New Approach for 2D Readout of GEM Detectors

D.K. Hasell and R.P. Redwine
Massachusetts Institute of Technology

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

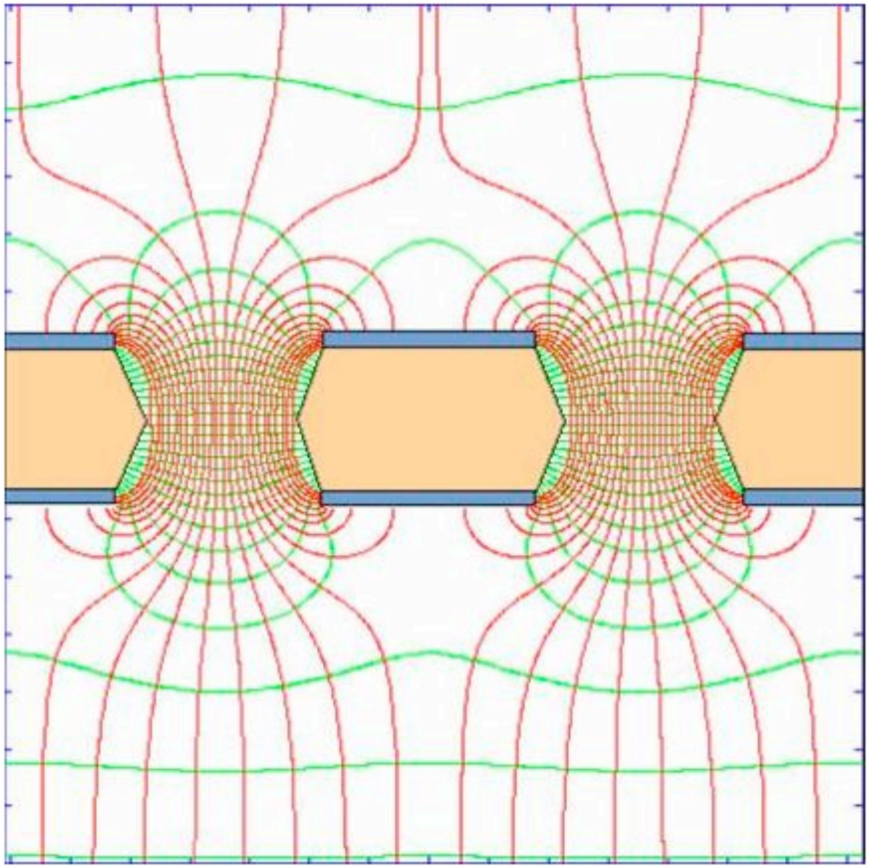
New Approach for 2D Readout

Experience with Production

Gas Electron Multiplication - GEM

First proposed in 1996

- F. Sauli (CERN)
  - Nucl. Instr. Meth. A386 (1997) 531
- 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

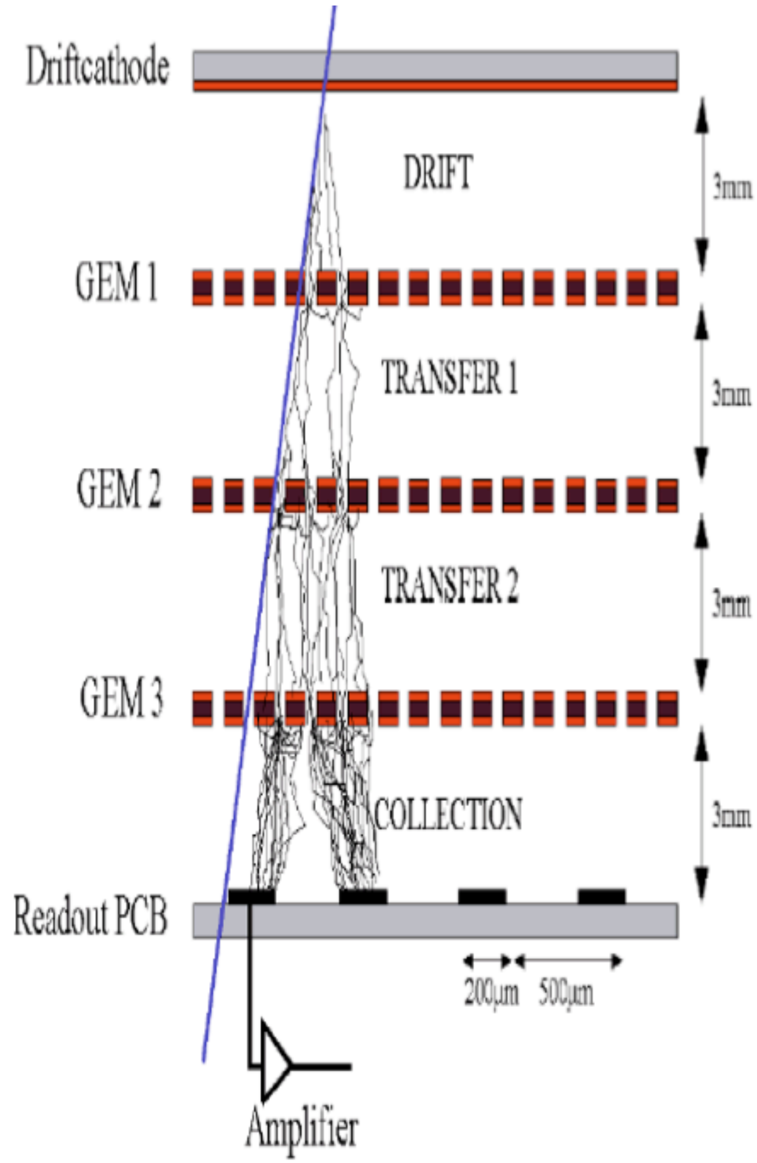
- Gain ~80,000 in triple GEM

Readout board detects charge

- Various designs possible
  - Pads, strips
  - 2D patterns

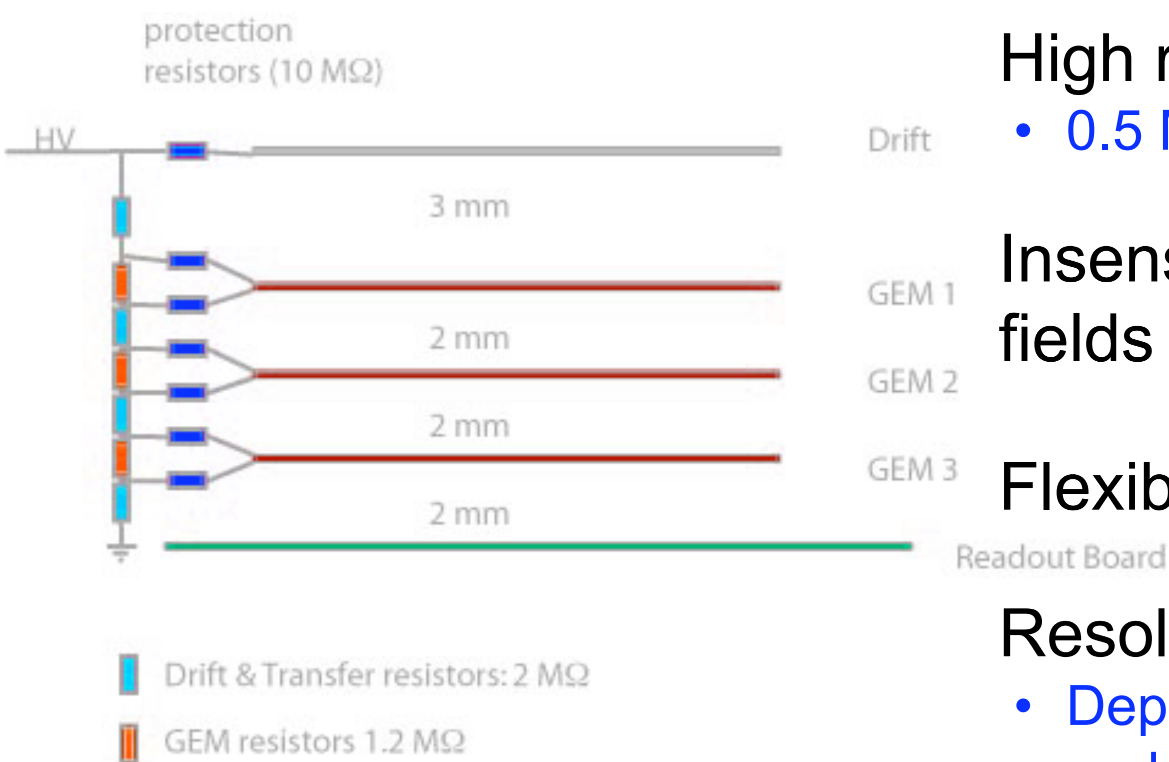
Position resolution

- Depends on gas, geometry, and readout



Advantages of GEM Detector

Cascading HV scheme



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

High rate
- 0.5 MHz/cm^2

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

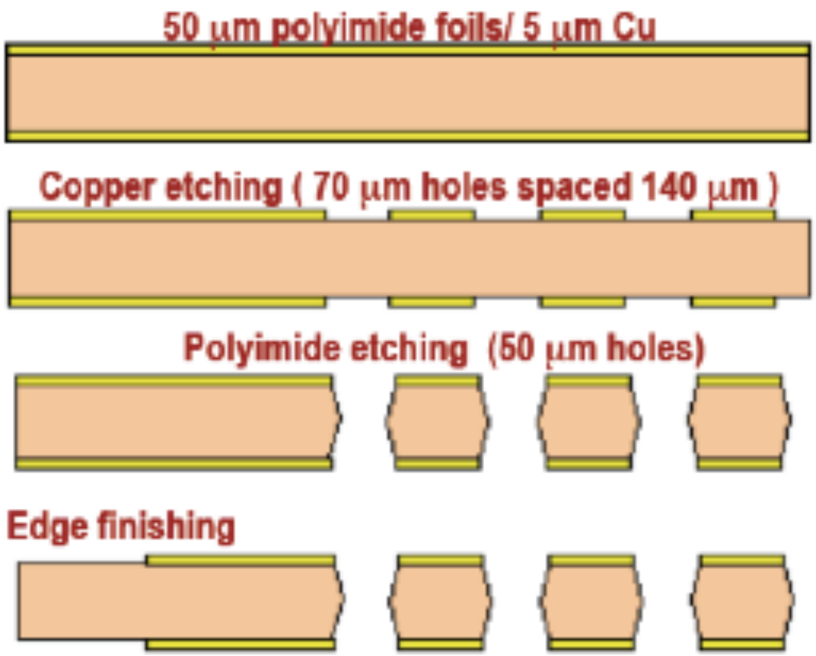
Tech-Etch, Inc.

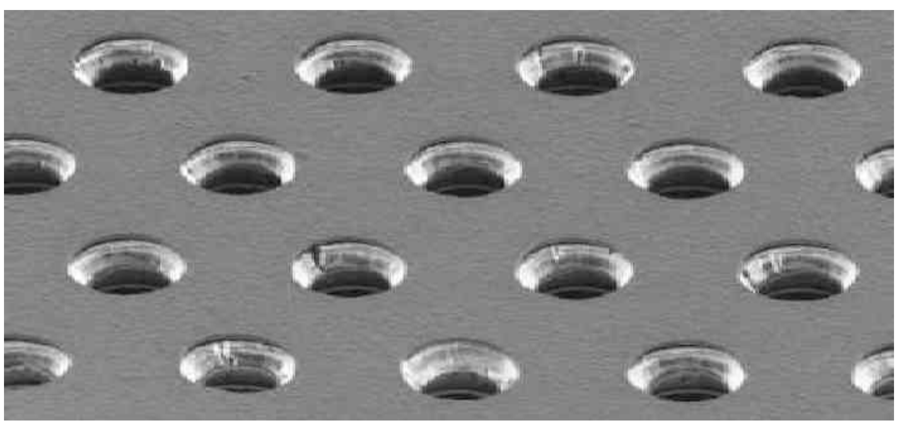
- http://www.tech-etch.com
- Plymouth, MA
- Dedicated GEM production line
- Quality control and testing facilities

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 m^2

GEM Technology



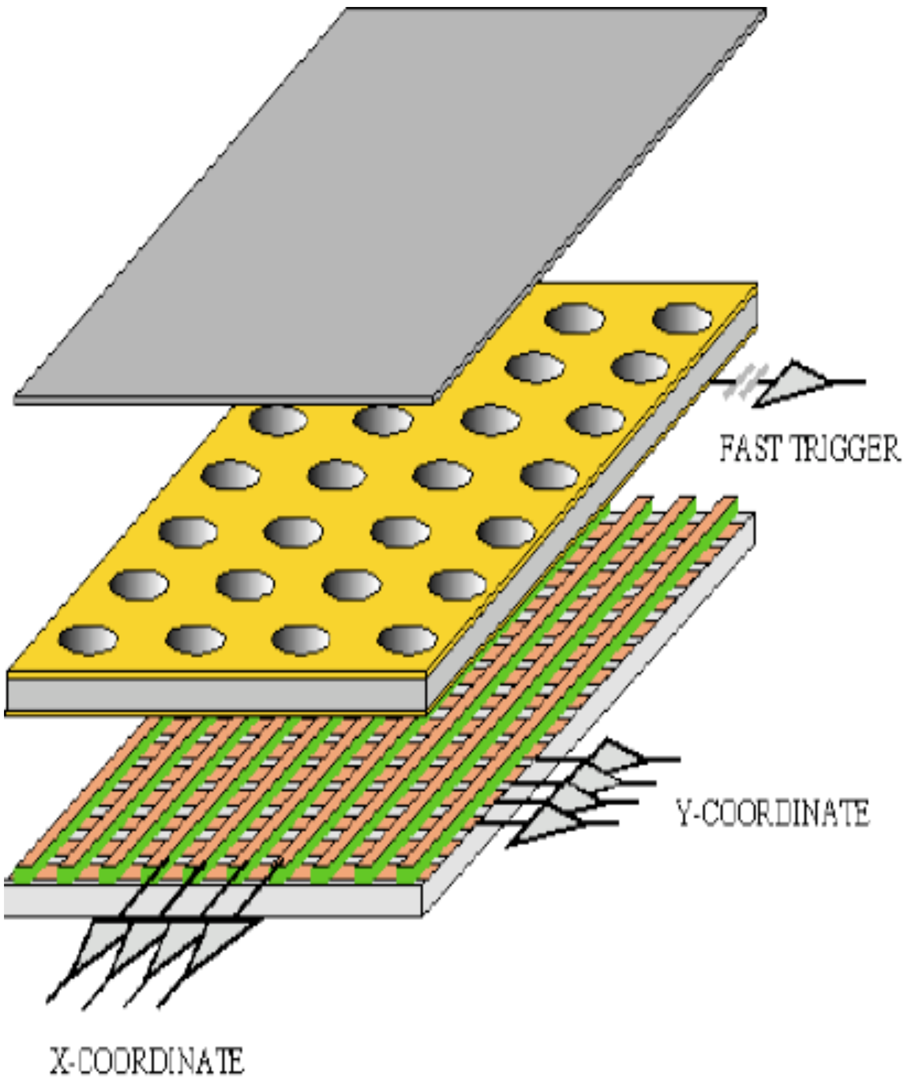


Flexible PCB technology

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

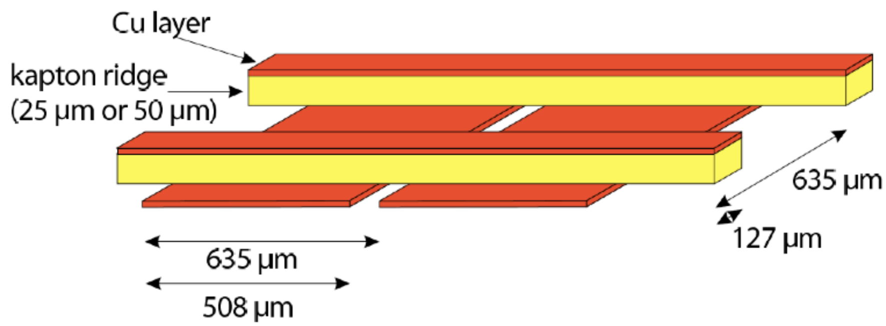
Bottom of last GEM foil can provide faster trigger

- 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

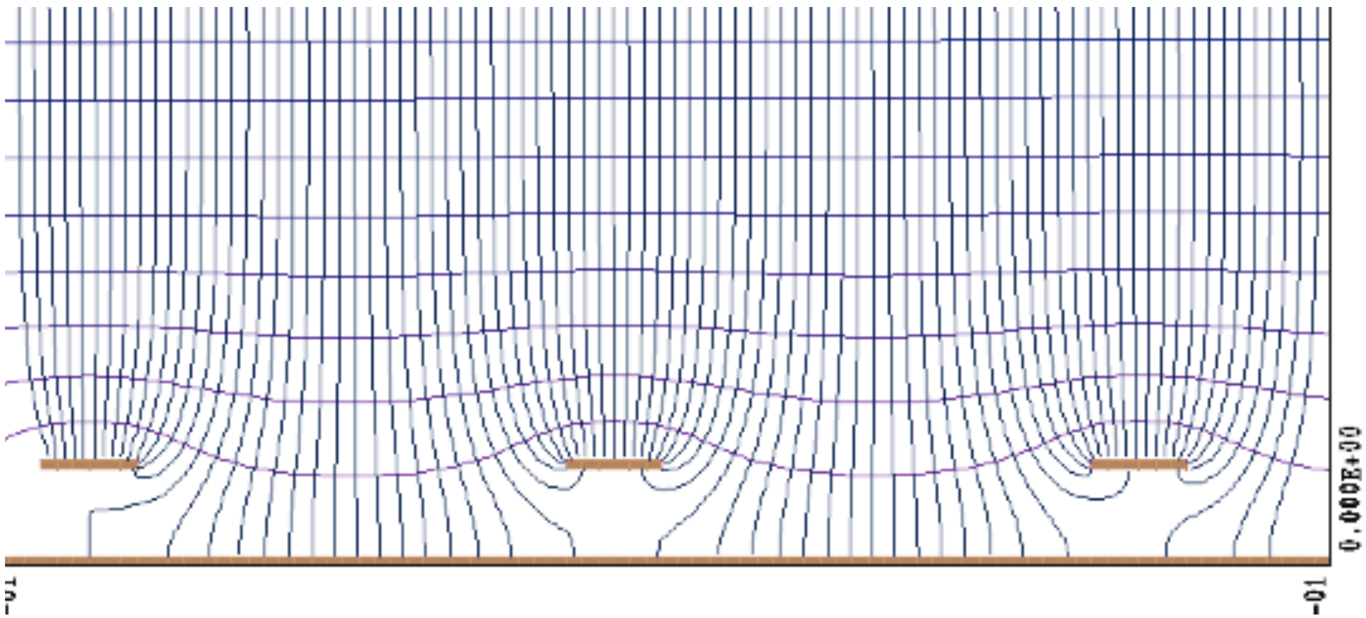
- Helps resolve ambiguity if there are multiple hits
- Must be the same over entire area

Useful if ratio is close to unity

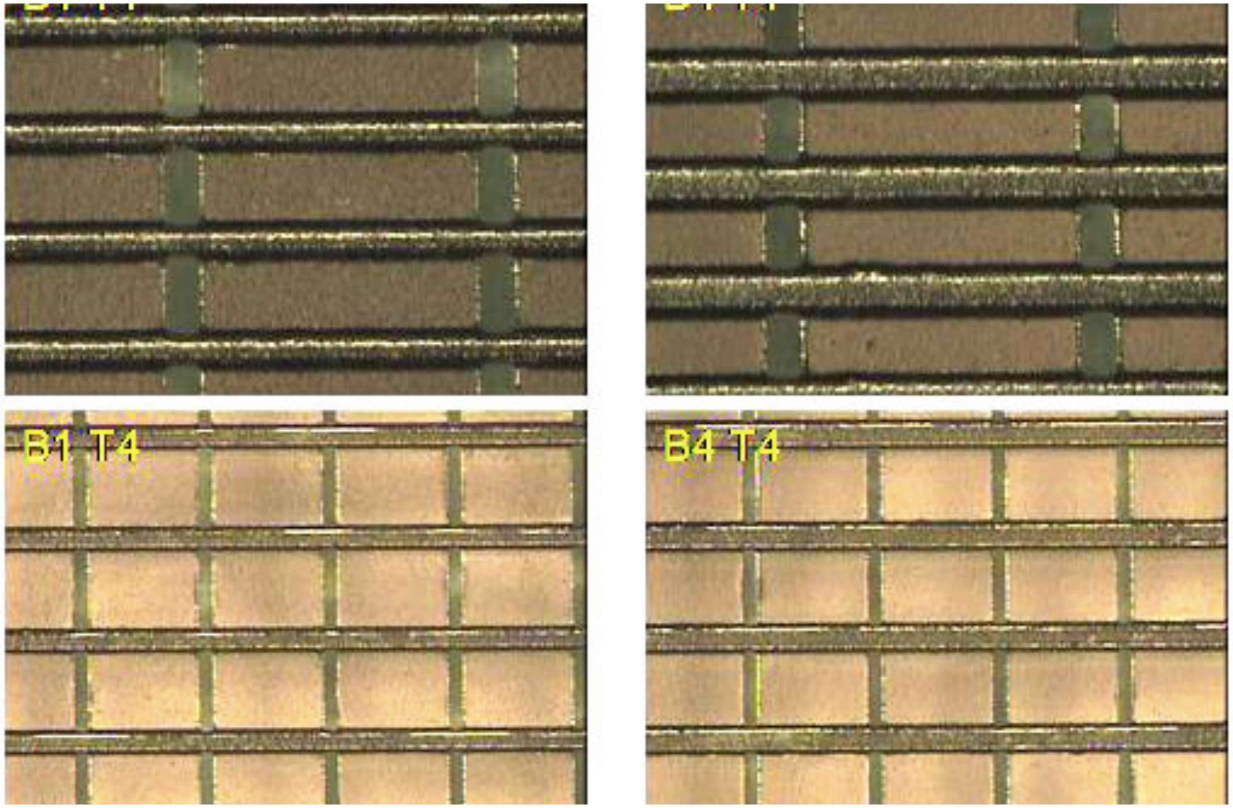
- Same electronic gain can be used for top and bottom lines

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

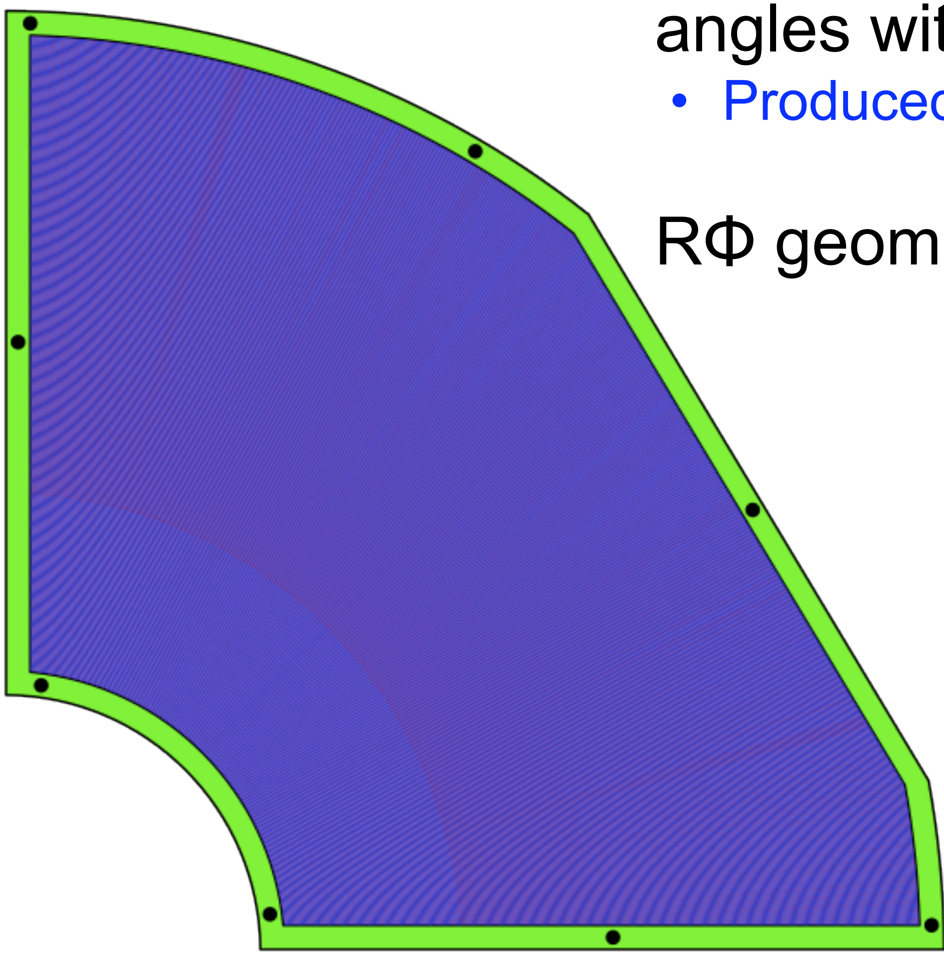


Narrow top lines

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

Width	Pitch
100	275
120	400
130	525
140	650

Complex Example: STAR FGT 2D Readout

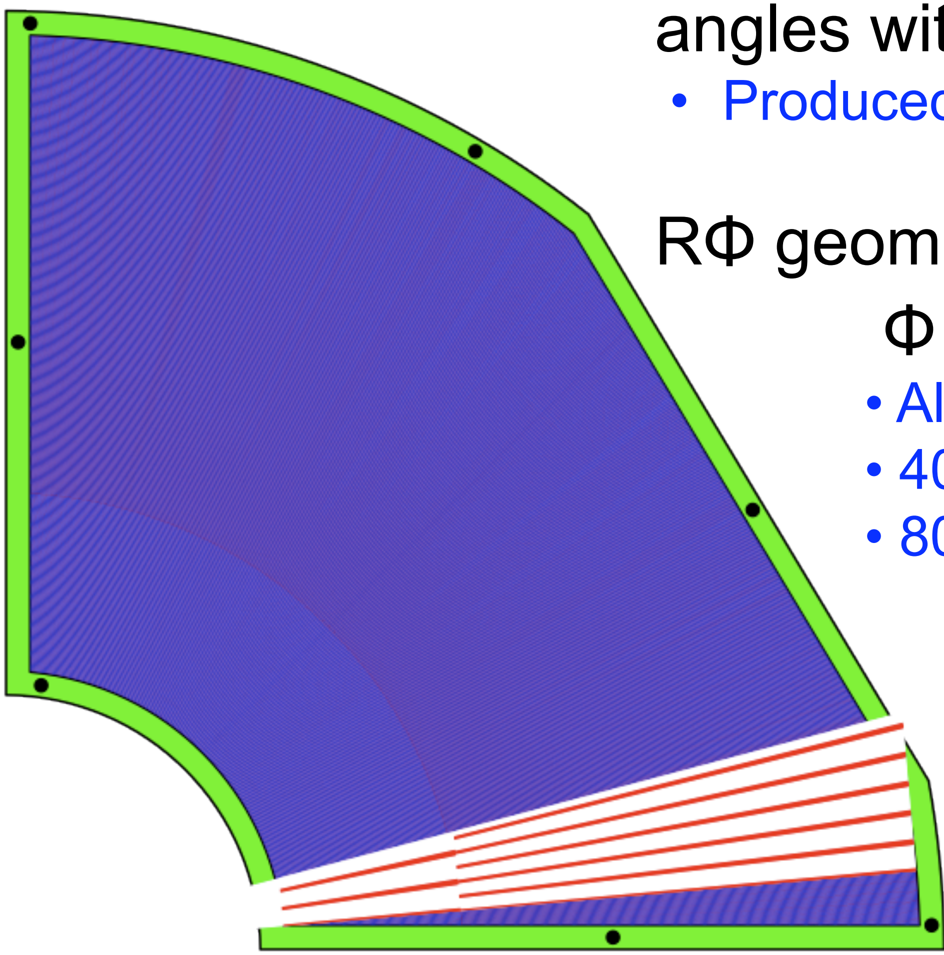


Disks of triple GEM detectors at small angles with respect to beamline

- Produced in quadrants

RΦ geometry most suitable

Complex Example: STAR FGT 2D Readout



Disks of triple GEM detectors at small angles with respect to beamline

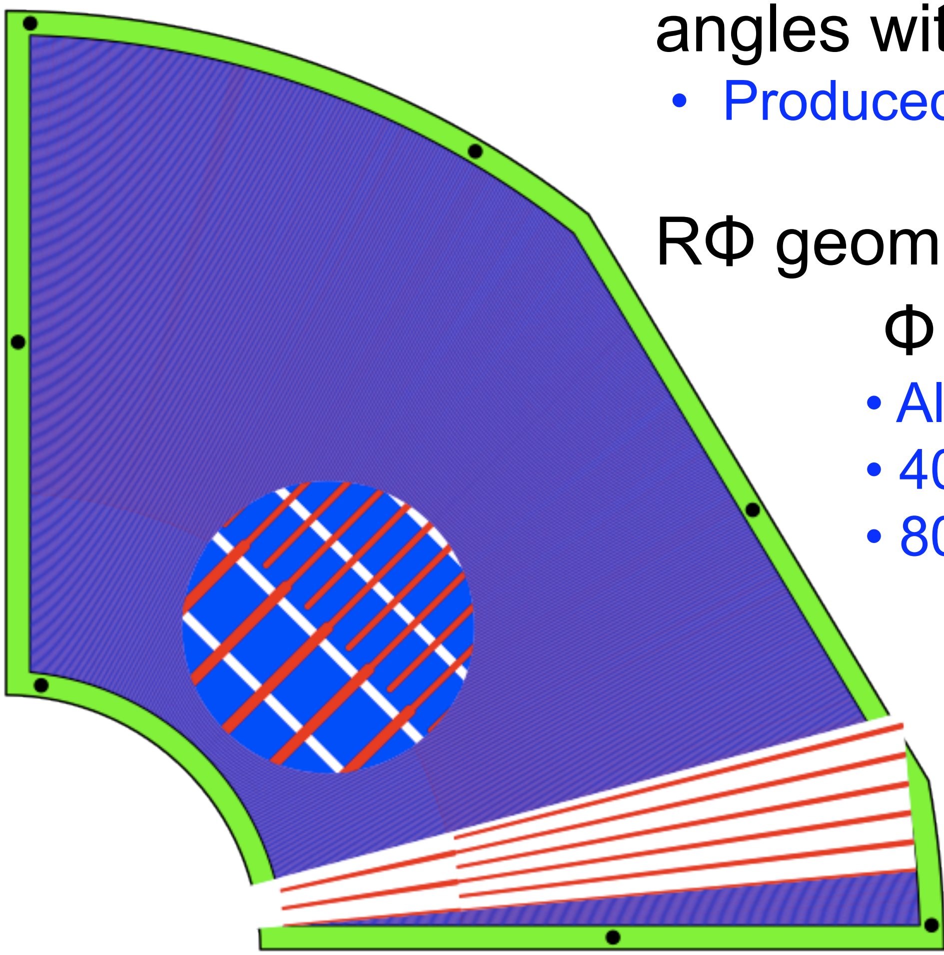
- Produced in quadrants

RΦ geometry most suitable

Φ readout

- Alternate lines end at 18.8 cm
- 400-800 μm pitch varying with R
- 80-120 μm line width varying with R

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

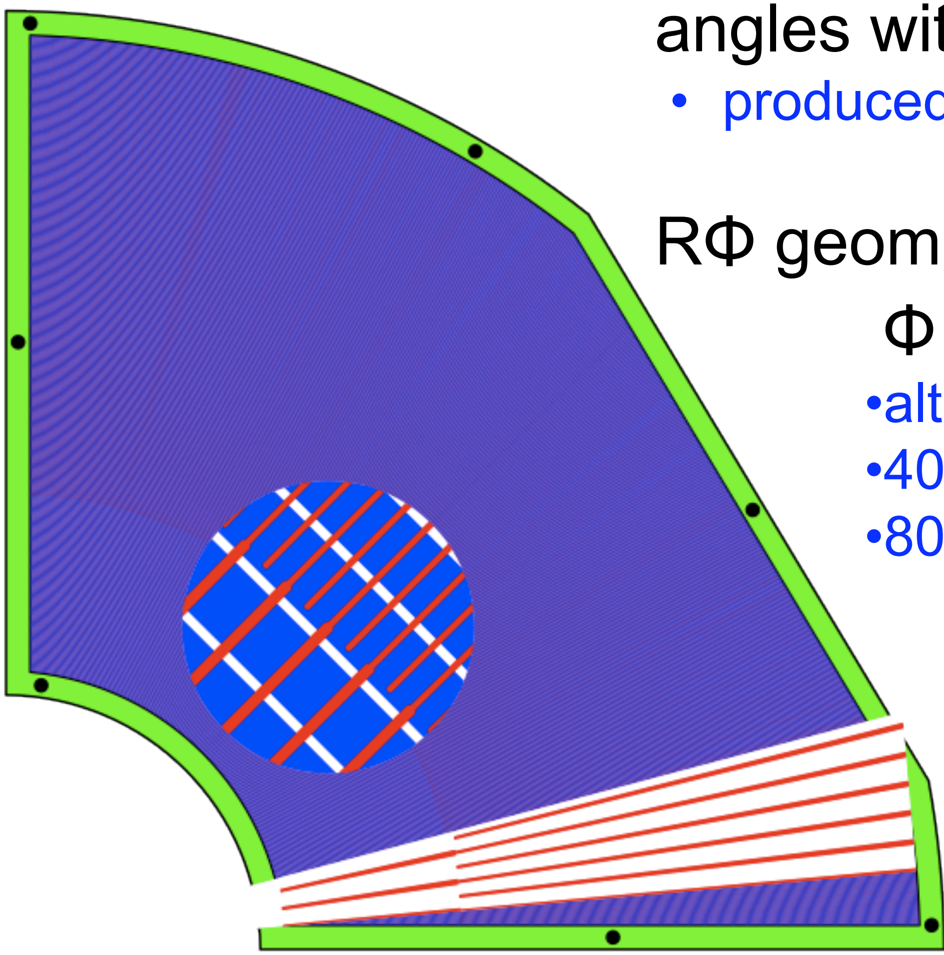
Φ readout

- Alternate lines end at 18.8 cm
- 400-800 μm pitch varying with R
- 80-120 μm line width varying with R

R readout

- 800 μm pitch
- 700 μm line width

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

Φ readout

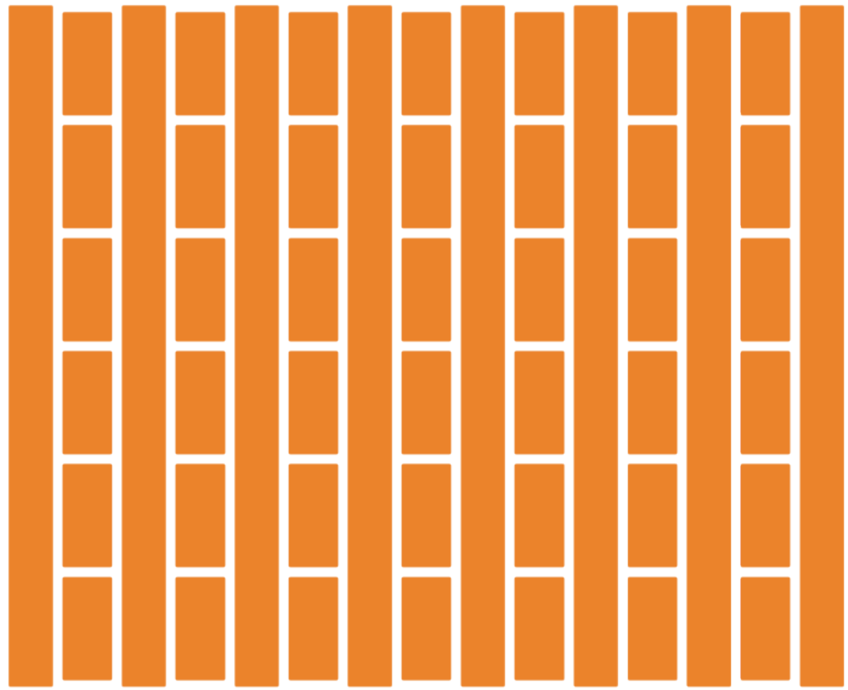
- alternate lines end at 18.8 cm
- 400-800 μm pitch varying with R
- 80-120 μm line width varying with R

R readout

- 800 μm pitch
- 700 μm line width

Very challenging to produce with traditional approach

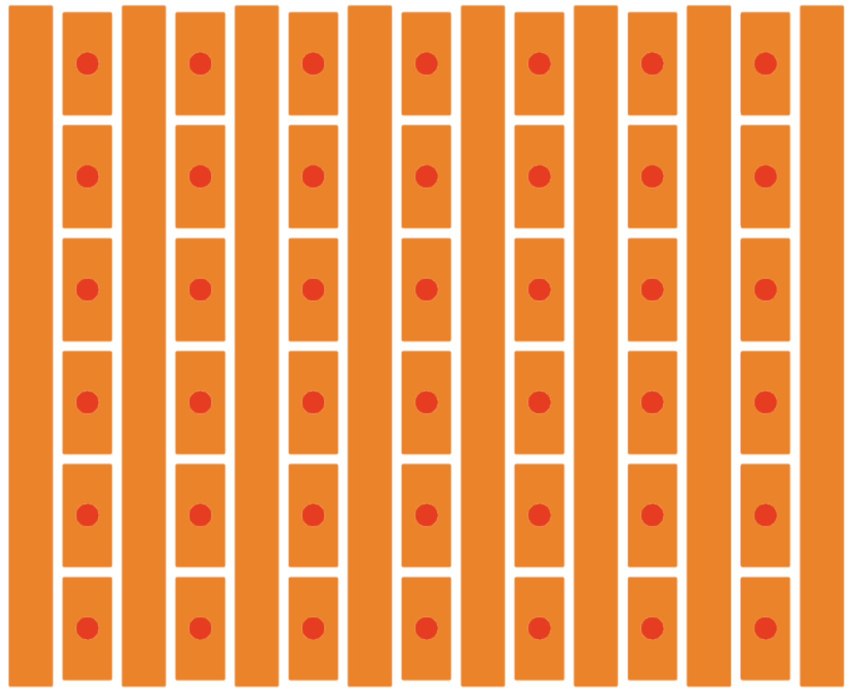
New 2D Readout Layer Concept



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

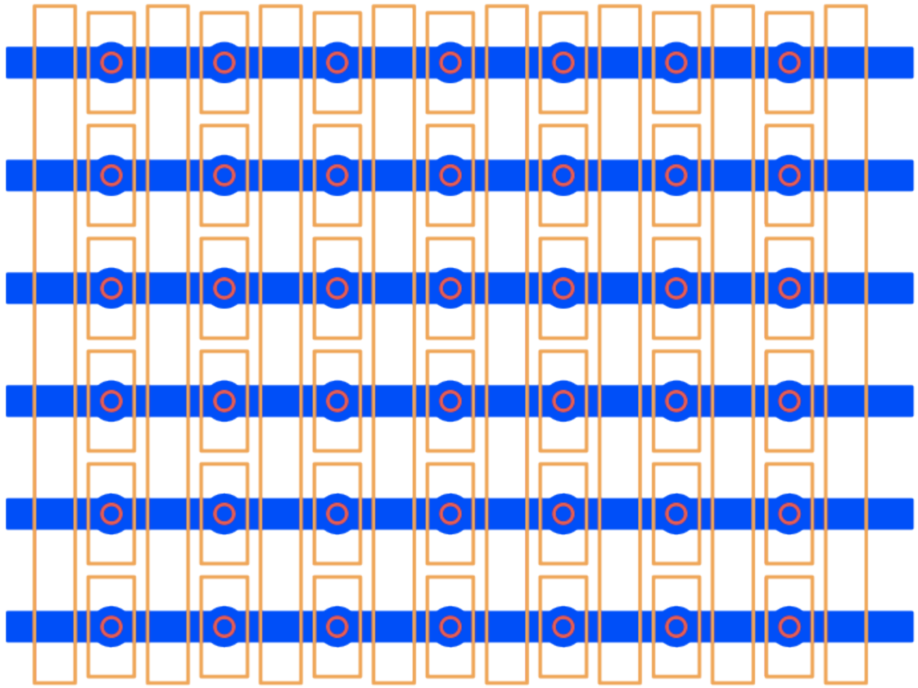
New 2D Readout Layer Concept



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

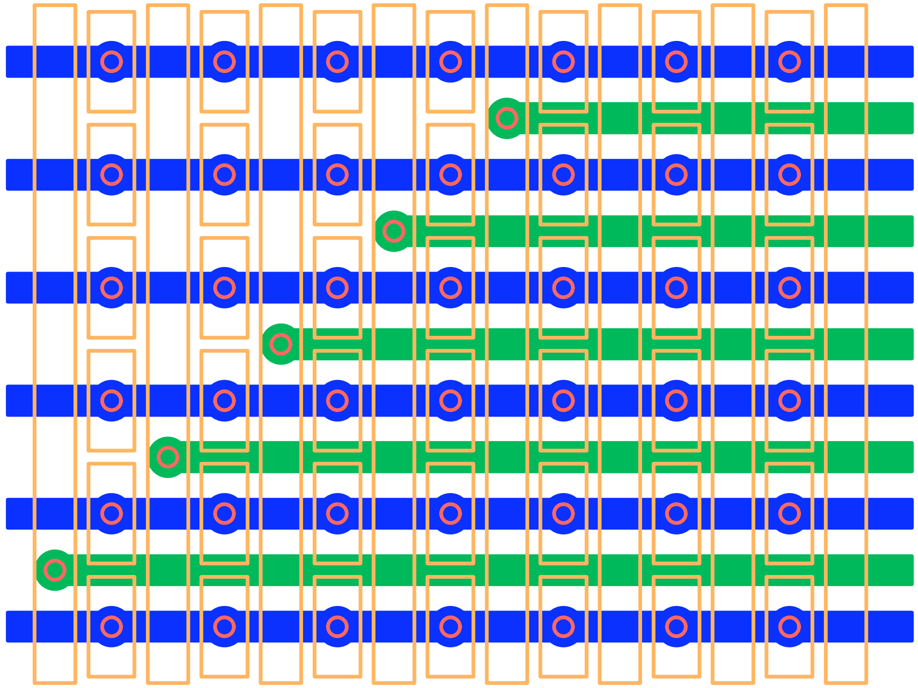
New 2D Readout Layer Concept



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

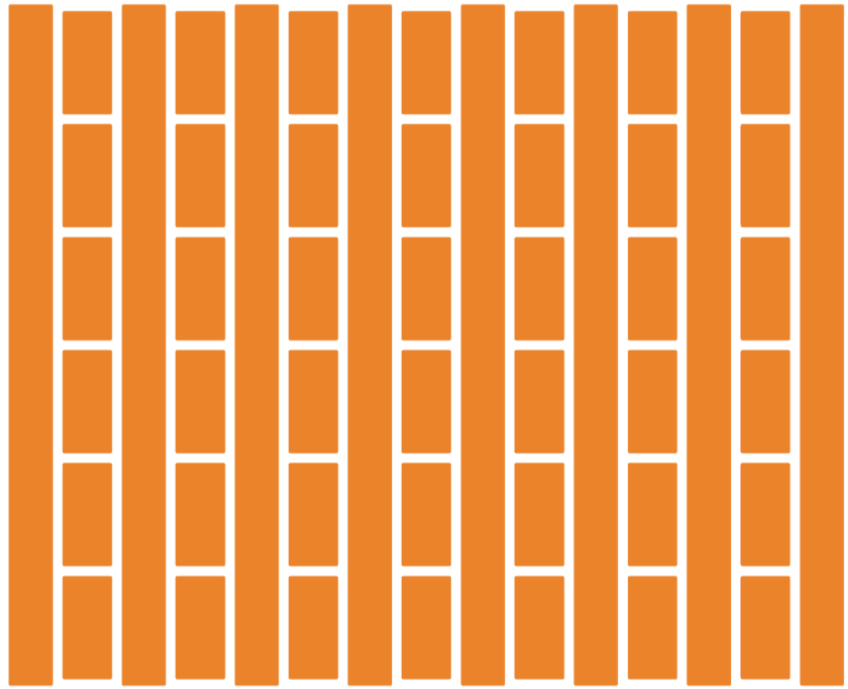
New 2D Readout Layer Concept



Could also connect lines through vias to bottom layer

- Route lines to same edge of board as pads to connect to readout electronics

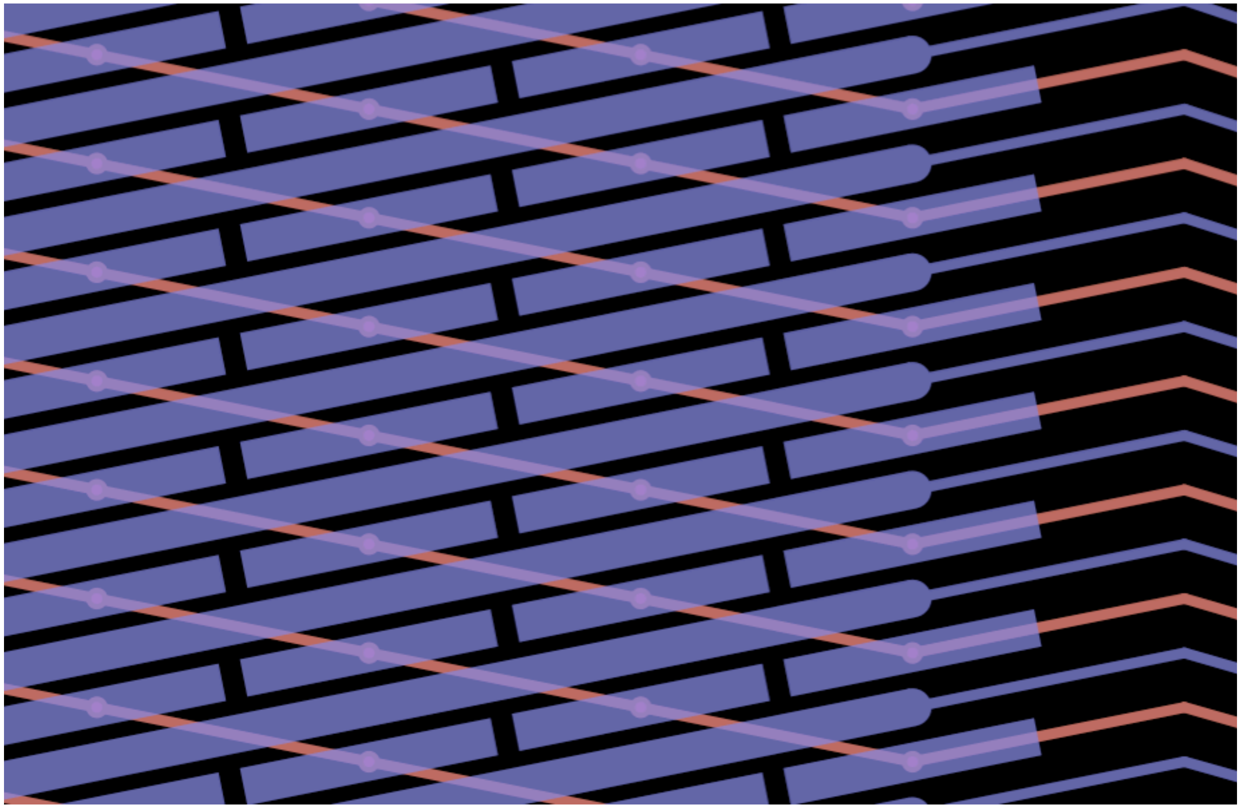
New 2D Readout Layer Charge Sharing



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

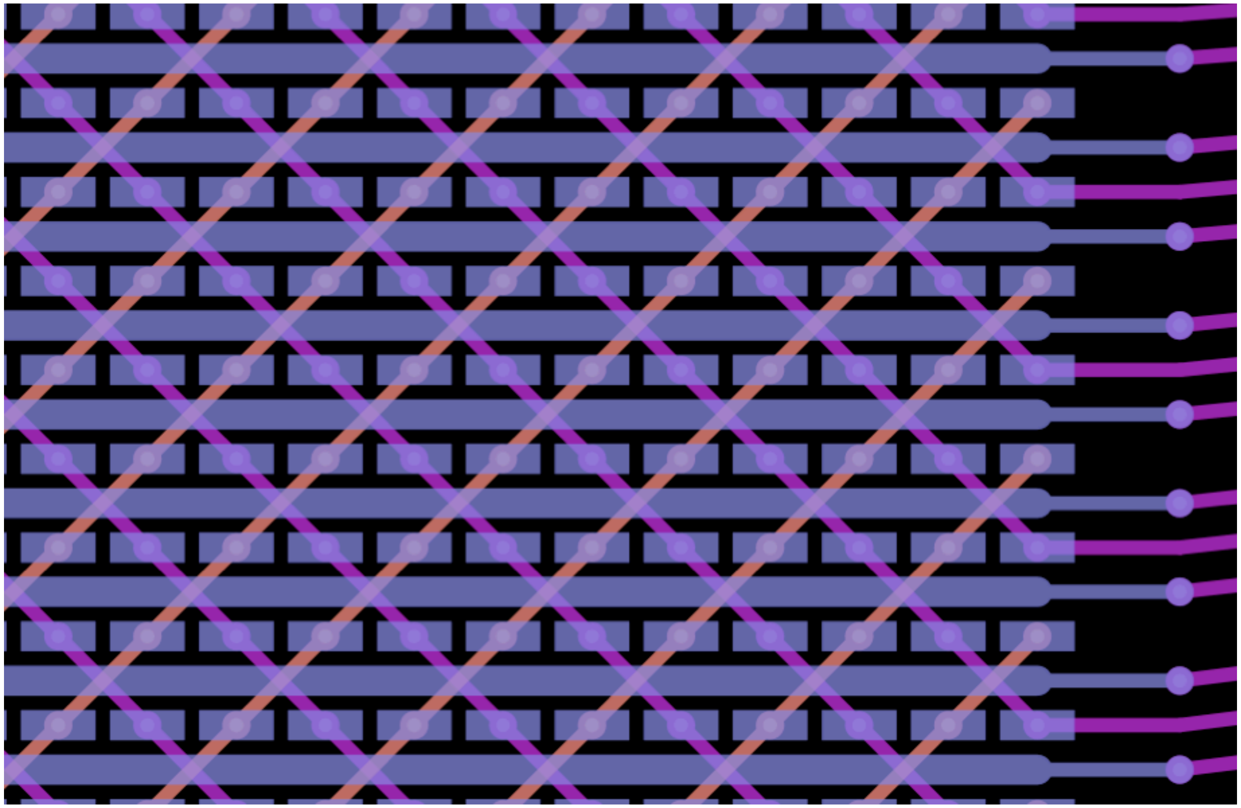
Other Geometries Possible – e.g. Stereo



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

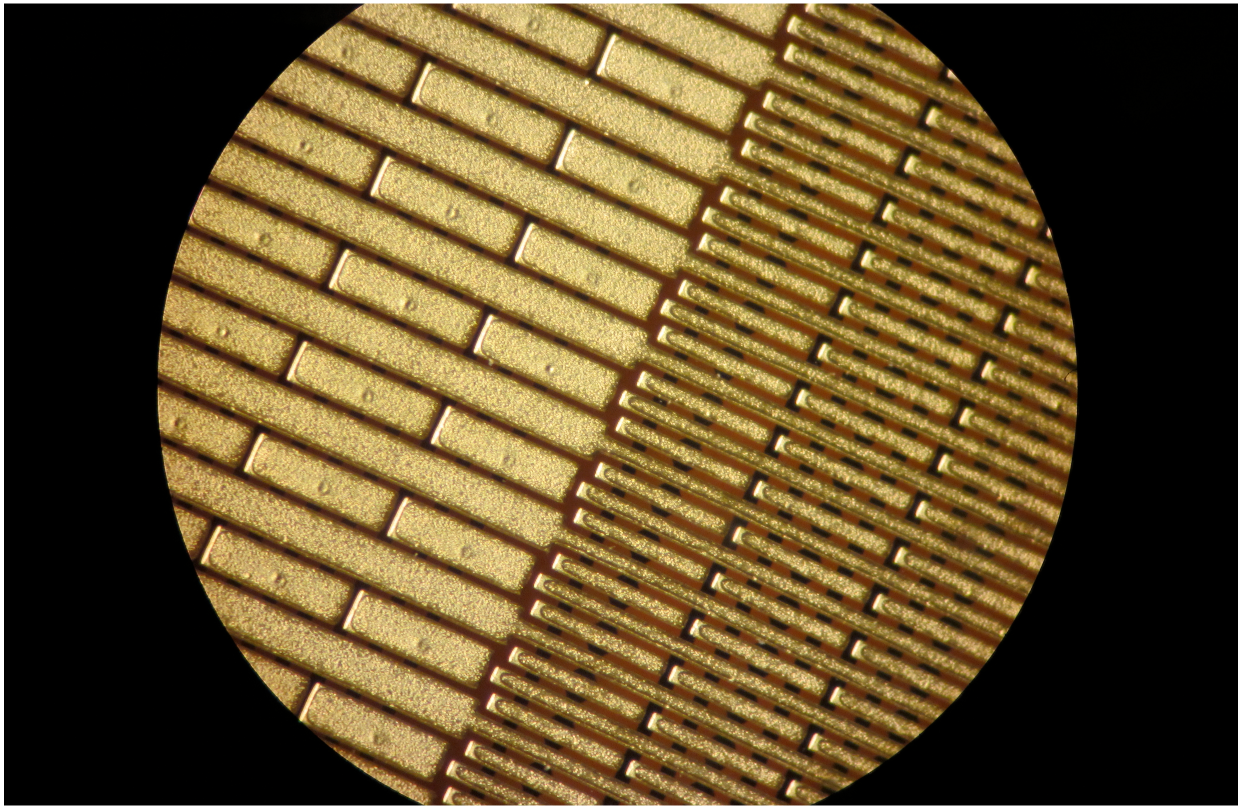
Other Geometries Possible – e.g. XUV



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



RΦ geometry with pitch and line width varying with R

- Transition region where pitch changes from 600 to 300 μm
- 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

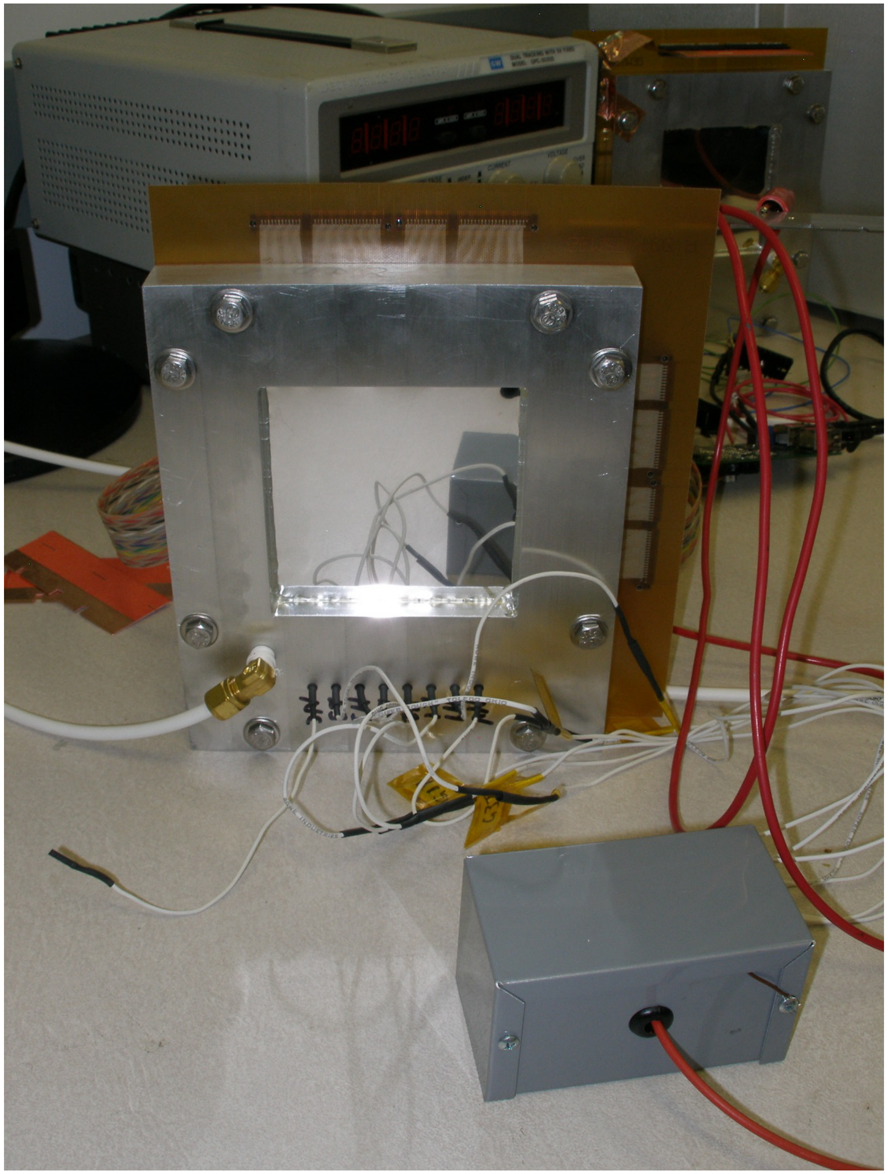
Readout boards are read out using APV25-S1 chip

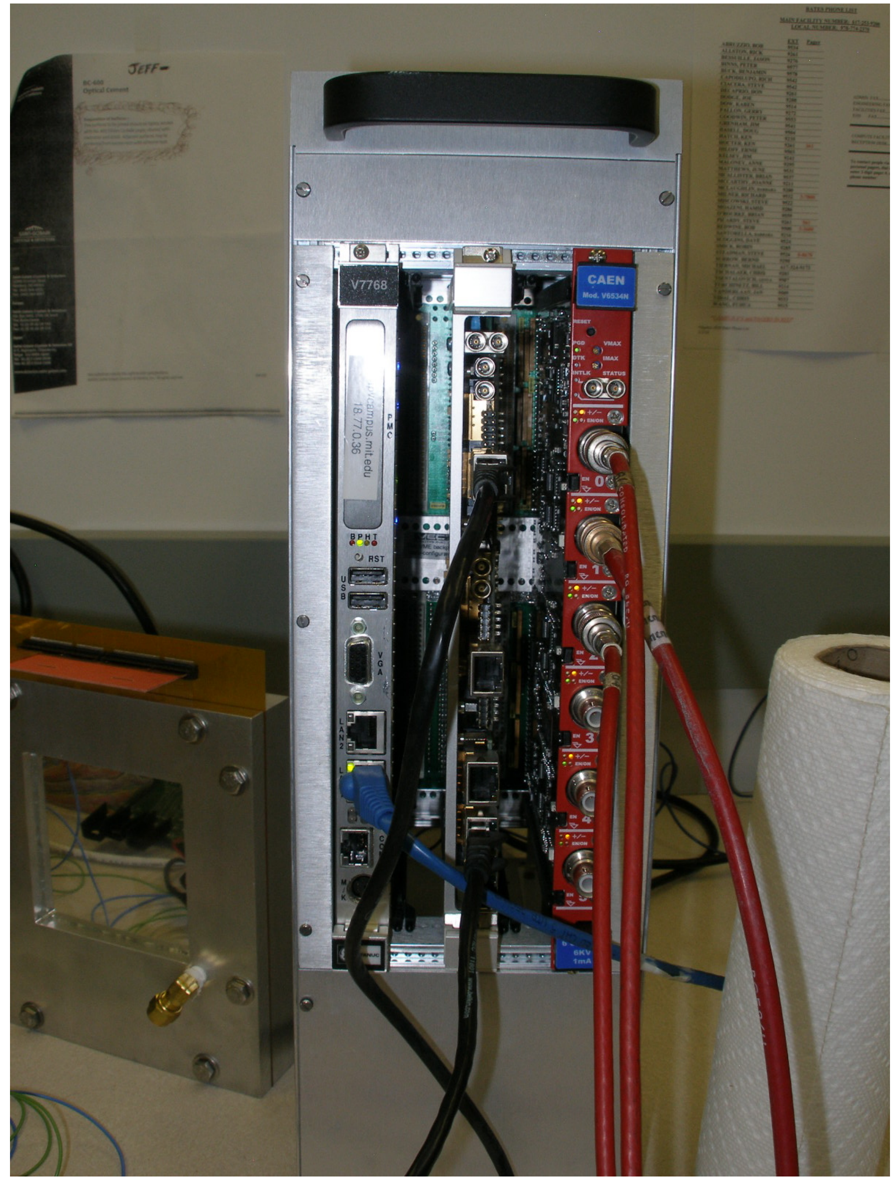
- 128 channels, 40 MHz sampling, 192 bucket analogue ring buffer
- Developed BGA packaged APV chip together with STAR and Yale
  - Greatly simplifies production of APV boards

APV chips are read out via a VME based FPGA board

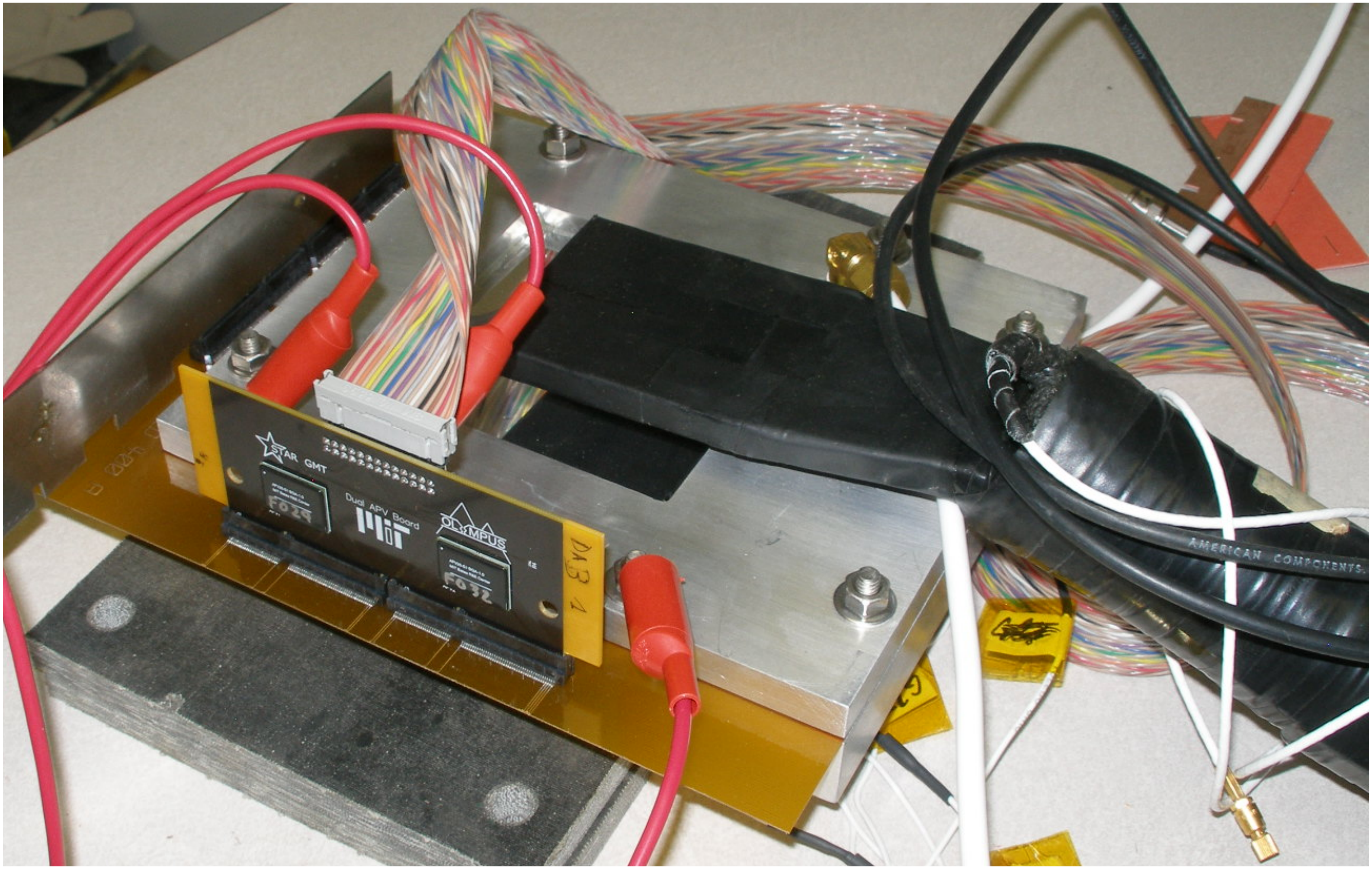
- Main board has 3 mezzanine card slots
- ADC mezzanine card can read each 4 APV chips
- Control mezzanine card powers and controls up to 12 APV chips

GEM2D Test Setup

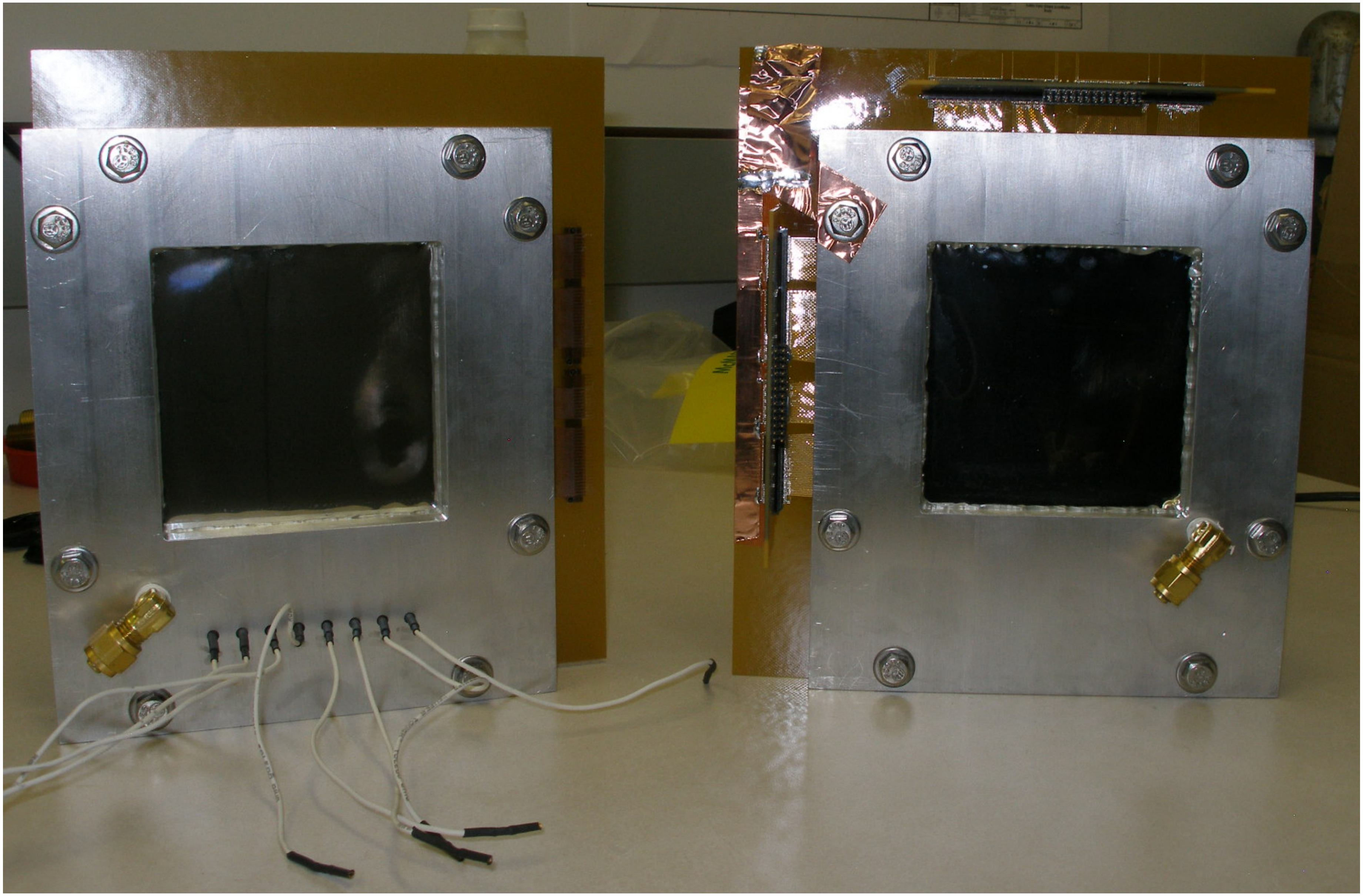




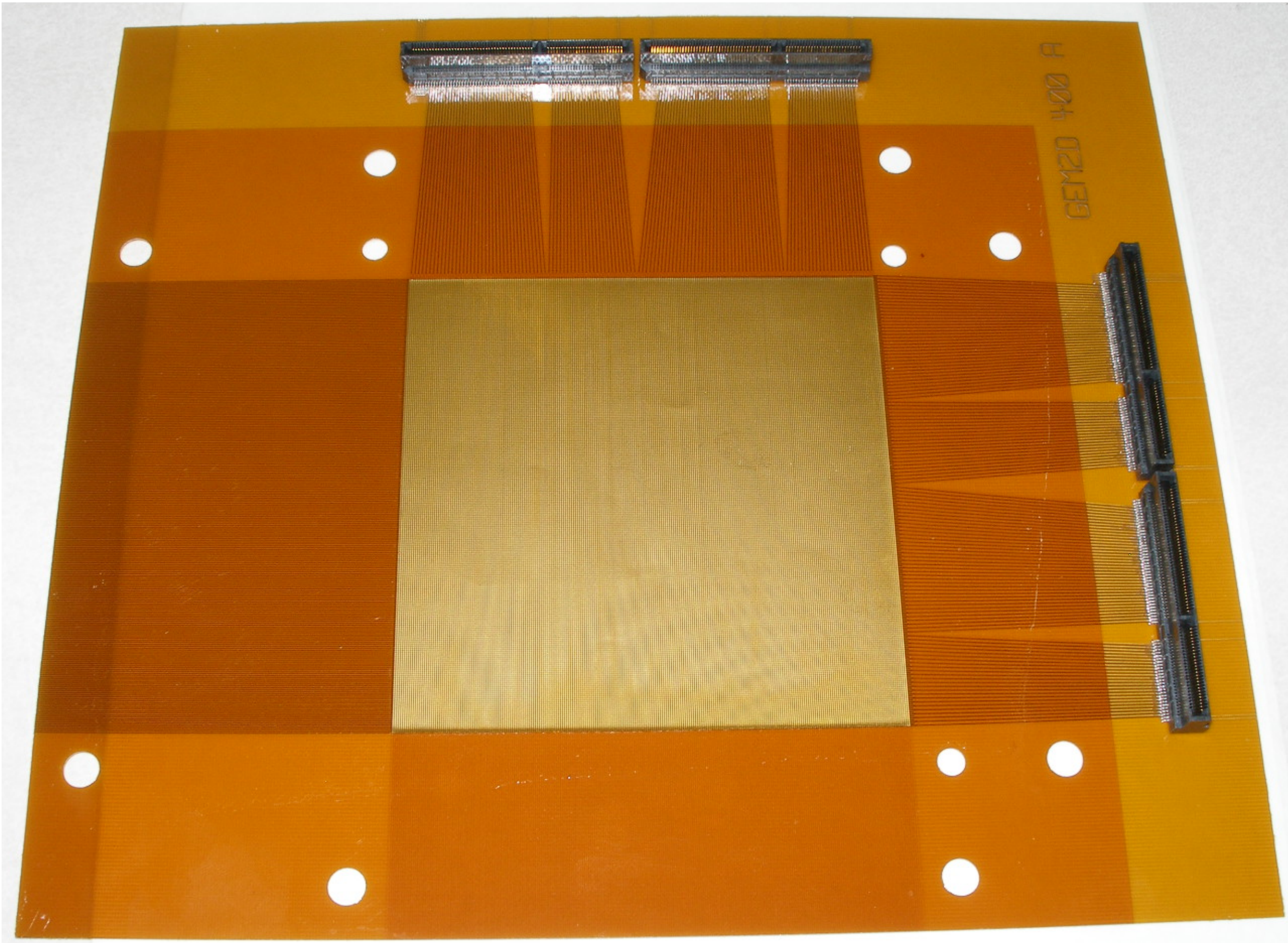
GEM2D Test Setup



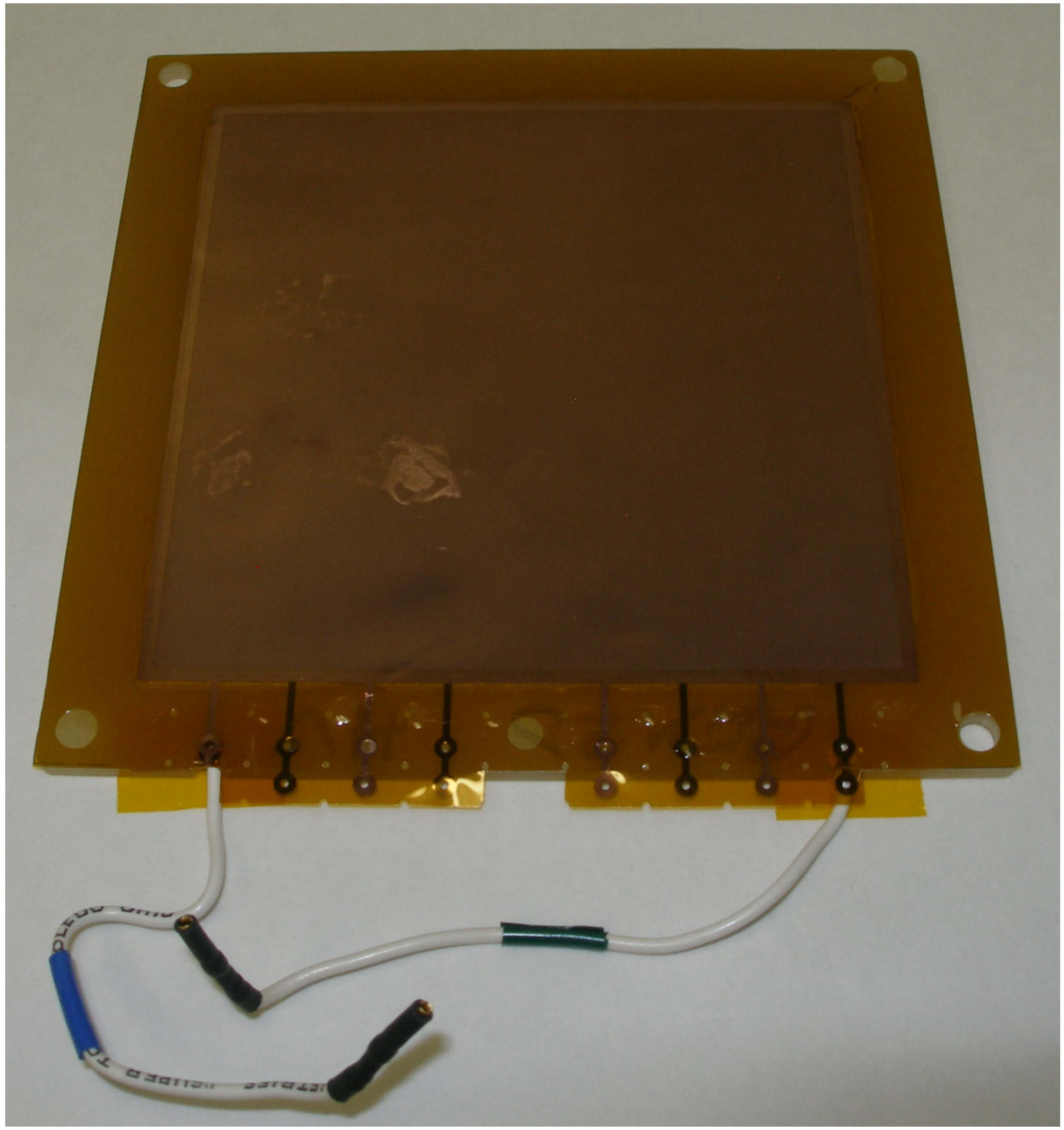
GEM2D Test Boxes



2D Readout Board



GEM Foil on Frame



2D Readout Board Designs

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

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
- CO_2 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