The spatial resolution in the first beam test of a GEM-based readout module for the ILD-TPC equipped with a large aperture GEM-like gating device

Yumi Aoki (SOKENDAI/KEK) on behalf of the LCTPC collaboration
2018.3.20 Annual meeting @ KEK
Outline

We checked performances of the module with the gating GEM
  · Spacial resolution (Y.Aoki)
  · dE/dx (A.Shoji)
  · Amplification GEM optimization by simulation (T.Ogawa)
I mainly talk about the spacial resolution

1. About TPC
2. Momentum Resolution Goal
   & Ion Feedback Problem
3. A large aperture GEM-like gating device
4. Beam test
5. Results - Pad response
6. Results - Spacial resolution
7. Summary
## Presentation

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<tr>
<th>Month</th>
<th>Name</th>
<th>URL</th>
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<td>Shoji</td>
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**International Linear Collider**
Electron positron Collider (250~500 GeV)

http://www.linearcollider.org/images/

**Time Projection Chamber**
- reconstruct tracks, measure their momentum and dE/dx.
  (charged particles)

**International Large Detector**
TPC

- Readout modules
  - Amplification device
  - Anode

E field
B field 3.5 T
E field 230 V/cm

About 2 m
About 2.2 m

T2K gas  Ar : CF4 : iC4H10 = 95 : 3 : 2

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Momentum Resolution Goal

Momentum resolution Goal: \[ \sigma \frac{1}{P_T} = 1 \times 10^{-4} GeV^{-1} \]

Glueckstern Formula

\[
\frac{\sigma_{P_T}}{P_T} \sim \sqrt{\left( \frac{\alpha' \sigma_x}{BL^2} \right)^2 \left( \frac{720}{n+4} \right) P_T^2 + \left( \frac{\alpha'C}{BL} \right)^2 \left( \frac{10}{7} \left( \frac{X}{X_0} \right) \right)}
\]

Momentum resolution depends on Position resolution \( \sigma_x \), Measurement points \( n \), Magnetic field \( B \), Lever arm length \( L \)

ILC-TPC: \( n = 220 \) points \( B = 3.5 \) T \( L = 1.5 \) m

Spatial resolution goal: \( \sigma_{r\phi} < 100 \mu m \)

However the ion feedback prevent us to achieve this goal
Ion Feedback Problem

Positive ions created by gas amplification back-flow into the drift volume → distort electric field → deteriorate position resolution

The ions for a single bunch train form a disk with about 1cm thickness. Since the ion drift velocity is $O(1000)$ times slower than that of electrons, there will be up to 3 ion disks in the drift volume. Hit point distortion due to the 3 ion disks: $60 \mu m$
A Large Aperture GEM-like Gating Device

※ developed this with FUJIKURA company.

Gating GEM: the insulator sheet put between capper electrodes.

It works by adding electric potential difference to copper electrode.

honeycomb structure

Gate OPEN
Gate CLOSE

1 train = 1321 bunches

200 ms
0.73 ms
50 μs

554 ns
Beam test

Purpose: check performances of the module with the gating GEM

Oct.31-Nov.13, 2016 (beam time) @DESY TPC large prototype

The first beam test of a GEM-readout TPC module with a gating GEM

20 participants from Japan, France, Germany, China, Sweden
The electron beam passes two trigger counter and through the prototype. The sensitive volume of the TPC is inside a solenoid. The TPC is mounted on a movable stage so we can change drift distance ($Z$) and two angles, $\theta$ and $\phi$. 

DESY Large TPC Prototype Test Facility

PCMAG(1T solenoid) from KEK

Electron beam (5 GeV)

Modules

Stage

Trigger counters
Module with Gating GEM

The Module

Gating GEM

Amplification GEM
100μm thickness

Gating GEM
(or a field shaper when data were taken without gate)

Pad plane(anode)
The data I analyzed in this study

<table>
<thead>
<tr>
<th>Center Module</th>
<th>with gatingGEM</th>
<th>without gatingGEM</th>
</tr>
</thead>
</table>

| Z[cm] (Drift distance) | 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 55 |
| φ [degree]             | 0 |
| θ [degree]             | 0 |
| $V_{gate}$[V]          | 3.5 |
| B[T]                   | 1 |

Beam: 5 GeV electron beam  
Gas: T2K gas (Ar : CF$_4$ : Iso-C$_4$H$_{10}$ = 95 : 3 : 2 [%])  
Flame work: MarlinTPC (20000 event/1 run)
The beam goes through our module with the gating GEM in the region far enough from the module boundaries.
Event Selection

Track angle cut [rad]

$4.64 < \phi_{0\text{loc}} < 4.72$

I applied a track angle cut to exclude angled tracks and a cut on nTrks to eliminate events with multiple tracks caused by electromagnetic showers created upstream.
The difference between Cd of with gate and its of without gate is significant. They should be almost same.

→We are trying to find the reason.
GM Resolutin (Module3 Row16)

\[ \sigma_x = \sqrt{\sigma_0^2 + \left( \frac{C_D}{\sqrt{N_{\text{eff}}}} \right) z} \]

\( \chi^2/\text{ndf} = 6.53/6 \)
\( \sigma_0 = 54.6 \pm 2.4 \) [\( \mu m \)]
\( C_D/\sqrt{N_{\text{eff}}} = 18.6 \pm 0.21 \) [\( \mu m/\sqrt{\text{cm}} \)]

\( \chi^2/\text{ndf} = 3.59/6 \)
\( \sigma_0 = 55.1 \pm 2.2 \) [\( \mu m \)]
\( C_D/\sqrt{N_{\text{eff}}} = 17.8 \pm 0.21 \) [\( \mu m/\sqrt{\text{cm}} \)]
The extrapolation to B=3.5 T

- Extrapolation to 3.5T based on 1.0T data
- Ar:CF$_4$:iC$_4$H$_{10}$ = 95:3:2
- Finite pad width = 1.15 mm
- (a) $\sigma_{\text{PRF}} = 0.210$ mm (ILD-TPC configuration) MIP
- (b) $\sigma_{\text{PRF}} = 0.277$ mm re-optimized case
- Polya$\theta$ = 0.6
- $C_g = 27$ $\mu$m/\sqrt{cm}$ (B = 3.5T)
- Neff = 23.4 / 1.4

5 GeV electron $\rightarrow$ MIP

(a) Extrapolate prototype directly

(b) Optimize to keep $\sigma_{\text{PRF}}$ in 1T

When we decide hit points by center of gravity, the graph is (a) because of bias.

When we optimize to keep $\sigma_{\text{PRF}}$ in 1T, we get graph (b)

$\rightarrow$ The spatial resolution (100 $\mu$m) can be achieved
Summary

We checked performances of the module with the gating GEM by analyzing beam test data in this fiscal year.

- The extrapolation of the beam test result to 3.5 T/2.2 m drift ILD-TPC shows that achieve spatial resolution goal of 100 μm with the gating GEM.

Future work

- Understand Cd difference
- Analyze angled data
Back up Slides
Diffusion Constant

To reduce short term effect, I calculated $\sigma_{r\phi} + \sigma_{PR}$. The difference of $C_D$ is less than its by ordinary way.
Readout Pads

- Gating GEM
- Amplification GEM
- Pad plane (anode)

Upper part: 192 Pads/Row
Lower part: 176 Pads/Row

1 Pad: 5.26 mm
About 1.2 mm
28 Rows
We achieved the target electron transmission rate of > 80%.

We get about 86 % electron transmission rate with gating GEM.

### Table 1: Electron Transmission Rate

<table>
<thead>
<tr>
<th></th>
<th>Cd (w/ gate) [µm/√cm]</th>
<th>Cd (w/o gate) [µm/√cm]</th>
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<tbody>
<tr>
<td>measurement</td>
<td>90.05±0.25</td>
<td>92.7±0.25</td>
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<table>
<thead>
<tr>
<th>Cd/√Neff</th>
<th>w/ gate</th>
<th>w/o gate</th>
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<tr>
<td>Cd/√Neff</td>
<td>18.6±0.3</td>
<td>17.8±0.3</td>
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<table>
<thead>
<tr>
<th>Cd [µm/√cm]</th>
<th>Neff (w/ gate)</th>
<th>Neff (w/o gate)</th>
<th>ratio [%]</th>
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<tbody>
<tr>
<td>measurement</td>
<td>23.4±0.6</td>
<td>27.2±0.8</td>
<td>86.4±3.1</td>
</tr>
</tbody>
</table>
Cd vs Row
Field shaper
Data quality check - Hit efficiency

- Mi

With Gating GEM

Very preliminary

More statistics necessary to reduce the errors (now 2000 events)

Error: $\sqrt{\frac{\eta(1-\eta)}{N}}$
Hit efficiency estimation

Looked at row-16 (module 3)

7 rows away to avoid effects by the diffusion.

Basic idea:

Test if Row16 has a hit associated with a track that has hits both on Row9 and Row23.

To reduce biases, minimum number of hits per track is set to be a relatively small value (=10) in the track reconstruction step.
Drift velocity

Very preliminary

\[ \approx 7.5 \text{ cm/}\mu\text{s} \]

Garfield simulation

W/ gate  76.7 cm/\mu s +/- 0.0013%

W/O gate  7.68 cm/\mu s +/- 0.0022%

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<tr>
<th></th>
<th>W/ gate</th>
<th>W/O gate</th>
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<tbody>
<tr>
<td>Temp [K]</td>
<td>291.28</td>
<td>290.4</td>
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<tr>
<td>Pres [hPa]</td>
<td>1010.79</td>
<td>1005.31</td>
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There seems to be no electron attachment (P/T correction is not included)
Hodoscope effect

Hodoscope is one of the tracker.
The detector using scintillators.
(not using the center of gravity method)
Therefore, we call the single pad effect “hodoscope effect”.

\[
\sigma_{\phi} = \sqrt{\sigma_0^2 + \left(\frac{C_D}{\sqrt{N_{\text{eff}}}}\right)^2 z^2}
\]

\[\chi^2/\text{ndf} = 8.07/6\]
\[\sigma_0 = 57.2 \pm 2.3 \text{ [\mu m]}\]
\[C_D/\sqrt{N_{\text{eff}}} = 18.2 \pm 0.22 \text{ [\mu m/\sqrt{cm}]}\]

\[\chi^2/\text{ndf} = 12.1/6\]
\[\sigma_0 = 59.5 \pm 2.2 \text{ [\mu m]}\]
\[C_D/\sqrt{N_{\text{eff}}} = 17.2 \pm 0.23 \text{ [\mu m/\sqrt{cm}]}\]
1996 Fabio Sauli (CERN) developed GEM

We can amplify electrons by using several GEM
However · · · Positive ion is also created

Make high electric field in GEM holes by HV
Electrons accelerate, collide and ionize gas molecules
(=avalanche)
Data Quality Cuts

Charge-weighted hit position

exclude row number 0, 22, 27.

Row 0, 27 may have distortion of electric field because they are the edge of module.

Row 22 has dead pad.
$B = 0 \text{T}$

Electron Transmission rate [%]

- Errors are statistical only.
- The curves are only to guide the eye.

- Black circle: $^{55}\text{Fe}$
- Red square: Laser
- Green - Blue simulation

Gate-GEM Voltage [V]

Electron transmission [%]

- (Exp) $B = 0.0 \text{T}, E_{\perp} = E_{\parallel} = 230 \text{ V/cm}$
- (Exp) $B = 1.0 \text{T}, E_{\perp} = E_{\parallel} = 230 \text{ V/cm}$
- (Sim) $B = 0.0 \text{T}, E_{\perp} = E_{\parallel} = 230 \text{ V/cm}$
- (Sim) $B = 1.0 \text{T}, E_{\perp} = E_{\parallel} = 230 \text{ V/cm}$
- (Sim) $B = 3.5 \text{T}, E_{\perp} = E_{\parallel} = 230 \text{ V/cm}$

ANSYS+Garfield++: Hexagonal holes, $335 \mu \text{m}$ pitch, $29 \mu \text{m}$ rim-width, PI $12.7 \mu \text{m}$ thick
Ar Cross Section
That used in Magboltz

\[ \sigma_{Ar}^0 \approx \pi r(3)^2 \]
\[ \approx \pi (1.5 \times 10^{-8} [\text{cm}])^2 \]
\[ \approx 7.1 \times 10^{-16} [\text{cm}^2] \]

\[ R_{Ar} = 1.8 \times 10^{-8} [\text{cm}] \text{ (exp.)} \]

\[ \epsilon_{dip} \approx \frac{1}{2} m \left( \frac{e \alpha_{\text{QED}}}{n} \right)^2 \approx 1.5 [\text{eV}] \]
$D_T = D_L$
Data analysis & Result

1. Event Reconstruction
   - Hit Reconstruction
   - Track Reconstruction
   - Data Quality Cuts

2. How to calculate Spatial Resolution

3. How to estimate the election transmission

4. Result
Event Reconstruction

- Cluster making
  - make cluster from ADC

- Hit making
  - determine the hit point by center of gravity
  - Coordinate calculation

- Track finding + fitting
  - determine the track parameter
Cluster making

- make cluster from ADC

Time direction
  Set pedestal $\sigma$ as the standard (This time, $\sigma = 0.5$)
  The time bins above the threshold: $3\sigma$ are regarded as a cluster
  However if the peak ADC below the threshold 3 ADC counts, it is not regarded as a hit
  We include in the cluster, the 1 time bin before the first time bin above the threshold, and the 3 bins after the last time bin above the threshold.
Hit making

Pad row direction

We collect all time clusters in the row direction which are touching each other.

However if the peak cluster below the threshold 12 ADC counts, it is not regarded as a hit.
Hit making

Coordinate calculation

① Row direction
Determine the hit coordinate by the center of gravity in the pad row direction

\[
C.O.G = \frac{\sum (Q_i \cdot x_i)}{\sum Q_i}
\]

② Time
the inflection point
\[
t = \mu - \sigma
\]
(50 ns/1 bin)
Track Reconstruction

We use Kalman filter to reconstruct tracks (MyTrackMakingKalmanFilterProcessor)

① Find a hit point around a predicted area

② Fit tracks

③ Get 5 track parameters

\[ \mathbf{a} \equiv (d_\rho, \phi_0, \kappa, d_z, \tan \lambda)^T \]

- \( d_\rho \) : The distance between pivot and track in the plane vertical from z-axis
- \( \phi_0 \) : Azimuthal angle of the pivot to the center of the helix
- \( \kappa \) : Q/Pt (transverse momentum)
- \( d_z \) : The distance between pivot and track in z-axis
- \( \tan \lambda \) : The dip angle from vertical plane to helix axis
How to get spatial resolution

$$\sigma_{r\phi} = \sqrt{\sigma_{r\phi(in)} \sigma_{r\phi(out)}}$$

- $\sigma_{r\phi(in)}$: hit in question included in the track fit
- $\sigma_{r\phi(out)}$: excluded from the fit

![Graph showing hit point and track with residual](image)

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<td>Mean</td>
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<td>RMS</td>
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<td>RMS</td>
<td>0.1438</td>
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Neff : Effective number of ionization electrons which decides spatial resolution

\[
N_{\text{eff}} = \left( \frac{1}{N} \right) \left( \frac{G}{\bar{G}} \right)^2 \right]^{-1}
\]

G : gas amplification
\( \bar{G} \) : average of gas amplification

Ratio of Neff \( \approx \) Electron transmission ratio

\[
\frac{N_{\text{eff}}(\text{w/ Gate})}{N_{\text{eff}}(\text{w/o Gate})} \approx R_{e.t.}
\]
How to get Neff

For large enough drift distances, spatial resolution with respect to drift distance can be written in the following form

\[ \sigma_{r\phi}(Z) = \sqrt{\sigma_0^2 + \frac{C_d^2}{N_{eff}}} \cdot Z \]

\( \sigma_{r\phi} \): spatial resolution for azimuth angle \( r \phi \)

\( \sigma_0 \): spatial resolution without electron diffusion (constant term)

\( C_d \): diffusion constant

\( N_{eff} \): Effective number of ionization electrons

\[ N_{eff} = \left[ \left\langle \frac{1}{N} \right\rangle \left\langle \left( \frac{G}{\bar{G}} \right)^2 \right\rangle \right]^{-1} \]

\( G \): gas amplification

\( \bar{G} \): average of gas amplification

The diffusion constant can be obtained from pad response.

I’ll explain how to get \( C_d \) from pad response.
Pad response ($\sigma_{PR}$)

The width of the pad response function ($\sigma_{PR}$) is obtained as follows:

First, we plot the charge fraction on each pad as a function of the distance of the pad center from the hit point. Then we fit this distribution to a Gaussian and get $\sigma_{PR}$ as the standard deviation.

On the other hand, $\sigma_{PR}$ can be expressed as follows:

$$\sigma_{PR}^2 = \frac{w^2}{12} + \sigma_{PRF}^2 + C_d^2 z$$

![Diagram showing pad response function and charge fraction]

- $w$: Width of the pad response function
- $\sigma_{PRF}$: Standard deviation due to pad response function
- $C_d$: Constant related to drift path
- $z$: Distance from the hit point to the pad center

The charge fraction on each pad is plotted as a function of the distance of the pad center from the hit point. The distribution is fitted to a Gaussian, and $\sigma_{PR}$ is obtained as the standard deviation.

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<th>Entries: 41390</th>
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<tbody>
<tr>
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<td>Mean $x$: 0.09979</td>
</tr>
<tr>
<td></td>
<td>Mean $y$: 0.3068</td>
</tr>
<tr>
<td></td>
<td>RMS $x$: 1.156</td>
</tr>
<tr>
<td></td>
<td>RMS $y$: 0.275</td>
</tr>
</tbody>
</table>

On the other hand, $\sigma_{PR}$ can be expressed as follows:

$$\sigma_{PR}^2 = \frac{w^2}{12} + \sigma_{PRF}^2 + C_d^2 z$$

where $w$, $\sigma_{PRF}$, and $C_d$ are constants determined by the experimental setup.
How to get electron transmission

Pad response ($\sigma_{PR}$)
- Plot vs distance $Z$

\[ \sigma_{PR}^2 = \sigma_{PR}(0)^2 + (CD^2)z \]
- Diffusion constant

GM resolution ($\sigma_{r\phi}$)
- Plot vs distance $Z$

\[ \sigma_{r\phi} = \sqrt{\sigma_0^2 + \left(\frac{CD^2}{N_{eff}}\right)z} \]

Calculate $N_{eff}$

Calculate electron transmission

\[ \frac{N_{eff}(w/\text{Gate})}{N_{eff}(w/o\text{Gate})} \approx R_{e.t.} \]