Drift field improvement and test in a GEM-TPC prototype*

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Abstract: With the help of Maxwell, Ansys and Garfield, a simulation of the electric field and the deviation of electron drift in the drift volume of a GEM-TPC prototype has been accomplished under the following conditions: Field Cages with one-side and double-side strips, with and without a guard ring. The advantage and necessity of a Field Cage with mirror strips and a guard ring were foreseen. According to the simulation results, TU-TPC was modified and tested; a larger effective area and better resolution were achieved.

Key words: GEM-TPC, electric field simulation, electron drift, spatial resolution

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1 Introduction

Invented by David Nygren 30 years ago, the Time Projection Chamber (TPC) has been used as a central tracking detector in many particle and heavy ion physics experiments with great success [1–3]. A TPC is typically a gas-filled cylindrical chamber with one detector or two endplate detectors separated by a long drift distance. When particles pass through the gas-filled chamber, electrons are released from collisions along the particles' tracks. An electric field in the drift chamber of an ideal TPC is defined to be constant, completely along the z axis, along which electrons will drift to the collecting electrode. By measuring the arrival, in space for projection and in time for drift time t, the TPC can reconstruct the paths of the original charged particles (x-y are given by the projection and z by $v\times t$) [4]. A magnetic field B parallel to E could furthermore be added as large as possible to minimize the transverse diffusion, which limits the obtainable resolution [5]. The TPC's 3D localization makes it extremely useful in tracking charged particles and in identifying particles by their ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements.

The performance of a TPC is determined by many factors, one of which is the electron drift quality. The electron drift velocity ought to be stable in the Z direction and negligible in the R direction. Therefore, the electric field in the drift volume should be initialized with a constant E_z (electric field in the z direction) and negligible E_r (electric field in the r direction) [6].

At Tsinghua University, a TPC prototype with a 50 cm drift length based on GEM readout (named TU-TPC) has been designed (Fig. 1) [7]. Its performance has been studied using cosmic-rays with and without a magnetic field, and very good performance has been achieved [8, 9]. In this prototype, the readout area is determined by the size of the GEM foil (10 cm×10 cm). The readout electrode has been divided into pads of 62 columns in the x direction and 10 rows in the y direction. Due to the limitation of the DAQ channel, only the middle 32 columns and 10 rows are read out. However, in earlier studies, the edge effect was found and the active area was reduced further by using only the data from the middle 6 rows.

Studies to extend the active area of the TU-TPC are presented in this paper. The main effort was focused on improving the Field Cage design and applying a guard ring around the top GEM foil. Finite element software Maxwell SV 2D and Ansys were applied to the electric field calculation, together with Garfield for electron drift simulation in the drift volume.

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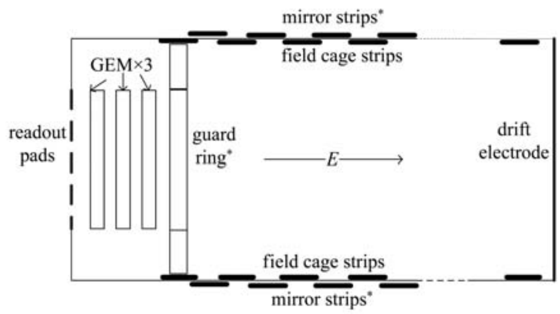

Fig. 1. Scheme of the TU-TPC (structures with "*" only exist in the modified TPC).

2 Simulation studies

2.1 Drift field under different field cage designs

The electric field between infinite electrode planes is ideal for the drift volume, which is unfortunately unrealizable. In most TPC systems, a Field Cage has been used, that is to say, many conductor strips are placed around the z axis along the drift chamber, with graded potential on each strip, and the potential difference between neighboring strips $\Delta V = E\times\Delta P$ [9, 10] (E stands for the ideal electric field intensity and ΔP for the pitch). The strips are designed either as one-sided or in two-sided (mirror strips) [11].

Maxwell SV 2D is used to simulate the electric field distribution for both Field Cage designs. As the Field Cage is symmetrical, a 2D model in the r-z cross section with a proper boundary and symmetry set is sufficient. The whole drift distance H equals 50 cm and radius r=11.75 cm. The width of each strip is 3 mm with a pitch of 5 mm, and the thickness of the Kapton layer is 0.1 mm.

With the required calculation precision, Maxwell has exported proper results. Fig. 2 presents 4 curves of E_z/E (E=100 V/cm) as a function of the z position for 4 different r values. For one-sided strips Field Cage, the maximum deviation of E_z/E from 1 is approximately 0.1, with few V/cm for maximum E_r. For the design of mirror strips, the values are 0.005 and 0.3 V/cm, respectively, much less compared with those above.

In addition, the statistics for E_z and E_r in the drift volume have been calculated and are listed in Table 1.

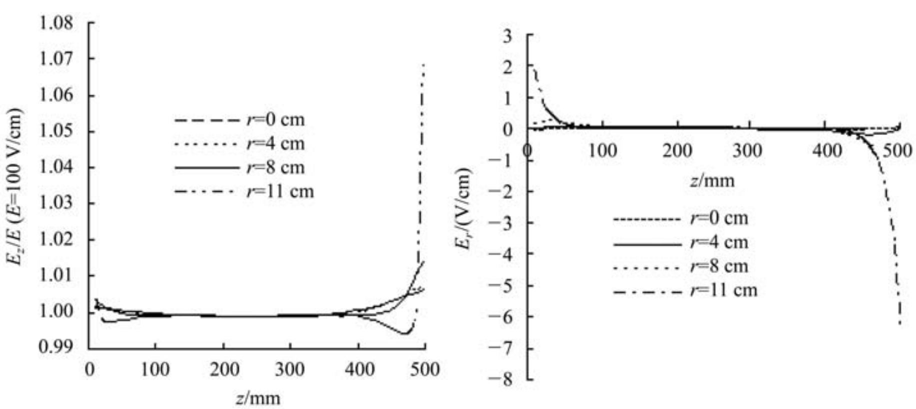

Fig. 2. Left: E_z/E as a function of z for different r. Right: E_r as a function of z for different r.

Table 1. Statistics for E_z and E_r for each Field Cage model.

	one-sided strips field cage		mirror strips field cage	
	E_z/(V/cm)	E_r/(V/cm)	E_z/(V/cm)	E_r/(V/cm)
standard deviation	0.69	0.26	0.01	0.01
medium value	100.04	−0.04	100.00	0.06×10^{-2}
maximum deviation	11.78	−6.61	0.45	−0.03

It is clear that the Field Cage with mirror strips can provide a much better electric field, both for E_z and E_r, which is essential for the steady drift velocity along the z axis and small drift in the r direction. TU-TPC now employs a Field Cage with one-sided strips and will be improved with a new Field Cage with mirror strips to achieve better performance.

2.2 Drift field with and without guard ring

In TU-TPC, since GEM foils are smaller than the cross section of the cylindrical chamber, the electrode planes at each end of the chamber have different sizes and shapes. This will seriously affect the distribution of E_z and E_r, and eventually the drift of electrons. In order to match the two electrodes, a guard ring [12] around the top GEM foil is proposed and its effect was simulated with Maxwell 2D. The curves of E_z/E as a function of z are displayed in Fig. 3. Without the guard ring, E_z near the collecting electrode has a considerable distortion from ideal installation. Fig. 3 also reveals the improvement for E_z with a guard ring at z=1 cm, as the program for TU-TPC.

2.3 Electron drift deviation

With Ansys and Garfield [13], the drift of electrons in the TPC volume under two Field Cage models with and without a guard ring has been simulated, and the deviation in the r direction of the positions where it starts and ends is also calculated. Fig. 4 provides the deviation result for electrons generated at different positions in the r-z plane. The drift length in the r direction is less than 0.01 cm (Fig. 4, left) in one-sided strips Field Cage with a proper guard ring. Without a guard ring, the electrons from outside the volume defined by the readout area also drift to the GEM foils (Fig. 4, right) or the Field Cage strips, giving the wrong projection information and worsening the performance.

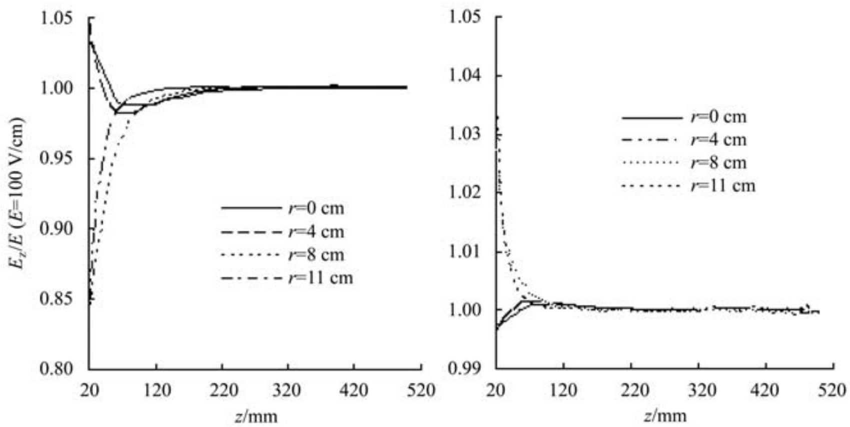

Fig. 3. E_z/E curves as a function of z. Left: without guard ring. Right: with guard ring.

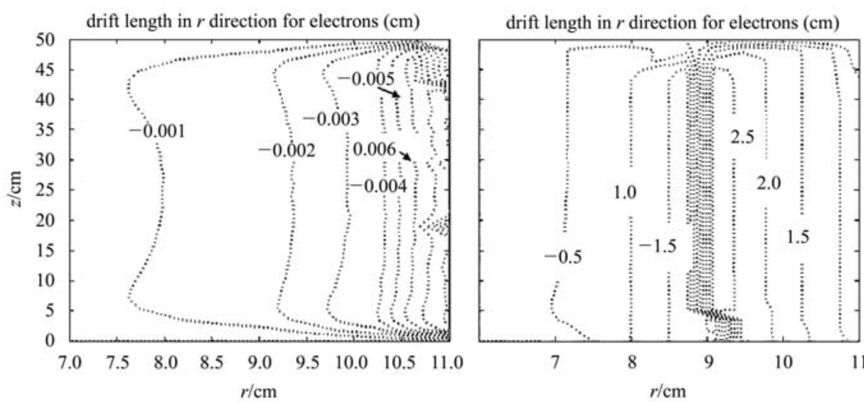

Fig. 4. Deviation in the r direction for electrons generated in different positions in one-sided strips Field Cage. Left: with a proper guard ring. Right: without a guard ring.

3 Modification on TU-TPC

Based on the above calculation and simulation results, TU-TPC has been modified with a new mirror strips Field Cage and a guard ring at z=10 mm, in order to improve the electric field condition and performance as well.

4 Performance test of TU-TPC

The performance of the old and modified TPCs has been tested and compared in order to demonstrate the effect of the new attempts.

4.1 Spatial resolution and N_{eff}

Figure 5 presents the results of transverse resolution using Ar/Iso/CF4(94/3/3) gas for the original and modified TPCs with different GEM voltages. An obvious decrease in σ_x is achieved in the modified TPC, especially for a large drift distance.

The x-resolution σ_x can be estimated with $\sigma_x^2 =$

$\sigma_0^2 + (C_D/\sqrt{N_{\rm eff}})^2 z$, in which C_D is the transverse diffusion and $N_{\rm eff}$ is the effective number of ionization electrons. Both of them are significant for x-resolution. Table 2 gives C_D and $N_{\rm eff}$ at different GEM voltages in this gas. Clearly, the transverse diffusion of the modified TPC is much less than that of the original one, and closer to the calculation result using Garfield (310 μm/$\sqrt{\rm cm}$). The effective number of ionization electrons is much bigger, beneficial to SNR (signal-to-noise ratio) of the charge signal and pad response.

Figure 6 presents the results of longitudinal resolution using the same gas for the original and the modified TPC prototypes with different GEM voltages. The longitudinal resolution has been improved a lot. For example, for the drift length of 300 mm, a decrease of 0.5 mm was obtained.

4.2 Effective readout area

In data analysis, after the hit position was calculated with the center of gravity, the data from different rows – 6 rows in the middle, 8 rows in the middle, and all 10 rows – were used to fit the tracks and estimate σ_x and σ_z. Table 3 shows σ_x for different drift lengths before and after the modification, while Table 4 shows the results for σ_z.

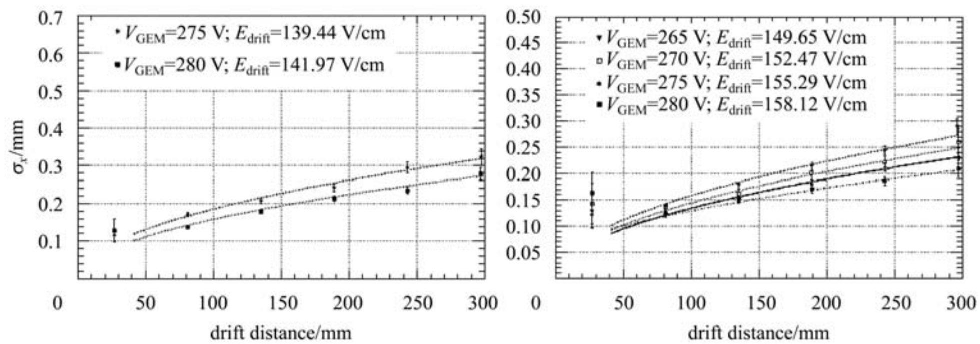

Fig. 5. The x-resolution using Ar/Iso/CF4(94/3/3) gas for the original (Left) and modified (Right) TPCs.

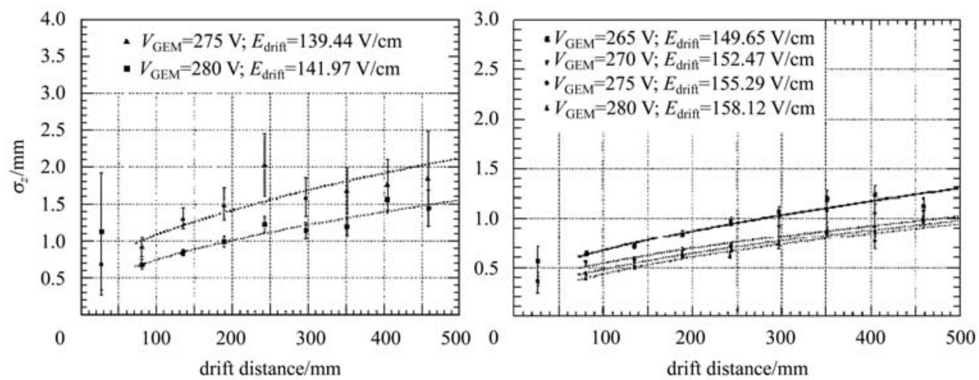

Fig. 6. The z-resolution using Ar/Iso/CF4(94/3/3) gas for the original (Left) and modified (Right) TPCs.

Table 2. C_D and $N_{\rm eff}$ at different $V_{\rm GEM}$ in Ar/Iso/CF4(94/3/3)("–" means no data).

	one-sided strips field cage		mirror strips field cage	
	$C_D/(\mu{\rm m}/\sqrt{\rm cm})$	$N_{\rm eff}$	$C_D/(\mu{\rm m}/\sqrt{\rm cm})$	$N_{\rm eff}$
$V_{\rm GEM}$(265 V)	–	–	287	32.9476
$V_{\rm GEM}$(270 V)	–	–	287	39.6127
$V_{\rm GEM}$(275 V)	359	20.2390	284	44.8647
$V_{\rm GEM}$(280 V)	357	28.8199	283	60.7798

Table 3. σ_x (mm) of different drift lengths in the original and modified TPCs ($V_{\rm GEM}$ =270 V).

	drift length/mm (original TPC)				drift length/mm (modified TPC)			
	81	189	296	404	81	189	296	404
Row#6	0.1984	0.3485	0.6092	0.6230	0.1211	0.1803	0.2399	0.3060
Row#8	0.1987	0.3425	0.5402	0.7010	0.1242	0.1696	0.2505	0.3000
Row#10	0.1991	0.3424	0.5410	0.6930	0.1274	0.1740	0.2585	0.2890

Through the comparison of σ_x and σ_z for different drift lengths in each fitting condition of 6, 8 and 10 rows, it is obvious that the spatial resolution is getting worse if we choose more rows to fit the tracks in the original TPC, especially σ_z. It is exciting to get basically constant spatial resolution when we decide to use more rows in the modified TPC. Clearly, the reform of the electric field has got much better spatial resolution in the whole GEM area.

Table 4. σ_z (mm) of different drift lengths in the original and modified TPCs (V_{GEM} =270 V).

	drift length/mm (original TPC)				drift length/mm (modified TPC)			
	81	189	296	404	81	189	296	404
Row#6	0.9252	1.5013	1.5964	1.7654	0.4347	0.6047	0.7210	0.8653
Row#8	1.5101	3.9147	4.3912	2.0564	0.4316	0.5797	0.7507	0.9224
Row#10	2.1404	3.7209	4.1385	2.0512	0.4707	0.6466	0.9568	0.9473

5 Conclusions

The electric fields in different models have been simulated, which indicate that the improvement with the reform of the Field Cage and the option of a guard ring; TU-TPC has been modified under the guidance of simulation studies and much better spatial resolution has been achieved in the whole GEM area. These simulation methods and results are proved effective in predicating TPC performance. This has accumulated useful experience for future GEM-TPC design and application.

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