charge distribution is plotted in Figure 5 (b). In this distribution, APV saturation is observed around 1600 ADC counts and these saturated events are excluded from the calculation of the 99^{th} percentile of the maximum charge which determines the dynamic range of the input charge for VFAT electronics.



(a)



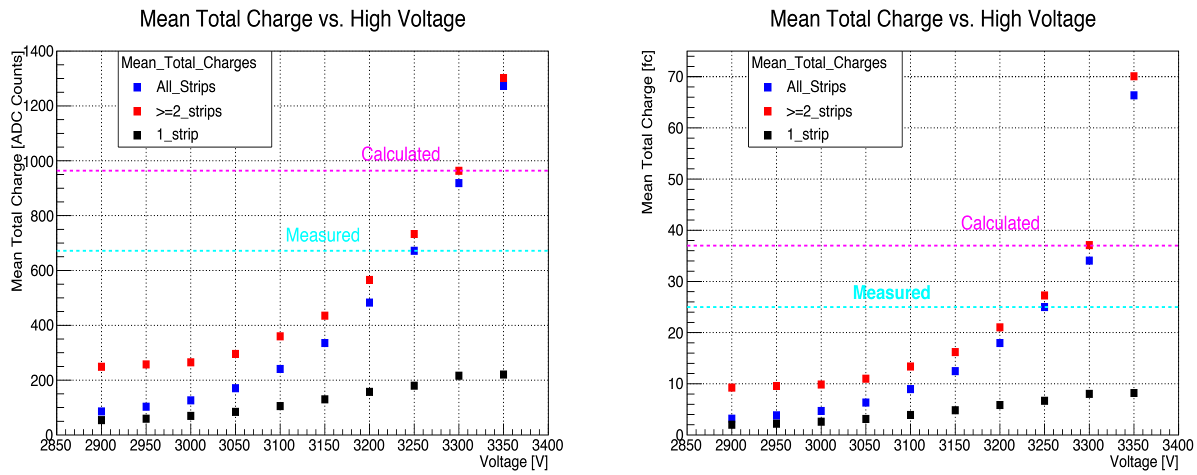
(b)

Figure 6: Charge distribution of GEM detector with radial zigzag strip readout: (a) Total Cluster charge distribution fitted with Landau function. (b) Individual strip charge distribution fitted with Landau function.

Similarly, the charge distribution is plotted for the GEM detector with zigzag readout board. Figure 6 shows total cluster charge and individual strip charge distributions. These distributions are again fitted with the Landau function and the resulting means, sigmas, and MPVs are plotted vs. drift voltage below. Since we are using Ar/CO_2 gas in the same proportion and with the same drift and transfer gaps in the detector as above, the calculation of the expected mean charge for this configuration is the same as above, i.e. 37 fC. From the Landau distribution of the total cluster charge, the measured mean charge for this detector at its operating voltage is about 26 fC, similar to the result for the straight strips. In Figure 6(b) saturation of APVs is again seen around 1600 ADC counts and these events are again excluded from the analysis.

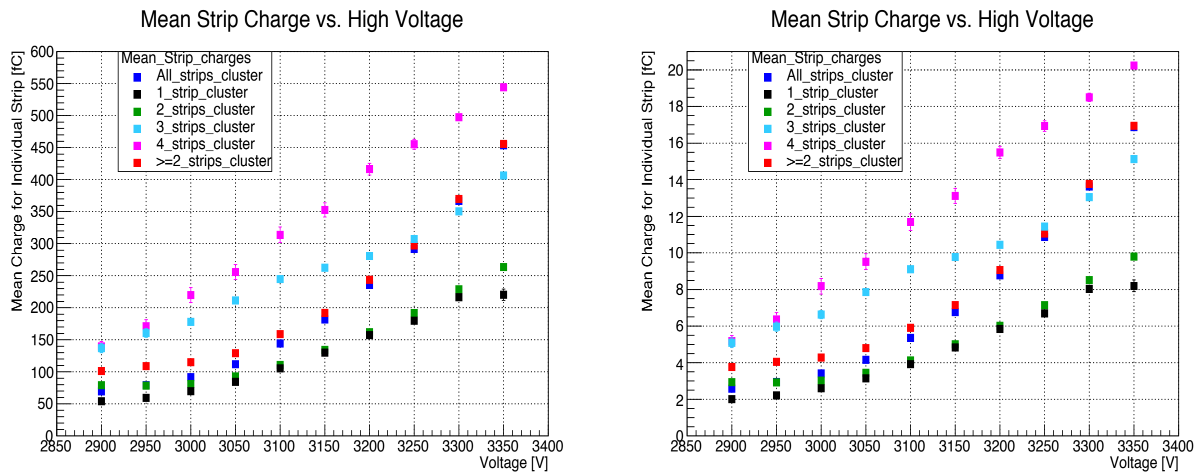
4.1.1 Mean Charge Distributions

The means of the charge distributions are plotted against the drift voltage using different cuts on the cluster strip multiplicities. Figures 7 and 8 show mean charges for the GE1/1 detector in ADC counts and fC units for clusters and individual strips. At 3250 V, the measured mean cluster charge is 25 fC, while the overall mean strip charge is 11 fC. This mean strip charge at operating voltage can be taken as the typical charge input for the electronics.



(a) (b)

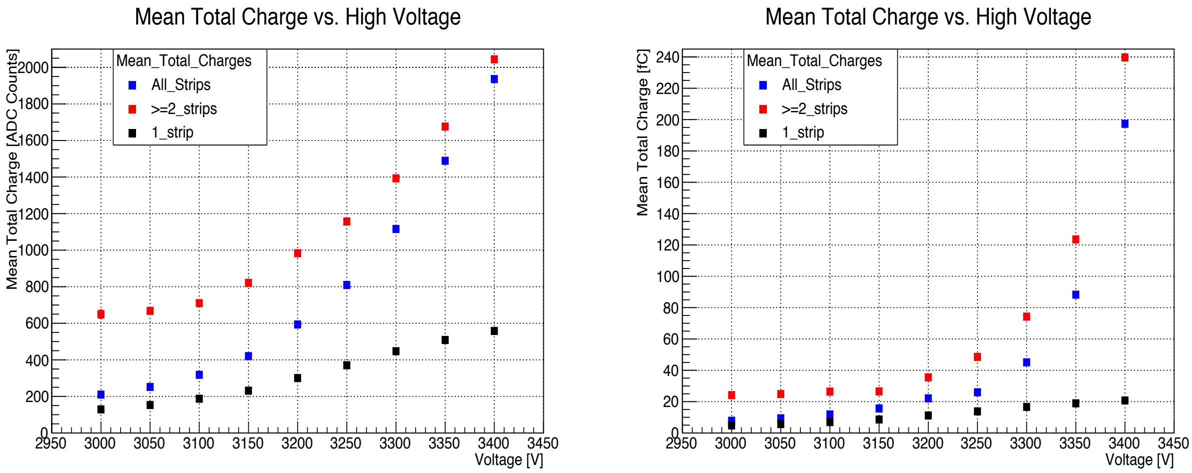
Figure 7: GE1/1 Detector: (a) Mean of total cluster charge in ADC units. (b) Mean of total cluster charge in fC.



(a) (b)

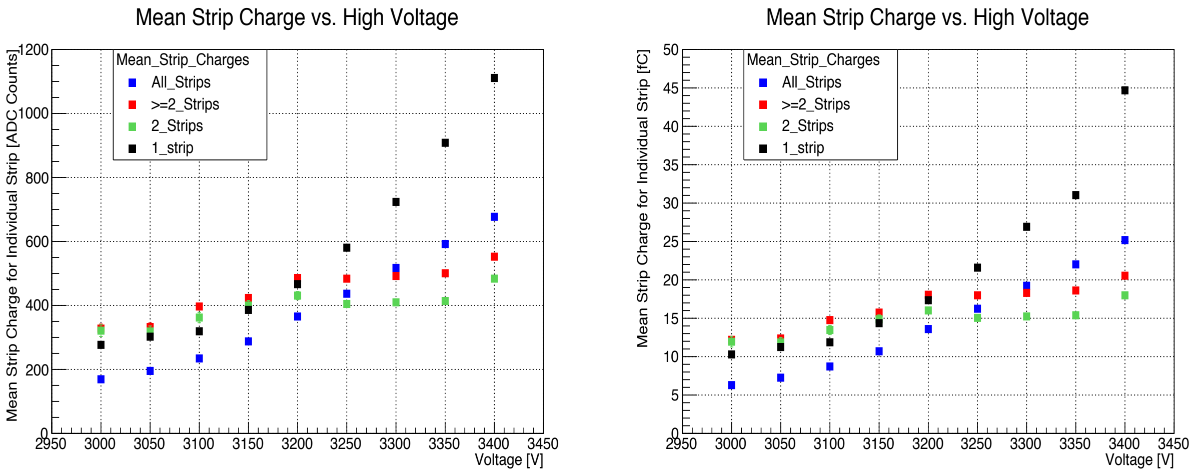
Figure 8: GE1/1 Detector: (a) Mean of strip charge distribution in ADC units. (b) Mean of strip charge distribution in fC.

Similarly, mean charge values from Landau fits are plotted against the drift voltage of the GEM detector with radial zigzag strip readout. Mean cluster charge and mean strip charge are shown in Figures 9 and 10, respectively. Mean charge value increases with higher drift voltage. In Figure 10 (b), mean strip charge is ∼26 fC at operating voltage. While the mean cluster charge is similar to what is observed with the straight-strip readout, the mean strip charge value for radial strps is higher than for straight strips because more charge is induced on an individual zigzag strip because it is wider.



(a) (b)

Figure 9: GEM detector with zigzag readout: (a) Mean of total cluster charge in ADC units. (b) Mean of total cluster charge in fC.

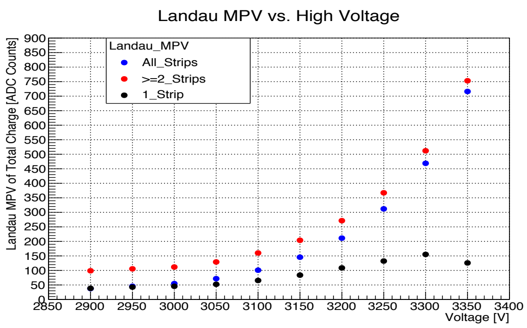


(a) (b)

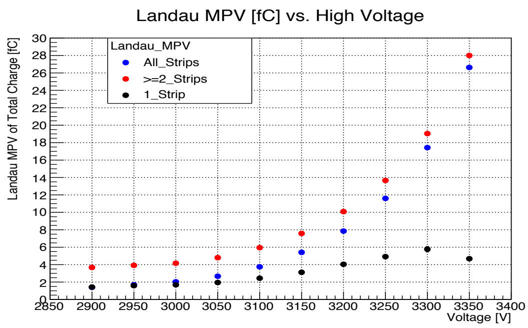
Figure 10: GEM detector with zigzag readout: (a) Mean strip charge distribution in ADC units. (b) Mean strip charge distribution in fC.

4.1.2 MPV and Sigma Distributions

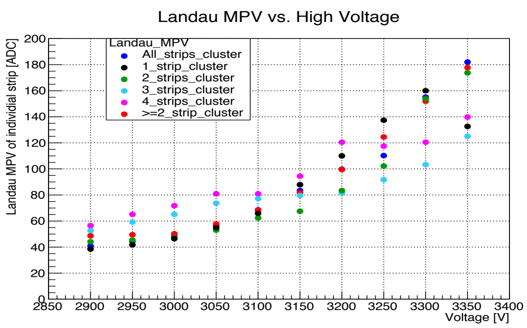
In this section, all Landau MPV and Landau sigma value plots for total cluster charge and strip charge distribution are summarized for reference. Figures 11 and 12 show MPV and sigma vs. drift voltage for the GE1/1 detector, while Figures 13 and 14 summarize corresponding plots for the GEM detector with radial zigzag strip readout.



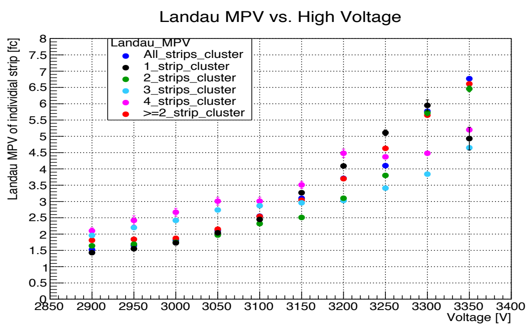
(a)



(b)

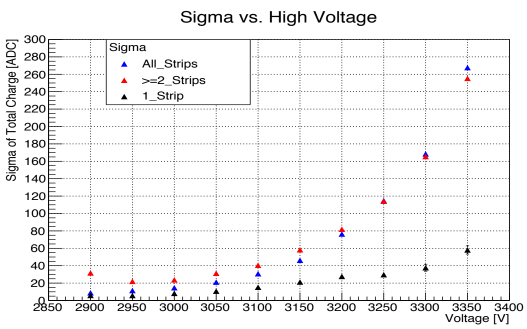


(c)

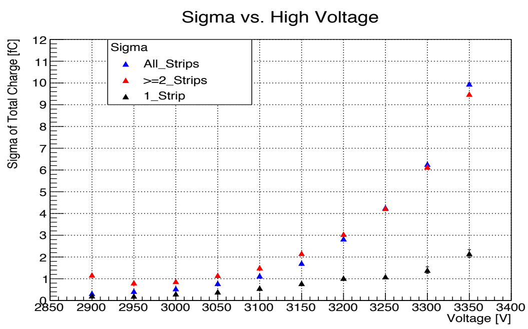


(d)

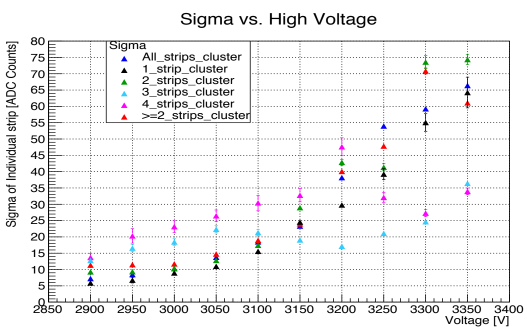
Figure 11: GE1/1 Detector: (a) MPV of total cluster charge distribution in ADC units. (b) MPV of total cluster charge distribution in fC. (c) MPV of strip charge distribution in ADC units. (d) MPV of strip charge distribution in fC.



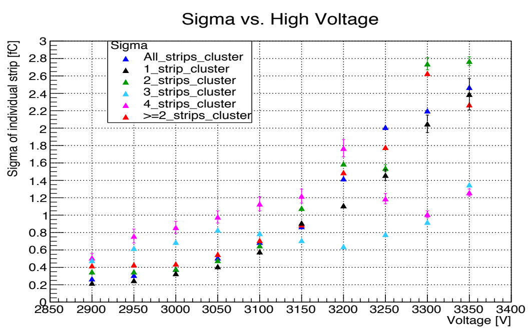
(a)



(b)

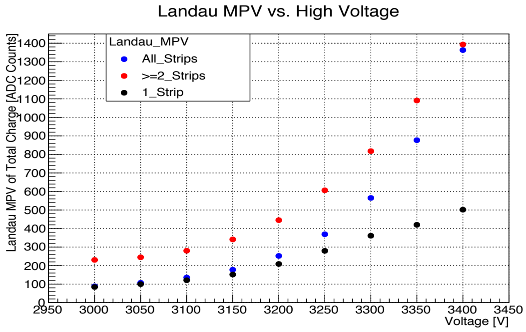


(c)

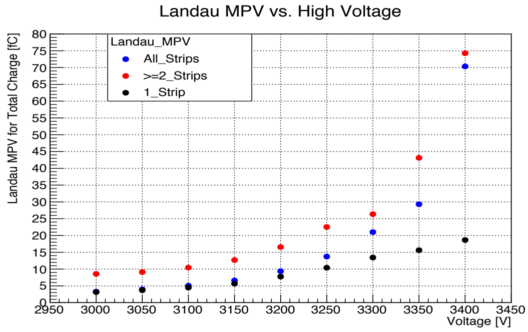


(d)

Figure 12: GE1/1 Detector: (a) Sigma of total cluster charge distribution in ADC units. (b) Sigma of total cluster charge distribution in fC. (c) Sigma of strip distribution in ADC units. (d) Sigma of strip charge distribution in fC.



(a)



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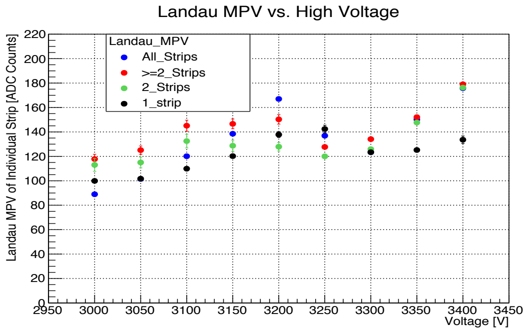
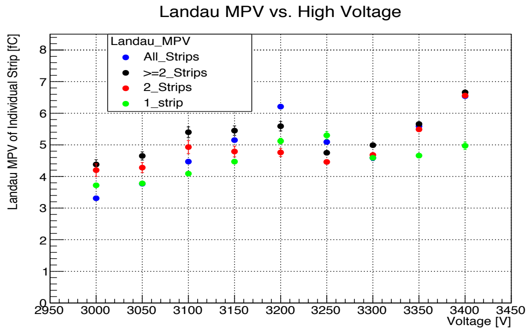
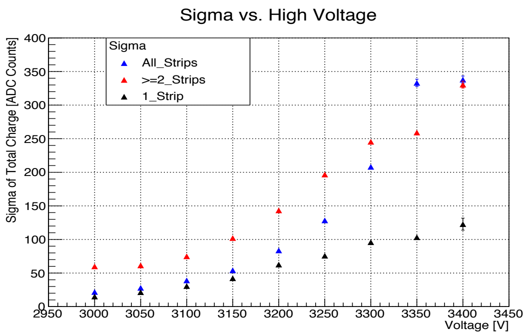


(c)

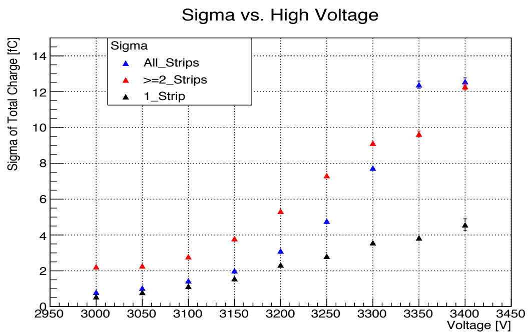


(d)

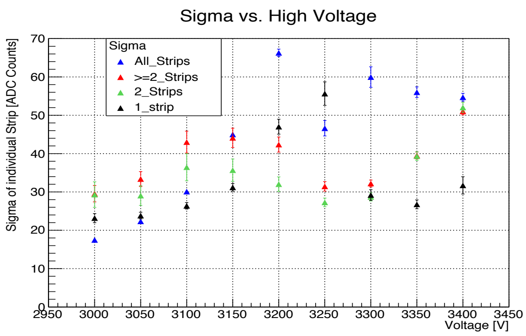
Figure 13: GEM Detector with radial zigzag strip readout: (a) MPV of total cluster charge distribution in ADC units. (b) MPV of total cluster charge distribution in fC. (c) MPV of strip charge distribution in ADC units. (d) MPV of strip charge distribution in fC.



(a)



(b)



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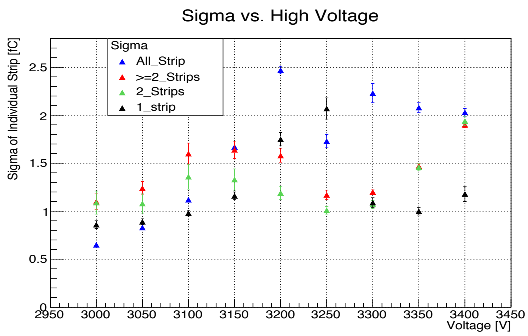
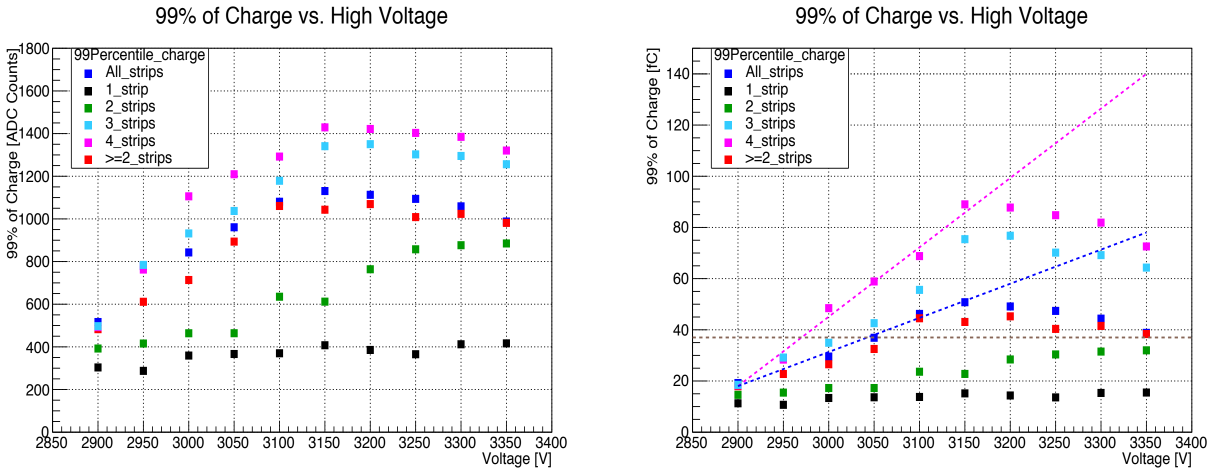


(d)

Figure 14: GEM detector with radial zigzag strip readout: (a) Sigma of total cluster charge distribution in ADC units. (b) Sigma of total cluster charge distribution in fC.(c) Sigma of strip distribution in ADC units. (d) Sigma of strip charge distribution in fC.

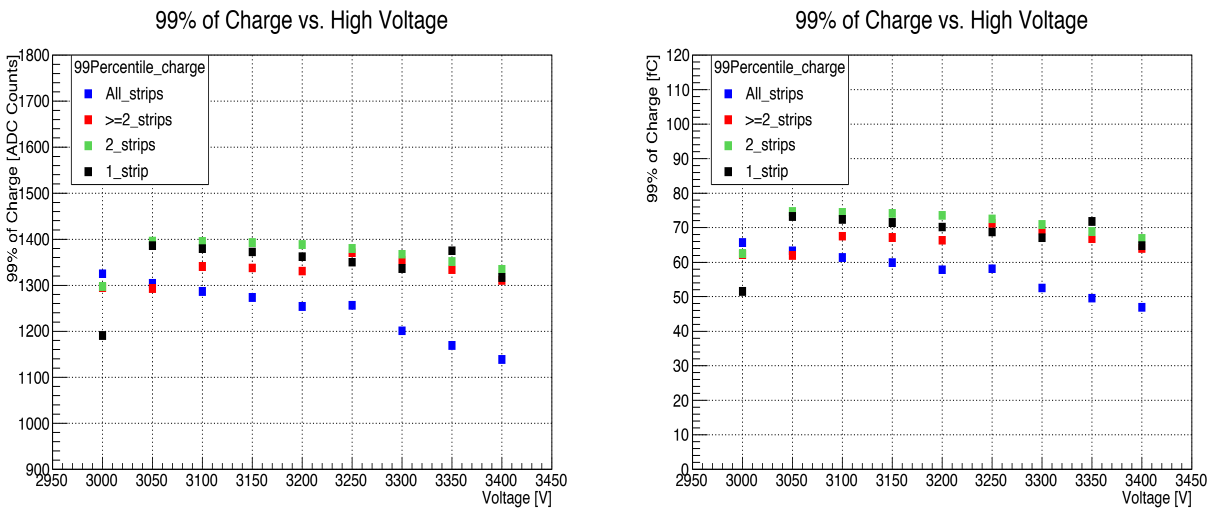
4.1.3 99^{th} Percentile of the Maximum Charge of the Individual Strip Distribution

Finally, the 99^{th} percentile of the strip charge distribution is calculated to find the maximum range of the charge that we can expect at the input of the VFAT3 chip. For each voltage, the strip charge distribution is plotted with different cuts on the strip multiplicity of the clusters. Due to the limited dynamic range of the APV readout system, saturation of signal pulses is again observed causing the curves to flatten out at high drift voltages. From Figure 15 (b), the 99^{th} percentile charge at operating voltage is about 43 fC. We attempt to determine the maximum range for strip charges by extrapolating a linear fit to compensate for the APV saturation at large operating voltages. With this approach, we find a maximum strip charge of 78 fC at 3350 V. To cover the extreme case, we extrapolate the data for 4-strip clusters, which gives a maximum strip charge of 140 fC at 3350 V. We conclude that the GE1/1 readout electronics should be prepared to handle a dynamic range for the input charge on one channel up to 140 fC.



(a) (b)

Figure 15: GE1/1 Detector: (a) 99^{th} percentile of strip charge distribution in ADC units. (b) 99^{th} percentile of strip charge distribution in fC with linear extrapolation of data that suffers little APV saturation.



(a) (b)

Figure 16: GEM detector with radial zigzag strip readout: (a) 99^{th} percentile of strip charge distribution in ADC units. (b) 99^{th} percentile of strip charge distribution in fC.

The 99^{th} percentile of the maximum charge for the GEM detector with zigzag strip readout is calculated in a similar way. The only difference in this case is that we are unable to produce data points for 3-strip and 4-strip clusters due to saturation effects. Figure 16 shows the 99^{th} percentile of the maximum charge in ADC as well as in fC units. We measure 58 fC as 99% of the maximum charge for all strips at operating voltage and 75 fC for 2-strip clusters. These curves appear to be close to saturation for basically all drift voltages and are consequently only of limited value.

5 Summary and Conclusion

We study the charge distribution in a GE1/1 triple-GEM prototype detector to estimate the expected input charge range for VFAT3 readout electronics for the GE1/1 muon upgrade. We use linear and non-linear conversion factors as appropriate for converting ADC counts to fC for the analog readout system (APV25) used in the study. From the number of total electron/ion pairs in the drift region and from the gas gain we estimate the expected mean charge in a GE1/1 detector to be 37 fC at 3250V drift voltage. A direct measurement of this charge from the mean total cluster charge distribution using a Landau fit gives 25 fC, which is within 27% of the calculated charge value. When operating 50 V above the start of the efficiency plateau in an Ar/CO_2 70:30 gas mixture, i.e. with 3250 V applied to the drift electrode, the most probable value, mean value, and 99^{th} percentile value of the Landau distribution of the charge induced on a single strip are found to be 4 fC, 11 fC, and 115 fC, respectively. Measurements for highest charges are somewhat hampered by the saturation of the APV chip. The largest input charge range for the VFAT readout electronics is estimateed to be 140 fC based on an extrapolation of the 99^{th} percentile of the individual measured strip charge distribution in 4-strip clusters. We conclude that the VFAT3 electronics should be designed in such a way that it can comfortably handle input charges over a range of 0-140 fC. Studies done for the same GEM detector equipped with a radial zigzag strip readout give similar results.

References

[1] F. Sauli, "GEM: A new concept for electron amplification in gas detectors," Nucl. Instrum. Meth. A 386 (1997) 531.

[2] P. Aspell, et al.,"The VFAT production test platform for the TOTEM experiment," in Proc. Topical Workshop on Electronics for Particle Physics 2008, CERN-2008-008.

[3] CMS Coll., "CMS Technical Design Report for the Muon Endcap GEM Upgrade," CERN-LHCC-2015-012, CMS-TDR-013, ISBN 978-92-9083-396-3.

[4] V. Bhopatkar, et. al., "Performance of a Large-Area GEM Detector Prototype for the Upgrade of the CMS Muon Endcap System," in Proc. IEEE Nucl. Sci. Symp. 2014, Seattle, WA, NI50-5, arXiv:1412.0228v2.

[5] A. Zhang, et.al., "Performance of a large-area GEM detector read out with wide radial zigzag strips," Nucl. Instrum. Meth. A 811 (2016) 30, arXiv:1508.07046.

[6] L. Jones, "APV25-S1 User Guide," Version 2.2, 2001, available at https://cds.cern.ch/record/1069892/files/cer-002725643.pdf.

[7] K. Gnanvo, et. al., "Calibration of the gain and measurement of the noise for the APV25 electronics," available at http://hallaweb.jlab.org/12GeV/SuperBigBite/SBS-minutes/2012/apvGain20121107.pdf.