Study of GEM-TPC Performance in Magnetic Fields

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This paper reports on the progress made since the last LCWS meeting in Paris 2004 on the study of the resolution properties of GEM-TPCs in magnetic fields, using the Victoria TPC prototype. In 2004 large datasets of cosmic ray and UV laser tracks were collected with this TPC in a DESY test magnet. Two pad planes with different pad widths were used. A full simulation of the cosmic ray tracks in the TPC is used to better understand the properties of the data.

1. INTRODUCTION

The use of a time projection chamber (TPC) as the main tracker in an International Linear Collider experiment is under consideration by the LDC and GLD detector concept groups. In order to improve the momentum and multi-track resolutions, as required by the physics objectives, it is proposed that the wire grids be replaced by micropattern gas avalanche detectors, such as a gas electron multipliers (GEMs) [1] or micromegas [2]. For these types of devices, $\mathbf{E}\times\mathbf{B}$ effects, which limit the resolution in traditional TPCs, can be negligibly small. Furthermore, since the pad signals are due to the motion of electrons as they arrive on the readout pads, the spatial extent of the signals can be much narrower and their risetimes much faster, thereby improving the multi-track resolution.

In fact, the signals can be so narrow as to present a challenge for conventional pad readout in a large detector, because the spatial resolution will be very poor if only single pads in each row detect a signal. The radius of a linear collider experiment main tracker is to be approximately 2 m and to keep electronics costs reasonable, the readout pads need to be no smaller than about 2 mm $\times$ 6 mm [3]. The magnetic field strength for a future linear collider experiment is to be about 4 Tesla. In this magnetic field, gases with fast drift velocity at low drift fields can have transverse diffusion of order 30 μm for 1 cm drift distance. To achieve optimal transverse resolution with 2 mm wide pads, a mechanism to defocus the electron charge cloud after amplification is required.

One way to defocus the charge cloud is to use gas diffusion between the GEM foils and the readout pads. In these regions the electric field is typically much larger, and by selecting an appropriate gas, the diffusion constant can be much larger there than in the drift region. This is the type of device that is considered here. Ideally, the defocusing should be sufficient so that the standard deviation of the charge clouds should be at least $\frac{1}{4} - \frac{1}{3}$ of the pad width [4, 5].

2. THE DETECTOR

2.1. TPC Design

The TPC, shown in figure 1 consists of a cylindrical drift volume, approximately 30 cm long, which is terminated by a circular endpiece, with a 10 cm square hole, equal to the size of the GEM foils. Two GEM foils are located past the endpiece, followed by an array of pads. Two pad planes have been used, the original with a pitch of 2 mm $\times$ 7 mm, arranged in staggered rows of 32 pads. A new pad plane with the horizontal pitch reduced to 1.2 mm was constructed to compare the performance with greater charge sharing. The pad arrangement is shown in figure 2.

The drift field was operated between 100 and 300 V/cm. The transfer field between the two GEMs was nominally 2.5 kV/cm, and the induction field to the readout pads was nominally 3.5 kV/cm.

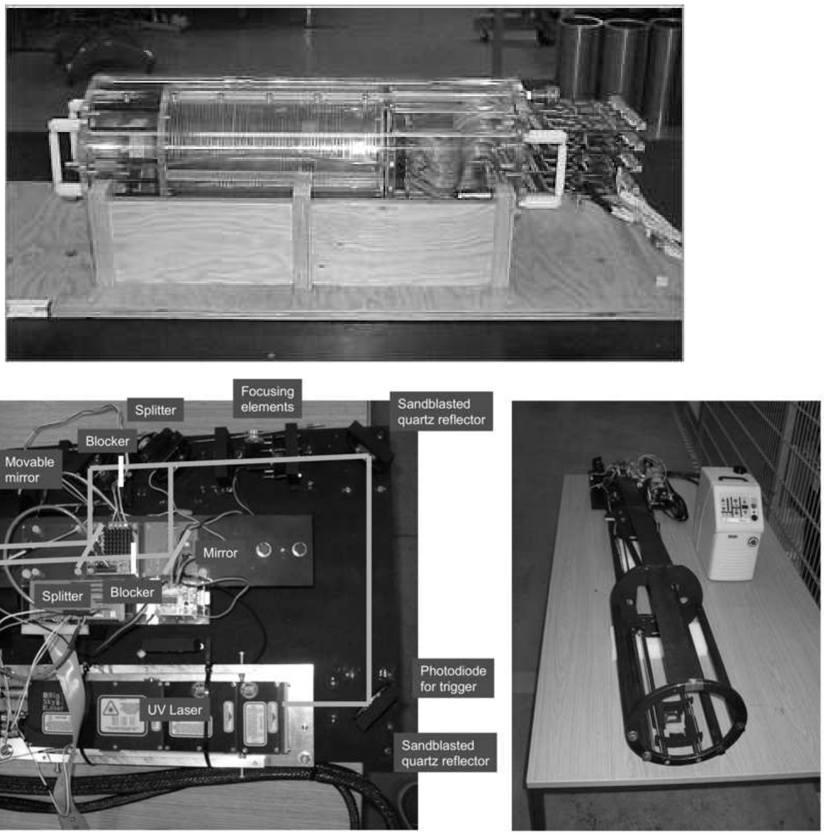

Figure 1: The upper photograph shows the prototype TPC, with the STAR front end cards connected on the right. The lower figures show the laser delivery system including the holding bracket for the TPC and the laser power supply.

2.2. Readout Electronics

The pads are connected by ribbon cables to front end cards developed for the STAR TPC [6]. The card contains charge sensitive preamplifiers and when a trigger is received, the amplified signals are stored in a 512 time bin switched capacitor array. The signals are digitized asynchronously and 10 bits per channel per 50 ns time bin are stored in the raw data files. For cosmic ray studies, trigger signals are formed from the coincidence of scintillator paddles placed above and below the TPC. For laser studies, trigger signals are provided by a photodiode.

2.3. Laser System

In order to perform controlled studies of the GEM TPC, a laser delivery system was constructed for use in the DESY magnet system with an ultraviolet (266 nm wavelength) Nd:YAG laser. The system is able to provide a single beam or a pair of beams to the TPC perpendicular to the drift direction, at any location along the drift distance, under remote control. The TPC outer acrylic tube was fitted with long quartz windows to accept the laser light.

3. DATA SAMPLES

In 2004, cosmic ray and laser data were collected in a DESY test magnet at a few magnetic field strengths for two different gas mixtures: P5 (Ar:CH_4 95:5) and a mixture referred to as TDR gas (Ar:CH_4:CO_2 95:3:2). The initial data taking was with the wider pads, after which the TPC was briefly opened to insert the narrow pads. The data taking started with P5 gas, but because the gas lines were copper and exposed to atmosphere, it took many days for

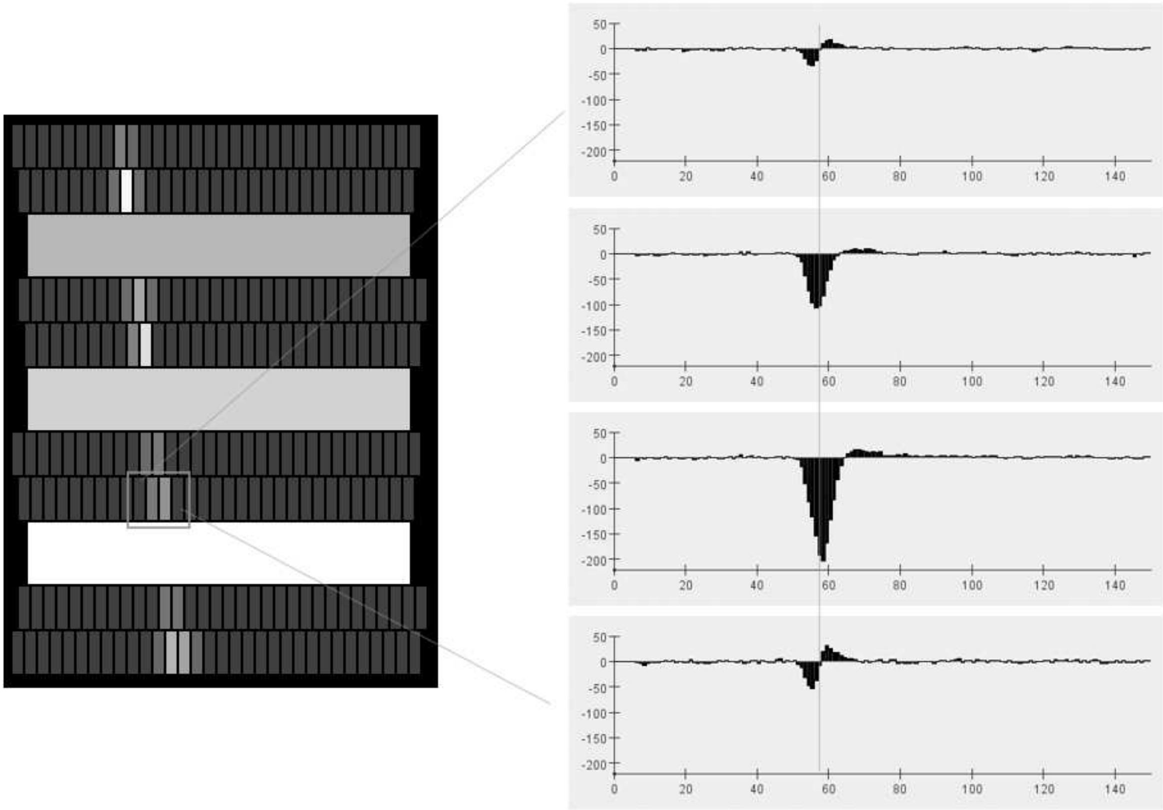

Figure 2: A typical cosmic ray track observed with the wide pad layout at 4T with P5 gas. The brightness of the pads indicates the amount of charged collected. The wide pads are used during data taking for selecting events that contain a track in the active area. The pulses for 4 neighbouring pads are shown on the right.

the gas properties to stabilize. The drift field was chosen to be near the drift velocity maximum, and the GEM gain adjusted to avoid saturation in the electronics. The data analysis is performed with the jtpc package.

A typical cosmic event is shown in figure 2, along with representative pulses on some of the pads. Pads near the center of the track have signals due to the collected charge that are significantly different in shape than pads further away, which have signals induced by the motion of electrons in the transfer gap. Due to the shaping of the readout electronics, the induced pulses are transformed into a bipolar pulse.

To estimate the charge collected by pads, clusters of signals in a row are searched for, and the time bin with the largest sum of signals in the group of pads is taken to be the arrival time of the center of the electron cloud. For each pad, the sum of the pulse height in that time bin and the three previous and three following time bins is formed to estimate the collected charge. Studies show that the induced signals roughly cancel out with this algorithm.

4. STATUS OF ANALYSES

To reconstruct the ionization track parameters in the plane transverse to the drift from the measurements of charge deposited on the readout pads, a maximum likelihood track fitting algorithm was developed.[7] This method takes into account the non-linear dependence between the track parameters and the expected charge deposition. The charge measurements for all the rows are used to evaluate the likelihood, which is maximized to estimate the track parameters.

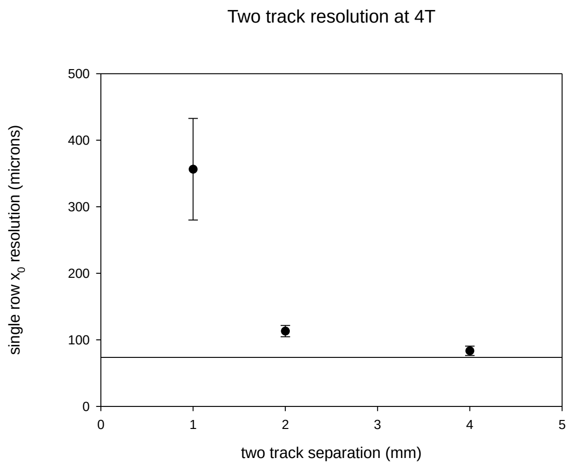

Figure 3: The degredation in transverse resolution is shown as a function of transverse separation between two parallel laser tracks. This is shown for P5 data at 4T.

4.1. Check of Transverse Resolution Estimates

Since the likelihood track fit does not generate space points along the length of the track, there is no possibility to use the scatter of such points to estimate the transverse resolution per point. Instead, the likelihood fit of all data is used to define a reference, and then the data from a single row is used to estimate the horizontal coordinate, leaving the other track parameters fixed according to the reference. The standard deviation of the residual between the reference and single row fit is a measure of the resolution. The process is then repeated, this time the reference fit does not use the information from the single row. To properly estimate the resolution from a single row, the geometric mean of these two standard deviations is used. [5]

Since the laser track location was very stable, the mean location moving typically less than 10 μm over a period of several hours, the laser data can provide a check of this method. For a typical P5 data run at 4T, the standard deviation of the distribution of the reconstructed transverse coordinate was about 28 μm, from the 8 row fit. This corresponds to a single row resolution of approximately 79 μm. When the geometric mean is used for the same laser run, the estimated resolution is found to be 77 μm if straight tracks are fit, and 74 μm if curved tracks are fit. The estimate for transverse resolution appears to be reasonably good.

4.2. Two Track Separation Power

If two ionization tracks are near enough, some pads will collect charge from both tracks, and the tracking resolution for each track will degrade. To measure this effect, two parallel laser beams were brought close together at the same drift distance. By using beam blockers, events with the individual beams were recorded, as well as events with both beams present. The increase in the standard deviation of the transverse coordinate of the track coordinates when both beams are present is used to quantify the two track separation power.

The maximum likelihood track fit was modified to include the charge from two tracks. The fit allows for non-uniform ionization along the track direction by treating the ratio of the charges sampled from the two tracks as an additional nuisance parameter for each row. In other words, the relative amplitudes of the pulses from each track are not assumed to be one half, or some other fixed value, but instead the relative amplitudes for each row are varied in the maximization of the likelihood.

This test represents the most difficult situation, where the tracks are parallel and at the same drift distance. Nevertheless, the transverse resolution is only found to degrade significantly when the two tracks are separated by less than about the pad width. A typical result with 2 mm pads is shown in figure 3.

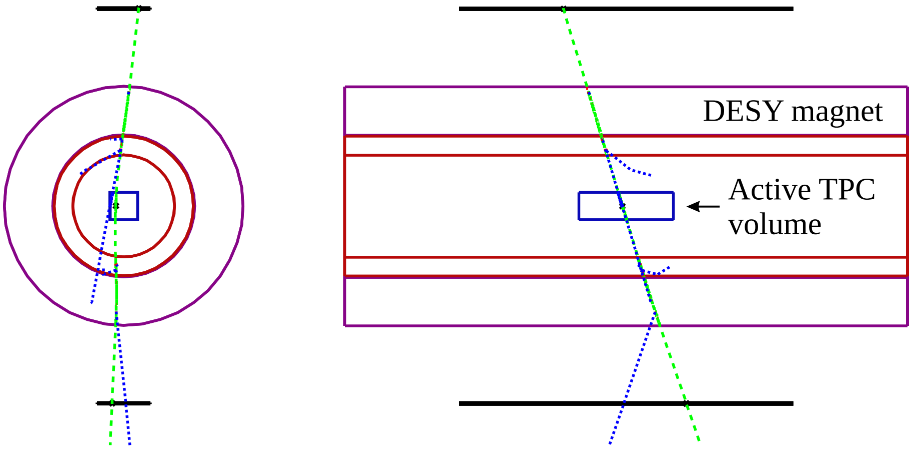

Figure 4: Example event from the GEANT3 simulation of cosmic events.

4.3. Cosmic Ray Tracking Simulation Studies

To better understand the results from the cosmic ray samples, a full GEANT3 simulation of cosmic events was developed. The geometry of the DESY setup was incorporated, including the magnet, its field, and the trigger scintillators, as shown in figure 4. Muons were generated according to the cosmic ray spectrum and angular distribution. For events in which a muon passes through both scintillators and the active volume of the TPC, the energy loss of particles traversing the gas of the TPC is recorded in small steps of approximately 0.1 mm. The location and energy deposits are converted to electrons in the jtpc simulation package and they are transported in the gas, and amplified. The pad signals are shaped, digitized, and saved in data files that can be analyzed by the same package that analyzes the real data.

Overall, the reconstructed track parameter distributions of the simulated samples agree well with the data distributions. The data events, however, show a tail in the track width, σ. These are found to be due to occasional events with a very large pulse from a delta ray. As a result, a number of neighbouring pads show large induced signals, which are interpreted as real charge by the analysis. Since the simulation does not generate induced signals, this effect is not seen in the simulated samples.

4.4. Cosmic Ray Tracking Resolution

The resolution in the wide pad data is found to be in reasonable agreement with the simulated cosmic ray data, ranging from 90-100 μm for drift distances between 3 and 30 cm (per 7 mm row), as shown in figure 5. The simulated sample shows a greater dependence on drift distance, ranging from 70-115 μm. These results are for the first data collected, before the gas had stabilized, having a larger than expected diffusion constant (70 $\mu\mathrm{m}/\sqrt{\mathrm{cm}}$). The radius of curvature compares well, both in offset (presumably due to the greater number of μ^+ than μ^-), and width.

As noted in the earlier data taking, P5 does not provide sufficient defocusing for 2 mm wide pads at 4T. A P10 gas mixture could have sufficient defocusing, but that gas could not be used in the test area. Instead, to study the effect of improved charge sharing, a new pad plane with 1.2 mm wide pads was used. As expected, the data from the narrower pads shows improved resolution, showing a resolution of 60-80 μm for drift distances between 3 and 30 cm. At the time of the presentation, there were unexplained row to row biases of about 100 μm. Subsequently, it was discovered that an error in the narrow pad board design caused the pad rows to be offset from their intended locations by various amounts of order 100 μm. When the actual locations of the pads are used in the analysis, the row to row biases reduced to below 10 μm.

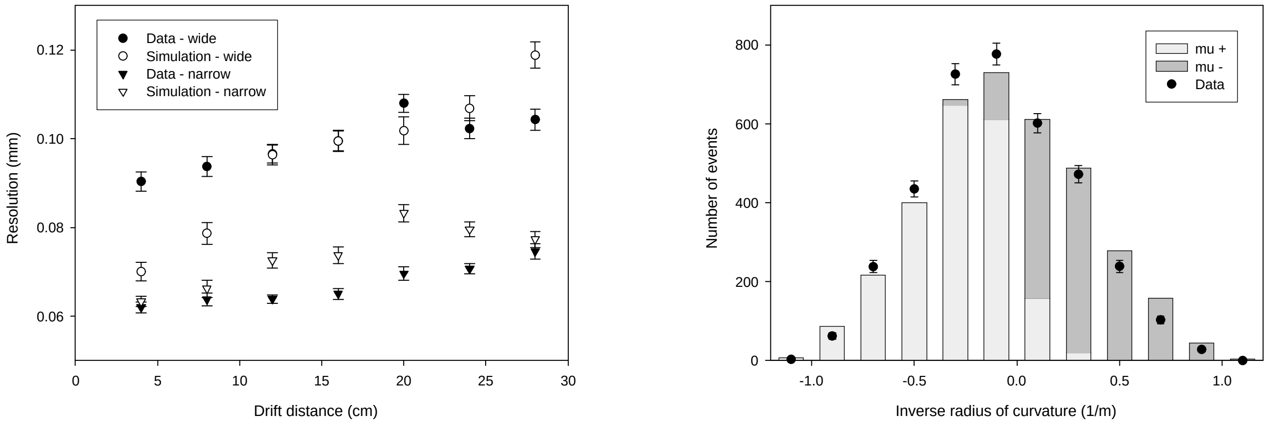

Figure 5: On the left, the measured resolution for wide and narrow pad cosmic data is shown, and compared to simulation results. On the right, the signed inverse radius of curvature is shown for the wide pad data, compared to the expected distributions separately shown for positive and negative cosmic muons.

5. SUMMARY

From the initial studies of the data from the Victoria prototype TPC, it appears that a TPC operated in 4T with GEM readout can achieve the required level of performance, both in spatial resolution and two particle separation power, demanded by the physics program at the ILC. A more thorough analysis of this data is underway, including improvements to the simulation package.

Acknowledgments

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