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

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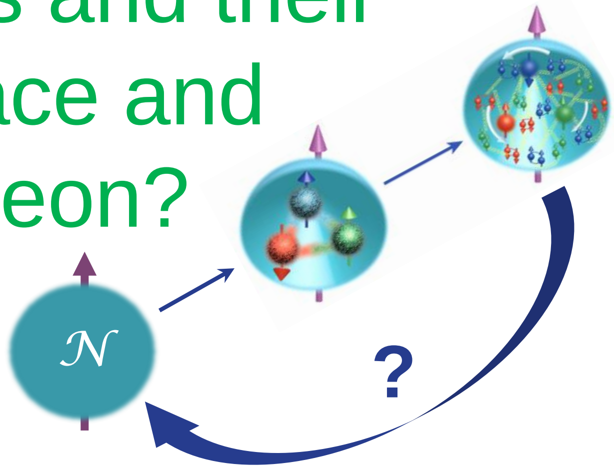
QCD @ Electron Ion Collider

Next QCD Frontier: Strong color fields in nuclei

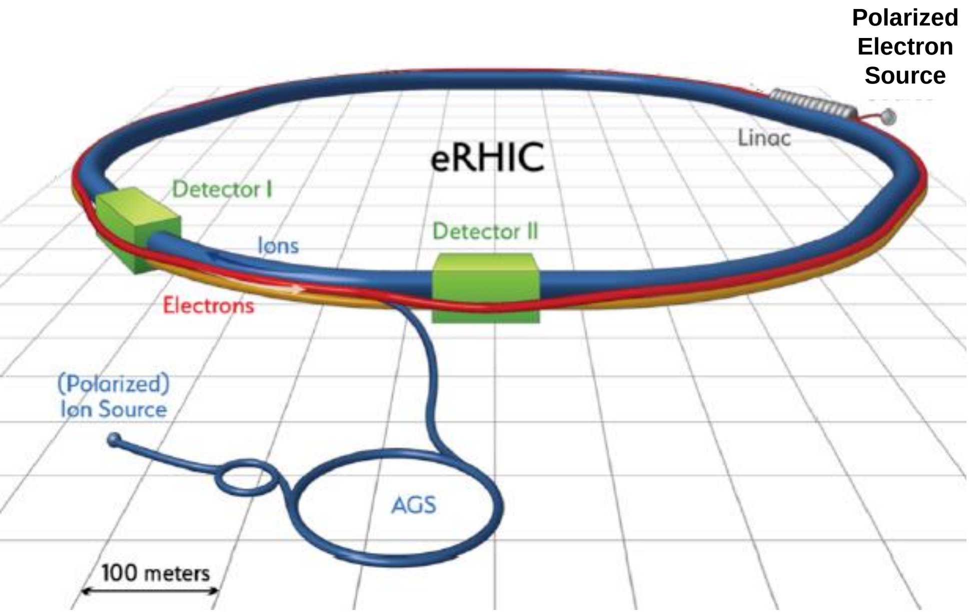
"Understanding the GLUE that binds us all"

- 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.



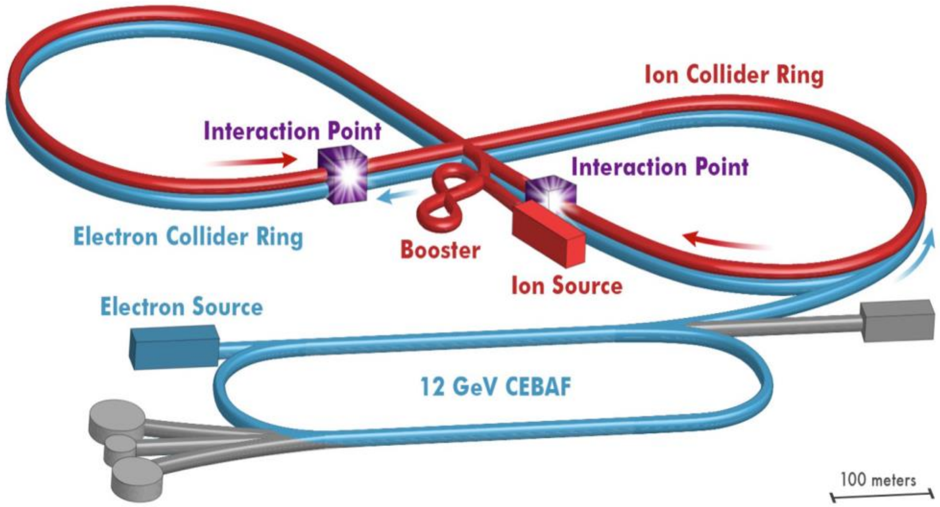
EIC Designs

Brookhaven Lab



- Use existing RHIC
- Add electron ring

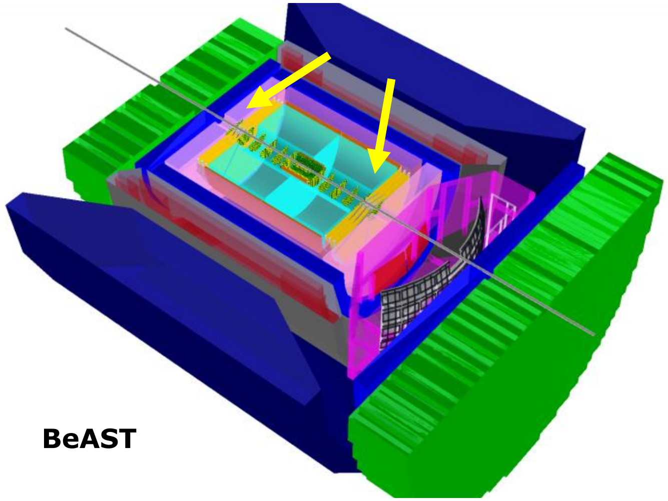
Jefferson Lab

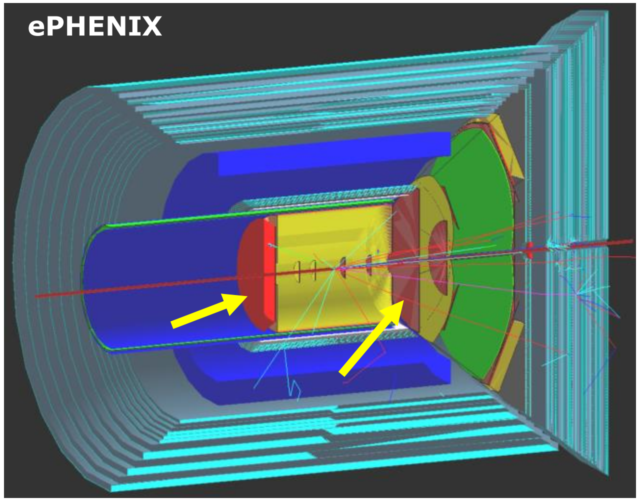


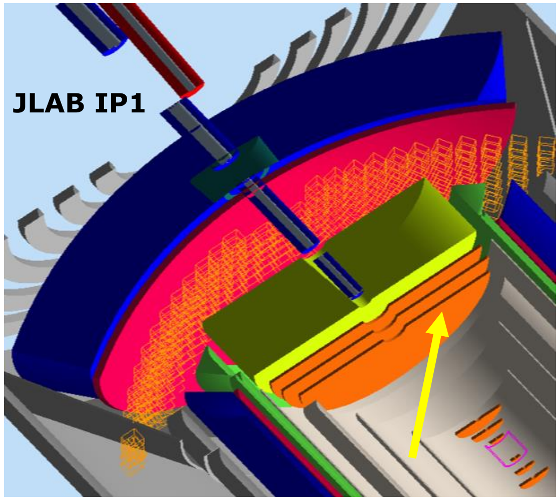
- Use existing CEBAF
- Add ion ring

Large GEMs for EIC Detectors

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



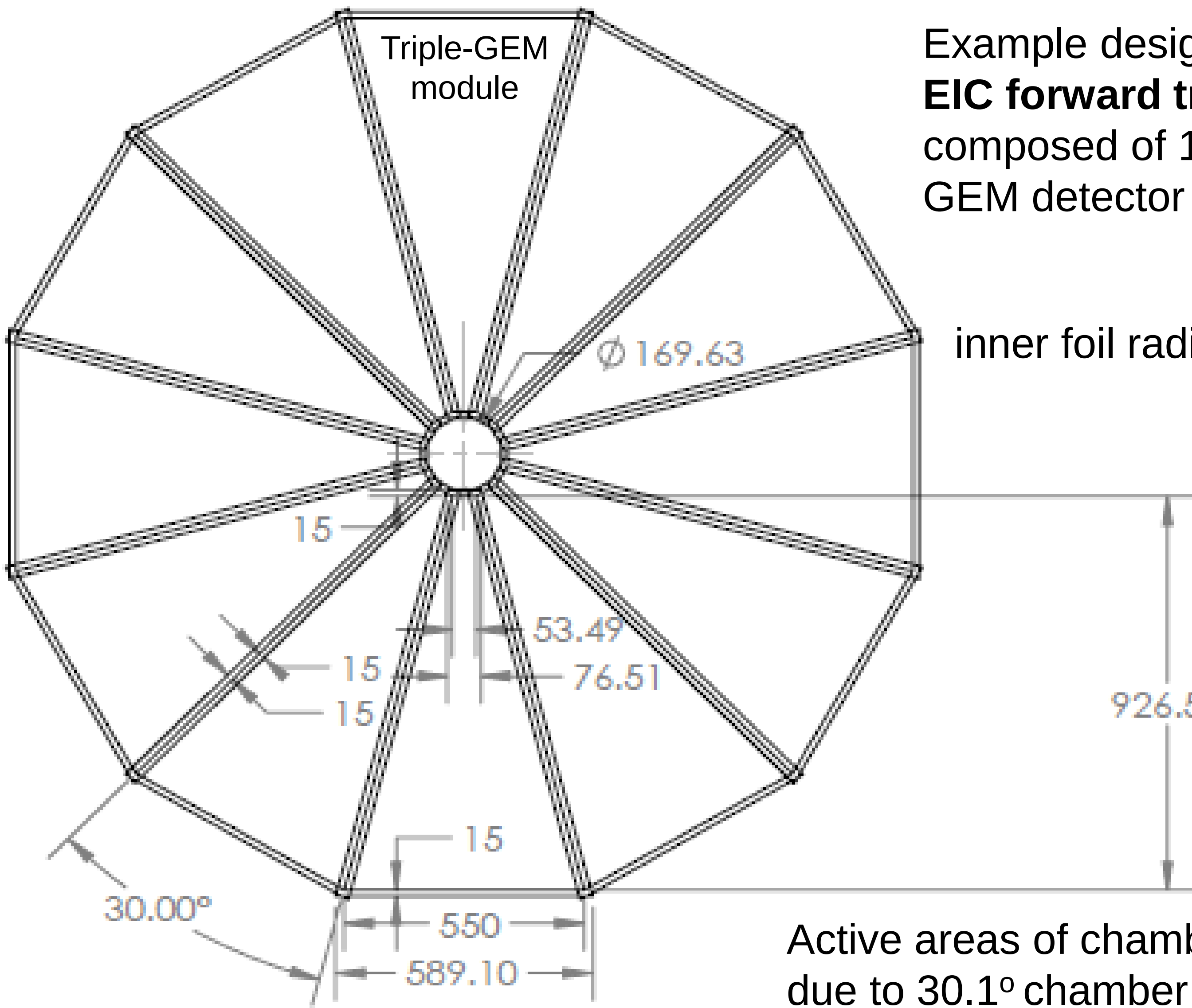




<u>R&D effort dedicated to EIC forward tracking since 2011:</u>

Florida Tech & U. Virginia (eRD6), Temple U. (eRD3)

EIC FT Geometry Option



Example design for an **EIC forward tracker (FT) disk** composed of 12 trapezoidal GEM detector modules

inner foil radius ~ 8cm

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

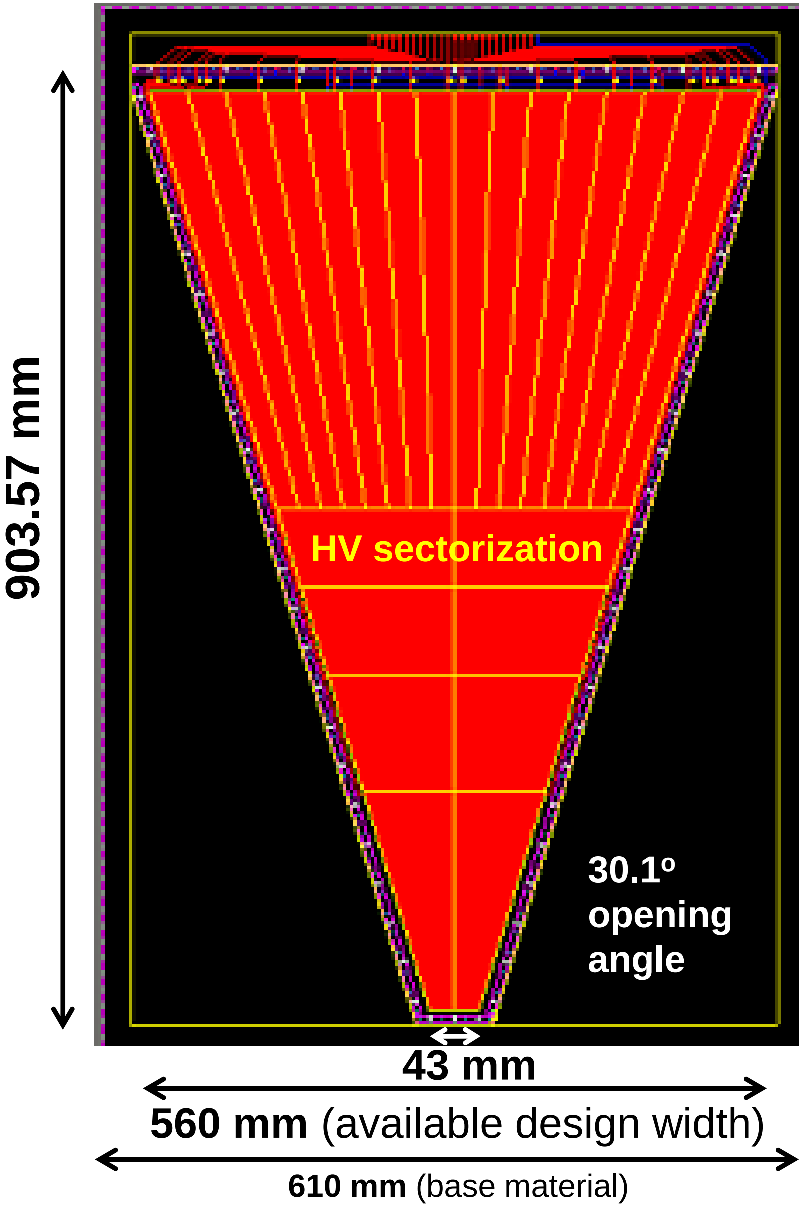
Desired Module Properties

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

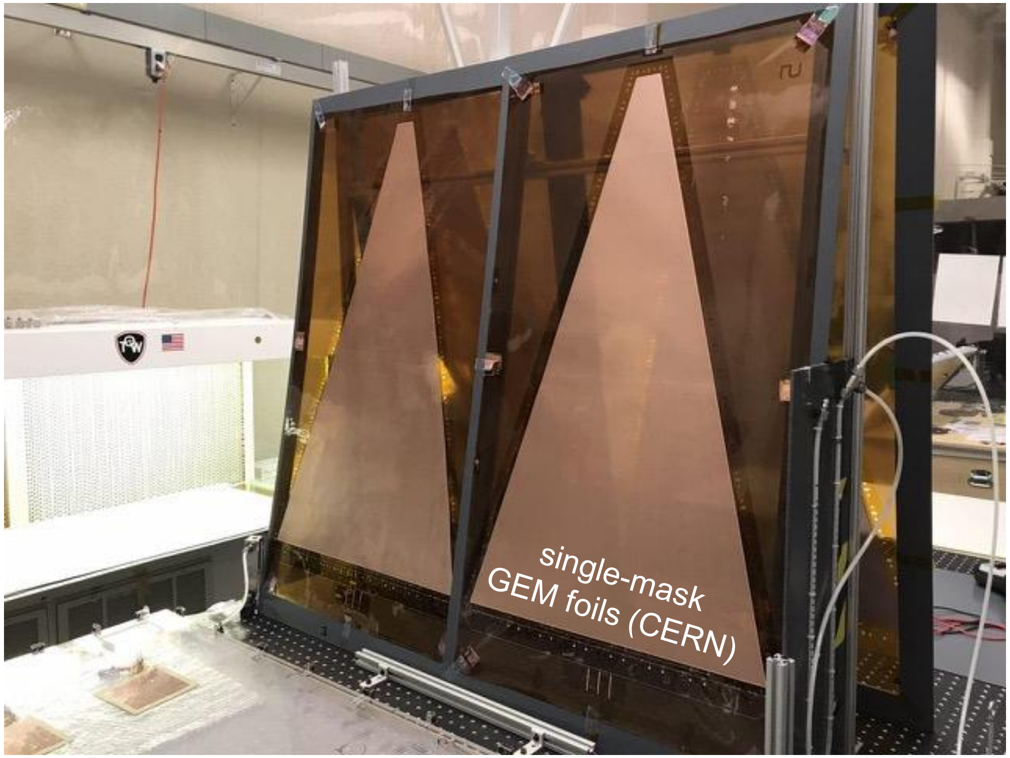
Prototype Module Features

- 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

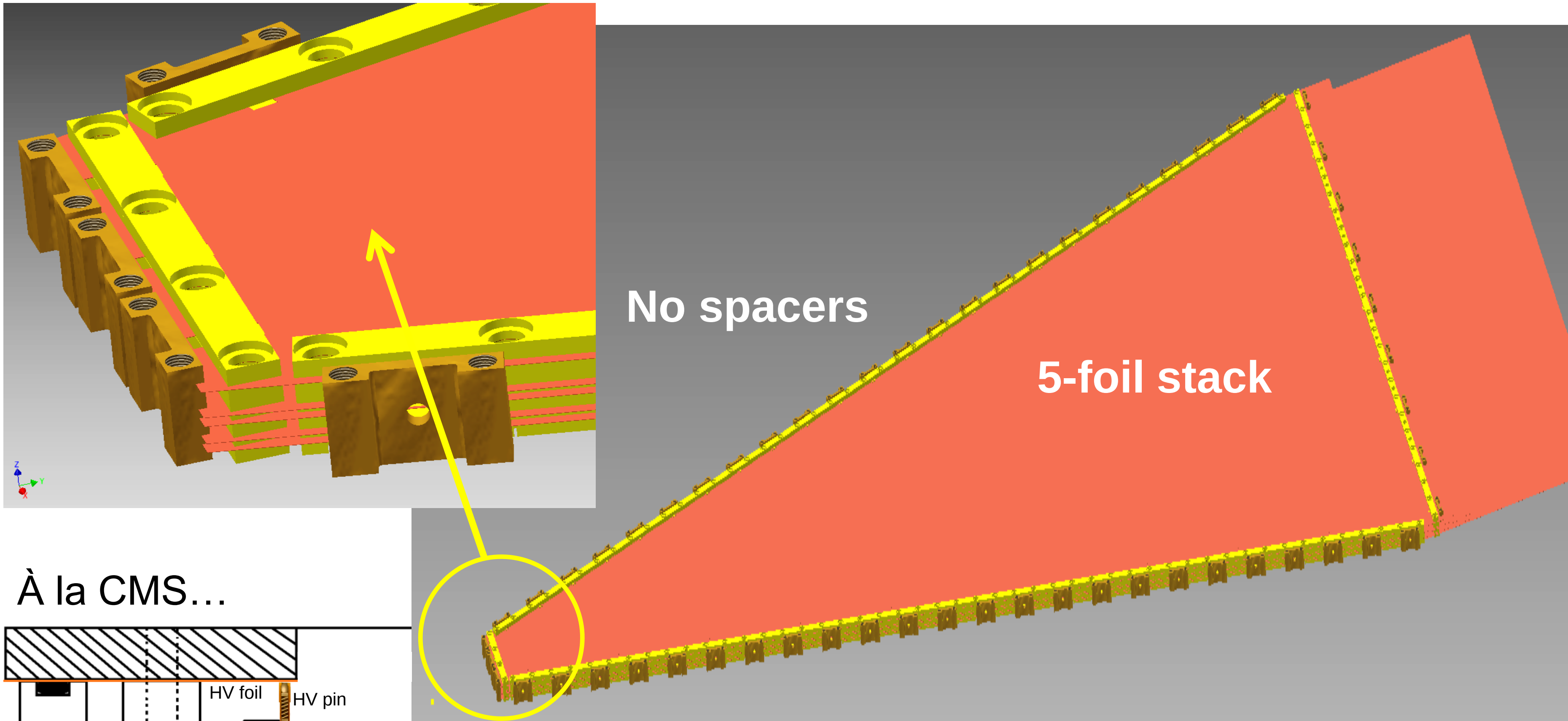
EIC GEM Foil Design



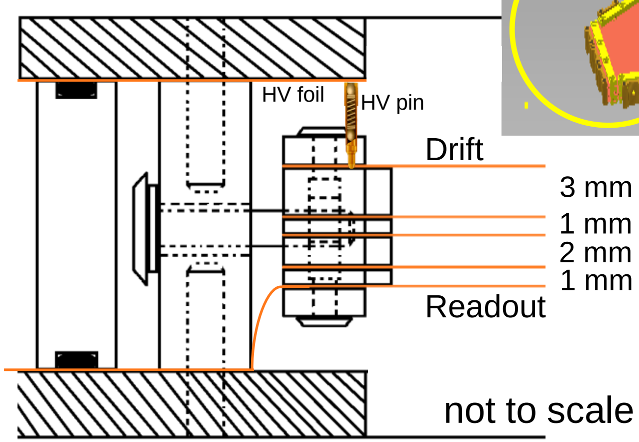
- Active area is divided into 8 HV sectors in R direction at inner R and 18 HV sectors in azimuthal directions at outer R. Reduces energy of any potential discharges.
- Each **HV sector is ~100 cm^2** and gaps between sectors are 0.1 mm.
- HV connections are made at wide end



Mechanical Foil Stretching



À la CMS…



Stack of 5 foils:

- 3 GEM foils
- 1 drift foil (also a GEM foil)
- 1 readout foil

Material Accounting

Active Area:

Detector with PCBs	Thickness (mm)	% of Rad. Length
2 PCBs	**3.180**	**3.914**
3 GEMs	**0.180**	**0.261**
Kapton	0.150	0.051
Copper	0.030	0.210
Total		**4.175**

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

Factor 6.8 reduction

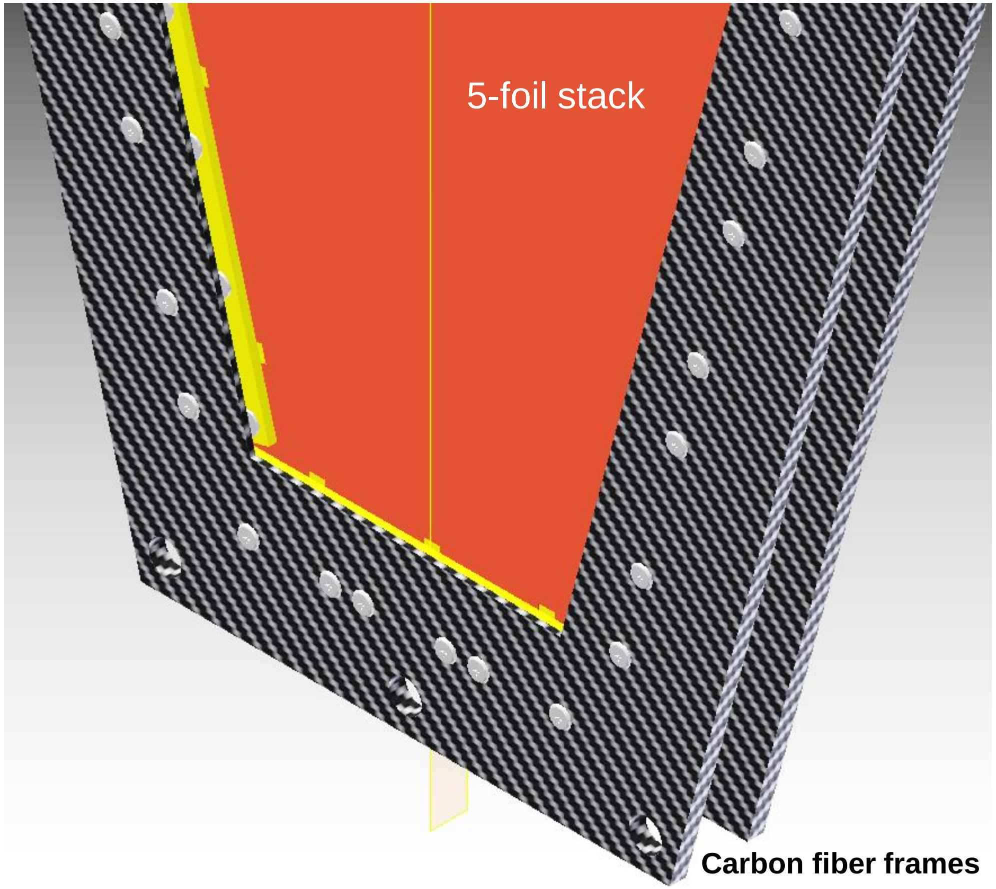
Multiple Scattering

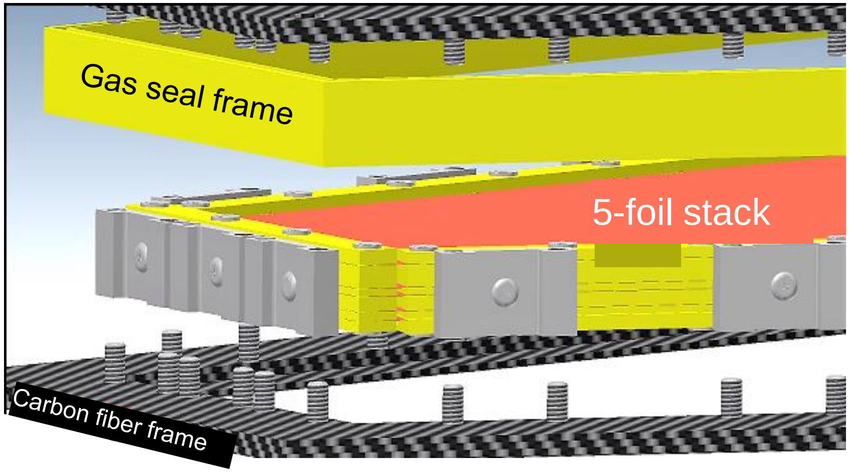
Minimizing material **reduces multiple scattering** of tracks in the GEM detectors

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

Carbon Fiber Frames





Exploded assembly view

Assembled detector

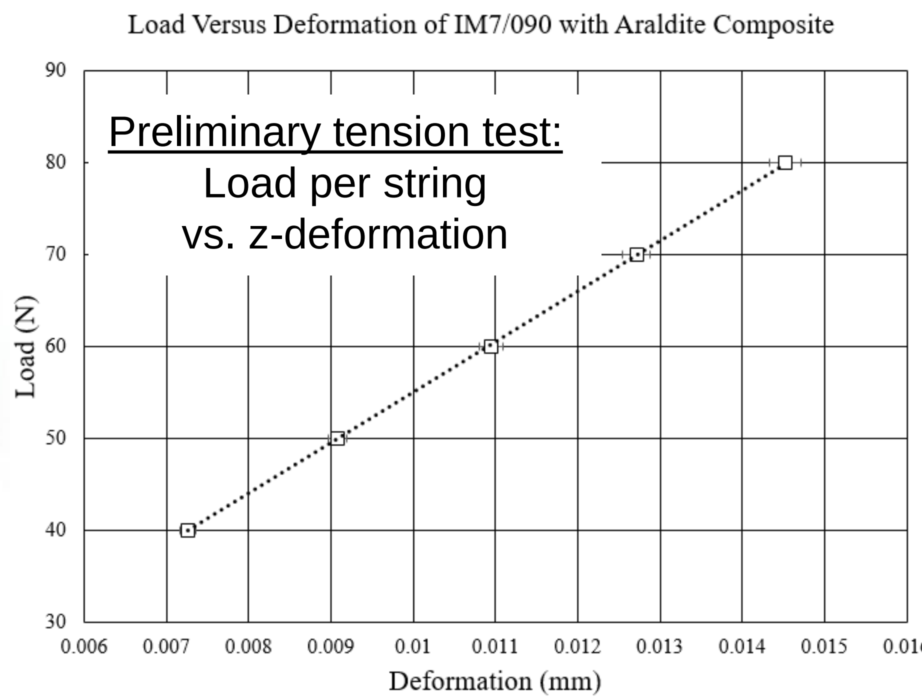
- Mechanical support structures are **outer frames with thin windows** (e.g. aluminized mylar foil, not shown here) instead of solid PCBs to reduce radiation length in the active area
- **Frames are made from carbon fiber composites** that have high strength to take up the tension from the stretched foils

Carbon Fiber Frames cont'd

Plate for front-end electronics

Carbon Fiber Composite:

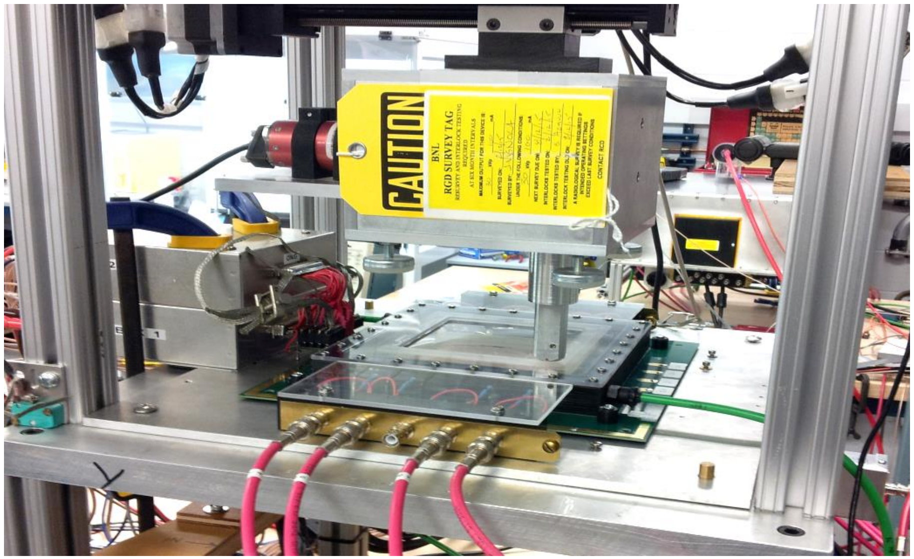
- Araldite epoxy (AY103)
- Intermediate-modulus uni-directional carbon fiber ("IM7")
- 8 layers of CF each; ~ 4mm thick
- Produced in-house



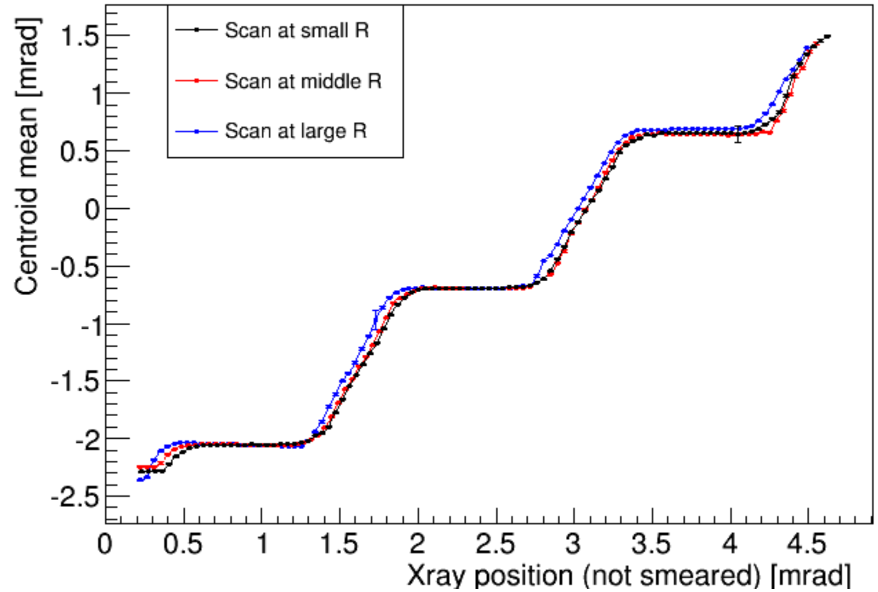
Expect < 1 mm deformation in z (bending) with 5 fully stretched foils

First 1-m Zigzag Readout: Non-linearity

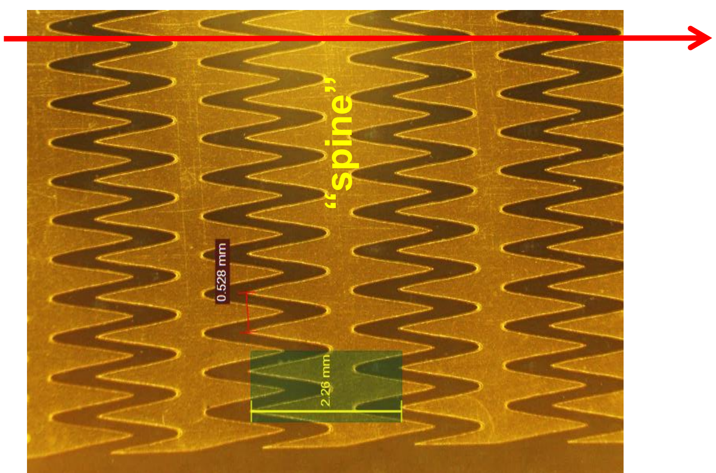
2D stage and highly collimated X-ray gun (140µm) at BNL



Reconstructed position vs. X-ray position (azimuthal)



Scans across strips at 3 different radii

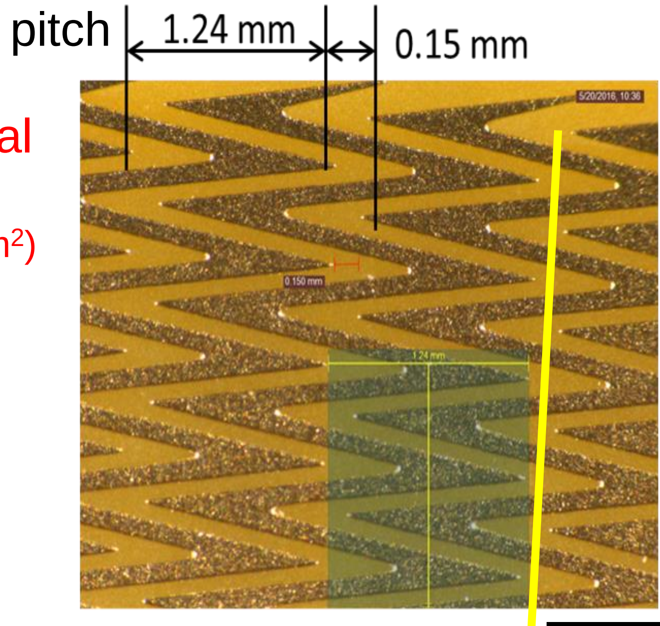


- **Overetching** of tips and **underetching** of valleys of zigzag strips creates "spines" along strip centers
- GEM avalanche induces signal only on single strip
- Without charge sharing among adjacent strips:
  - Readout is insensitive to hit positions near the strip centers
  - Overall spatial response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

Improved Zigzag Strip Readout Design

Zigzag strips interleave almost all the way to centers of both neighboring strips:

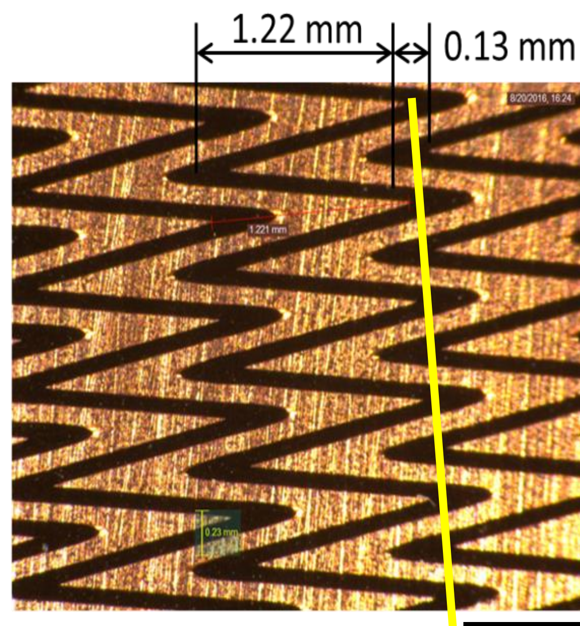
Industrial PCB (10×10 cm^2)



strip center

ACE Board #2 Left
Interleaving: 1-(0.15/2)/1.24=**94%**
Copper thickness: 9 µm (1/4 oz)

CERN Foil (10×10 cm^2)



strip center

CERN Board Left
Interleaving: 1-(0.13/2)/1.22=**95%**
Copper thickness: ~ 5 µm

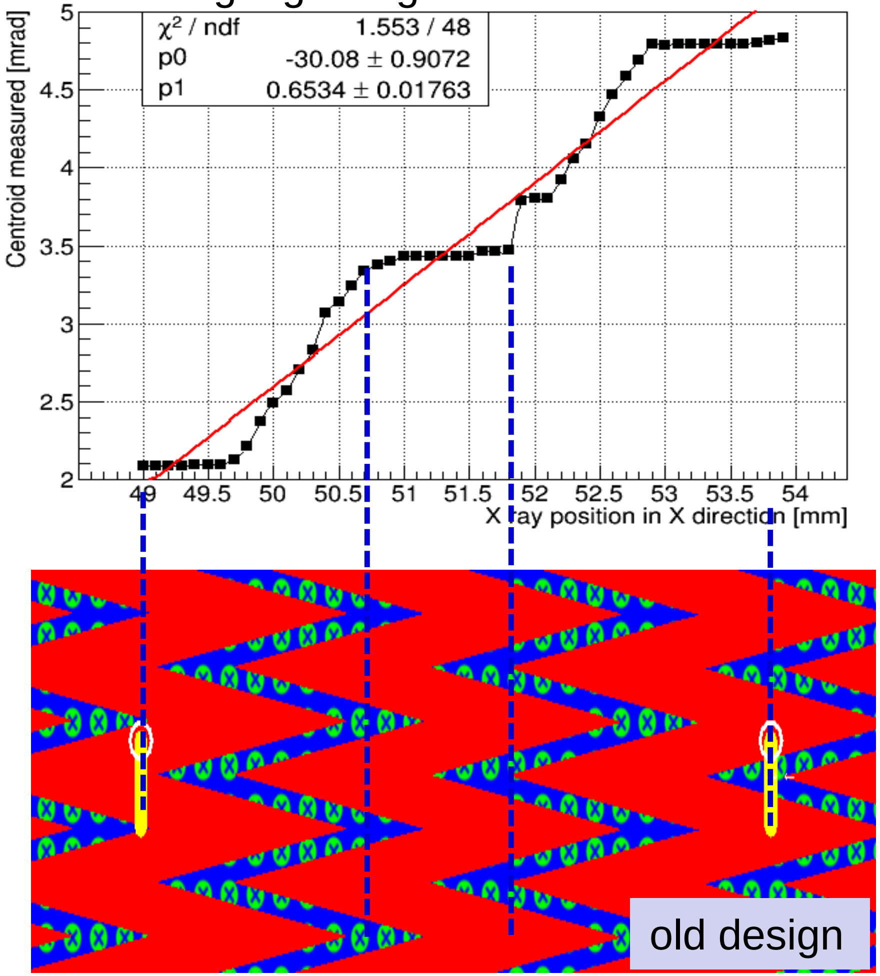
$\mathbf{C_{strip\text{-}\,adj.\,strip} = (22 \pm 2)\ pF;\ C_{strip\text{-}GND} = (28 \pm 2)\ pF}$ (direct measurement on 10 cm strips)

- The design **pushes the PCB manufacturing limit** since spaces are below 3 mils (76 um)
- 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

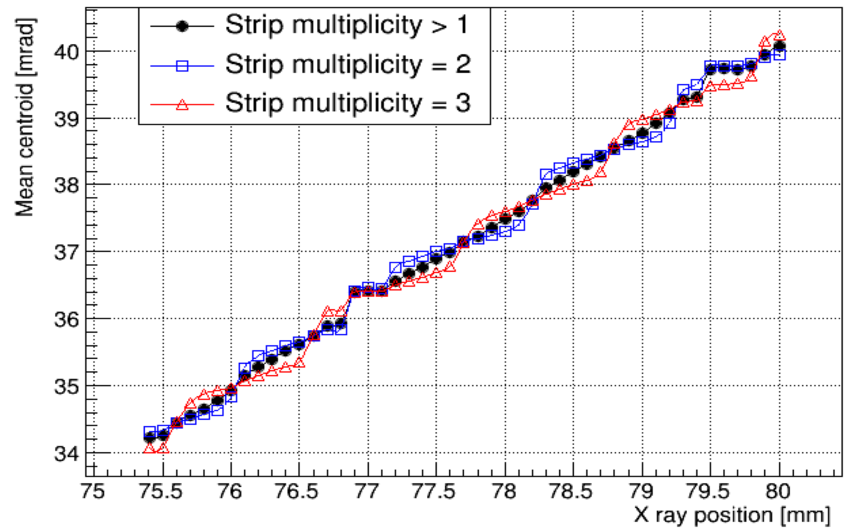
Improved Linearity

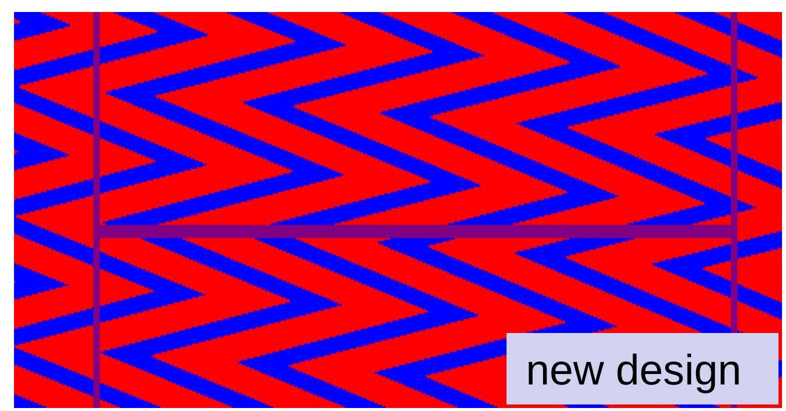
Mean centroid measurement vs. X ray position (scan across strips)

Previous zigzag design



New board (same angle pitch)





Flat regions insensitive to hit positions.

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

Spatial Resolution

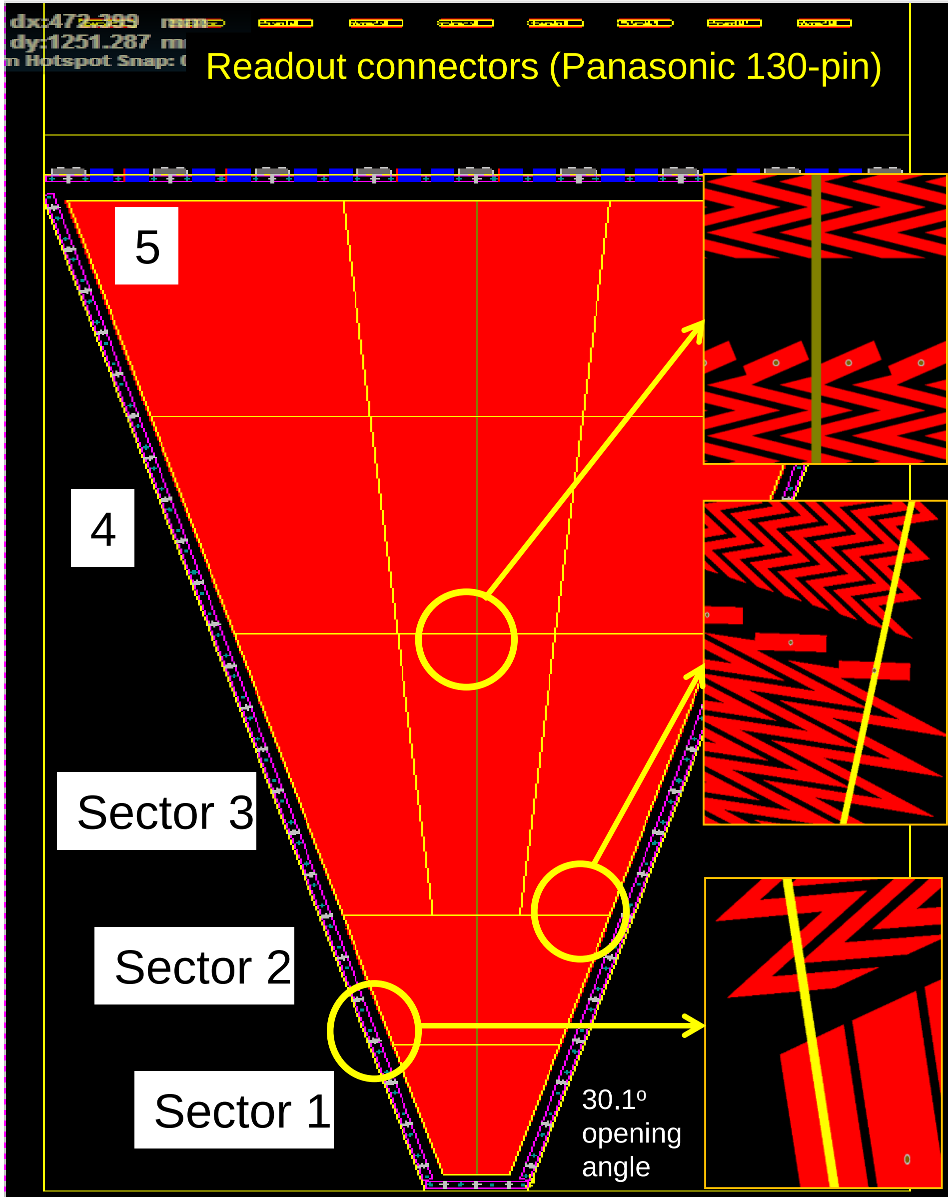
Measured resolutions for improved zigzag-strip readout boards/foils:

Spatial resolution (µrad / µm)	V_{drift} (V)	Approx. gas gain	Strips with angle pitch 4.14 mrad, r ≈ 229 mm			Strips with angle pitch 1.37 mrad, r ≈ 784 mm		
			2-strip clusters	3-strip clusters	2 & 3-strip clusters	2-strip clusters	3-strip clusters	2 & 3-strip clusters
Industrial PCB	3340	3000	288 / 66	480 / 110	384 / 88	57 / 45	97 / 76	84 / 66
CERN foil	3340	3000	397 / 91	393 / 90	397 / 91	-	-	-
CERN foil	3380	4000	-	-	-	57 / 45	92 / 72	71 / 56
Previous PCB			-	-	-			193 µrad

Ar/CO_2 70:30

Resolutions (well) below 100 µm

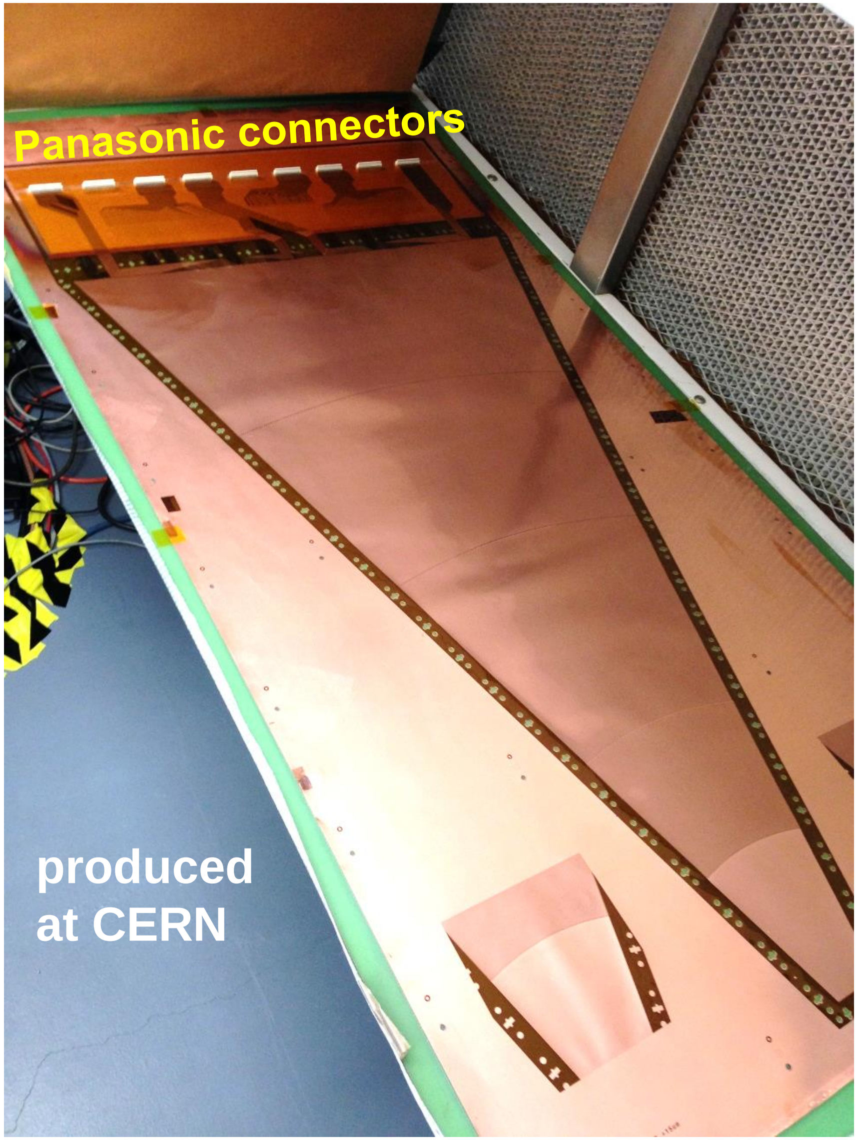
Full-size Zigzag Readout Foil

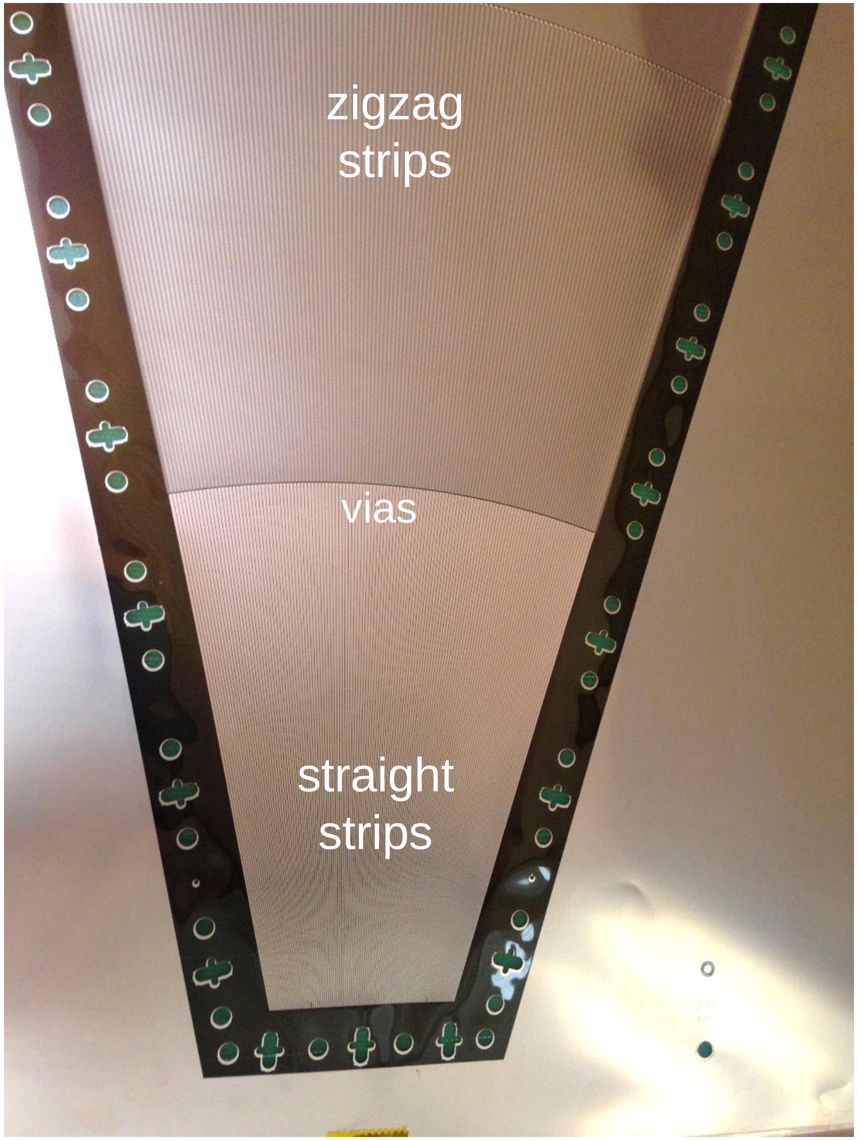


Sec. Nr.	Strip type	No. of strips	Angle pitch (mrad)	Sector Length (cm)
1	Straight	128	4.14	12
2	Zigzag	128	4.14	12
3	Zigzag	384 (3×128)	1.37	22
4	Zigzag	384	1.37	22
5	Zigzag	384	1.37	22

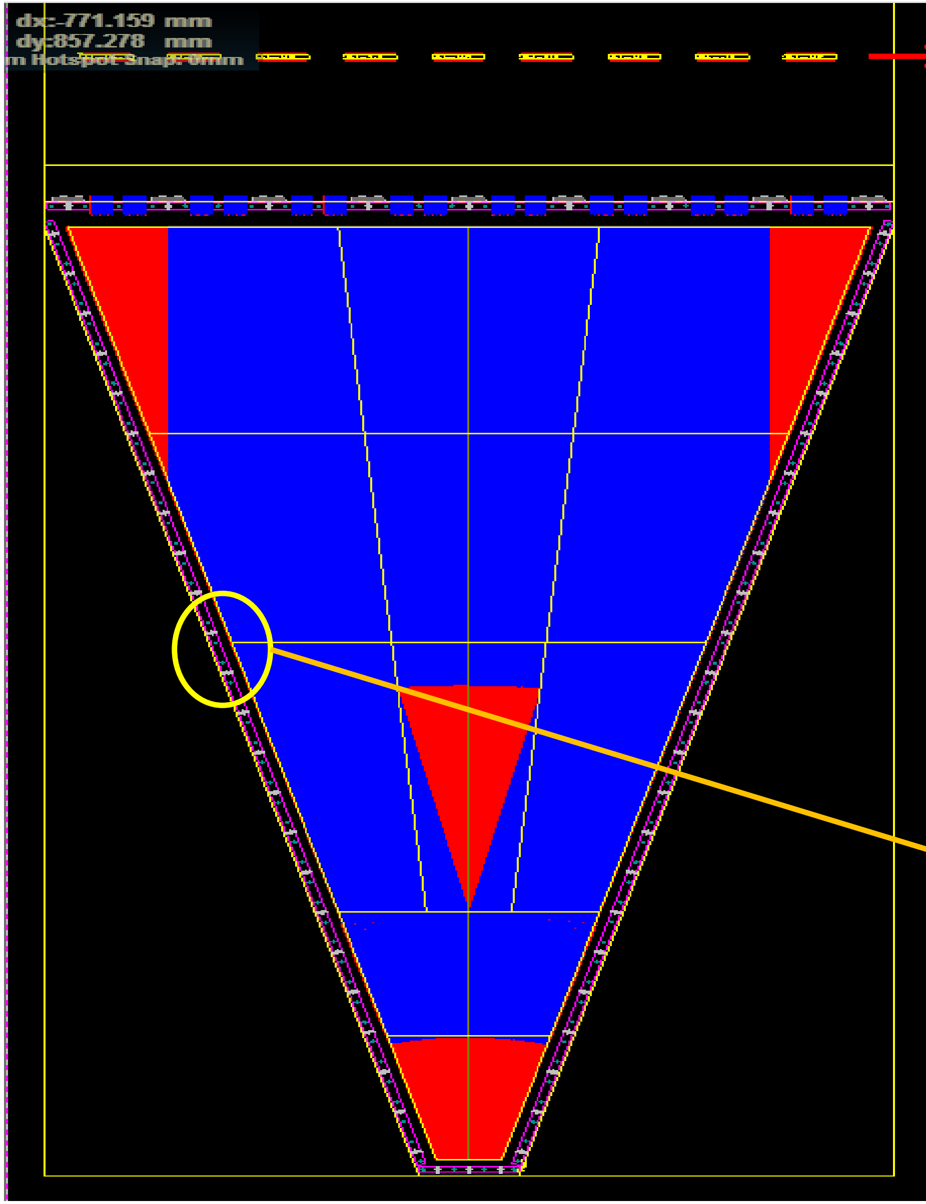
- **Adopt the improved zigzag strip design** but use straight strips in small innermost sector 1
- Divide readout into **5 main eta sections**
- Produce r/o on a foil material (<100 μm thickness) so that total material in detector is reduced
- Total **number of channels is 1152** (=128*9)
- Only 9 APV 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

Readout Foil – Zigzag side



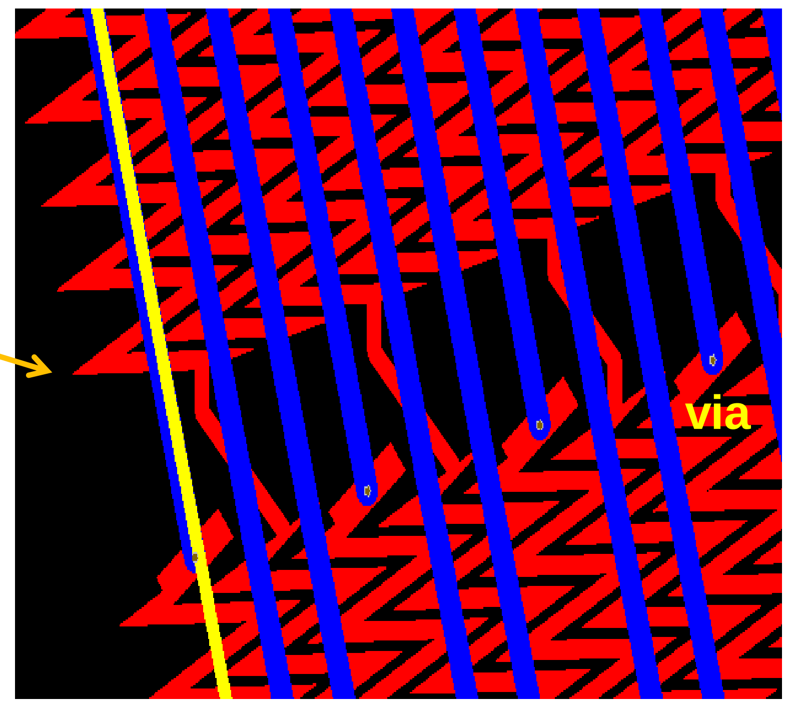


Readout Foil – Routing Side



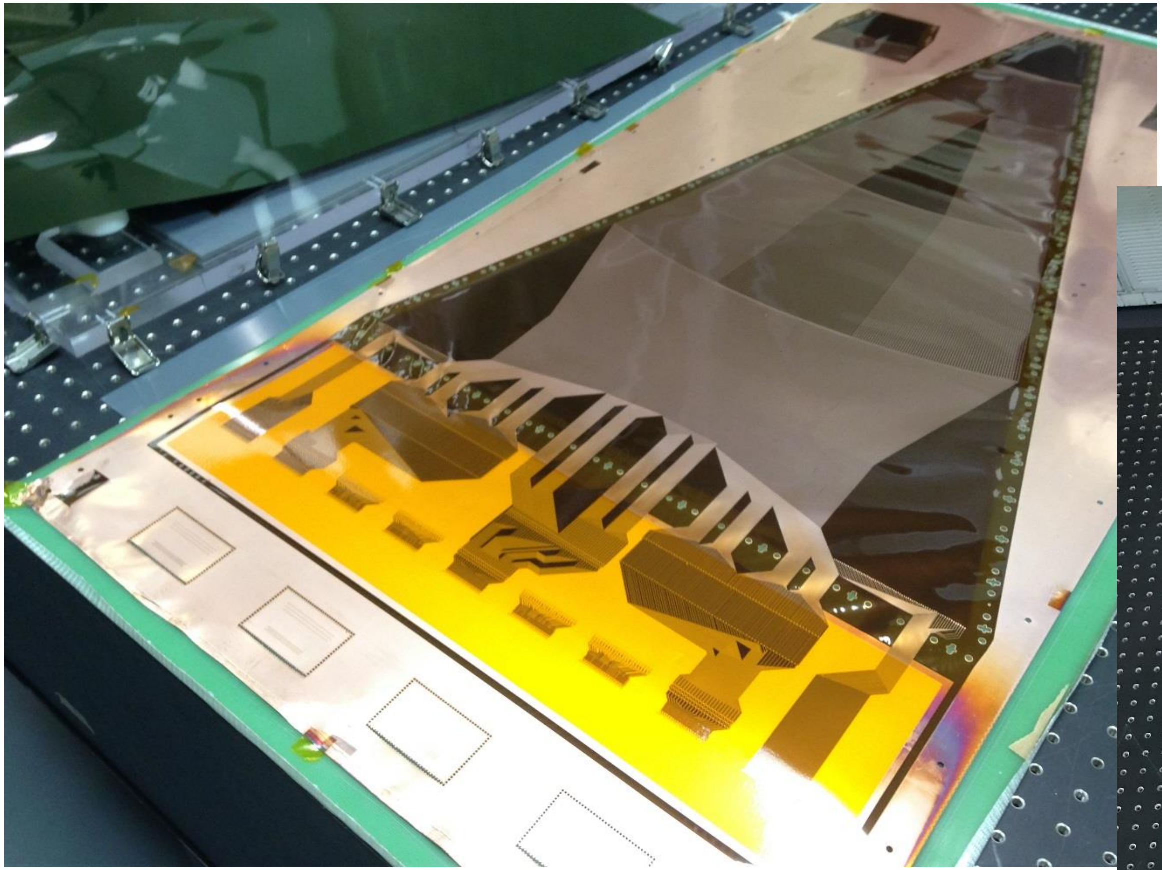
9 connectors for FE chips (APV hybrids)

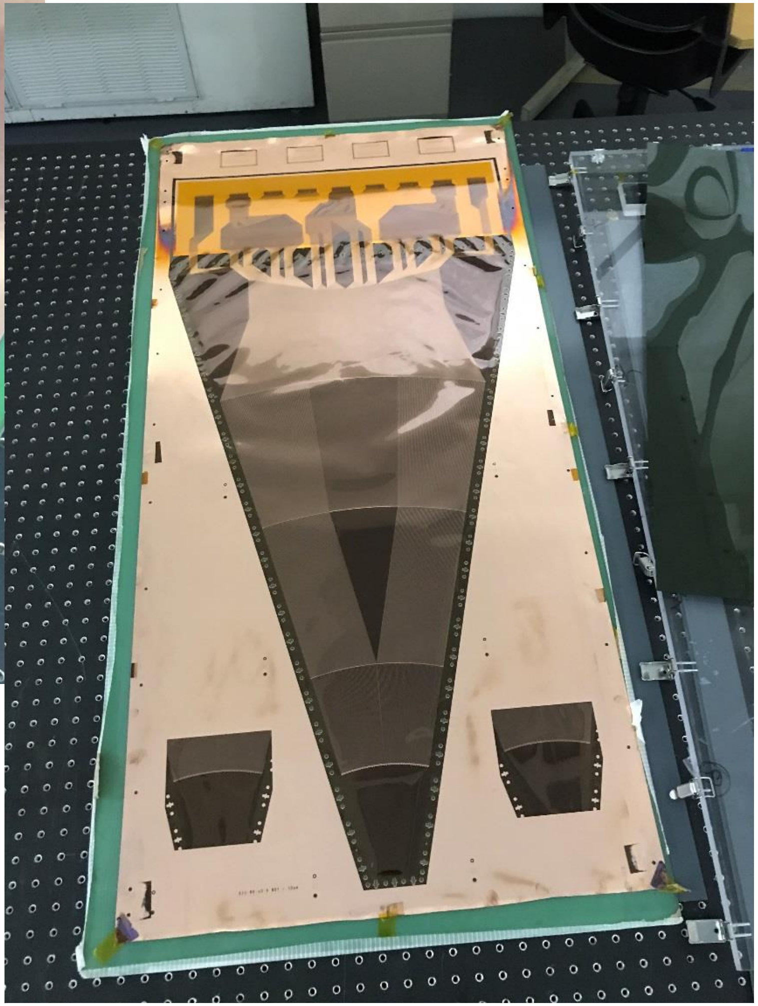
- Signal lines are blue (top side)
- Zigzag strips are red (bottom side)
- Connections made with numerous vias



Readout Foil – Routing Side

Produced on same base material as GEM foils (with ~15 μm Cu due to 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^{o})
    - 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

The End

Thank you!