Track Resolution Measurements for a Time Projection Chamber with Gas Electron Multiplier Readout

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Abstract-- **We present measurements of track resolution from two gas electron multiplier TPC prototypes under study in Canada. The results are from measurements of cosmic rays using relatively large rectangular pads that rely on diffusion to spread the charge across more than one pad per row. Results with magnet fields up to 5.3 Tesla are shown and compared to Monte Carlo simulations. This represents the first demonstration of the tracking capabilities of a GEM TPC in magnetic fields.**

I. INTRODUCTION

A leading candidate for the central tracking system at a future linear collider experiment [1], [2] is a time projection chamber (TPC) readout by micropattern gas detectors (MPGDs), such as gas electron multipliers [3] or micromegas [4] detectors. This concept may offer two distinct benefits over traditional TPCs; improved tracking resolution and better two particle separation. When operated in a uniform magnetic field, the resolution of a traditional TPC, one with gas amplification provided by a wire grid, is limited by the so-called **E**×**B** effect. This refers to electric field components transverse to the magnetic field in the amplification region which cause segments of ionization to rotate. Since the ionization is not uniform along the track, the rotation results in degraded spatial resolution. The feature separation of an MPGD, the hole or mesh pitch, is much smaller than can be achieved with a wire grid. As a result, the transverse electric field components are much smaller and the **E**×**B** effect is significantly reduced.

The electronic signals measured in a traditional TPC are primarily due to the motion of positive ions away from the anode wires. These signals tend to be relatively slow, are spread over a large region, and therefore limit the capability of separating two nearby tracks. The signals observed with a MPGD TPC are due to the motion of electrons across a small gap and by the collection of the electrons on pads, giving faster and narrower signals and therefore improved capability to separate two nearby particles.

The narrower signal distribution presents a new challenge for large scale TPCs, such as those being considered for a future linear collider. When operated in a strong axial magnetic field in a fast gas, the transverse width of the charge distribution as it reaches the TPC endplate may be only a few hundred microns across. Populating an endplate whose area is several square meters with pads with sub-millimeter dimensions would be cost prohibitive due to the associated electronic readout system. This paper explores one solution to this challenge, whereby gas diffusion in the region near gas electron multipliers (GEMs) is used to spread the charge over a wider area without sacrificing the track resolution.

II. TPC WITH GEM CONCEPT

The concept of a large scale TPC with GEM readout is shown in Fig.1 with a relatively long drift volume coupled to a double GEM readout system.

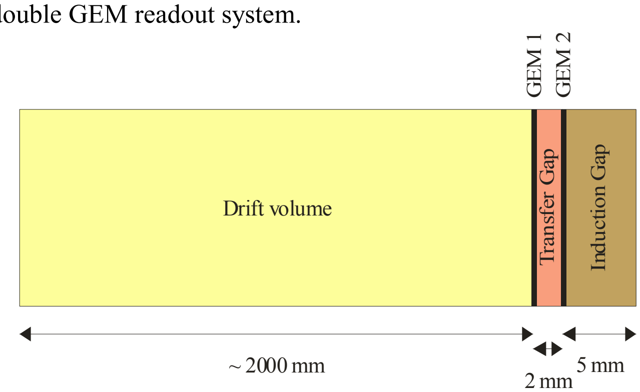

Fig. 1. Concept of a large scale TPC, such as that envisaged for a future linear collider experiment. The electric field in the drift volume is parallel to the magnetic field, resulting in low transverse diffusion for the drifting electrons. In the transfer and induction gaps, the transverse diffusion is significantly larger, which will help spread the charge over a larger region as they are collected by the pads at the endplate.

For an appropriate choice of operating gas, this device can have very low transverse diffusion in the long drift volume and large diffusion in the transfer and induction gaps. It is essential to have low transverse diffusion in the drift volume, in order to

Manuscript received October 27, 2003. This work was supported in part by the National Sciences and Engineering Research Council of Canada.

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best preserve the centroid of the electrons from the primary ionization. Once these electrons are amplified, additional spreading of the charge in the transverse direction, referred to in the following as defocusing, will not significantly increase the uncertainty of the centroid estimate, since the number of electrons involved is much larger. In order to retain good two-particle separation power, however, the defocusing in the transfer and induction gaps should be as small a possible.

Fig. 2 shows the transverse diffusion constant as a function of electric field in the gas mixture Ar CH_4 (95:5) for three magnetic fields. Also indicated are the typical operating points used in the studies presented here.

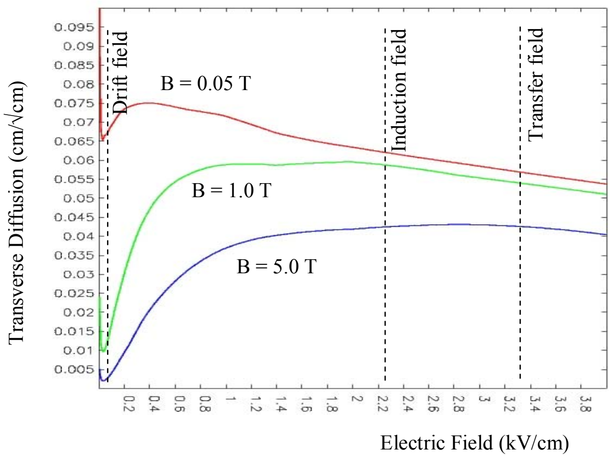

Fig. 2. Transverse diffusion coefficient for Ar CH_4 (95:5) as a function of electric field for three magnetic fields as calculated by the MAGBOLTZ [5] program. Significantly larger diffusion is possible in the induction and transfer gaps, as compared to the drift volume, for high magnetic field operation.

In simulation studies, it has been shown that the standard deviation of the sampled charge cloud should be at least ¼ of the pad width, in order not to degrade the position resolution [6]. Further defocusing will only reduce the two-particle separation power, and so it is important to limit the defocusing to about that amount. In this situation, the charge is typically detected in only two pads per row, for which a simple centroid estimate, by linearly weighting the pad centers by the observed charge, performs poorly. To account for the non-linear charge sharing between pads we apply a maximum likelihood track fit according to a model with a charge distributed about the path of ionization in a Gaussian fashion [6]. The track fit uses the observed charges seen in a number of rows to determine four track parameters: x_0, the horizontal coordinate at $y = 0$; ϕ_0, the azimuthal angle at that point; σ, the standard deviation of the charge cloud about the track direction; and $1/r$, the inverse radius of curvature.

III. TPC Prototype Studies

Two prototypes were designed and constructed in Canada to demonstrate the capabilities of TPCs with MPGD readout. TPC1, shown in Fig. 3, has a 15 cm drift volume and is operated at Carleton University without magnetic field. TPC2, shown in Fig.4, has a 30 cm drift volume and was designed for operation in magnetic fields at the TRIUMF and DESY laboratories. The two TPCs use pad sizes consistent with the requirements for a linear collider experiment. The performance of the TPCs has been studied using cosmic rays.

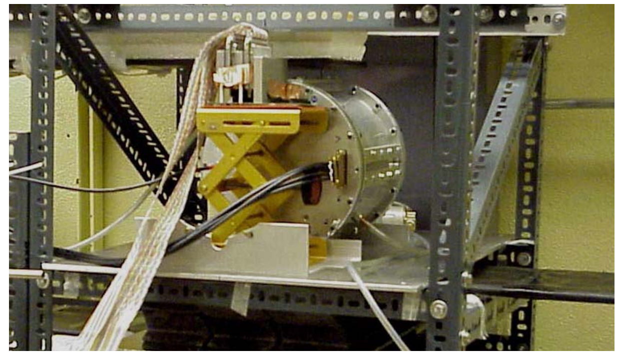

Fig. 3. Photograph of TPC1, located at Carleton University. The scintillator paddles that form the cosmic ray trigger are visible.

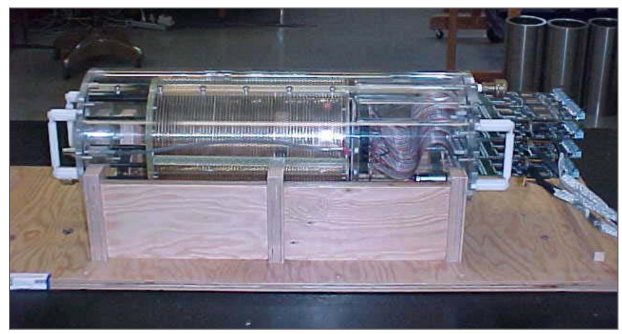

Fig. 4. Photograph of TPC2, located at the University of Victoria. Located on the right endcap are front end cards produced for the STAR TPC.

A. *TPC1 Studies*

Two gases have been used to study the performance of the GEM TPC without magnetic fields, Ar CH_4 (90:10) and Ar CO_2 (90:10). The latter gas has a lower transverse diffusion. For both gases, short drift distances mimic the operation with large magnetic fields, in that the charge distribution arriving at the first GEM is very narrow.

Fig. 5 shows an example event recorded by the detector. The electronics readout consisted of 64 channels of 8-bit, 200 MHz custom built FADC. To sample the 192 pads, three fold multiplexing was used, which results in the complex pattern of signals on the event picture.

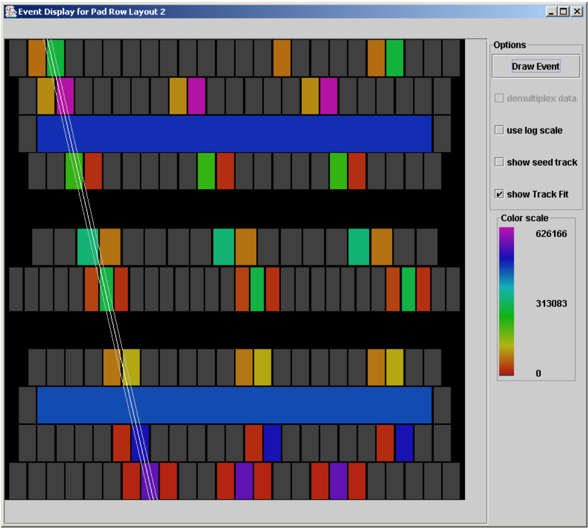

Fig. 5. Event display from a cosmic ray event recorded by TPC1. The color of the pads represents the size of the signal recorded by the corresponding electronics channel (see scale on right). Three fold multiplexing was used.

The outer six rows of 2.5 mm × 5 mm pads are used to define the track coordinates. The inner two rows are used to determine the resolution from a single row of pads. The resolution determined for the lower row, with 2 mm × 6 mm pads is shown in Fig. 6, as a function of drift distance. To determine the resolution, the track fit is performed to the one row, allowing only x_0 to vary. The standard deviation of the x_0 residuals is used as an estimate of the resolution.

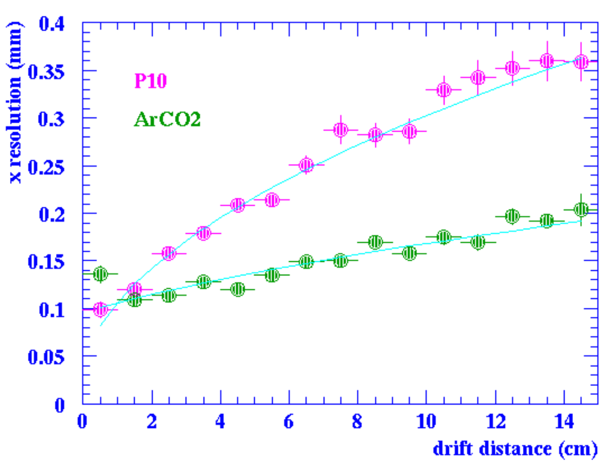

Fig. 6. Resolution in the horizontal component as a function of drift distance for TPC1. The lowest drift distance bin contains only a few events.

The resolution is clearly dominated by diffusion effects for drift distances greater than 2 cm. For short drift distances, the tracking resolution is slightly more than 100 µm for the 2 mm × 6 mm pads. More results from this TPC were presented in a satellite workshop preceding this meeting [7].

B. *TPC2 Studies*

In June of this year, TPC2 was operated in a warm 0.9 T solenoid at TRIUMF, initially with Ar CH_4 (90:10). Fig. 7 shows events recorded by the TPC at zero, half, and full magnetic field. For each event, the drift distance was approximately 25 cm, and the reduction in transverse diffusion is easily seen. Eight rows of 2 mm × 7 mm pads are sampled at 20 MHz and digitized to 10 bits by electronics developed for the STAR TPC at RHIC [8].

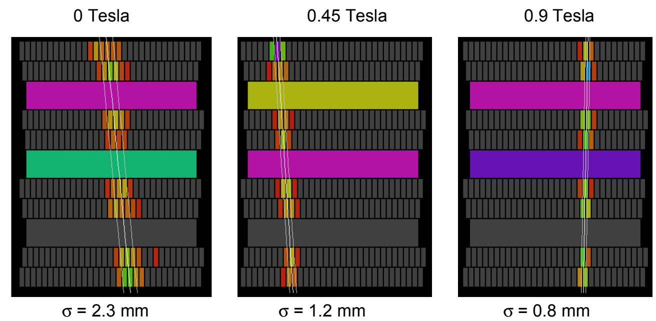

Fig. 7. Event displays from cosmic ray events recorded by TPC2 at TRIUMF. The color of the pads represents the size of the signal recorded by the corresponding electronics channel. Each track drifted about 25 cm. Below the displays are shown the standard deviation of charge distribution about the track as determined by the track fit.

The resolution as a function of drift distance is shown in Fig. 8 for zero, half, and full magnetic field. For full field operation, the resolution still has a component from transverse diffusion.

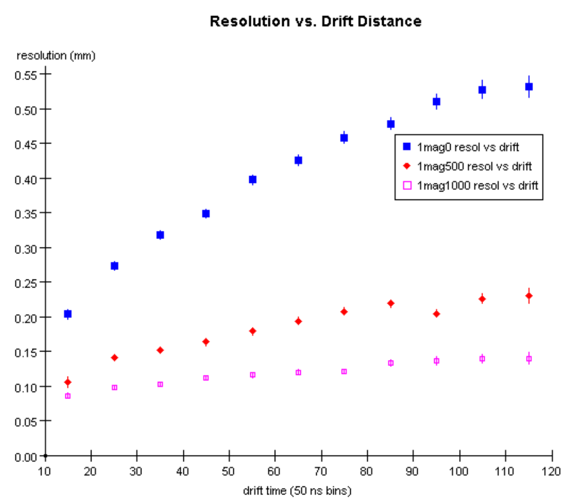

Fig. 8. Resolution (mm) is shown as a function of drift time (50 ns time bins) for TPC2 in Ar CH_4 (90:10). The horizontal axis corresponds to drift distances between 3 and 30 cm. The upper (blue) points are at zero field, the middle (red) points are at 0.45 T, and the lower (magenta) points are at 0.9 T. These data are from a preliminary analysis.

A simple Monte Carlo simulation program has been developed to understand the performance of the GEM TPCs. Primary ionization clouds of electrons are produced and diffused through the gases volumes, amplified at the GEM foils and collected by the pads. Signals are generated on the pads according to the arrival time of the electrons and the response of the electronics. The simulated and real events are analyzed by the same program, and the derived resolutions are compared in Fig. 9. The agreement between the data and simulated resolution estimates is good.

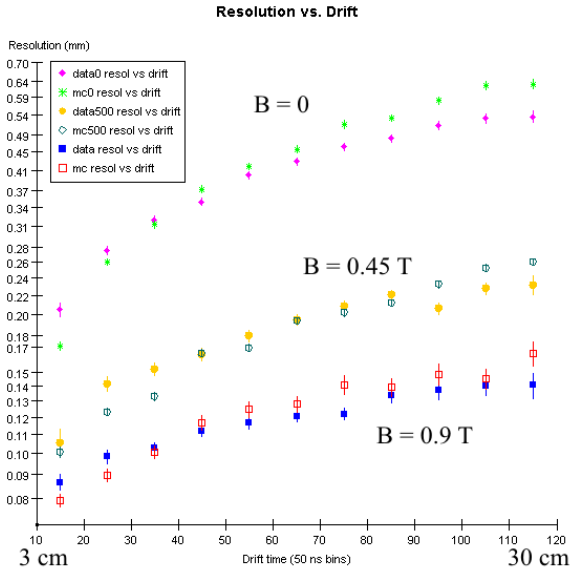

Fig. 9. Resolution (mm) is shown as a function of drift time (50 ns time bins) for TPC2 in Ar CH_4 (90:10). The horizontal axis corresponds to drift distances between 3 and 30 cm. The solid points correspond to real data, the open points are from simulated data. The results shown here are to be considered preliminary.

In July and August of this year, the TPC was operated in magnetic fields up to 5.3 T at the DESY laboratory in Hamburg, Germany. Two gases were used, Ar CH_4 (95:5) and Ar CH_4 CO_2 (93:5:2), the latter identified in the TESLA TDR as a good choice for dE/dx stability. The observed resolution is shown in Fig. 10 for magnetic fields up to 1.5 T, where it is seen that 100 μm resolution is achieved for all drift distances.

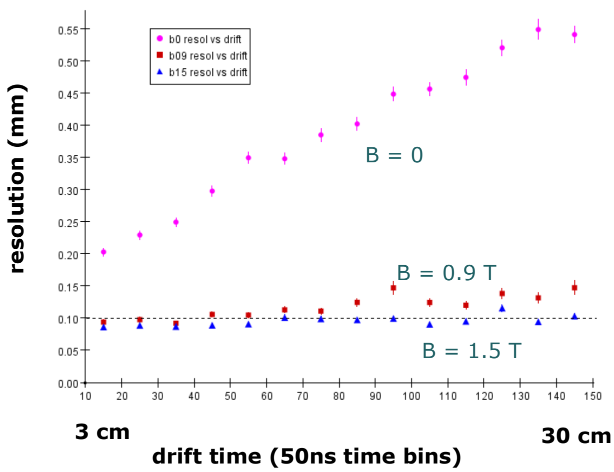

Fig. 9. Resolution (mm) is shown as a function of drift time (50 ns time bins) for TPC2 in Ar CH_4 (95:5). The horizontal axis corresponds to drift distances between 3 and 30 cm. The results shown here are to be considered preliminary.

For magnetic fields above 1.5 T, the resolution does not significantly improve. The average resolution is shown in Table I for data and simulation. With the present preliminary analysis, systematic effects appear to be limiting the resolution at the 90-100 μm level.

TABLE I
RESOLUTION FOR HIGH MAGNETIC FIELDS
(PRELIMINARY)

B(T)	measured (μm)	simulation (μm)
1.5	97	88
2.5	93	73
3.5	95	63
4.5	95	58
5.3	92	-

The amount of defocusing observed in the TPC is compared to expectations from simulation in Table II. This table shows the mean standard deviation extrapolated to zero drift distance. There is more defocusing in the data than expected from the diffusion in the transfer and induction gaps. The origin of the extra defocusing is not understood at this time. It is possibly a result of induced signals on neighboring pads that are being misinterpreted as real charge, or an effect of UV photons produced in the avalanche process.

TABLE II
DEFOCUSING VALUES
(PRELIMINARY)

B(T)	σ_0 (mm)	sim σ_0 (mm)
0.	1.14	0.21
0.9	0.66	0.43
1.5	0.60	0.42
2.5	0.52	0.40
3.5	0.53	0.38
4.5	0.55	0.36
5.3	0.51	-

IV. CONCLUSIONS

This work has demonstrated, for the first time, the tracking resolution capabilities of a TPC with GEM readout in magnetic fields. Transverse resolutions of less than 100 μm are achieved for drift distances up to 30 cm, using relatively large pads, appropriate for an experiment at a future linear collider. The work shown here has been done in context of a global research and development effort for TPCs at a future linear collider. More information about that effort is reported at this meeting [9].

V. ACKNOWLEDGMENT

We thank the technical support staff at Carleton University and the University of Victoria for the design and construction of the prototype TPCs and for assistance with the associated electronics; Lawrence Berkeley National Laboratory for the use of prototype STAR electronics system for TPC2; staff at the TRIUMF and DESY laboratories for the setup and use of the magnet facilities; and DESY physicists, P. Wieneman, F. Sefkow, and T. Lux for operational assistance.

VI. References

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