Development of Thin-gap GEM-μRWELL Hybrid Detectors at Jefferson Lab

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Coordinating Panel for Advanced Detector Workshop (CPAD2025) – Oct. 07 - 11, 2025 Univ. of Pennsylvania, Philadelphia

Outline

- ❖ Motivation for thin-gap GEM-μRWELL Hybrid Detector
- ❖ Performance studies of thin-gap GEM-μRWELL prototypes in test beam
- ❖ Thin-gap GEM-μRWELL detectors for EIC ePIC MPGD Barrel Outer Tracker
- ❖ Proposal for double-sided thin-gap GEM-μRWELL technology for HFCC Muon Detector

Thin-gap GEM-µRWELL Hybrid Detectors: Motivation

Challenges with standard (> 3-mm drift gap) MPGD

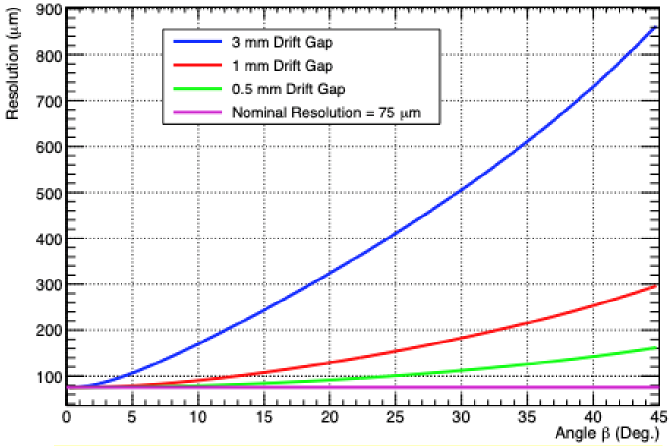
- ❖ Degradation of the spatial resolution with track angle .
- ❖ E × B in magnetic field negatively impact resolution

Development of Thin-gap MPGDs:

- ❖ Smaller gap to minimize the dependence of resolution
- ❖ Smaller gap ➔ minimize E × B effect in magnetic field
- ❖ Improve the detector timing performance

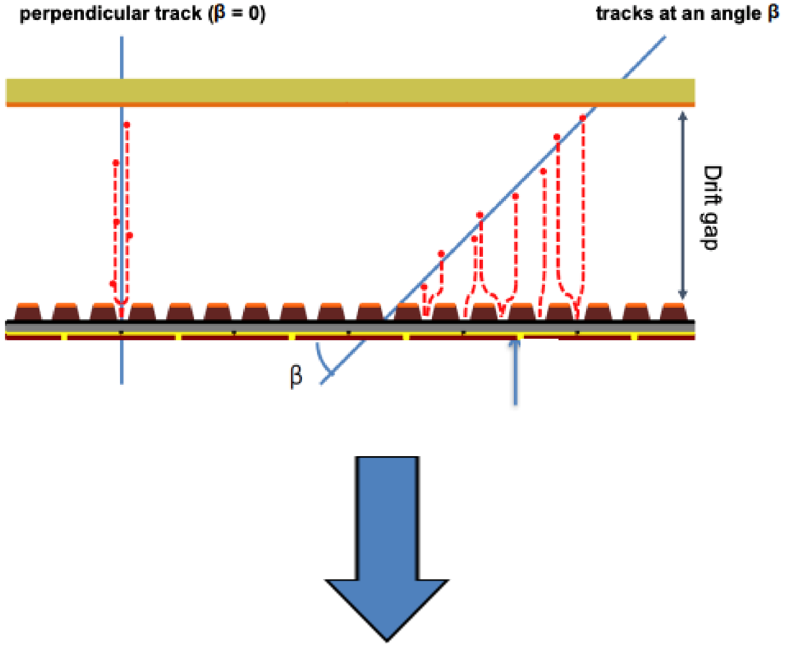
Thin Gap MPGD R&D effort:

- ❖ Thin-gap triple GEMs developed @ UVa
- ❖ Thin-gap GEM-µRWELL hybrid @ Jlab
- ❖ Thin-gap GEM-Micromegas @ Vanderbilt Univ.

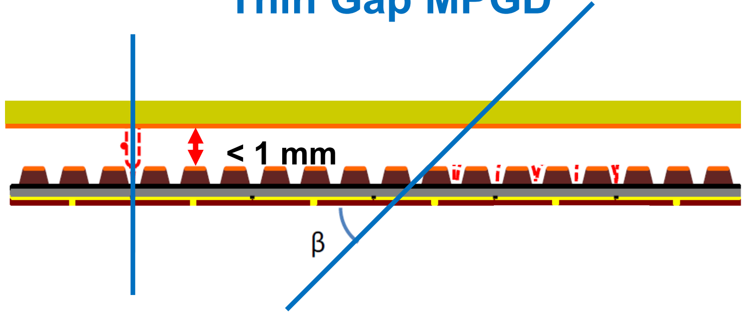


parametrization from *EPJ Web of Conferences **174**, 06005 (2018)*

standard Gap µRWELL



Thin Gap MPGD



Development of Thin Gap MPGDs for EIC Trackers

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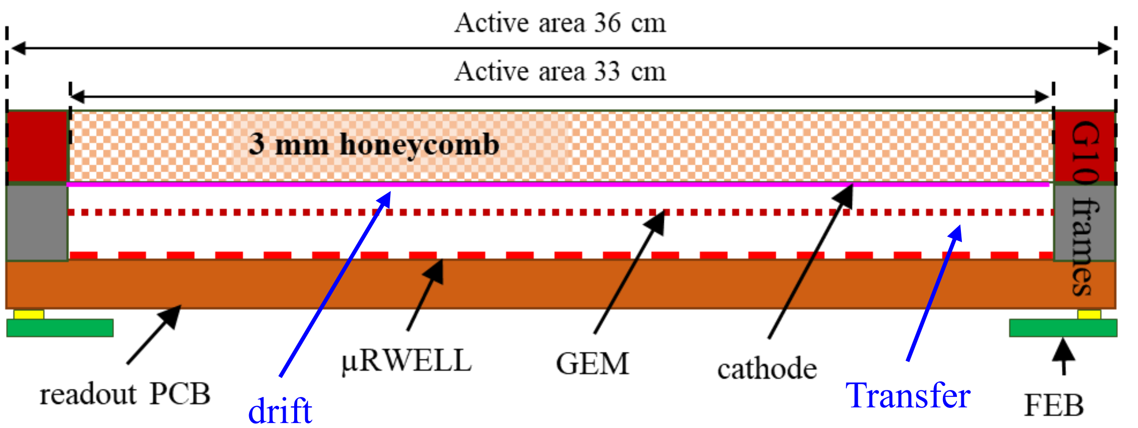
Thin-gap GEM-µRWELL hybrid prototypes @ JLab

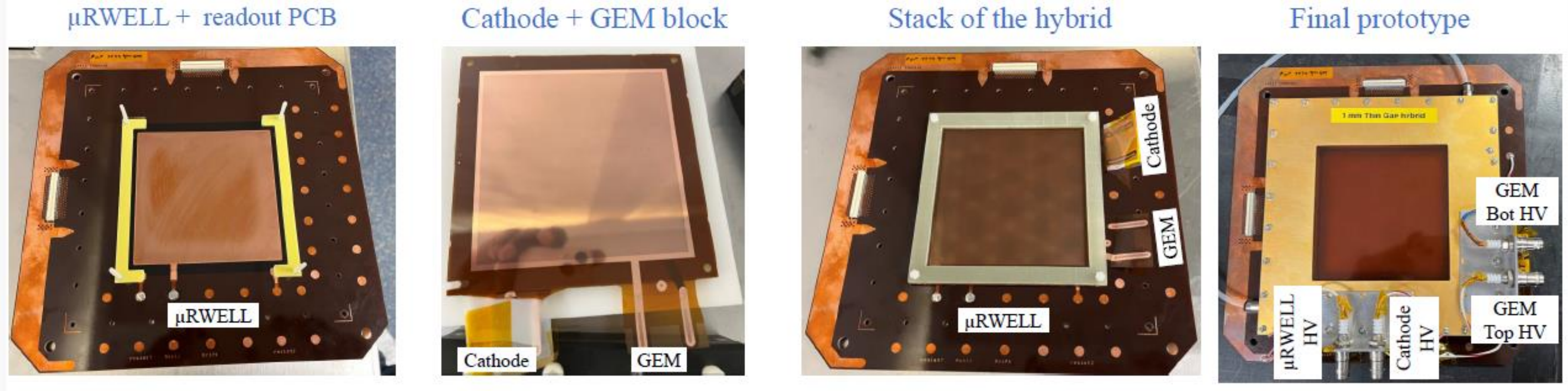
3 thin-gap prototypes fabricated at Jefferson Lab :

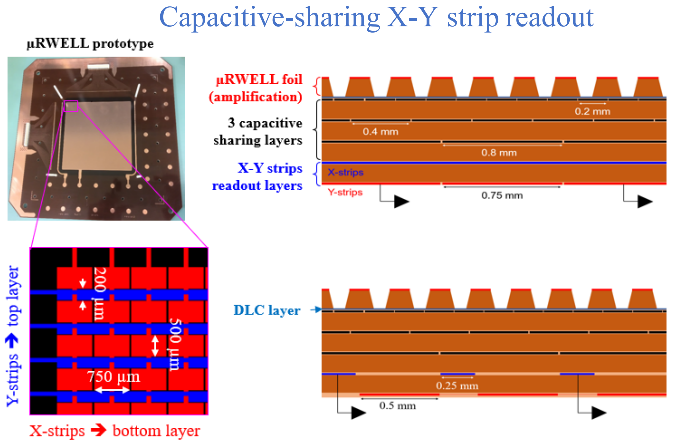
- **Proto1:** 1 mm drift gap & 1 mm transfer gap (between GEM & µRWELL)
- **Proto 2:** 1.5 mm drift gap – 1 mm transfer gap
- **Proto 3:** 0.5 mm drift gap – 1 mm transfer gap
- **Double amplification:** High gain & stable detector operation
  - Hybrid amplification ➔ GEM + µRWELL
- **X-Y strip readout with capacitive-sharing structures:**
  - 2 capacitive-sharing layers
  - Strip pitch = 800 µm
  - https://doi.org/10.1016/j.nima.2022.167782



cross-section view of thin-gap GEM-µRWELL detector

K. Gnanvo et a.: https://doi.org/10.1016/j.nima.2025.170791





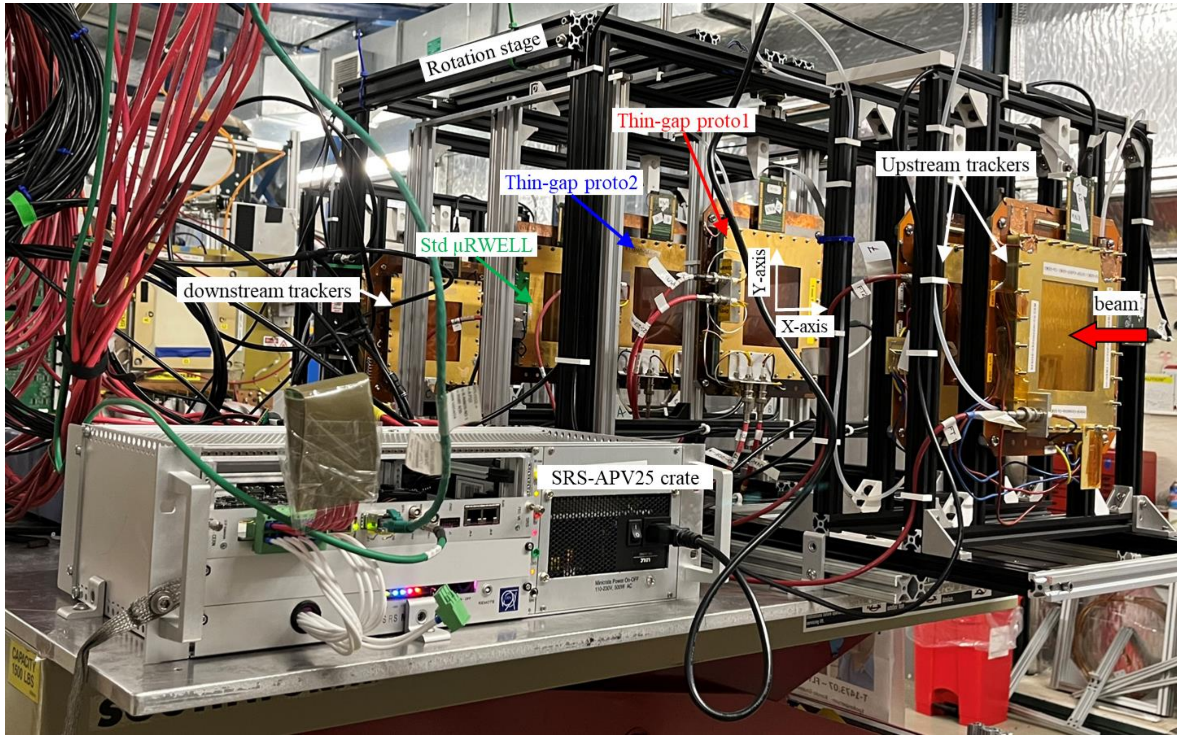
Assembly of small (10 cm × 10 cm) thin-gap GEM-µRWELL hybrid detector

Thin-gap GEM-μRWELL: Performance studies in test beam

Test beam campaigns @ FNAL (2023) and @ JLab (2025) for performance study and optimization of thin-gap GEM-μRWELL prototypes

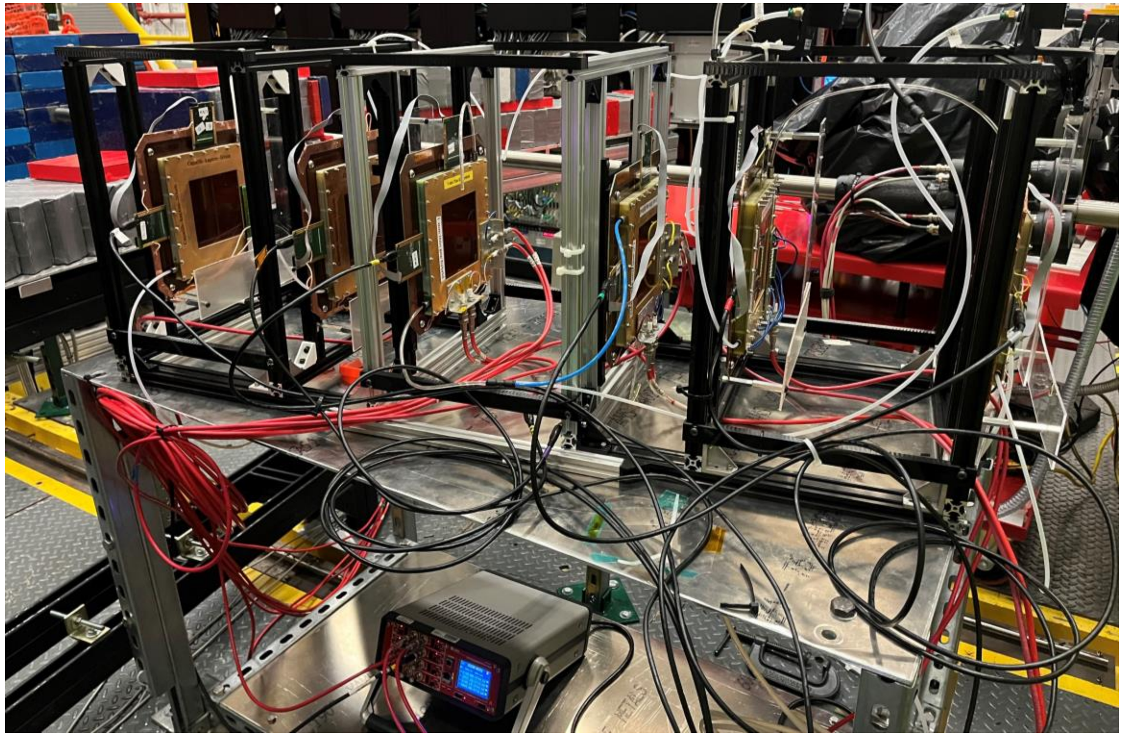
FNAL test beam (06/2023): Position resolution vs. track angle

- **3 protos**: 0.5 & 1 mm thin-gap GEM-μRWELL, 3-mm std μRWELL
- 4 HV scans for efficiency study with Ar:CO_2 (80:20) gas mixture
- Track angle scan (0 – 45^{O}) for position resolution comparison studies



Jlab Hall D test beam (06/2025): - Efficiency vs. gas mixtures

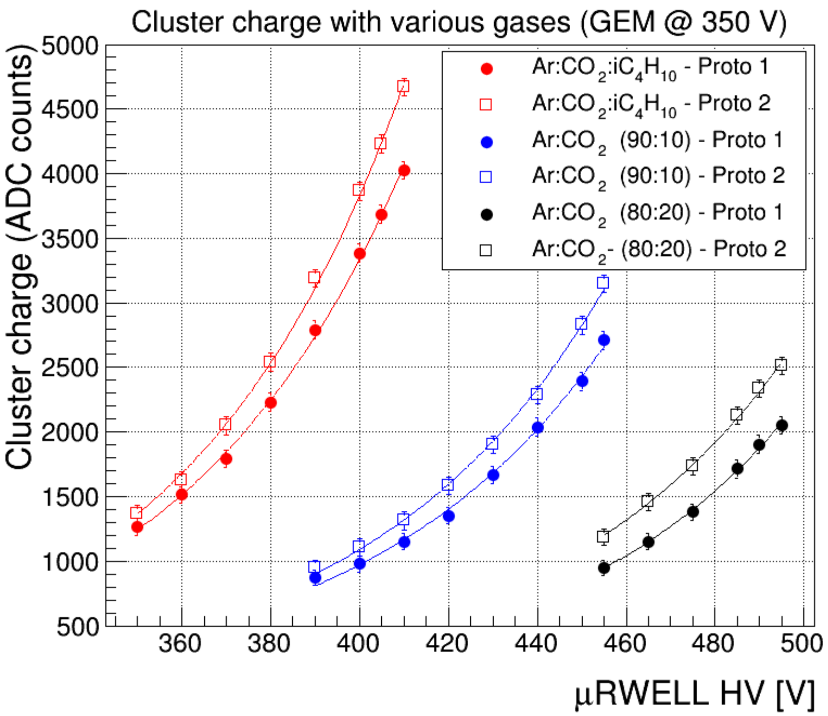
- **2 protos**: 1-mm and 1.5-mm thin-gap GEM-μRWELLs
- HV scan for efficiency study various Ar-based mixtures
- Argon gas mixture: (Ar/CO_2 & Ar/CO_2/Iso)

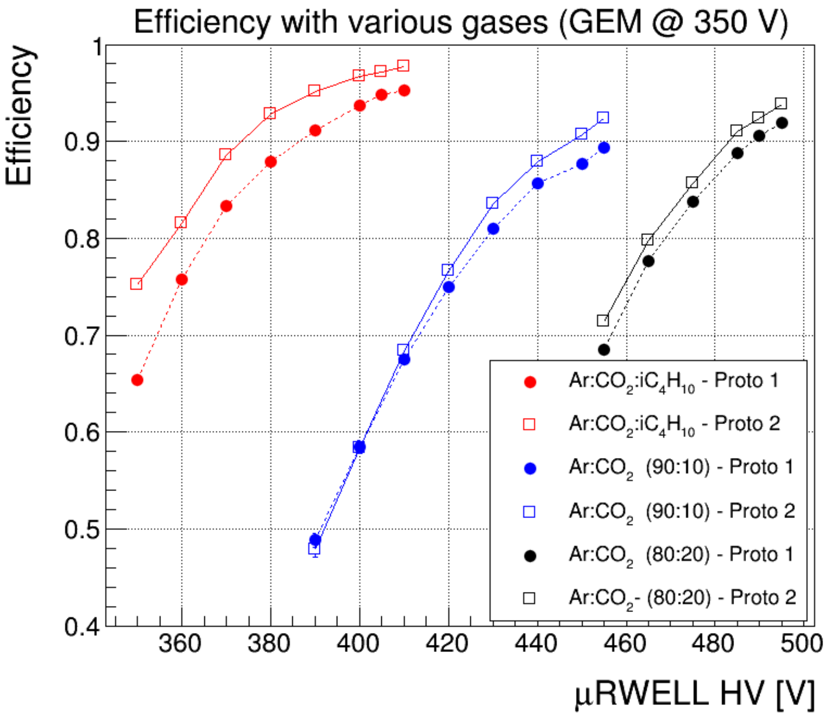


Third campaign is in preparation for the performance study of the prototypes in 1.5T field in the GOLIATH magnet in SPS H4 line @ CERN

Thin-gap GEM-µRWELLs: Performance with various gases

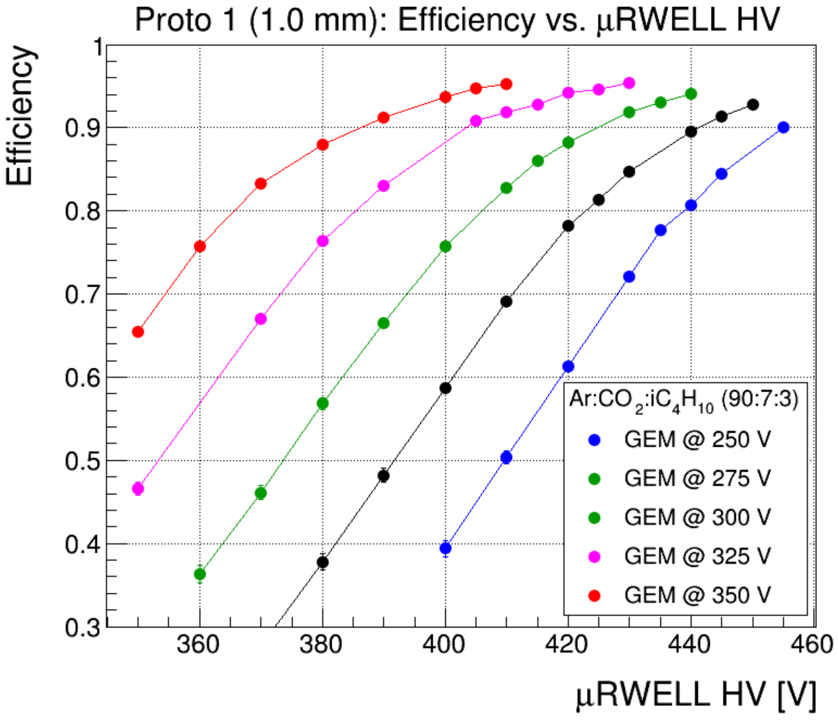
- Exponential rise of the cluster signal amplitude (mean ADC counts) for all three gases tested
  - High amplitude (red curves) signal at low voltages for the $Ar{:}CO_2{:}iC4H_{10}$, twice lower amplitude for $Ar{:}CO_2$ (80:20) at larger voltages
- High efficiency is achieved for both thin-gap prototypes even in $Ar{:}CO_2$:iso at moderate voltage applied in both amplification layers
  - Proto 1 (1-mm gap): Efficiency ~96% at high voltage across both GEM (<350 V) and the µRWELL (< 450 V)
  - Proto 2 (1.5-mm gap): Efficiency ~98% at high voltage across both GEM (<350 V) and the µRWELL (< 450 V)

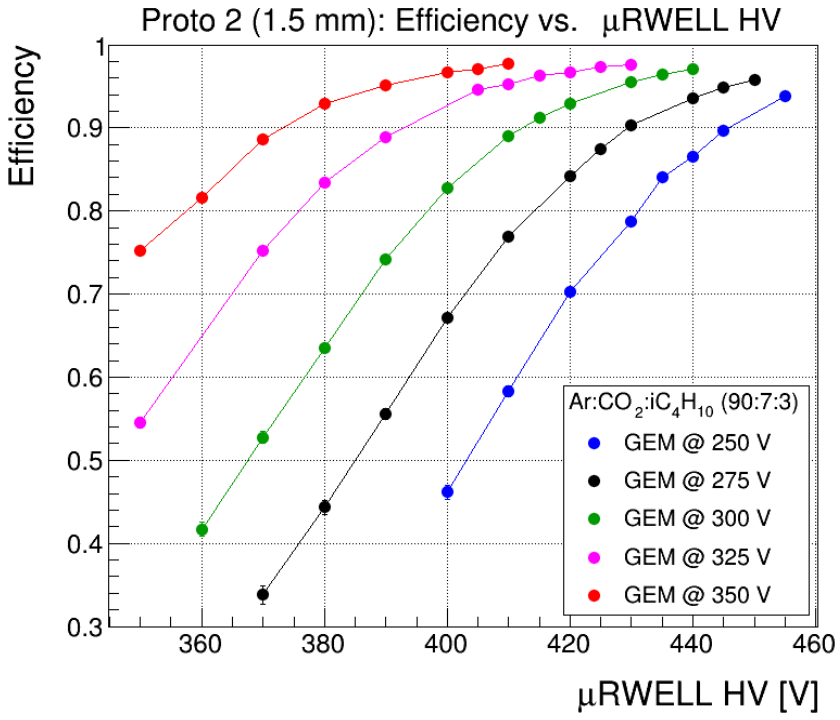




Thin-gap GEM-µRWELLs: µRWELL HV scan with $Ar:CO_2:iC4H_{10}$

- High efficiency is achieved for both thin-gap prototypes even in $Ar:CO_2:iC4H_{10}$ at moderate voltage applied in both amplification layers
  - Proto 1 (1-mm gap): Efficiency ~96% at high voltage across both GEM (<350 V) and the µRWELL (< 450 V)
  - Proto 2 (1.5-mm gap): Efficiency ~98% at high voltage across both GEM (<350 V) and the µRWELL (< 450 V)

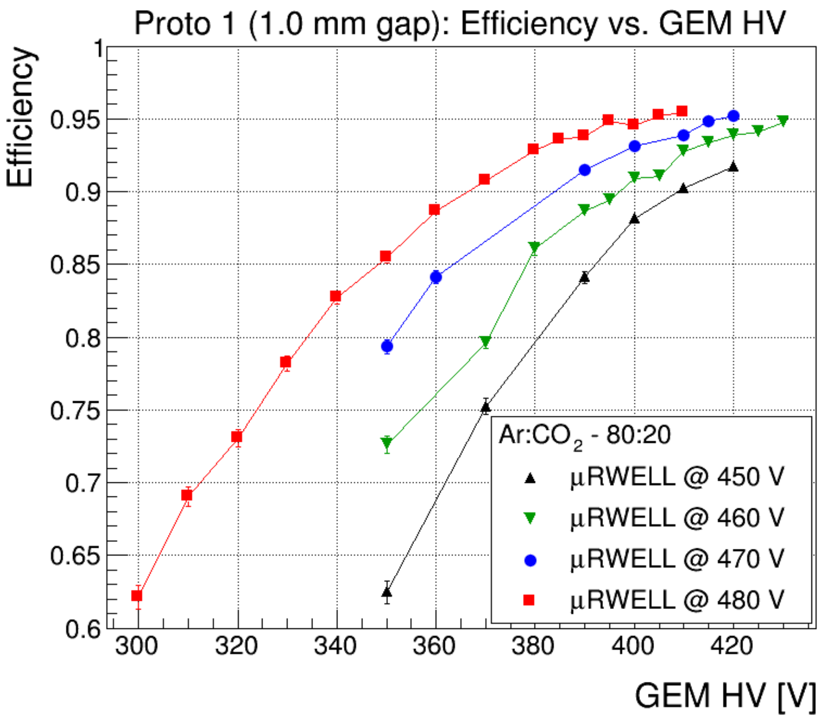


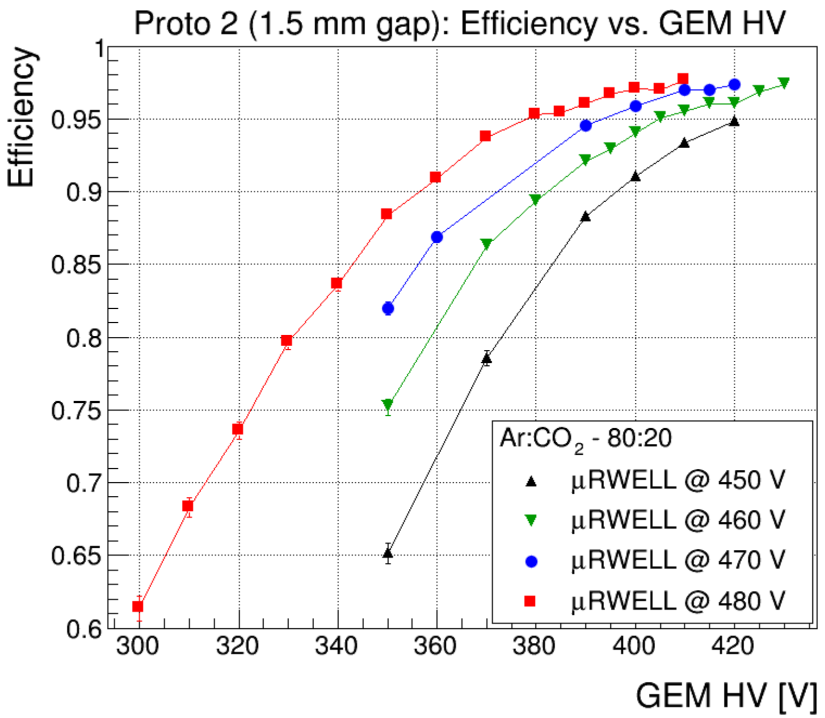


Preliminary results ➔ the analysis is still ongoing

Thin-gap GEM-µRWELLs: GEM HV scan with $Ar:CO_2$ (80:20)

- High efficiency is achieved for both thin-gap prototypes even in $Ar:CO_2$ but at high voltage in both amplification layers
  - Proto 1 (1-mm gap): Efficiency ~95% at high voltage across both GEM (400 V) and the µRWELL (> 450 V)
  - Proto 2 (1.5-mm gap): Efficiency > 97% at high voltage across both GEM (400 V) and the µRWELL (> 450 V)

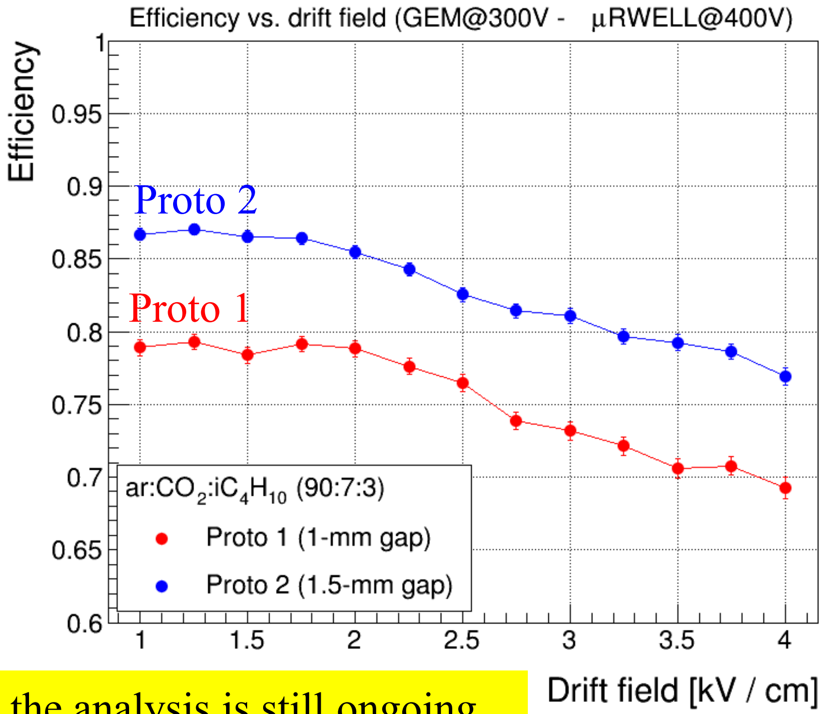


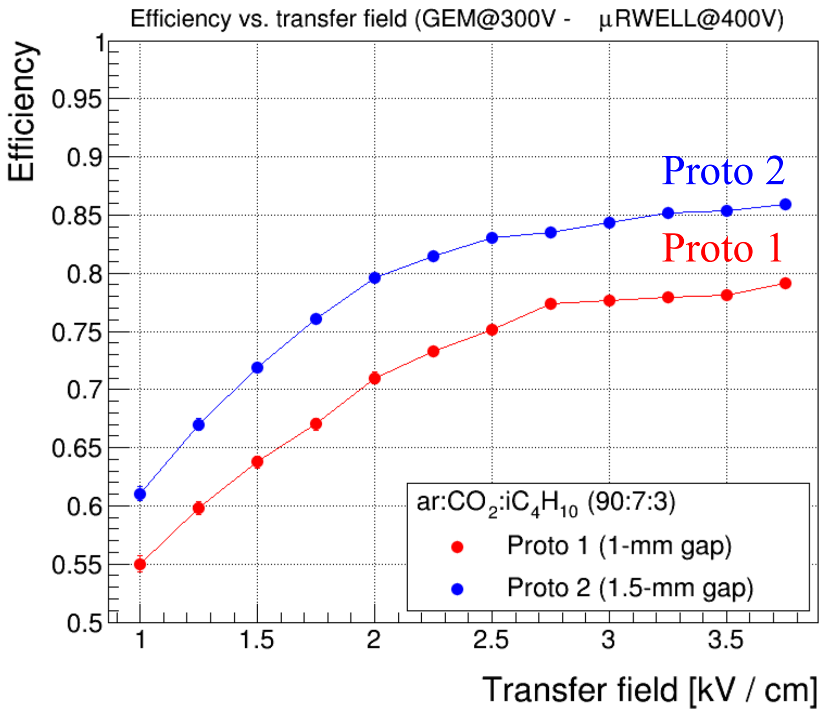


Preliminary results ➔ the analysis is still ongoing

Thin-gap GEM-µRWELLs: Performance with various gases

- Efficiency shows small dependance with the electric field in the drift region up to 2 kV / cm and slowly decreases above 2.5 kV / cm
  - We want to typically operate the detector at > 2.5 kV/ cm to optimize timing performance and minimize E×B effect
- Conversely, efficiency steadily increases from 1 kv / cm to ~2.5 k /cm in the transfer gap between the GEM and the µRWELL PCB then reach a plateau above 2,5 kV /cm
  - We want to typically operate the detector at > 2.5 kV/ cm to optimize timing performance and minimize E×B effect
- Similar performance is observed for the Ar:CO2 (90:10 and 80:20) that were tested





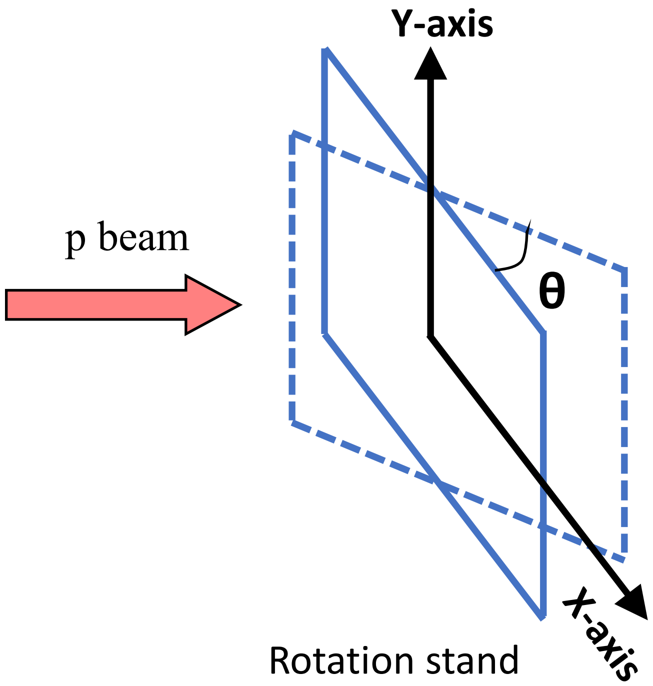
Preliminary results → the analysis is still ongoing

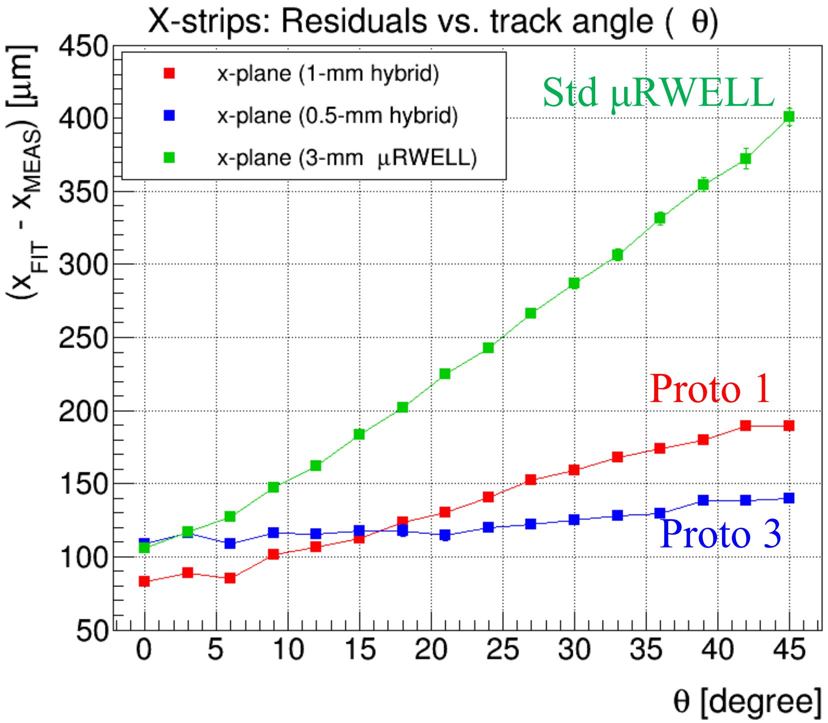
Thin-gap GEM-µRWELL: Position resolutions

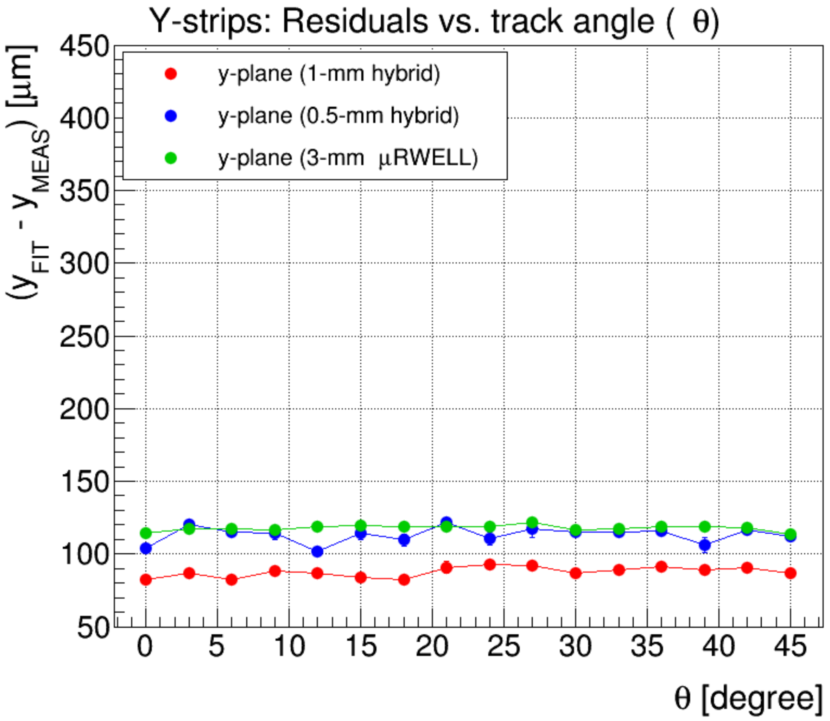
FNAL test beam (06/2023): Position resolution vs. track angle

- Proto 1 (1 mm gap) and proto 3 (0.5 mm gap) and a standard 3-mm gap µRWELL detector installed in a rotation stand for a angle scan of the detectors plane w.r.t vertical axis
- Track angle scan (0 – 45°) for position resolution comparison studies
- Position resolution in X-strips significantly improves for the thin gap detectors (red and blue curves) with respect to the standard µRWELL
- Position resolution is constant for Y-strips (no plane rotation)

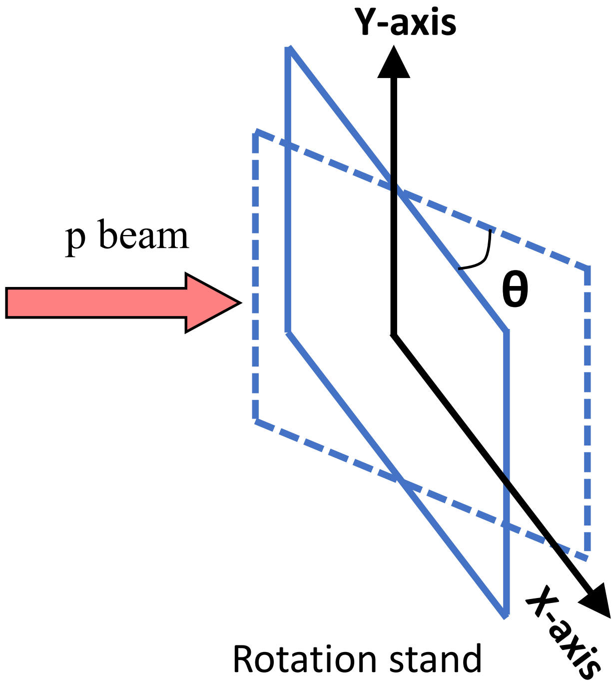
K. Gnanvo et al.: https://doi.org/10.1016/j.nima.2025.170791

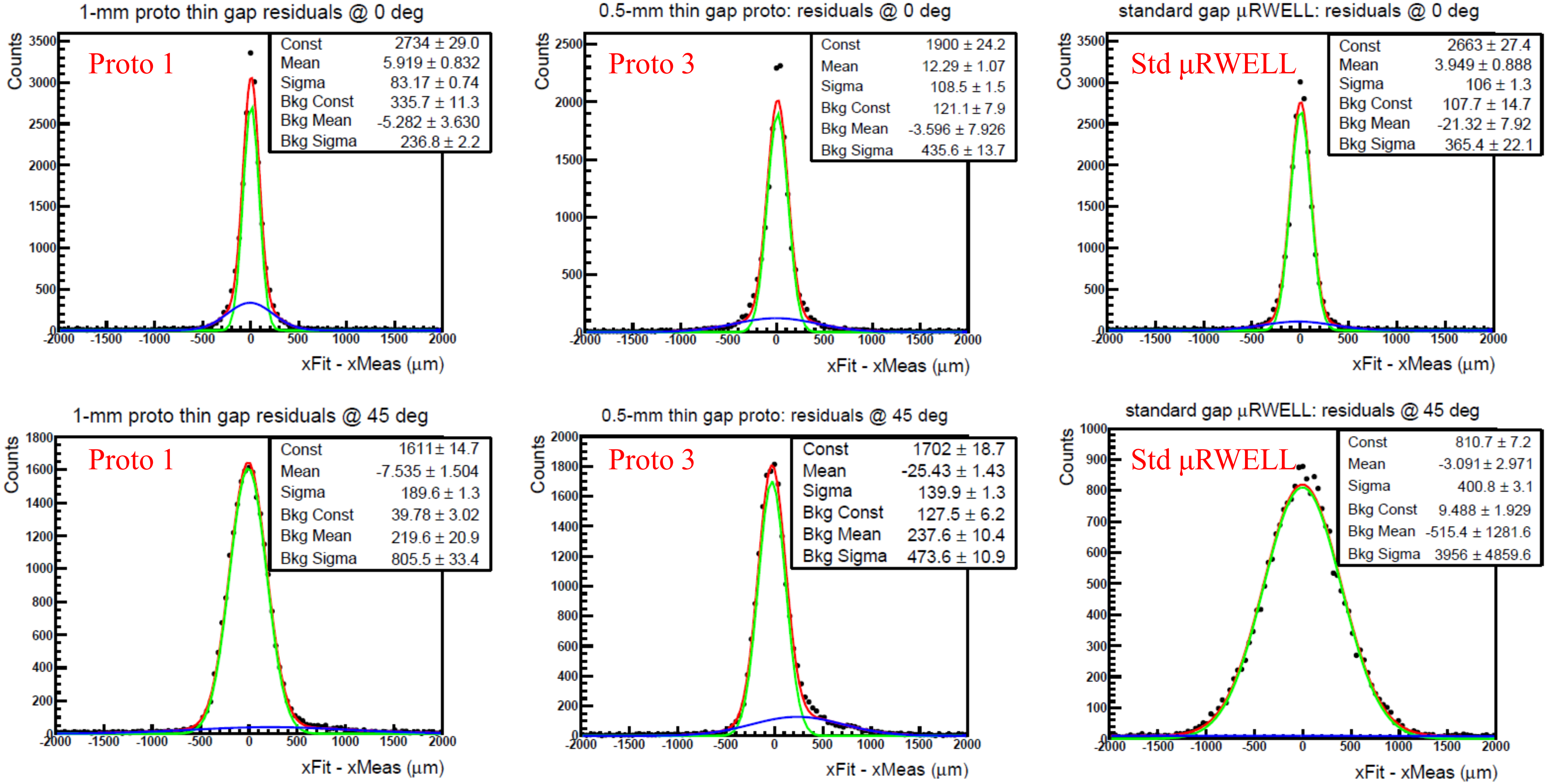






Thin-gap GEM-μRWELL: Position resolutions





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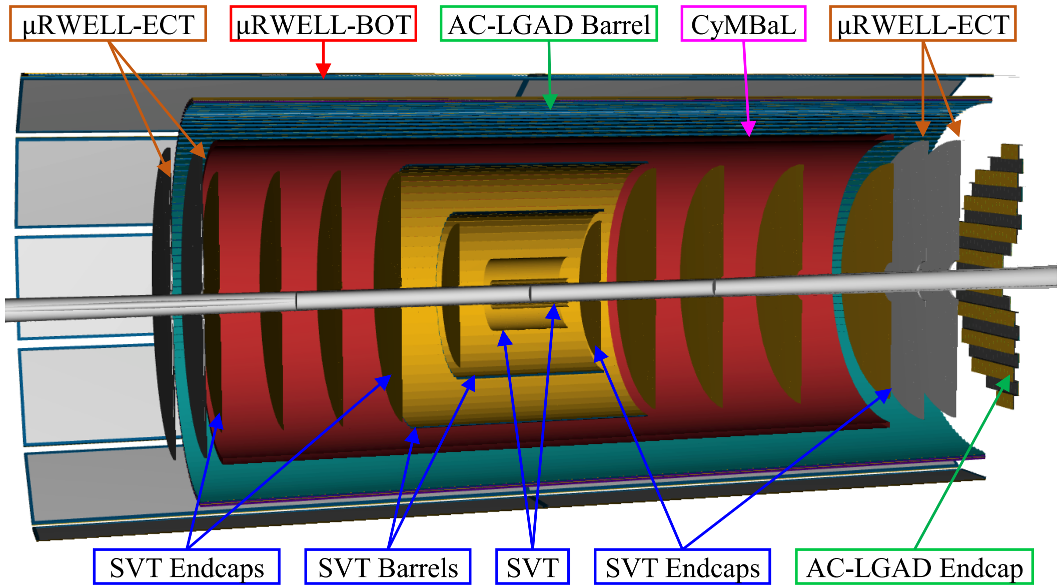
ePIC @ the EIC: µRWELL Barrel Outer Tracker (µRWELL-BOT)

3 MPGD tracking subsystems in ePIC central detector:

- CyMBaL: Barrel Inner Iracker (Cylindrical Micromegas Barrel Layer)
- µRWELL-ECT: End Cap Tracker Disc (GEM-µRWELL hybrid),
- **µRWELL-BOT: Barrel Outer Tracker (Thin-gap GEM-µRWELL)**

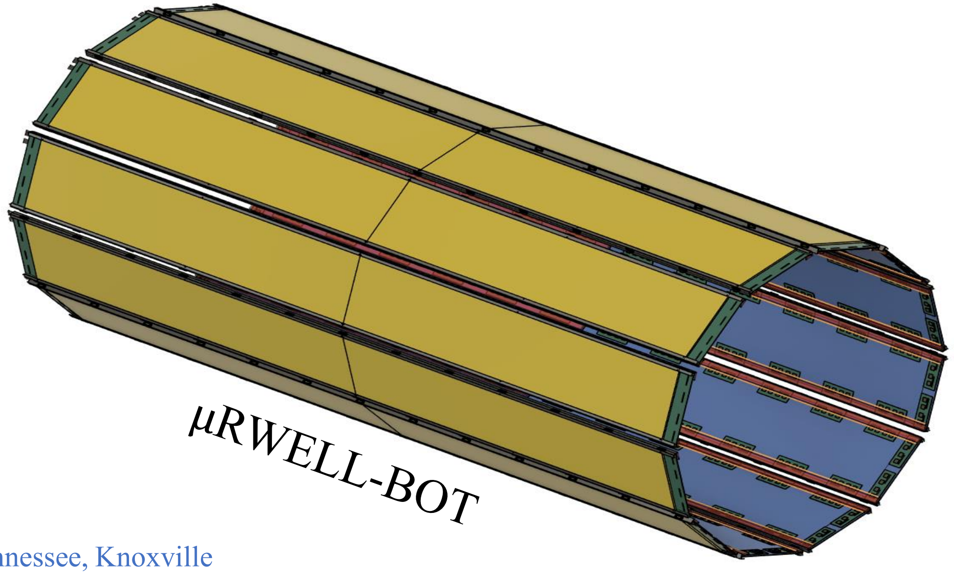


µRWELL -BOT performance requirements:

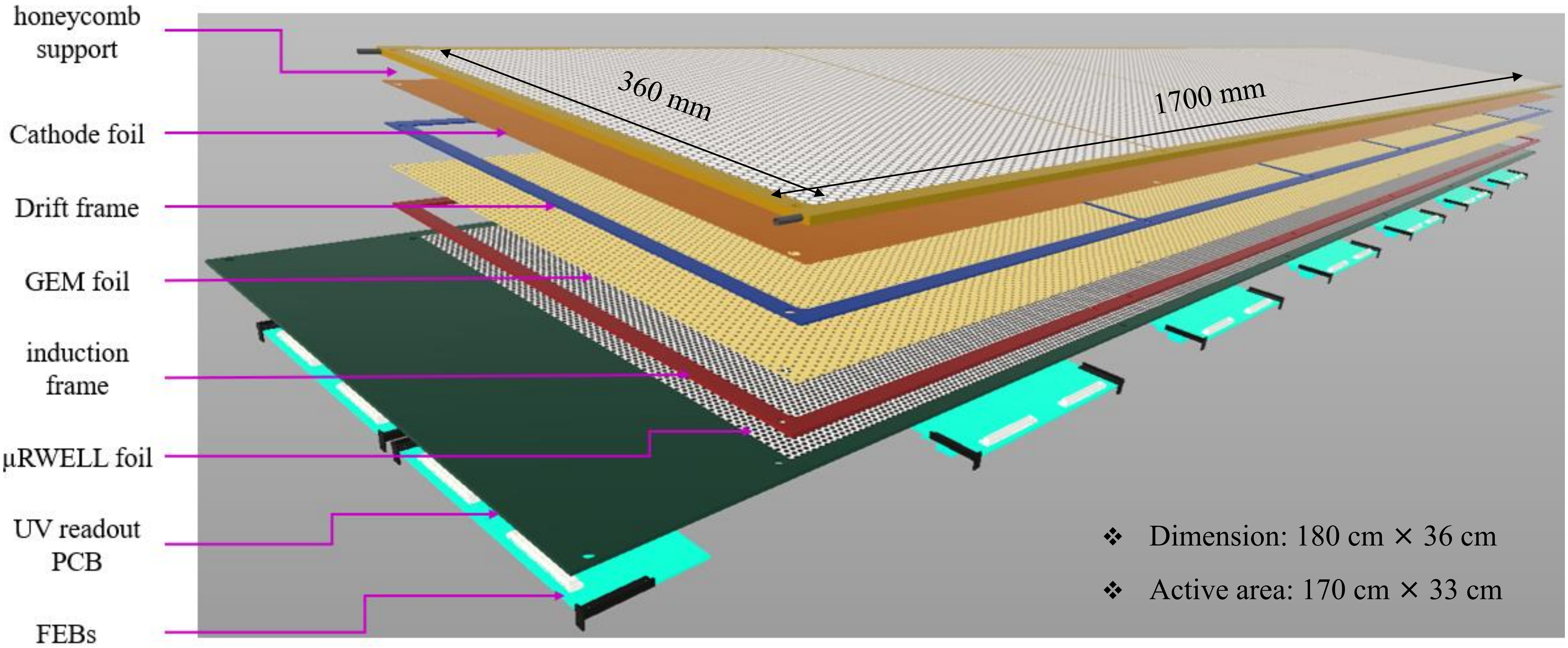
- Fast timing for pattern recognition (~10 ns) time resolution
- Additional hit point to central tracker for redundancy (resolution ~150 µm)
- Good angular resolution for the event reconstruction at the hpDIRC
- Efficiency ≥ 95%
- Material budget ~2% X0

24 planar detector modules:

- 12 sectors in r*φ × 2 modules in z @ R = 72.5 cm
- **Based on Thin-gap GEM-µRWELL hybrid technology**
- ASIC: SALSA (under development @ Saclay): 64 chs
- ~86k readout electronic channels



μRWELL-BOT: Project Engineering Design Test Article



- Dimension: 180 cm × 36 cm
- Active area: 170 cm × 33 cm

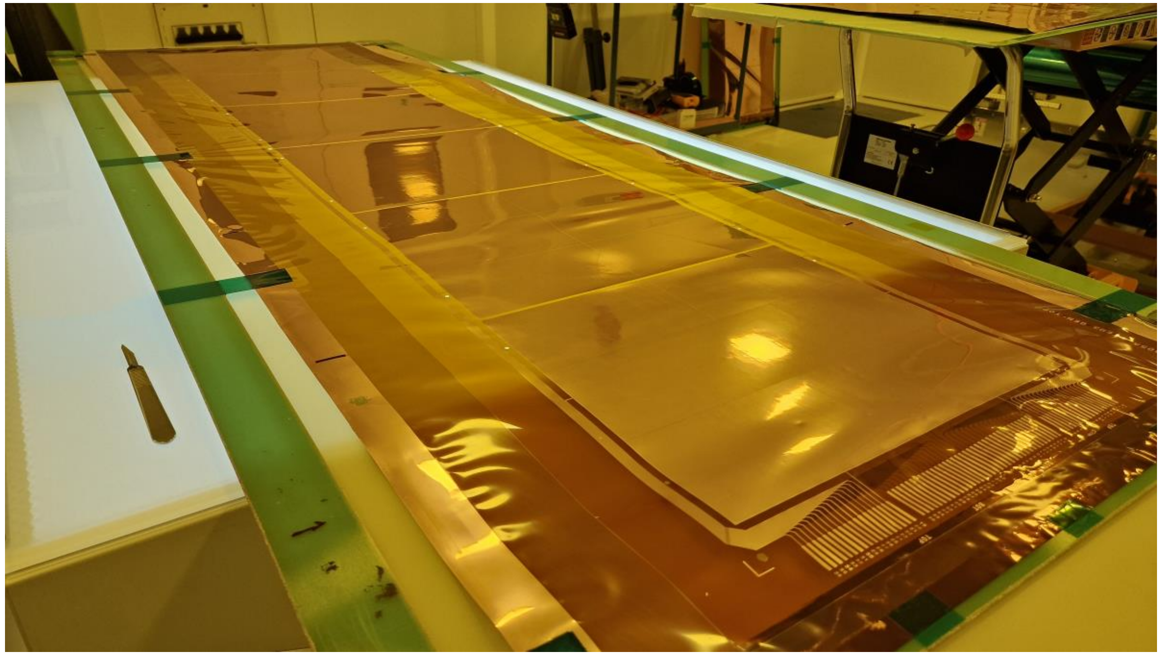
μRWELL-BOT Test Article design

µRWELL-BOT Test Article: Project Engineering Design

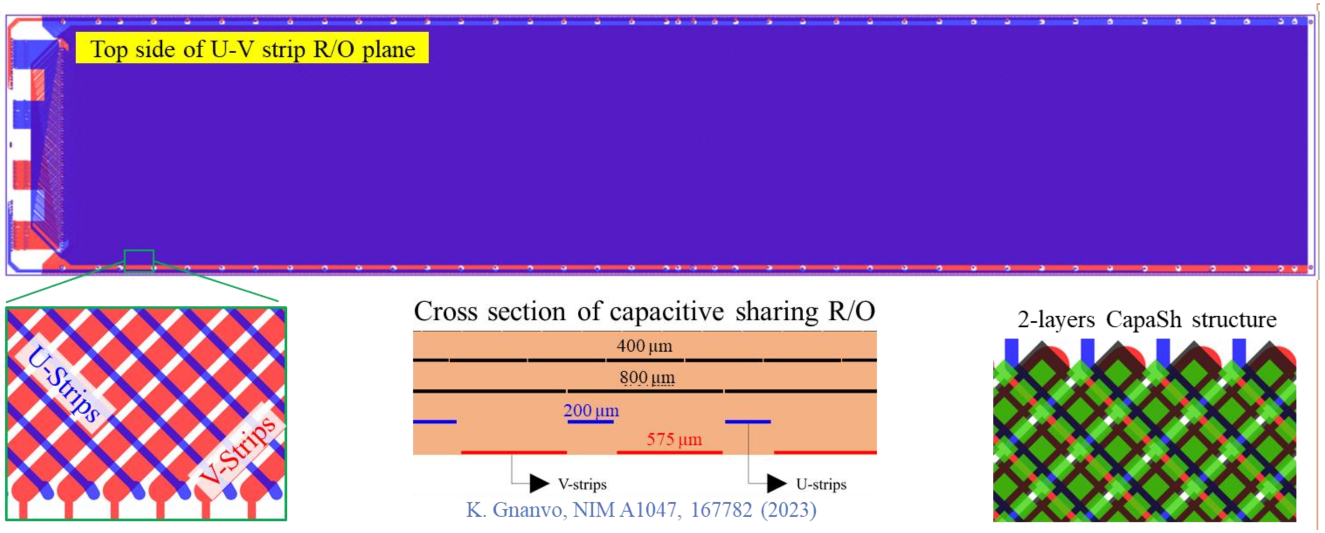
Detector major components are ready

- ❖ GEM foil, µRWELL / CapaSh-X-Y strip readout PCB and detector support frames are all in hand at JLab
- ❖ Clean room infrastructure and equipment at JLab almost complete
- ❖ Assembly start week of Oct.13th ➔ Completed by December 15th
- ❖ Plan to test performance in beam in Spring-Summer 2026
- ❖ Test article validation in 2026 ➔ Pre-production modules in 2027

µRWELL / CapaSh readout PCB: Front view



GEM foil

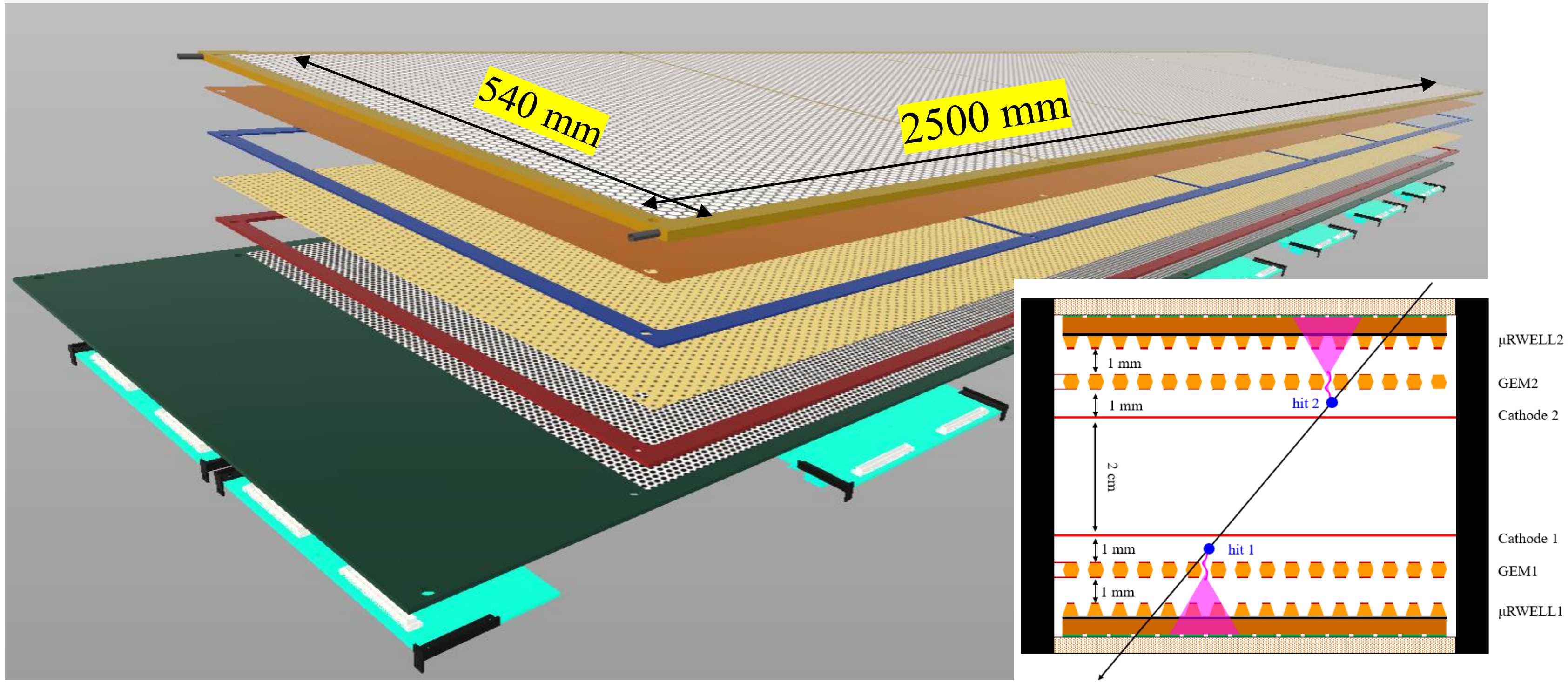


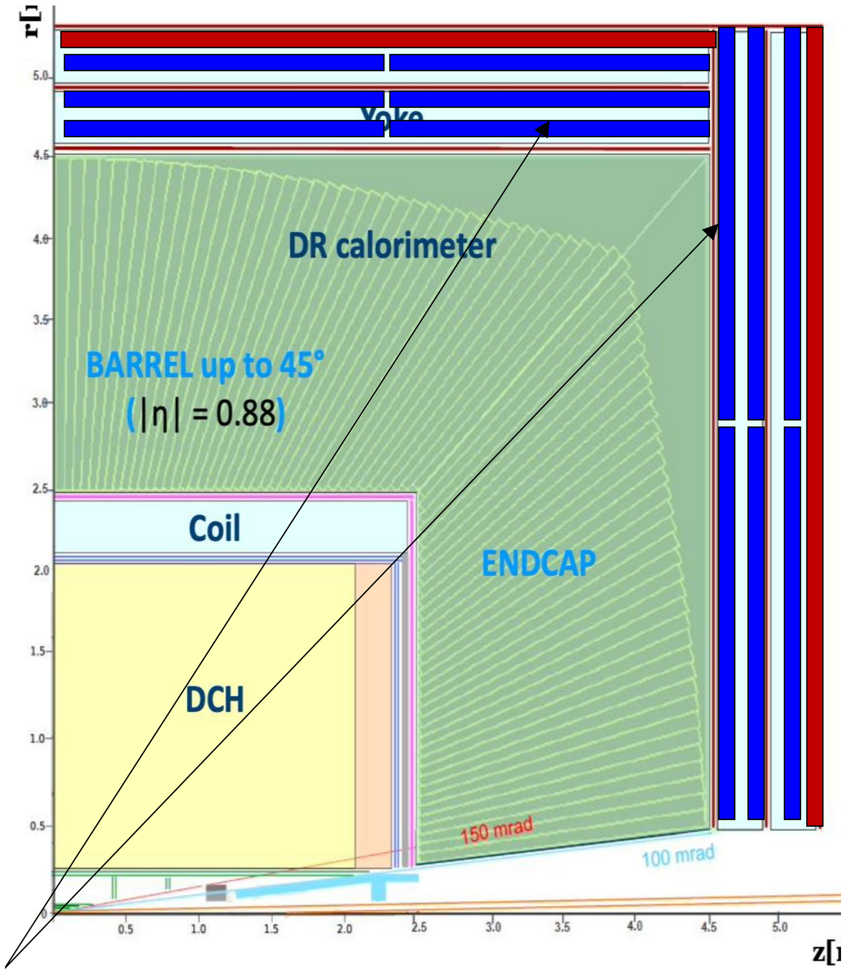
Capacitive sharing readout with X-Y strips @ 45º

Proposal for HFCC Muon Detector: Double-sided thin-gap GEM-µRWELL

IDEA Muon Tracker Technology: Large double-sided thin-gap GEM-µRWELL hybrid

- **Detector layout**: 3 layers @ 5 m from IP ➔ 720 modules, ~3M readout channels
- **Detector module:** Active area: 2500 mm × 540 mm (~2.5 × ePIC µRWELL-BOT area)
- **Double amplification:** GEM + µRWELL ➔ High gain and HV stability
- **Readout:** Capacitive-sharing U-V strips ➔ Low chs count / good spatial resolution
- **Double-sided:** 2-hit points per module ➔ Full efficiency, track reconstruction, redundancy





IDEA Detector concept @ FCC-ee

Thin Gap MPGD Consortium

Dr. Xinzhan Bai, Dr. Kondo Gnanvo, Dr. Seung Joon Lee,

Dr. Sourav Tarafdar

Prof. Marcus Hohlmann, Pietro Iapozzuto

Dr. Huong Nguyen, Prof. Nilanga Liyanage

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contracts DE- AC05-06OR23177

Double-sided Thin-gap GEM-µRWELL Hybrid Detectors

See following talk from Sourav Tarafdar (RDC6 session)

Plans for EIC generic R&D based on MPGD technology

Oct 9, 2025, 11:20 AM
20m
Regent

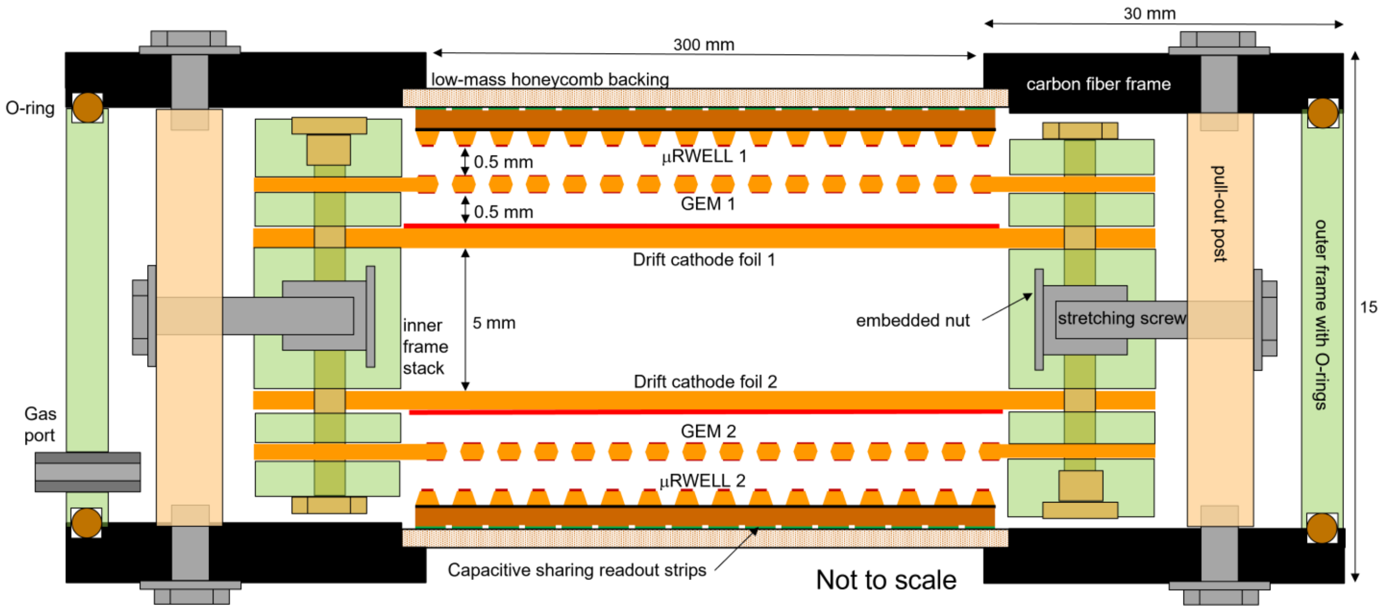
Parallel session talk | RDC 6 Gaseous Det... | RDC 6 Gaseous Detect...

Speaker

Sourav Tarafdar (Jefferson Lab)

Description

The versatility of MPGD technology has drawn tremendous interest in both Nuclear and High Energy Physics communities to use as particle detector in experiments. Particle tracking detectors are integral part of Nuclear Physics experiment and MPGDs has established themselves as reliable tracking detectors due to their moderate material budget, low cost, moderate spatial resolution and relatively easier fabrication as large size detector. Many Nuclear and High Energy experiments including ePIC at EIC has incorporated multiple MPGD technologies as tracking detectors and there is possibility of utilizing same technology either as possible second EIC detector or any future Nuclear and High Energy Physics experiment.
Apart from its role as tracking detector, MPGD technology has also demonstrated excellent timing performance with timing resolution of a few tens of picoseconds. Even it is in early stage of R&D, MPGDs has potential for being an alternate for currently existing technologies for Time-of-Flight Particle Identification Detectors in Nuclear and High Energy Physics experiments. Over the past decade significant progress has been made on this front in terms of optimizing the amplification structure, optimizing gas mixture, improving longevity of photocathode and increasing the active area of the detector itself.
The EIC generic R&D program is focused on advancing cutting edge detector technologies for Nuclear Physics experiment and currently there are focus on advancement of MPGD technology both as tracking detectors and picosecond timing detectors in Nuclear and High Energy Physics experiments. This presentation will focus on overview of various ongoing R&Ds using MPGD technology under EIC generic R&D program.



Summary

❖ Thin Gap MPGD is a new approach to improve spatial and timing resolution of Micro pattern Gaseous Detectors and achieved better than 150 um in a wide range of the impact angle of the incoming particle

❖ The development of thin gap prototypes and performance studies in beam test demonstrate that spatial resolution improvement by a factor two is achieved at 45O particle angle compared to standard MPGD

❖ Thin-gap GEM- µRWELL hybrid prototypes with GEM pre-amplification and µRWELL as second amplification coupled with capacitive-sharing readout structures show excellent efficiency and spatial resolution capabilities

❖ Recent test beam results show that efficiency of 96% and 98% could be achieved with 1-mm gap and 1.5 mm gap thin gap GEM-µRWELL hybrid detectors with $Ar:CO_2:iC4H_{10}$ (90:7:5=3) gas mixture

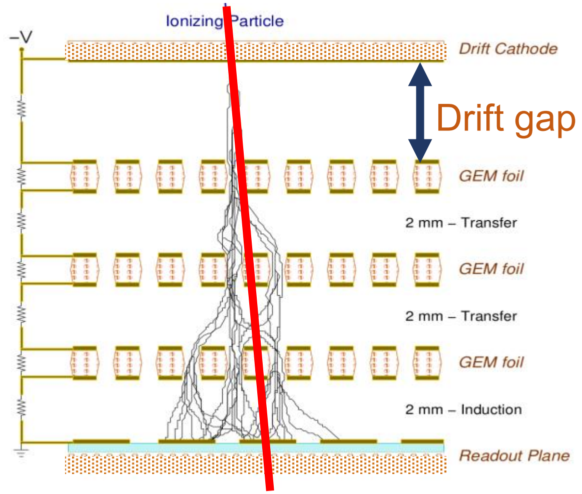
❖ Large thin-gap GEM- µRWELL hybrid is the chosen technology for the barrel outer tracker of the ePIC detector at the EIC

❖ The technology is an ideal candidate for the muon tracking system for the future HFCC detector

Back-up

Thin-gap Triple GEM prototypes @ UVa

Structure of UVA Triple GEM Prototypes

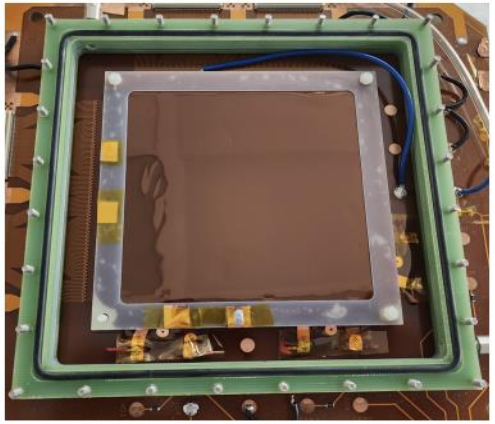


	Cathode	Drift Gap	Tested at FNAL in June 2023
Proto I	Copper-Kapton foil	1.0 mm	ArCO2, HV & Angle Scan
Proto II	Copper-Kapton foil	1.5 mm	ArCO2 & KrCO2, HV & Angle Scan
Proto III	Copper-Kapton foil	3.0 mm	ArCO2, Angle Scan
Proto IV	400 µm-pitch fine Copper wire	1.5 mm	ArCO2, HV & Angle Scan
Proto V	800 µm-pitch fine Copper wire	1.5 mm	ArCO2, HV & Angle Scan

❖ **<u>UVA Tripple GEM Prototypes</u>:**

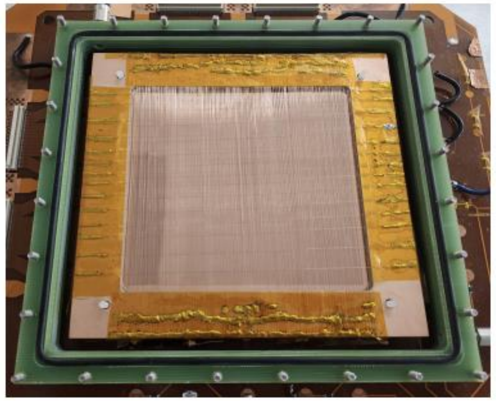
- Amplification: 3 GEM foils
- RO plane: 400 µm-pitch X-Y strips
- Three prototypes having different drift gaps (1.0 mm, 1.5 mm, 3.0 mm), the same cathode
- Three prototypes having different Cathode structures, the same drift gap (1.5 mm)

(a) Copper-Kapton Cathode



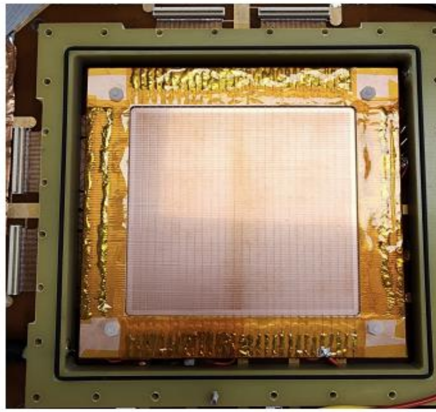
(a)

(b) 400 µm wire-pitch cathode



(b)

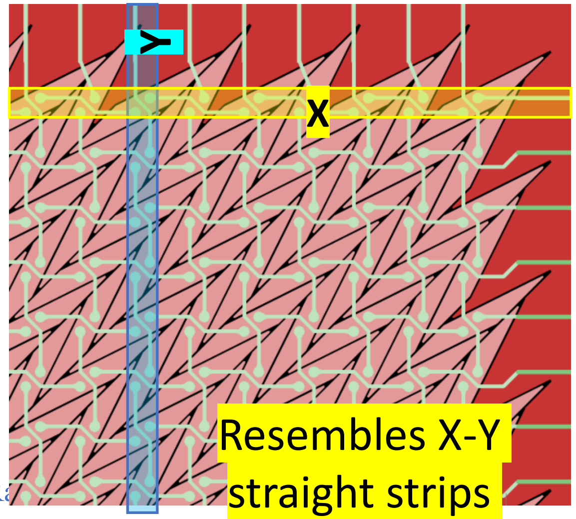
(c) 800 µm wire-pitch cathode

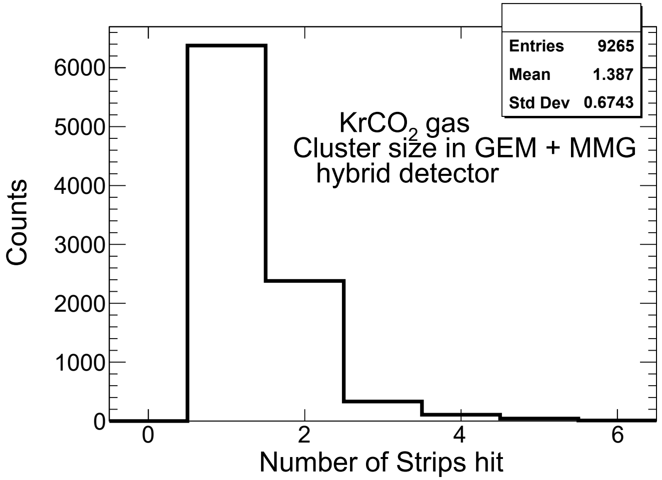


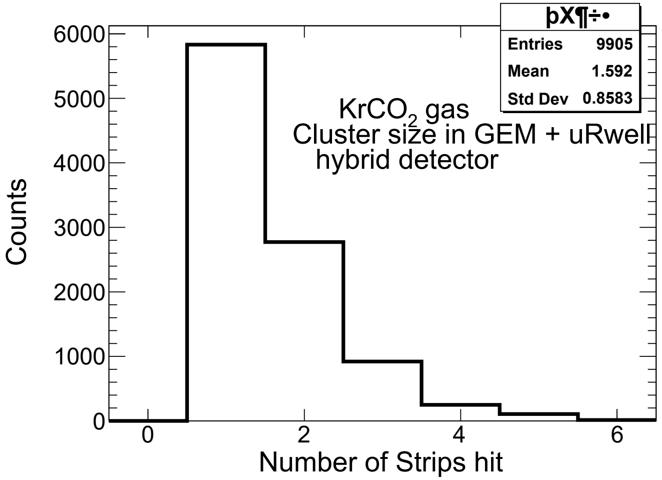
(c)

Thin-gap GEM-Micromegas Hybrid prototypes @ Vanderbilt U.

Prototypes	Specifications	Data taken (Fermilab test beam)
GEM +MMG	• Active area = 10 cm x10 cm • Drift gap = 1 mm • Transfer gap = 1 mmm • 2D chevron R/O with 1.6 mm pitch	• ArCO2 gas (HV scan + track angle scan) • KrCO2 gas (HV scan + track angle scan)
GEM + µRWELL	• Active area = 10 cm x10 cm • Drift gap = 1 mm • Transfer gap = 0.5 mm • 2D chevron R/O with 1.6 mm pitch	• ArCO2 gas (HV scan + track angle scan) • KrCO2 gas (HV scan + track angle scan)
µRWELL	• Active area = 10 cm x10 cm • Drift gap = 1 mm • 2D chevron R/O with 1.6 mm pitch	No data taken

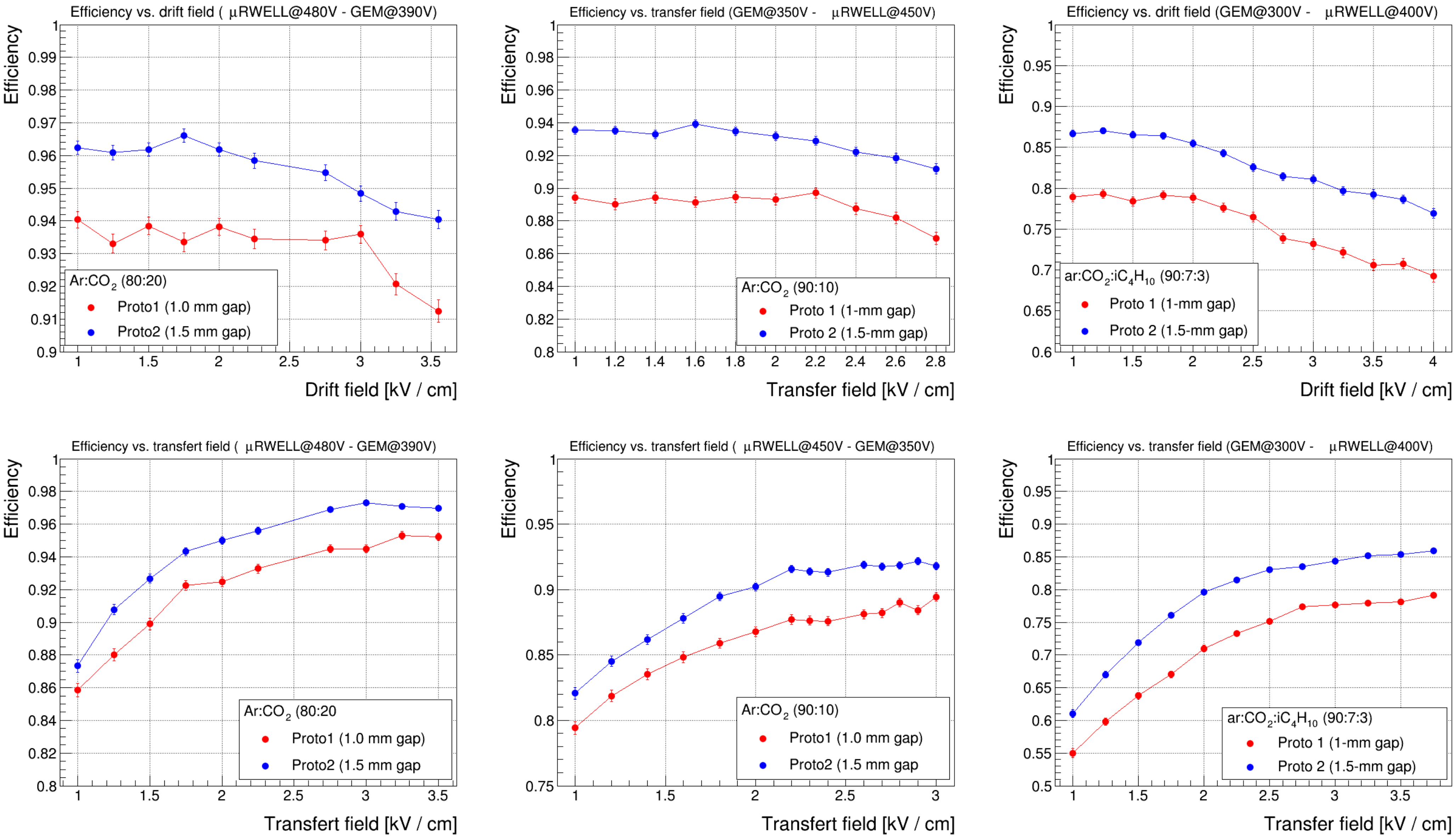






- Mostly single strips are getting fired most of the time
- Challenging to decipher hot channel with real hit
- Ongoing analysis

Thin-gap GEM-µRWELLs: Performance with various gases



The ePIC Detector @ the Electron Ion Collider (EIC)

EIC is the flagship Nuclear Physics (NP) Facility in the US (2031+)

- **High Luminosity:** L= 10^{33} – 10^{34} $cm^{-2}sec^{-1}$, 10 – 100 fb^{-1}/year
- **Highly Polarized Beams:** 70%
- **Large Center of Mass Energy Range:** E_{cm} = 20 – 140 GeV
- **Large Ion Species Range:** Protons – Uranium
- **Particle production rate:** ~5 @ 500 kHz
- **ePIC Detector:** Large Acceptance and Good Background Conditions

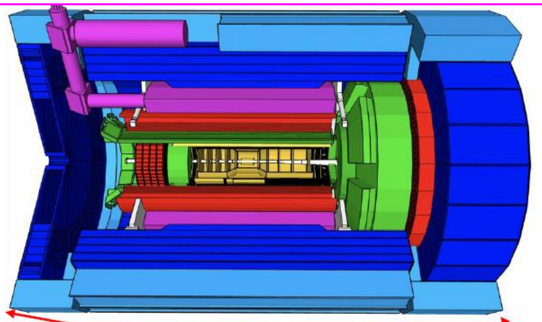
Vertexing and Tracking:
- Silicon Vertex Tracker (MAPS)
- MPGD (µRWELL/µMegas)

Particle Identification:
- TOF (AC-LGAD also for tracking)
- pfRICH (Aerogel/HRPPD)
- hpDIRC (Quartz/MCP-PMT)
- dRICH (Aerogel+C_2F_6/MCP-PMT)

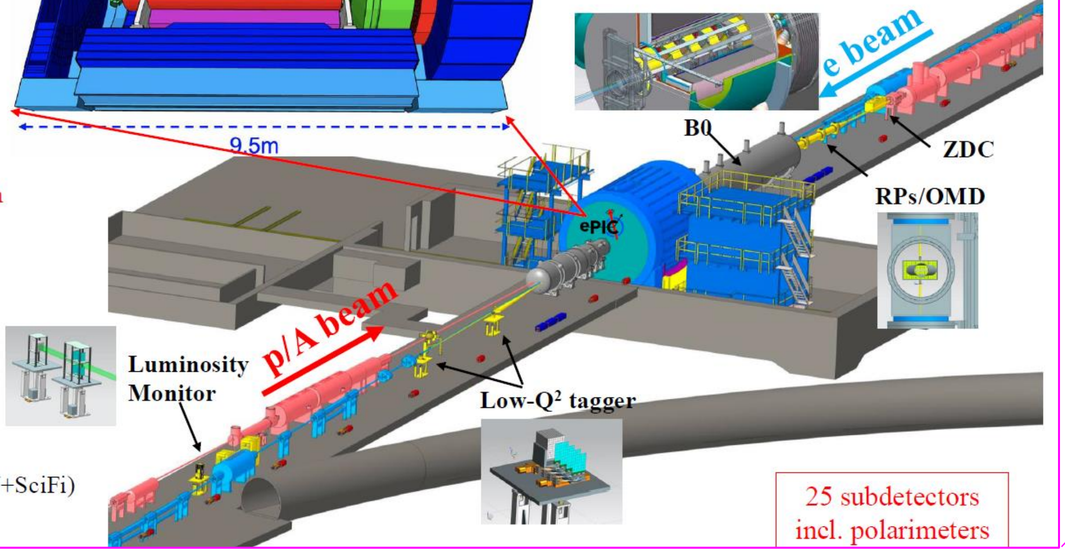
EM Calorimeters:
- EEMCal ($PbWO_4$/SiPM)
- Barrel EMCal (Pb+SciFi/SiPM) with imaging layers (Pb+SciFi/AstroPix)
- FEMC (W+SciFi)

Hadronic Calorimeters:
- Backward HCAL (Fe+Sc/SiPM)
- Barrel HCal (sPHENIX re-use)
- LFHCAL (Fe+Sc&W+Sc/SiPM)

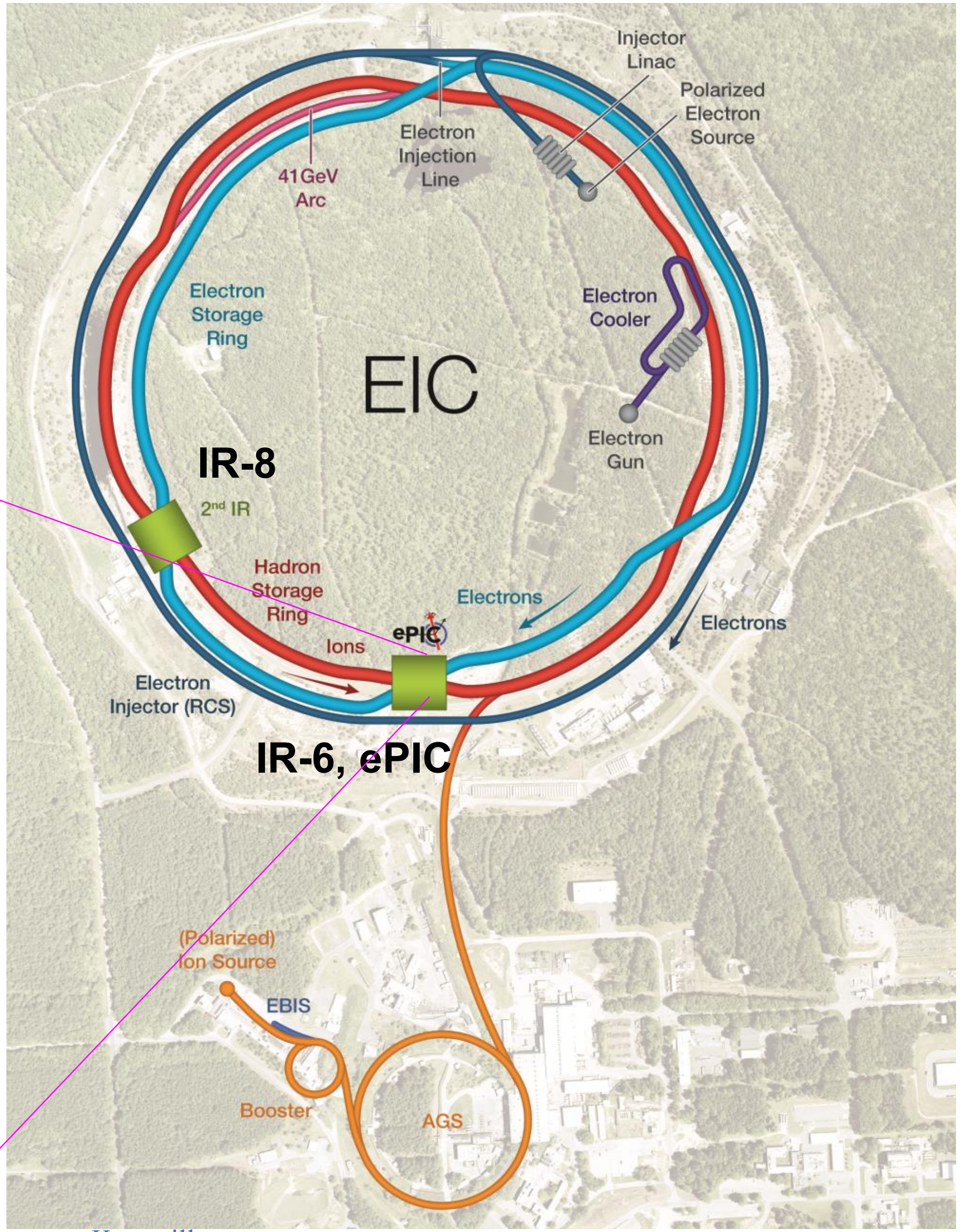
Far-Backward:
- Luminosity monitor (AC-LGAD, W+SciFi)
- Low-Q^2 tagger (Si/Timepix4)



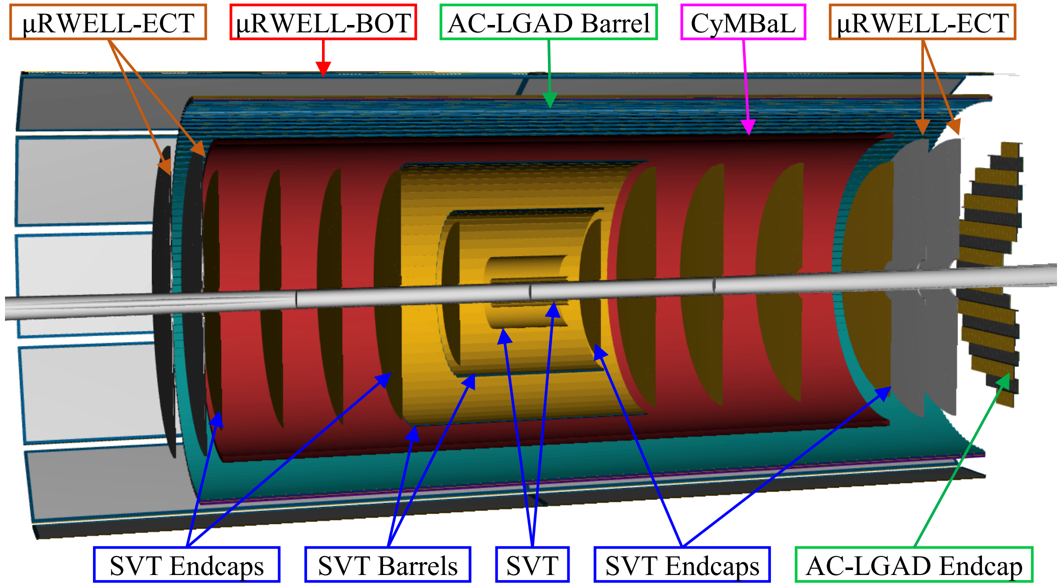
Far-Forward:
- Roman Pots (AC-LGAD)
- B0 Magnet Spectrometer (AC-LGAD, $PbWO_4$)
- Off-Momentum Detector (AC-LGAD)
- Zero Degree Calorimeter ($PbWO_4$, Fe/SiPM)



25 subdetectors incl. polarimeters



ePIC Central Tracking Detectors - Requirements & Performances



Silicon Vertex Tracker (SVT): ~6 µm point resolution

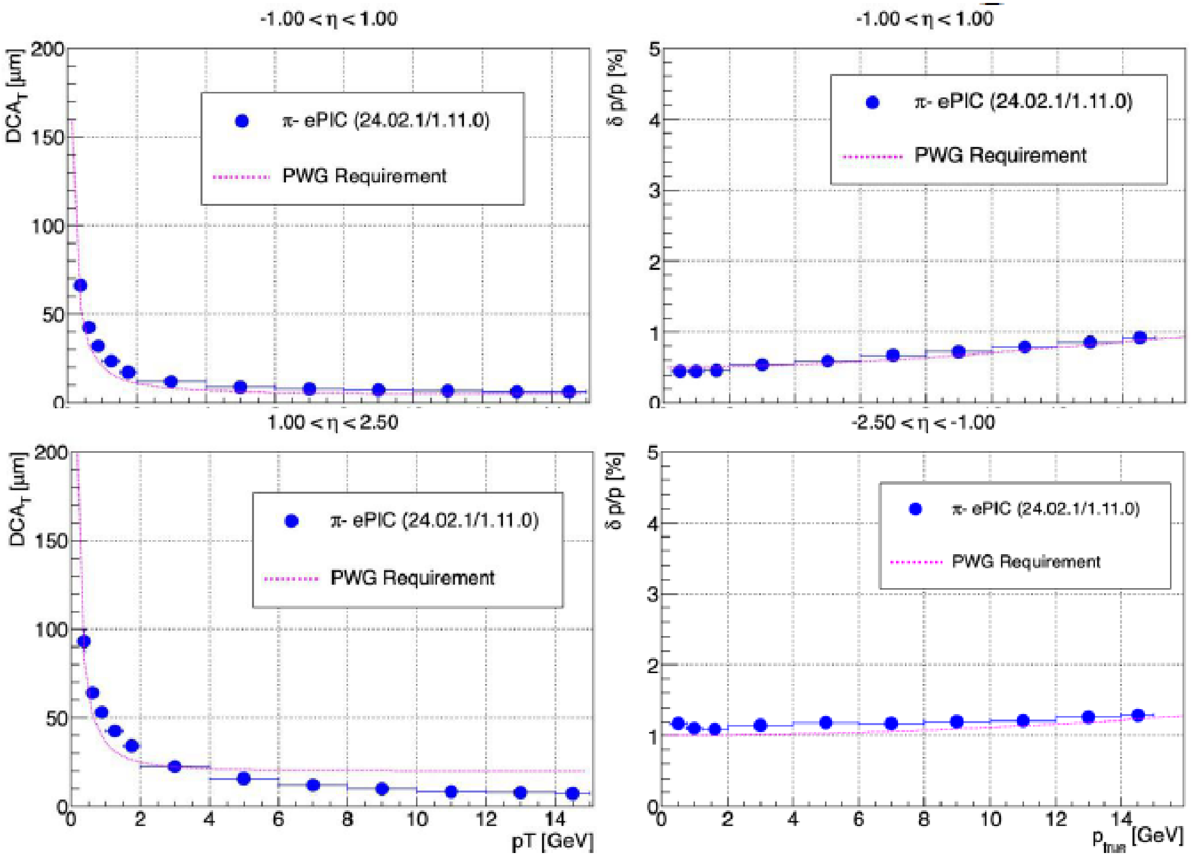
- 3 inner barrels: ITS3-curved wafer-scale sensor, 0.05% X/X0
- 2 outer barrels: ITS3-based sensors (EIC-LAS), 0.25/0.55% X/X0
- 5 disks (forward/backward), EIC-LAS, 0.25% X/X0

Micro Pattern Gaseous Detectors (MPGD): 10 ns & 150 µm resolutions

- **2 × 2 End cap disks:** GEM-µRWELL hybrid detectors
- **One inner barrel layer:** Cylindrical Micromegas
- **One outer barrel layer:** Thin-gap GEM-µRWELL hybrid detectors

AC-coupled LGAD TOF: 30 µm + 30 ps resolutions

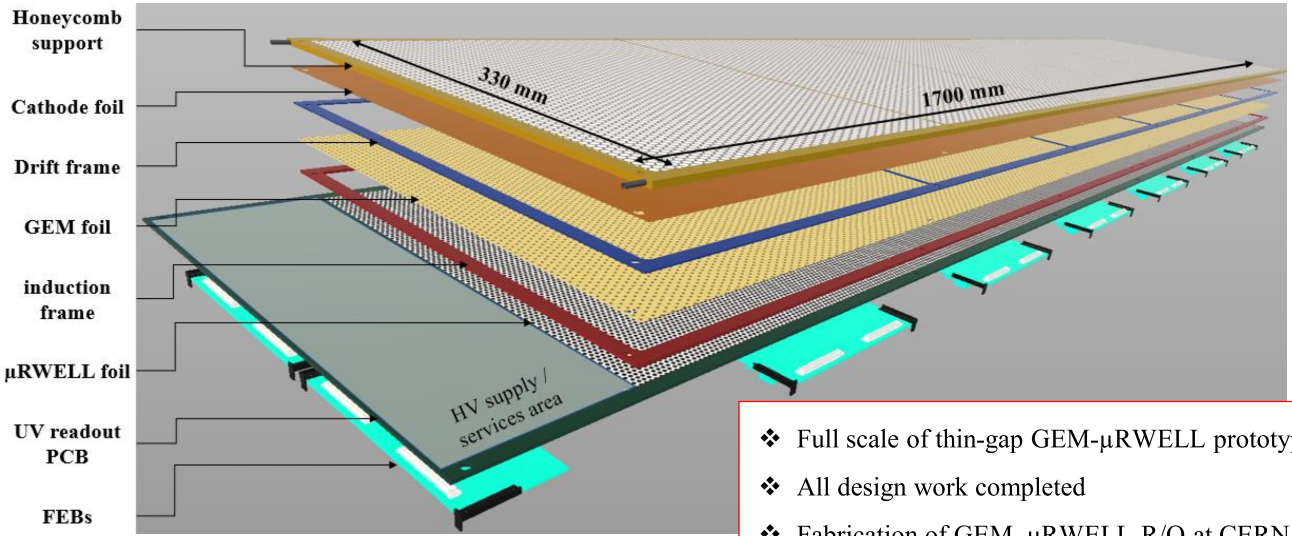
- Barrel TOF: 0.05 x 1 cm strip, 1% X/X0
- Forward TOF: 0.05 x 0.05 cm pixel, 5% X/X0



Rapidity Range	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	$\sim 0.10\% \times p \oplus 2.0\%$	$\sim 30/pT\ \mu m \oplus 40 \mu m$
Backward (-2.5 to -1.0)	$\sim 0.05\% \times p \oplus 1.0\%$	$\sim 30/pT\ \mu m \oplus 20 \mu m$
Barrel (-1.0 to 1.0)	$\sim 0.05\% \times p \oplus 0.5\%$	$\sim 20/pT\ \mu m \oplus 5 \mu m$
Forward (1.0 to 2.5)	$\sim 0.05\% \times p \oplus 1.0\%$	$\sim 30/pT\ \mu m \oplus 20 \mu m$
Forward (2.5 to 3.5)	$\sim 0.10\% \times p \oplus 2.0\%$	$\sim 30/pT\ \mu m \oplus 40 \mu m$

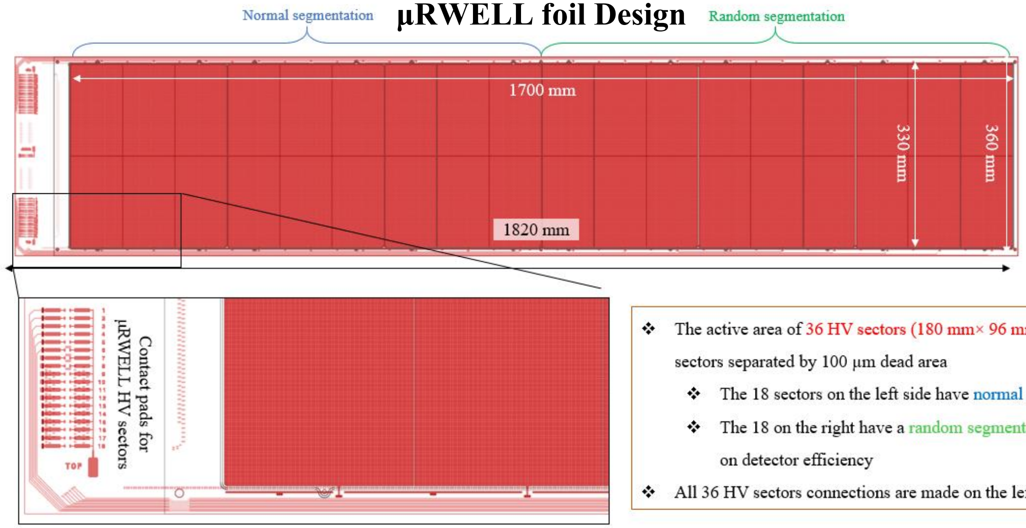
µRWELL-BOT module: Design of full scale engineering test article

CAD design of thin-gap GEM-µRWELL engineering test article



- Full scale of thin-gap GEM-µRWELL prototype
- All design work completed
- Fabrication of GEM, µRWELL-R/O at CERN
- Assembly and test at JLab ➔ second half off 2025

µRWELL foil Design



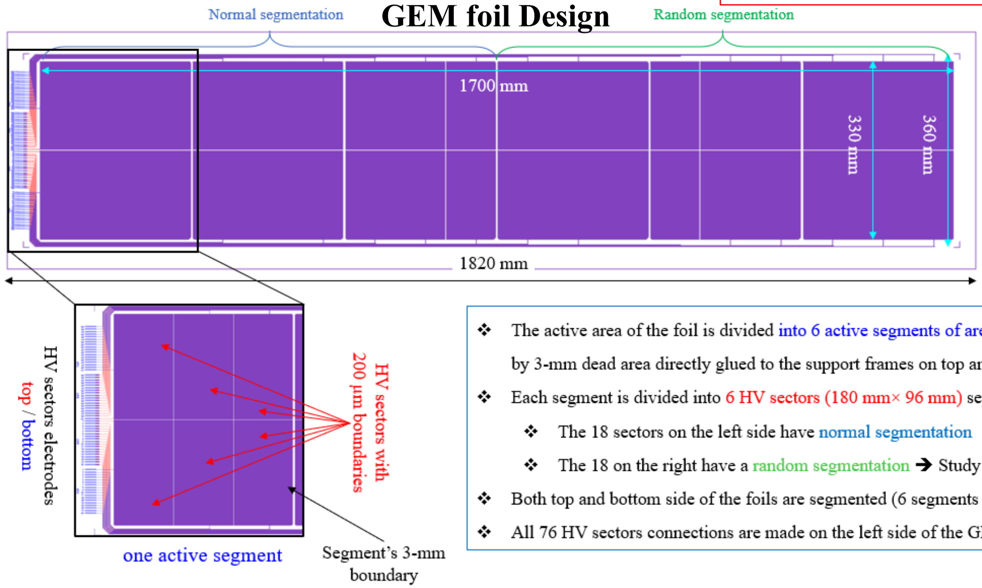
Two of the 36 µRWELL sectors

µRWELL dimension

- **Overall:** 1820 mm × 360 mm
- **Active area:** 1700 mm x 330 mm

- The active area of 36 HV sectors (180 mm× 96 mm) similar to the HV sectors separated by 100 µm dead area
  - The 18 sectors on the left side have normal segmentation
  - The 18 on the right have a random segmentation ➔ Study impact on detector efficiency
- All 36 HV sectors connections are made on the left side of the GEM foil

GEM foil Design

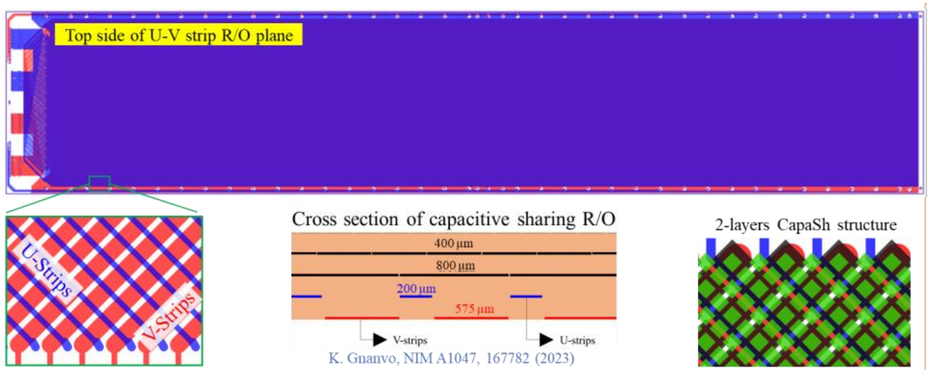


Foil dimension

- Total: 1820 mm × 360 mm
- Active area: 1700 mm x 330 mm

- The active area of the foil is divided into 6 active segments of area 330 mm × 283 mm separated by 3-mm dead area directly glued to the support frames on top and bottom
- Each segment is divided into 6 HV sectors (180 mm× 96 mm) separated by 100 µm dead area
  - The 18 sectors on the left side have normal segmentation
  - The 18 on the right have a random segmentation ➔ Study impact on detector efficiency
- Both top and bottom side of the foils are segmented (6 segments of 6 HV sectors each)
- All 76 HV sectors connections are made on the left side of the GEM foil

Capacitive-sharing U/V strip readout plane Design

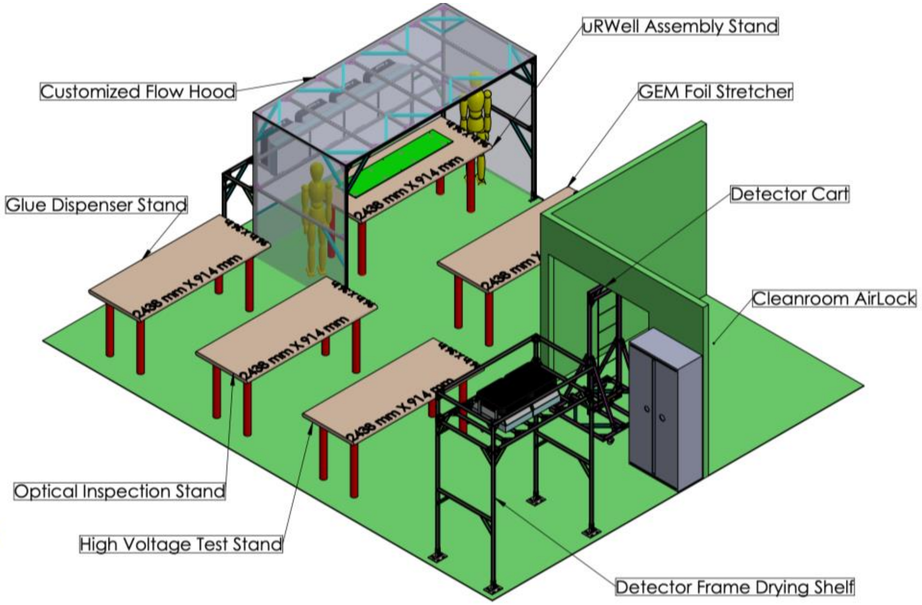


μRWELL-BOT: Clean room & assembly equipment @ JLab

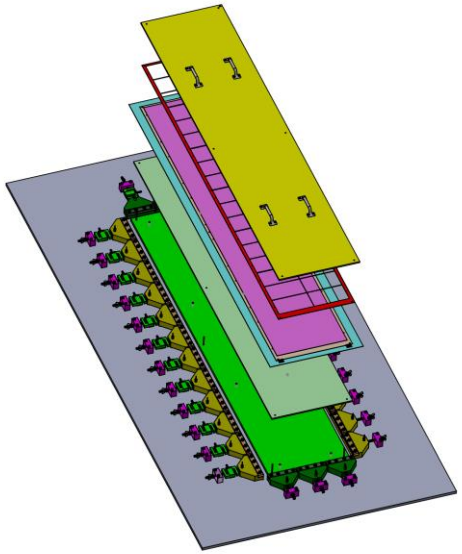
MPGD Cleanroom in JLab Room EEL121

- Major instruments order delivered (Ultrasonic bath, Optical microscopes)
- Major instruments order placed
  - Fume Hood ➔ purchase requisition in JLab procurement system
  - Instruments manufacturing job submitted to JLab machine shop

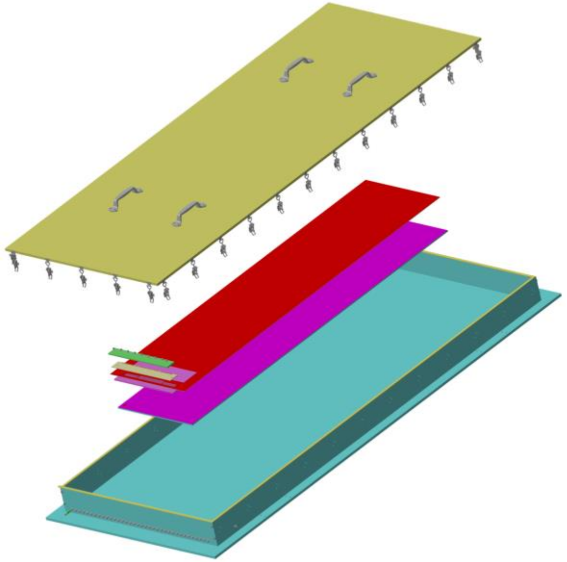
Cleanroom layout with main equipment & instrumentation



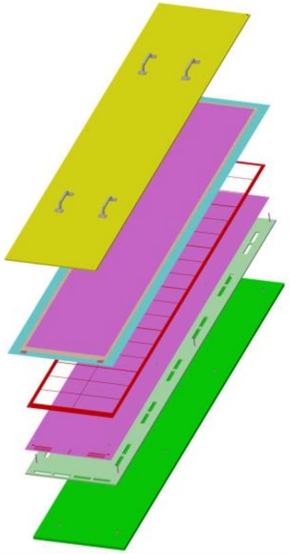
Under fabrication in machine shop @ JLab



GEM Stretcher

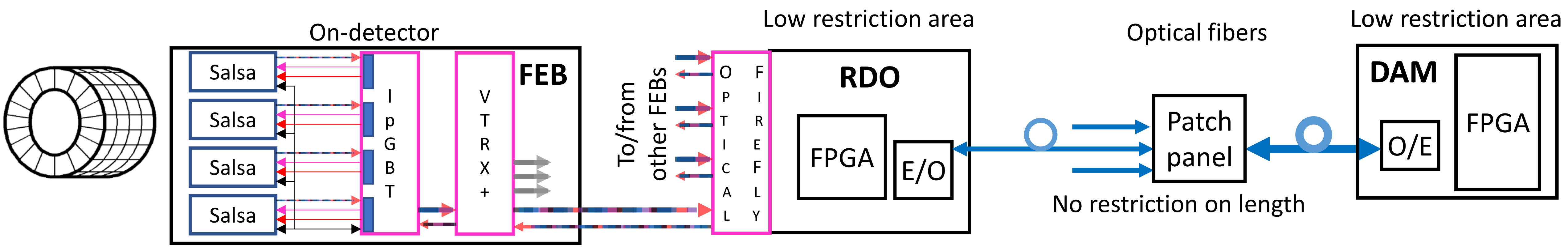


N2 box for HV Test



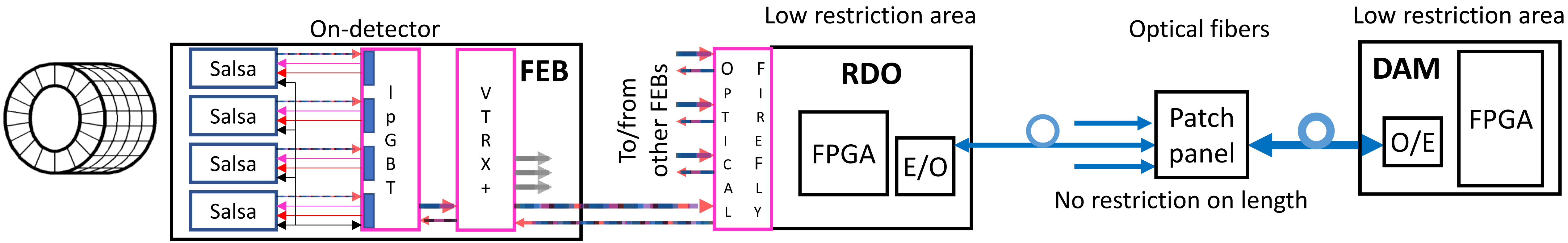
Assembly Stand

SALSA Electronics: Front end board (FEBs) + Optical links



- FEB – frontend board with readout ASICs
  → Sub-detector specific
- RDO – readout module – first stage of FEB data aggregation, last stage to dispatch clock & control
  → Common design between sub-detectors, different form factor
- DAM – data aggregation module – interface with computing and global timing and control unit (GTU)
  → Common design for all sub-detectors
- Downstream towards detector : clock, control, monitoring
- Upstream towards storage : physics, calibration, monitoring data

SALSA Electronics: Front end board (FEBs) + Optical links



256-channel FEB: On-detector Front End Board (4 SALSA ASICs)

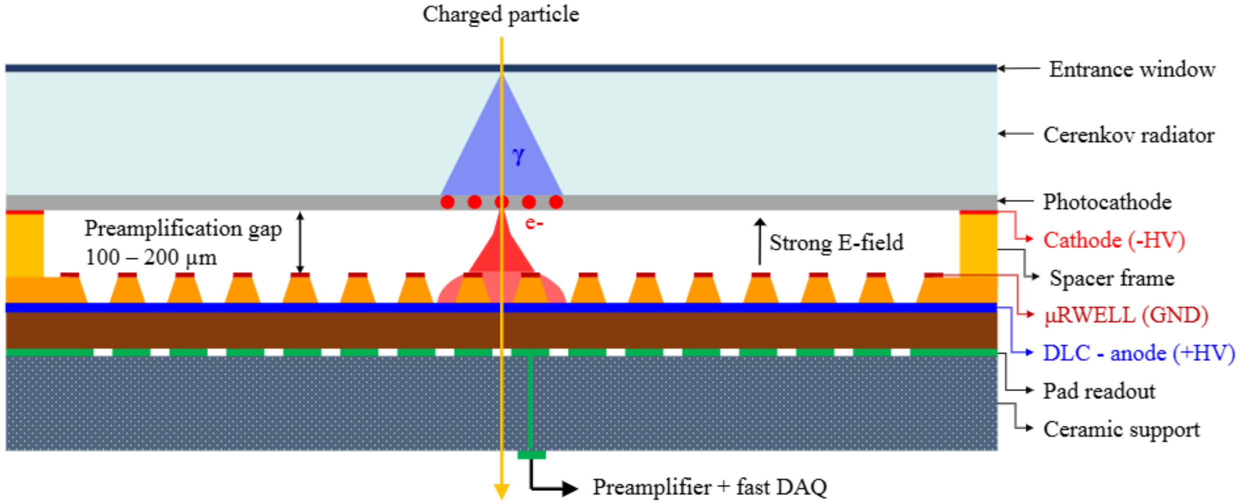
- SALSA receives recovered clock and sync data from an lpGBT eLink group
- SALSA sends physics, calibration and monitoring data to a number of lpGBT lines of the eLink group
- SALSA's are configured over daisy chained I2C interface from lpGBT
- lpGBT provide a bidirectional interface between 4 Salsas and remote FPGA on RDO
- VTRX+ is used with only one T_X line
- All ASICs are radiation hard

1024-channel RDO : common hardware with adaptation based on FireFly transceivers from Samtec

- Single 4-lane bidirectional FireFly is enough to serve 4 FEBs
  - Placed anywhere in user friendly area
- No particular restrictions on power consumption, cooling infrastructure, radiation, magnetic field

Proposal for FCC-ee Muon Detector: Twin Thin-Gap GEM-µRWELL

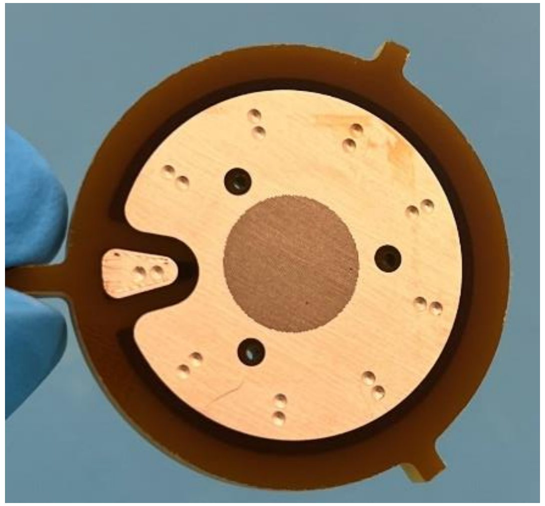
Concept: **µRWELL-PICOSEC detector (MPGD with Cherenkov radiator)**

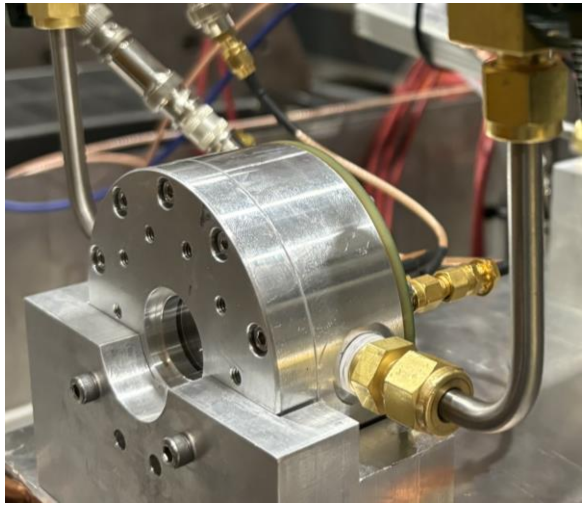


R&D Goals

- Fast timing detector (picosecond) based on µRWELL) technology.
- For application of Time-Of-Flight (TOF) detector for PID
- PID upgrades @ JLab, EIC detectors upgrade, medical field

https://indico.phy.ornl.gov/event/510/contributions/2248/attachments/1787/4116/20241120_CPAD_Knoxville_PICOSEC_KG.pdf





single-pads µRWELL-PICOSEC prototype

Timing resolution of single pad prototype