New Approach for 2D Readout of GEM Detectors

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Goals

• Develop 2D readout for GEMs using single layer for charge collection
  • Simplifying production, reduce cost, and better control production and uniformity

• Determine charge sharing between the two dimensions and the dependence on line and pad sizes

• Determine limitations for this approach

• Investigate novel 2D designs

• Measure resolutions obtained with new readout designs
New Approach for 2D Readout of GEM Detectors

GEM Detectors

Traditional 2D Readout

New Approach for 2D Readout

Experience with Production
Gas Electron Multiplication - GEM

First proposed in 1996

- F. Sauli (CERN)
- Insulating foil (Kapton)
  - ~50 µm thick
- Copper layer on both sides
  - ~5 µm thick
- Millions of tiny holes
  - 50 µm ID, 150 µm spacing
- Apply potential across copper
  - ~400 V
- High electric field inside holes
  - ~40 kV/cm
- Electrons entering the holes are accelerated by the electric field and ionize the gas creating more electrons which repeat the process
  - Electron multiplication factor 80-100
GEM Detector Concept

Initial ionization in drift volume
  • Charged particle ionizes gas

Electrons attracted to GEM foil
  • Electron multiplication in first foil
  • Factor 80-100 in electron gain

Use three (or more) layers
  • Gain ~80,000 in triple GEM

Readout board detects charge
  • Various designs possible
    • Pads, strips
    • 2D patterns

Position resolution
  • Depends on gas, geometry, and readout
Advantages of GEM Detector

Thin
- ~1 cm thick physically
- ~0.3 % $X_0$ material

High rate
- 0.5 MHz/cm²

Insensitive to magnetic fields and radiation tolerant

Flexible readout schemes

Resolution
- Depends on gas, geometry, and readout
- ~ 50 µm achieved
GEM Technology

Previously GEM foils only produced at CERN

SBIR grant to develop technology

Tech-Etch, Inc.
• http://www.tech-etch.com
• Plymouth, MA
• Dedicated GEM production line
• Quality control and testing facilities

Currently limited by 24” x 22” material and equipment
• Effective 22” x 20” for GEM
• Possibility to increase size in future?
• CERN now capable of 2.0 x 0.5 m²
Flexible PCB technology

But needs great care and attention to details

- Start with double sided material
- Photo- lithography to apply hole pattern to copper on both sides
  - Alignment critical
    - Misaligned holes affect gain and uniformity
  - Glass masks needed for large areas
    - Evacuated to remove air pockets
- Chemically etch holes in copper
- Further chemical etching produces holes in Kapton
  - Etching time and uniformity crucial
  - Double cone shape important
    - Increases breakdown voltage
  - Uniformity of inner hole important
    - Determines gain uniformity
- Rinsing and handling important
GEM Detector Readout

Electron shower at readout
- 2-3 mm in diameter
- Depends on gas, geometry, and angle of initial ionization

Bottom of last GEM foil can provide faster trigger
- Useful to trigger readout
- Can be segmented – position

Readout layer can be tailored to requirements
- Pads or strips with separate, independent readout
- 2D schemes
  - Cartesian, spherical, Rφ
- Pitch and resolution as required
Traditional 2D Readout Board

Start with double sided PCB with desired geometry
• e.g. horizontal lines on the top and vertical lines on the bottom

Etch between the top lines to expose the bottom lines, but
• Under etching leaves shoulders which obscures bottom lines
• Over etching reduces support for top lines and weakens foil
• Resulting board very fragile, often mounted on a supporting layer
• Chemical etching possible for uniform cartesian geometries
  • Varying gaps or pitches are not etched uniformly
• Laser etching manages complex geometries but difficult and costly
Charge Sharing Problematic with Traditional

Need to know ratio of charge sharing between top / bottom
• Helps resolve ambiguity if there are multiple hits
• Must be the same over entire area

Useful if ratio is close to unity
• Same electronic gain can be used for top and bottom lines

However, top lines are closer to shower and collect more charge
• Necessitates thinner top lines and broader bottom lines
• Limits combinations of pitch and line widths possible with chemical and laser etching
Traditional 2D Readout Boards

Narrow top lines
- varying width and pitch for equal charge
- etching must be correct and uniform
- bottom width and pitch not critical

<table>
<thead>
<tr>
<th>Width</th>
<th>Pitch</th>
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<tbody>
<tr>
<td>100</td>
<td>275</td>
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<tr>
<td>120</td>
<td>400</td>
</tr>
<tr>
<td>130</td>
<td>525</td>
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<tr>
<td>140</td>
<td>650</td>
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</table>
Complex Example: STAR FGT 2D Readout

Disks of triple GEM detectors at small angles with respect to beamline
- Produced in quadrants

RΦ geometry most suitable
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RΦ geometry most suitable

Φ readout
• Alternate lines end at 18.8 cm
• 400-800 µm pitch varying with R
• 80-120 µm line width varying with R
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R readout
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- 700 µm line width
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R readout
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Very challenging to produce with traditional approach
New 2D Readout Layer Concept

Produce desired pattern of lines and pads in copper on the readout layer facing the electron shower

- Standard technology, feature sizes limited by capabilities of company
- Vertical lines can be extended to edge of readout board to connect to readout electronics
New 2D Readout Layer Concept

Connect pads to bottom side with plated through vias

• Standard technology but pad sizes < ~1 mm require laser drilling
• Limited by size and number of vias, and capabilities of companies
New 2D Readout Layer Concept

On bottom side connect vias (pads) in horizontal rows

- Route lines to edge of board to connect to readout electronics
- Need landing pads for vias
- Routing lines should be narrow to reduce capacitance
New 2D Readout Layer Concept

Could also connect lines through vias to bottom layer

- Route lines to same edge of board as pads to connect to readout electronics
New 2D Readout Layer Charge Sharing

Charge sharing is fixed by width of lines / width of pads

- Length of pads does not contribute to charge sharing
- Negligible effect from gaps between pads
- Negligible effect from rounding of pad corners during production
- Thus easy to get 1:1 ratio or whatever is desired
Other Geometries Possible – e.g. Stereo

Lines and lines of pads close to parallel, 22° opening angle

- Effectively halving the pitch – improved resolution, in one direction
- Poorer resolution in other direction
Other Geometries Possible – e.g. XUV

Pads connected in two directions ±45° with respect to lines
  - Requires three layer readout board
  - Resolves ambiguity for multi-hit events without resorting to charge sharing
Complex Example: STAR FGT 2D Readout

R\(\Phi\) geometry with pitch and line width varying with R
- Transition region where pitch changes from 600 to 300 \(\mu\)m
- Only every other line continues across boundary (right to left)
- R pitch constant
- Charge sharing ratio near unity over entire area
Experience with Production

Production depends on capabilities of PCB company

Any PCB manufacturer can manage
- 10/10 design rules – 10 mil lines / 10 mil gaps and 20 mil holes
- For proposed 2D readout design this means 2.5 mm pitch and an expected position resolution around 1 mm
  - Not very interesting for most nuclear physics applications

Better PCB manufacturers can handle
- 4/4 design rules and 12 mil holes
- 2D designs with 1.25 mm pitch and resolutions around 200 µm
  - Potentially interesting for low resolution applications

High tech PCB manufacturers can reach
- 1.5 / 1.5 design rules and 1 mil laser drilled holes
- Possible to reach 200 µm pitches
  - But electron shower size (~2 mm) and signal to noise ratio dominate resolutions
  - 600 µm pitches achieve ~50 µm resolution
Test Equipment

To evaluate different 2D readout board designs
- Designed and built 5 test boxes
  - Enclosed gas volume with O-ring seals
- Contains HV foil and three GEM foils on frames plus the readout layer
- Test boxes can be opened to exchange any layer
  - Useful for testing GEM foils as well as readout boards
- External connections for all 7 HV levels used by triple GEM detector
  - Useful for testing different drift fields and GEM operating voltages

Readout boards are read out using APV25-S1 chip
- 128 channels, 40 MHz sampling, 192 bucket analogue ring buffer
- Developed BGA packaged APV chip together with STAR and Yale
  - Greatly simplifies production of APV boards

APV chips are read out via a VME based FPGA board
- Main board has 3 mezzanine card slots
- ADC mezzanine card can read each 4 APV chips
- Control mezzanine card powers and controls up to 12 APV chips
GEM2D Test Setup
GEM2D Test Setup
GEM2D Test Boxes
2D Readout Board
GEM Foil on Frame
2D Readout Board Designs

<table>
<thead>
<tr>
<th>Pitch µm</th>
<th>Gap µm</th>
<th>Line Width µm</th>
<th>Pads µm</th>
<th>Via µm</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>300</td>
<td>800</td>
<td>800 x 1700</td>
<td>250</td>
<td>Any PCB manufacturer</td>
</tr>
<tr>
<td>800</td>
<td>200</td>
<td>200</td>
<td>200 x 600</td>
<td>100</td>
<td>Needs laser drilled vias</td>
</tr>
<tr>
<td>600</td>
<td>100</td>
<td>200</td>
<td>200 x 400</td>
<td>100</td>
<td>Test effect of gap between pads</td>
</tr>
<tr>
<td>400</td>
<td>75</td>
<td>125</td>
<td>125 x 325</td>
<td>50</td>
<td>Test limits of resolution</td>
</tr>
<tr>
<td>1000</td>
<td>150</td>
<td>350</td>
<td>350 x 2350</td>
<td>100</td>
<td>±11° Stereo</td>
</tr>
<tr>
<td>1250</td>
<td>200</td>
<td>425</td>
<td>425 x 1050</td>
<td>100</td>
<td>XUV 45°</td>
</tr>
</tbody>
</table>

2 mm pitch board any PCB manufacturer can produce
- Finer pitches driven by via size (not line or gap size) and need a manufacturer capable of laser drilling vias

400 µm pitch design is a practical limit
- 300 µm pitch was possible but difficult and plating caused shorts
- 100 µm gap with 100 µm line and 100 x 300 µm pad better choice

Stereo and XUV designs have not yet been received
Comparison of 2D Readout Designs

Traditional designs - two layers exposed to electron shower
- Foils are very fragile requiring a support layer adding material
  - Surfaces still easily damaged
- Process must be carefully managed to be uniform over area
- Lines on top layer must be narrow to achieve equal charge sharing

Chemical etch can only handle constant line and gap sizes
- Rate of etching depends on feature sizes
- Under etching covers bottom lines, over etching reduces support

Laser etching more flexible but complicated and costly
- YAG laser can achieve fine features but can also vaporize copper
- CO₂ laser reflects from copper but less control (at company tested)

Cost comparison e.g. one STAR FGT 2D readout board
- $8600 laser etched, not possible with chemical etching
- $950 with line and pad with vias approach
Plans for the Future

All test boxes, GEM detectors, readout system, readout board designs have been completed

• Waiting delivery of stereo and XUV readout boards

Investigation of production and charge sharing complete

Still to be done

• HV optimization of GEM detector
  • Vary drift fields and GEM operating voltages
• Investigate using bottom of last GEM foil as fast trigger
• Optimize readout system
  • Investigate effect of line length, capacitance, grounding schemes on noise
• Study position resolutions
  • Using 3 GEM2D boxes as a telescope with cosmic rays study track reconstruction and resolutions as a function of operating conditions and readout designs