Development of a time projection chamber using gas electron multipliers (GEM–TPC)

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Abstract

We developed a prototype time projection chamber using gas electron multipliers (GEM–TPC) for high energy heavy ion collision experiments. To investigate its performance, we conducted a beam test with three kinds of gases (Ar(90%)–CH\textsubscript{4}(10%), Ar(70%)–C\textsubscript{2}H\textsubscript{6}(30%) and CF\textsubscript{4}). Detection efficiency of 99%, and spatial resolution of 79\,\mu m in the pad-row direction and 313\,\mu m in the drift direction were achieved. The test results show that the GEM–TPC meets the requirements for high energy heavy ion collision experiments. The configuration and performance of the GEM–TPC are described.

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1. Introduction

High particle multiplicity is an important feature to be considered in detector designs for high energy heavy ion collision experiments. In $\sqrt{s_{NN}} = 200$\,GeV Au + Au collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, the average charged particle multiplicity (d$N_{ch}$/d$y|_{p_T=0}$) is 170 [1]. Therefore, average charged particle density is 0.03 cm\textsuperscript{-2} at a distance of 30 cm from the vertex. Additionally, experiments at RHIC are performed at a high event rate of about 10 kHz and the charged particle rate is 300 cps/cm\textsuperscript{2} at a distance of 30 cm from the vertex. This harsh environment demands highly efficient central tracking detectors.

A wide variety of observables are measured in high energy heavy ion collision experiments: such as charged particle multiplicities, yield ratios and spectra of identified hadrons, elliptic flow, suppression of high $p_T$ particle production and heavy flavor production [2]. Therefore, several particular features are required for the detectors used. A relatively wide transverse momentum range ($p_T \sim 0.2$–20\,GeV/c) is required to be covered to take in the broad interests of high energy heavy ion collisions and the magnetic field should be kept low ($\sim$1 T). However, good momentum resolution of $p_T/p_T^2 \sim 3 \times 10^{-3}$ (GeV/c)$^{-1}$ is required for future measurements, such as the $J$ state measurement at RHIC-II [3]. To achieve such good momentum resolution with a magnetic field of 1 T, a 1-m radius solenoidal tracker with spatial resolution of $\sim 200$\,\mu m is needed. Double track resolution is also required to be better than 1 cm to cope with the high
particle multiplicity. Such high flux operational and multi-hit capabilities have recently also been required in particle physics experiments [4].

One of the candidates as a detector that satisfies the above requirements is a combination of a time projection chamber (TPC), a sophisticated detector for particle tracking and particle identification, and micro patter gas detectors (MPGDs) [5] such as gas electron multipliers (GEMs) [6]. Although existing wire chambers need gating wires to collect positive ions and have limitations in their double track resolution by the wire spacing, the novel structure of a GEM has the following advantages in its application to TPC readout:

- Two dimensional symmetry of the GEM structure provides a large flexibility in the readout geometry.
- Large areas can be covered with a low amount of material since support mechanics for a GEM are simple.
- The intense electric field region will be limited inside the holes and the $E \times B$ effect is expected to be reduced. (In a strong magnetic field, this effect results in a broadening of the electron cloud and a worsening of the resolution.)
- The signal of the readout pad is induced by amplified electrons, and is spatially narrow and fast.
- The generated ions do not affect the signal and the ion tail of the signal will be suppressed.
- The positive ion feedback into the drift region can be suppressed by a factor of about 10 due to the electric field around the GEM holes and so gating wires might be unnecessary.

Therefore, a TPC using a GEM for signal amplification (GEM–TPC) may achieve high rate capability as well as excellent double track and spatial resolution. A GEM–TPC is a strong candidate to be a central tracking detector in high energy heavy ion collision experiments [7–11].

2. GEM–TPC prototype

2.1. Mechanical structure

A GEM–TPC prototype, consisting of an end cap chamber, a gas vessel and a field cage, was developed [12]. Photographs of the GEM–TPC prototype are shown in Fig. 1. Fig. 2 shows a schematic view of the GEM–TPC.

The end cap chamber mounts a triple GEM (the effective area is $10 \times 10 \text{cm}^2$) on readout pads. The triple GEM was constructed from GEM foils made at CERN [13]. As shown in Fig. 2, the gap between neighboring GEMs was 2 mm and the gap between the bottom GEM and the pads was 1.5 mm. High voltages are applied to the triple GEM through connectors penetrating the end cap chamber with a resistor chain. When the voltage across the GEMs ($V_{\text{GEM}}$) is 360 V, the electric fields in the transfer region and the induction region are $E_t = 360 \text{V}/2 \text{mm} = 1.8 \text{kV/cm}$ and $E_i = 360 \text{V}/1.5 \text{mm} = 2.4 \text{kV/cm}$, respectively. The operated drift electric field is shown in Table 1. Two kinds of readout pads with different shapes, rectangle and chevron (zigzag), were used to study the dependence of...
the spatial resolution on shape (see Fig. 3). Since chevron pads may increase the number of hits on pads by charge sharing, chevron pads are expected to have better spatial resolution than rectangular ones [14]. Both kinds of pads, both made of gold-plated copper, have the same area of $1.09 \times 12.0 \text{ mm}^2$ and the same pitch of 1.27 mm. Relatively narrow width pads are required for charge sharing for small diffusion gases such as CF$_4$ [12,15].

The field cage is a cuboid with dimensions of $36 \times 17 \times 17 \text{ cm}^3$ and creates a uniform electric drift field. The electric field uniformity is $|E_{\text{avg}}(E_{\perp})| \leq 1 \text{ mm}$ in the center area of $10 \times 10 \text{ cm}^2$ which corresponds to the GEM effective area. The field cage consists of 115 gold-plated copper strips connected with 1-M$\Omega$ resistors in series on FR4 boards. At the end of the resistor chain, additional resistors are placed to match the voltage at the bottom of the field cage with the surface voltage of the top GEM.

The gas vessel is made of aluminum plates and has a volume of $60 \times 29 \times 29 \text{ cm}^3$.

### 2.2. Front end electronics

A charge sensitive preamplifier, consisting of two kinds of operational amplifiers (AD8058 and AD8132, Analog Devices, Inc.), was used for the GEM–TPC. Its time constant is $\tau = 1 \mu\text{s}$ and its effective gain $G = 3.2 \text{ V/pC}$. The gain of the preamplifier was determined from the expected signal amplitude and the dynamic range (0~−1 V) of a flash ADC (FADC) module (RPV-160, REPIC Co., Ltd.). The resolution and the sampling rate of the FADC are 8 bits and 100 MHz, respectively. Signals from 24 pads (3 rows × 8 columns) are transmitted from the preamplifiers to the FADCs through 8-m shielded twisted cables.

### 2.3. Gas

Three kinds of gases with different properties, a mixture of argon(Ar)(90%)–methane(CH$_4$)(10%) (commonly called P10), a mixture of argon(Ar)(70%)–ethane(C$_2$H$_6$)(30%) and pure tetrafluoromethane(CF$_4$) gas, were used to study the performance of the GEM–TPC. Properties of these gases are shown in Table 1. Drift velocities and diffusion coefficients were calculated by Magboltz [16].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ar(90%)-CH$_4$(10%)</th>
<th>Ar(70%)-C$_2$H$_6$(30%)</th>
<th>CF$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift velocity (cm/μs)</td>
<td>5.48</td>
<td>4.02</td>
<td>8.90</td>
</tr>
<tr>
<td>Transverse diffusion (μm/√cm)</td>
<td>570</td>
<td>306</td>
<td>104</td>
</tr>
<tr>
<td>Longitudinal diffusion (μm/√cm)</td>
<td>378</td>
<td>195</td>
<td>82</td>
</tr>
<tr>
<td>Mean energy for ion-electron pair production (eV)</td>
<td>26</td>
<td>26</td>
<td>54</td>
</tr>
</tbody>
</table>

Fig. 3. Readout pad layout. There are three rows × ten columns for both rectangular and chevron pads. The outer two columns are not read out. Each pad has an area of $1.09 \times 12.0 \text{ mm}^2$. The drift direction is shown in the figure.
high energy heavy ion collision experiments. However, a high electric field is needed to achieve a fast drift velocity with CF$_4$.

The gas flow rate was set at ~200 ml/min using a mass flow controller (SEC-E40, ESTEC Co., Ltd.). Gas pressure was set at the atmospheric pressure using a bubbler filled with silicone oil.

Effective gas gains were measured using an $^{55}$Fe X-ray (5.9 keV) source. An X-ray creates primary electrons by a photoelectric effect with a gas molecule. The obtained $^{55}$Fe X-ray charge spectrum with CF$_4$ is shown in Fig. 4. The spectrum around the 5.9-keV peak is fitted by a Gaussian function and the gain $G$ is calculated as

$$G = \frac{\langle Q \rangle}{e} \frac{W}{5.9\text{keV}}$$

where $\langle Q \rangle$ stands for the mean of the Gaussian function, $e$ is the electron charge, and $W$ is the mean energy for ion–electron pair production and is given in Table 1. The obtained $^{55}$Fe X-ray charge spectrum with CF$_4$ is shown in Fig. 4. The energy resolution is $\sigma_E/E = 13\%$.

The characteristics of the GEM–TPC evaluated in the performance test were detection efficiency, spatial resolution in the pad-row direction and the drift direction and particle identification capability by dE/dx measurement. The dependence of these characteristics on the three kinds of gases (Ar(90%)-CH$_4$(10%), Ar(70%)-C$_2$H$_6$(30%) and CF$_4$), the GEM gain ($6 \times 10^2$–$2 \times 10^4$), the drift length (20–290 mm), the readout pad shape (rectangle and chevron), the beam momentum (0.5–3.0 GeV/$c$) and the beam rate was also evaluated. Except for the GEM gain dependence measurement, $V_{\text{GEM}}$ was fixed to 332, 341 and 498 V for Ar–CH$_4$, Ar–C$_2$H$_6$ and CF$_4$, respectively.

Fig. 5 shows a typical signal of the GEM–TPC operated with Ar–C$_2$H$_6$. The signal was recorded for 640 samples (= 640 samples) in one event. One channel of the ADC corresponded to ~4 mV. To extract the pulse height and the arrival time of the signal, the following function is fitted to the FADC spectrum,

$$\text{ADC}(t) = p_0 + p_1 \cdot \exp(-t - p_2)/p_3$$

where $t$ is sampling time. The fitting parameters in the above function can be recognized as follows: $p_0$ is the pedestal, $p_1$ is the pulse height, $p_2$ is the arrival time, $p_3$ is

3. Performance test

A beam test was performed at the π2 secondary beam line of the 12-GeV Proton Synchrotron at KEK (KEK-PS) to evaluate the basic performance of the GEM–TPC.

The characteristics of the GEM–TPC evaluated in the performance test were detection efficiency, spatial resolution in the pad-row direction and the drift direction and particle identification capability by dE/dx measurement. The dependence of these characteristics on the three kinds of gases (Ar(90%)-CH$_4$(10%), Ar(70%)-C$_2$H$_6$(30%) and CF$_4$), the GEM gain ($6 \times 10^2$–$2 \times 10^4$), the drift length (20–290 mm), the readout pad shape (rectangle and chevron), the beam momentum (0.5–3.0 GeV/$c$) and the beam rate was also evaluated. Except for the GEM gain dependence measurement, $V_{\text{GEM}}$ was fixed to 332, 341 and 498 V for Ar–CH$_4$, Ar–C$_2$H$_6$ and CF$_4$, respectively.

Fig. 6 shows a schematic view of the detector setup for the performance test. Three plastic scintillation counters (S1, S2 and S3) were used for event triggering and time of flight measurements for particle identification. Two gas Cherenkov counters (GCC1 and GCC2) filled with 2.5-atm CO$_2$ gas were used for electron identification. Two silicon strip detectors (SSD1 and SSD2), each of which consists of two single-sided strips (strip pitch of 80 µm) crossing at right angles, were used for particle tracking. Two hadron blind detectors (HBD1 and HBD2) were tested at the same time and the results are shown in Ref. [20]. The GEM–TPC was operated without a magnetic field.

Fig. 7 shows a typical signal of the GEM–TPC operated with Ar–C$_2$H$_6$. The signal was recorded for 64 μs (640 samples) in one event. One channel of the ADC corresponds to ~4 mV. To extract the pulse height and the arrival time of the signal, the following function is fitted to the FADC spectrum,

$$\text{ADC}(t) = p_0 + p_1 \cdot \exp(-t - p_2)/p_3$$

where $t$ is sampling time. The fitting parameters in the above function can be recognized as follows: $p_0$ is the pedestal, $p_1$ is the pulse height, $p_2$ is the arrival time, $p_3$ is
the time constant of the electronics and $p_4$ is the rise time. The obtained pulse height and arrival time are used for determinations of the hit position. The hit position in each pad row is determined by an amplitude weighted mean of pad positions and arrival times:

\[ x_i = \frac{\sum_{j=0}^{S-1} p_{1,ij} \cdot j \cdot D}{\sum_{j=0}^{S-1} p_{1,ij}} \]  

(3)

in the pad-row direction and

\[ z_i = \frac{\sum_{j=0}^{S-1} p_{1,ij} \cdot p_{2,ij} \cdot t_{\text{drift}}}{\sum_{j=0}^{S-1} p_{1,ij}} \]  

(4)

in the drift direction, where $p_{k,ij}$ is the $k$th parameter of the $i$th row and the $j$th column pad ($0 \leq i < 3$ and $0 \leq j < 8$), $D = 1.27$ mm is the pad spacing (see Fig. 3) and $t_{\text{drift}}$ is the drift velocity.

4. Results

4.1. Detection efficiency

Single-pad-row detection efficiency was measured as a function of $V_{\text{GEM}}$ with the three kinds of gases. Measurements were done with 1-GeV/c $\pi^-$ beams with a drift length of 20 mm with Ar–CH$_4$ and 85 mm with both Ar–C$_2$H$_6$ and CF$_4$. Tracks having hits in the first and third pad rows were selected for the efficiency evaluation, and the fraction of the hits in the second pad row was used as the detection efficiency. Results are shown in Fig. 8. The detection efficiency reaches a plateau at a gain of $\sim 4 \times 10^3$ with Ar–CH$_4$ and Ar–C$_2$H$_6$. The small diffusion of CF$_4$ makes the efficiency reach a plateau at a smaller gain of $\sim 2 \times 10^3$. The efficiency plateaus are 99.3%, 99.6% and 99.8% with Ar–CH$_4$, Ar–C$_2$H$_6$ and CF$_4$, respectively. These results are very similar to results from another research group findings of Ar(70%–CO$_2$(30%)) and Ar(93%–CH$_4$(5%–CO$_2$)(2%)) [10].

The gain scales for Ar–CH$_4$ and Ar–C$_2$H$_6$ in Fig. 8 are determined by the obtained gain–$V_{\text{GEM}}$ relation in Fig. 5 and the one for CF$_4$ is determined by measured pulse heights using the relation between the gains and measured pulse heights with Ar–CH$_4$ and Ar–C$_2$H$_6$. The gain with CF$_4$ in Fig. 8 is larger than the one in Fig. 5. This difference may be due to differences of the atmospheric pressure $p$ and the temperature $T$ because the GEM gain strongly depends on $p/T$ [19]. Unfortunately, the atmospheric pressure and the temperature were not monitored during the performance test.

4.2. Transverse diffusion coefficient

Transverse diffusion coefficients were measured with 1-GeV/c $\pi^-$ beams. The coefficients are evaluated using the spatial distribution of secondary electrons in the pad-row direction. The secondary electron distribution is fitted by a Gaussian distribution. The obtained sigma of Gaussian, $s_x$, can be expressed as

\[ s_x^2(L) = s_{x0}^2 + C_{DT} \cdot L \]  

(5)

where $L$ is the drift length, $C_{DT}$ is the transverse diffusion coefficient and $s_{x0}$ is the intrinsic width of the induced charge distribution determined by the readout system configuration. Fig. 9 shows $s_x^2$ as a function of the drift length. The measured $s_{x0}$ and $C_{DT}$ are shown in Table 2. The measured values of $C_{DT}$ of Ar–C$_2$H$_6$ and CF$_4$ agree well with the calculated values of $C_{DT}$ shown in Table 1; however, for Ar–CH$_4$ the measured one is slightly smaller than the calculated one.

4.3. Spatial resolution

Single-pad-row spatial resolution in the pad-row and drift directions was evaluated for a drift length range of 20–290 mm with 1-GeV/c $\pi^-$ beams. The single-pad-row spatial resolution in both directions was evaluated by the
residual between the hit position of the second pad row and the interpolated hit position from the first and third pad rows. The measured spatial resolution is shown in Fig. 10. The effect of diffusion on the spatial resolution in both directions is clearly seen. The best resolution is 79 μm in the pad-row direction and 313 μm in the drift direction, obtained with Ar–C₂H₆ gas and rectangular pads at 13-mm drift. The spatial resolution of the chevron pads is almost the same as that of the rectangular ones. If the charge distribution is Gaussian, the spatial resolution of the chevron pads should be better than that of the rectangular ones [14]. A possible reason for the result obtained is that the finite sizes of the GEM holes distort the charge distribution from a Gaussian distribution and

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pad shape</th>
<th>σₓ (μm)</th>
<th>C_DT (μm/√cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar(90%)-CH₄(10%)</td>
<td>Chevron</td>
<td>385 ± 101</td>
<td>508 ± 7</td>
</tr>
<tr>
<td>Ar(90%)-CH₄(10%)</td>
<td>Rectangle</td>
<td>387 ± 101</td>
<td>505 ± 7</td>
</tr>
<tr>
<td>Ar(70%)-C₂H₆(30%)</td>
<td>Rectangle</td>
<td>402 ± 43</td>
<td>317 ± 4</td>
</tr>
<tr>
<td>CF₄</td>
<td>Chevron</td>
<td>383 ± 37</td>
<td>107 ± 6</td>
</tr>
</tbody>
</table>

The effect of diffusion on the spatial resolution in both directions is clearly seen. The best resolution is 79 μm in the pad-row direction and 313 μm in the drift direction, obtained with Ar–C₂H₆ gas and rectangular pads at 13-mm drift. The spatial resolution of the chevron pads is almost the same as that of the rectangular ones. If the charge distribution is Gaussian, the spatial resolution of the chevron pads should be better than that of the rectangular ones [14]. A possible reason for the result obtained is that the finite sizes of the GEM holes distort the charge distribution from a Gaussian distribution and
so the non-Gaussian tails worsen the spatial resolution of the chevron pads.

The dependence of the spatial resolution in the pad-row direction on the drift length of $L$ can naively be understood as

$$\sigma_x^2(L) = \sigma_{x0}^2 + C_{DT}^2 \cdot L/N_{\text{eff}}$$

where $\sigma_{x0}$ is the extrapolated resolution at a zero drift length and $N_{\text{eff}}$ is the effective number of secondary electrons [11]. $N_{\text{eff}}$ is mainly determined by the number of secondary electrons, $N$, and pad geometry [21]. The calculated number of secondary electrons, $N$, and the measured number of effective secondary electrons, $N_{\text{eff}}$, for 1-GeV/$c\ \pi^-$ beams and a track length of 12 mm are shown in Table 3. A small fraction of the secondary electrons effectively contribute to spatial resolution.

### 4.4. Beam rate dependence

One of the advantages of the GEM–TPC is its ion feedback suppression. The effect of ion feedback on GEM–TPC performance was studied by measuring the beam rate dependence of the detection efficiency and spatial resolution. The beam rate was determined by the beam slit width and the rate was monitored with the S2 scintillator $(2.5 \times 2.5 \text{cm}^2)$. The beams of $e^+$, $\pi^+$ and $p$ at a momentum of 2 GeV/$c$ and Ar–CH$_4$ gas were used, while the drift length was 85 mm. The results are shown in Fig. 11. The results of the detection efficiency and the spatial resolution in the previous subsections were obtained with a beam rate of $500 \text{ cps/cm}^2$. At the maximum beam rate of $4800 \text{ cps/cm}^2$, the detection efficiency and the spatial resolution were worsened by factors of $2.5 \pm 0.5\%$ and $11 \pm 3\%$, respectively. The maximum total beam rate in the active GEM–TPC region was in the order of $10^4 \text{ cps}$.

This result is worse than the results from the other research group with beams of $1.5 \times 10^5 \text{ cps/cm}^2$ [7]. Because of the limited readout area of our GEM–TPC $(1 \times 3.6 \text{ cm}^2)$, it was not possible to fully distinguish double

![Graph showing spatial resolution in pad-row and drift direction](image)

**Fig. 10.** Spatial resolution in the pad-row direction (top) and the drift direction (bottom).

**Table 3**

The number of effective secondary electrons, $N_{\text{eff}}$, and the number of secondary electrons, $N$, for 1-GeV/$c\ \pi^-$ beams and the track length of 12 mm

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pad shape</th>
<th>$N_{\text{eff}}$</th>
<th>$N$</th>
<th>$N_{\text{eff}}/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar(90%)–CH$_4$ (10%)</td>
<td>Chevron</td>
<td>31 ± 1</td>
<td>119</td>
<td>0.26 ± 0.01</td>
</tr>
<tr>
<td>Ar(90%)–CH$_4$ (10%)</td>
<td>Rectangle</td>
<td>30 ± 1</td>
<td>119</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>Ar(70%)–C$_2$H$_6$ (30%)</td>
<td>Rectangle</td>
<td>31 ± 1</td>
<td>113</td>
<td>0.23 ± 0.01</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>Chevron</td>
<td>86 ± 23</td>
<td>147</td>
<td>0.58 ± 0.15</td>
</tr>
</tbody>
</table>

![Graph showing detection efficiency and spatial resolution vs beam rate](image)

**Fig. 11.** Dependence of the detection efficiency (top) and the spatial resolution (bottom) on the beam rate.
tracks, which worsened the detection efficiency and the spatial resolution.

The beam rate exceeds the typical rates in $\sqrt{s_{NN}} = 200\text{ GeV } \text{Au} + \text{Au}$ collisions at RHIC and $\sqrt{s_{NN}} = 5.5\text{ TeV } \text{Pb} + \text{Pb}$ collisions at LHC, which are 300 cps/cm$^2$ and 1400 cps/cm$^2$, respectively, at a distance of 30 cm from the vertex. Since 4800 cps/cm$^2$ is much larger than these numbers, the effect of the ion feedback on the GEM–TPC performance can be regarded as negligible for our purpose.

4.5. Particle identification using dE/dx

Energy losses, dE/dx, were measured for positrons, muons, pions, protons and deuterons in a beam momentum range of 0.5–3.0 GeV/c to evaluate the particle identification capability. In this measurement, the drift length was 85 mm and Ar–CH$_4$ was used. The summation of pulse heights for three pad rows is regarded as the energy loss. Since there was a time variation in the GEM gain (30% peak to peak, for 5 h), the measured value of the mean pulse height, $\langle PH \rangle_{\text{meas}}^i (i = e^+, \mu^+, \pi^+, p, d)$, was corrected with pions at each momentum to eliminate the effect of this time variation as follows:

$$
\langle PH \rangle_{\text{corr}}^i = \frac{\langle PH \rangle_{\text{meas}}^i}{\langle PH \rangle_{\text{exp}}^i / \langle PH \rangle_{\text{meas}}^i} \tag{7}
$$

where $\langle PH \rangle_{\text{corr}}^i$ is the corrected mean pulse height and $\langle PH \rangle_{\text{exp}}^i$ is the expected mean pulse height. Fig. 12 shows the corrected mean pulse heights and curves of the expected mean pulse heights. As previously mentioned, the gain variation may be due to the change of $p/T$. Another candidate as a reason for the gain variation is the charging-up of the insulator of a GEM foil [22].

To estimate the particle identification capability of a large GEM–TPC, a Monte-Carlo simulation was performed using measured pulse height spectra for 1-GeV/c pions and protons. To improve the energy resolution, a truncated mean method, where 8 of the pad rows having the largest signals are removed, was used. Energy resolution of pions will be 9% and the pion rejection factor with 99% proton efficiency is expected to be 200 with a 50-cm track length. This energy resolution is comparable with that of the STAR TPC (8%) with a track length of more than 67 cm [17].

5. Conclusion

A GEM–TPC prototype was constructed to develop a tracking detector for use in high event rate and high particle multiplicity environments in high energy heavy ion collisions.

To evaluate the performance of the GEM–TPC, a beam test was performed at KEK. Detection efficiency of $\geq 99.3\%$ was achieved with three kinds of gases, Ar(90%–CH$_4$ (10%), Ar(70%–C$_2$H$_6$ (30%)) and CF$_4$. Spatial resolution of 79 m in the pad row direction and 313 m in the drift direction was achieved with Ar–C$_2$H$_6$ and rectangular pads for 13-mm drift. The GEM–TPC showed high detection efficiency and good spatial resolution with a particle rate of 4800 cps/cm$^2$, which exceeds the particle rate of RHIC and the LHC. Energy loss measurements showed a good particle identification capability.

These results indicate that the GEM–TPC meets the requirements for central tracking detectors for use in the next generation of high energy heavy ion collision experiments.

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