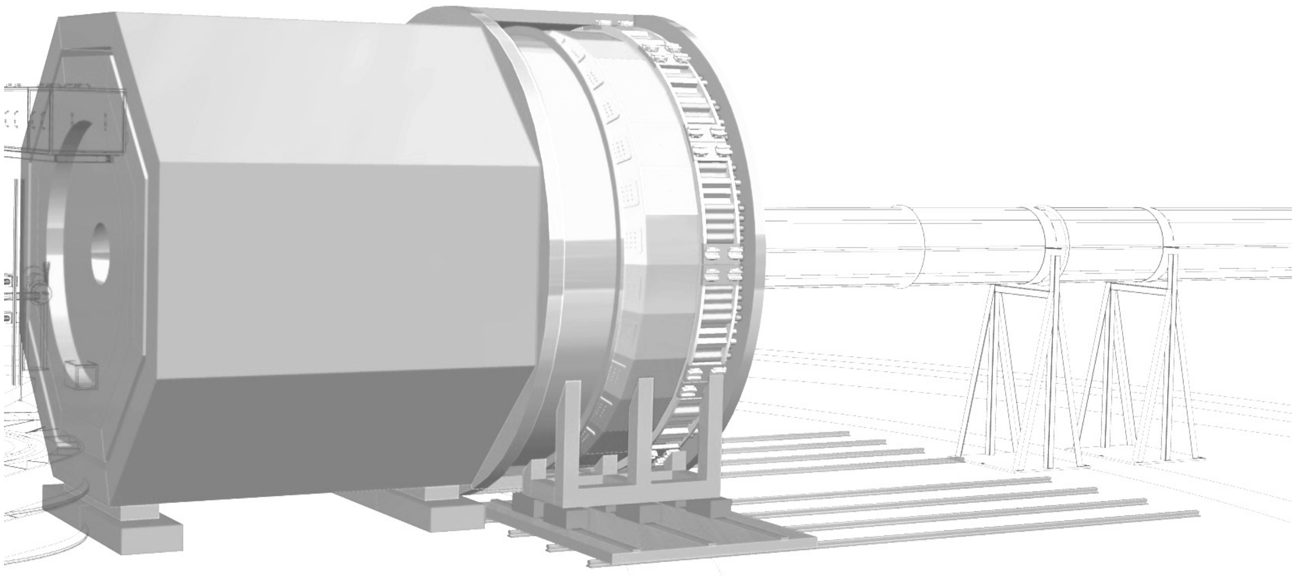
Gas Electron Multiplier (GEM) Tracker



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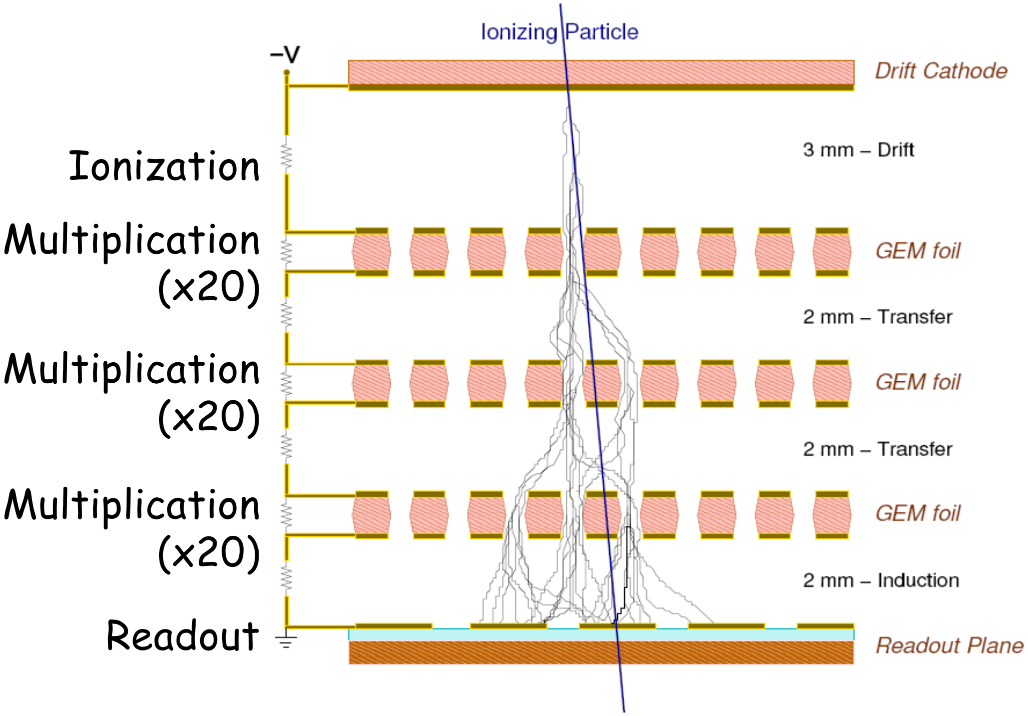
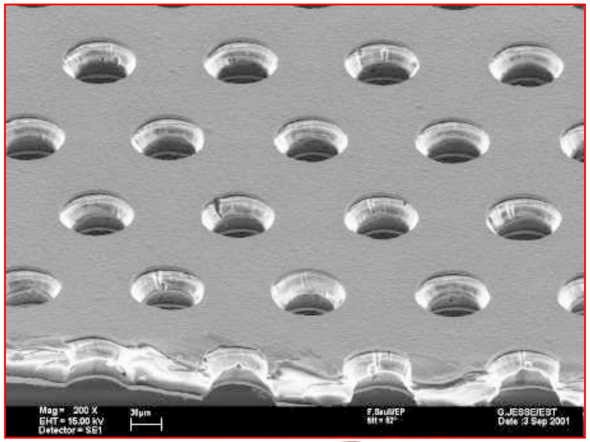
SoLID GEM Group
University of Virginia

Why GEMs

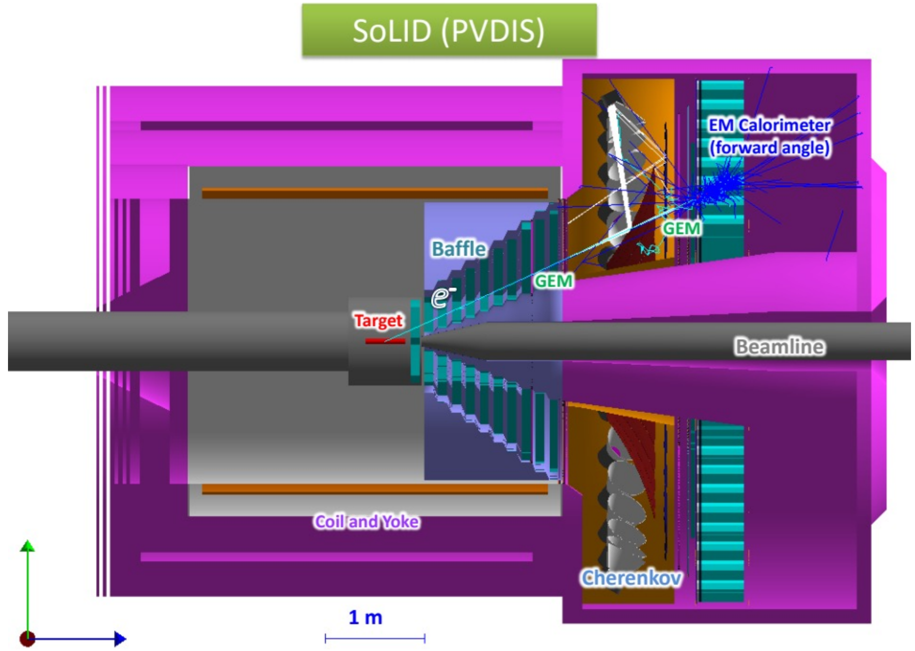
- SoLID concept leads to need for high rate trackers with good position resolution.
- GEMs: cost effective for high resolution tracking under high rates over large areas.
  - Rate capabilities higher than many MHz/cm^2
  - High position resolution (< 75 μm)
  - Ability to cover very large areas (10s – 100s of m^2) at modest cost.
  - Low thickness (~ 0.5% radiation length)
- Used for many experiments around the world: COMPASS, CMS upgrade, ALICE TPC, pRad, **SBS** etc.

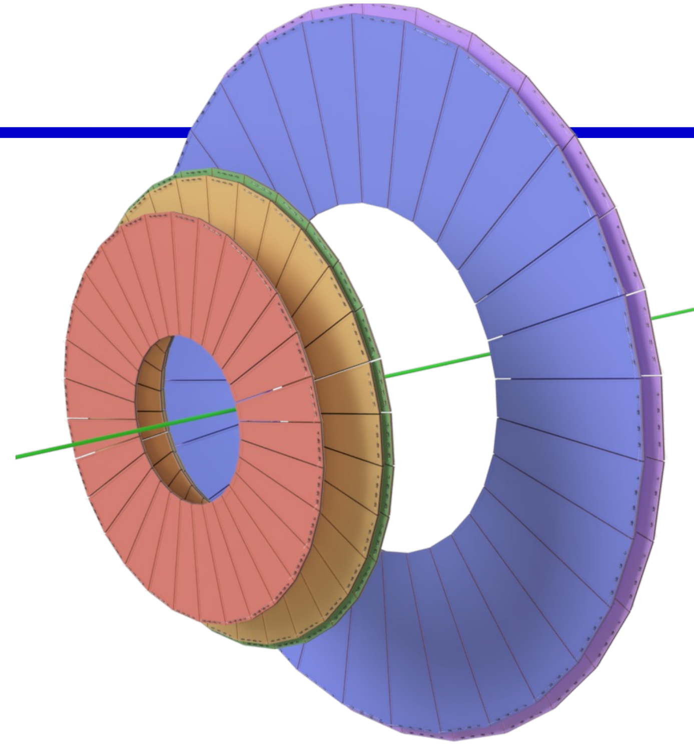


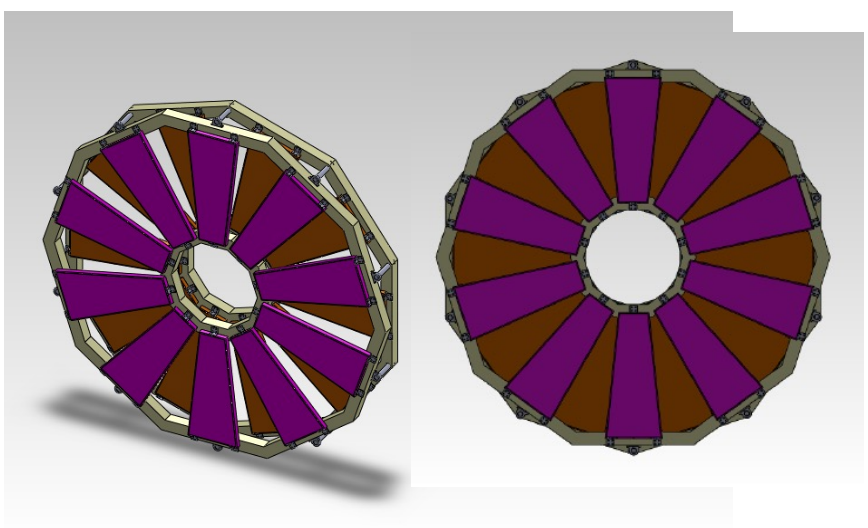
GEM foil: 50 μm Kapton + few μm copper on both sides with 70 μm holes, 140 μm pitch

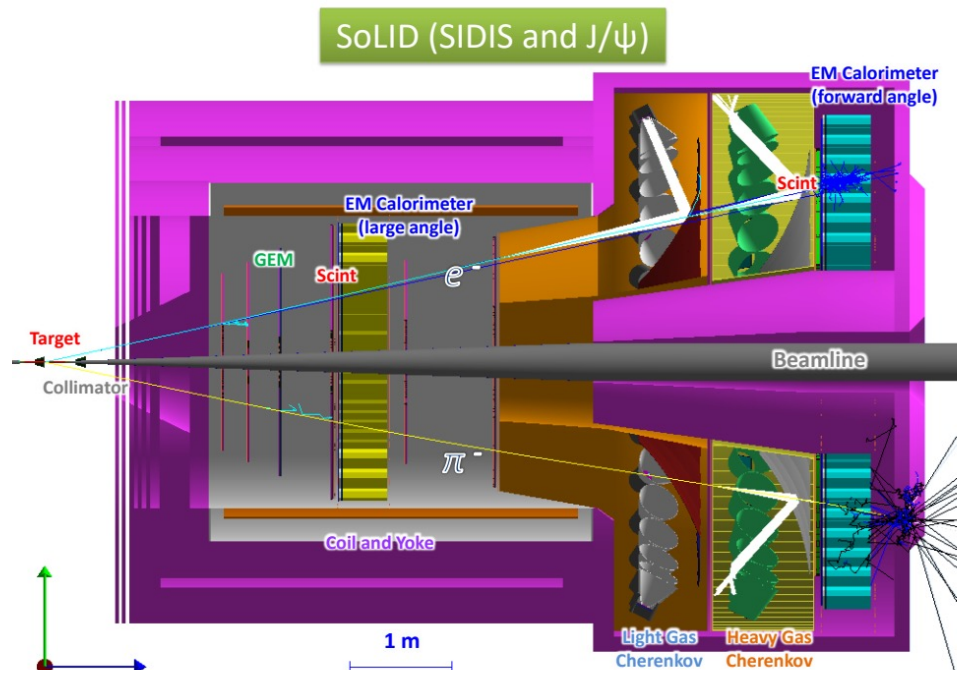


GEM Overview





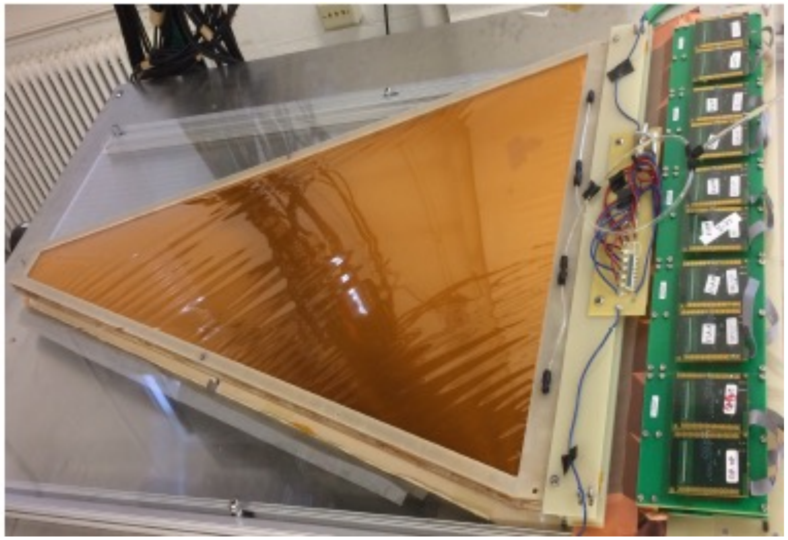


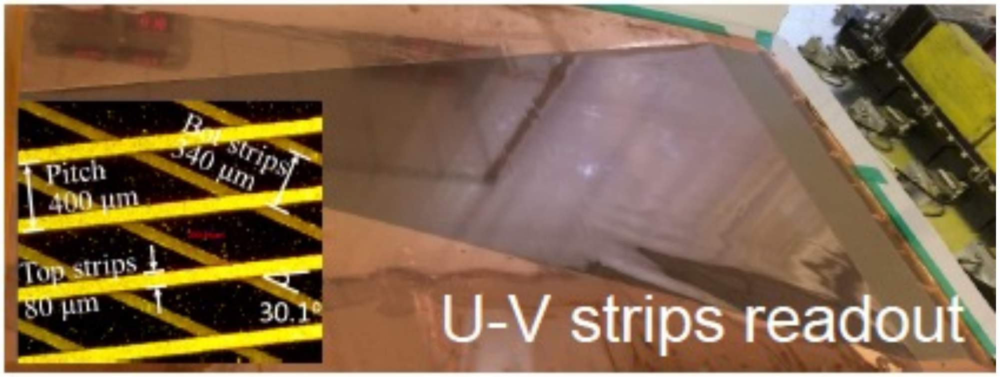


GEM Requirements: for all experiments

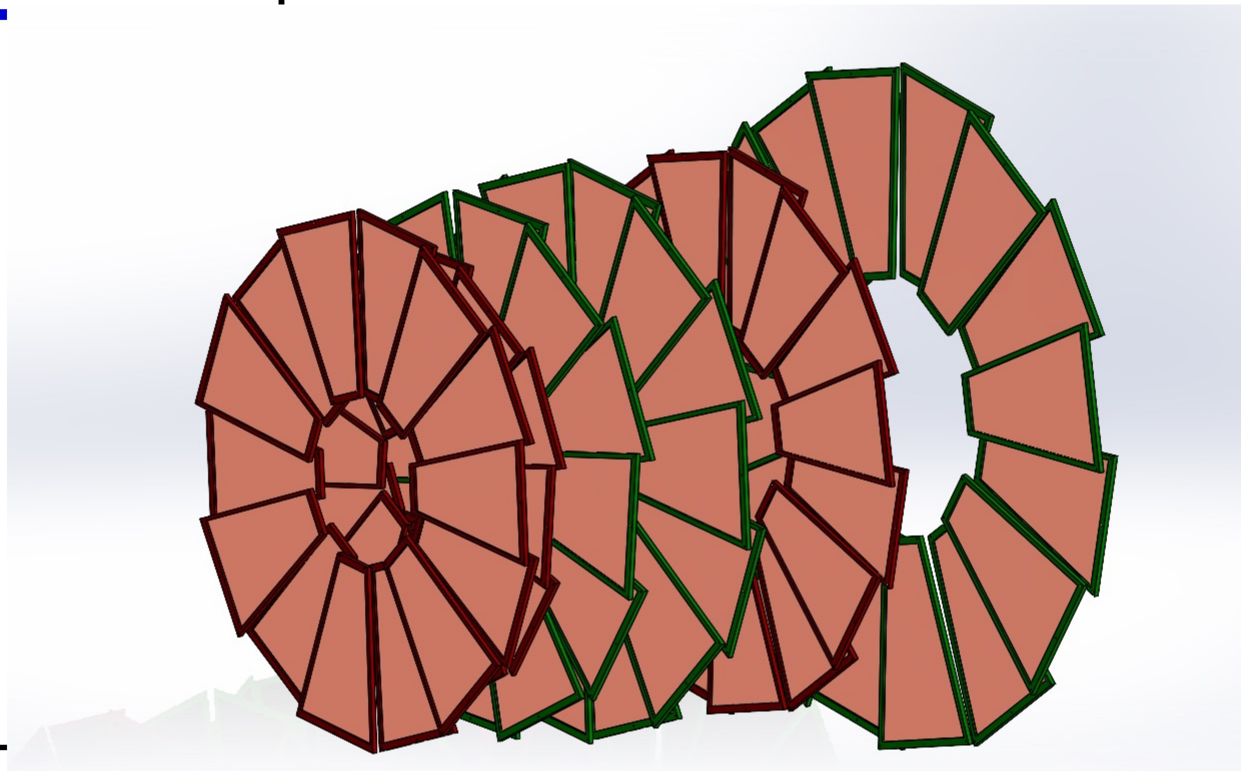
- Good position resolution
  - 100 µm (1 mm) in azimuthal (radial) direction.
    - 2D U-V readout with 12-degree or 24-degree stereo angle between strips
    - 400 µm (600 µm) strip pitch for layers 1-3 (5-6)
    - The high occupancy at layer #1: split each readout strip into two channels
    - Total number of channels ~ 215 k (with 15% spares)
- 92 % overall GEM-module efficiency.
- modules with a trapezoidal geometry
- All readout electronics located at the outer edge: Given radiation exposure map.
- Side frames need to be very narrow: minimize material thickness in active area (especially for SIDIS, J/Ψ)

All requirements follow from tracking and neutron/radiation dose simulation to meet SoLID conditions.





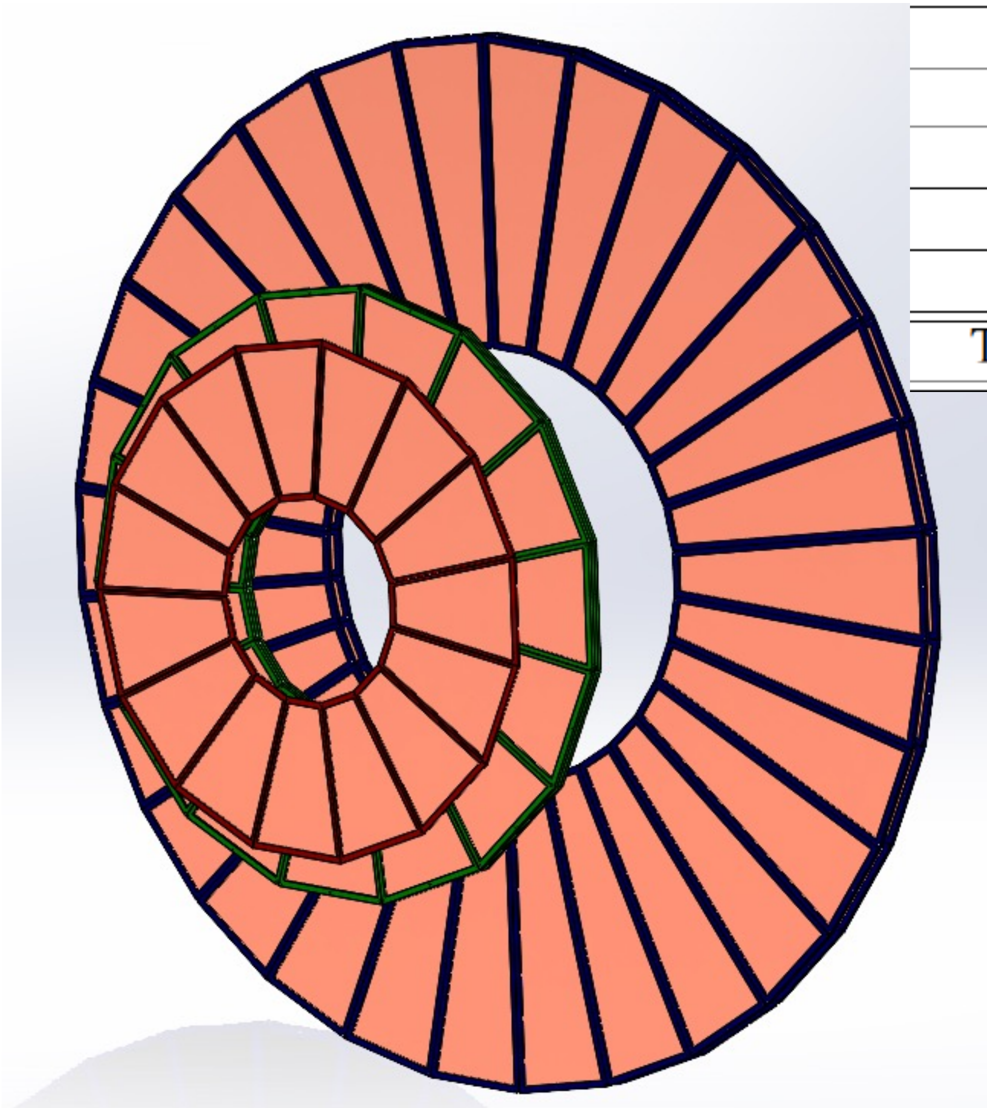
GEM configuration – Under optimization for SIDIS



Plane	Z (cm)	R_I (cm)	R_O (cm)	Length (cm)
1	-175	36	87	51
2	-150	21	98	77
3	-119	25	112	87
4	-68	32	135	103
5	5	42	100	58
6	92	55	123	68

Total active area ~ 21 m^2

GEM configuration – working to see how many SIDIS GEMs could be used for PVDIS

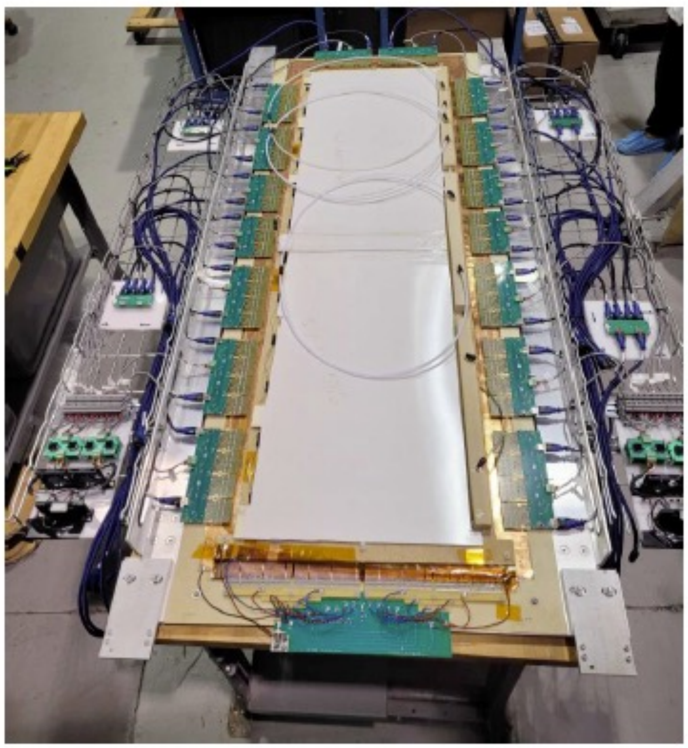


Location	Z (cm)	R_{min} (cm)	R_{max} (cm)
1	157.5	51	118
2	185.5	62	136
3	190	65	140
4	306	111	221
5	315	115	228
Total			

Total active area ~ 37 m^2

SBS GEM trackers: gaining GEM operation experience under conditions exceeding SoLID requirements

- 50 cm x 60 cm GEM modules for SBS rear tracker: 48 modules –All installed, 28 in beam
- 150 cm x 40 cm large GEM modules for SBS front tracker: 4 modules – all in in beam; two more under construction now



UV (shown)
40 x 150 sq.cm
Single module

XY (shown)
60 x 200 sq.cm
4 modules

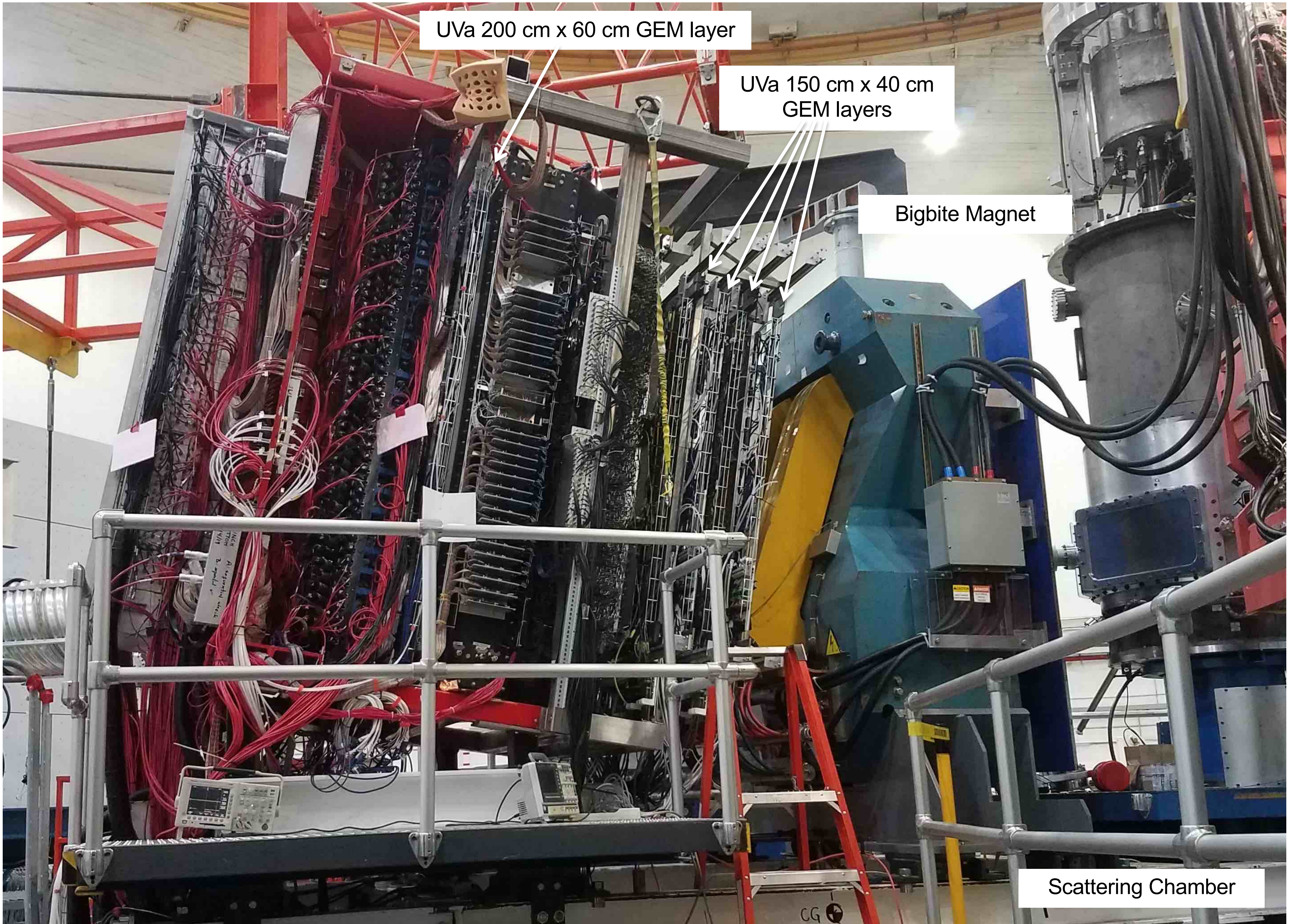
Active areas larger than the largest SoLID GEM detectors needed

SBS GEM trackers: gaining GEM operation experience under conditions exceeding SoLID requirements

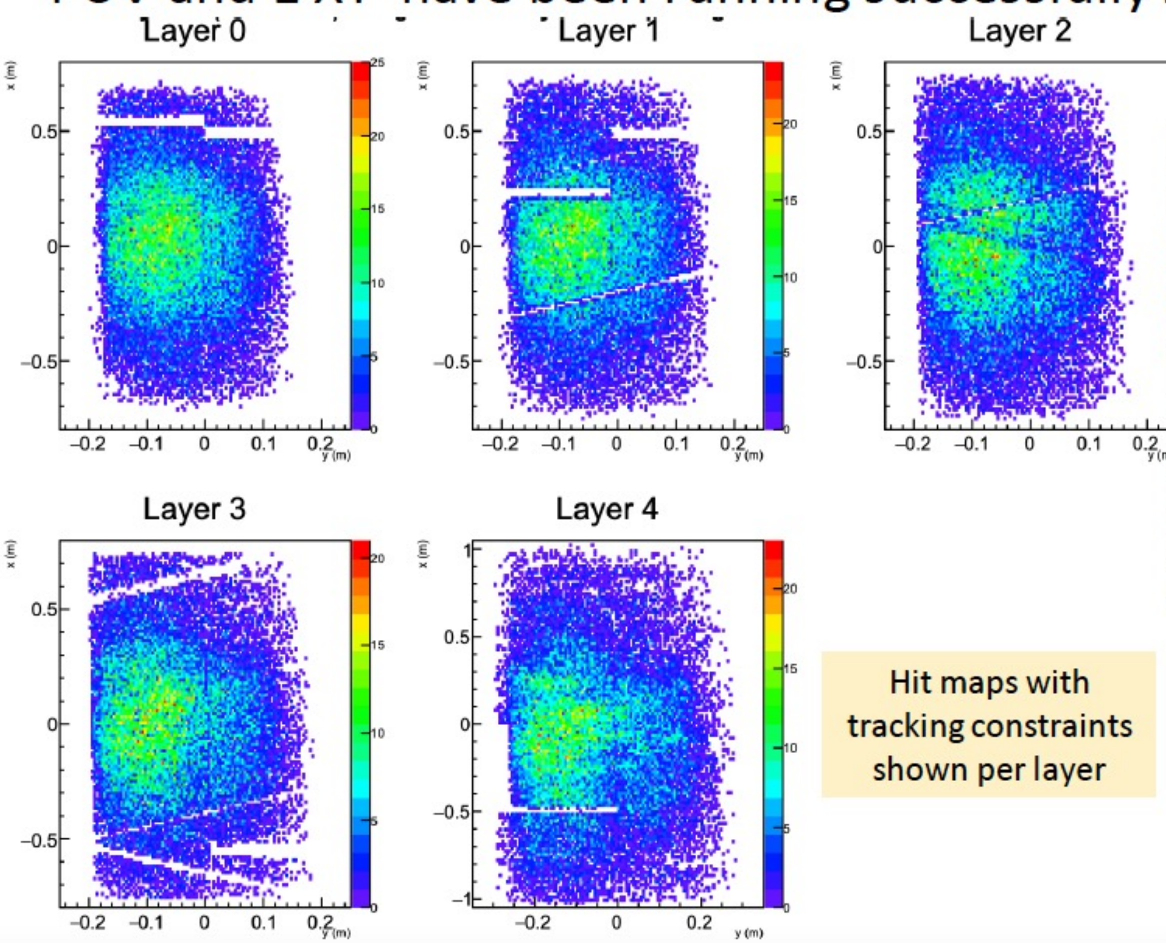
- SBS GEM trackers have been running well for about 14 months in GMn, nTPE and Gen-II experiments.
- In Gen-II: up to 45 uA on 60 cm 3He target: luminosity ~ 5 times higher than proposed SoLID 3He SIDIS run.
- In GMn: already ran the BB GEM tracker in unprecedented integrated rates (active area x local rate): stable running with 12 uA beam on 15 cm LD2 target: test runs up to 36 uA on LD2: luminosity ~ 3 x $10^{38;}$ within about factor of 3 of SoLID PVDIS.
- In SBS all this without baffles and direct line of sight to target: GEM hit rates and occupancies already achieved in SBS are higher than the worst case predicted for SoLID

SBS GEM trackers: Important conclusions about long term running under very high exposure conditions

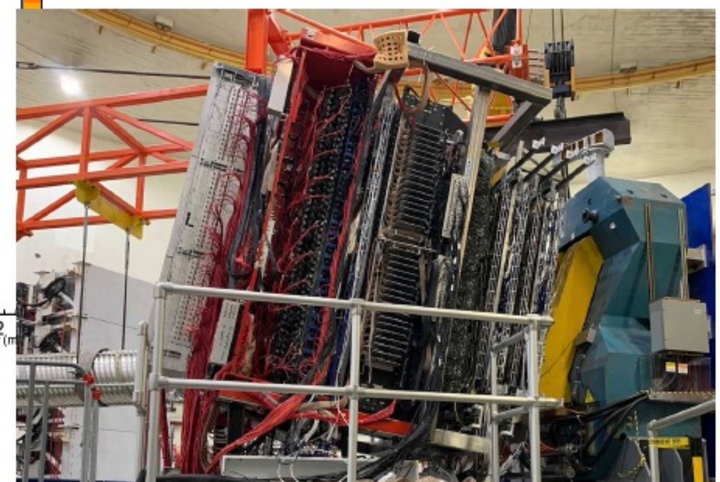
- UVa GEM tracker layers have been working very well:
  - stable operation: not too many HV trips
  - Robust under harsh conditions. So far only 1 out of the 32 detectors in beam had to swapped out due to suspected short in one sector (out of 30 in the detector).
  - No radiation damage observed
  - No detector aging effects observed
  - Noise levels sufficiently low
  - Good gain: signals well above noise
  - Very good resolution: ~ 70 um for tracks perpendicular to detector.
  - Real time firmware zero suppression has been working very well.
  - Data volumes manageable
- Most important lesson: The current drain to detector is too high for the resistive voltage dividers to handle; caused efficiency drop.
- The Good solution with new power supply scheme: tested and demonstrated to work

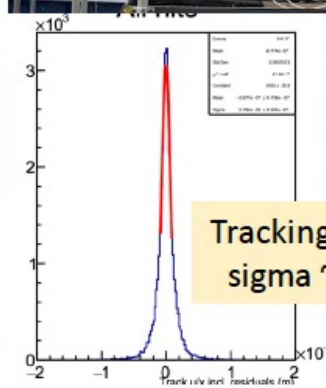

UVa 200 cm x 60 cm GEM layer
UVa 150 cm x 40 cm GEM layers
Bigbite Magnet
Scattering Chamber

4 UV and 1 XY have been running successfully in BigBite since 2021

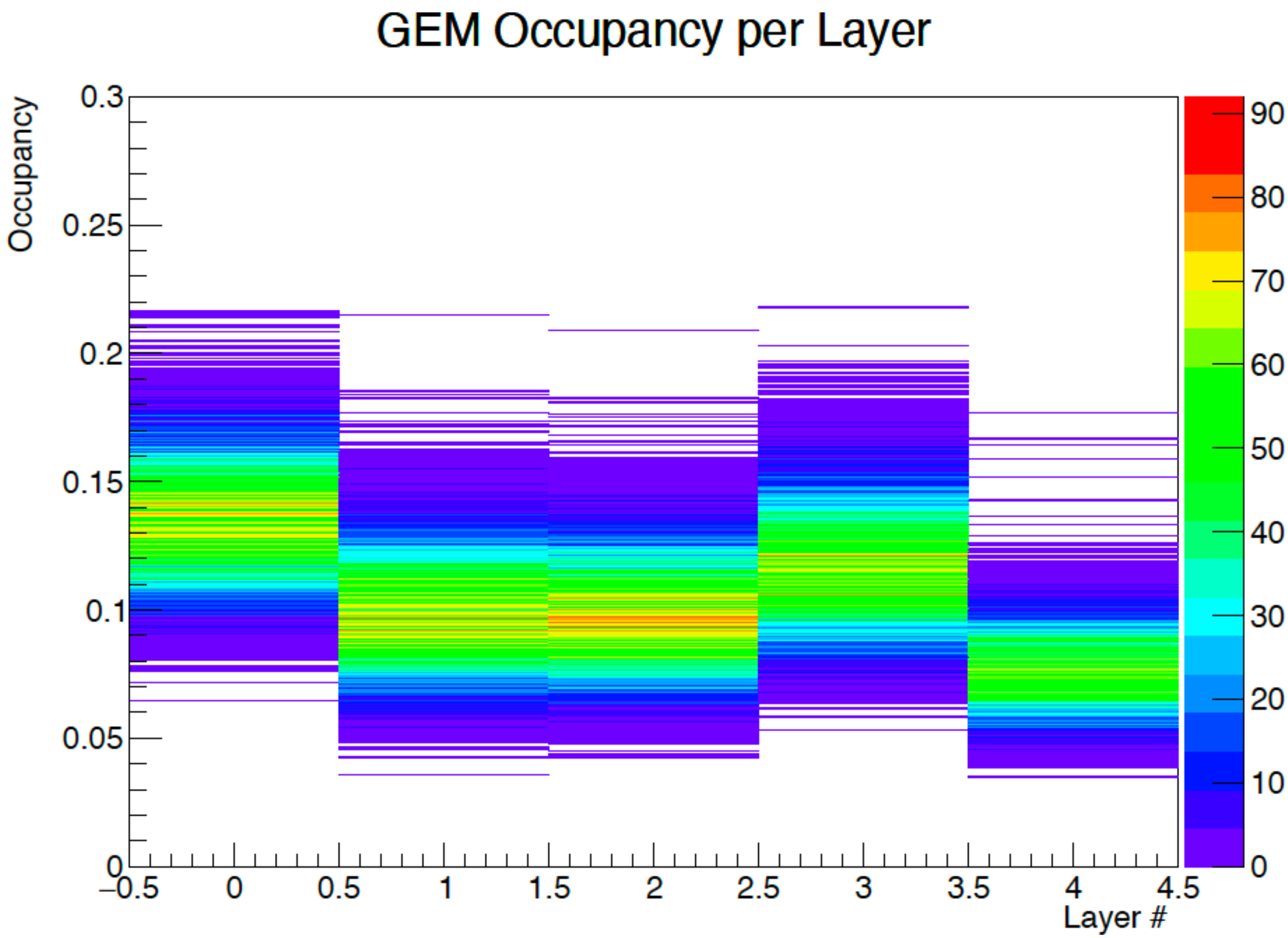


Hit maps with tracking constraints shown per layer





Tracking residual sigma ~ 70 µm

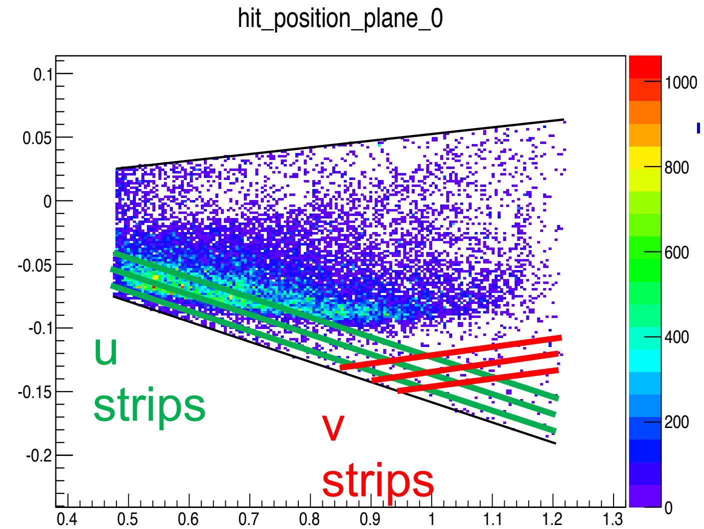


Gen-II run 2551 - 45 uA on polarized 3He target

PVDIS GEM occupancies		
Plane	Total strip number (u+v) per sector	Raw Occupancy (%)
1	1156	4.48
2	1374	2.55
3	1374	2.21
4	2287	0.82
5	2350	0.75

SBS achieved occupancies higher than what is projected for PVDIS and SIDIS

However, we need to be careful – SoLID occupancy is not uniform, hot-spots at small radius

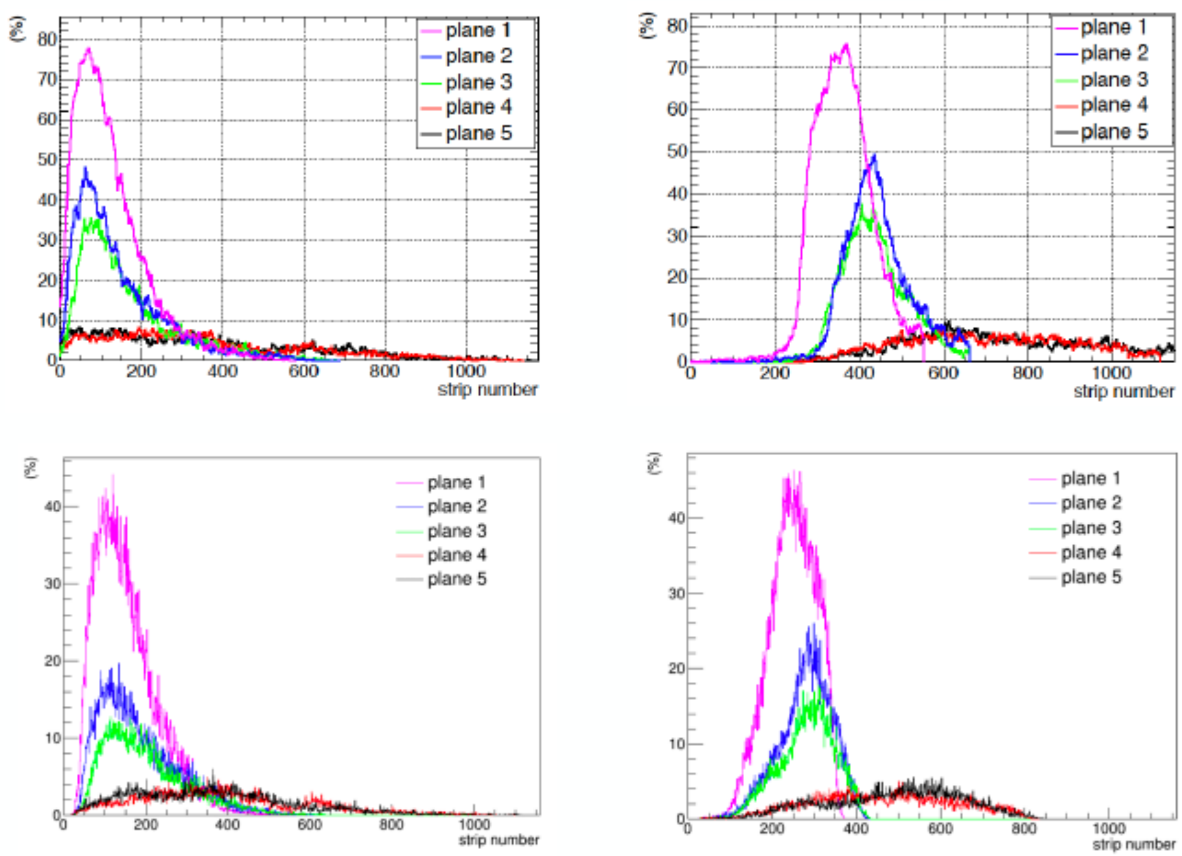


U plane

V pl

APV25

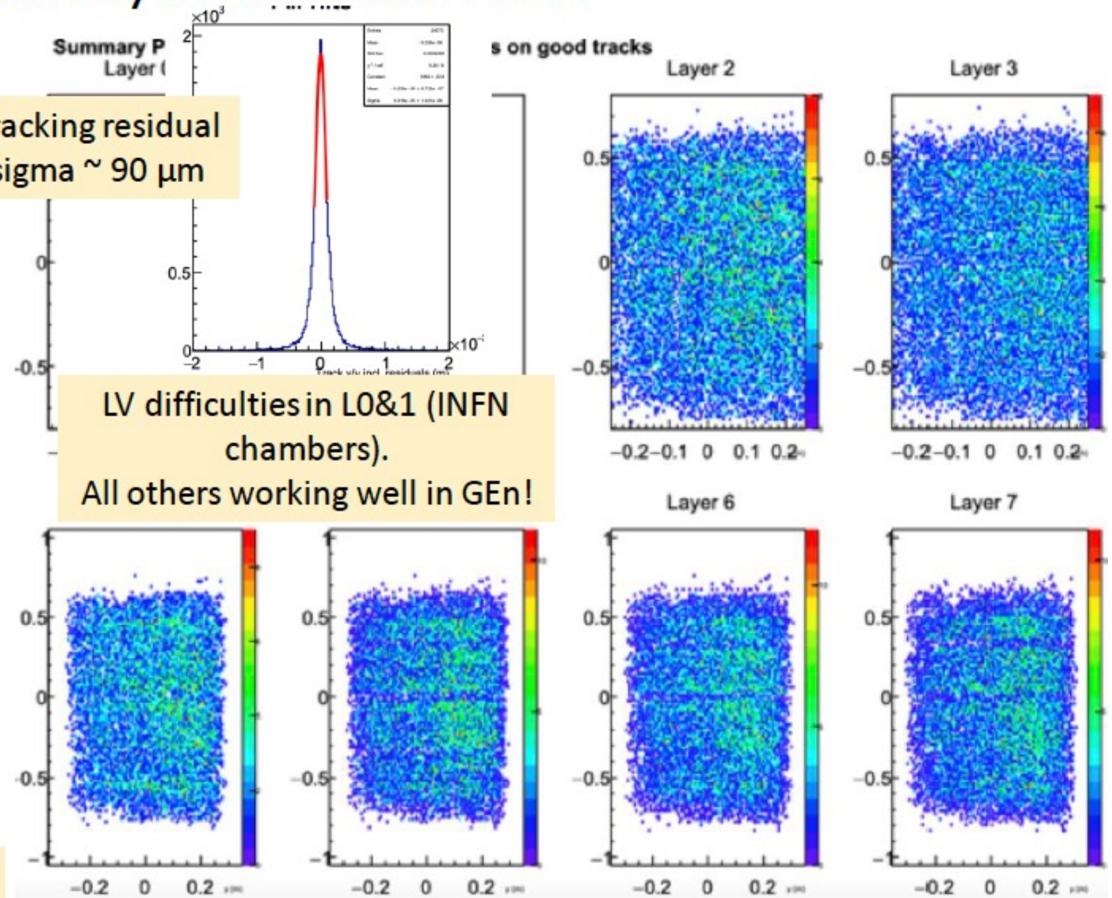
VMM3



6 XY have been running successfully in SBS since 2022

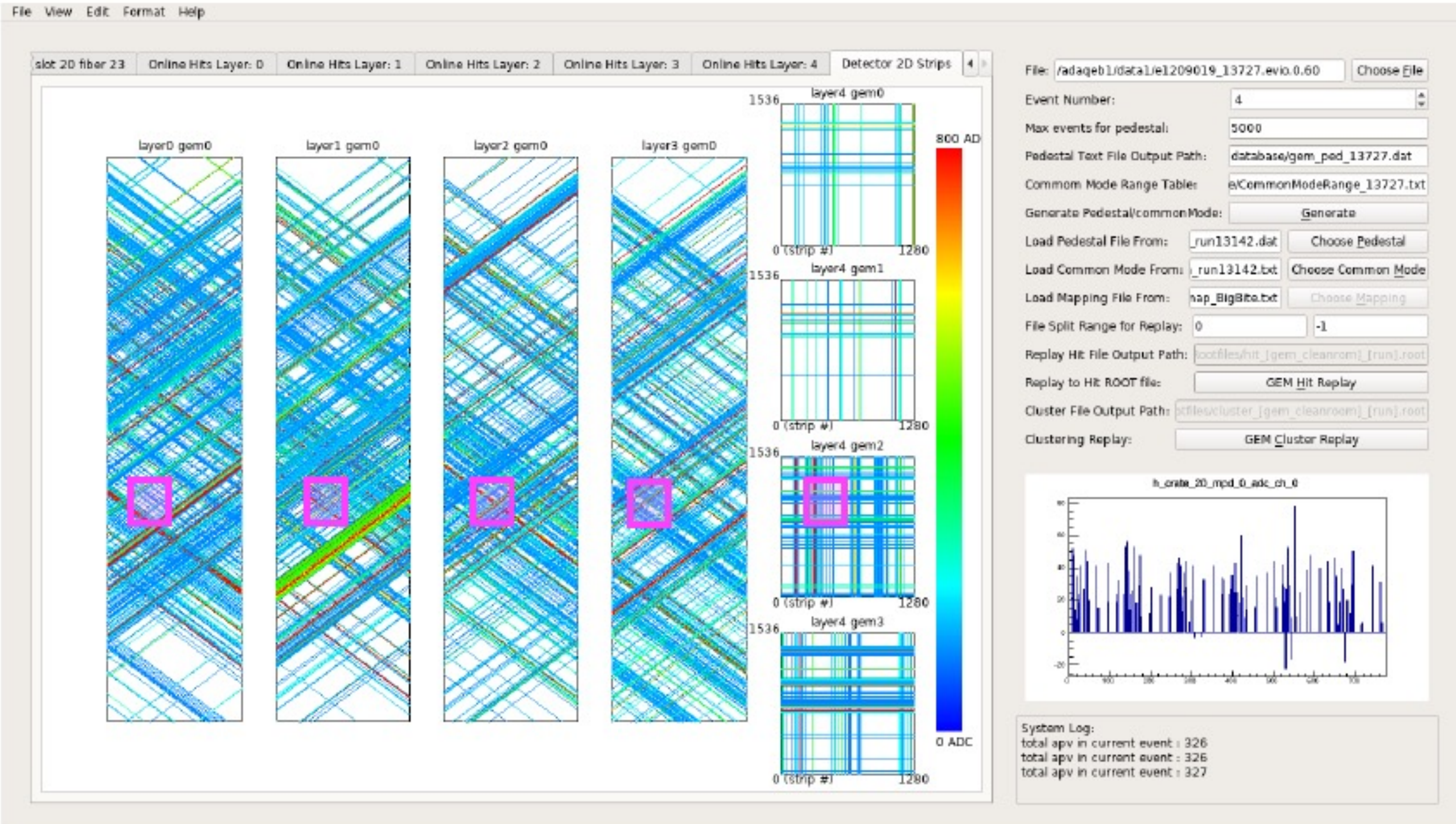
Tracking residual sigma ~ 90 µm

LV difficulties in L0&1 (INFN chambers).
All others working well in GEn!



GEn-RP will run with all layers next spring (prior to GEp)

run 13727, 12 uA LD2, $Q^2 = 4.5\ GeV^2, E = 4\ GeV$

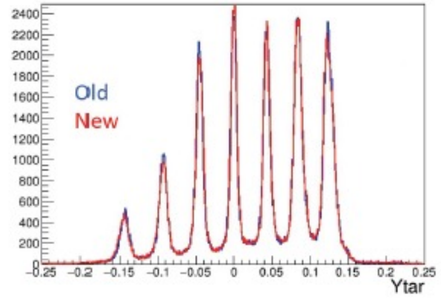


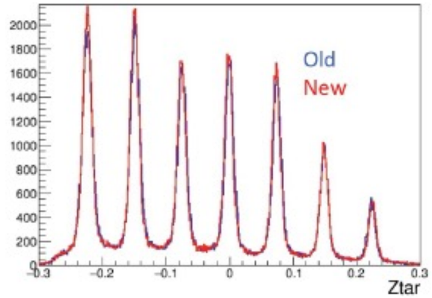
Clean tracking despite high occupancy

GEN Optics calibration (by Holly)

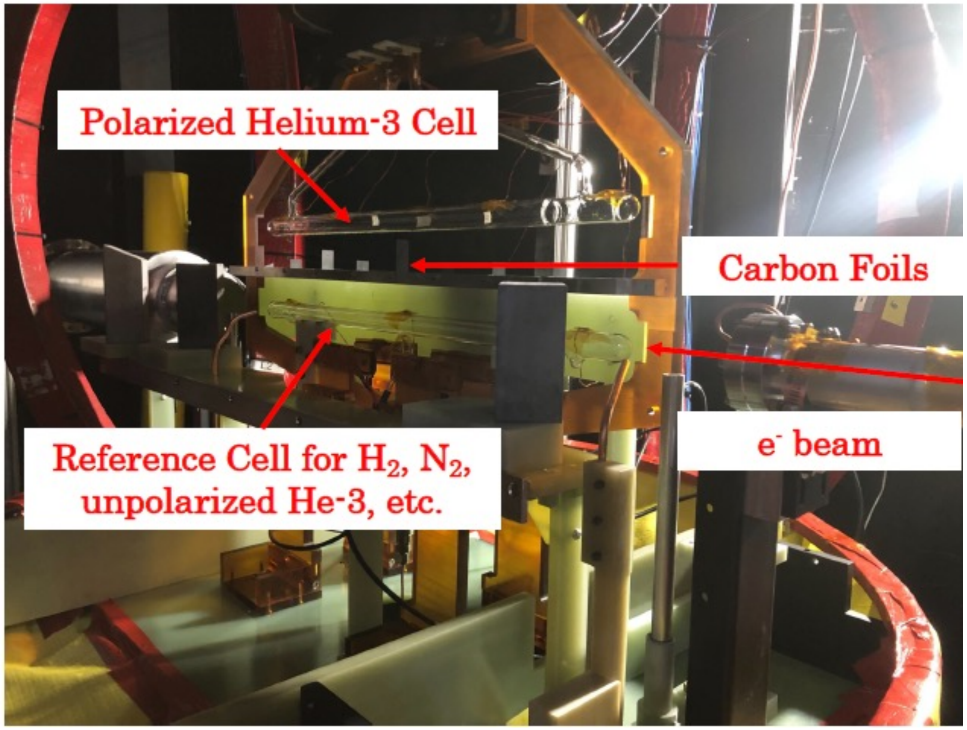
https://sbs.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=344

Comparing the old and new reconstruction.



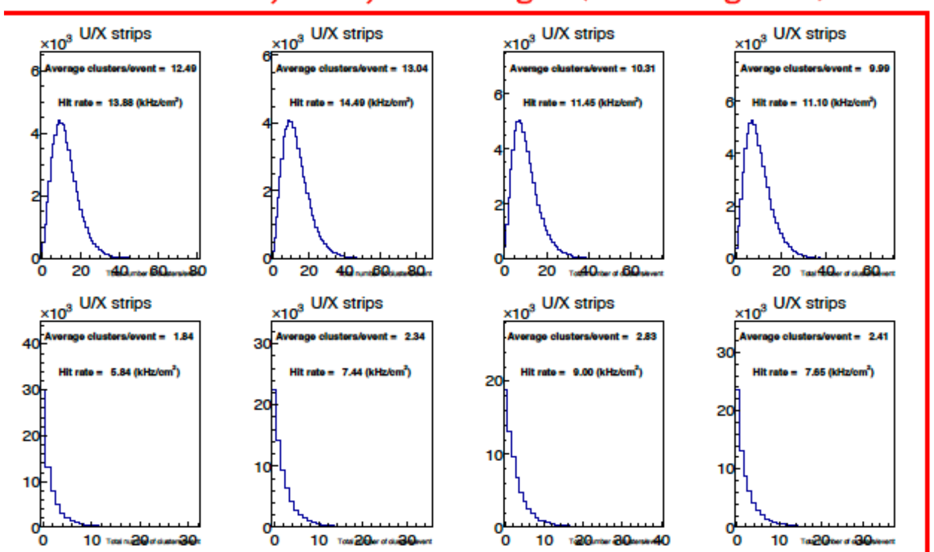


- Lessons learned from GMN experience allow “pretty good” starting optics model for BigBite from simulation

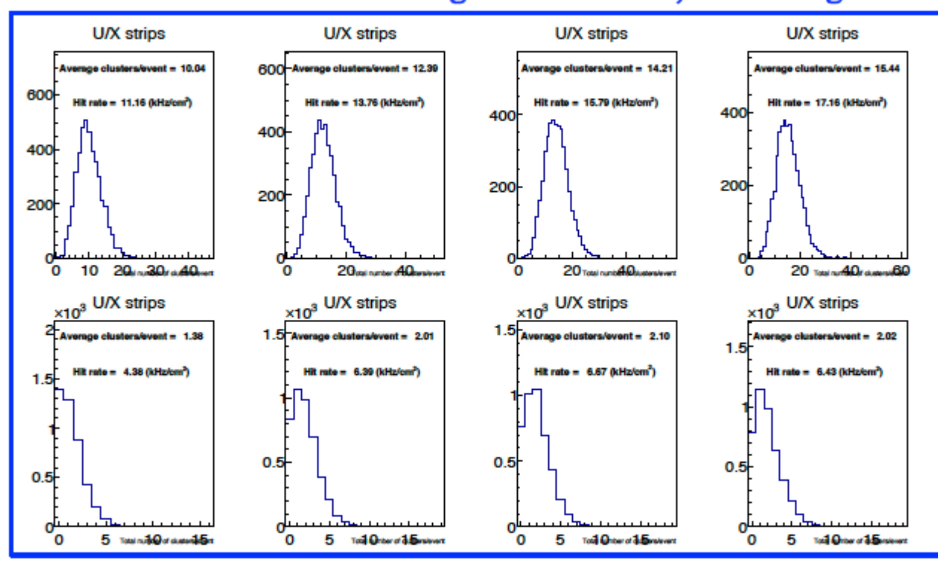


- Optimized simulation and analysis by Andrew shows the GEM rates and occupancies in GMn are consistent with the simulation
- Need to understand the GEM current draws as well: ionization levels and GEM gains in addition to the rates.
- Work underway towards this and to tune SoLID simulation accordingly.
- Get firm estimates for current drains for SoLID GEMs: plan the HV supplies accordingly.

Run 13656, 3 uA, LH2 target (no timing cuts)

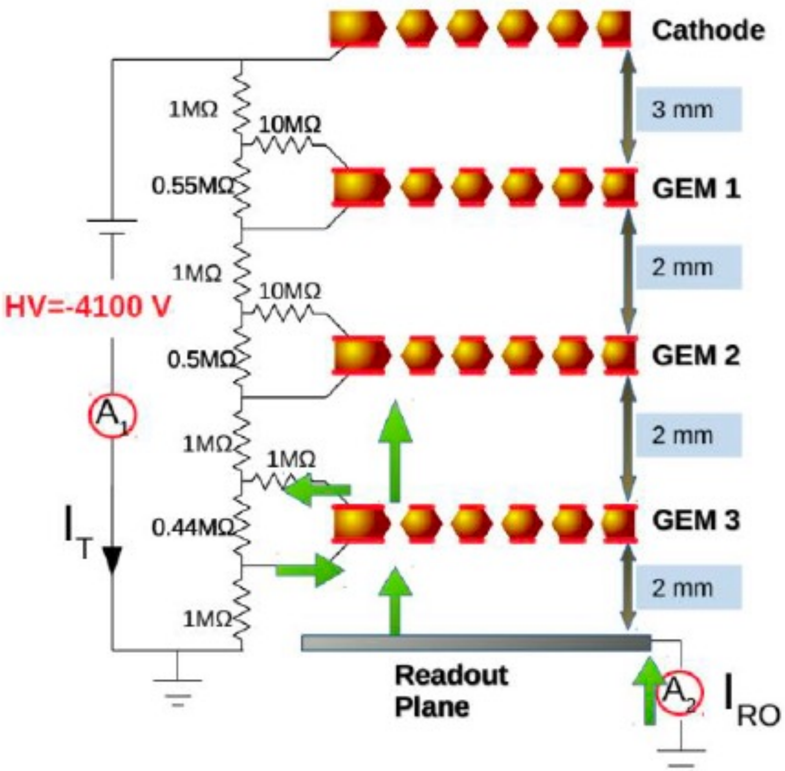


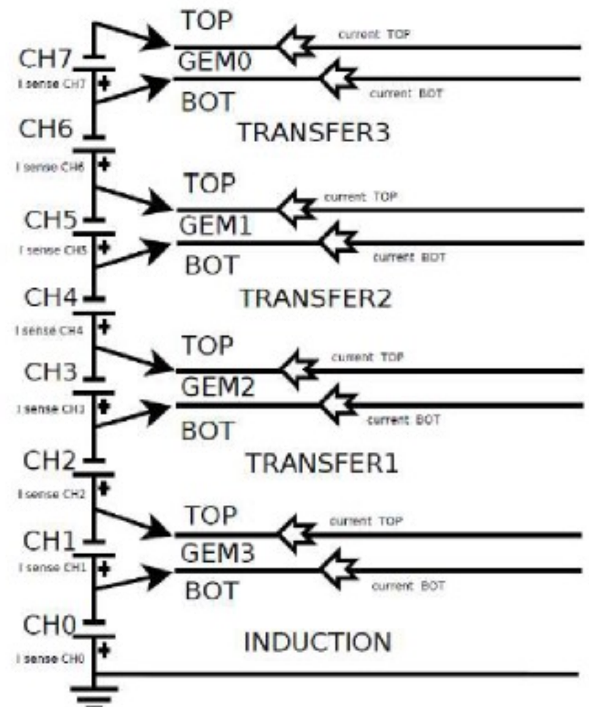
G4SBS simulated background @3 uA, LH2 target

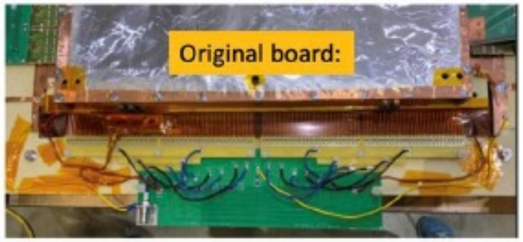


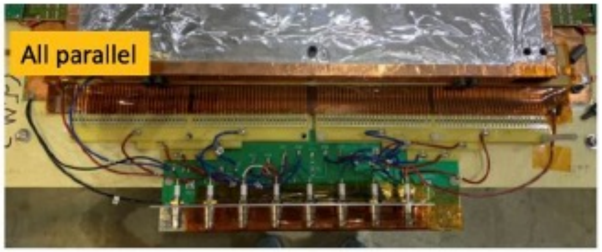
- At low beam current (3 uA on 15-cm LH2), reconstructed cluster multiplicities per event agree between real data and Monte Carlo to within a factor ~1.5 without any fine-tuning of simulated pedestal/common-mode noise, GEM gain, zero suppression thresholds, electronics effects like crosstalk, etc.
- Suggests *g4sbs* rate estimate is more reliable than initially feared, after full digitization and reconstruction with simulated beam-induced background, *under conditions where GEM gain/efficiency drop were not significant during GMN!*

SBS GEM: HV supply issue









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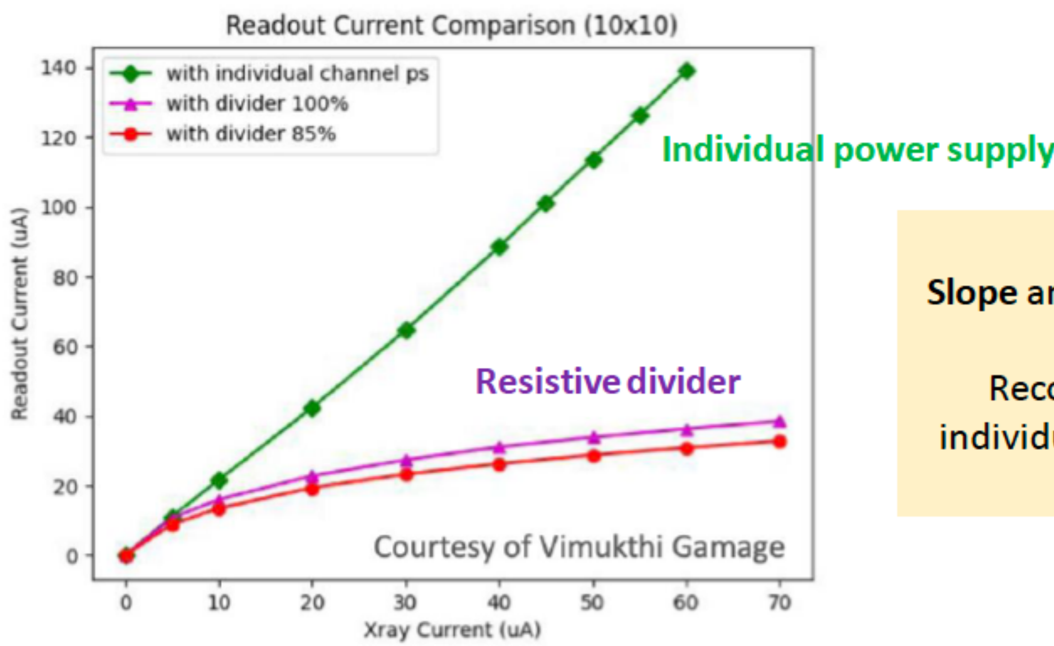
Individual power supply scheme tested successfully in Gen-II

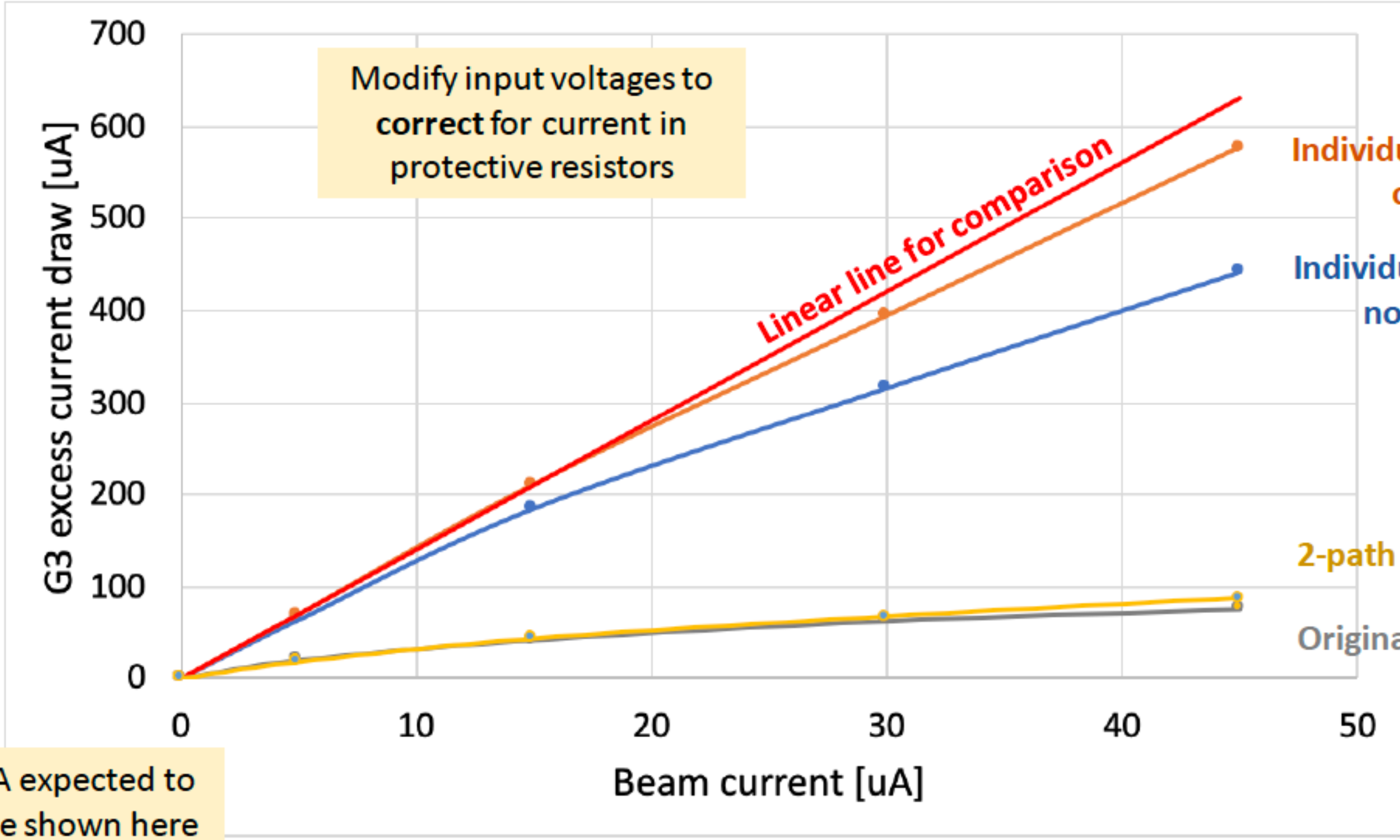
- Observed a loss of tracking efficiency that was correlated with occupancy due to the HV divider configuration
- Observed a non-linear increase in the current draw with increased occupancy (replicated in the lab in the red curves below) as related to the divider



Slope analogous to **gain!**

Recover gain with individual power supply

Luminosity scan with different HV divider configurations during GEn (on optics target)



GEp at 50uA expected to increase rate shown here for 45uA by 2.7x

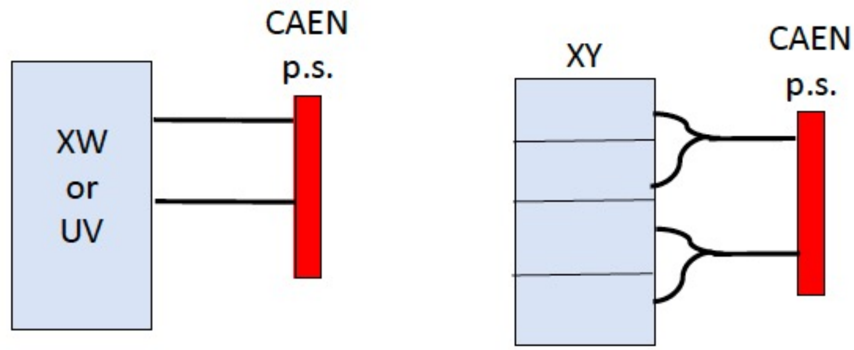
- All SBS GEMs will be upgraded to parallel power supplies: work starting this week
- Cost per module ~ $ 14 k: could power 1 – 4 modules depending on the exposure

High voltage

Install parallel-path HV supply on every layer

CAEN A1515BTG designed for triple GEMs:

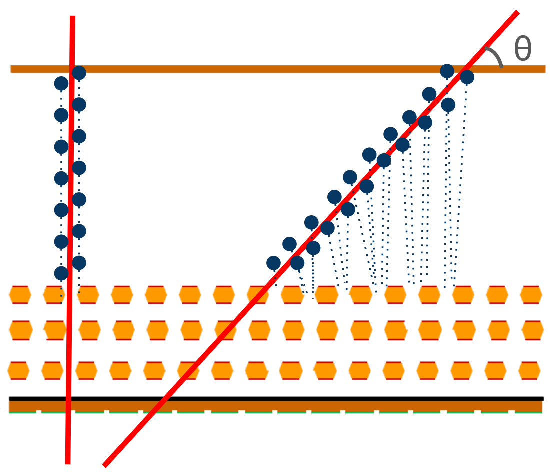
- 2 channels with 7 outputs each
- 1 and 3 mA max per output
- Floating ground
- Can trip together



- Hall A (and INFN + UVa) has purchased 16 modules
- SoLID will need ~ 30 to 40 more depending on the rates (to be evaluated with simulation)
- Alternate approach: Build an active divider
  - CERN GEM electronics group has a design.
  - Cheaper, but need to make sure no extra noise.
  - Need support from Jlab electronics group

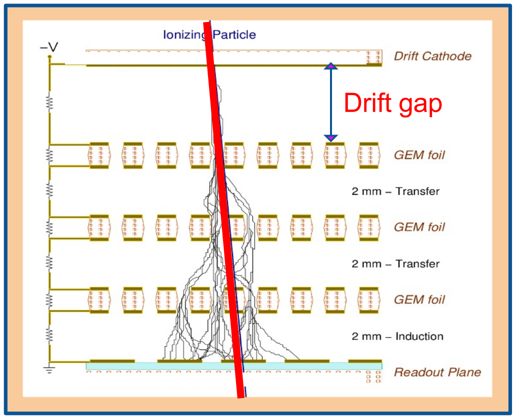
Ongoing R&D to improve resolution and lower GEM background

- Overall, SBS GEM data show that SoLID conditions are achievable.
- However, given localized high occupancy areas we need to work to minimize GEM background for SoLID.
- The resolution need to be maximized for a range of angles: 8^o – 35^o
  - Standard GEM resolution gets worse with increasing angle



Jefferson Lab

- **Standard Triple-GEM detectors**

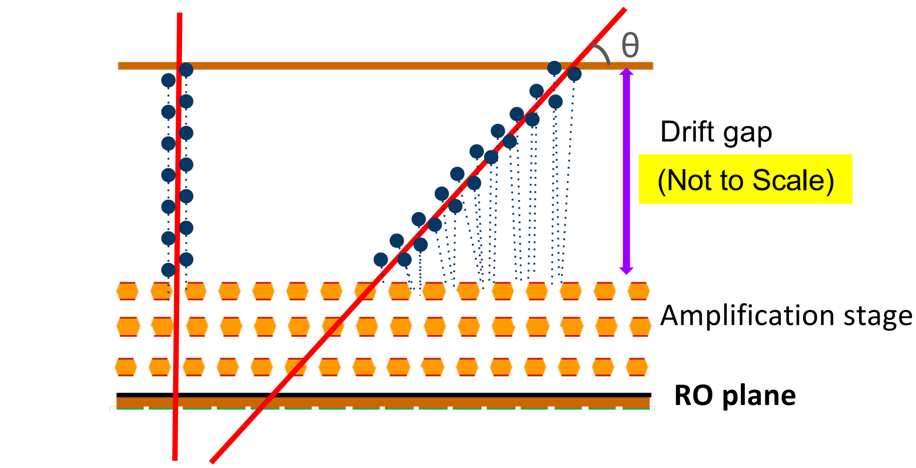


⇨ Standard 3mm drift gap

⇨ Spatial resolution for small angle tracks determined by RO structure

⇨ For perpendicular track: σ ≅ 70 μm

- **Challenges with Triple-GEM detectors at wide angles**



⇨ Deterioration in the spatial resolution growing with the track angle

⇨ Spatial resolution no longer determined by the RO structure but the drift path that particle traverses before reaching the amplification stage

⇨ Track bending in magnetic field also has negative impact on spatial resolution

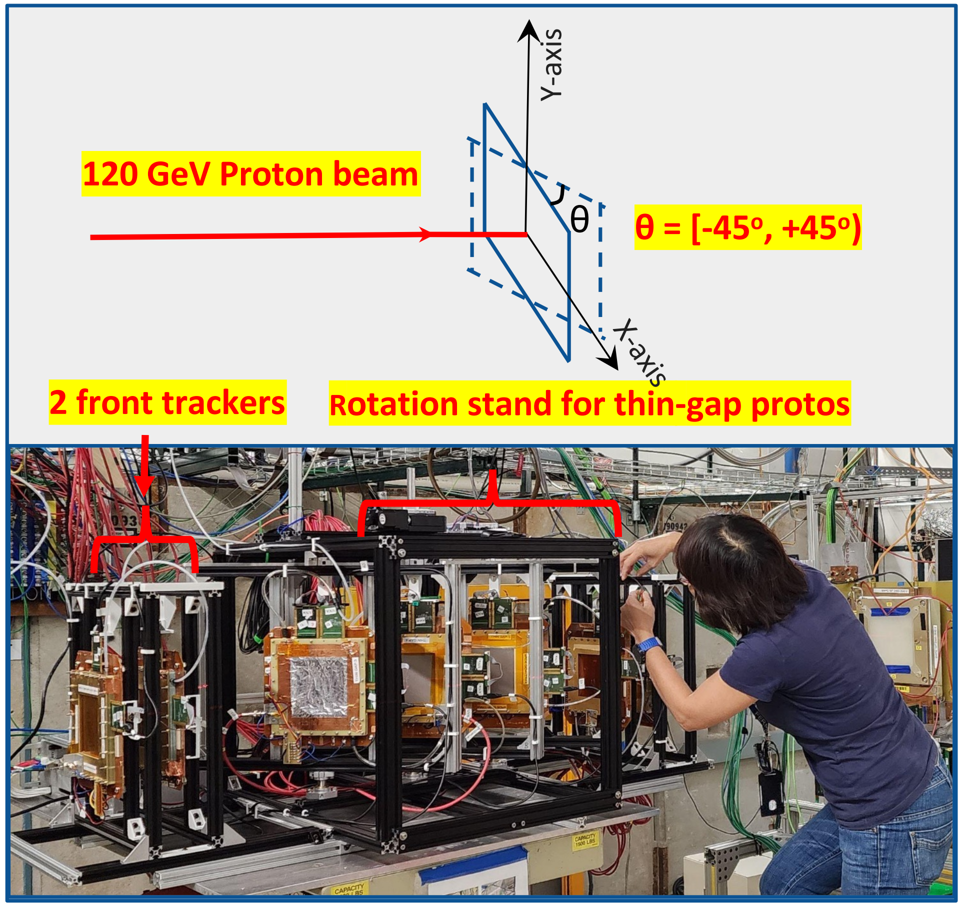
FermiLab Beam Test Setup for Spatial Resolution Study

Setup for spatial resolution study:

- ⇨ Setup for spatial resolution studies was designed and built by K. Gnanvo and J. Lee (JLab)
- ⇨ 4 trackers: 2 trackers upstream and 2 trackers downstream
- ⇨ A rotation stand placed in the middle allows to test up to 3 prototypes at the time
- ⇨ Rotation stand rotates the X-Y plane by an angle θ ➡️ x-spatial resolution will be affected the most as θ increases

Investigate spatial resolution with track angle spanning from 0° to 45° for :

- ⇨ Three prototypes (10cm x 10 cm) having the same structure, different drift gap 1.0, 1.5, 3.0 mm
- ⇨ Same prototype in different gas mixtures ($KrCO_2$ & $ArCO_2$)



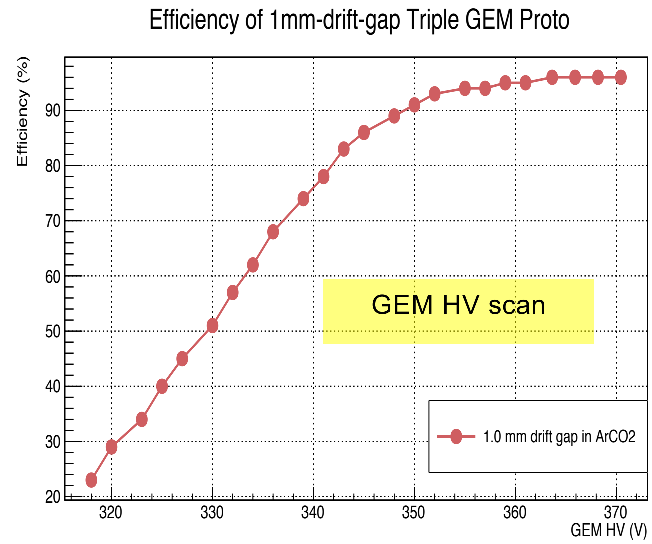
Thin-gap GEM beam test results

Efficiency vs. Drift Gap studies

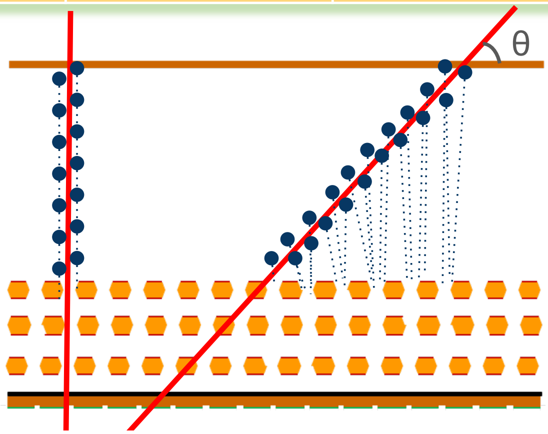
- Efficiency of **Proto I** (1.0 mm drift gap) in $ArCO_2$ (80%/20%).
- **Proto I** achieves a high **efficiency of 96%** similar to a standard mm drift gap triple GEMs

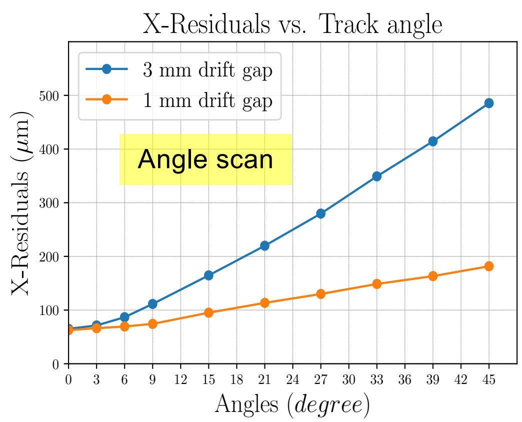
Spatial resolution vs. track angle studies

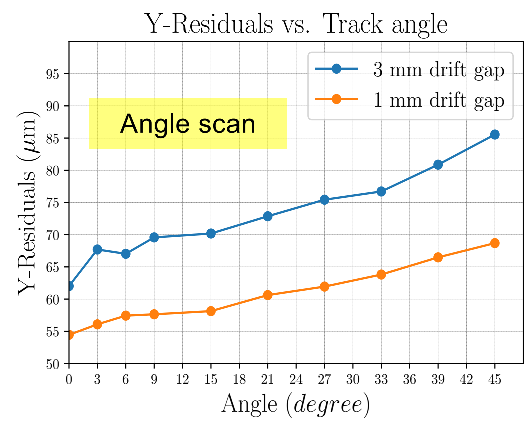
- Investigated spatial resolution of **Proto I** (1 mm drift) and **Proto III** (3mm drift) in $ArCO_2$ with track angle from 0° to 45°
- At large track angle, spatial resolution of **Proto I** significantly better than **Proto III**



Drift Gap	Resolution in Y-plane @ 45°	Resolution in X-plane @ 45°
1 mm	69 µm	**182 µm**
3 mm	86 µm	**486 um**

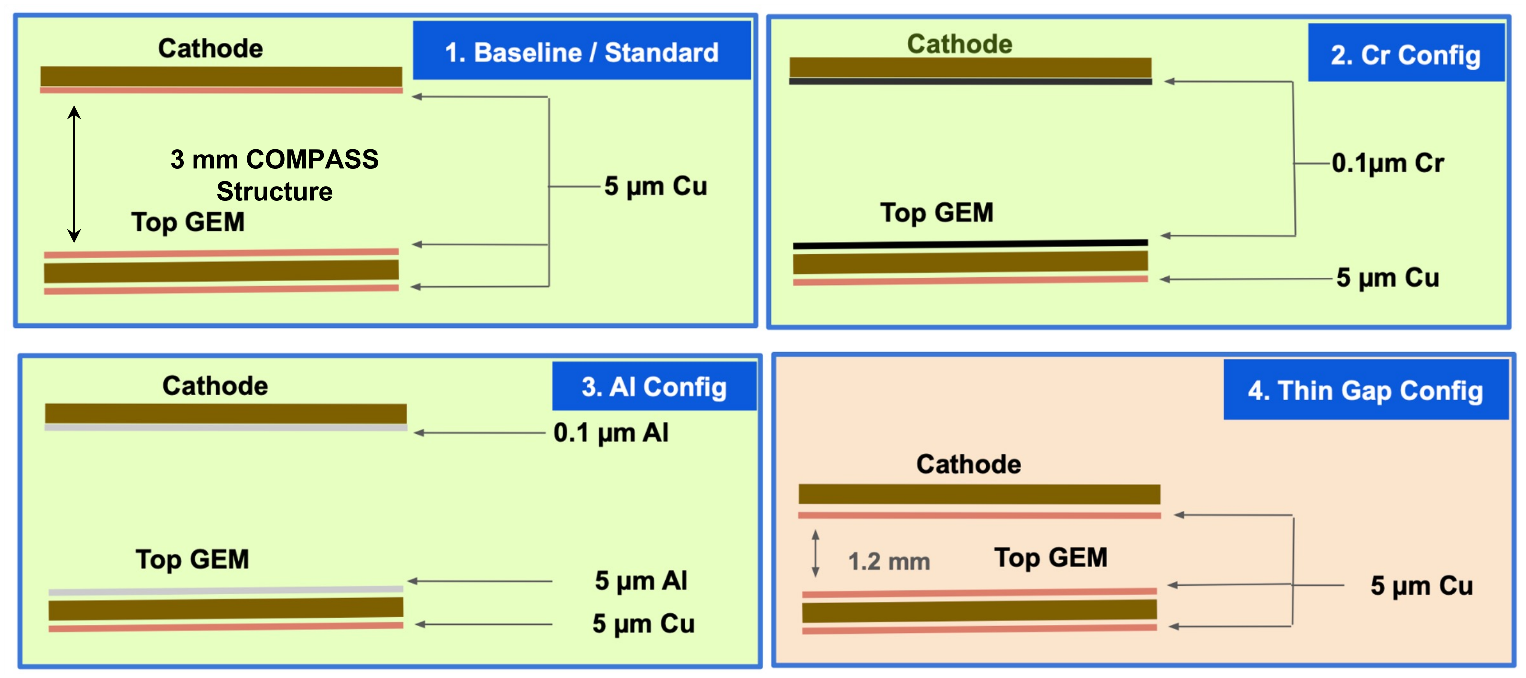






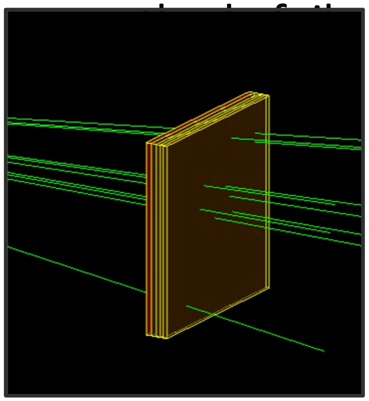
Geant4 Simulation on Optimizing GEM Foil/Detector Structure

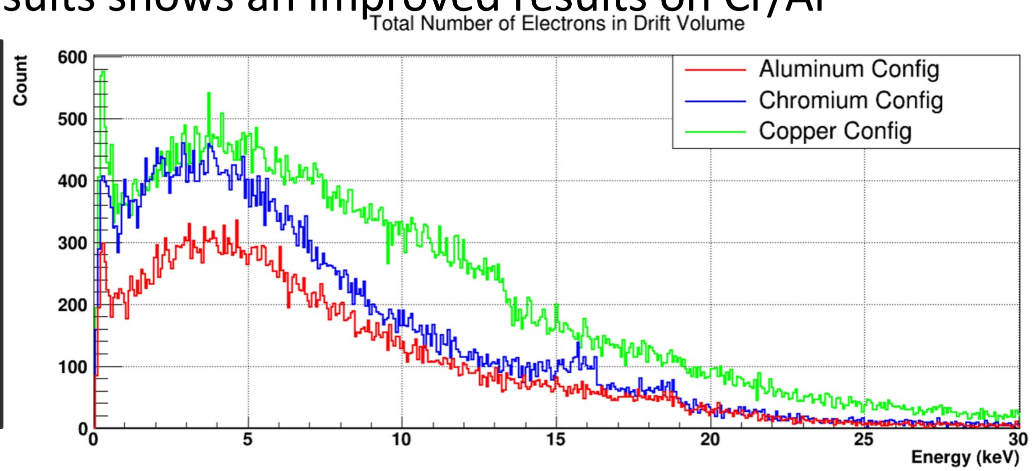
- ❑ Effort to reduce the photon conversion rate on GEM detectors
- ❑ Simulation on different GEM foil/detector structure



Geant4 Simulation on Optimizing GEM Foil/Detector Structure

- Prototypes of different configurations completed
- Under test using x-ray
- Similar setup in Geant4
- Simulation results shows an improved results on Cr/Al

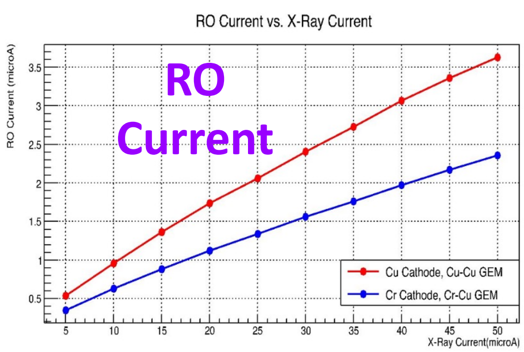


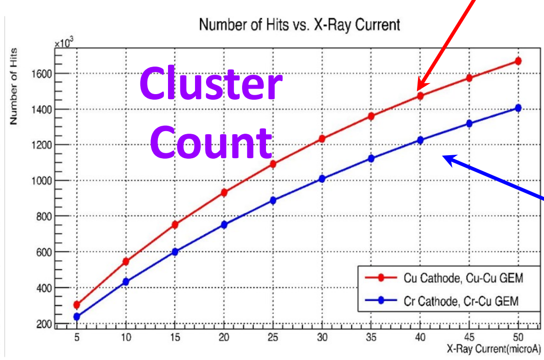


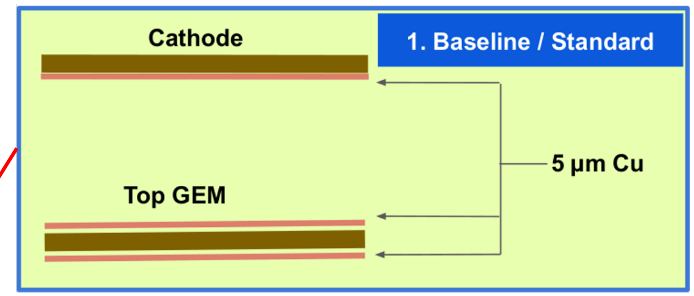
UVA x-ray

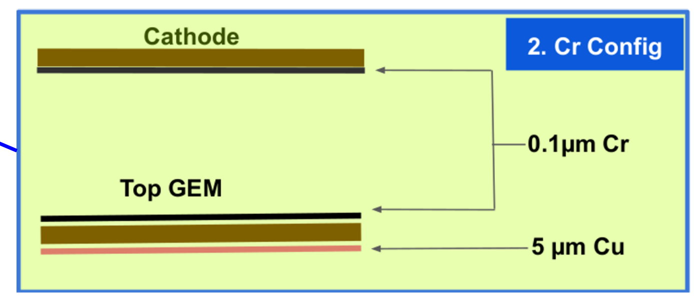
Geant4 Simulation on Optimizing GEM Foil/Detector Structure

- Photon conversion – cathode foil, drift region (thin-gap)
- Experimental measurements
  - **Current from readout board**
  - **cluster count** under **a fixed amount of time**
- Significant photon-converted cluster count reduction: **16%** for **Cr GEM detectors**



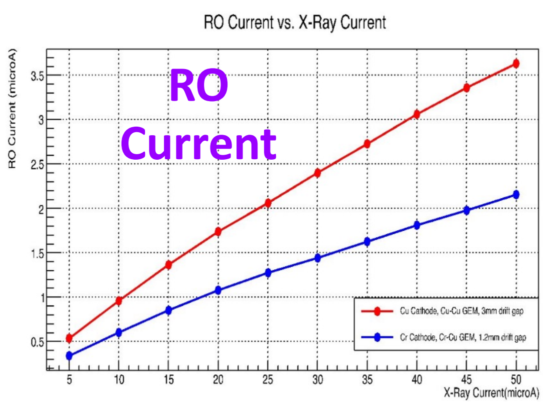


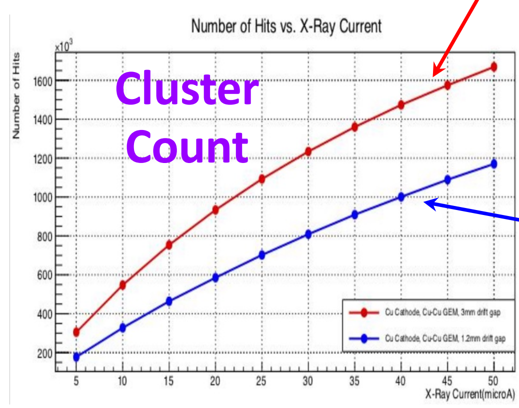


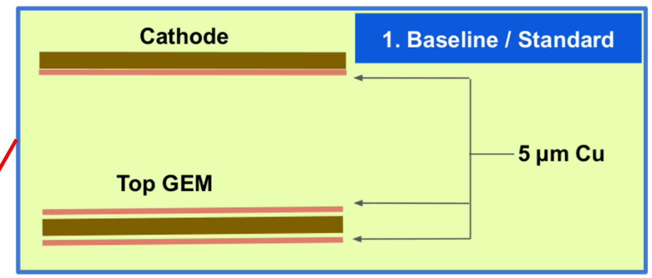


Geant4 Simulation on Optimizing GEM Foil/Detector Structure

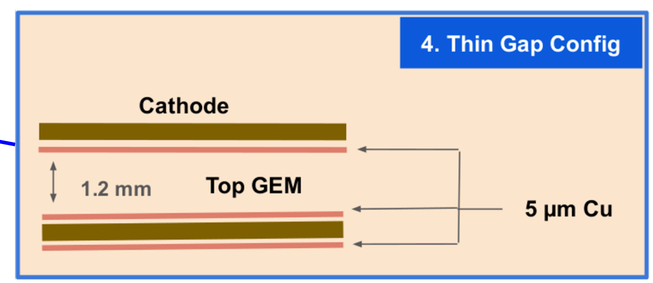
- Photon conversion – cathode foil, drift region (thin-gap)
- Experimental measurements
  - **Current from readout board**
  - **cluster count** under **a fixed amount of time**
- Significant photon-converted cluster count reduction: **30%** for **Thin-Gap GEM detectors**
- Simulation study on-going – Garfield / Geant4







See Kondo's Monday talk on thin-gap beam test results

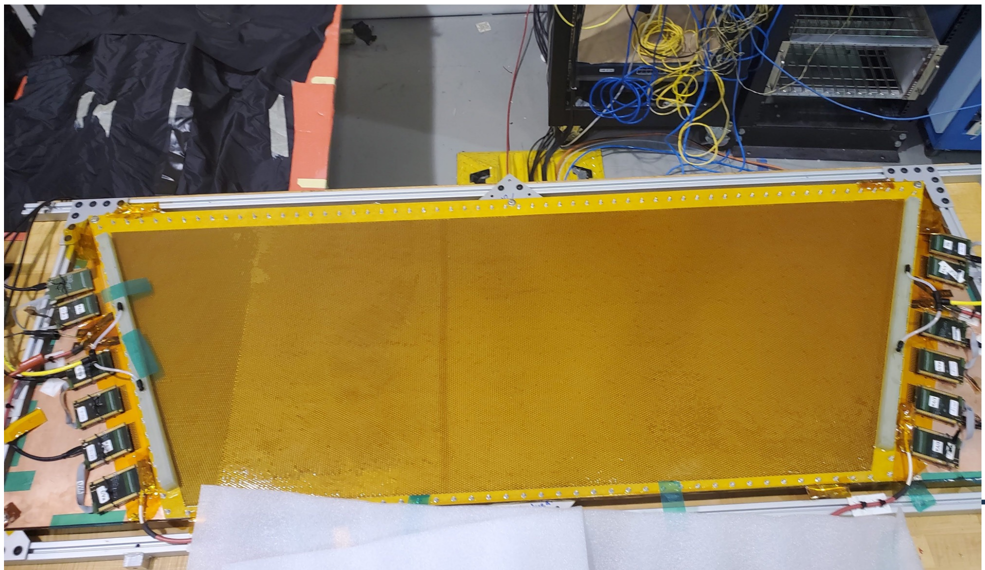


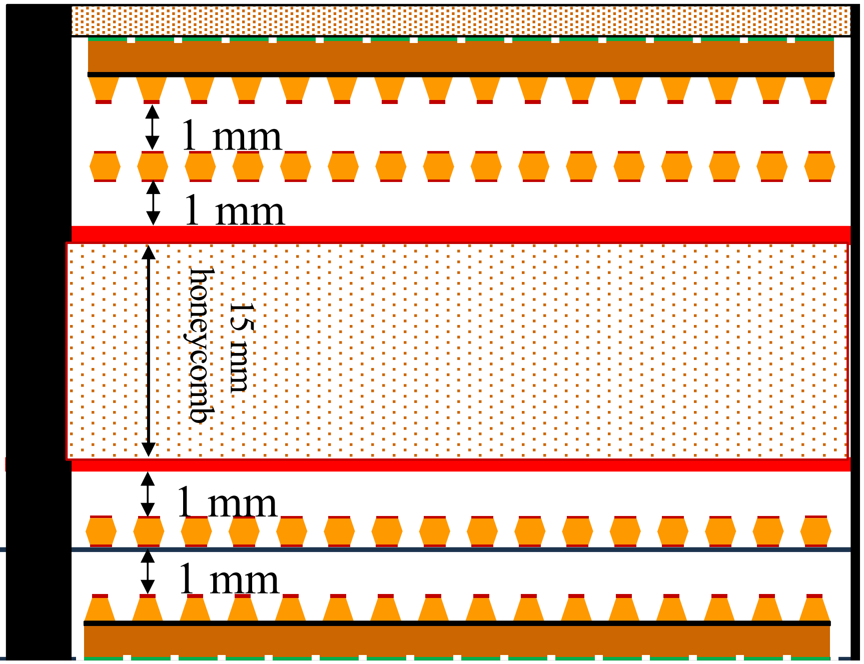
Possible Advance funding soon: time to get organized

- SoLID GEMs: very large project.
- Need to be a multi-institution project: Jlab, UVa, SBU, MIT….etc.
- Large scale logistics involved
- Project coordination should come from Jlab.
  - Coordination of the targeted R&D effort
  - Coordination of designs, reviews, and prototyping and production
  - Component procurements
  - Organization of all accessories: Readout, Gas, HV, LV etc.
  - Installation, commissioning and operation
- UVa has facilities and expertise for fabrication of part of the modules and participate in design, installation and commissioning.
- Need to regroup on the simulation and tracking effort: need to incorporate the experience from SBS. Xinzhan Bai is starting on this and hopefully Andrew Puckett will join.

What is needed in the next year

- Get organized with the interested institutions on a targeted R&D effort.
- Come up with the protype designs: plans for building and testing these
- Explore possibilities for uRwell for lower exposure layers.
    - Interface with Hall B effort and Jlab-EIC
- Tune the SBS simulation to different condition SBS GEM data and apply to SoLID simulation: revisit rates, occupancies, estimate current drains
- Start engineering designs for modules and trackers





Summary

- SBS run demonstrates that ambitions goals of SoLID tracking are achievable with GEMs.
- Need to calibrate SoLID simulation based on SBS data and plan accordingly.
- Time to get organized.

Back up

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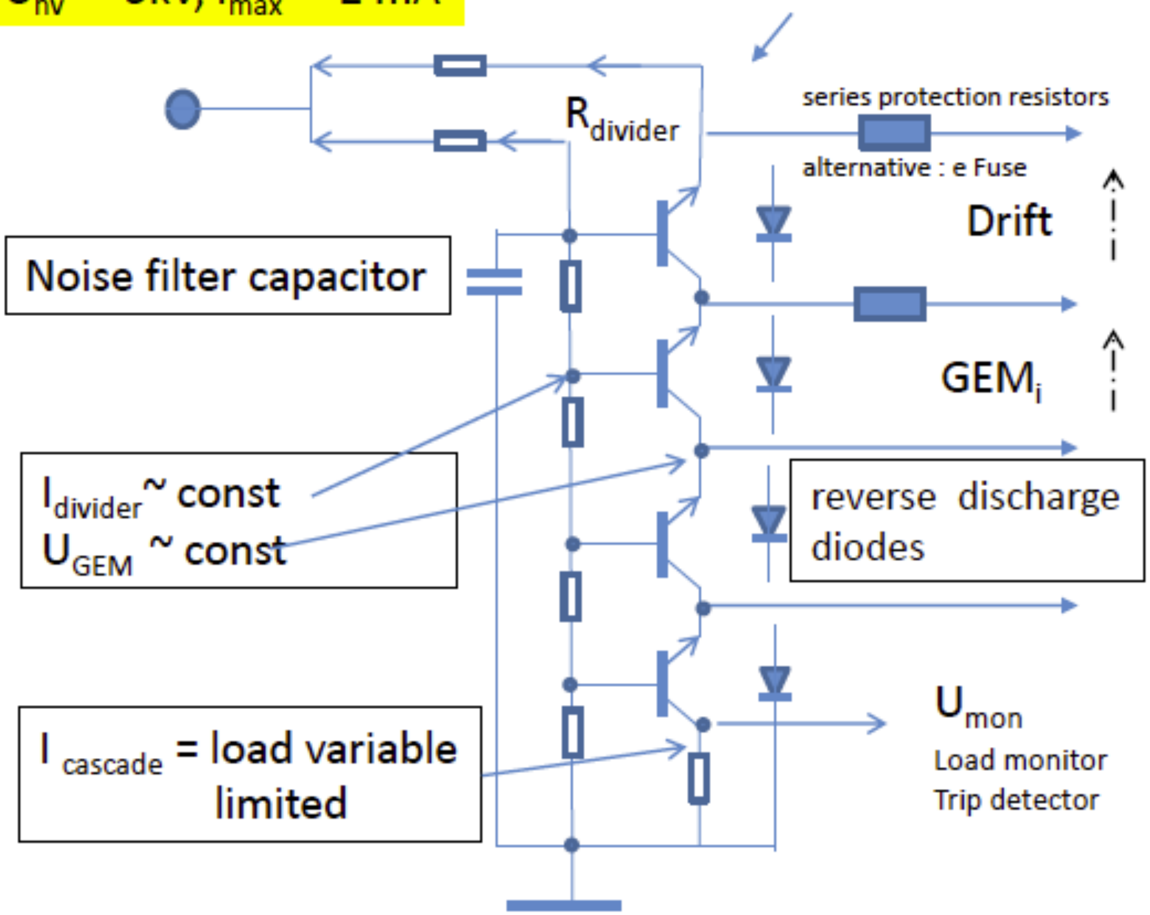
AVD basic principle npn:

max 600V between stages

U_{hv} = -5kV, I_{max} = 2 mA

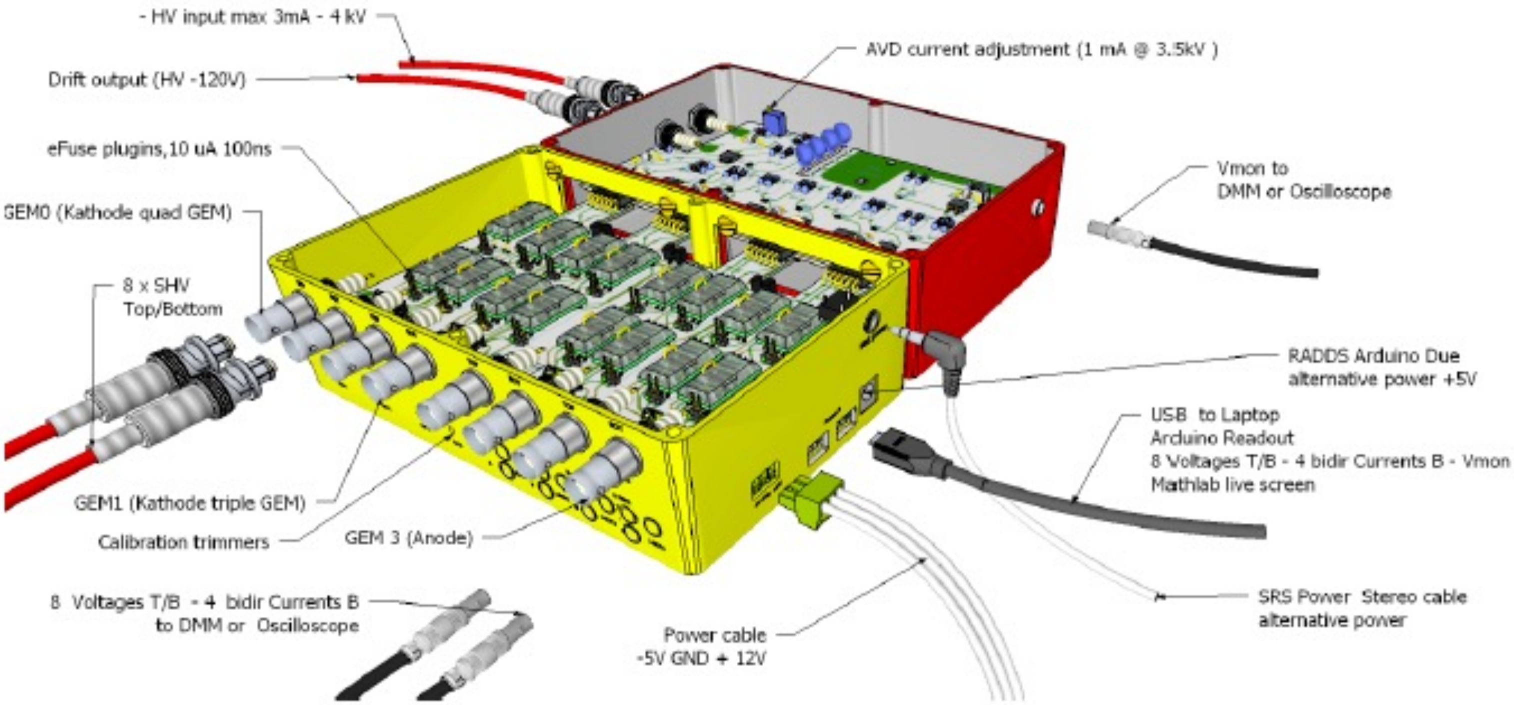


Principle:

- GEM Voltages follow Voltages of resistor divider by ~ 0.8 V but at low output impedance (=> constant voltage)
- load dependent currents flow Through transitor cascade, current load through $R_{divider}$ divided by gain of the transistors (~ 100)
- Regulation max 600 V for Drift and GEM_i
- Primary filter capacitor decoupled From discharge into detector
- Dynamic currents available as U_{mon} for load monitoring and HV trip of all load-induced currents.
- U_{mon} available as very fast trip signal for primary HV supply
- Reverse diodes discharge detector at ramp down

Advantage npn: voltages follow closely $R_{divider}$ U_{EB} variation +/- 0.2V @ T=const
Disadvantage npn: I_{EB} forward currents O(5uA) reflect up 5% load into $R_{divider}$

AVD_{2015} Prototype Implementation



2016: put all (including external HV module) into a single box

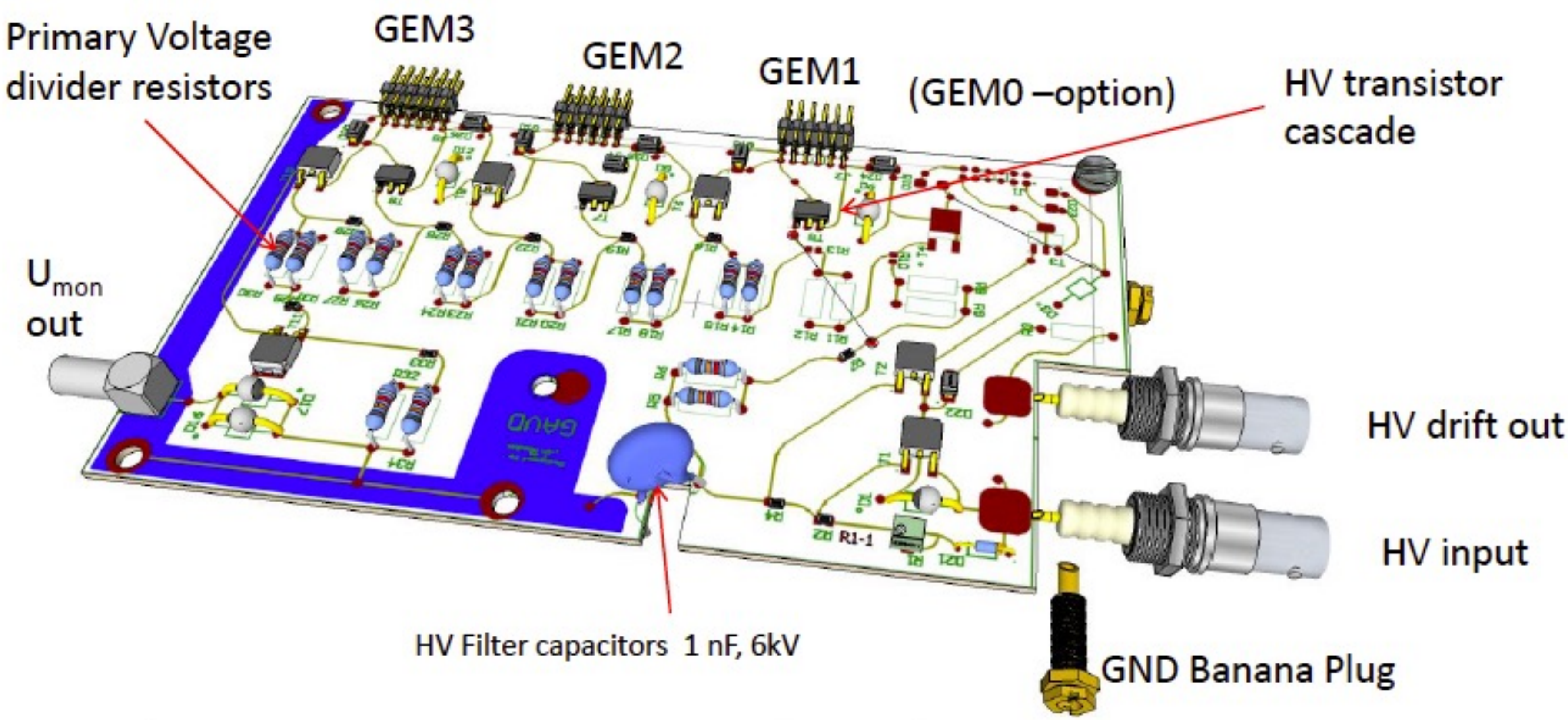
was successful but quite bulky

AVD_{2015} board

(single layer, ceramic)

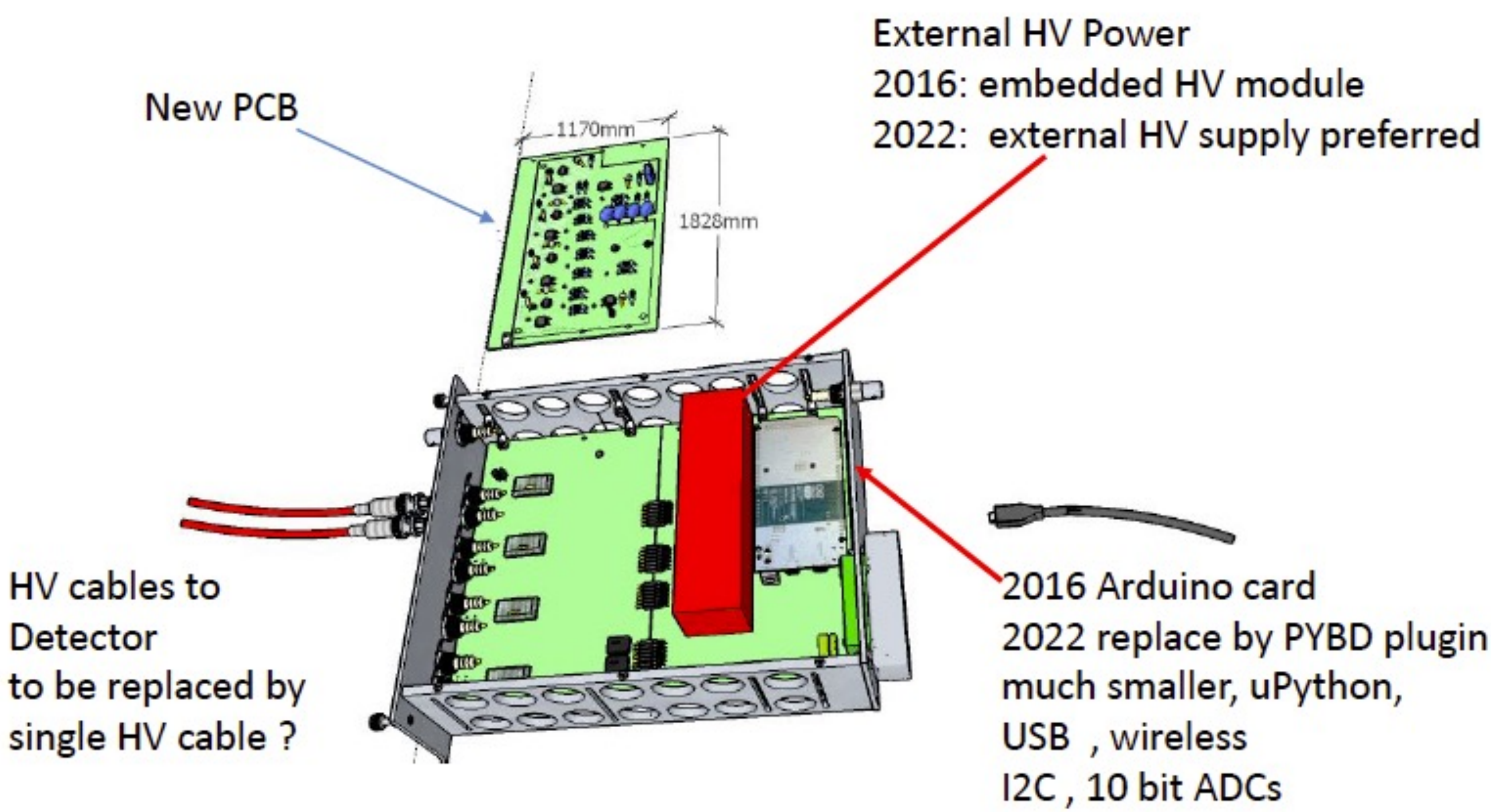
⇒ make some component and connector updates

⇒ fit into NIM module PCB size



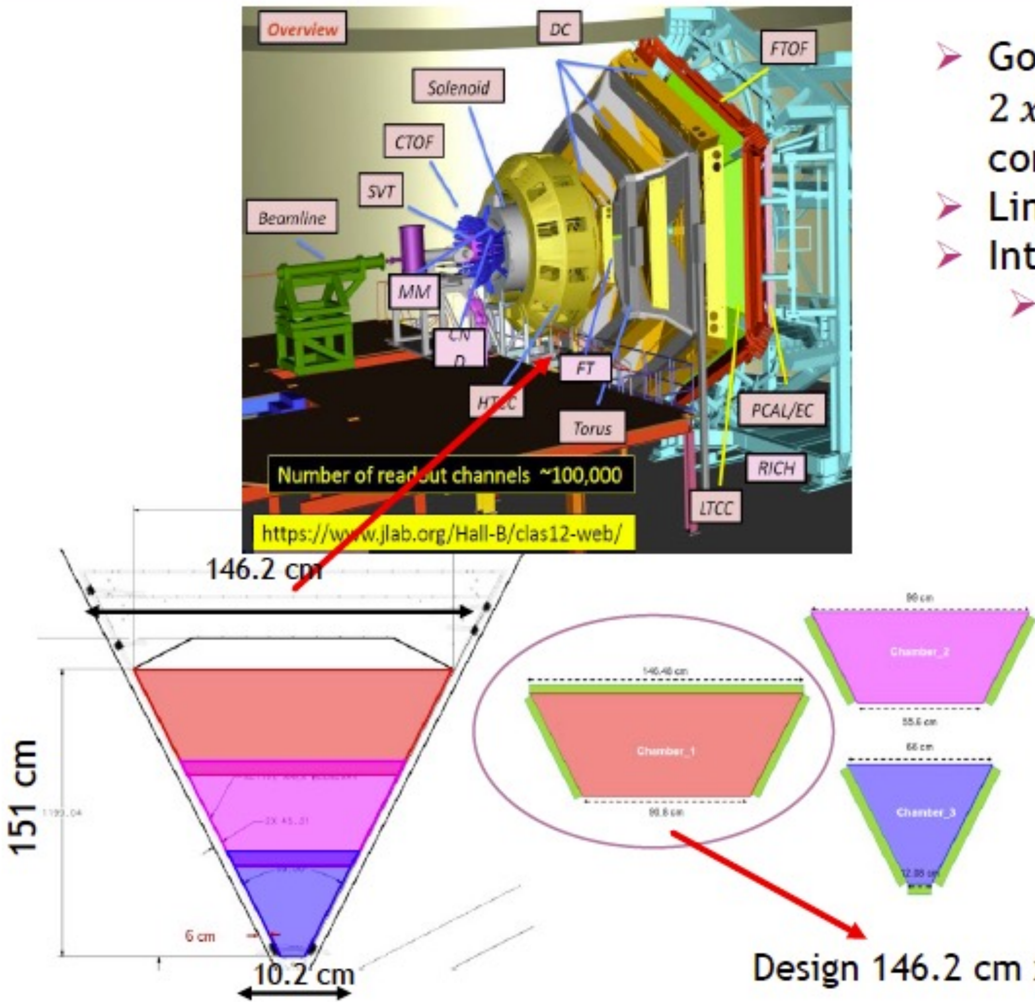
2022 re-boxing of AVD:

fit in NIM module (shown status 2017)



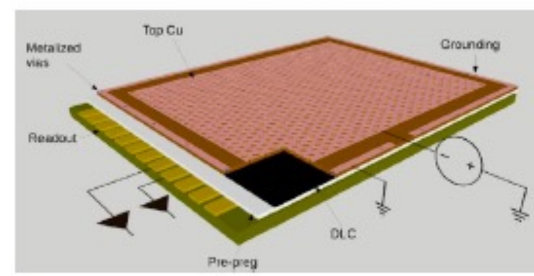
Full size prototype of μRWELL detector

Hall B of JLab: Upgrade of CLAS12 Forward Tracker with "μRWELL" detectors

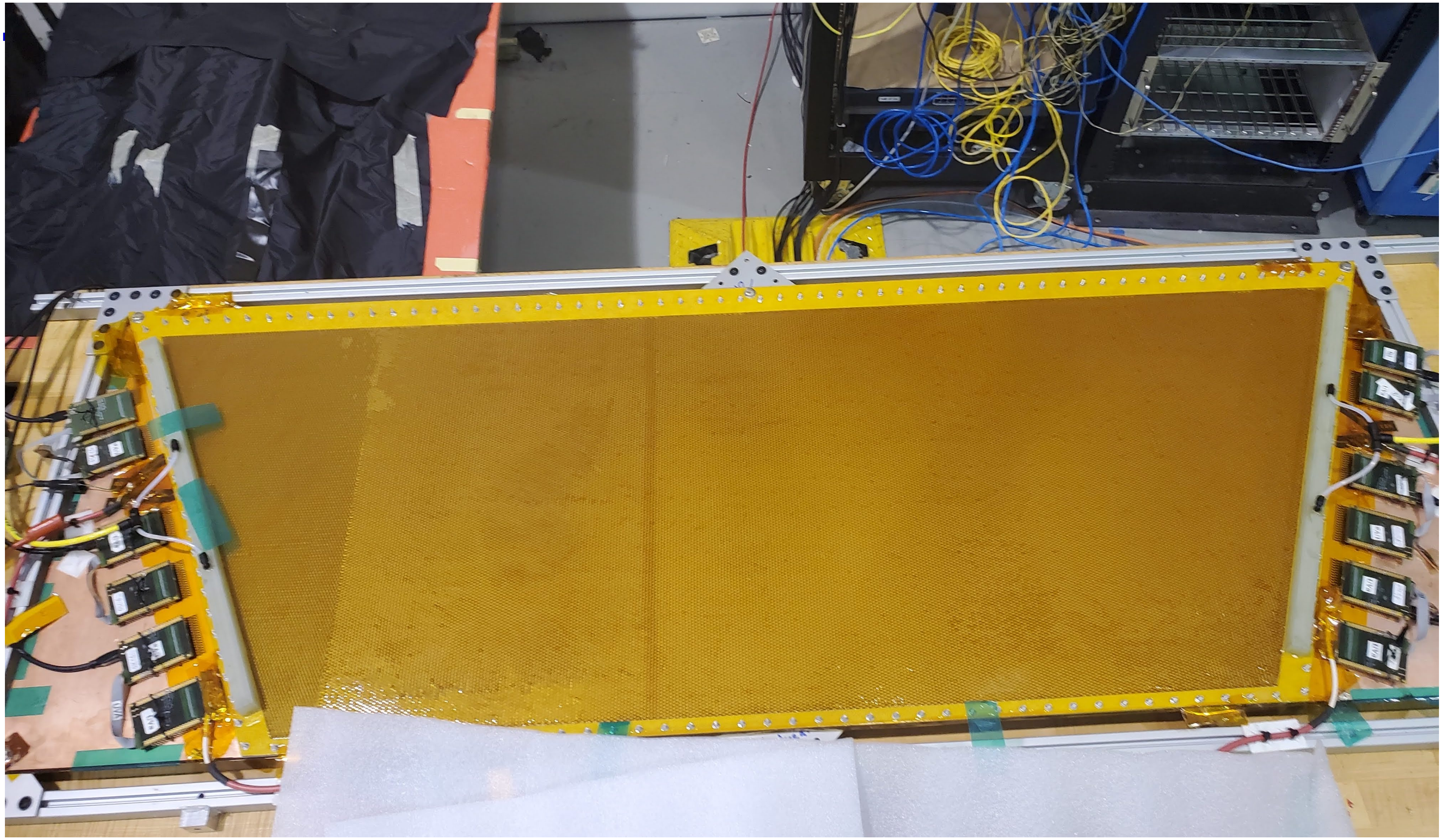


- Goal for upgrade: achieve higher luminosity $2\,x\,10^{35}\,cm^{-2}\,s^{-1}$ than current running conditions $0.7x\,10^{34}\,cm^{-2}\,s^{-1}$ per nucleon
- Limiting factor is forward tracker (FT)
- Introduce uRWELL technology in FT detectors
  - Low-material budget detector; "low mass"

μRWELL technology



Design 146.2 cm x 101.2 cm Chamber 1 prototype at UVa/JLab



Large area uRwell prototype under testing at Jlab