The first beam test of a GEM-readout TPC module with a large aperture GEM-like gating device

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2017.5.22 MPGD2017@Temple univ.
Outline

1. About ILC, TPC
2. A large aperture GEM-like gating device
3. Results - Electron transmission rate (from charge)
4. Results - Electron transmission rate (from N effective)
5. Conclusion
The first beam test of a GEM-readout TPC module with a large aperture GEM-like gating device
International Linear Collider

Electron positron Collider (250~500 GeV)

Time Projection Chamber

reconstruct tracks, measure their momentum and dE/dx.
(charged particles)

Required momentum resolution

\[
\frac{\sigma_{P_T}}{P_T} \approx 1 \times 10^{-4} P_T \text{ GeV/c}
\]
TPC

B field 3.5 T

E field 230 V/cm

About 2 m

End Plate (Readout Modules)

About 2.2 m

T2K gas \( \text{Ar} : \text{CF}_4 : \text{iC}_4\text{H}_{10} = 95 : 3 : 2 \)

The amplification device: GEM or Micromegas
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 1 cm 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: 60 \mu m

Goal: \sigma_r < 100 \mu m (over maximum drift distance 2.2 m in B=3.5 T)

We need a gate to stop ions from returning to the drift volume.
The first beam test of a GEM-readout TPC module with a large aperture GEM-like gating device
A large aperture GEM-like gating device

We developed a large aperture GEM-like gating device (gating GEM) with FUJIKURA. It works as a gate by changing voltage applied to the Cu electrode. The gate should stop the ions but not disturb the transmission of electrons. The gate works by changing the voltage applied to the Cu electrode. The electron transmission is also important.

The gate should stop the ions but not disturb the transmission of electrons. The achievable electron transmission rate in the magnetic field is approximately equal to the Optical transparency.

Optical transparency = 82 %  25 µm thick

To achieve the target resolution, we need an electron transmission rate > 80%.

We measured the electron transmission by a beam test.
Electron transmission and ion stopping power

By using $^{55}$Fe source
10cm×10cm prototype (0 T, 1 T)

- [Exp] Type 3, $B = 0.0T$, $E_d = E_i = 230$ V/cm
- [Exp] Type 3, $B = 1.0T$, $E_d = E_i = 230$ V/cm

K. Ikematsu, IEEE2014 NSS

By using $^{55}$Fe source
and laser module size prototype (0 T)

- Black line: $^{55}$Fe
- Red line: Laser

A. Shoji, JPS2016 fall

Previously, we measured transmission by using $^{55}$Fe and laser. We found that the electron transmission is maximum at 3.5 V so we decided to use this voltage in the beam test.

The ion stopping power estimated using electron is 99.97 % or better at -15.5 V

Detail: https://agenda.linearcollider.org/event/7371/contributions/37927/
The first beam test
of a GEM-readout TPC module
with a large aperture GEM-like gating device
Beam test

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

15 participants from Japan, France, Germany, China, Sweden
The electron beam pass two trigger counter and through the prototype like this. A readout parts are covered with a solenoid. All devices are on the stage so we can change the length $Z$ from readout parts to electron beam and two angle, $\theta$ and $\phi$. 
Modules

Module 0

Module 3
Module with Gating GEM

The Module

Gating GEM

Module 0

Gating GEM

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

Amplification GEM

100μm thickness

Pad plane(anode)

(Gathering 5152 pads)
The beam goes through our module with the gating GEM in the region far enough from the module edge.
How to get electron transmission[1]

The electron transmission calculated by hit charge

Examples of the pulse height distribution

<table>
<thead>
<tr>
<th># of hit</th>
<th>With gate</th>
<th># of hit</th>
<th>Without gate</th>
</tr>
</thead>
</table>

Row 16
Drift length 25mm

![](image1.png)

\[
R_{\text{e.t.}} = \frac{\langle Q_{\text{w/Gate}} \rangle}{\langle Q_{\text{w/o Gate}} \rangle} \times 100 \% \]

Peak1
ADC

Peak2
ADC

Row 16
Drift length 25mm

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Electron transmission vs Drift length

Gas gain correction has been made here for temperature and pressure variations.

As expected there is no drift length dependence. After averaging over drift distance, we got 82.1% for the electron.
How to get electron transmission[2]

**Pad response (σ\textsubscript{PR})**

Pad response standard deviation

$$Q_i / \sum Q_i$$

$r_{\phi_{hit}} - r_{\phi_{i-th pad center}} [mm]$  
$i = -4, -3, ..., 0, ..., 3, 4$

**GM resolution (σ\textsubscript{rφ})**

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

hit in question included in the track fit

hit in question excluded from the fit

**Hit point**

**Residual**
How to get electron transmission[2]

Pad response (σ_{PR})

\[ \sigma_{PR}^2 = \sigma_{PR}(0)^2 + (C_D^2)z \]

GM resolution (σ_{rφ})

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

N effective

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

Calculate Neff

Rate of Neff ≈ Electron transmission rate

\[ \frac{N_{eff}(w/\text{Gate})}{N_{eff}(w/o \text{Gate})} \approx R_{e.t.} \]
Pad Response (Module 3 Row 16)

\[ \sigma_{PR}^2 = \sigma_{PR}(0)^2 + (C_D)^2 \times z \]

Garfield simulation

Cd(with gating GEM) \(94.0 \ \mu m/\sqrt{cm} \pm 0.2\%\)
Cd(without gating GEM) \(94.2 \ \mu m/\sqrt{cm} \pm 0.3\%\)

\( \chi^2/\text{ndf} = 24.4/6 \)
\( \sigma_{PR}(0) = 477.9 \pm 1.7 \ [\mu m] \)
\( C_D = 92.7 \pm 0.25 \ [\mu m/\sqrt{cm}] \)

\( \chi^2/\text{ndf} = 33.5/6 \)
\( \sigma_{PR}(0) = 481.2 \pm 1.6 \ [\mu m] \)
\( C_D = 90.05 \pm 0.25 \ [\mu m/\sqrt{cm}] \)

B = 1 T
Gate GEM Voltage 3.5 V
\( \varphi, \theta = 0^\circ \)
Position resolution ($r \phi$)

GM Resolution (Module3 Row16)

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

\[
\begin{align*}
\chi^2/\text{ndf} &= 6.53/6 \\
\sigma_0 &= 54.6 \pm 2.4 \, [\mu m] \\
C_D/\sqrt{N_{\text{eff}}} &= 18.6 \pm 0.21 \, [\mu m/\sqrt{\text{cm}}]
\end{align*}
\]

\[
\begin{align*}
\chi^2/\text{ndf} &= 3.59/6 \\
\sigma_0 &= 55.1 \pm 2.2 \, [\mu m] \\
C_D/\sqrt{N_{\text{eff}}} &= 17.8 \pm 0.21 \, [\mu m/\sqrt{\text{cm}}]
\end{align*}
\]

B = 1 T
Gate GEM Voltage 3.5 V
\( \phi, \theta = 0^\circ \)

The ratio of \( \sigma_{r \phi} \) [%]

<table>
<thead>
<tr>
<th>Ratio/%</th>
<th>2.5</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>101.7</td>
<td>±0.1</td>
<td>101.2</td>
<td>±0.1</td>
<td>102.9</td>
<td>±0.1</td>
<td>100.7</td>
<td>±0.1</td>
<td>105.8</td>
<td>±0.1</td>
<td>105.8</td>
<td>±0.1</td>
<td>102.4</td>
<td>±0.1</td>
</tr>
</tbody>
</table>
| Expected ratio : 110 %
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Preliminary
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**Electron transmission rate**

<table>
<thead>
<tr>
<th>Used Cd values [µm/√cm]</th>
<th>Neff(W/ gate)</th>
<th>Neff(W/O gate)</th>
<th>rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured</td>
<td>23.4±0.6</td>
<td>27.1±0.7</td>
<td>86.4±3.0</td>
</tr>
<tr>
<td>Simulated (Garfield++)</td>
<td>26.7±0.7</td>
<td>30.0±0.9</td>
<td>89.1±3.3</td>
</tr>
</tbody>
</table>

The result is consistent within the statistical errors.

This result are consistent within the statistical errors.
Conclusion

The ion stopping power estimated using electron is 99.97 % or better at -15.5 V.

We succeeded in the first beam test of a GEM-readout TPC module with a large aperture GEM-like gating device

The electron transmission from Neff measurements is $86.4 \pm 3.0\%$

The electron transmission from charge measurements is $82.1 \pm 0.4\%$

We achieved the target electron transmission rate of $> 80\%$.

Remainig issue
The difference between Cd values measured with and without the gating GEM.

We will investigate this issue further.
Back up Slides
Event Selection

Track angle cut [rad]

- $4.64 < \phi_0 < 4.72$

I applied a track angle cut to exclude angled tracks and a cut on nTrks to eliminate events with multiple tracks caused by electromagnetic shower in the upstream.

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### Condition

<table>
<thead>
<tr>
<th>Module 3</th>
<th>With Gating GEM</th>
<th>Without Gating GEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 0</td>
<td>Without Gating GEM</td>
<td>Without Gating GEM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z [cm] (Drift length)</th>
<th>1.25, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 55</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ [degree]</td>
<td>0, 10, 20</td>
</tr>
<tr>
<td>θ [degree]</td>
<td>-20, -10, 0, 10, 20</td>
</tr>
<tr>
<td>$V_{gate}$ [V]</td>
<td>-3.5, 0, 3.5</td>
</tr>
<tr>
<td>B [T]</td>
<td>0, 1</td>
</tr>
</tbody>
</table>

Analyze condition of [ ]

Beam: 5 GeV electron
Gas: T2K gas (Ar : CF$_4$ : Iso-C$_4$H$_{10}$ = 95 : 3 : 2 [%])
Analytics framework: MarlinTPC (Analysis 20000 event/1 run)
Introduction- Why we need high electron transmission?

Spatial Resolution vs Electron Transmission

\[ \sigma_{r\phi} \propto \frac{1}{\sqrt{N_{\text{eff}}}} \propto \frac{1}{\sqrt{R_{\text{e.t.}}}} \]

\[ \frac{\sigma_{r\phi}(\text{w/ Gate})}{\sigma_{r\phi}(\text{w/o Gate})} \approx \frac{1}{\sqrt{R_{\text{e.t.}}}} \]

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

\[ R_{\text{e.t.}} = \frac{\langle Q_{\text{w/ Gate}} \rangle}{\langle Q_{\text{w/o Gate}} \rangle} \]

We need high electron transmission to keep good resolution:

\[ R_{\text{e.t.}} > 0.8 \]

for point resolution better than 100µm at B=3.5 T over the full drift length of 2.2 m of the ILC TPC.

So we measured resolution and other parameters related it.
Readout Pads

Amplification GEM

Gating GEM

Pad plane (anode)

Upper part:
- 192 Pads/Rows

Lower part:
- 176 Pads/Rows

1 Pad:
- 5.26 mm

About 1.2 mm

28 Rows
Field shaper

- To arrange the electric filed
Data quality check - Hit efficiency

Hit efficiency (Module3 Row16)

With Gating GEM

- Missing track is about 1%

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

Error: $\sqrt{\frac{n(1-n)}{N}}$
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

\[ \text{Garfield simulation} \]

\[ \begin{array}{ll}
\text{W/ gate} & 76.7 \text{ cm/\(\mu\)s } +/- 0.0013\% \\
\text{W/O gate} & 7.68 \text{ cm/\(\mu\)s } +/- 0.0022\%
\end{array} \]

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

Very preliminary

<table>
<thead>
<tr>
<th></th>
<th>W/ gate</th>
<th>W/O gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. [K]</td>
<td>291.28</td>
<td>290.4</td>
</tr>
<tr>
<td>Pres. [hPa]</td>
<td>1010.79</td>
<td>1005.31</td>
</tr>
</tbody>
</table>

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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”.

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

- With Gating GEM
  - \( \chi^2/\text{ndf} = 12.1/6 \)
  - \( \sigma_0 = 59.5 \pm 2.2 [\mu m] \)
  - \( C_D / \sqrt{N_{\text{eff}}} = 17.2 \pm 0.23 [\mu m/\sqrt{\text{cm}}] \)

- Without Gating GEM
  - \( \chi^2/\text{ndf} = 8.07/6 \)
  - \( \sigma_0 = 57.2 \pm 2.3 [\mu m] \)
  - \( C_D / \sqrt{N_{\text{eff}}} = 18.2 \pm 0.22 [\mu m/\sqrt{\text{cm}}] \)

\( (\text{Without Gating GEM}) \)

\( (\text{With Gating GEM}) \)
Expected ratio: 110%

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

If Neff become 80%:

\[ \text{Ratio} = \sqrt{1/0.8} = \sqrt{1.25} = 1.1 \]