A Large Low-mass GEM Detector with Zigzag Readout for Forward Tracking at EIC

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Next QCD Frontier: **Strong color fields in nuclei**

"Understanding the GLUE that binds us all"

- How do the properties of nucleons and nuclear matter (mass, spin) and the nuclear force emerge from quark-gluon interaction?
- How are gluons and sea quarks and their spins distributed in position space and momentum space inside a nucleon?
- EIC experiments will image gluons & quarks and their interactions in the nuclear environment.
EIC Designs

Brookhaven Lab

- Use existing RHIC
- Add electron ring

Jefferson Lab

- Use existing CEBAF
- Add ion ring
Large GEMs for EIC Detectors

All proposed EIC detector concepts feature a form of large GEM tracker at forward and backward rapidities:

R&D effort dedicated to EIC forward tracking since 2011: Florida Tech & U. Virginia (eRD6), Temple U. (eRD3)
Example design for an EIC forward tracker (FT) disk composed of 12 trapezoidal GEM detector modules.

Active areas of chambers overlap due to 30.1° chamber design.

inner foil radius ~ 8cm
Desired Module Properties

- Easy assembly
- Mechanical stability
- Low multiple scattering
- High spatial resolution
- Reasonable cost
Prototype Module Features

• Trapezoidal Triple-GEM Detector
• Mechanical detector assembly **without any spacers** (as in CMS GEMs)
• Construction **without PCBs** (drift, readout)
  – implement the readout on a foil
  – use a GEM foil as drift electrode
  – use stiff carbon fiber frames on perimeter for stability
• **Zigzag strip readout** to minimize number of strips and electronic channels
  – reduce system cost
  – maintain good spatial resolution
EIC GEM Foil Design

- Active area is divided into 8 HV sectors in R direction at inner R and 18 HV sectors in azimuthal directions at outer R. Reduces energy of any potential discharges.
- Each HV sector is $\sim 100 \text{ cm}^2$ and gaps between sectors are 0.1 mm.
- HV connections are made at wide end.
Mechanical Foil Stretching

Stack of 5 foils:
- 3 GEM foils
- 1 drift foil (also a GEM foil)
- 1 readout foil

À la CMS…

5/24/2017 M. Hohlmann, A large low-mass GEM detector with zigzag readout for forward tracking at EIC; MPGD 2017 at Temple U.
### Material Accounting

**Active Area:**

<table>
<thead>
<tr>
<th>Detector with PCBs</th>
<th>Thickness (mm)</th>
<th>% of Rad. Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 PCBs</td>
<td>3.180</td>
<td>3.914</td>
</tr>
<tr>
<td>3 GEMs</td>
<td>0.180</td>
<td>0.261</td>
</tr>
<tr>
<td>Kapton</td>
<td>0.150</td>
<td>0.051</td>
</tr>
<tr>
<td>Copper</td>
<td>0.030</td>
<td>0.210</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4.175</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector with foils only</th>
<th>Thickness (mm)</th>
<th>% of Rad. Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Al-Mylar foils</td>
<td>0.103</td>
<td>0.038</td>
</tr>
<tr>
<td>Mylar</td>
<td>0.102</td>
<td>0.036</td>
</tr>
<tr>
<td>Al</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>3 GEMs</td>
<td>0.180</td>
<td>0.261</td>
</tr>
<tr>
<td>Kapton</td>
<td>0.150</td>
<td>0.051</td>
</tr>
<tr>
<td>Copper</td>
<td>0.030</td>
<td>0.210</td>
</tr>
<tr>
<td>1 GEM as drift foil</td>
<td>0.060</td>
<td>0.087</td>
</tr>
<tr>
<td>Kapton</td>
<td>0.050</td>
<td>0.017</td>
</tr>
<tr>
<td>Copper</td>
<td>0.010</td>
<td>0.070</td>
</tr>
<tr>
<td>Readout foil</td>
<td>0.060</td>
<td>0.087</td>
</tr>
<tr>
<td>Kapton</td>
<td>0.050</td>
<td>0.017</td>
</tr>
<tr>
<td>Copper (15 um each side b/c of vias)</td>
<td>0.030</td>
<td>0.210</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>0.613</strong></td>
</tr>
</tbody>
</table>

Factor 6.8 reduction
Multiple Scattering

Minimizing material reduces multiple scattering of tracks in the GEM detectors

For an EIC detector, this helps with:

• matching electron tracks to EM clusters in the calorimeter
• seeding RICH ring reconstruction from incidence of hadron tracks on the RICH
Mechanical support structures are outer frames with thin windows (e.g. aluminized mylar foil, not shown here) instead of solid PCBs to reduce radiation length in the active area.

Frames are made from carbon fiber composites that have high strength to take up the tension from the stretched foils.
Carbon Fiber Composite:
- Araldite epoxy (AY103)
- Intermediate-modulus uni-directional carbon fiber (“IM7”)
- 8 layers of CF each; ~ 4mm thick
- Produced in-house

Expect < 1 mm deformation in z (bending) with 5 fully stretched foils
2D stage and highly collimated X-ray gun (140µm) at BNL

Reconstructed position vs. X-ray position (azimuthal)

- **Overetching** of tips and **underetching** of valleys of zigzag strips creates “spines” along strip centers
- GEM avalanche induces signal only on single strip
- Without charge sharing among adjacent strips:
  - Readout is insensitive to hit positions near the strip centers
  - Overall spatial response is non-linear
  - Spatial resolution degrades (360 µm)
Zigzag strips interleave almost all the way to centers of both neighboring strips:

- The design **pushes the PCB manufacturing limit** since spaces are below 3 mils (76 \( \mu \text{m} \)).
- Produced a **foil readout board at CERN** to verify that there is no problem with producing high-quality zigzag strips on a large-area kapton foil at CERN.
- Same design is implemented on large 1-m zigzag readout foil produced at CERN.

\[
\begin{align*}
C_{\text{strip-adj. strip}} &= (22 \pm 2) \text{ pF}; \quad C_{\text{strip-GND}} = (28 \pm 2) \text{ pF} \quad \text{direct measurement on 10 cm strips} \\
\end{align*}
\]
Improved Linearity

Mean centroid measurement vs. X ray position (scan across strips)

Previous zigzag design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>1.553 / 48</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$-30.08 \pm 0.9072$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$0.6534 \pm 0.01763$</td>
</tr>
</tbody>
</table>

Flat regions insensitive to hit positions.

New board (same angle pitch)

- Linear response over whole range
- > 95% events fire 2 or 3 strips.

5/24/2017 M. Hohlmann, A large low-mass GEM detector with zigzag readout for forward tracking at EIC; MPGD 2017 at Temple U.
Spatial Resolution

Measured resolutions for improved zigzag-strip readout boards/foils:

<table>
<thead>
<tr>
<th>Spatial resolution (µrad / µm)</th>
<th>$V_{\text{drift}}$ (V)</th>
<th>Approx. gas gain</th>
<th>Strips with angle pitch 4.14 mrad, $r \approx 229$ mm</th>
<th>Strips with angle pitch 1.37 mrad, $r \approx 784$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2-strip clusters</td>
<td>3-strip clusters</td>
</tr>
<tr>
<td>Industrial PCB</td>
<td>3340</td>
<td>3000</td>
<td>288 / 66</td>
<td>480 / 110</td>
</tr>
<tr>
<td>CERN foil</td>
<td>3340</td>
<td>3000</td>
<td>397 / 91</td>
<td>393 / 90</td>
</tr>
<tr>
<td>CERN foil</td>
<td>3380</td>
<td>4000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Previous PCB</td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Ar/CO$_2$ 70:30

**Resolutions (well) below 100 µm**
**Full-size Zigzag Readout Foil**

- **Adopt the improved zigzag strip design** but use straight strips in small innermost sector 1.
- **Divide readout into 5 main eta sections**
- **Produce r/o on a foil material (<100 µm thickness)** so that total material in detector is reduced.
- **Total number of channels is 1152** (=128*9)
- **Only 9 APV chips to read out the full detector**
- **Foil is a 2-layer design; signal routing from strips to connectors for APV front end was a challenge**

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<table>
<thead>
<tr>
<th>Sec. Nr.</th>
<th>Strip type</th>
<th>No. of strips</th>
<th>Angle pitch (mrad)</th>
<th>Sector Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Straight</td>
<td>128</td>
<td>4.14</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>Zigzag</td>
<td>128</td>
<td>4.14</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>Zigzag</td>
<td>384 (3×128)</td>
<td>1.37</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Zigzag</td>
<td>384</td>
<td>1.37</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Zigzag</td>
<td>384</td>
<td>1.37</td>
<td>22</td>
</tr>
</tbody>
</table>

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**Table:**

- **Sec. Nr.:** Sector number.
- **Strip type:** The type of strip used.
- **No. of strips:** Number of strips per sector.
- **Angle pitch (mrad):** Angle pitch in milliradian.
- **Sector Length (cm):** Length of the sector in centimeters.

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**Diagram:**

- **Sector 1**
- **Sector 2**
- **Sector 3**

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**Notes:**

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9 connectors for FE chips (APV hybrids)

- Signal lines are blue (top side)
- Zigzag strips are red (bottom side)
- Connections made with numerous vias
Cross-talk measurements will be interesting…
(but occupancy is low at the EIC)
Summary & Outlook

• Forward GEM tracking R&D for EIC since 2011
  • Conceptual design for EIC FT disk made from 12 trapezoids

• New prototype detector
  • Much reduced material with “all-foil” design (~ 0.6% rad. length)
  • Designed at Florida Tech and manufactured at CERN:
    – Large trapezoidal GEM foil (30.1°)
    – Complex large readout foil with zigzag strips
  • Produced carbon fiber frames with promising stiffness
  • Zigzag strip readout gives linear response and good spatial resolution

• Status & Outlook
  • Currently working with industry on stack frames and gas seal frame
  • Will assemble detector and put through battery of quality control tests
  • Tests with X-rays and possibly beam test in 2017 or 2018
Thank you!