GEMs and GEM-TPC
Activities from CNS-Tokyo

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Outline

• Introduction
• Development of GEM in Japan
• Study of the characteristics of GEM
• Prototype GEM-TPC R&D
• Next Step for the GEM-TPC Upgrade
Introduction

- R&D of GEM detectors has begun in 2002.
- The primary motivation was for the PHENIX upgrade of inner detectors.
  - Hybrid of HBD + TPC

**Hybrid of HBD + TPC**
- Discussion started in 2001.
- HBD: CsI+GEM (Cherenkov)
  - Use CF$_4$ Gas
  - eID and Dalitz rejection to improve S/N in Lmee.
- Finally, only HBD was installed in 2007.
Introduction

• Three directions in R&D of GEMs at CNS.
  – 1: Making GEMs in Japan and its development
    • Fabrication process
    • Thick GEM, Resistive GEM
  – 2: Application of GEM
    • GEM-TPC
    • HBD, Imaging detectors (X-rays, neutrons)
  – 3: Characteristics and performance evaluation
    • Gas gain
    • Gain variation vs. time and P/T
    • Ion Feedback
    • Thick GEM (100um, 150um)
    • Resistive GEM (Resistive-Kapton) and Glass-GEM
Having started using CERN-GEM

• First measurement using CERN-GEMs in 2002.

HV 1 (-1.5~2.2kV)    
HV 2 (-1.4~1.6kV)    
GEM 1  2mm  1MΩ  1MΩ  1MΩ  1MΩ
Drift Plane
GEM 2  3mm  1MΩ
GEM 1  2mm

Spectrum for Fe55 with triple GEMs

P10
V_{GEM} = 335V
Ed = 2kV/cm

ArCO₂
V_{GEM} = 380V
Ed = 2kV/cm

CF₄
V_{GEM} = 535V
Ed = 0.3kV/cm
Having started using CERN-GEM

- Gas Gain of CERN-GEM

3-GEM, P10
2-GEM, P10
3-GEM, ArCO₂
3-GEM, CF₄


Weizmann Institute of Science; December, 2002
GEMs made in Japan

- Many development of Making GEMs in Japan
  - CERN-GEM: Chemical etching
  - CNS-RIEKN-SciEnergy: Dry (Plasma+Laser) etching
    - NIM A525, 529, 2004
    - Cylindrical shape → thicker GEM (100-150um)

<table>
<thead>
<tr>
<th>Etching method</th>
<th>CERN-GEM</th>
<th>CNS-GEM</th>
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<td>chemical</td>
<td>plasma</td>
<td>plasma+laser</td>
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<th>Cross-section of GEM hole</th>
<th>CERN-GEM</th>
<th>CNS-GEM</th>
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<td>bi-conical shape</td>
<td></td>
<td>cylindrical shape</td>
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</table>
Gain of CNS-GEM

• Comparable gain to CERN-GEM

Figure 3.13: A schematic view of the GEM test setup.

Figure 3.18: The $V_{GEM}$ dependences of the gain for Ar(90%)/CH$_4$ (10%) (left panel) and for Ar(70%)/CO$_2$ (30%) (right panel). The blue and the red symbols represent the results of the CNS–GEM and that of the CERN–GEM, respectively. These results are the ones corrected to the STP conditions.
Gain Stability

- Gain of CNS-GEM is stabilized in shorter time.
- Difference may be due to the difference in hole shape?
  - Less probability for charge-up due to cylindrical shape.
- Other reasons like surface conditions.
Gain vs. P/T

- Electron multiplication in gas depends on P/T – a function of E/p, or more precisely E/n ~ ER(T/p)
- \( M \sim A \exp[aE/n] = A \exp[(aE/n_0)(1 - \delta n)]; n = n_0 + \delta n \)
- Similar between CERN-GEM and CNS-GEM.

Figure 3.15: The P/T dependences of the relative gain for Ar(90%)/CH\(_4\) (10%) (left panel) and for Ar(70%)/CO\(_2\) (30%) (right panel).
Thick GEM

• Thicker GEM has a potential to achieve higher gain with smaller voltage.

\[ V_{\text{GEM}} = 250V/50\text{um} \]

Electric field along the center and edge of a GEM hole calculated by Maxwell-3D.

- 150um-GEM \( V_{\text{GEM}} = 750V \)
- 100um-GEM \( V_{\text{GEM}} = 500V \)
- Standard-GEM (50um) \( V_{\text{GEM}} = 250V \)

Higher Electric field is realized for thickness>100um.
Gas Gain of Thick GEM

- Insulator: LCP (Liquid Cristal Polymer)
  - Can be pierced easily than Kapton by dry etching.
  - Less water absorption property

![Graph showing gain vs. voltage for different GEM thicknesses]

- 150µm-GEM
- 100µm-GEM (Gain^{3/2})
- 3 layers of standard-GEM
- Large gain for thicker GEM
- At the same V_{GEM}(=300V/50µm), Gain(100/50)=450 and Gain(150/50)=1600.
- For 150µm GEM, sparks happened at low voltage
  - investigation is under way
  - LCP? Overhung?
  - limit for charge density?
**Gas Gain vs. P/T and time for Thick GEM**

- Gas gain vs. P/T and time for thick GEM

**Ar(80%)/CO₂(20%)**

- Sensitivity of Gain w.r.t P/T depends on thickness of GEM
- Thicker GEM is less sensitive to P/T.
- Gain of thick GEM is stable in 1% for 9 hours.
Measuring Ion Feedback

Ion feedback factor: 

\[ F = \frac{I_c}{I_a} \]

- What to measure:
  - pad current: \( I_a \)
  - mesh current: \( I_c \)

- Parameters
  - \( V_{\text{GEM}} \): voltage applied to each GEM (V)
  - \( E_d \): electric field in the drift region (kV/cm)
  - \( E_t \): electric field in the transfer region (kV/cm)
  - \( E_i \): electric field in the induction region (kV/cm)
  - number of GEMs: 1, 2 or 3

Typical values: \( HV1 = -2200 \text{V}, \) \( HV2 = -2100 \text{V}, V_{\text{GEM}} = 350 \text{V} \)

GEM: CERN-GEM
Dependence of $I_a$ and $I_c$ on $V_{GEM}$

- Both $I_a$ and $I_c$ increase exponentially with $V_{GEM}$
- Growth of $I_a$ and $I_c$ gets larger for triple GEMs
- Growth of $I_c$ is smaller than that of $I_a$ for triple GEM

$Ed = 0.33$ (kV/cm)

Gain is $\sim 700$ (Triple) at $V_{GEM} = 320$ V
Dependence of $F$ on $V_{\text{GEM}}$

- $F$ decreases with increase of $V_{\text{GEM}}$
- $F$ for triple-GEM is large compared to single- and double-GEM
- At large $V_{\text{GEM}}$, $F$ value for triple-GEM approaches those of single- and double-GEM

$E_d = 0.33\,(\text{kV/cm})$
Dependence of $F$ on $E_d$

- $F$ increases with increase of $E_d$
- Ion feedback is less than 5% with small $E_d$.
  - Current of $I_a$ doesn’t depend on $E_d$.
  - This is one way for the ion feedback suppression.
- Another way:
  - More GEM layers and make $E_t$ between GEMs lower.
- Key issues for the upgrade
Development of Resistive-GEM

• To protect GEMs from spark
  – Resistive Materials to the electrodes.
  – Being developed with RIKEN Cosmic-Ray Group

![Image of Resistive-GEM structure]

**Figure 1.** Structure of Resistive-GEM.

![Image of experimental setup]

**Figure 2.** Experimental setup for testing Resistive-GEM.

![Graph showing effective gain vs. applied voltage]

**Figure 3.** Effective gain vs. applied voltage for different setups.

- Respective-Resistive-GEM (RE-GEM) was 5.5 mm apart, and this volume is the drift region, with a diameter of 200 µm. A high voltage was supplied via a chain of 10 MΩ resistors for protection.

- The readout pad and the RE-GEM were placed under the RE-GEM. The volume between the readout pad and the RE-GEM foil, and a readout pad. The drift plane, RE-GEM, and the readout pad have an equal effective area of 26 mm², where the electron transparency has been normalized to the readout pad. The schematic view of creative processes: (a) Creating subs-

- The charge signals amplified by RE-GEM were fed into a preamplifier (AmpTek A225) which had both features of delay and discriminator. The signal from the preamplifier was fed into a main custom amplifier.

- The gas gain just the gain. We measured the effective gas gain as a function of an applied voltage of 620 V and 4–5 times as large as that taken with the W-N setup. This trend is commonly seen for GEM foils with the conical hole structure [9]. The gain curve of RE-GEM taken with the N-W setup was similar to that taken with the W-N setup. The gain of RE-GEM was about 600. The normalization of the gain curve of RE-GEM, using the non-collimated X-rays of 5.9 keV X-rays (8 keV) from a generator. The incoming beam of X-ray was collimated to 1000 µm. A high voltage was supplied via a chain of 10 MΩ resistors. We also had

- As a photogaph of RE-GEM. The effective area is 26 mm² – 30% CO₂ – 55 µm. The electric field inside the multiplication channel was 5.5-7.5 kV/cm in Ar/CO₂ (70%/30%). The electric field of the drift region (RE-GEM was 5.5 mm apart, and this volume is the drift region, with a diameter of 200 µm. A high voltage was supplied via a chain of 10 MΩ resistors for protection.

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More recent developments

• Large GEM
  – Many issues so far for the large GEMs (ex) 30x30 cm²
    • Gain uniformity (uniform tension)
    • Large probability for discharge to happen
    • Fragile for the spark due to large capacitance
  – Improvement for the stable operation by SciEnergy Co Ltd. in Japan

• Glass GEM
  – Kapton and LCP will not be suitable for the long operation under sealed due to radiation damage and out gas.
  – New development of GEM made by glass started.
    • More hardness, no out gas
R&D of GEM-TPC

- Building TPC Prototype in 2003
- Endcap readout can be replaced with GEM or MWPC

End cap

Preamp+ diff. driver (AD8058, AD8132) $\tau=1\mu$s

Field cage
36x17x17cm$^3$
115 Au strips
1M$\Omega$ bwt. strips

Gas vessel
60x29x29cm$^3$
GEM or MWPC readout

- MWPC readout
- GEM readout

Two types of readout pads
2.5x2.5, 6x6, 9.5x9.5, 13.5x13.5mm²
Rectangular & chevron type with 1.09 mm x 12mm
Characteristic of $\text{CF}_4$

- Studied with GEM and MWPC Readout
  - Gas Gain
  - Use CERN-GEM

![Diagram of gas system and gain curves](image)

**Figure 2.8:** Schematic view of the gas system.

**Figure 2.9:** Schematic view of a triple GEM for gas gain measurement using a $^{55}\text{Fe}$ X-ray source.
Characteristic of CF$_4$

- Studied with GEM and MWPC Readout
  - Energy resolution
    - Resolution with GEM is $1.5 \times \sqrt{N_{\text{seed}}} \sim 9\%$
    - Smaller than that of MWPC ($\sigma = 37\%$)
    - Large attachment ($e^- + \text{CF}_4 \rightarrow \text{F} + \text{CF}_3$) in the larger field realized by the wire potential?

![Image of energy resolution graph]

- Gain at $3 \times 10^4$
  - $\sigma = 37\%$

- Gain at $4 \times 10^3$
  - $\sigma = 13\%$

![Image of gain curves]

- Table:
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<td>107</td>
<td>29.67</td>
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<td>300.3 ± 5.265</td>
<td>116.5 ± 0.2179</td>
<td>15.13 ± 0.1971</td>
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</table>
Characteristic of CF$_4$

- Studied with MWPC Readout (Pure CF$_4$)
  - Drift velocity
  - Longitudinal diffusion

N$_2$ Laser ($\lambda = 337$nm)

![Diagram of Gas Vessel and Drift Region](image)

Drift velocity

- 10 cm/μsec @900 V/cm/atm

Longitudinal diffusion

- 60 μm
Beamtest in 2004

- GEM-TPC beamtest at KEK in 2004 (CERN-GEM)
- Three gases (no magnetic field)
  - Ar(90%)-CH\(_4\)(10%)(P10), Ar(70%)-C\(_2\)H\(_6\)(30%), CF\(_4\)
- Tested items
  - Detection Efficiency
  - Position Resolution
  - Beam rate dependence
  - dE/dx
**Typical signal of GEM-TPC**

With 100 MHz FADC
Gas = Ar-C$_2$H$_6$  Drift length = 85mm  Rectangular pad
Beam = 1 GeV/c electron from KEK-PS in May 2004
Signals spread over 4 pads (~4.4mm) [PRF in backup slides]

Time (6.4µs=640bin, 1bin=10ns, 100MHz FADC)
Detection Efficiency

• Definition: \( N_{\text{hit}(1&2&3)}/N_{\text{hit}(1&3)} \)

Efficiency > 99% for enough gain
Position Resolution

• X (transverse) and Z (drift direction) resolution
• Resolution gets worse with increase of drift length
  – diffusion effect
  – magnitude depends on gas species

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<th>Drift velocity (cm/µs)</th>
<th>Diffusion (T)@1cm (µm)</th>
<th>Diffusion (L)@1cm (µm)</th>
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<td>130</td>
<td>5.5</td>
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<td>CF₄</td>
<td>570</td>
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**dE/dx Measurement**

- Energy loss measurement (d=85mm)
  - P10: $\sigma(55\text{Fe};5.9\text{ keV}) = 11\%$
  - $\text{Ne(primary)} \sim 222$ for 5.9keV Xray in P10 $\rightarrow \sim 1.7$ times larger than statistical estimate...
  - Obtained energy loss is as expected for various particles with different momentum
  - Need to see for CF4
Beam Rate dependence

- Beam rate dependence of gain, resolution
  - Tested for P10 (d=85mm, Ed=0.1kV/cm)
  - no change up to 5000 cps/cm²
- 50kHz Pb+Pb & \( \frac{dN}{d\eta} = 1600 \rightarrow 1200 \text{ cps/cm}^2 \) at \( r=100\text{cm} \)
  - good enough for HI applications

![Graphs showing beam rate dependence of detection efficiency, X resolution, and Z resolution.](image-url)
Two Track Separation

- Tested with P10 Gas (d=85mm, Ed=0.1kV/cm)
  - Pulse shape analysis/MC simulation
  - Two Track Separation in drift = 10mm
    - Comparable to TPC requirement
    - Much larger than diffusion ~ 1mm
    - AD8058 (used in preamp) is not adequate for pileup due to large leakage current (S/N). Faster clock is also needed.

\[ \sum \frac{1}{2} \]
**Issues for GEM-TPC**

- GEM-TPC is a promising candidate under the high rate and fast operations.
- Issues to be investigated:
  - Ion feedback suppression
    - How much we will need for the continuous readout?
    - Reduce drift field only (vs. diffusion)? Some more GEM layers (small $E_t$ field between GEMs or including gating GEMs)? Use thick GEM?
  - Gas mixture
    - Ne-CF$_4$? Ne-CF$_4$-X (X=N$_2$, isoC$_4$H$_8$)
    - Diffusion and PRF with existing pad size are reasonable?
    - Attachment and worse energy resolution with CF$_4$ are acceptable?
    - Preferable faster gas but need to have high sampling rate to achieve good resolution in drift direction, two track separation.
  - Stability of GEMs against P/T, time, rate..
Go to Next Step

• We are very interested in GEM-TPC upgrade.
• There are lots of activities in Japan for the GEM-based detectors.
  – Well organized by MPGD working group in Japan
    • KEK(for beam monitor, neutron, J-PARC exp), CNS-Tokyo(for ALICE), Saga Univ.(for ILC), Kobe Univ. (RD51 and for ATLAS), Kyoto-Univ. (for DM search, medical application)…
• We would like to join in some efforts by using our prototype GEM-TPC and test bench.
  – (ex) basic properties under Ne-CF$_4$ gas mixture
  – (ex) build another prototype of IROC with 100um-GEM
• Discussion on how to collaborate would be appreciated. → Hamagaki-san’s slide & Discussion.
• Beamtest in 2012 (before prototype installation in cavern?)
  – (We will have FoCAL beamtest in CERN in Sept.)
Backup slides
Pad Response Function

- PRF

Ar/CH4

Ar/C2H6

CF4
Pad Response Function

• PRF vs. drift length (Ar/C2H6)

D=20
D=85
D=150
D=220
D=290mm
Simulation by Maxwell-3D

- Simulation by Maxwell-3D

Figure 3.5: The electric potential of the CERN–like (left panel) and of the CNS–like (right panel) at $\Delta V_{\text{GEM}} = 350 \text{V}$.

Figure 3.6 shows the electric potentials in a hole of GEM as a function of the $z$ position, where the $z$ position is defined as the direction perpendicular to a GEM structure, and the origin is taken to be at the half of thickness of a GEM foil. The left and the right panel in Fig. 3.6 show the electric potentials in the hole center and at 10 $\mu$m from the hole edge, respectively. The crossed and the open circle symbols represent the results for the CNS–like and for the CERN–like, respectively. It is found that there are little difference between the electric potential distribution of the CNS–like and the CERN–like.

Figure 3.7 shows the calculation results of the electric field distribution of GEM as a function of the $z$ axis. The hole is located between $z = +30 \mu$m and $z = -30 \mu$m indicated as dash lines in Fig. 3.7. The electric field along the $z$ position through the hole is shown in the left panel of Fig. 3.7. Whereas there is remarkable difference in the results of electric field strength between the CNS–like and the CERN–like along the $z$ axis at 10 $\mu$m from the hole edge as shown in the right panel of Fig. 3.7. The electric field of the CERN–like near the hole edge is distorted due to a bulge of a insulator.
Simulation by Maxwell-3D

- Example of Avalanche for CNS-GEM

Figure 3.8 shows an example of the avalanche simulated for the CNS-like at $V_{GEM} = 350$V with the Monte-Carlo integration method. The electric field in a GEM structure points upward. The yellow solid line and the red solid line indicate the drift line of electrons and positive ions, respectively. It is found that some of positive ions are absorbed by the upper GEM electrode. Some of secondary electrons are lost due to absorption by the lower GEM electrode as well.

Figure 3.8: Example of the avalanche simulated for the CNS-like at $V_{GEM} = 350$V.

Here, it is found that the gain of a single GEM can be defined as the following equation.

$$ G = M \cdot T, $$

where $G$, $M$, and $T$ mean the gain, the multiplication factor, and the transmission, respectively.

$Ed \sim 1.5kV/cm$

$Ei \sim 1.5kV/cm$
Gas characteristics

Drift velocity

Longitudinal diffusion
CF4 quench

Drift velocity

Longitudinal diffusion
Experimental Configurations

• Voltage configuration

- \( E_d = \frac{(HV1 - HV2)}{0.3} \) [kV/cm]
- \( V_{GEM} = \frac{HV2}{6} \) [V]

• \( E_t \) and \( E_i \) changes together with \( V_{GEM} \).

• Measure \( F \) as functions of \( V_{GEM}, E_d, \) and \( E_t/E_i \)

• 3 GEM configurations

Triple

Double

Single
Ion feedback

- Strong positive ion feedback suppression


GEM HV configuration should be determined carefully.

J-PARC seminar, K. Ozawa
Dependence of $F$ on $E_t/E_i$

- $F$ increases with increase of $E_d$
- Ion feedback is less than 5% with small $E_d$
  - This is one way for the ion feedback suppression.
- $F$ decreases as $E_t/E_i$ increases.
- $F$ seems to be less sensitive to $E_i$, $E_t$ compared to $E_d$. 
Ion Feedback対策③ (GEM-MSTPC from U.T)

Et1が0[V]以下だと、4%より小さくなる

電子の減少は許容範囲内
Ion Feedback対策テスト④まとめ
(GEM-MSTPC from U.T)

26%あったイオンフィードバックを、2枚のGEMをシールド用に使い、実験に使いたいドリフト電場でも4%に抑えられた。

IFB＝4%

0 [V] = 0 [kV/cm/atm]
GEM = 90 [V]
GEM = 120 [V]
GEM = 480 [V]

80 [V] = 2.5 [kV/cm/atm]
Pad = 150 [V]

電場を逆転させた場合は1.2%

Drift field (kV/cm/atm)