GEM-TPC Performance in a Magnetic Field

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A Time Projection Chamber (TPC) readout with gas electron multipliers is a leading candidate for the central tracker of a future linear collider experiment. This talk presents the concept of using relatively large pads in such a device, and gives results from the Victoria prototype TPC operated in the 5 T magnet at DESY. Space point resolutions of about 100 μm are found for 7 mm sampling at high magnetic fields. Systematic effects, limiting the resolution, are investigated.

1 Introduction

A leading candidate for the central tracker at a future linear collider experiment is a Time Projection Chamber (TPC) read out with micro-pattern gas detectors (MPGDs), such as gas electron multipliers[1] (GEMs) or micromegas detectors[2]. It is envisaged to operate the TPC with a relatively fast gas in a strong axial magnetic field which results in very low transverse diffusion in the drift region. As compared with conventional wire grid amplification, the MPGD readout has reduced $\mathbf{E}\times\mathbf{B}$, and faster and narrower signals. This leads in turn to better resolution and two particle separation for the TPC.

The narrow signals present a new challenge for large scale TPCs. To keep the electronic readout costs reasonably low, relatively large pads (about 10 mm^2 area) are necessary to limit the channel count to about 1 million. The benefits of low transverse diffusion in the drift volume are lost if the ionization from traversing charged particles is sampled by only a single pad per row. GEMs offer a solution to this challenge, whereby large transverse diffusion defocuses the charge cloud in the few mm gaps between the GEMS and the readout pads, due to the stronger electric fields in those regions. Since the defocusing occurs during and after the gain stage, the tracking resolution is not sacrificed. To retain good two particle separation capability, the defocusing should be kept to the minimum required to obtain good space point resolution.

2 Using Large Pads in a GEM-TPC

Consider a charge cloud of N_p electrons arriving at the GEM plane. Due to diffusion in the drift volume, the electrons are distributed in the transverse direction, x, with standard deviation σ_d. If the GEMs provide a gain g (with negligable variance), the defocusing adds a variance σ_0^2 to the x distribution, and if the x coordinate of all of the resulting electrons are measured with no uncertainty, then the variance of the mean x coordinate is

$$\sigma_{\bar{x}}^2 = \frac{1}{N_p}\left(\sigma_d^2 + \frac{\sigma_0^2}{g}\right).$$

To achieve the diffusion limit, the GEM term (the second term) must be much smaller than the diffusion term. In reality, the GEM term has additional contributions from the variance in the gain for each electron, and the uncertainties in measuring the x coordinates for each electron.

In a GEM-TPC the x coordinate for each electron is not measured, but rather the charge shared by neighbouring pads is used to deduce the mean x coordinate. The degredation in resolution due to using large pads can be understood analytically. Consider two neighbouring semi-infinite pads with the boundary at $x = 0$. If the electrons are distributed according to the pdf $G(x)$, the expectation for the fraction of electrons over the postive-x pad is

$$\langle F \rangle = \int_0^\infty G(x), dx \quad .$$

If $G(x)$ is gaussian, with mean μ, standard deviation σ, the estimate $\hat{\mu}$ determined from the observed fraction F has variance,

$$\sigma_{\hat{\mu}}^2 = 2\pi\sigma^2 e^{(x-\mu)^2/\sigma^2}\sigma_F^2$$

where the variance of F is binomial, $\sigma_F^2 = \langle F \rangle (1 - \langle F \rangle)/N$ and N is the number of electrons. If $\mu = 0$, so that the pdf is centered on the border between the pads, the variance on the estimate $\hat{\mu}$ is $\sigma_{\hat{\mu}}^2 \approx 1.6\sigma^2/N$ or in other words a factor 1.6 worse than the variance that would result in perfect x coordinate measurements for each electron. As the pdf moves away from the pad boundary, the variance gets larger; for $\mu = 1\sigma$ (2σ) the factor increases to 2.3 (9.0). To keep the GEM contribution to the resolution small, the pad width needs to be less than about 3-4 σ. The same conclusion has been found in Monte Carlo simulations[3] and the analysis of TPC prototype data[4]. In the presense of noise and thresholds, pad sizes may need to be narrower.

When the pad width is several times the cloud standard deviation, charge is typically shared only over two pads. To determine the track parameters from data with limited sharing, it is important to include the non-linear sharing dependence on the track parameters, for example by using a maximum likelihood track fitter [3].

For the analyses presented here, the z coordinate is the drift direction, the y coordinate is vertical, and x horizontal. In the transverse plane, four track parameters are determined, x_0: the horizontal coordinate of the track for $y = 0$, ϕ_0: the azimuthal angle at $y = 0$, σ: the standard deviation of the charge cloud in the x direction, and r^{-1}: the inverse curvature.

3 Resolution Studies with the Victoria TPC

In the summer of 2003, the Victoria prototype TPC was operated in solenoid magnets at TRIUMF (up to 0.9 T) and DESY (up to 5.3 T), to measure its performance with cosmic ray tracks. The TPC has a maximum drift length of 30 cm, followed by 2 GEMs and a pad plane with 8 rows of 2 mm $\times$ 7 mm pads. The signals are readout using the STAR electronics readout system.

By examining how the cloud size varies with drift distance, the diffusion and defocussing are determined from the data. The diffusion constants so derived are in reasonable agreement with the calculations from the Magboltz program[6] for magnetic fields between 0 and 5.3 T, for P5 (Ar:CH_4 95:5) and TDR (Ar:CH_4:CO_2 93:5:2) gases. The defocusing is 10-20% larger in the data than the Magboltz calculation, however the defocusing estimate from the data is sensitive to the method by which induced signals are removed. For large magnetic fields, the defocussing is less than 400 μm, and therefore not sufficient to obtain the best resolution for 2 mm wide pads, as discussed in the previous section.

Track resolution studies are performed, and the results given below indicate the resolution from a single row of pads. These are determined by performing a reference track fit and then performing the fit again to a single row with all parameters fixed except x_0. The resolution is the geometric mean of the standard deviations of the residual distributions with and without including the row in the reference track fit.[4] From Monte Carlo simultion studies, this was found to correctly estimate the intrinsic resolution of a single row. The resolution from N such rows is found to scale like $1/\sqrt{N}$ as expected.

In the z direction, the resolution was somewhat less than 1 mm for both gases and all drift distances, with only a small contribution coming from longitudinal diffusion.

In the transverse direction, the x resolution was found to improve dramatically, as expected, with the magnetic field. For P5 gas at $B = 0$, the resolution was 200 to 500 μm for drift distances between 30 and 300 mm. For magnetic fields above 2 T, the resolution was roughly 100 μm, independent of drift distance. For the TDR gas, similar resolutions were found. Monte Carlo simulations reproduce the observed resolutions for magnetic fields below 2 T, but predict resolutions better than 100 μm for larger magnetic fields.

Closer examination of the data finds biases within a pad row of about 50-

100 μm, increasing with magnetic field. The resolution is seen to be best near the pad edges, as expected.

Other potential causes of degraded resolution considered were gain variations and noise. The analysis presented above does not apply any channel-to-channel gain calibrations. A study performed with cosmics, finds that the RMS of the distribution of gains is less than 5%. The effect of adding 5% RMS noise to a Monte Carlo sample does not significantly degrade its resolution. To account for the difference between Monte Carlo and data resolutions, the gain variation would need to be about 15%.

The data has an RMS noise of about 3000 e. By adding 4000 e noise to the Monte Carlo samples, resolution degradation is very small. About 8000 e noise would be required to account for the difference between Monte Carlo and data resolutions.

4 Future Work

A UV laser system is being prepared for the studies of the prototype TPC in the DESY magnet in August 2004. Laser tracks should help understand any track distortions that have been observed in the cosmic data, as well as allow direct measurements of two track resolution and possibly ion feedback effects. A pad plane with 1.2 mm wide pads ($3\times\sigma$) will be used, to verify that limited defocussing is limiting the resolution. Finally, a readout endplate with micromegas with a resistive foil is being prepared in order to understand the capabilities of that option.

Details of the work referred to in this paper is found at

www.linearcollider.ca:8080/lc/Members/karlen/analysis

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