Optimizing Structure and Operation of GEM Detectors for High Particle Rate at Jefferson Lab

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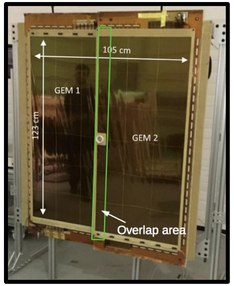
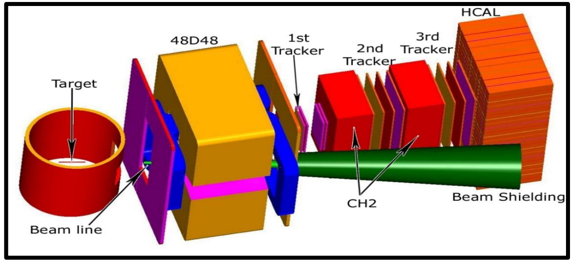
The GEM Program at JLab

❖ Versatile triple-GEM tracking systems at JLab

- **PRad** for Proton Charge Radius measurement
  - One GEM layer: constructed from two large GEM modules
  - Active area of each module: 120×55 cm2
- **SBS** (Super Bigbite Spectrometer) for Nucleon form factors
  - Front tracker: 6 GEM layers, active area of 150 × 40 cm^2
  - Back tracker: 11 layers, active area of 200 × 60 cm^2
- **MOLLER** for Precision measurement of weak charge of the electron Q^e_W
  - 4 GEM tracker layers: each has 7 trapezoidal shaped modules
  - Active area of each module ~2000 cm^2
- **SoLID** (Solenoid Intensity Device) for Precision Measurements in QCD & Electroweak sectors
  - 120 GEM modules expected, active area of each module ~3300 cm2

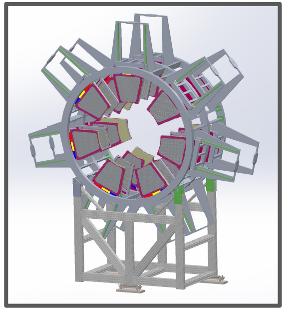


PRad



SBS

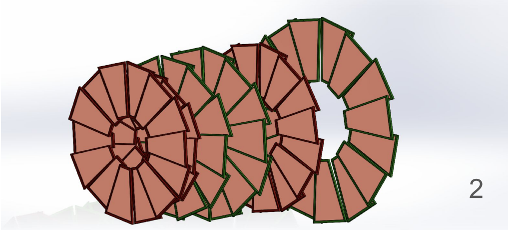
MOLLER



❖ UVA role in GEM program at JLab

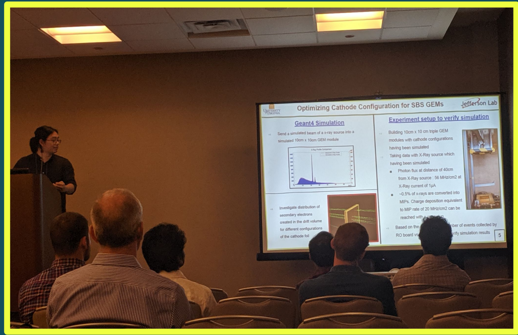
- **PRad:** Both GEM modules were constructed by UVa
  - Highly stable performance in beam during the whole PRad experiment
  - PRad GEMs will be used in the searches for Dark sectors
- **SBS**: Built 4 front-tracker layers & 11 back-tracker layers (48 modules)
  - SBS GEM modules are currently working very well in high intensity beam
- **Moller**: Completed prototype-I, start production of 18 modules in 2023
- **SoLID**: Completed one prototype, finalize design

SoLID



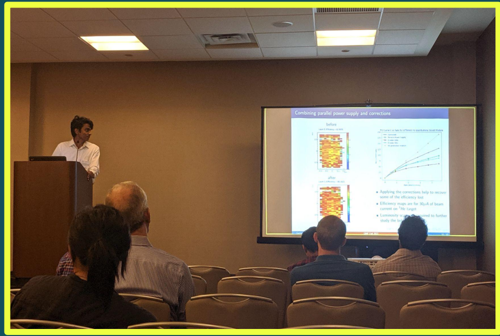
UVA Detector Lab

Simulation & Validation

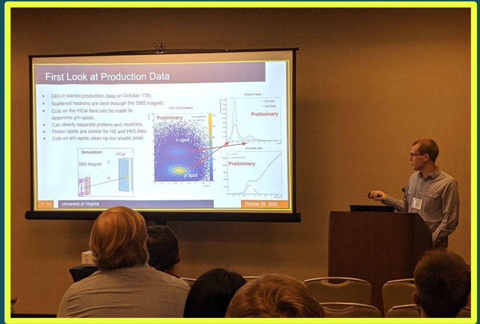


Design & Construction

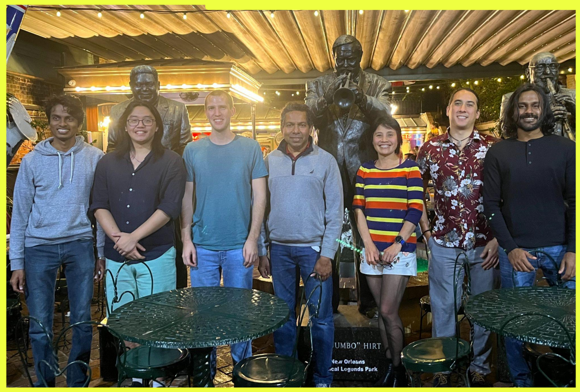
Characterize & Commision



Data & Physics Analysis



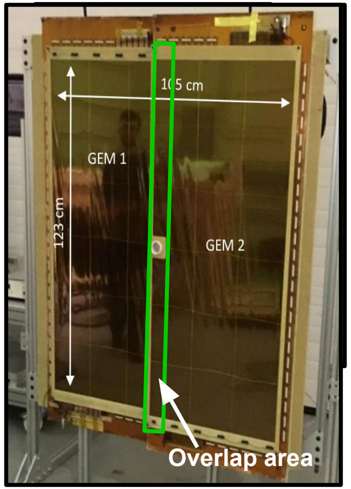
Conductors of the Lab



PRad GEM Detector

❖ PRad GEMs setup at Jefferson Lab

- Two large area GEM modules (150 x 55 cm^2) mounted with overlap region (4.4 x 150 cm^2) to form an opening hole for beam
- Used for position detection of the scattered electrons

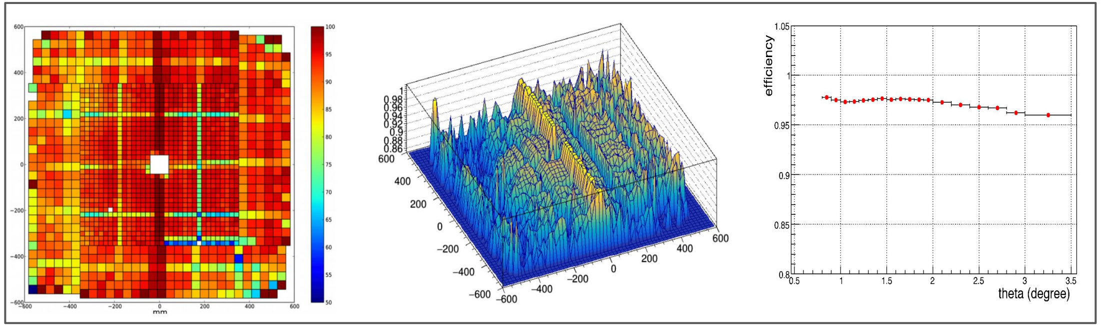


Two Chambers mounted overlap at the center

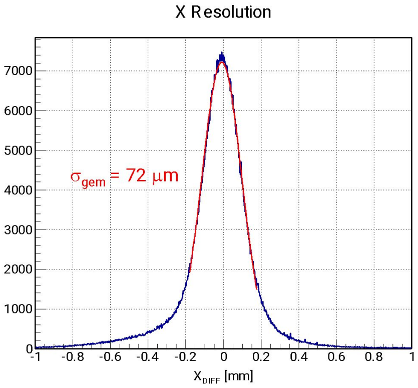
Chambers setup in Hall B at JLab

❖ Performance of PRad GEM detector in beam

- PRad GEM Efficiency in beam: > 95%

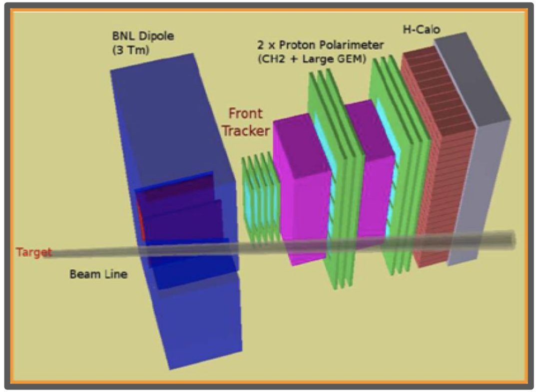


- PRad GEM position resolution: 72 μm

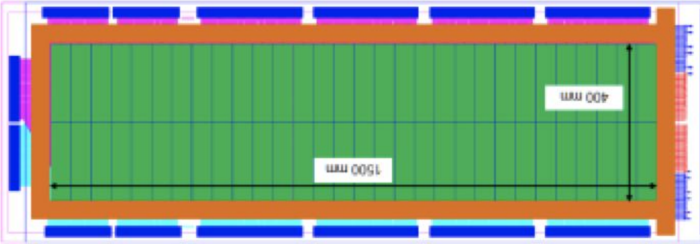


- GEM detector performed highly stable in beam during the whole experiment
- PRad GEM detector improved the experiment resolution by a factor of 20

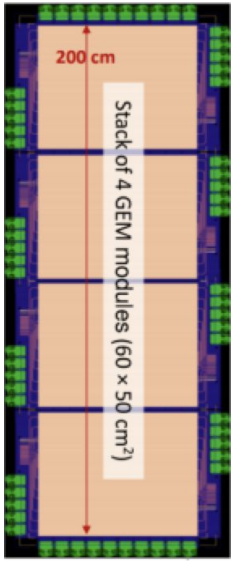
SBS Triple-GEMs Produced at UVA



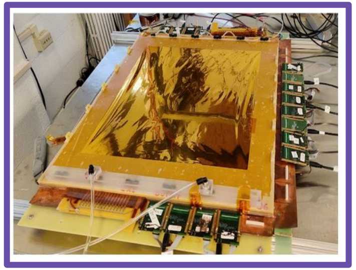
- **4 modules (150 x 40 cm) for front tracker**
  - Each module has 60 sectors
  - Segmentation and protective resistors on both sides of GEMs



SBS 150cm x 40cm



- **48 modules (50 x 60 cm) for rear tracker**
  - Each GEM has 30 sectors, segmentation and protective resistors on top side
  - Stack 4 modules to form a layer with active area of 200 x 60 cm^2



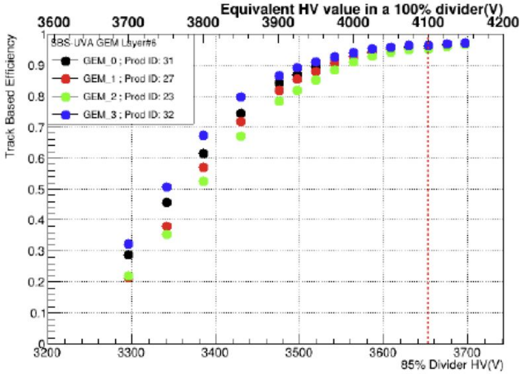
SBS 50cm x 60cm

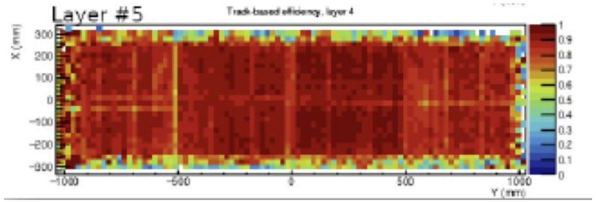
- **Performance of UVA GEMs in SBS High Rate Environment**
  - UVA GEMs have been in beam for GMn (Spring 2021) and GEn-II (Now) experiments
  - Working very stable at high luminosity (~10^{38}) and unprecedented integrated rates
  - Have sufficiently low noise levels; signals well above noise
  - Have very good resolution: close to what was achieved with cosmic's

- **Challenges for GEM tracking systems at JLab**
  - Hit rate exceeding 500 kHz/cm^2 over a large active area of GEM modules
  - High background from Intense low energy photon environment

Challenges from High Rate in SBS Experiments

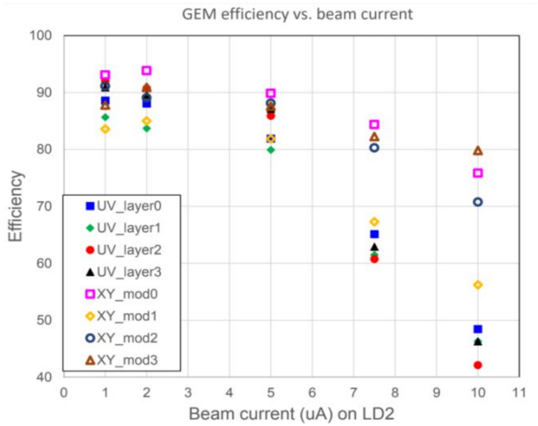
- **Cosmic data of SBS GEMs**
  - ➪ Stable with high efficiency
  - ➪ Sufficiently low noise levels
  - ➪ Good resolution





❖ Efficiency drop in SBS high-rate experiments:

- ➪ GEM efficiency during GMn experiment (Spring 2021) significantly drops as beam current increases
- ➪ Future SBS experiments (GEn-rp, GEp-V) are predicted to have 10x the luminosity of GMn experiment and expected to face similar limitations on a larger scale



❖ Possible causes:

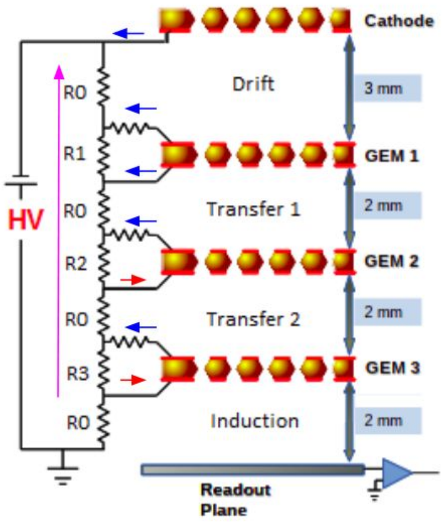
- ➪ High voltage (HV) power supply using resistive dividers limits appropriate field strength in multiple regions in GEM modules
- ➪ High rates increase the difficulty for tracking

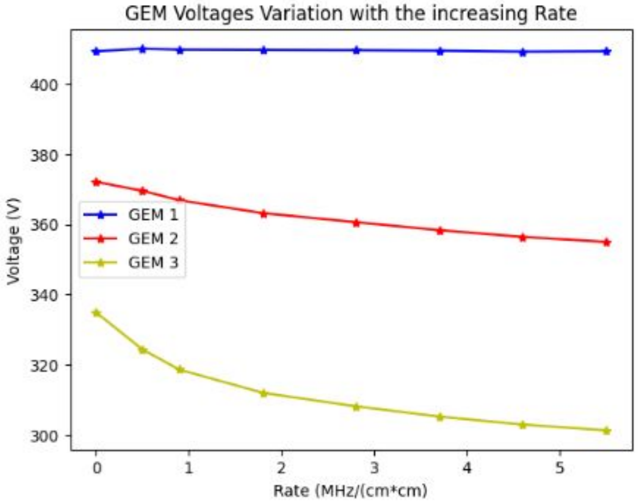
❖ Solving high-rate problem in SBS:

- ➪ **1st** Optimize tracking algorithm for high rate
- ➪ **2nd** Modify HV power supply to restore electric field in GEMs
- ➪ **3rd** Optimize cathode structure to reduce background created in GEM modules

Limitation of Resistive Divider in SBS GEM Modules

❖ Dropping of electric field in GEMs at high rate





- ➪ Currents in & out of GEM electrodes increase with rate
- ➪ They alter the HV distribution at higher rates, weaken the E field in GEM holes
- ➪ Voltage drop in protective resistors further weakens electric field in GEM holes
- ➪ Reduced E field in GEM holes ⇒ reduced gain ⇒ reduced efficiency

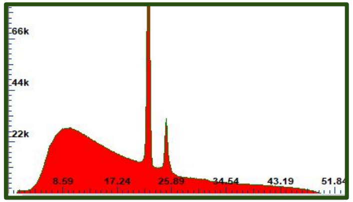
❖ Possible solutions to restore electric field in GEMs

- ➪ Partial solution: Lower resistance of HV divider to reduce ratio of GEM electrode current and main current in divider ⇒ reduce the problem with efficiency lost
- ➪ Better solution: use parallel power supply for each individual region in GEM module
- ➪ Cost-effective solution: Use active HV divider to adjust HV accordingly to beam current intensity

Optimizing HV Distribution for SBS GEM Modules

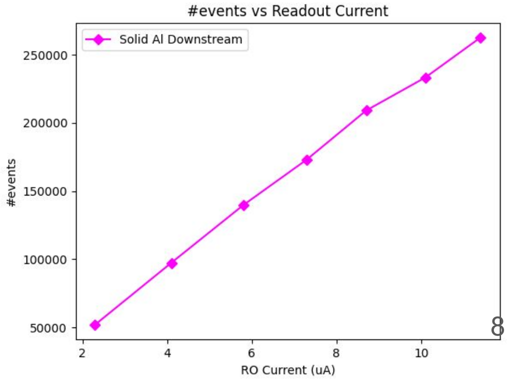
Generating high rate environment @ UVa

- A photon beam is sent from X-Ray source to GEMs:
  - 10x10 cm2 GEM modules placed 40 cm away from source
  - 50x60 cm2 GEM module placed 70 cm away from source
- X-ray generator specifications
  - Photon energy range: up to 50 keV
  - Photon flux at distance of 40cm: 56 MHz/cm^2 (50 keV /1 μA)
- Hit rates on GEMS
  - ~0.5 % of x-rays are converted into MIP equivalent
  - Charge deposition equivalent to MIP rate of 20 MHz/cm^2 can be reached



Evaluating the dependence of GEMs efficiency on HV distribution & hit rate

- Investigate the dependence of HV distribution on hit rate
- Measure readout (RO) current (collecting from RO connectors) vs. hit rate
- Estimate the gain vs. hit rate through the change of RO current vs. hit rate



Changes in Voltage Distribution vs. Hit Rate

❖ **Voltage across triple GEM regions change as hit rate increases**

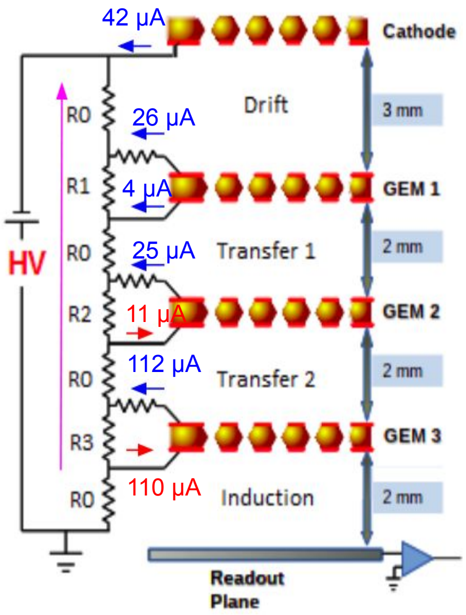
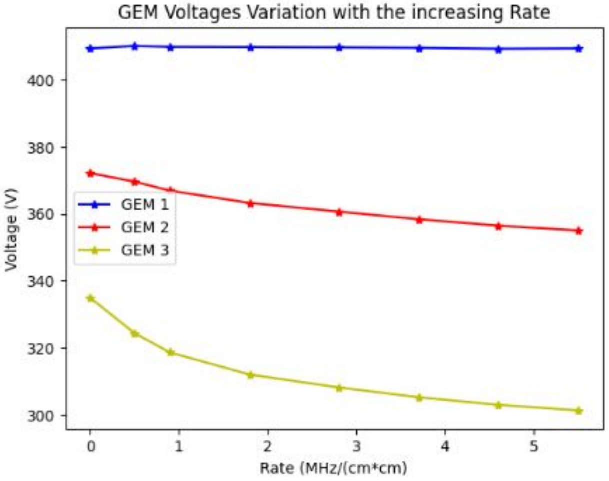
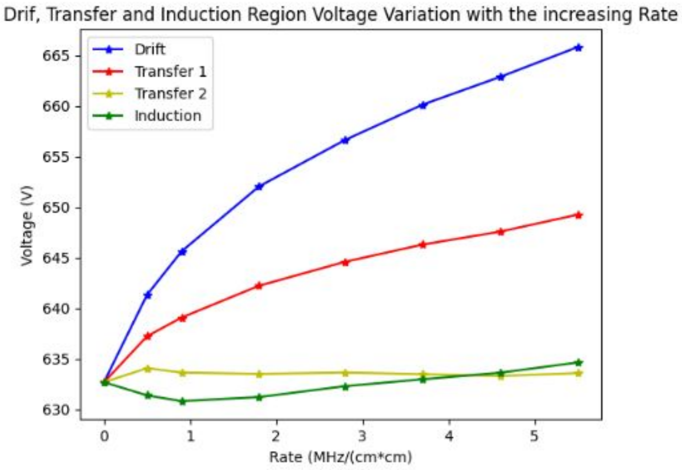


Figure: **Triple GEM regions**



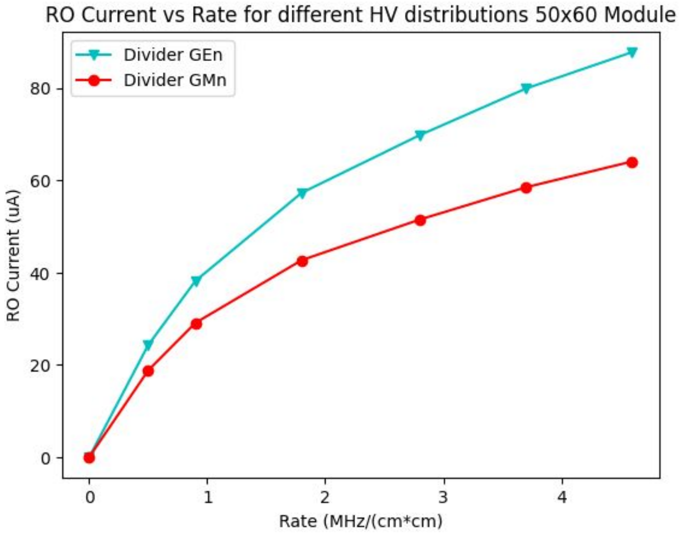


- Significant loss in voltage across GEM 3
- Effect is less severe in GEM 2 and GEM 1
- Voltage across drift, and the first transfer region goes up noticeably

Solutions to Restore Efficiency of SBS GEMs in High Rate

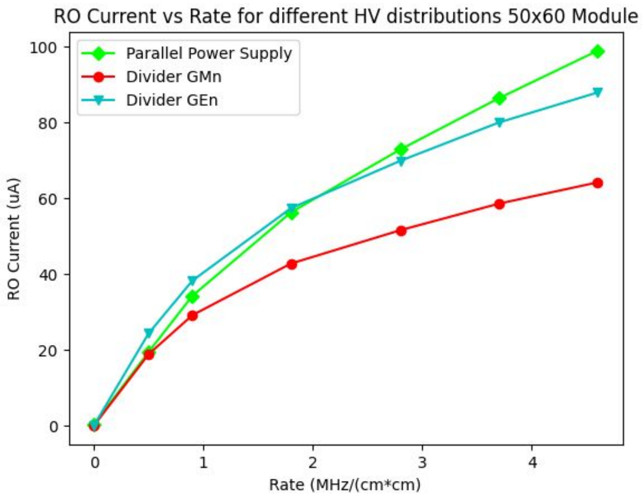
❖ Modify Resistive Divider

Resistive Divider (kΩ)		
Resistor	Old Divider (GMn)	New Divider (GEn)
R_0	850	425
R_1	550	275
R_2	500	250
R_3	450	220



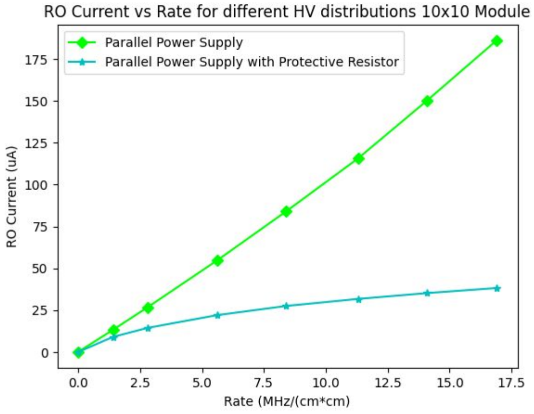
- Reduce divider resistance by a factor of two → reduce the ratio between currents on GEM electrodes and main current through divider
- 10% increase in resistance across GEM3 to compensate for voltage drop on protective resistors

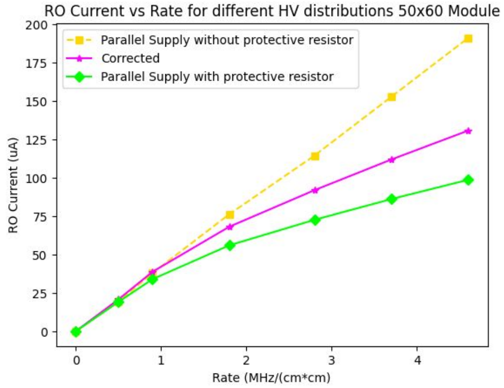
❖ Parallel power supply for individual GEM regions

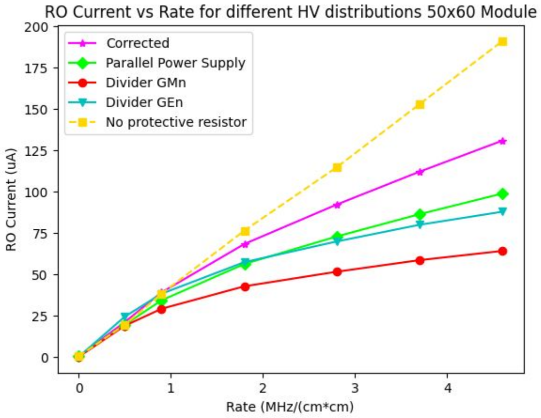


- Limitation of the divider is lifted
- Only the effect of protective resistors remains

Iterative Correction for Voltage Drop on Protective Resistors







- RO current increases linearly with the rate as:
  - Parallel power supply is used for individual regions in GEMs
  - Bypass the protective resistors
- Applying corrections on the parallel power supply to compensate for voltage drop on protective resistors
  - An iterative correction of 3 steps recovers > 90% of the efficiency loss

Recovery of Efficiency Lost in SBS GEM Modules

❖ All solutions tested at UVA are now implemented at GEn Experiment in Jefferson Lab:

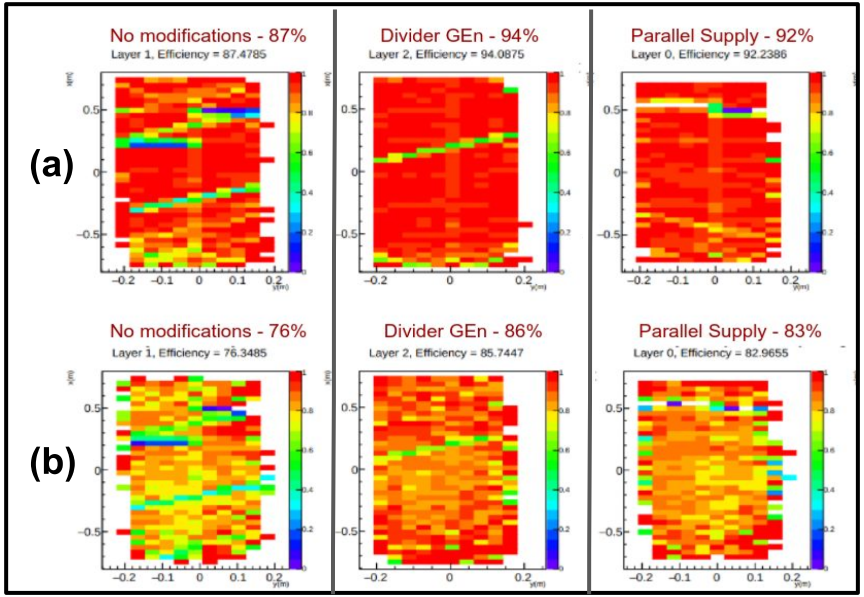


Fig. 1

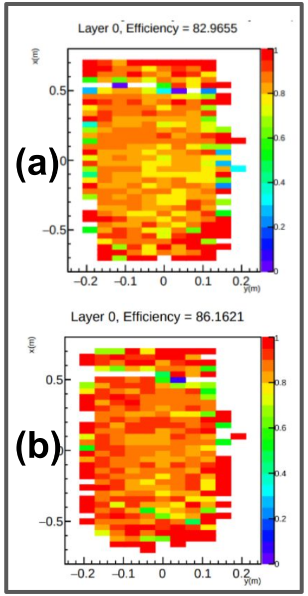


Fig. 2

Fig.1: Efficiency maps with: (a) low beam current on Carbon foil target
(b) 30μA of beam current on ^{3}He target

Fig.2: Efficiency maps with 30μA of beam current on ^{3}He target for GEM module using parallel power supply (a) without correction and (b) with correction

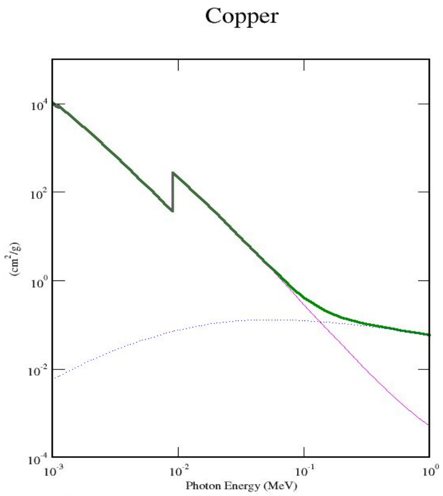
- Parallel Power Supply with iterative correction is used for front tracker GEMs
- Modified Resistive Divider is used for back tracker GEMs
- SBS GEMs worked well in beam with:
  - Stable performance, high efficiency and good resolution
  - Meeting (or exceeding) design parameters

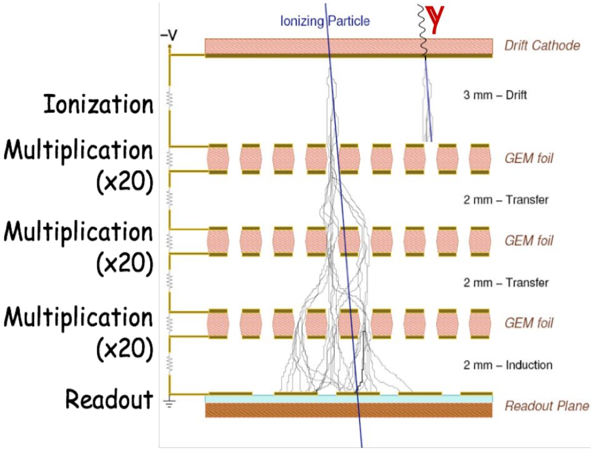
Reducing Background Created in GEM Detectors

- **Interactions between photon background and Cathode layer resulting in secondary electrons**
  - ⇨ Low-energy photons: Photoelectric Effect, Compton Scattering
  - ⇨ High-energy photons: Pair Production

- **Problems with secondary electrons created in drift cathode layer**
  - ⇨ Drifting towards GEM foils, multiplying in GEM holes, then creating false signals
  - ⇨ Lowers GEM efficiency
  - ⇨ Causing problem with GEM tracking analysis

- **Optimizing configuration of GEM cathode foil to reduce photon background effects**
  - ⇨ Material of the conducting layer of cathode layer
  - ⇨ Structure of conducting layer (absence/presence of etched out holes)
  - ⇨ Orientation of cathode layer in GEM module

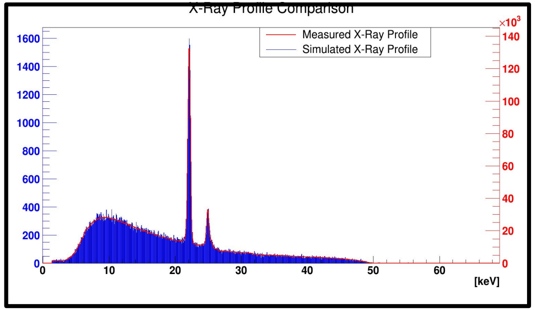




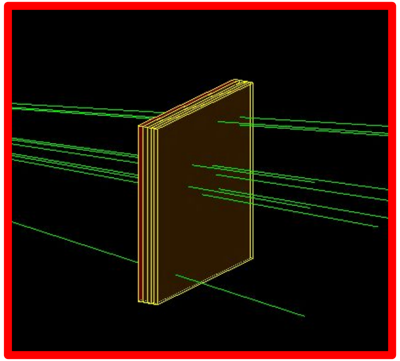
Optimizing Cathode Configuration for Moller GEMs

Geant4 Simulation

- Send a simulated beam of a x-ray source into a simulated 10cm x 10cm GEM module



- Investigate distribution of secondary electrons created in the drift volume for different configurations of the cathode foil



Experiment setup to verify simulation

- Building 10cm x 10 cm triple GEM modules with cathode configurations have been simulated

- Taking data with X-Ray source which have been simulated

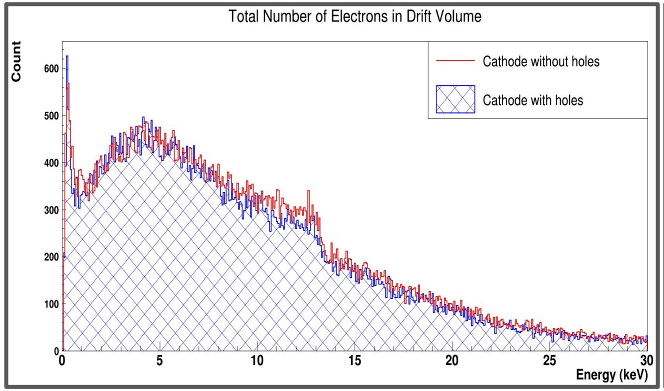
- Based on the distribution of number of hit collected by RO board vs. X-Ray current to verify simulation results

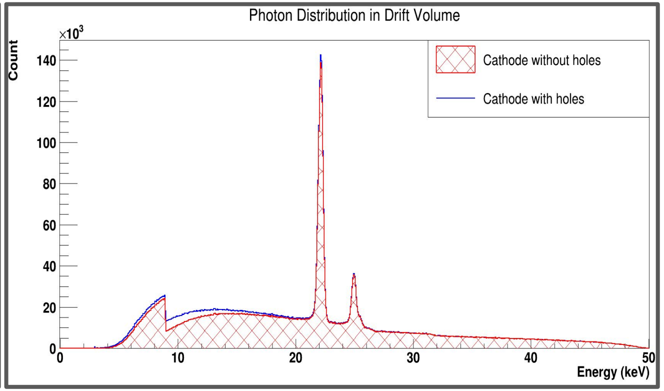
Cathode Structure vs. Background Levels

Investigating two structures of cathode foil in the GEM module:

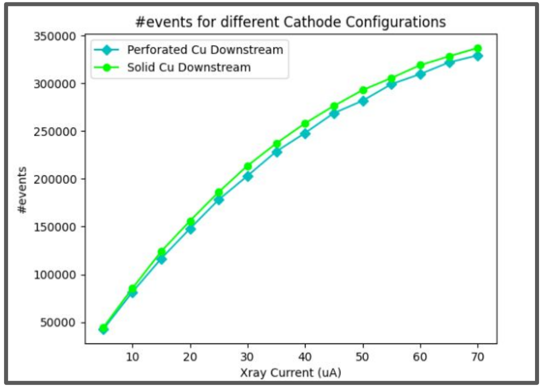
- Cathode foil has a perforated copper layer (similar hole pattern as GEM foils).
- Cathode foil has a solid copper layer

Simulation result





Experimental result



Conclusion

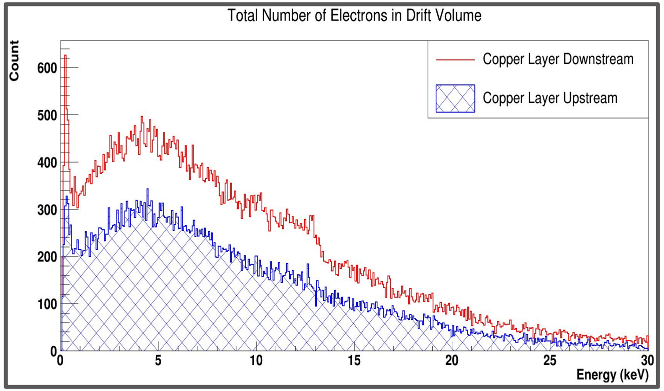
- Number of higher-energy secondary electrons in the drift volume is slightly lower with perforated cathode foil.
- Number of hits collected from RO board is slightly lower with perforated cathode foil
- Having holes in copper layer also helps to reduce multiple scattering of real signal
- Cathode foil in Moller prototype-I has solid copper conducting layer → will be changed to perforated copper conducting layer

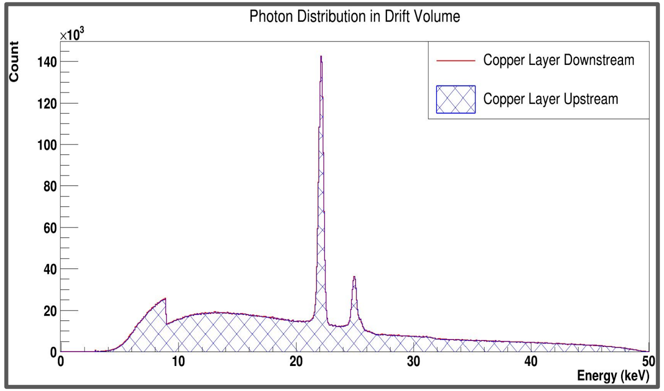
Cathode Orientations vs. Background Levels

Investigating two orientations of cathode foil in the GEM module:

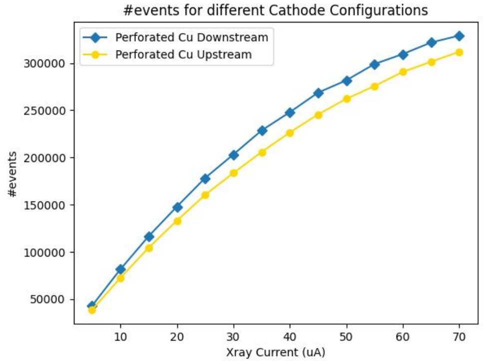
- Cathode foil made of two attached layers: Copper (5 µm) and Kapton (50 µm)
- Conducting copper layer of cathode foil is **upstream of beam** (facing towards incident particles)
- Conducting copper layer of cathode foil is **downstream of beam** (facing away from incident particles)

Simulation result





Experimental result



Conclusion

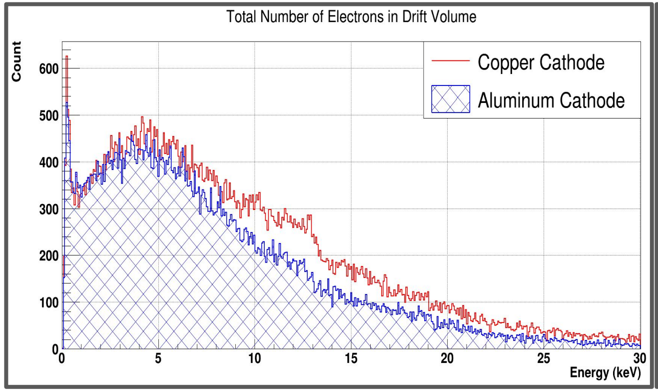
- Photon absorption is identical regardless of orientation
- Number of secondary electrons in the drift gas region is significantly lower with upstream orientation
- Number of hits collected from RO board is lower with upstream orientation

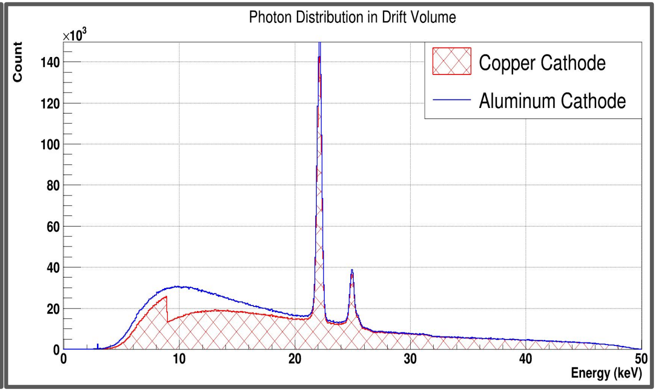
Cathode Material vs. Background Levels

❖ Investigating two conducting materials of cathode foil in the GEM module:

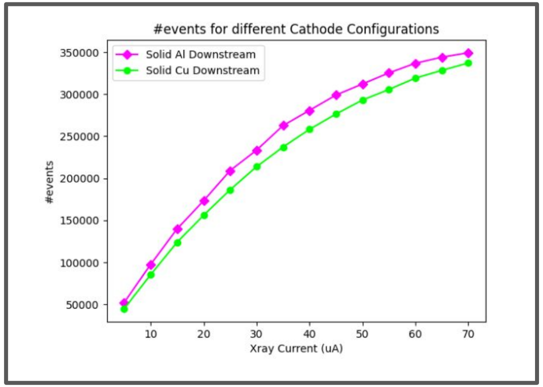
➪ Cathode foil: 5.0 μm copper layer vs. 1.0 μm aluminum layer

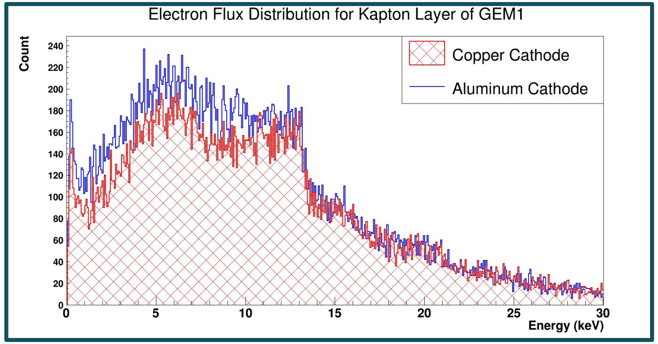
Simulation result





Experimental result





▪ Conclusion

➪ Photon absorption is significantly higher for copper layer

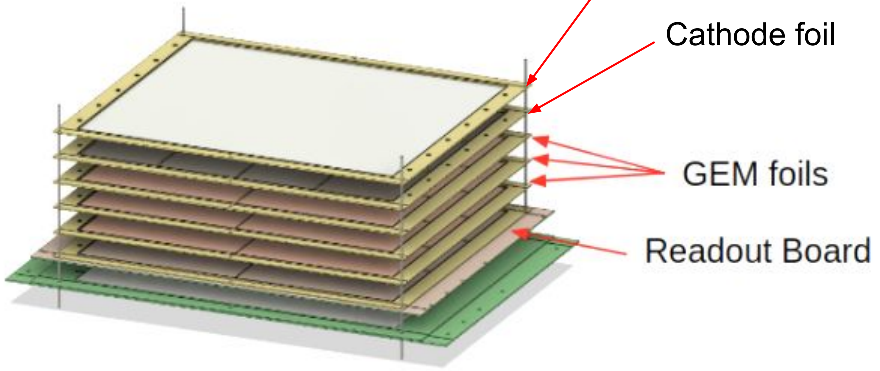
➪ Photons passing through aluminum cathode foil **strikes on copper layer of 1st GEM foil** & creates secondary electrons which induce false signals

➪ Number of hits collected from RO board is lower with copper cathode foil

➪ Need to optimize the top layer of GEM1 to reduce effect of photon bkgs

Possible Configurations for GEMs in High Rate

▪ Current Design of SBS GEMs Modules



▪ Possible modifications for SBS GEMs

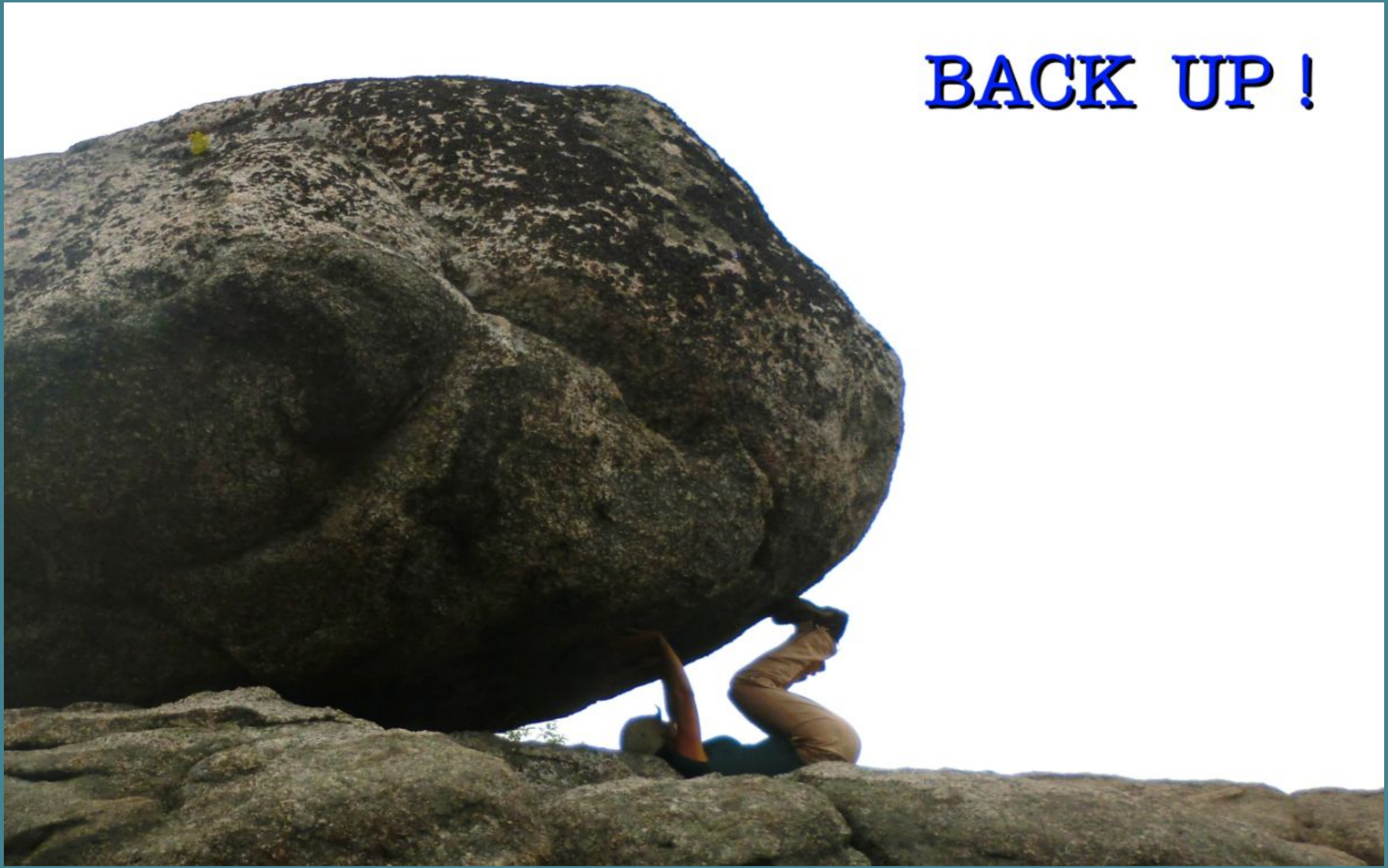
- Change in Window foil:
  - Use Copper-Kapton foil instead of Aluminum-Kapton foil
- Change in Cathode foil:
  - Use the foils with holes
- Explore option of combination of:
  - Al-Kapton window foil, Al-Kapton cathode foil, and GEM1 has Al as the top layer
  - Cu-Kapton window foil, Cr-Kapton cathode foil, and GEM1 has Cr as the top layer
- Random electrode sectorization in GEM foils

Summary

- **UVa GEM group has a highly successful fabrication program for large area GEMs**
  - Capable of operating under extreme high rate conditions
- **PRad detector performed stably in beam during the whole experiment**
  - Efficiency above 95%, position resolution of 72 µm
  - Improved the PRad experiment resolution by a factor of 20
- **Challenges for GEMs tracking from High Rate in SBS Experiments**
  - Challenges have been addressed and changes have been implemented to restore GEMs efficiency
    - Using Parallel Power Supply for HV distribution
    - Modifying resistive divider to reduce the effect of high rate on E field in GEMs
  - Explored changes in SBS GEMs configuration to reduce photon background effects
    - Modification in the combination of Window-Cathode-GEM1 foils
- **Incoming activities at UVA Detectors Lab**
  - Construct two more large GEM modules (150 cm x 40cm) for SBS experiments
  - Start the production of 18 modules for MOLLER experiment
  - R&D on Gas Detector for EIC (Electron Ion Collider)
  - **Looking for a Postdoc to join our team!**

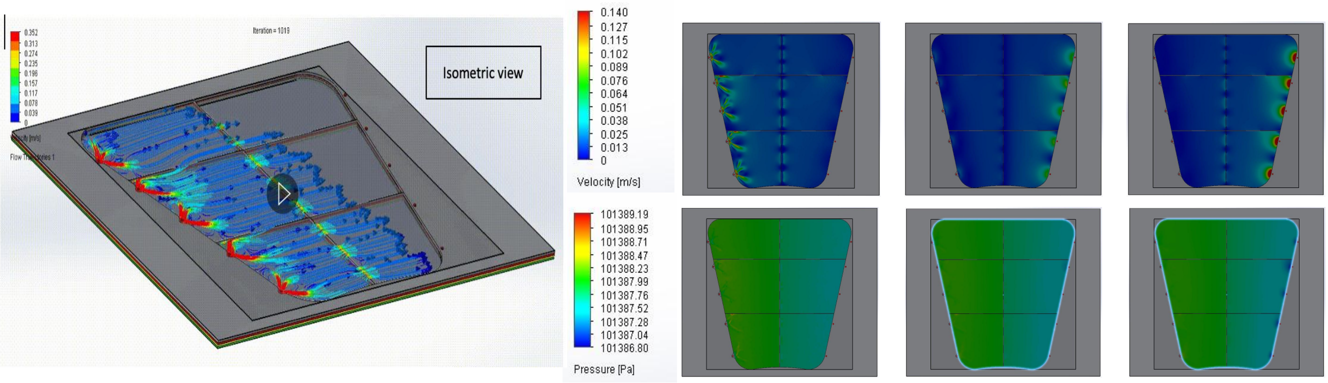
Acknowledgement

- ***Sincere thanks from our UVA Detector lab to:***
  - **The MPGD community for thorough R&D efforts**
  - **Continuous support from CERN/PCB Workshop**
  - **US Department of Energy, Office of science, Office of Nuclear physics award number DE-FG02-03ER41240**

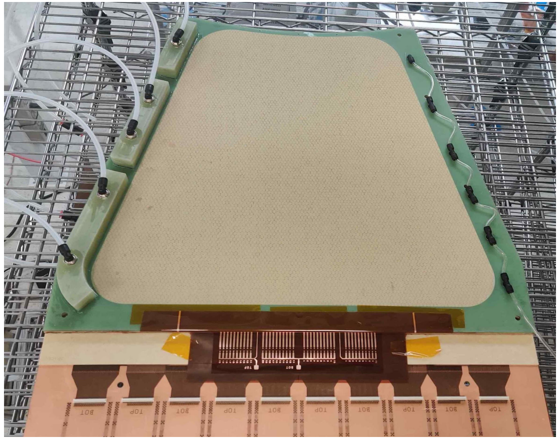

BACK UP !

Incoming GEMs Tracking Systems at JLab

❖ Triple-GEM Trackers for Moller Experiment



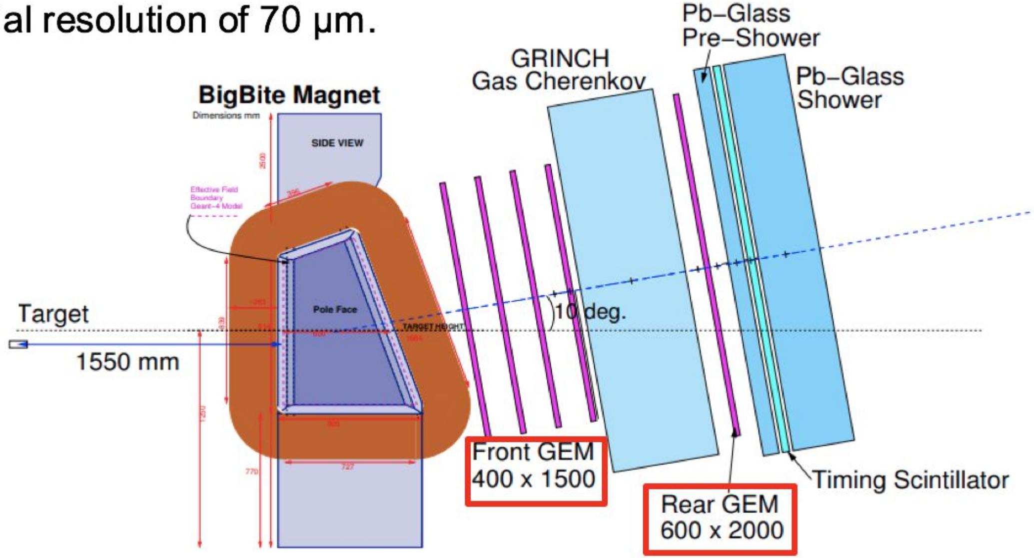
- Improvements in design for HV distribution, gas flow, shielding & readout based on experience with SBS GEMs



- Moller prototype-I was successfully assembled and expected to get cosmic and X-Ray data next week.
- Moller critical requirements:
  - Consistent internal gas flow and equal gas pressure in entire GEMs
  - Suppressing background created in GEM modules due to intense low energy photon environment

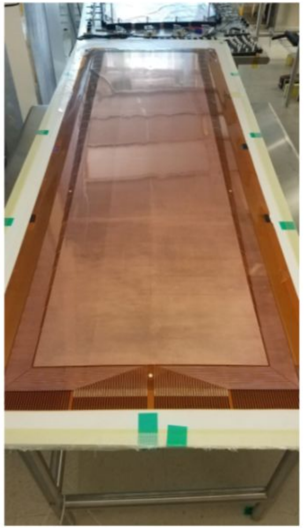
GEM use in SBS

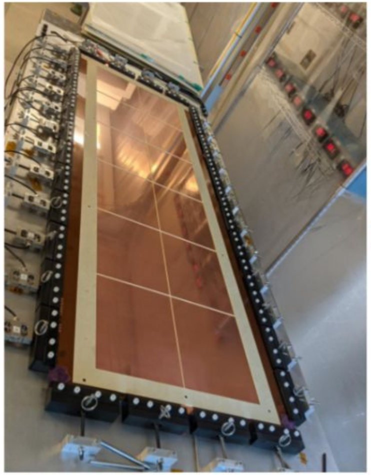
- GEMs in the electron arm will be used to track the particles trajectories.
- GEMs can meet all the requirements of the SBS program:
  - At least 500 kHz/cm^2 rates.
  - Large acceptance of 75 msr.
  - Good spatial resolution of 70 μm.

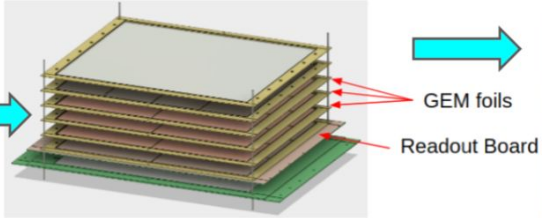


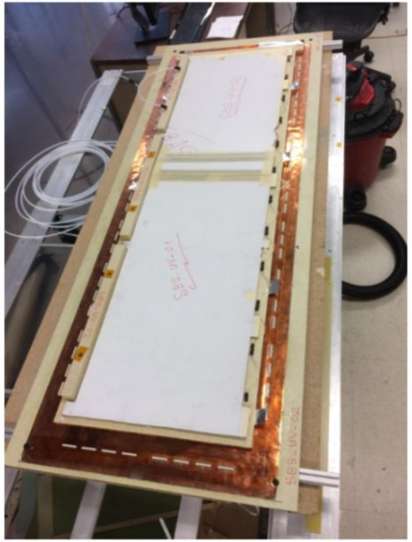
U-V GEM Construction

- Construction began in August 2020.
- Foils are stretched to guarantee flatness and glued together.
- Four U-V GEMs completed by May 2021.



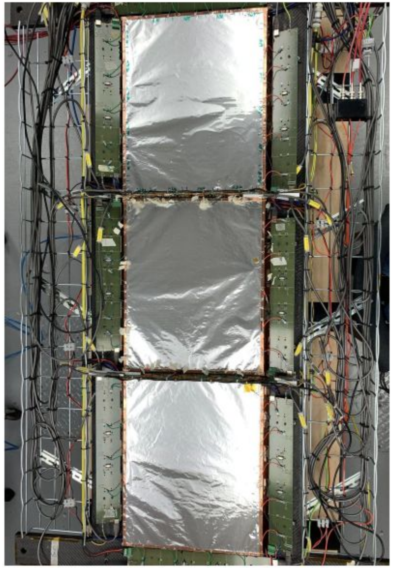




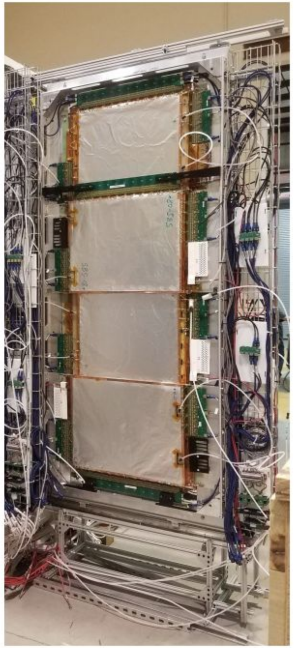


SBS GEM Types

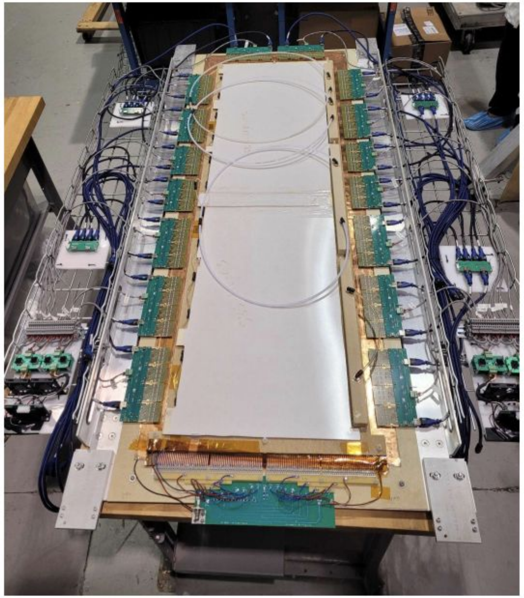
INFN X-Y



UVa X-Y

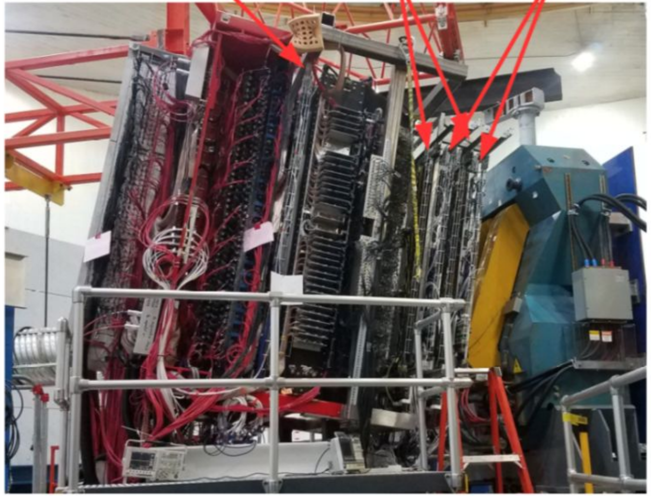


UVa U-V



SBS GMn/GEn Spectrometers

BigBite Spectrometer (Electron Arm)

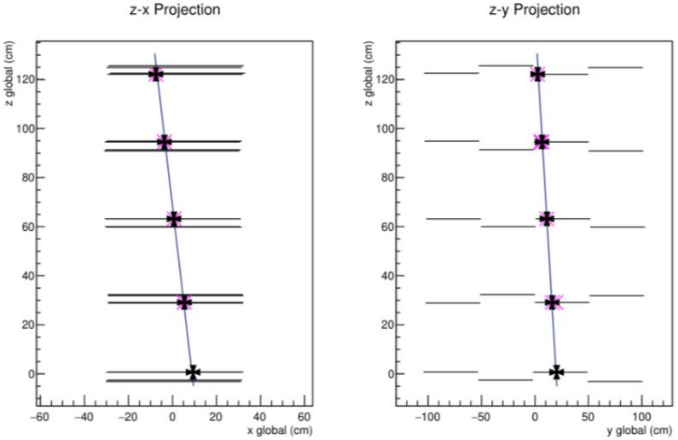


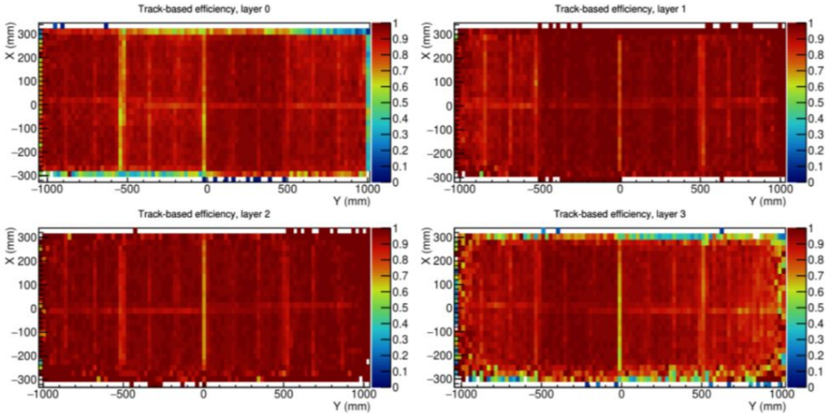
Super BigBite Spectrometer (Neutron/Proton Arm)

GEM Commissioning at JLab

- Layers stacked together on a large cosmic stand.
- Multiple layers with hits can be used to form tracks.
- Tracks are projected through all layers to look for real hits.

$$\text{Efficieny} = \frac{\text{\# of hits found}}{\text{\# of tracks that should hit}}$$





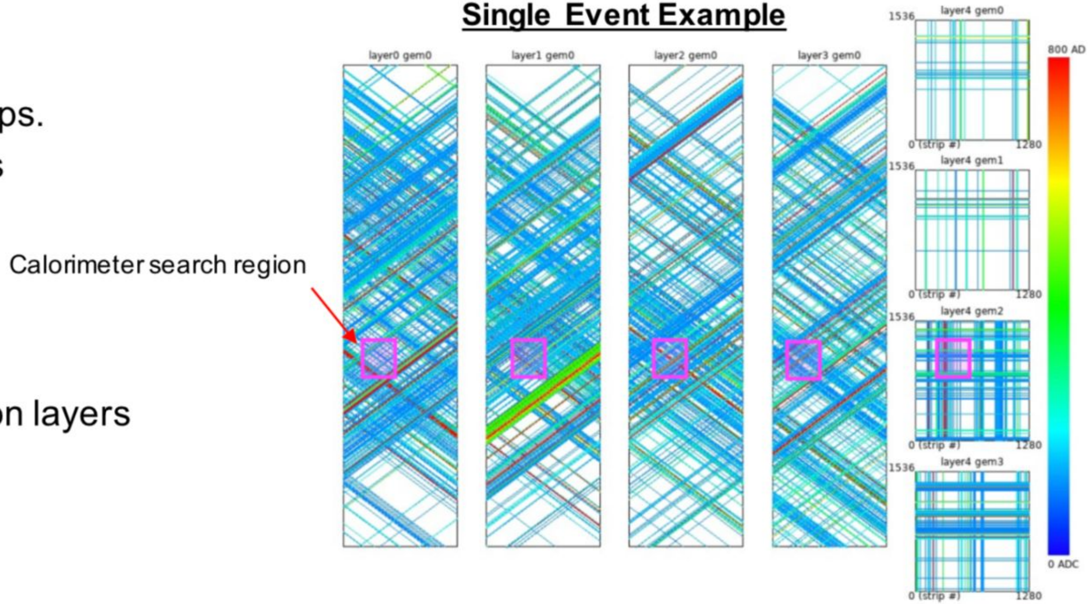
High Rate Tracking

- Large number of possible of 2D hit combinations.
- “Fake hits” from noise would artificially reduce the tracking efficiency.
- Signal on top of a large background could be lost, reducing the efficiency.

Tracking Procedure

- Form all 2D hit combinations from strips.
- Filter hits using a variety of thresholds
  - Cluster ADC
  - Correlation coefficients
  - ADC asymmetry
  - Timing cuts
- Form all possible tracks through hits on layers
  - Cut on calorimeter region
  - Cut on projection back to target

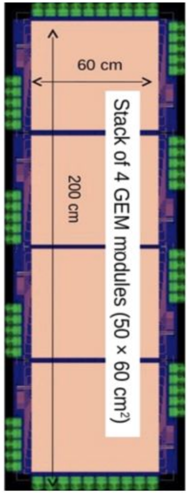
Single Event Example



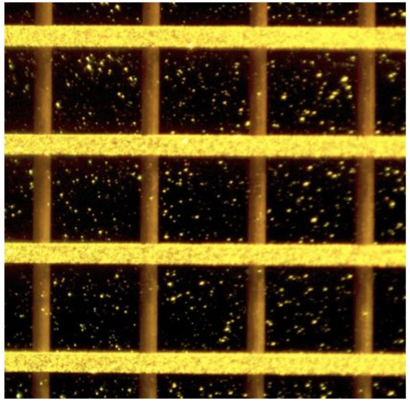
U-V GEM Readout

- UVa group has produced 50 X-Y and 4 U-V GEMs for the SBS experiments.
- National Institute for Nuclear Physics (INFN) in Italy has produced 12 X-Y GEMs.
- Technological improvements have made U-V orientation GEMs possible.
- U-V GEMs can be larger ⇒ Reduce size of dead areas.
- U-V GEMs provide extra coordinate information ⇒ Improved tracking results.

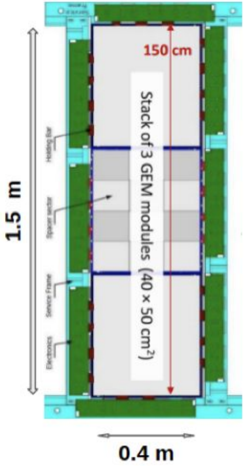
UVa X-Y



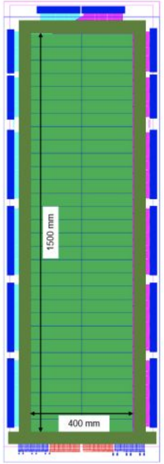
X-Y Readout Strips



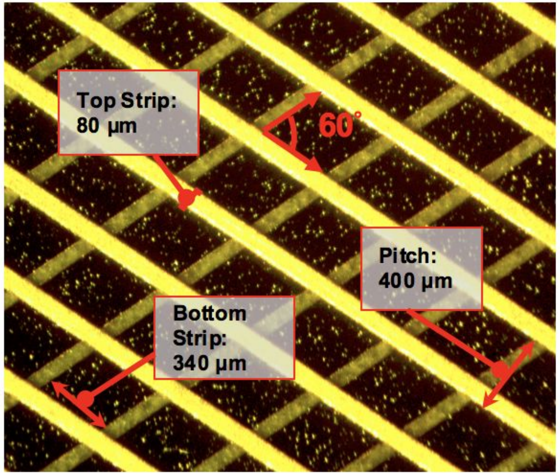
INFN X-Y



UVa U-V

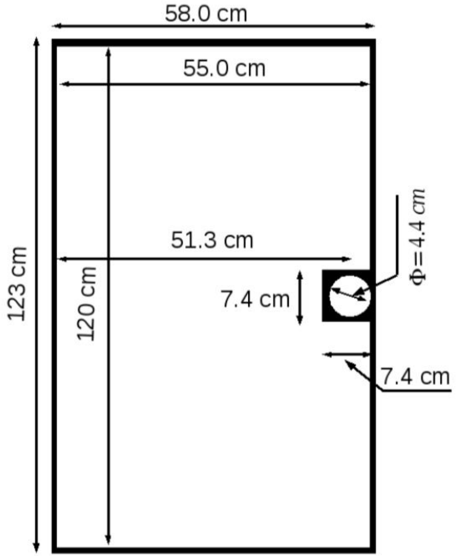


U-V Readout Strips

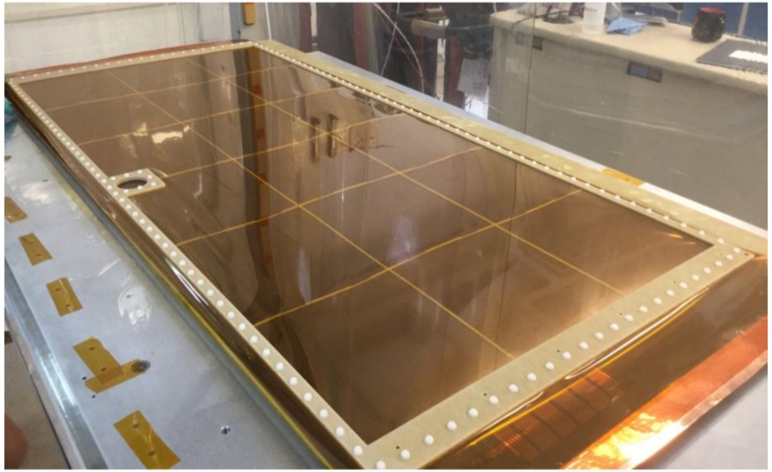


GEM Detectors

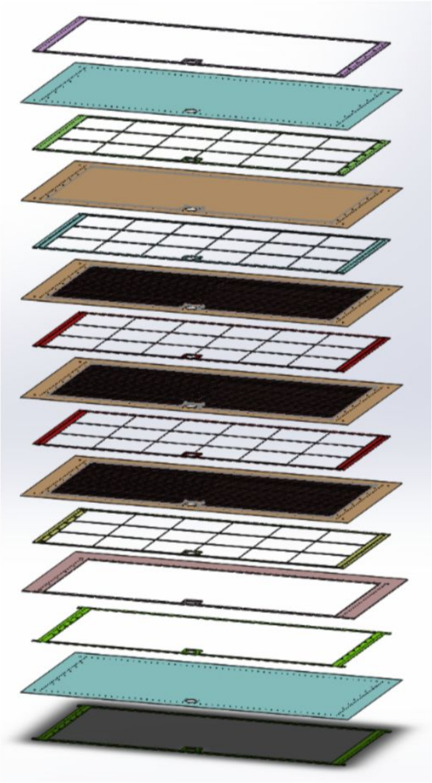
- Sensitive area: 120 x 120.6 cm^2
- Central hole: diameter 4.4 cm
- Non-sensitive area 7.4 x 7.4 cm^2



The world's largest GEM chambers



PRad GEM detector in UVa Detector Lab



Triple GEM detector

Active Divider

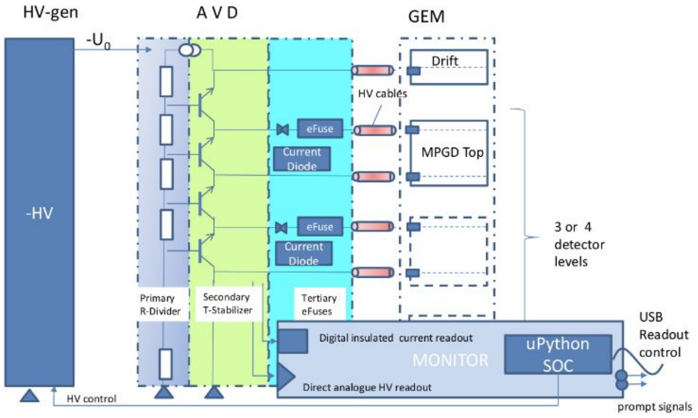


Figure: AVD Schematic

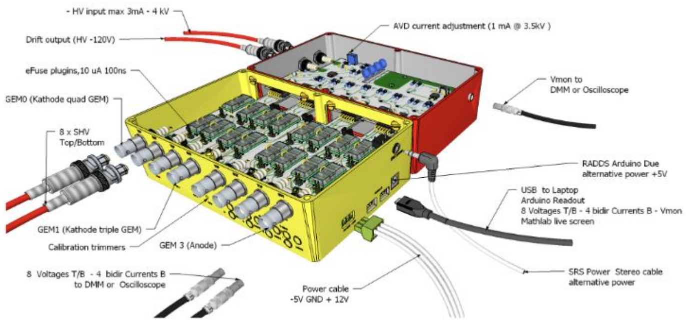


Figure: AVD Schematic

Credit : Hans Muller and his group at Cern

- we are going to give this a try too
- parallel power supply is the best solution but expensive

Performance of UVA GEMs in SBS High Rate Environment

- **Handling the rate of 500 kHz/cm2 is not difficult for GEMs, but the challenge here is doing that over a very large area**
  - Very high rates and high occupancy in long readout strips
  - High current drain into the GEMs causing voltage drops in divider and protective resistors
- **SBS high rate environment:**
  - Very high luminosity ~1038
  - GEMs are operating under unprecedented integrated rates (active area x local rate):~ 3 GHz/chamber
  - About 3 MHz in each readout strip
- **UVa GEM trackers are performing very well in high rates**
  - Overall good efficiency
  - Very stable: very few HV trips
  - Noise levels sufficiently low
  - Good gain: signals well above noise
  - Very good resolution: close to what was achieved with cosmic’s
  - Raw occupancy levels as high as 30%: with cuts, down to a few percent level.
  - Real time firmware zero suppression has been working very well.
  - Data volumes manageable

GEM HyCal Matching Mechanism in PRad

- The matching requires that for each GEM hit that originates from target, its projected position on HyCal must be within a 6σ range around the HyCal reconstructed position
  $R_{match} = 6 \times \sigma_{HyCal}$
- HyCal position resolution is 20 times larger than GEM position resolution