University of Virginia

R&D on Large GEM for the Forward Tracker at a future Electron Ion Collider (EIC)

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University of Virginia, Charlottesville, VA

RD51 Coll. Meeting, Sept. 12, 2016, Aveiro, Portugal

Outline

- EIC Overview
- R&D on Large Area GEM Trackers
- Preliminary results on Chromium GEMs

On behalf of:

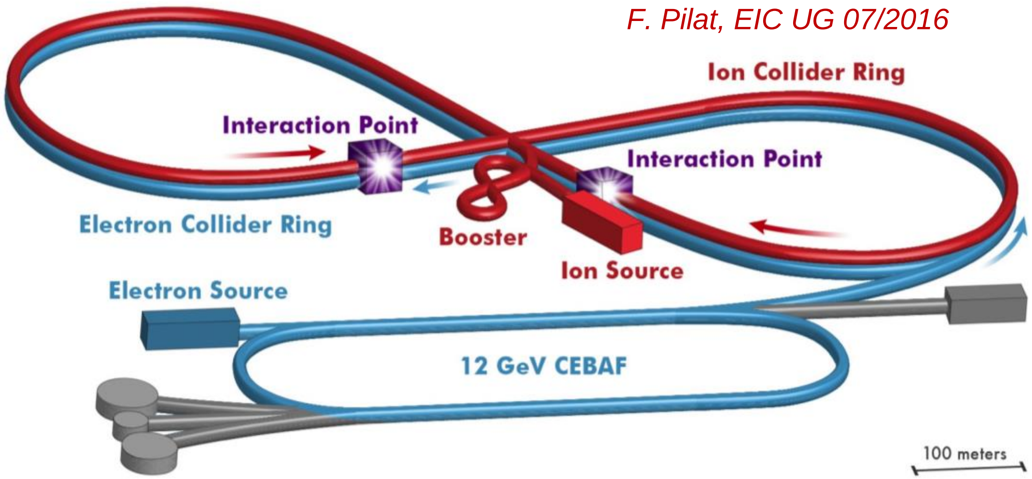
- K. Gnanvo, N. Liyanage **(Univ. of Virginia)**
- A. Zhang, M. Hohlmann **(Florida Tech)**
- M. Posik, B. Surrow **(Temple Univ.)**

EIC Overview: Accelerator Designs

- The future Electron Ion Collider (EIC) seeks to reveal the inner pictures of hadrons (including protons) at a much deeper level.
- The construction of the high-energy high-luminosity polarized EIC was recommended as the highest priority for new facility construction following the completion of FRIB by **the 2015 Long Range Plan for Nuclear Physics**

JLEIC @ Jefferson Lab (Jlab)

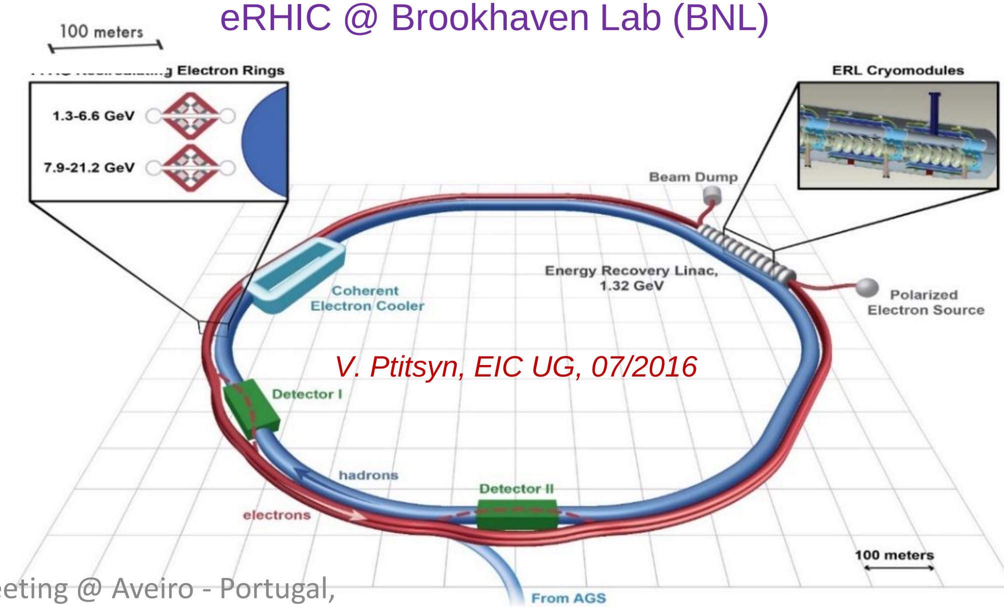
F. Pilat, EIC UG 07/2016



JLEIC energy range:

- **electrons: 3-10 GeV**
- **protons : 20-100 GeV**
- **Luminosity ~ 2 × 10^{34}**

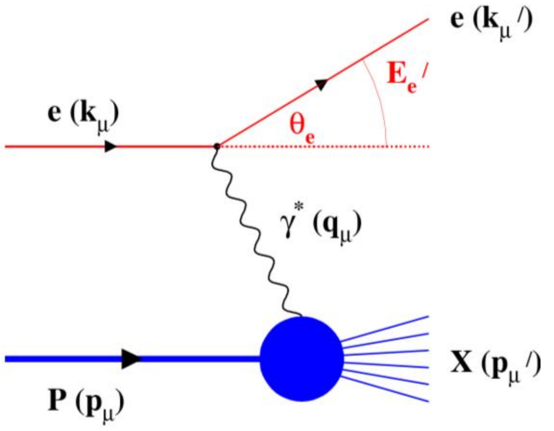
eRHIC @ Brookhaven Lab (BNL)



eRHIC energy range:

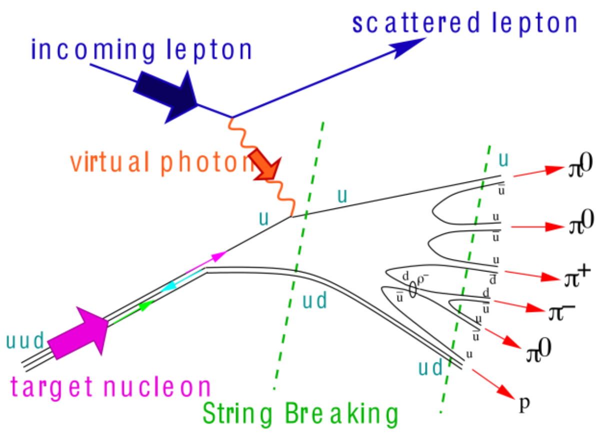
- **electrons: 10 GeV**
- **protons : 250 GeV**
- **CM: 100 GeV**
- **Luminosity ~0.1 to 1 × 10^{34} cm^{-2} s^{-1}**

EIC Overview: Physics



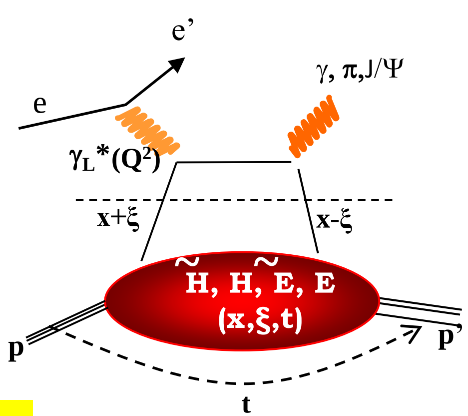
Inclusive Reactions in ep/eA:

- ❑ Nucleon Spin Structure Functions
- ❑ Gluon spin contribution
- ❑ Elastic form factors : g_1, F_2, F_L
  - ➢ Very good scattered electron ID
  - ➢ High energy and angular resolution of e' (defines kinematics $\{x,Q^2\}$)



Semi-inclusive Reactions in ep/eA:

- ❑ TMDs, Helicity PDFs, FFs (with flavor separation);
- ❑ di-hadron correlations; Kaon asymmetries, cross sections; etc
  - ➢ Excellent hadron ID: $p^{\pm}$,$K^{\pm}$,$p^{\pm}$ separation over a wide {p, h} range
  - ➢ Full F-coverage around g*, wide p_t coverage (TMDs)
  - ➢ Excellent vertex resolution (Charm, Bottom separation)



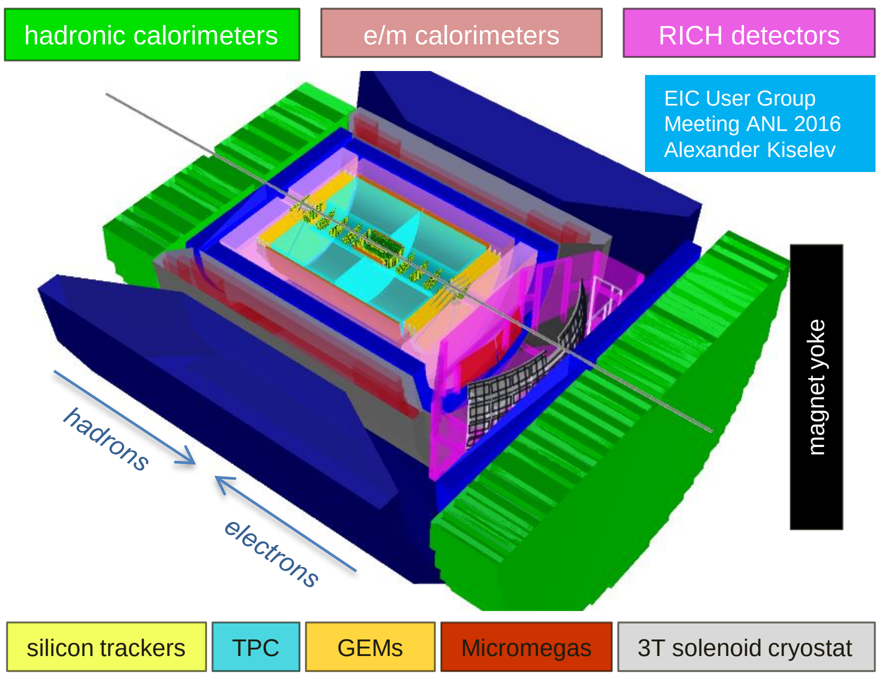
Exclusive Reactions in ep/eA:

- ❑ DVCS, exclusive VM production
- ❑ GPDs parton imaging in b_T
  - ➢ Large rapidity coverage; reconstruction of all particles in an event)
  - ➢ High resolution, wide coverage in *t* → Roman pots …
  - ➢ Sufficient acceptance for neutrons in ZDC

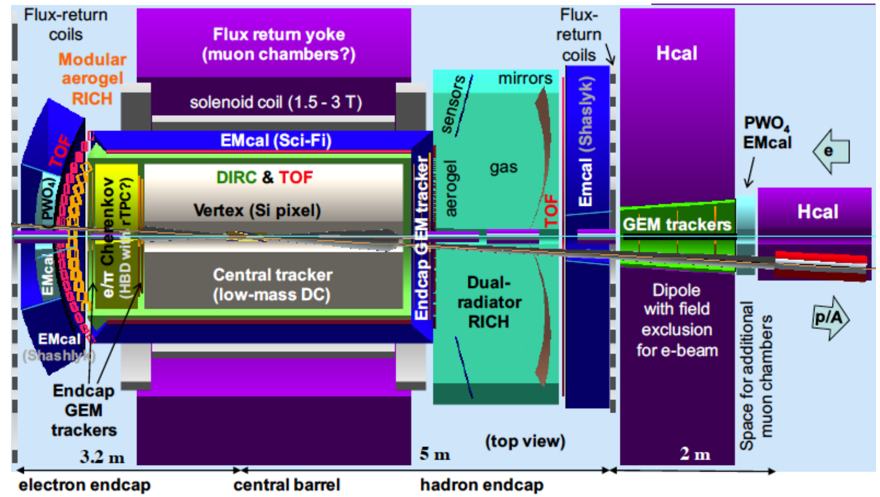
From A. Kiselev, EIC User Meeting July 2016

EIC Overview: Detector concepts

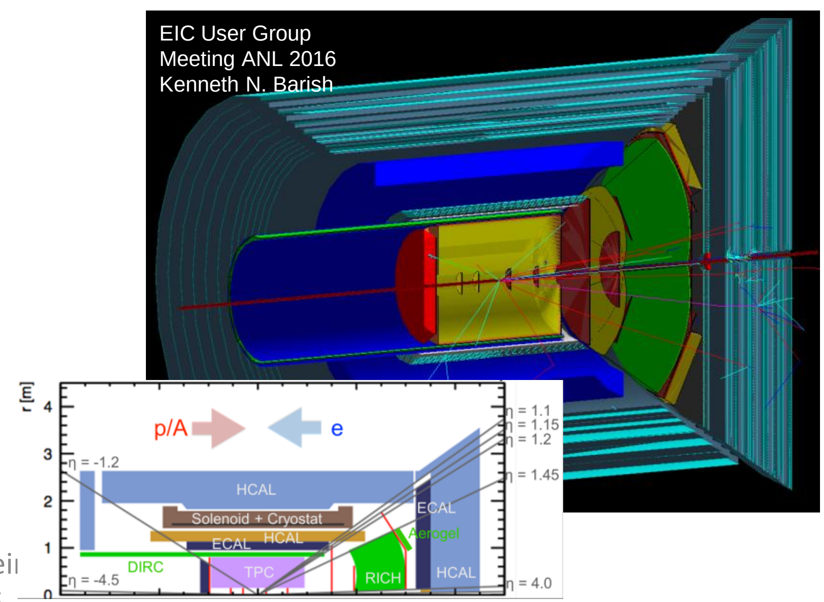
BeAST @ eRHIC



JLEIC Design

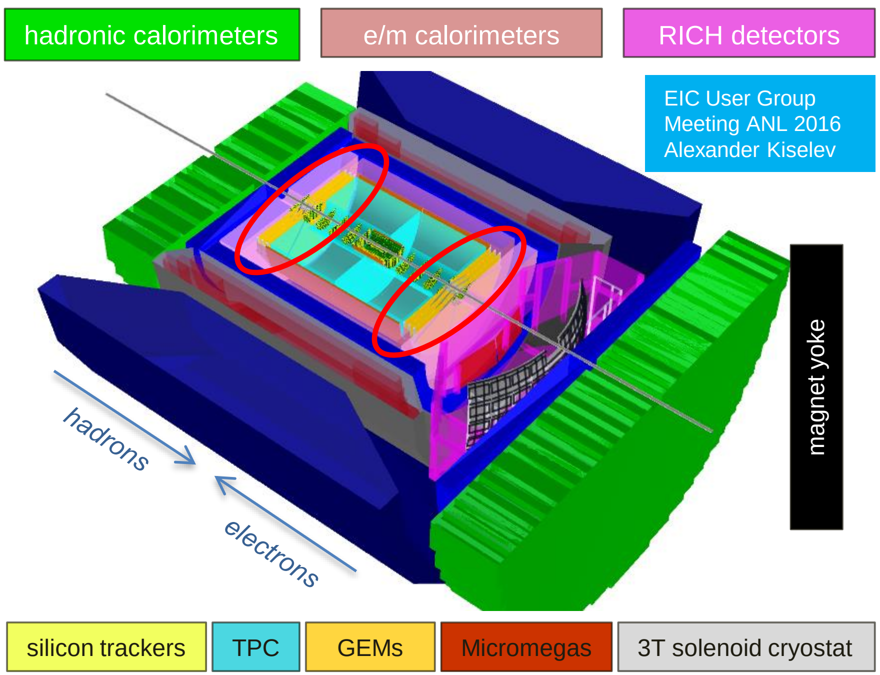


ePHENIX @ eRHIC

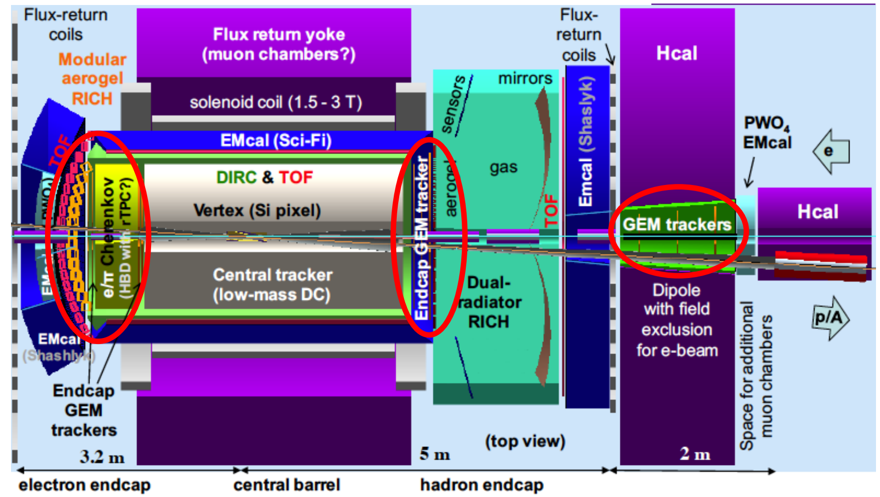


EIC Overview: Detector concepts

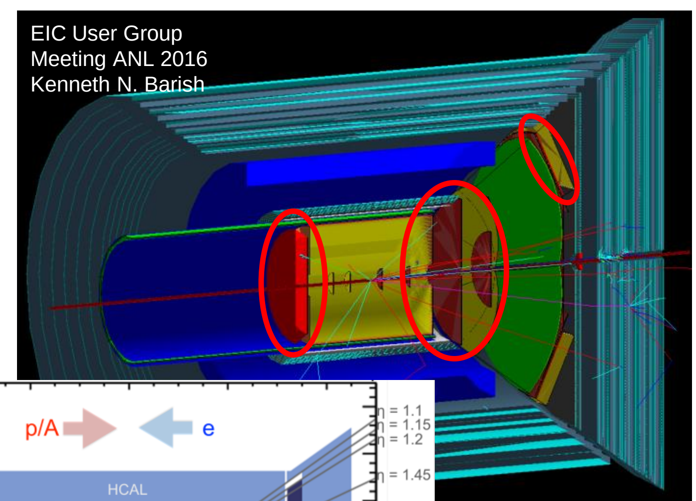
BeAST @ eRHIC

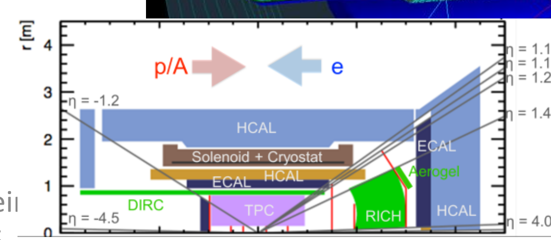


JLEIC Design



ePHENIX @ eRHIC





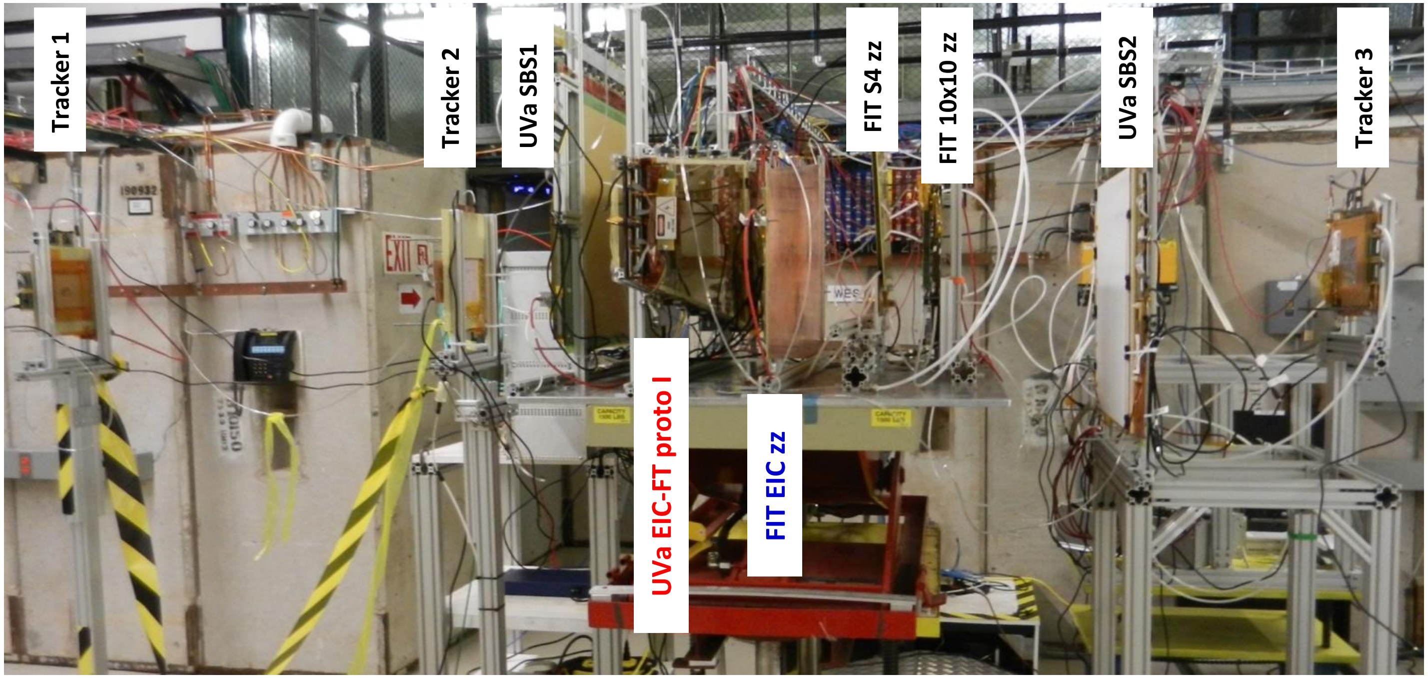
All designs have forward / backward trackers using large GEM detectors

R&D on Large Area GEM

- R&D on large GEMs for EIC Forward Tracker (FT) carried out at 3 Universities in the US: **University of Virginia (UVa) and Florida Institute of Technology (FIT) and Temple University (TU).**
- The TU is part of eRD3 and UVa & FIT as part of the eRD6 program supported by the EIC generic detector R&D program initiated and administered by BNL
- UVa & FIT took part of the eRD6 sector test in October 2013 at the Fermilab Test Beam Facility (FTBF) with a dedicated stand for large GEM performances studies

UVa EIC-FT Proto I

Large GEMs test beam setup (UVa & FIT) at FNAL FTBC 2013

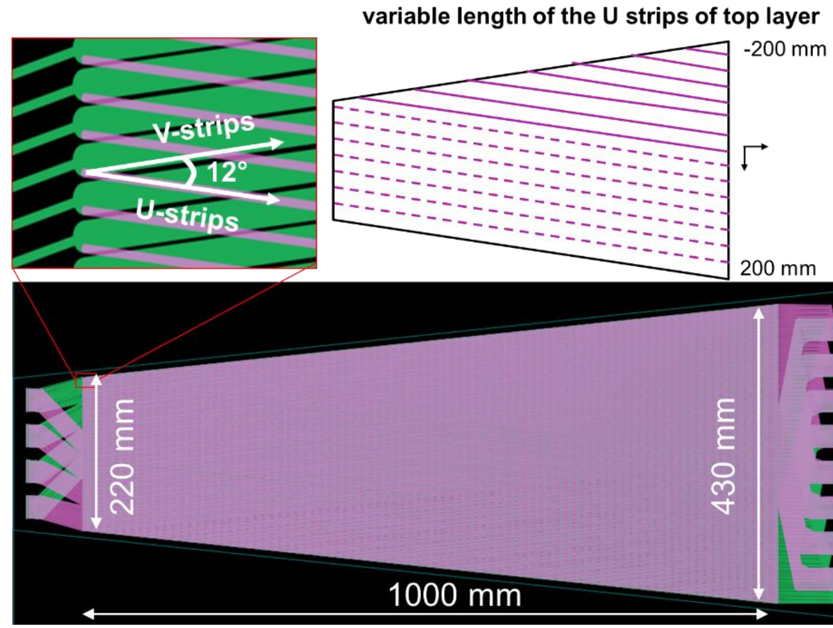


Past GEMs R&D: 2D U-V strips readout in FNAL Test Beam
(Oct. 2013)

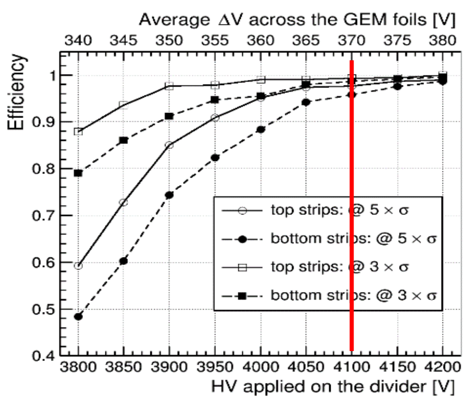
UVa EIC-FT-GEM proto I

- Trapezoid shape 1-m long triple-GEM (3-2-2-2): widths at the inner radius and outer radius equal to 23 cm and 44 cm respectively.
- Readout board**: 2D flexible U-V strips** (COMPASS style) with a pitch of 550 μm, top layer (**140 μm, wide U-strips**) run parallel to one radial side of the detector and bottom layer (**490 μm, V-strips**) run parallel to the other side and a stereo-angle of **12 degree**

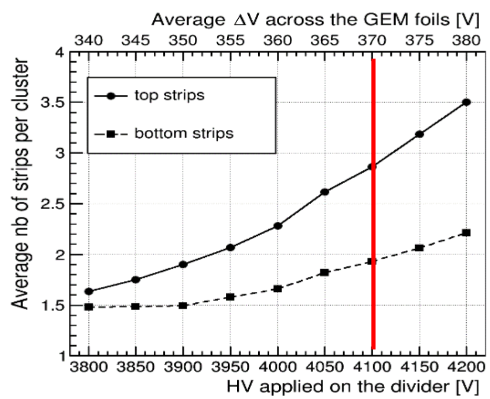
U-V strip Readout design



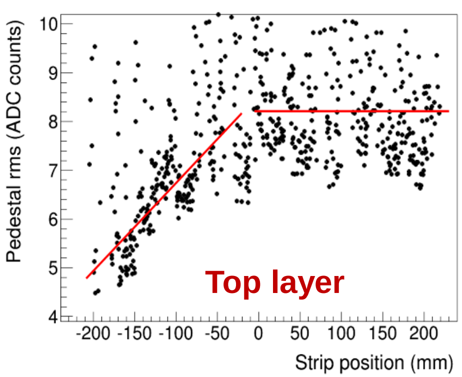
Efficiency

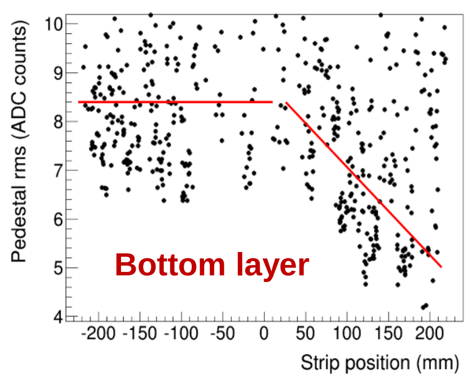


Mean cluster size

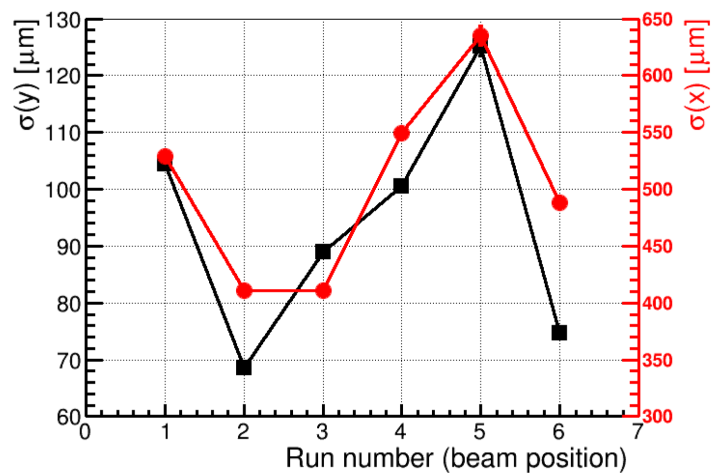


Correlation between strip length and pedestal RMS noise





resolution in x (radial) and y (azimuthal)

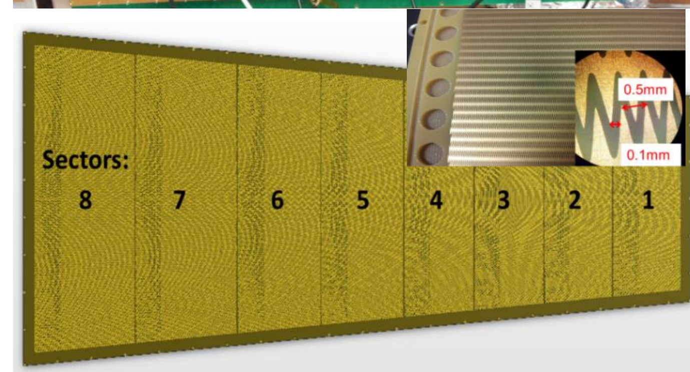


[NIM A 808 (2016) 83-92]

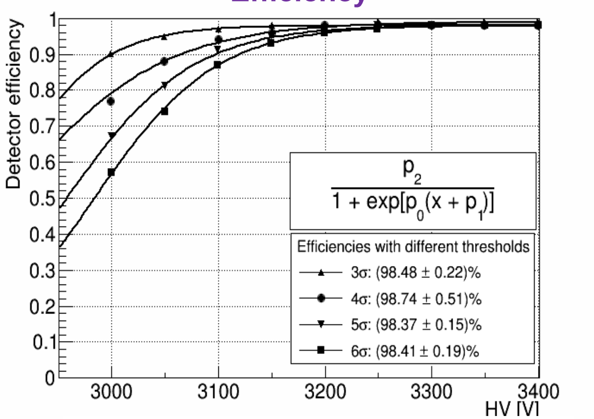
Past GEMs R&D: Zigzag strips readout in FNAL Test Beam (Oct. 2013)

Florida Tech EIC-zz-GEM

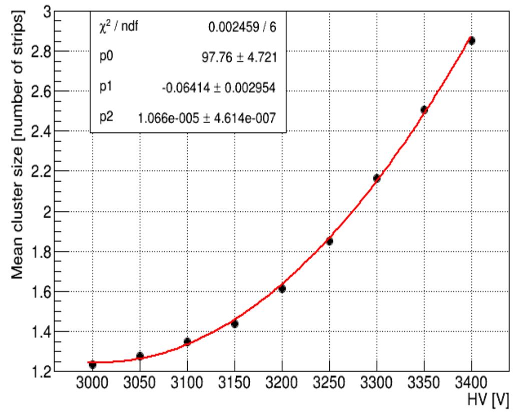
- Trapezoid shape with 1-meter long, gas gaps 3/1/2/1 mm, Ar/CO2(70:30).
- Readout board: **1D Zigzag strips** on rigid PCB: 128 strips × 8 sectors, angle **pitch strips is 1.37 mrad**, Zig-zag strips reduce the number of readout channels. The charge sharing among the zigs and zags among neighboring strips provides a good spatial resolution can be achieved.



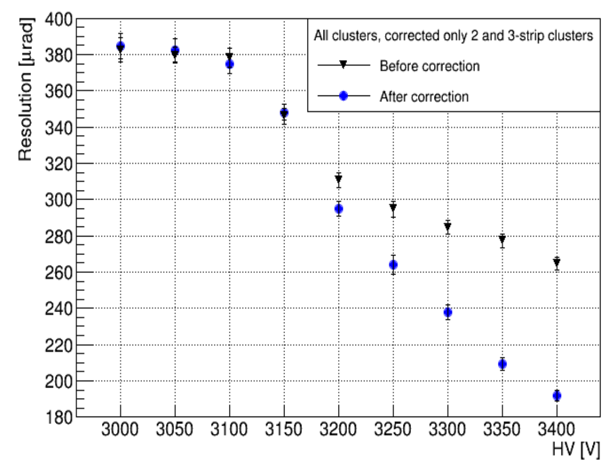
Efficiency



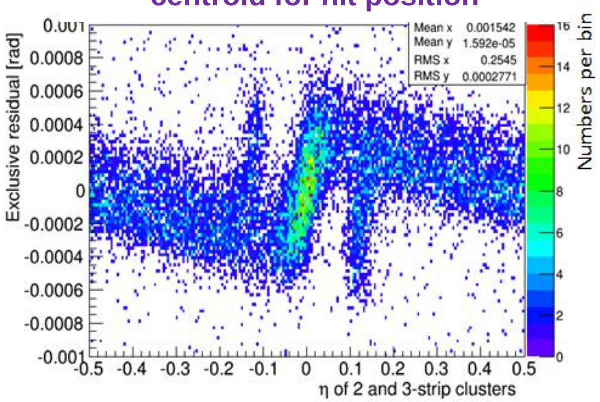
Mean cluster size



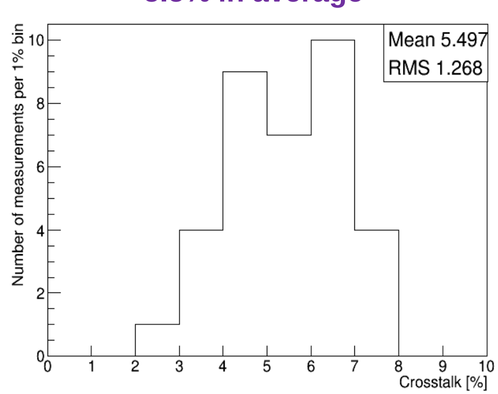
Angular resolution



nonlinear response when using centroid for hit position



Crosstalk between strips is 5.5% in average



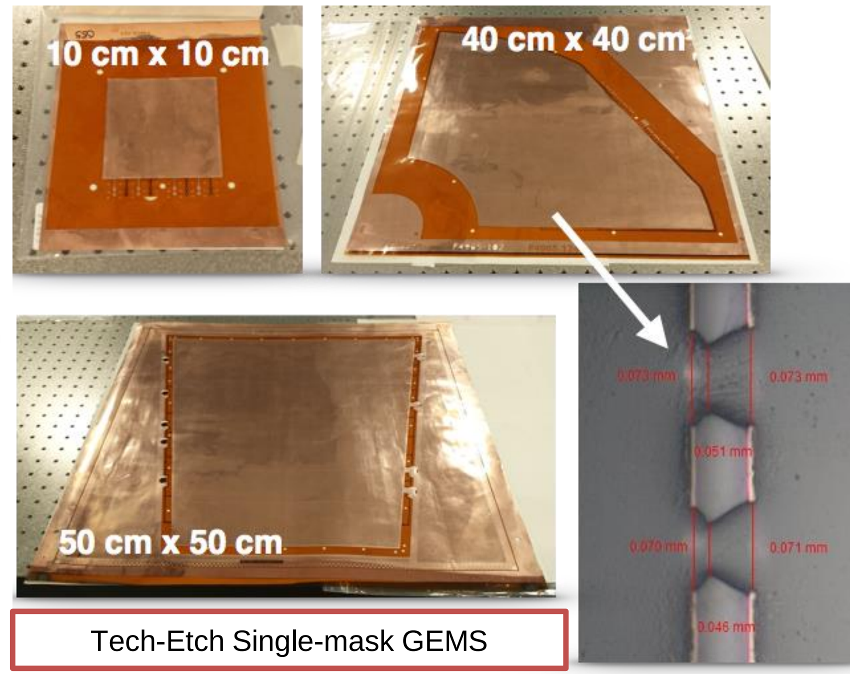
[NIMA 811 (2016) 30-41]

Images from A. Zhang (FIT)

R&D on Large GEMs: Commercial GEM foil production

Tech Etch,Temple U. and Single Mask Technique

- Tech-Etch has made GEMs via CERN's double-mask process for the FGT.
- **It has now employed CERN's single-mask method (needed for large foils) and produced foils larger than 50 cm.**
- Recent RD51 meeting called attention to the need to transfer GEM technology to commercial sources



Tech-Etch Single-mask GEMS

Temple U.'s analysis / feedback instrumental to the successful development of the Tech-Etch foils.

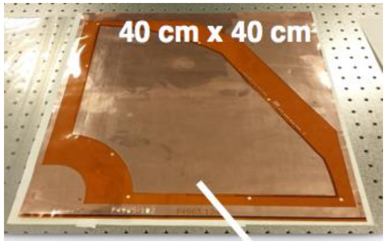
- Leakage currents **measured to be around 1 nA or lower** comparable to the CERN foils
- Optical analysis of the foils. (see next slides)

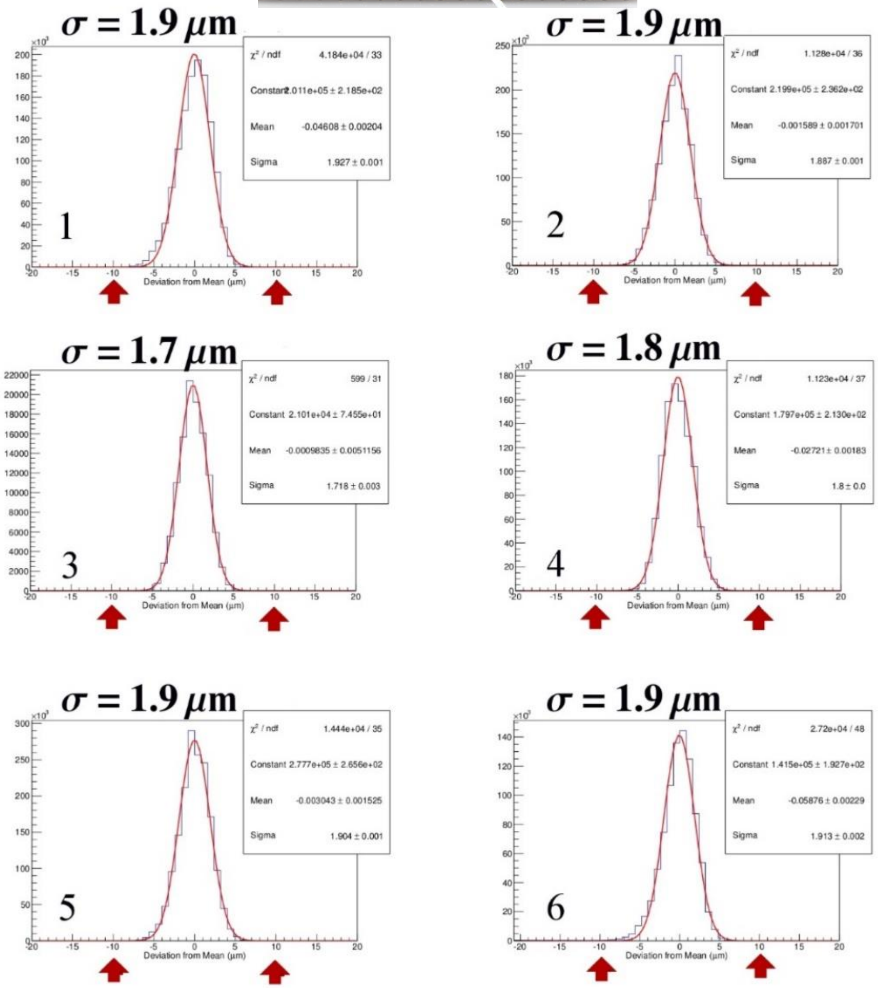
From M. Posik (Temple. U)

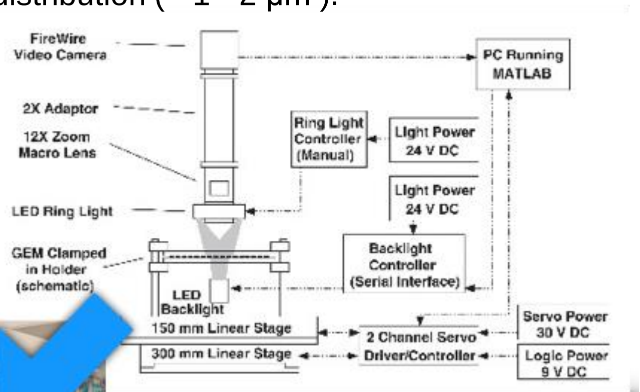
R&D on Large GEMs: Optical tests of GEM foils @ Temple U.

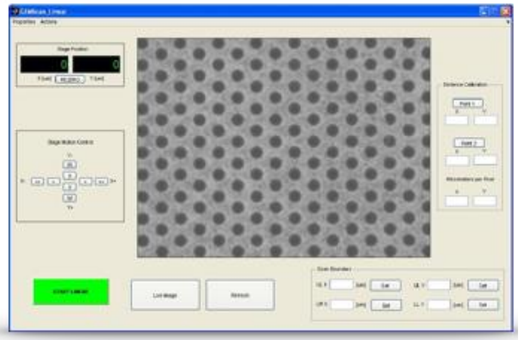
Tech-Etch single-mask 40 cm x 40 cm (FGT) GEM foils.

- Average deviation from the inner (outer) hole mean was found to be about 1.5 - 3.0 μm (1 - 2 μm) and comparable to CERN. Red arrows mark +/- 10 μm position
- Average inner (outer) diameter across 3 foils: ~53 μm, (~78 μm)
- Pitch measurements were consistently measured to be around **139 μm** with a narrow distribution (~ 1 - 2 μm).









MATLAB GUI

NIM A 802 (2015) 10-15

From M. Posik (Temple. U)

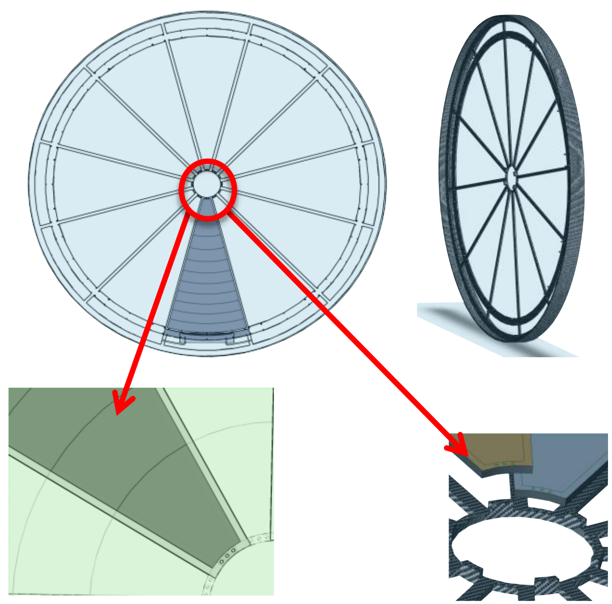
Large GEM foil Production: Industrialization

Slide from B. Surrow Temple Univ.

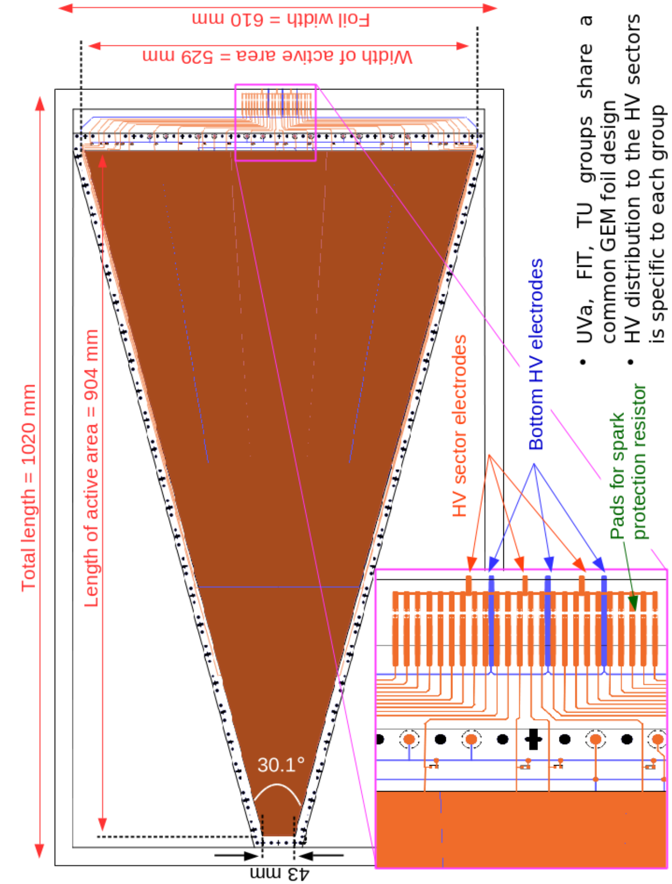
- Tech-Etch has produced
  - based on single-mask processing numerous GEM foils with consistent high quality in terms of leakage current and optical uniformity in addition to
  - HV foils and
  - 2D foils.
- CERN management and in particular ATLAS and CMS should be strongly encouraged to place large orders at Tech-Etch. Such a step is urgently needed to make the industrialization of GEM detector components a real success. Why has this not been actively pursued so far? Tech-Etch has never been contacted about this!
- This was also brought during the last LHCC meeting.

EIC GEM Tracker R&D: Common EIC GEM foil

EIC Front Tracker GEM disk made of trapezoidal shape triple GEM module

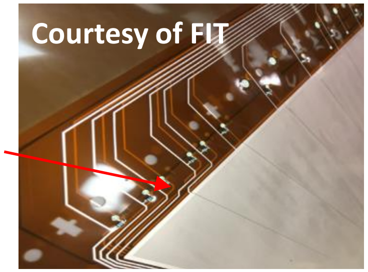


- A common GEM foil was designed by the 3 groups to build GEM prototypes with different assembly techniques and readout patterns
- The foil has a trapezoidal shape of **length 904 mm, width [43 – 529] mm** and an **opening angle of 30.1 degre**.
- 8 radial and 16 azimuthal HV sectors. Each HV sector is ~ 100 cm2
- All connections (HV, gas flow, and FE cards) **are made at outer radius.**



CERN has delivered GEM foils to UVa and FIT

FIT version has the protected resistors

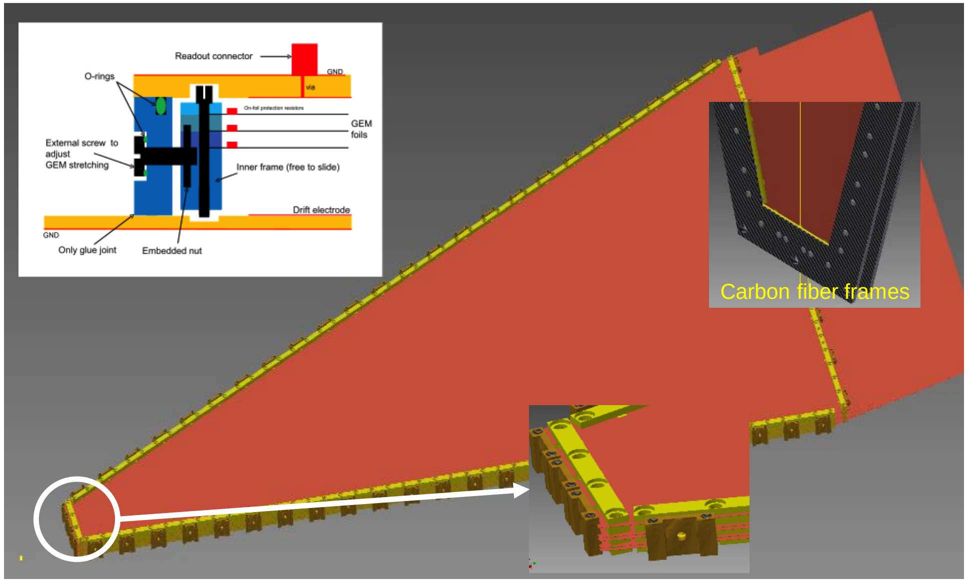


https://arxiv.org/abs/1511.07913

EIC GEM Tracker R&D: FIT design

assembly method:

- **Modified mechanical stretching** used by CMS GEM collaboration.
- Advantage to this stretching method is that there are **no spacers** needed, so no dead material in the active area.
- Currently looking into **reducing** detector materials (i.e. carbon fiber frames, assembly materials, mylar foils, etc.)

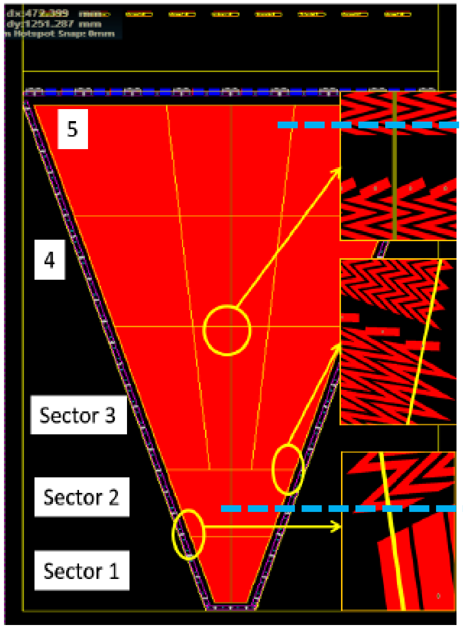


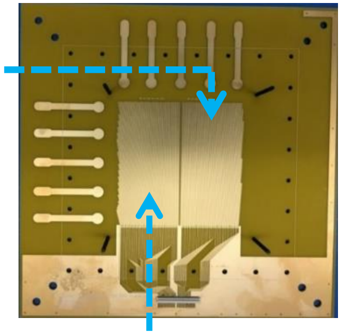
1D zigzag strips readout

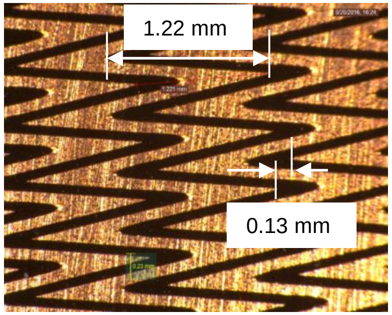
- Optimized EIC zig-zag readout will change pitch with radius.
- Small prototype board has been produced for test:
  - At R = **206-306 mm** → angle pitch **4.14 mrad** (left part).
  - At R = **761-861mm** → angle pitch **1.37 mrad** (right part).
- Initial tests of small board show **spatial resolution < 100 µm**.

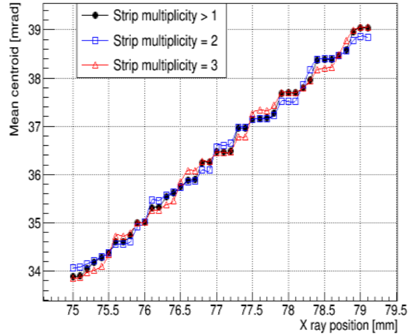
1D zigzag strips pattern

- The new zigzag strip **tips interleave to center** of each strip
- Test **show almost liner response** to the hit positions (scanned under fine collimated X ray).
- Most of events fire 2 or 3 strips, which are good to hit centroid calculation









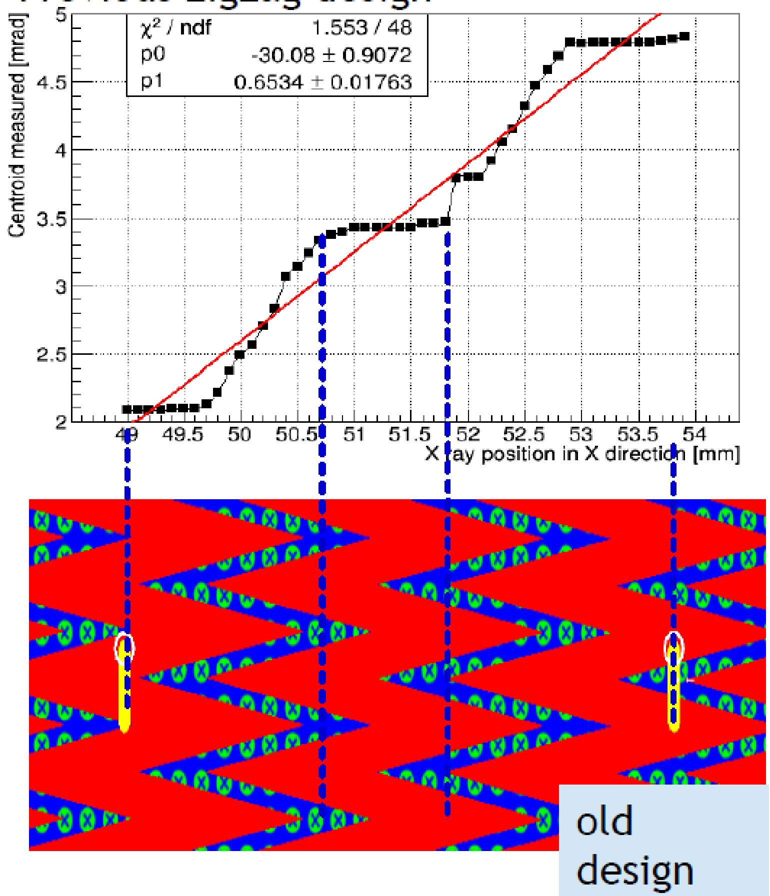
Images from A. Zhang (FIT)

EIC GEM Tracker R&D: FIT design

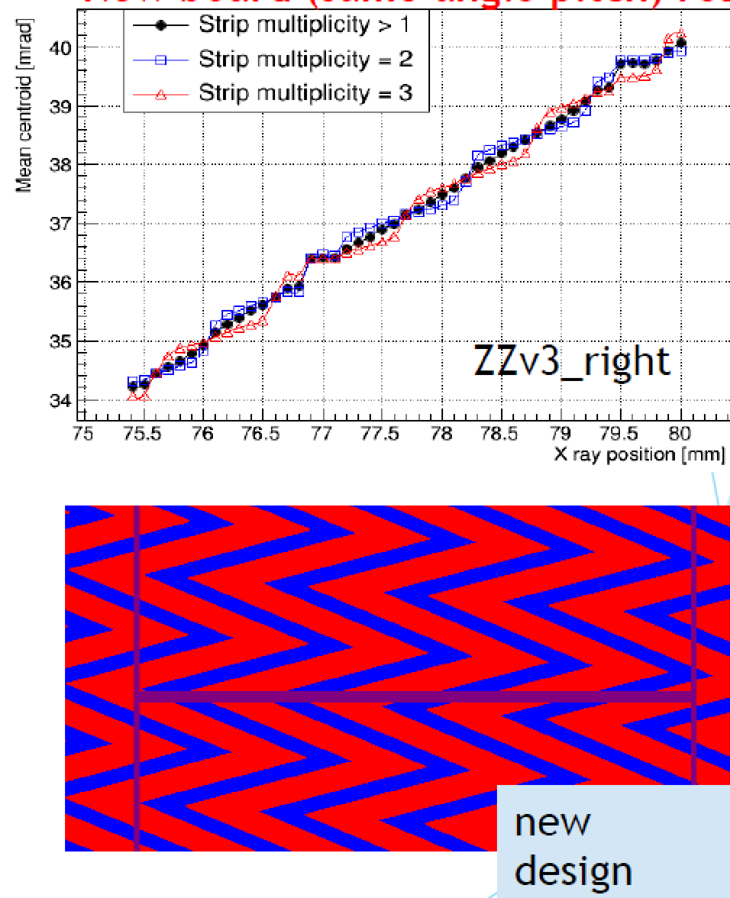
Topic 1: X-ray scans of PCBs with improved zigzag strip design

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

Previous zigzag design ZZ48



New board (same angle pitch) results:



(1) Flat regions are insensitive to hit positions.
(2) Too many events fire only 1 strip, some have 2 strips, few events fire ≥ 3 strips.

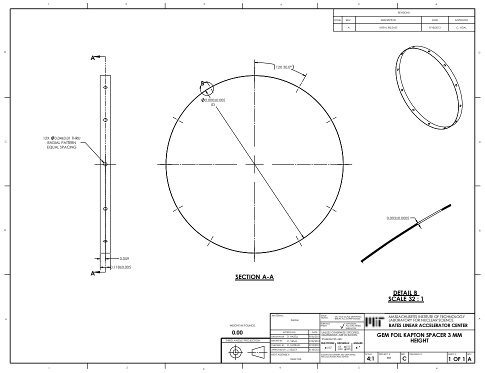
(1) Clearly linear response over whole range.
(2) > 95% events fire 2 or 3 strips.

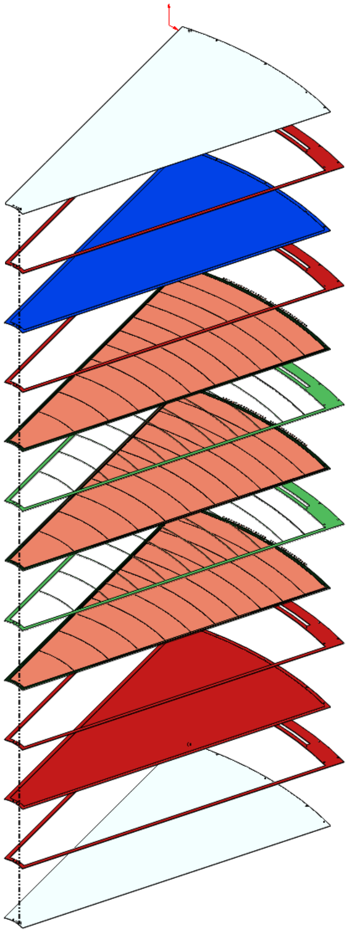
EIC GEM Tracker R&D: TU design

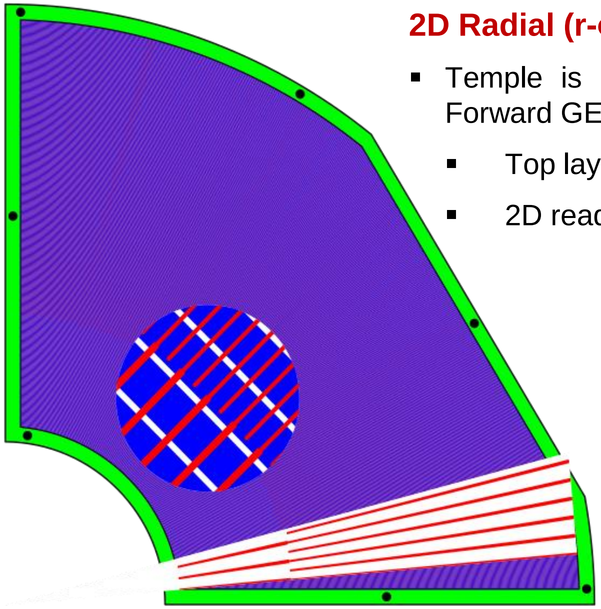
Assembly:

- Traditional stretching / framing / gluing method
- In order to help alleviate dead material, **Kapton rings** are being investigated to be used to separate the GEM layers rather than spacer grids.
- **Kapton rings: Perforated** walls to allow for gas flow
  - Inner diameter of **50.8 mm**.
  - Wall thickness of **0.127 mm**
  - Cut into lengths of **2mm** and **3mm**.
- Design with all HV, FE, gas connections on outer radius.

Drawings of the Kapton ring

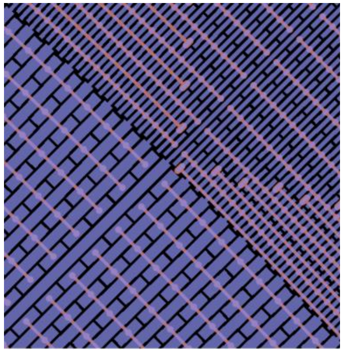






2D Radial (r-φ) readout strips board:

- Temple is using the same 2D readout scheme, used in the STAR Forward GEM Tracker (FGT) [NIM A 617 (2010), 196].
  - Top layer: φ-readout and bottom layer r-readout
  - 2D readout will be produced by Tech-Etch



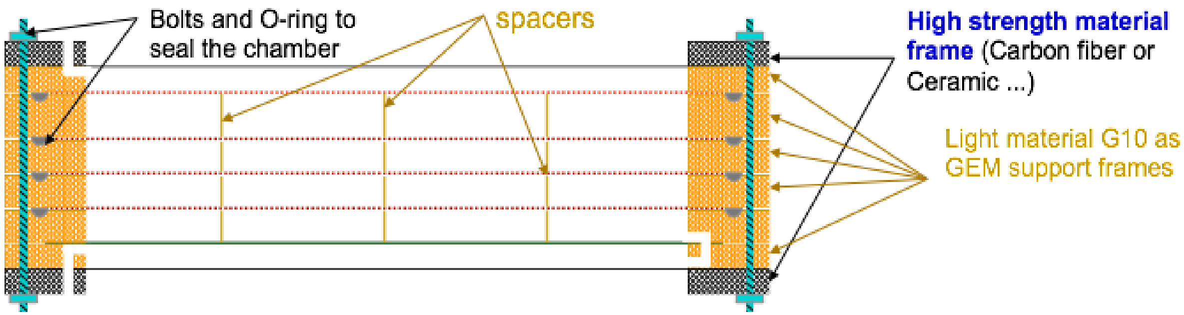
- **Active** layer is in **blue**:
  - **Lines** at constant **angle**.
  - **Pads** at constant **radius.**
- **Routing** layer in **orange**:
  - Each line is read out separat
  - Pads at each radius are con
- **300-800 micron** pitch design.

EIC GEM Tracker R&D: UVa design

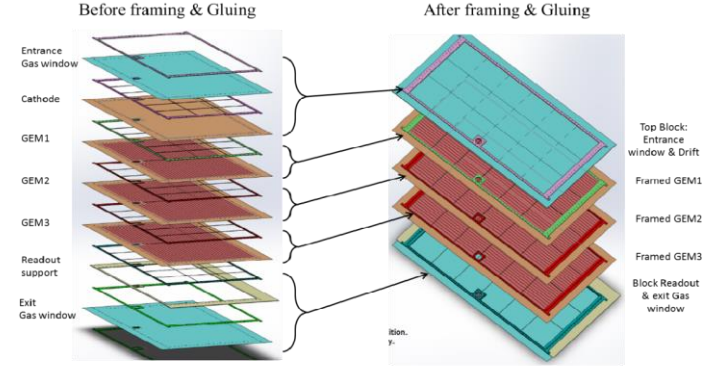
assembly method:

- Similar assembly technique for the PRad GEM chambers ⇨ Idea tested with PRad large GEM chambers with limited success
- Foils are glued to frames **but frames are not glued together** but sealed with O-rings and bolts could be re-opened.
- We are investigating low mass / light screws and bolts (Carbon fiber, ceramic …)
- Honeycomb support are removed for a low mass detector.

Novel assembly method for light weight GEM for EIC/SoLID



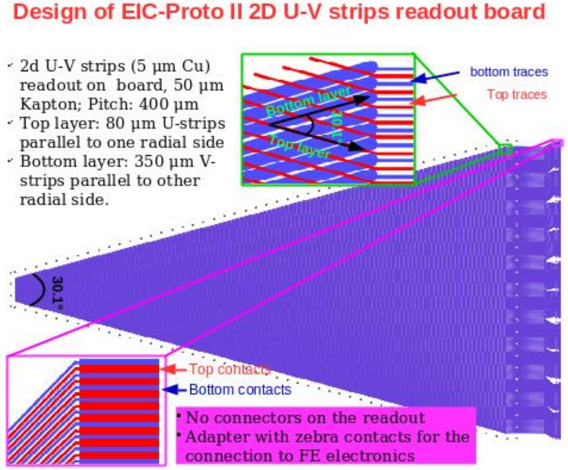
Exploded 3D view of pRad GEM design



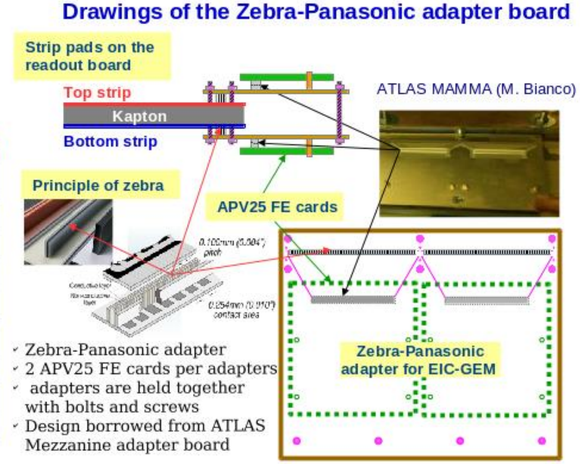
2D U-V strip readout with stereo-angle of 30.1°

- The readout strip pitch is equal to **400 µm:** improve spatial resolution, improve pedestal noise
- Electrical contacts between the strips and the FE electronics done with **zebra connectors** on the outer radius side of the detector.
- **Zebra-Panasonic adapter board ⇨ no mounted connectors and metallized holes (vias)**
- Needed to use existing APV25-SRS Front End Cards, final version, for EIC GEM trackers, the zebra strips will be directly on the FE cards

Design of EIC-Proto II 2D U-V strips readout board



Drawings of the Zebra-Panasonic adapter board

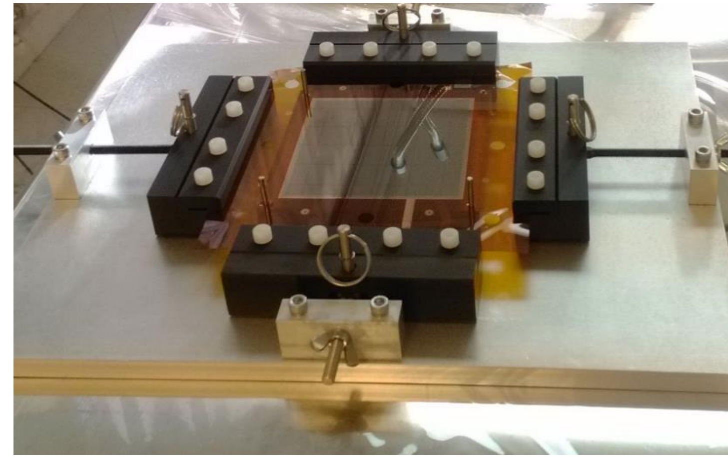


R&D on Large GEMs: Chromium GEM foil (UVa)

Characteristic of Cr-GEM foil:

- Copper (Cu) clad raw material comes with 100 nm Chromium (Cr) layer between Cu and Kapton, 5μm Cu layers removed, leave only 100 nm residual Cr layers as electrodes, **Cr-GEM foils provided CERN PCB workshop**
- This is particularly interesting for the Nuclear Physics community where will be used GEMs are used as tracker in a high background of low energy photon.
- Using Cr-GEM foil lead to almost 50% reduction of the material of an EIC light weight **triple-GEM detector**: this is because the material in a lightweight triple-GEM is dominated by GEM foils,

Standard GEM



Cr-GEM on the mechanical stretcher for assembly

Triple-GEM with standard GEM foil

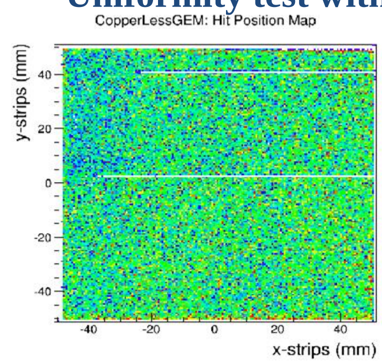
	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	5	8.96	14.3	1	0.0350	0.0045
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	5	8.96	14.3	0.2	0.0070	0.0009
Copper-350	1	5	8.96	14.3	0.75	0.0262	0.0034
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	0.471	**0.090**

Triple-GEM with Cr-GEM foil

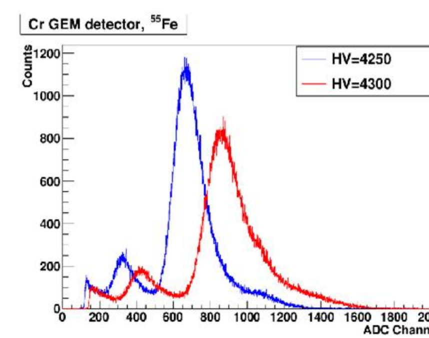
	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	0	8.96	14.3	1	0.0000	0.0000
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	0	8.96	14.3	0.8	0.0000	0.0000
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	0	8.96	14.3	0.2	0.0000	0.0000
Copper-350	1	0	8.96	14.3	0.75	0.0000	0.0000
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	0.235	**0.060**

About 50% reduction in the amount of material in a EIC-FT-GEM with Cr-GEM

Uniformity test with Cosmic



ADC Spectrum with Fe55

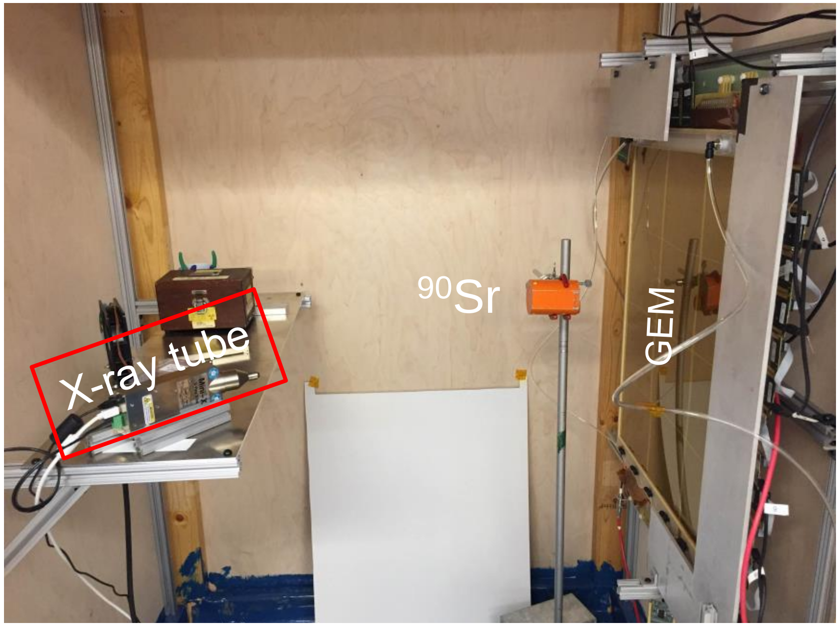


Preliminary tests of the prototype

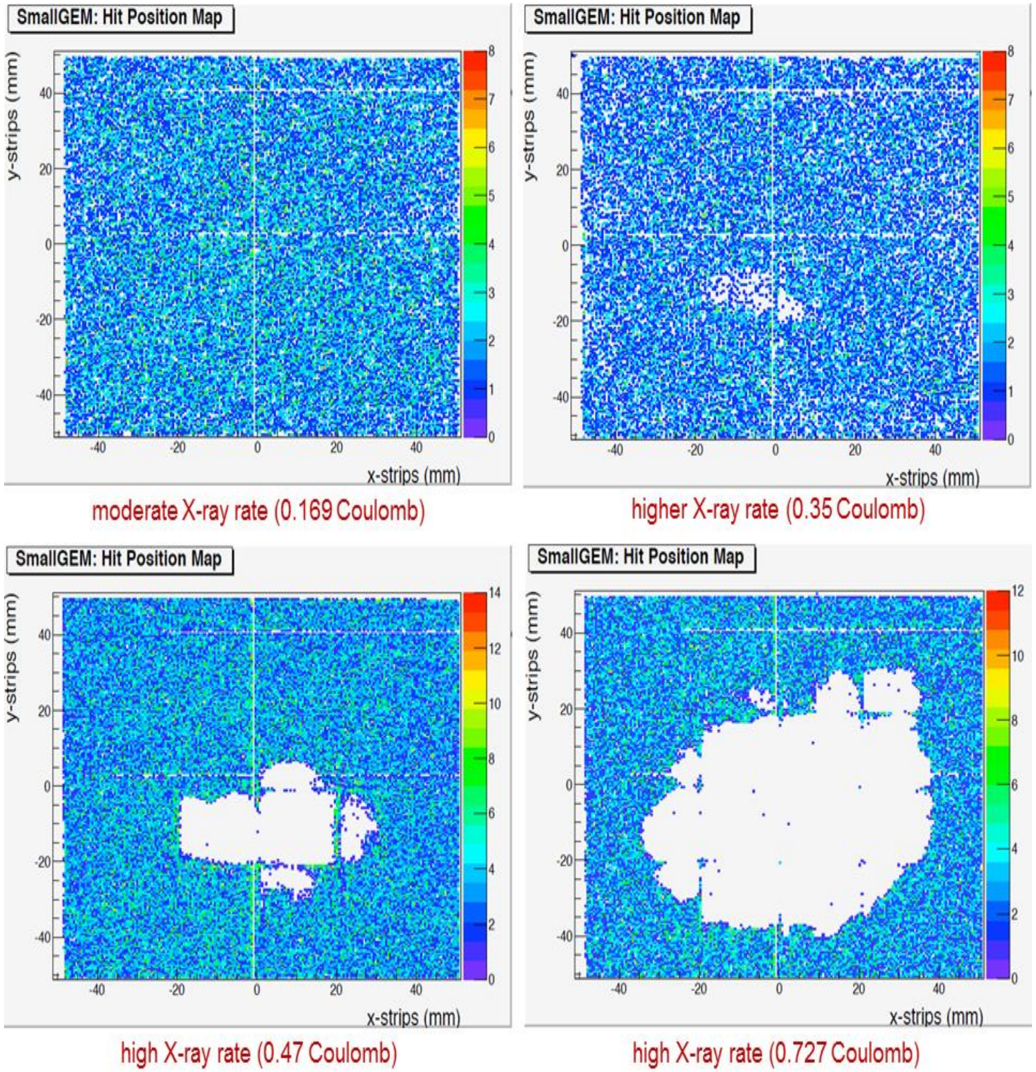
R&D on Large GEMs: Chromium GEM foil (UVa)

High particle rate study of the Cr-GEM:

- Exposure of the Cr-GEM with x-ray source ⇨ Each measurement = Accumulated charges (Coulombs) over 24 h
- The top left hit map plot shows no degradation at 0.17 C. and @ 0.35 C ⇨ appearance of small dead area (**top right Fig1**).
- The dead area size increases with increasing rate (**bottom 2 plots Fig1**) ⇨ almost half of the active area is dead @ 0.7 C

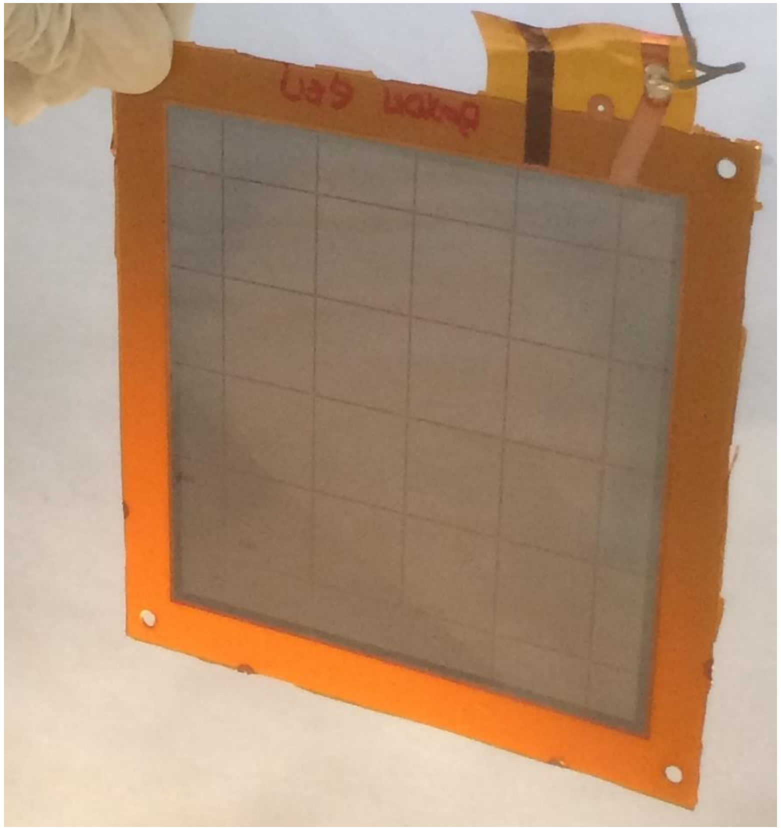


X-ray box for high rate studies

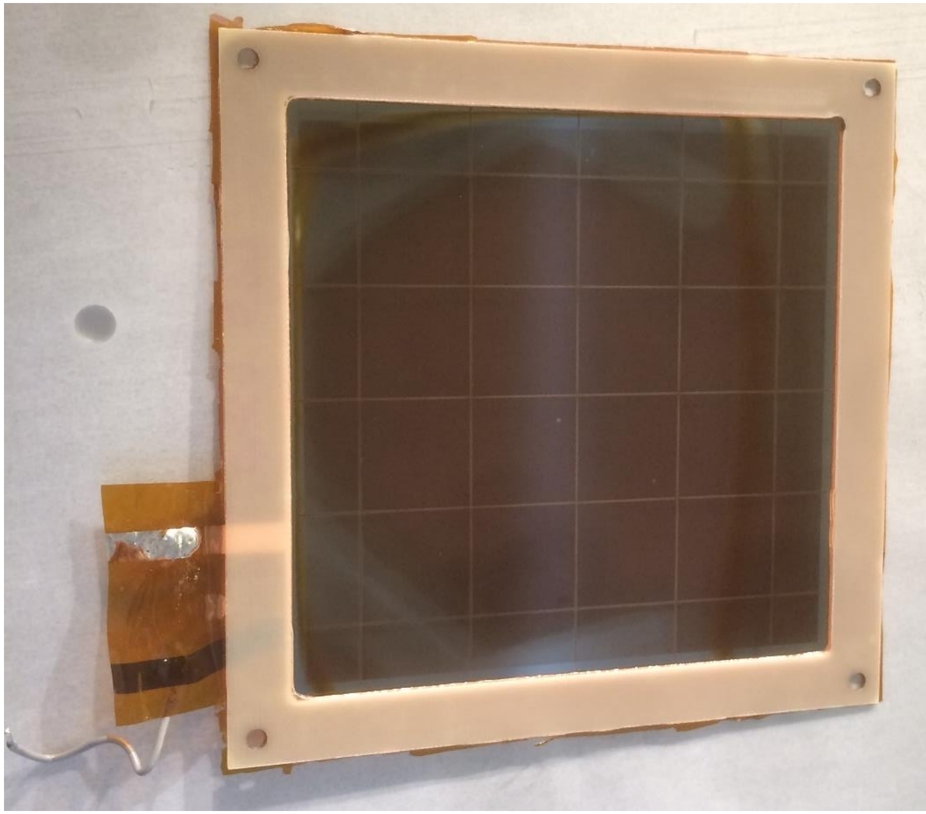


R&D on Large GEMs: Chromium GEM foil (UVa)

Visual inspection of the Cr-GEMs after we re-open the chamber …



top electrode side of the 3rd foil Cr-GEM



Bottom electrode side of the 3rd foil Cr-GEM

R&D on Large GEMs: Chromium GEM foil (UVa)

Inspection of Cr-GEM foils after high rate X-ray exposure:

- Top side of 3rd GEM foil, (closer to the readout board) is intact i.e. no apparent damage (**top left Fig2**)
- However Bottom electrode ⇨ Chromium layer almost completely **gone** ⇨ dark brown color is the Kapton **(top middle Fig2), but no evidence of short or Kapton meltdown** ⇨ Looks like the Cr has evaporated
- Causes of damages are unclear: ageing or small discharges @ high rate
- Two upper GEM foils show no damage ⇨ HV test OK
- **We just got a few new Cr-GEM foils from Rui ⇨ We plan to study the long term effect of continuous radiation (X-ray)**

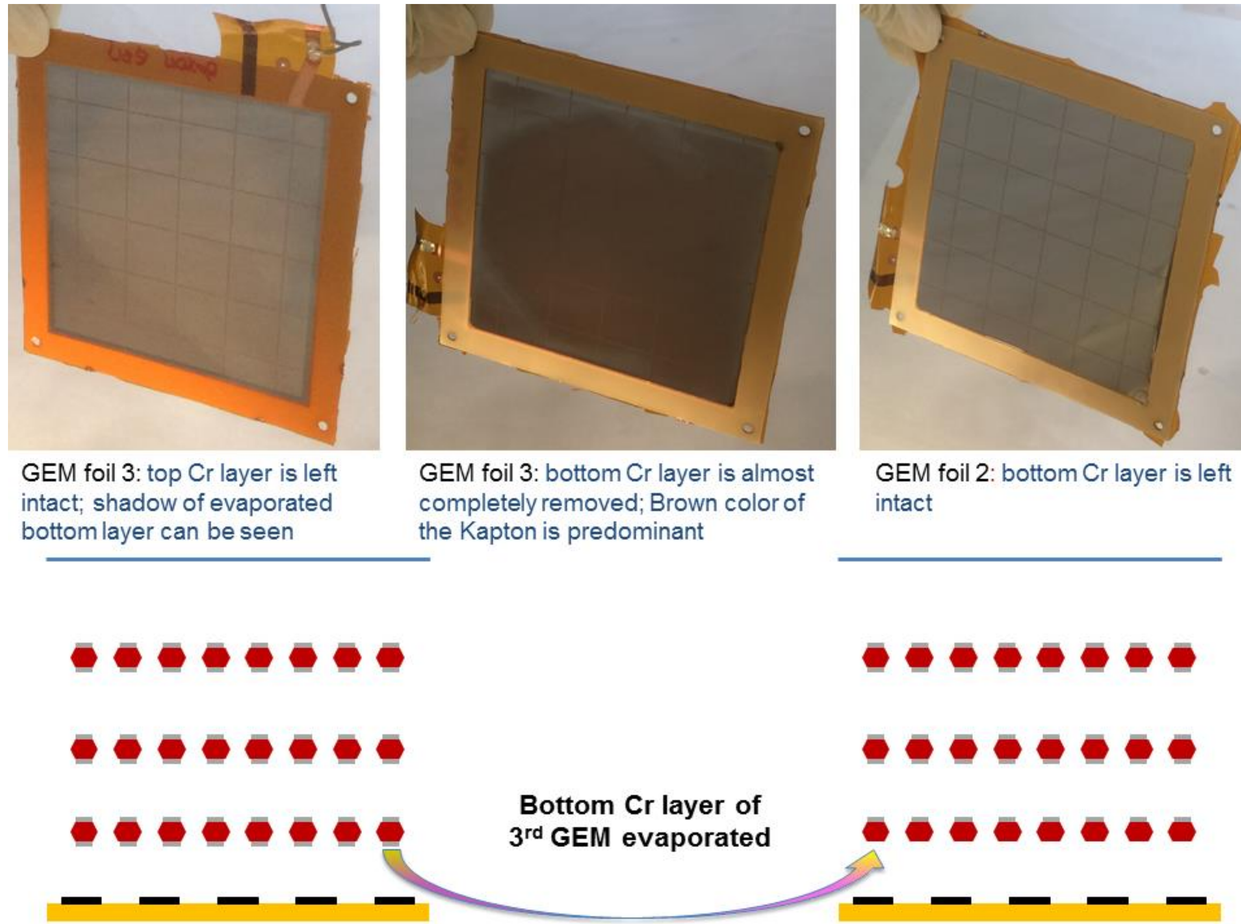


Fig2:Degradation of Cr-GEM in high particle rate environment with X-ray.

Summary

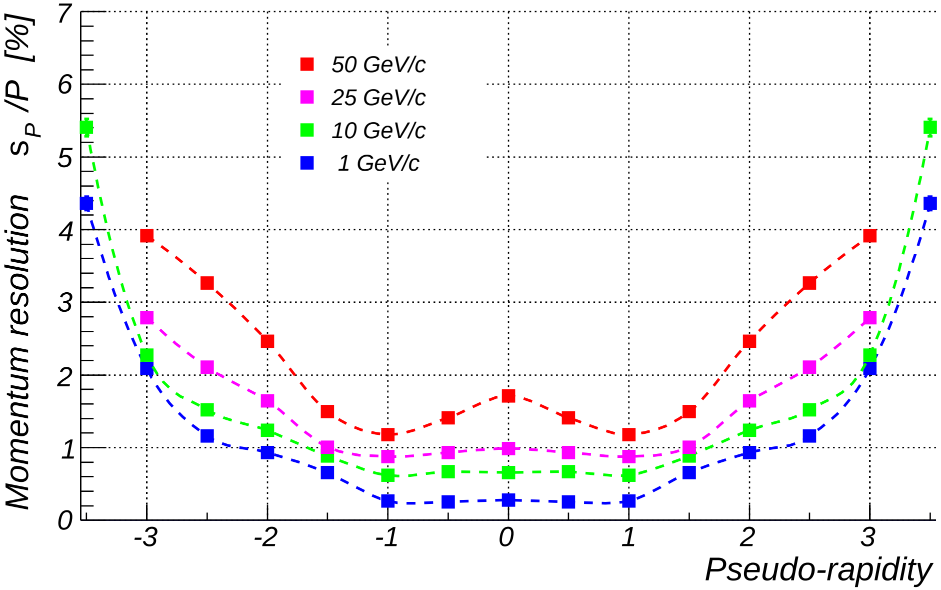
- All three current EIC detector concepts require the use large GEM for their forward tracking
- Significant detector R&D for EIC Forward GEM have been conducted over the past few years
  - 3 Universities **Univ. of Virginia, Florida Tech and Temple Univ.** are leading these effort.
  - Performances of large GEM prototypes and quality control of commercial GEM foils have been published as peer review papers.
- The 3 groups have collaborated in designing a common GEM foil design to:
  - Build 3 prototypes to explore different assembly techniques and readout structures
- Production of commercial large GEM foil by Tech-Etch using the single mask technique
  - The electrical properties of Tech-Etch foils are comparable to those produced at CERN
  - Optical inspection shows holes pattern and geometry also similar to CERN GEM foils
- New ideas are also being investigated to minimize the material of the EIC-FT-GEMs detectors.
  - The concept of ultra light GEM foils with Chromium (Cr-GEMs) has been demonstrated
  - Light material to be used for NS2 assembly technique under investigation

Backup

EIC Overview: Detector requirements

- The more close to 4π acceptance the better
- Low material budget
- Reasonably high momentum resolution
- Reliable electron ID
- Good π/K/p separation
- High spatial resolution of primary vertex
- *Ability to reconstruct jets*
- Close-to-beam-line acceptance detectors in order to register:
  - recoil protons
  - low Q^2 electrons
  - neutrons in hadron going direction
- Luminosity and polarization measurement

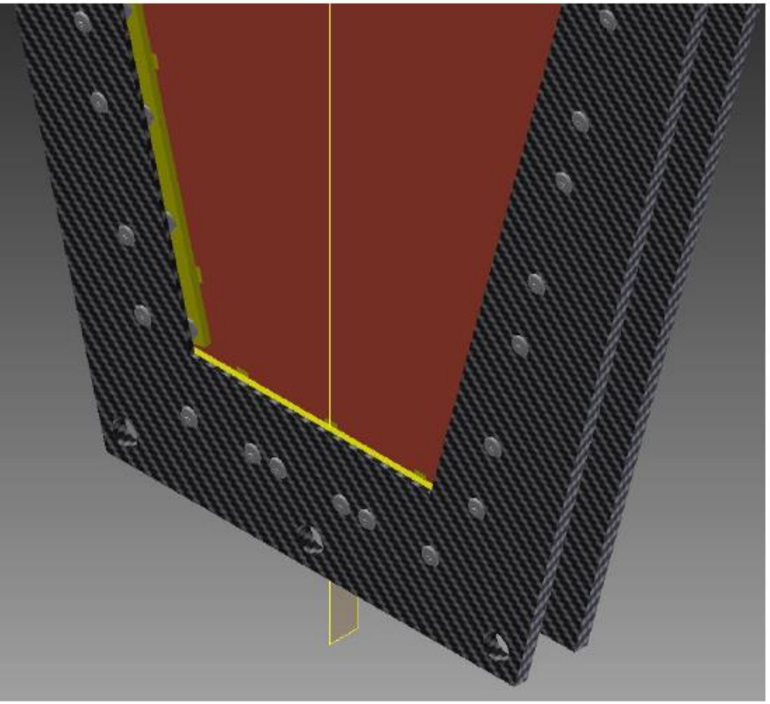
Tracking performance : Momentum resolution



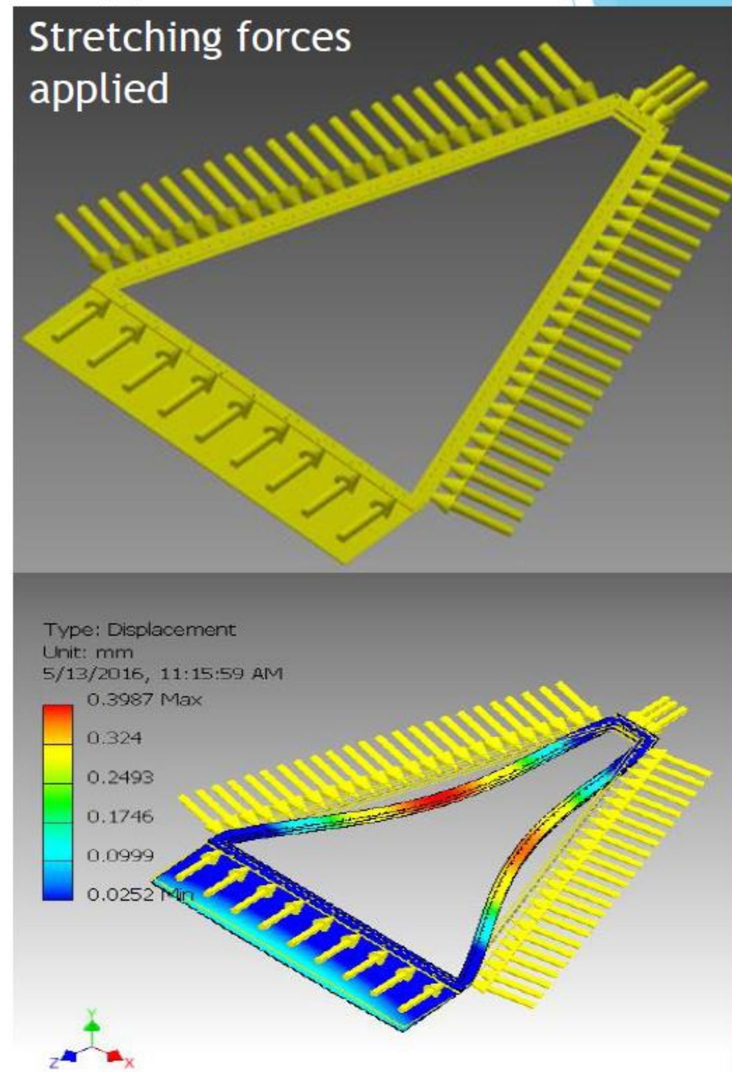
Slide from A. Kiselev, EIC User Meeting July 2016

Study of light material for NS2 assembly technique

Topic 2: Status of our 2nd EIC FT GEM prototyping



Simulated deformation for 10N force applied to each stretching screw



(Drift foil, 3 GEM foils, r/o foil; carbon fiber frames)

Model for stress analysis in Inventor: -->

- Applying an opposite force to each post (mimicking GEM foils being stretched against the posts)
- Observing the displacement of the frames. (see also next page)

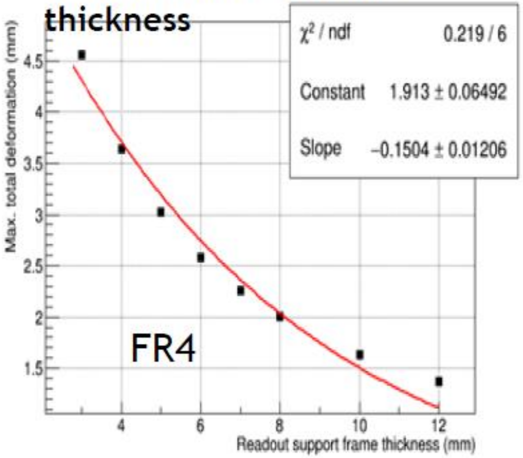
Study of light material for NS2 assembly technique

Topic 2: Status of our 2nd EIC FT GEM prototyping

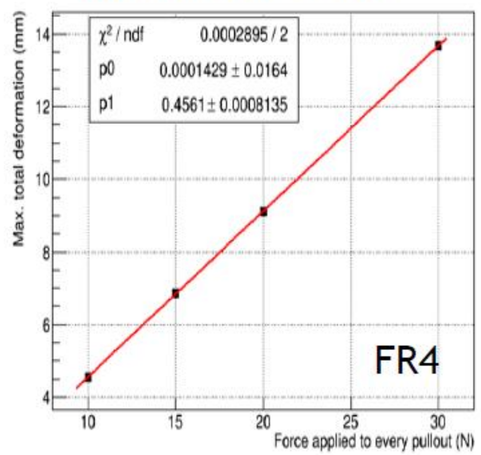
The **max. deformation** for different frame materials (10 N force, 3 mm frame thickness). Carbon fiber and ceramic materials gives small displacement. Plan to go with carbon fiber.

Frame material	Carbon fiber (M55UD)	Carbon fiber (UD std.)	Ceramic (Silicon Nitride)	FR4
Max. deformation (mm)	0.399	1.068	0.282	4.565

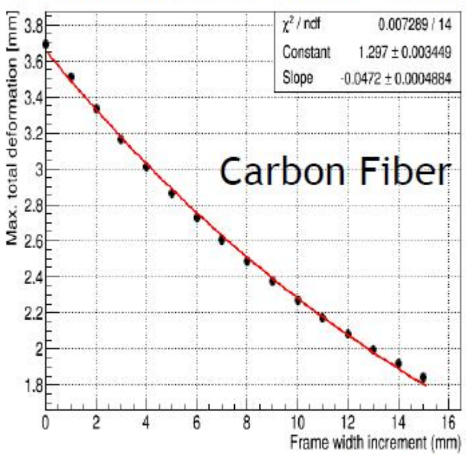
Deformation vs. frame thickness

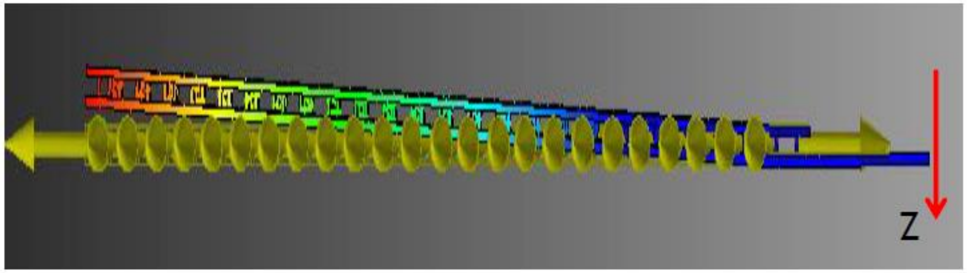


Deformation vs. force



Deformation vs. frame width

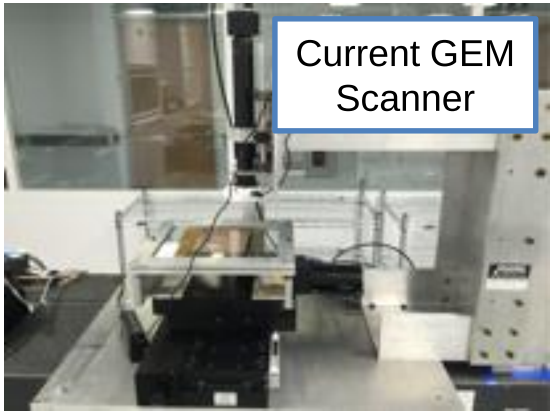


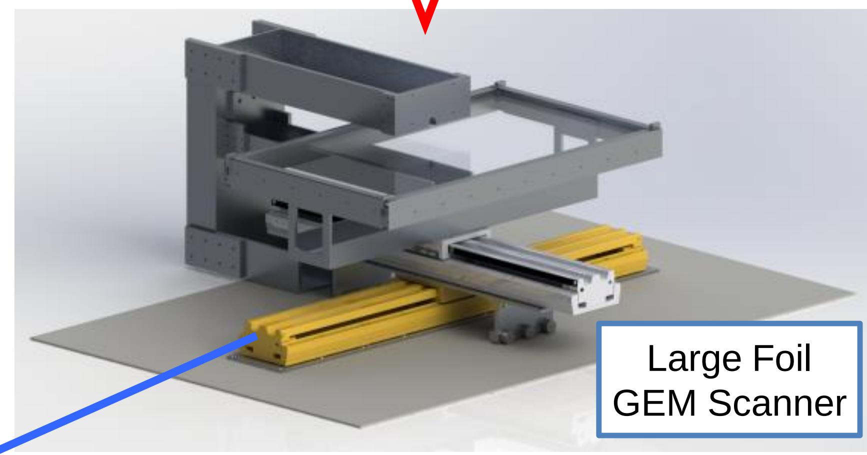


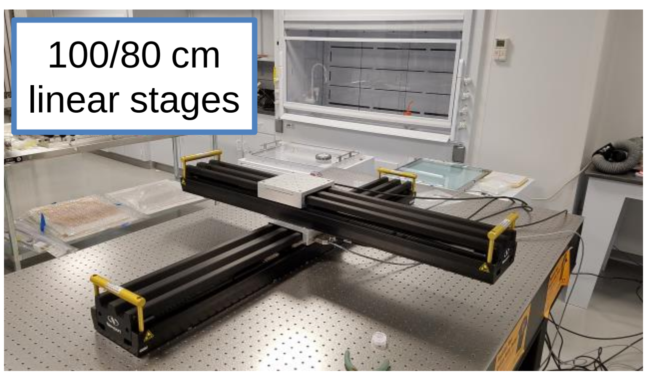
Frame buckling (displacement in Z direction) under stretching force (50 N each) while fixed at one end.

Carbon fiber frame bends < 2 mm.

Optical tests of GEM foils @ Temple U: Scanning large foil .







PRad GEM chamber with bolts and crews assembly technique