GEM-based tracking detectors for Nuclear Physics Experiments

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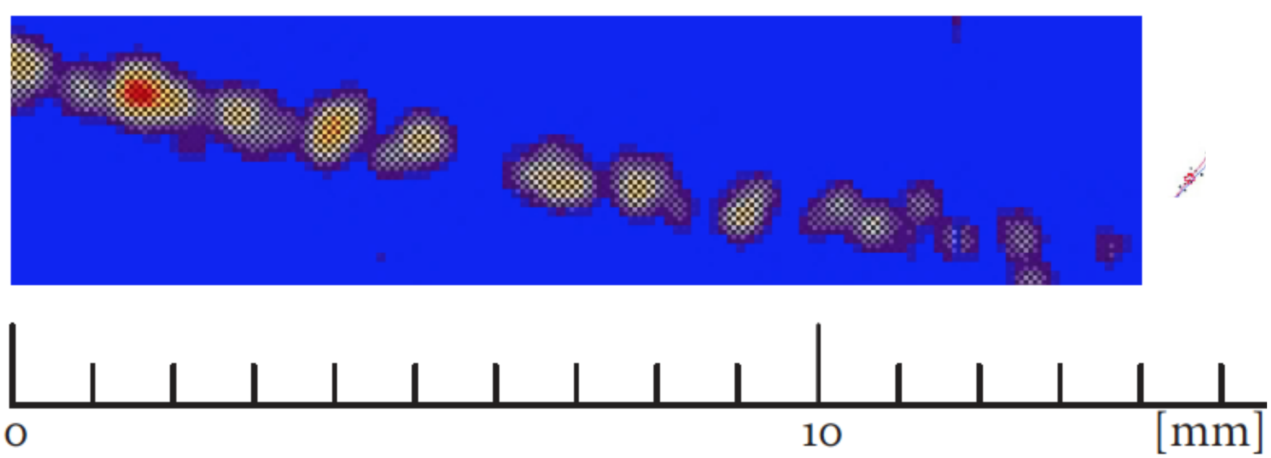
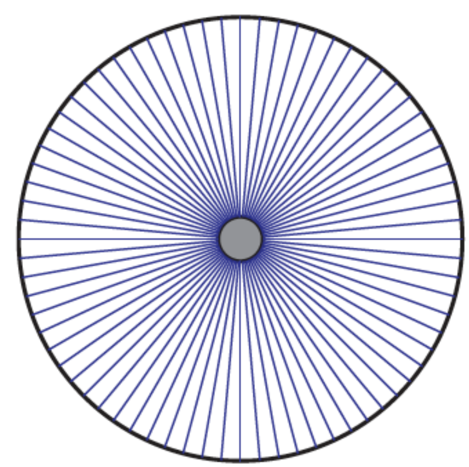
Gaseous Detectors

- Predate nuclear physics: invented by Hans Geiger in 1908 (Rutherford, Geiger, Marsden gold foil experiment 1911)
- Essential features:
  - Ionization/drift region: high energy particles creates a trail of electron-ion pairs in an inter gas (reduces recombination)
  - ~ 1-2 Primary ionizations per mm (at 1 atm), energetic electrons created; ionize more nearby atoms: ionization clusters.
  - ~ 27 eV needed per ionization in Argon
  - Electrons drift towards anode (v ~ few cm per μs), ions drift to cathode at speeds thousand times slower.
  - Region of strong electric field (>~ 10 kV/cm/atm): electrons gain sufficient energy between two collisions to cause ionization:
    - Avalanche Multiplication.





Gaseous Detectors

- Avalanche increases exponentially:

$$dN = N\alpha ds.$$

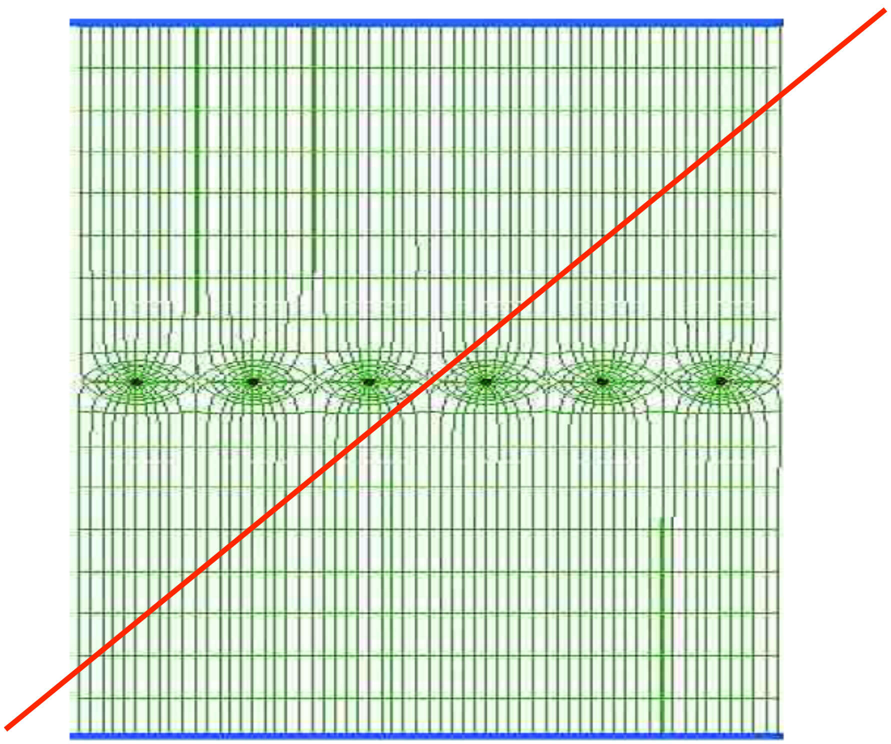
$$\frac{N}{N_o} = \exp \int_a^b \alpha ds.$$

α is the first Townsend coefficient: depends on E, gas composition and density. a and b are the boundaries of the region where E is sufficiently strong.

- Gas gain for a wire chamber could be ~ 10^5-10^6.
- Photons created in avalanche could cause after-pulses away from the primary track: unstable behavior and loss of resolution.
- A quencher, a molecular gas with high photo-absorption coefficient: ex, CO_2, hydrocarbon gases.

Gaseous Detectors: wire chambers

- Wire chamber Has been the work-horse of nuclear and particle physics.
  - highly efficient (> 99%)
  - cost effective
  - low mass
  - Rad-hard
  - could cover very large areas
  - good position resolution (~ 100- 200 μm for a MWDC)



Issues with wire chambers

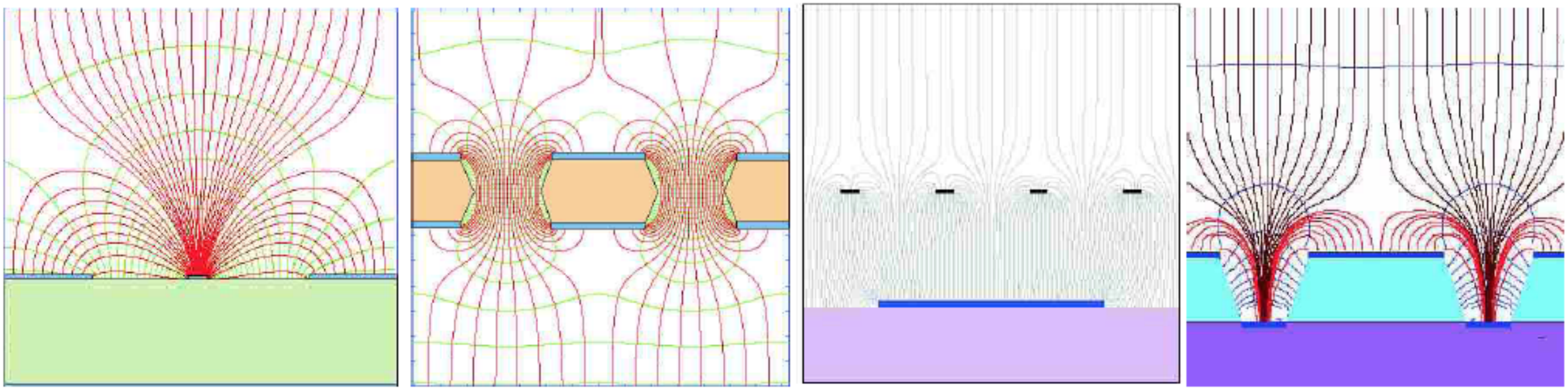
• Slow drift of ions back to the cathode causes space-charge issues that limit the rate ($< \sim 10^5/cm^2$, more commonly $< 10^4/cm^2$).
• High gain around sense wires contribute to high noise, unstable behavior.
• secondary avalanches.
• Ionization clusters limit position resolution
• Plasmas formed during avalanche formation in the strong E field cause aging
• Long electron drifts: susceptible to magnetic field effects.

• New high luminosity, high precision experiments asking for a new breed of tracking detectors to:
  - operate in high rate environments (MHz/cm^2 or higher)
  - provide high position resolutions ($< 75\ \mu m$)
  - cover very large areas (10s – 100s of m^2)

Micro-Patters Gas Detectors (MPGD)

- Developed in the last 25 years.
- Based on microelectronics-photo-lithography techniques.
- 50 – 100 μm amplification gap with adjacent charge collection cathodes: hugely reduced space-charge effects.
- Rates of (100 s of MHz/cm^2 or higher)
- 100-500 μm readout strip/pad/pixel sizes: charge weighted average of clusters along the track: ~ 50 mm position resolutions

  - Micro-strip gas chambers (MSGC)
  - Micro-mesh gas detector (Micromegas)
  - Micro-grove detectors
  - Gas Electron Multiplier (GEM) detectors.



Why GEMs ?

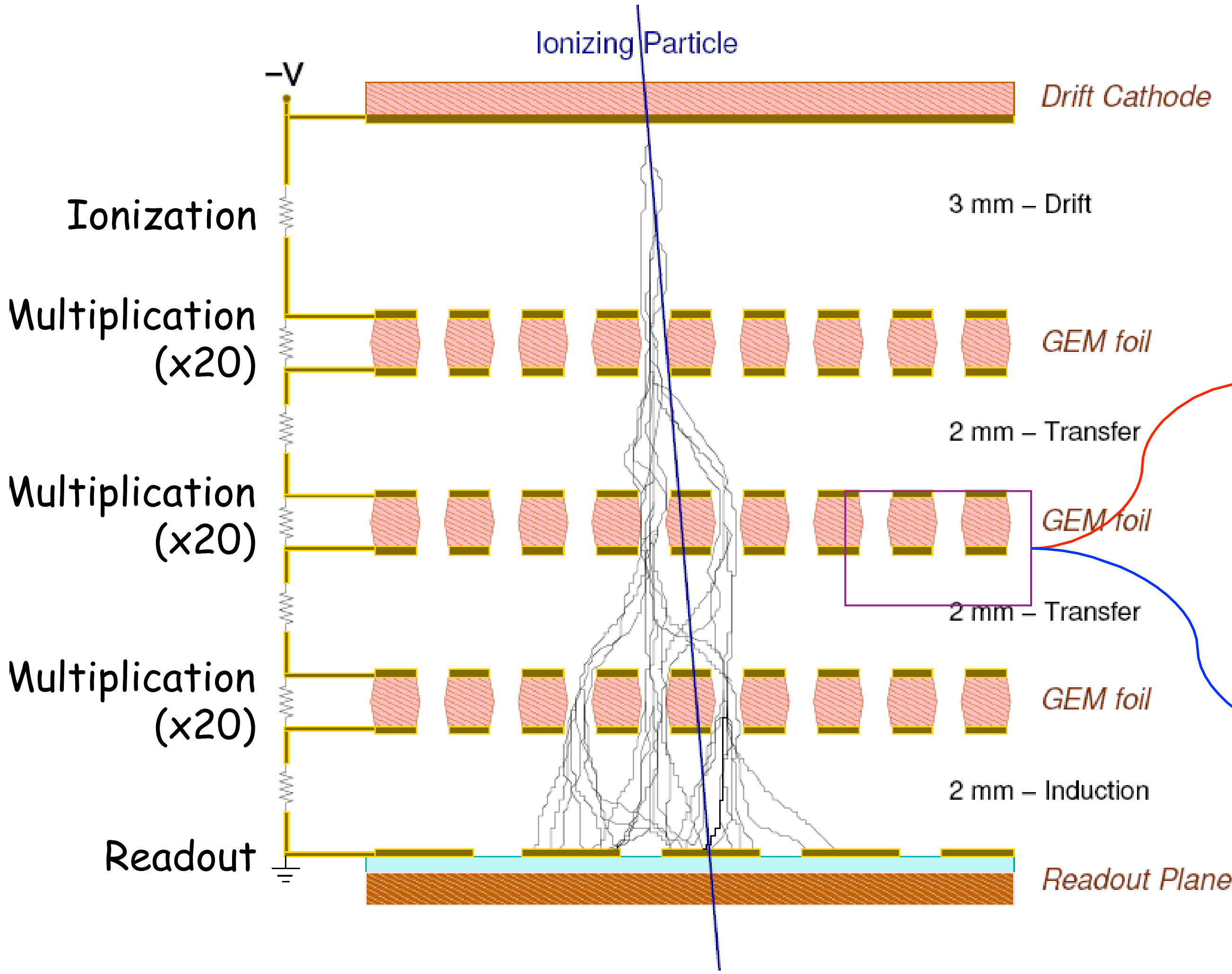
Requirement	Drift chamber	MPGD	Silicon
High rates up to 10 MHz/cm^2	NO	Yes	Yes
Resolution	~ 150 μm	~ 50 μm	< 30 μm
Cost of Large area coverage	Low	Low	Very high

GEM μMs

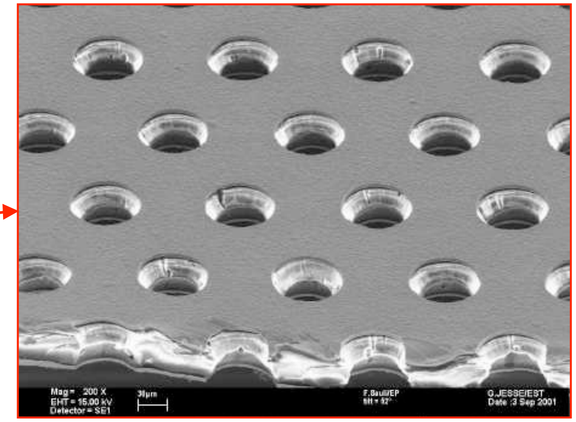
GEMs have had lower spark rates

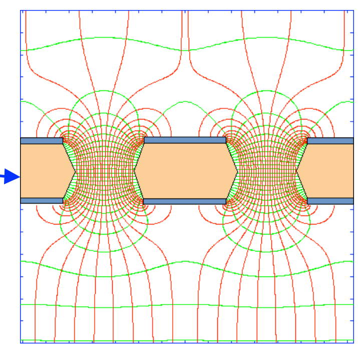
GEMs provide a cost effective solution for high resolution tracking under high rates over large areas.

GEM working principle



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



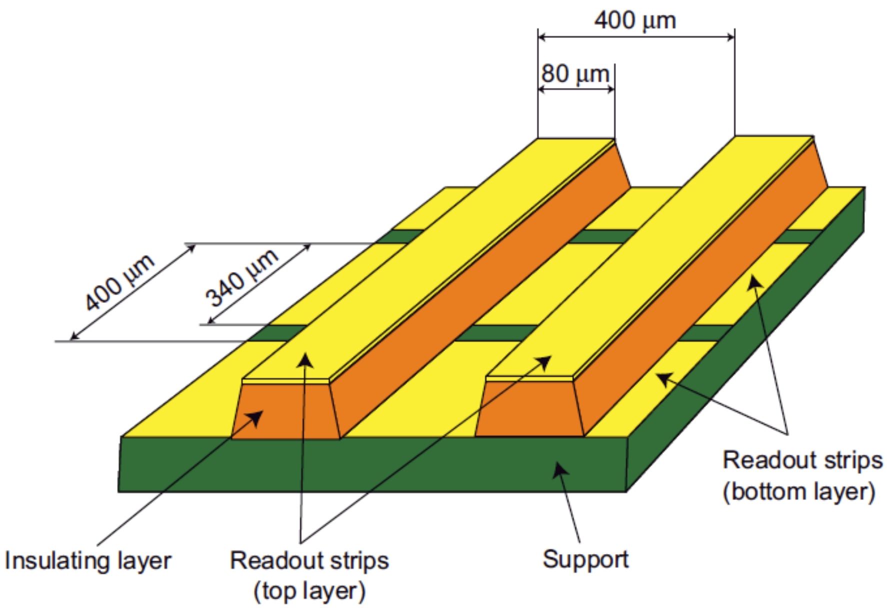


Strong electrostatic field in the GEM holes

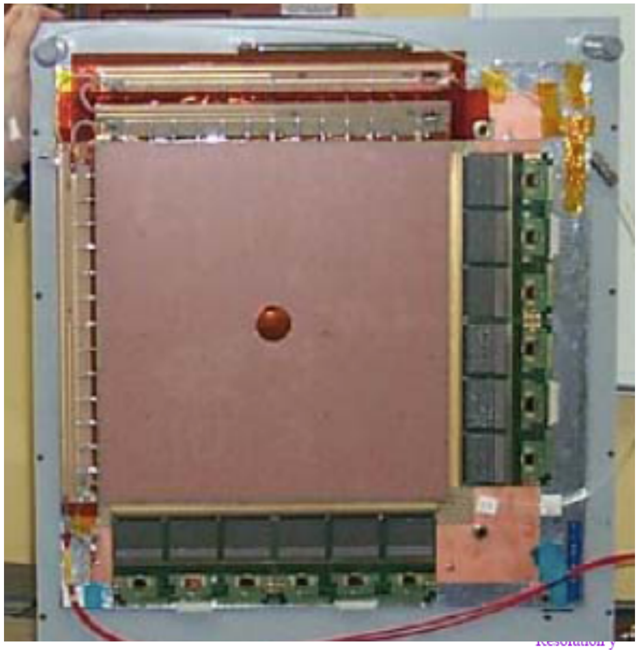
Recent technology: F. Sauli, Nucl. Instrum. Methods A386(1997)531

COMPASS GEM Tracker

- A tracker of twenty two 31 cm x 31 cm GEM chambers successfully operated for years
- Rates as high as 2.5 MHz/cm^2



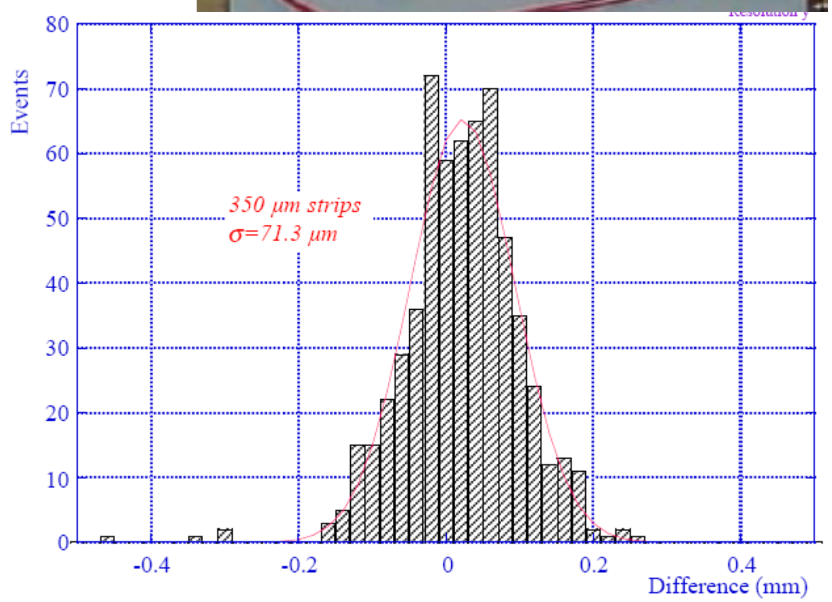
COMPASS readout plane (31x31 cm^2)



70 μm resolution achieved by strips centroid

⇒**Analog readout required (used the APV25 chip)**

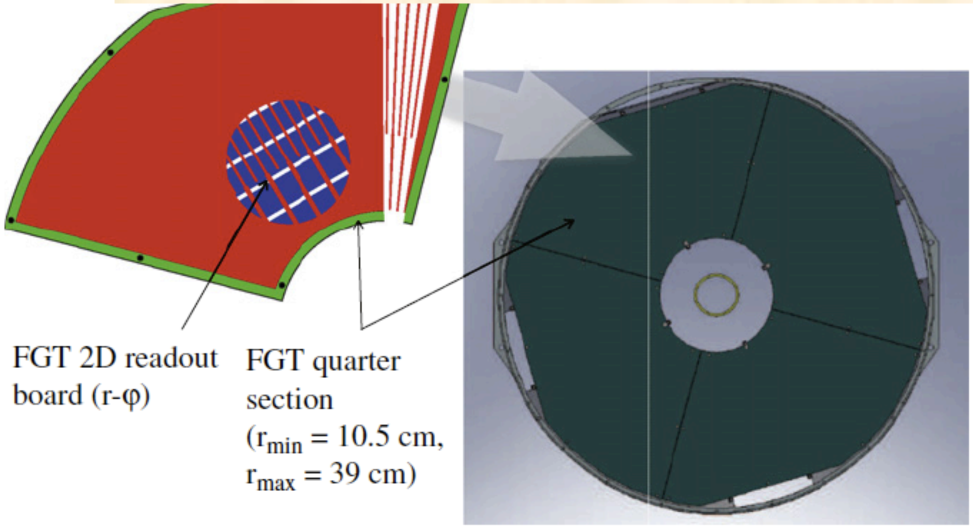
⇒ **Good position resolution and coarse timing (~ 10 ns)**

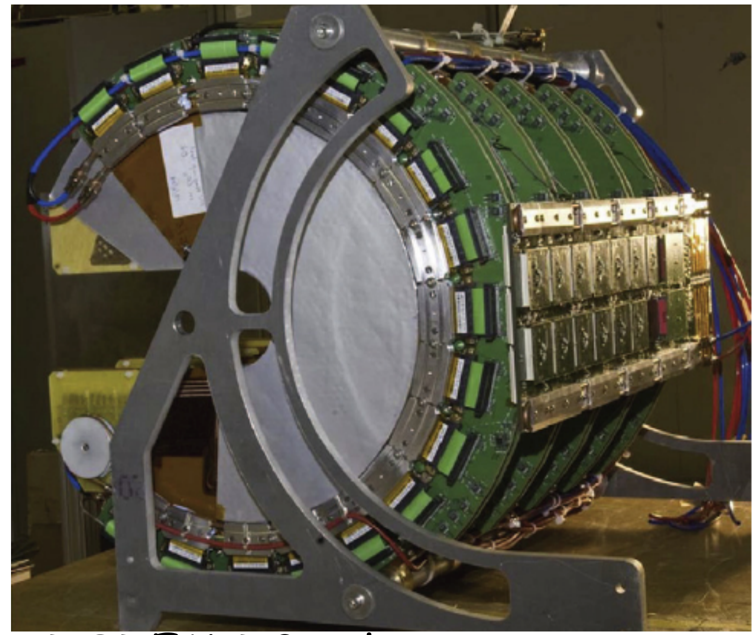


Recent GEM chamber projects

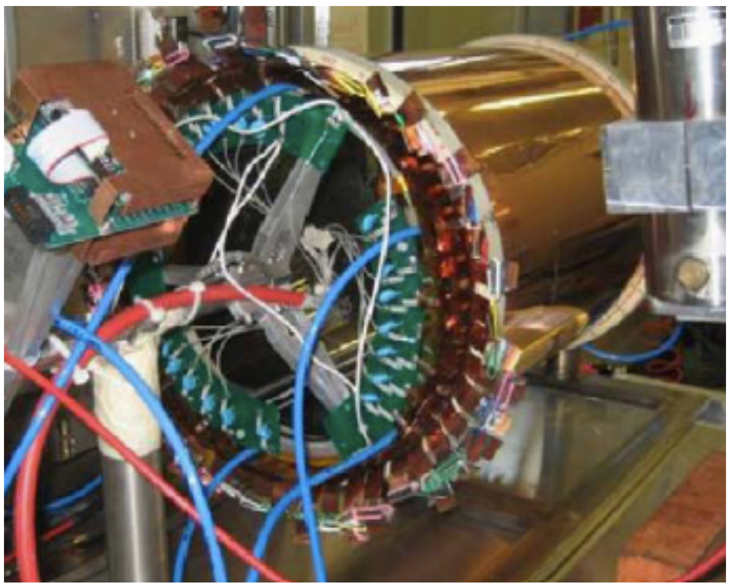
STAR Forward GEM Tracker

- 6 triple-GEM disks around beam
- IR~10.5 cm, OR~39 cm
- APV25 electronics





TOTEM T2 telescope

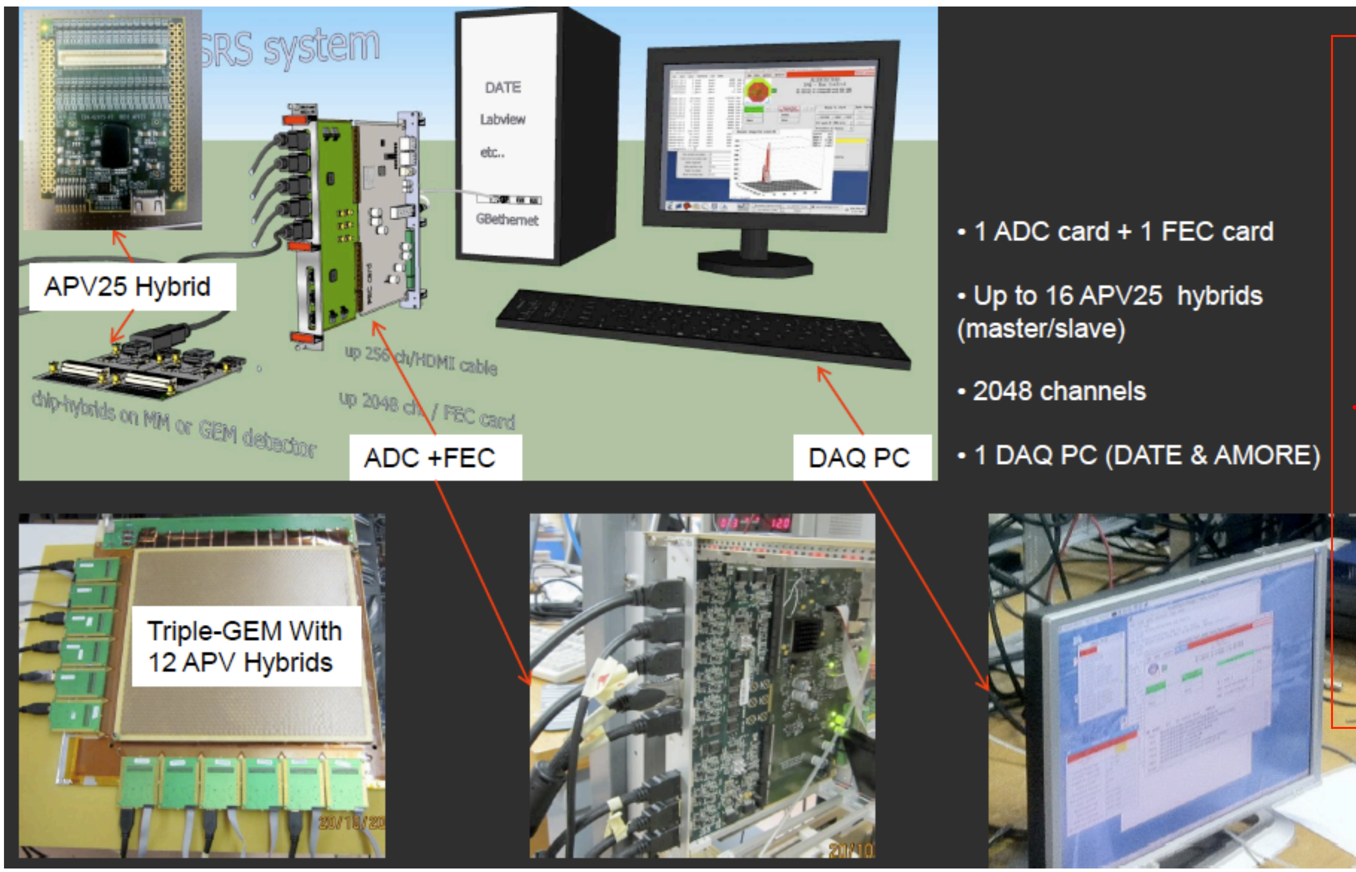


Cylindrical GEM for KLOE

Many GEM based TPCs and Cherenkovs. Also GEMs have found applications in, Medical imaging, National Security and other areas

GEM chamber electronics

- The RD-51 Scalable Readout System provides a low-cost, common platform that can accommodate different readout chips.
- Currently tested with APV25-S1 chip; other chips are also possible
- Current efforts to increase rates, commercialize production.



SRS system has the benefit of the large team effort backed by RD-51

RD-51 plans to commercialize the fabrication; there will be the possibility to get very large systems in the future.

The cost is ~< $ 3/chan

GEMs are now “all grown up” and ready for the next steps

Huge advances in the last 10 years

- Very large area GEM foils
- Industrial production of GEMs
- Timing GEMs
- New readouts
- Analysis techniques for high rate operation.
- New large Area GEM projects
- cylindrical GEMs
- pixel GEMs
- spherical GEMs
- ………

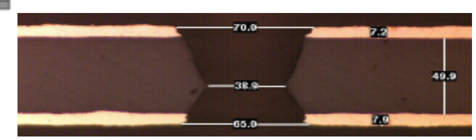
Recent developments towards large GEM foils

- Base material only ~ 50 cm wide roll.
- Used a double mask technique for etching: hard to align the two masks accurately: Max area limited to ~ 50 cm x 50 cm previously.

Double Mask

Bias top surface to – w.r.t chemical bath

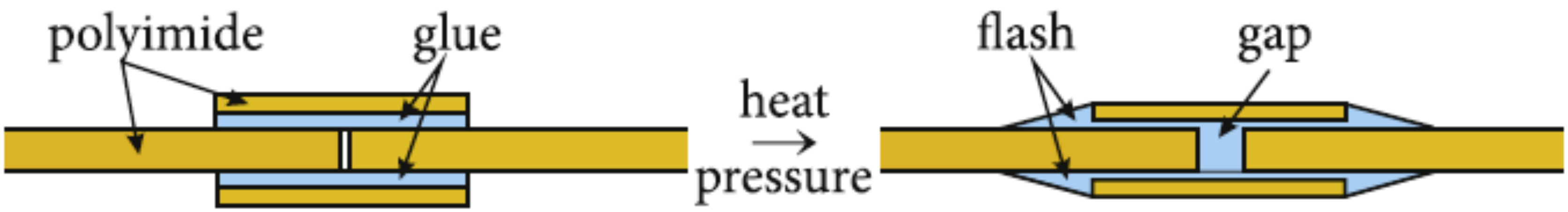
Single Mask

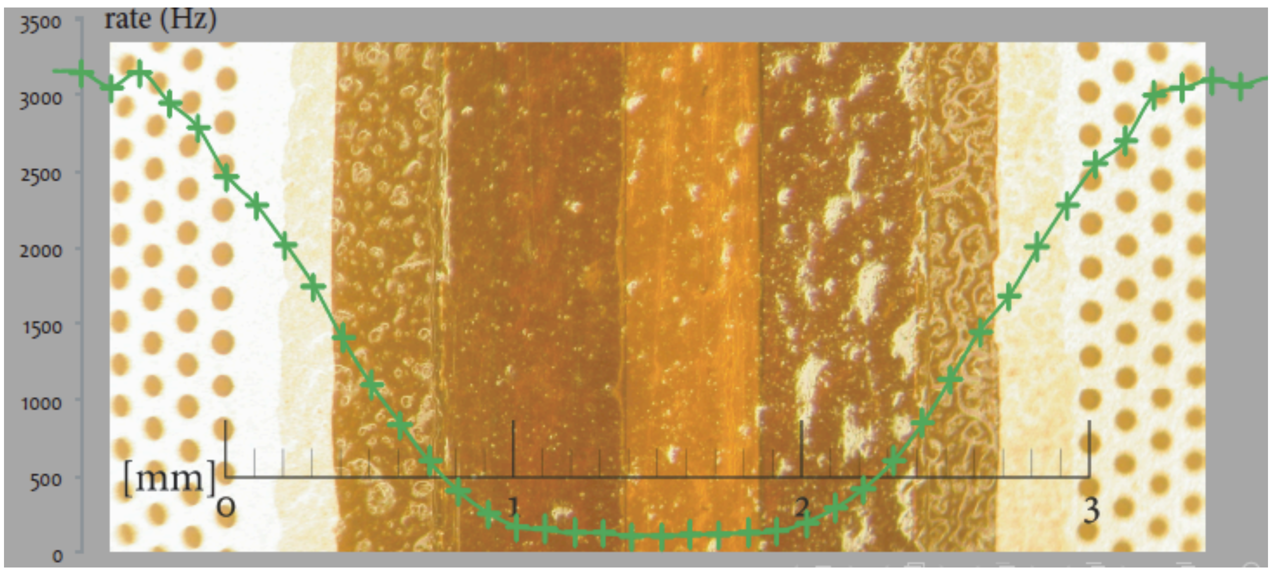


Single Mask technique allows to make GEM foils as large as 200 cm x 50 cm

• Splicing GEM foils together: seam is only 2 mm wide

• Performance of the rest of the GEM foil unaffected





Single Mask technique + splicing allows 200 cm x 100 cm foils

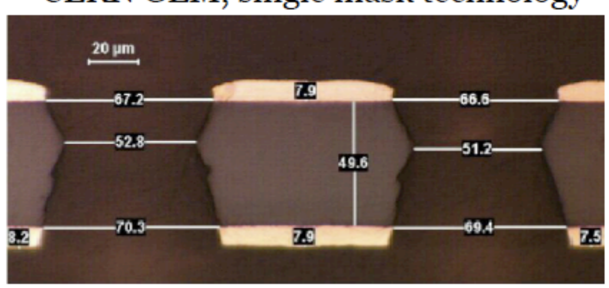
• CERN MPGD workshop (TE/MPE/EM Workshop) is now getting new machinery and will be moving to a new building:

•Increased production capacity

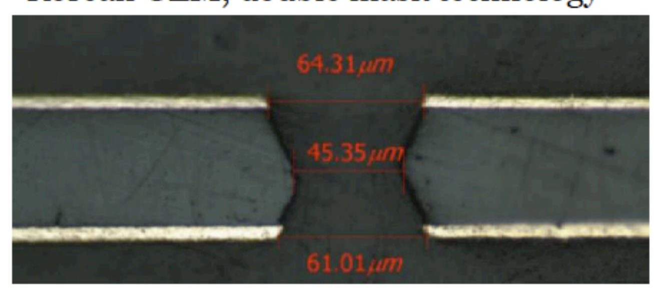
Industrial Production of GEMs

- Many anticipated users of GEMs in the near future; CERN shop can't keep up.
- Several Industrial production around the world starting with CERN technology transfer:
    - TechEtch, Plymouth, MA, USA : GEM foils up to ~ 40 cm; produced all foils for STAR FGT.
    - NewFlex Technology, South Korea: produced the tested foils up to 10 x 10 cm2; plans for large production up to 1 m foils.
    - TechTra in Poland
    - India
    - China
    - …

CERN GEM, single mask technology

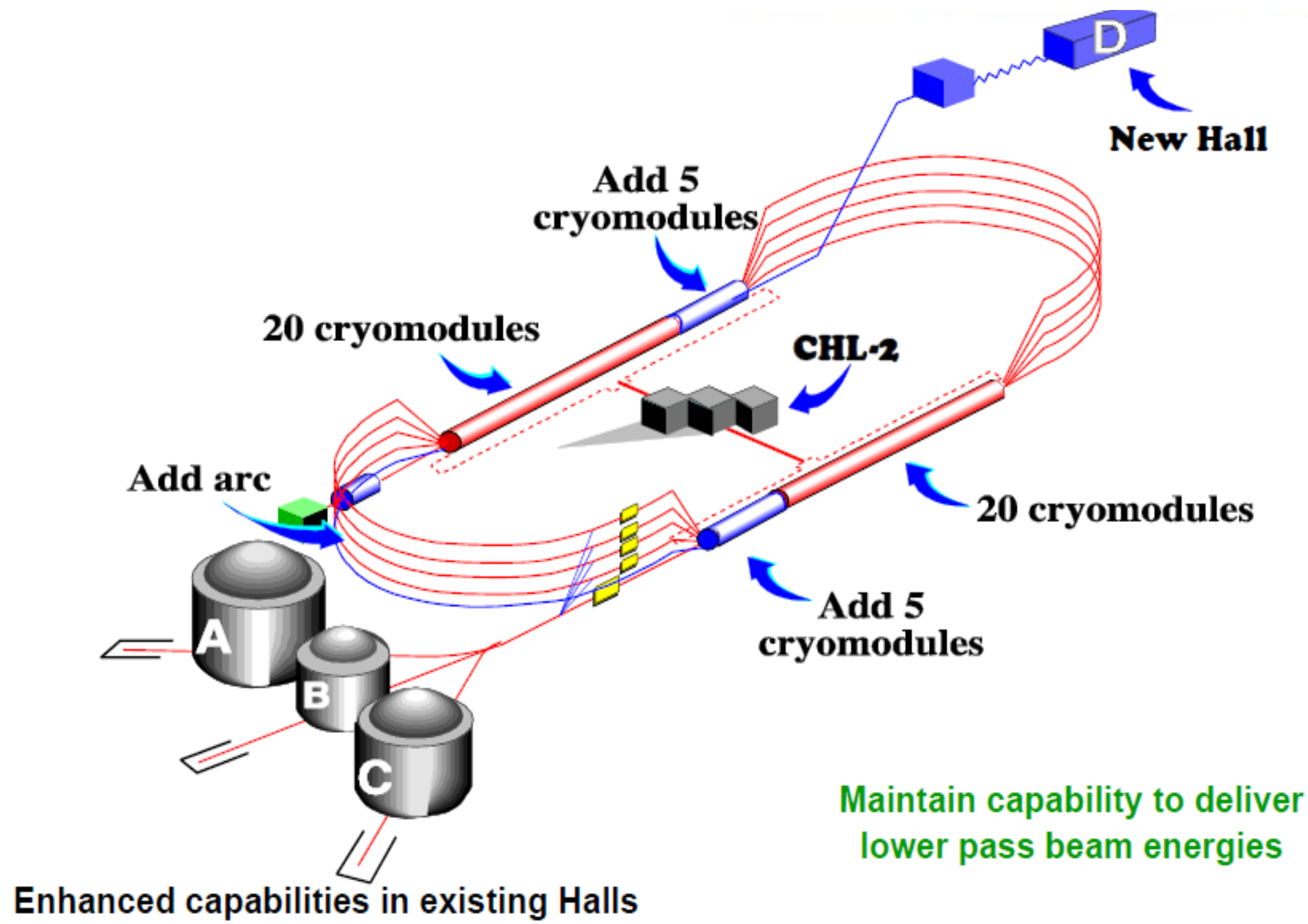


Korean GEM, double mask technology



- Still most of the GEM foils in the world come from the CERN MPGD workshop (TE/MPE/EM Workshop).
- Recently upgraded new machinery and located in a new building
  - Increased production capacity

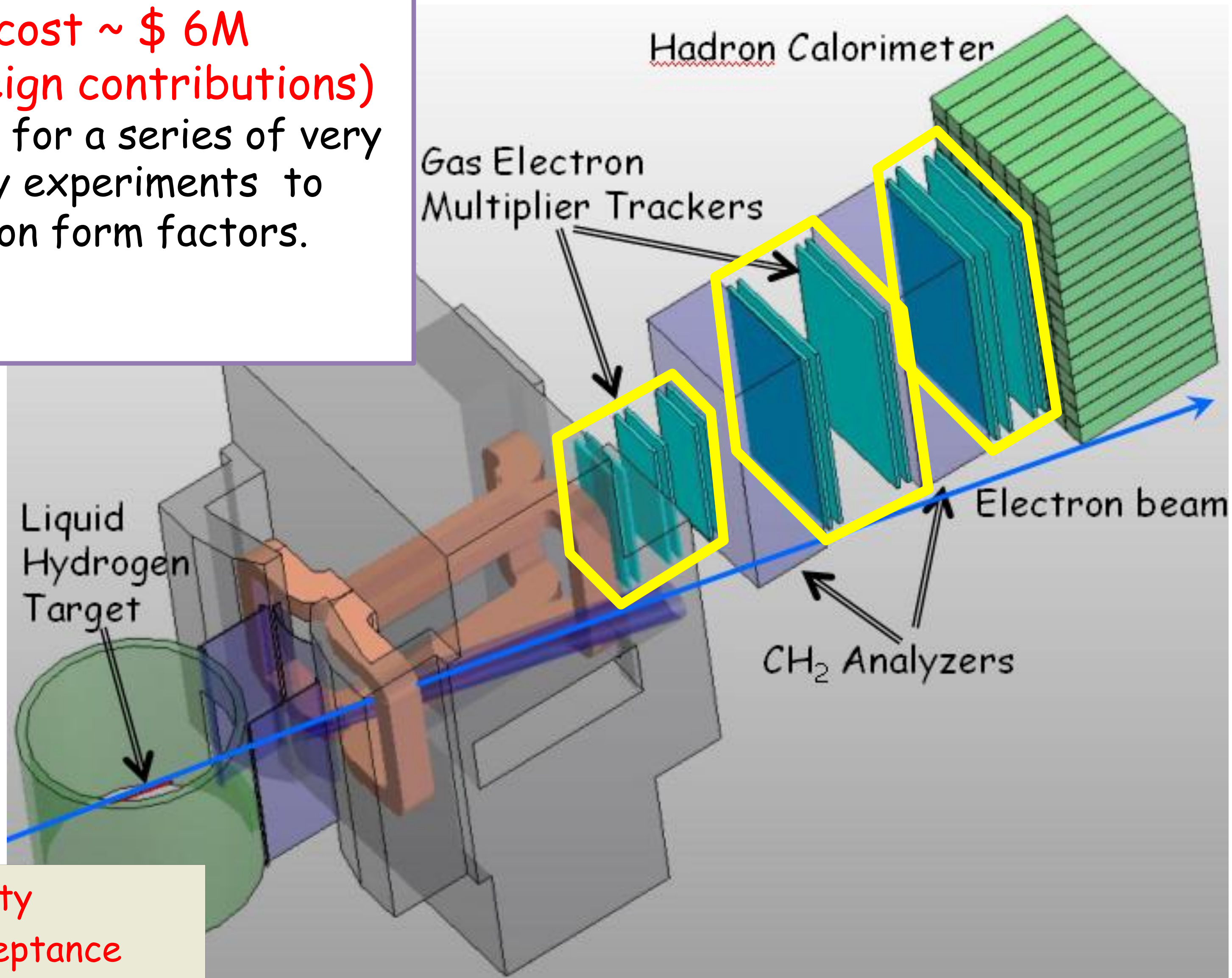
Large Area GEM chamber projects for 12 GeV Jefferson lab.



Jefferson Lab SuperBigbite Spectrometer

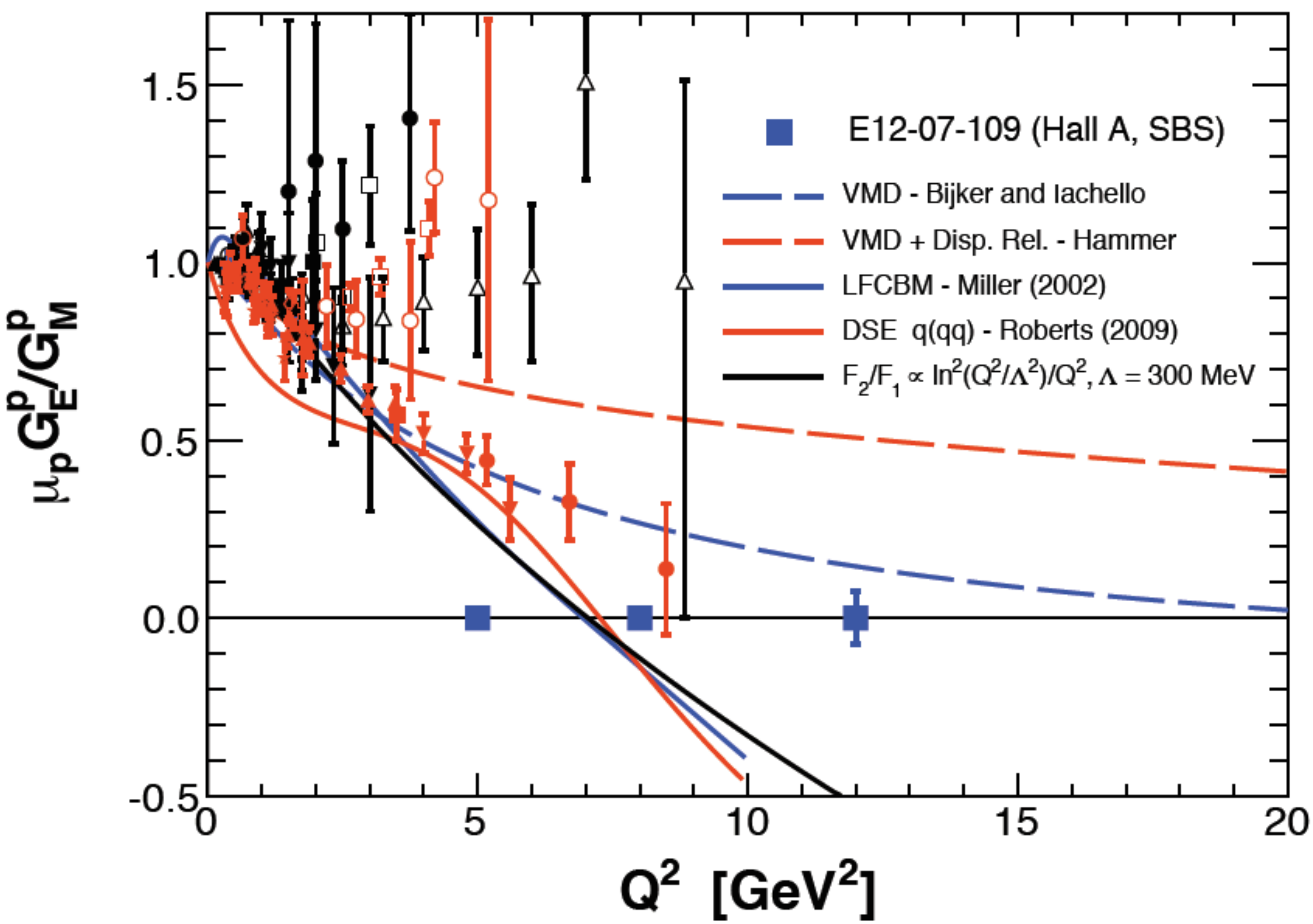
Total project cost ~ $ 6M
(including foreign contributions)

- Spectrometer for a series of very high luminosity experiments to measure nucleon form factors.
- SIDIS
- DIS

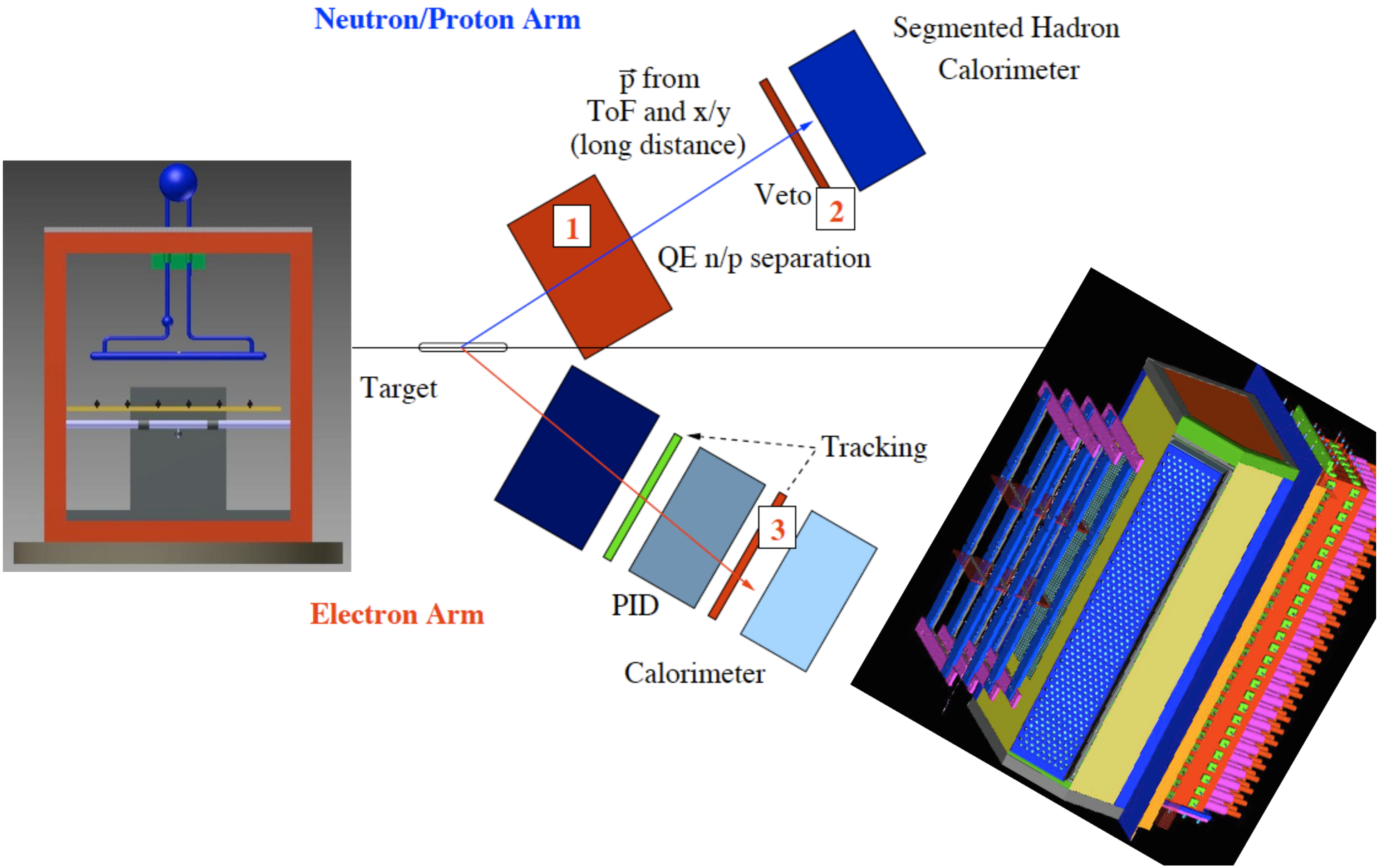


- Large luminosity
- Moderate acceptance
- Forward angles
- Reconfigurable detectors

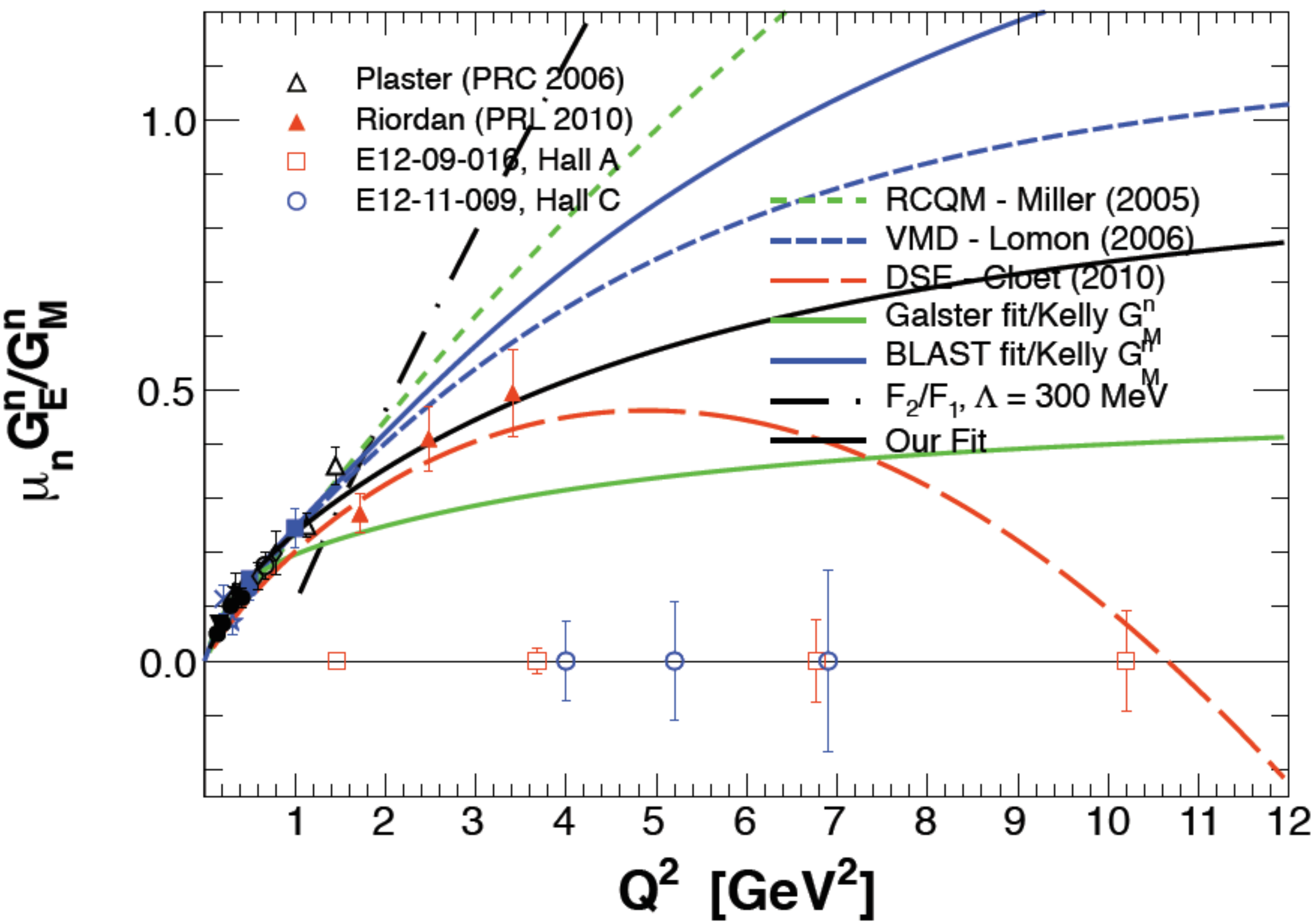
SBS projected data for GEp/GMp



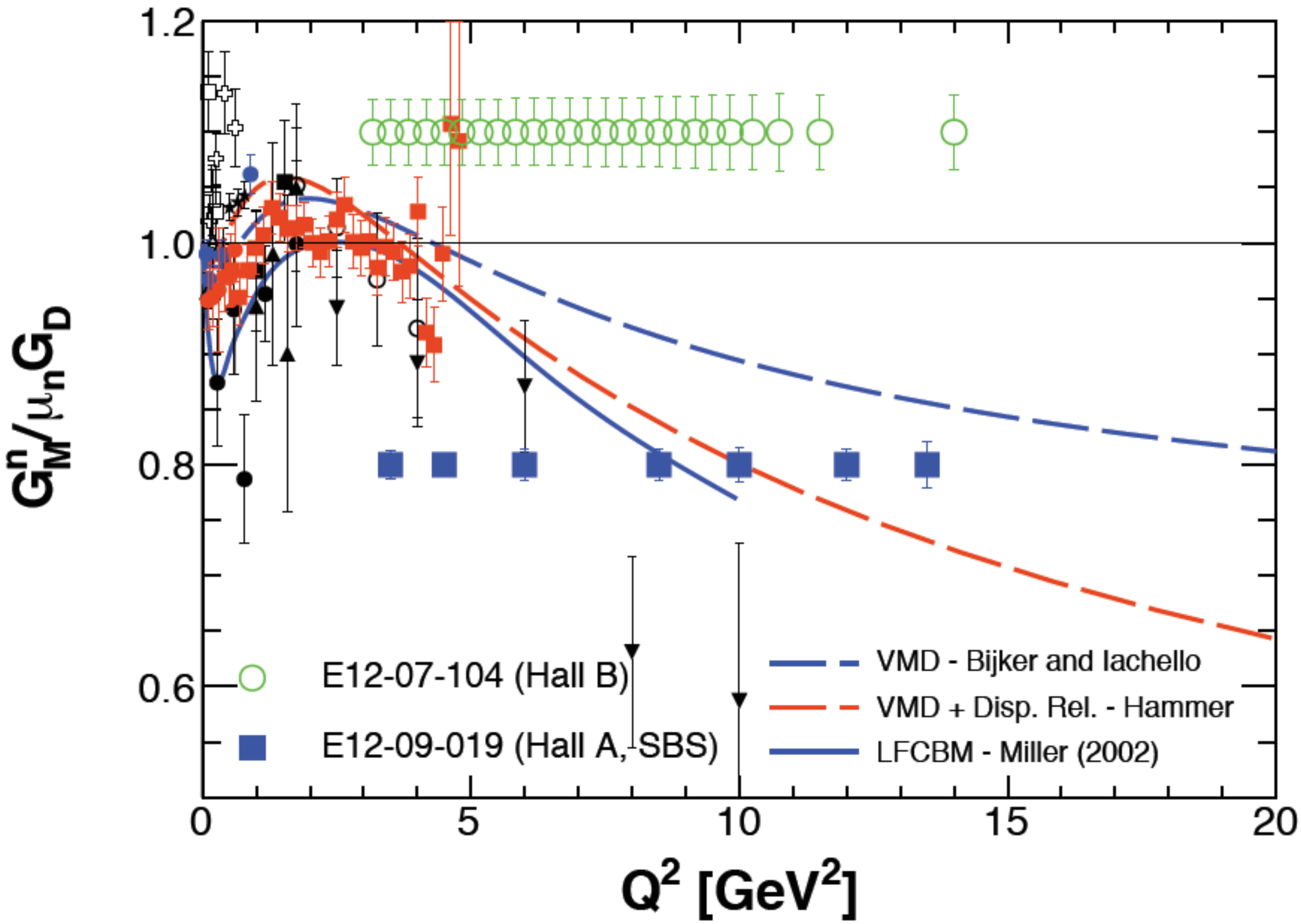
SBS setup for for GEn and GMn measurements



SBS projected data for GEn/GMn



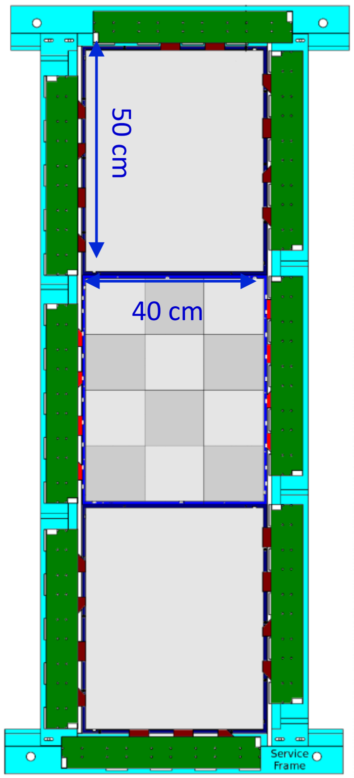
SBS projected data for GMn

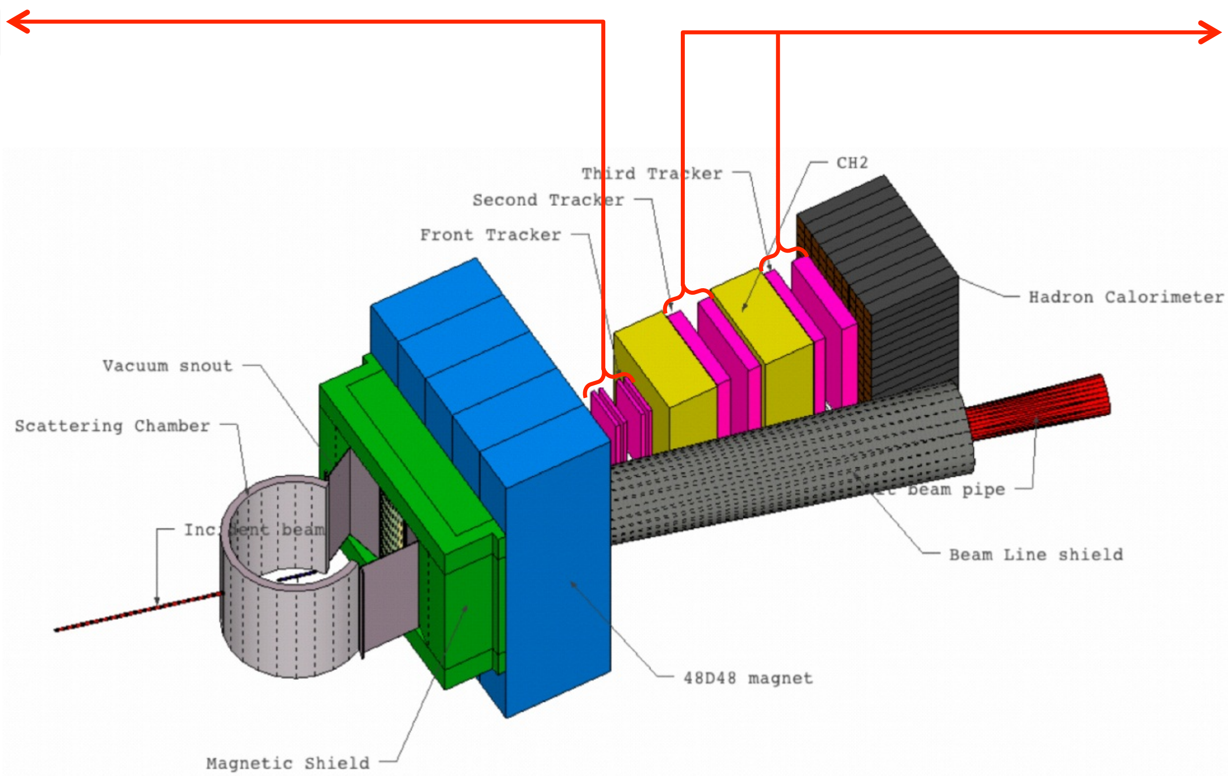


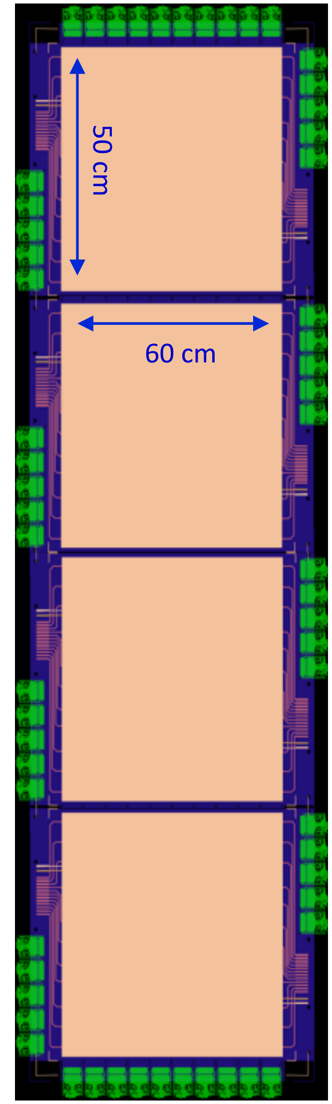
GEM Trackers for SBS

- Front Tracker:
- 6 GEM Layers (150 × 40 cm²)
- Each layer = 3 GEM modules (50 × 40 cm²)
- R&D and Production by INFN Roma, Catania

- Back Tracker
- 10 GEM Layers (200 × 60 cm²)
- Each Layer = 4 GEM modules (50 × 60 cm²)
- R&D and Production @ University of Virginia





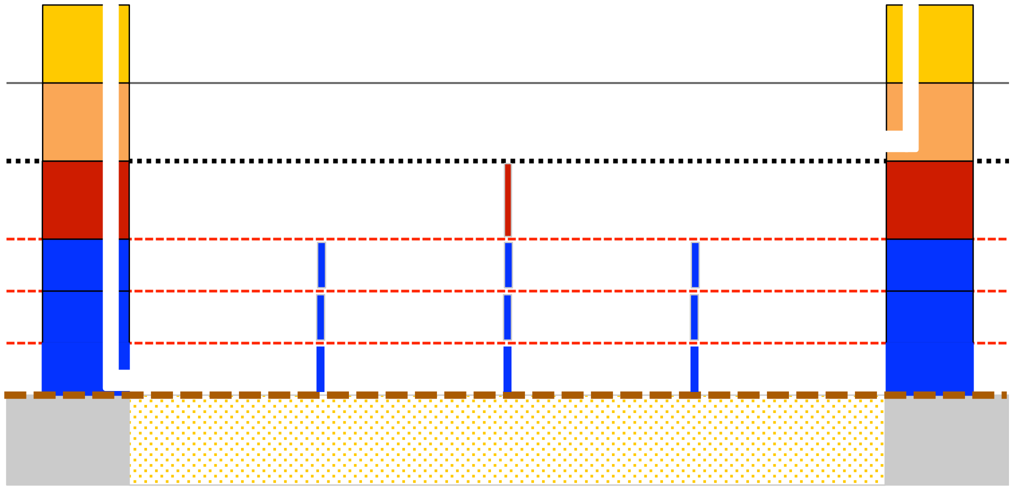


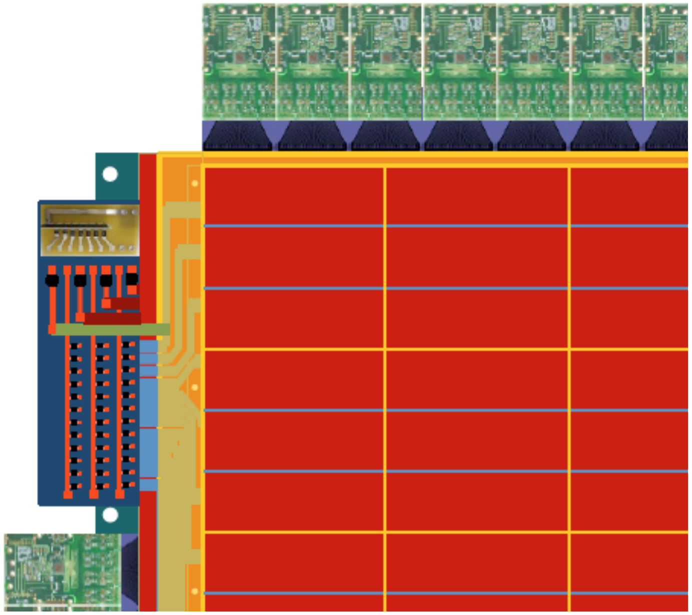
Proton arm layout for GEp (5) experiment

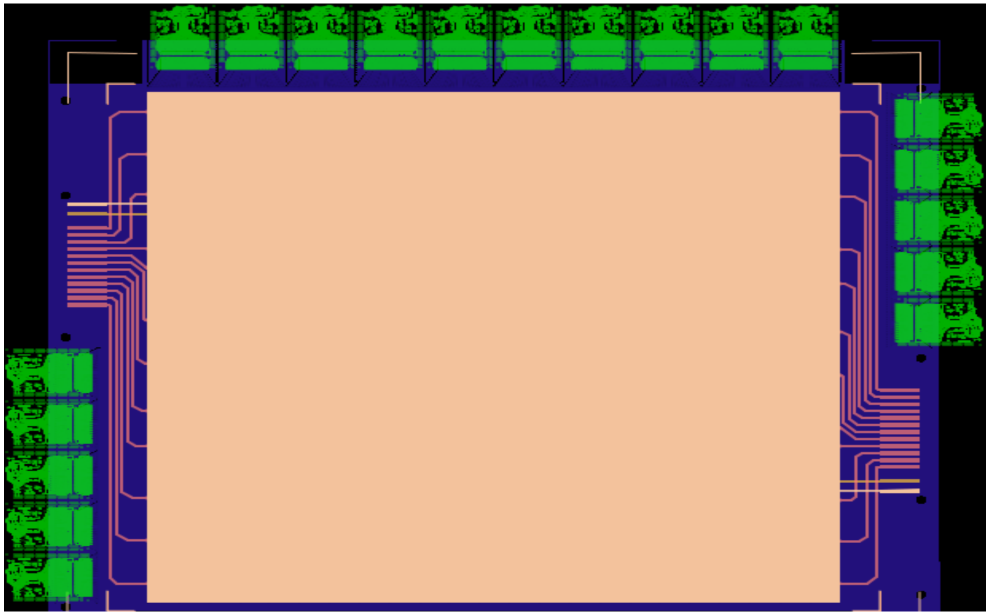
Total Area ~ 16 m² : Largest area of GEM coverage ever

Basic Module of SBS Back Trackers

- Features:
  - size: 50x60 cm^2 active area
  - thin frame: only 8 mm wide
  - single mask tech. GEM foils
  - 2D strip readout (a la COMPASS) - 0.4 mm pitch
  - X= 0.54%X0

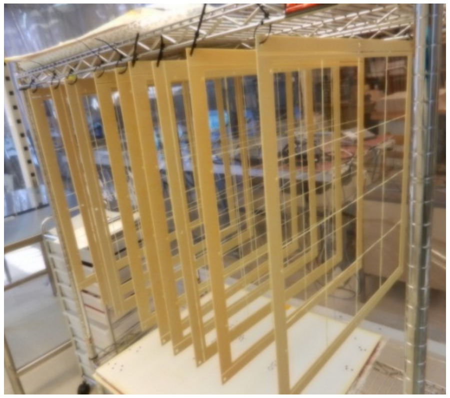






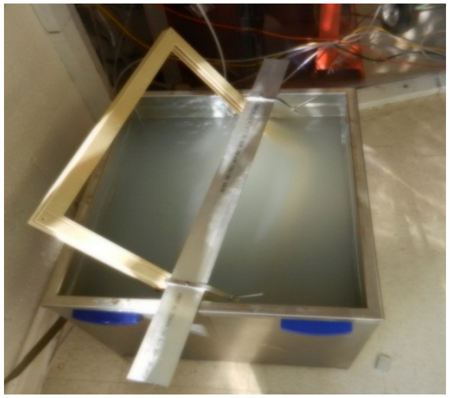
UVa GEM Lab

Storage of the frames

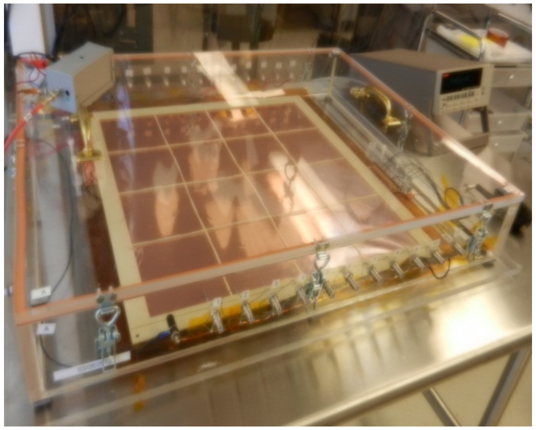


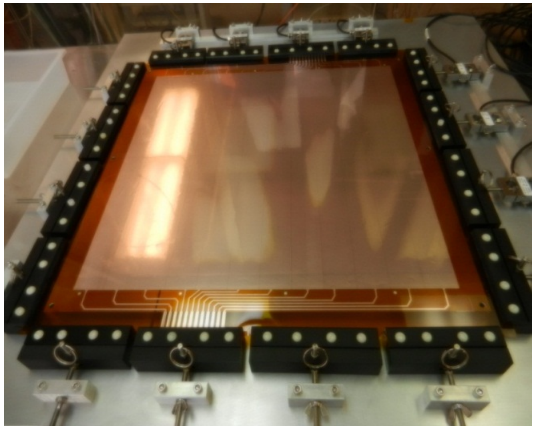
Frames holder for cleaning in USB

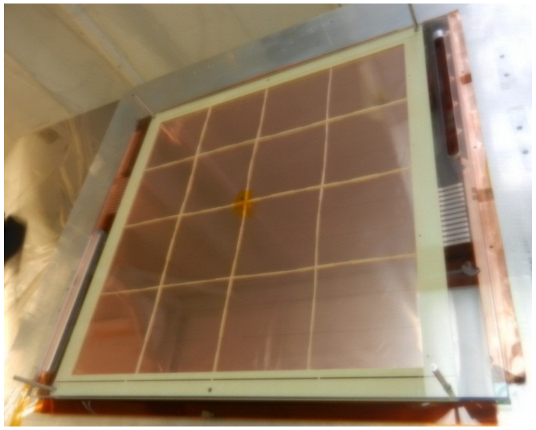
Ultra sonic bath (USB) with demineralized Water



Large area (3×7 m^2) class 1000 Clean Room





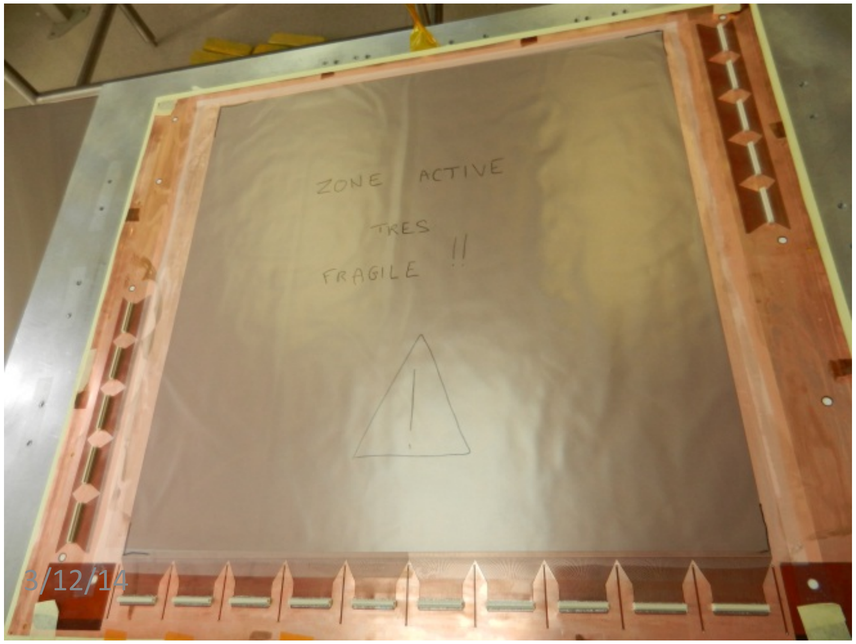


Polarimeter GEM module: components

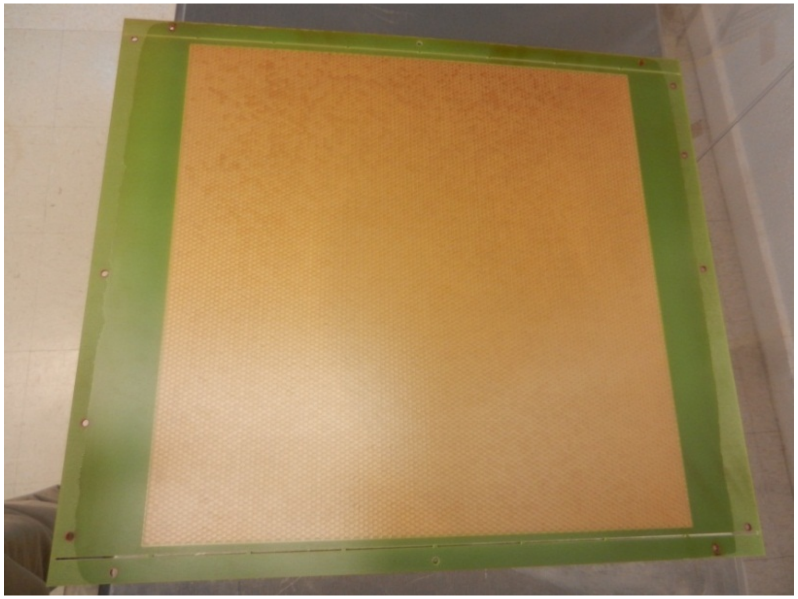
GEM foil (CERN PCB workshop)

Support frame with spacers (RESARM Belgium)

Flexible 2D readout board (CERN PCB workshop)

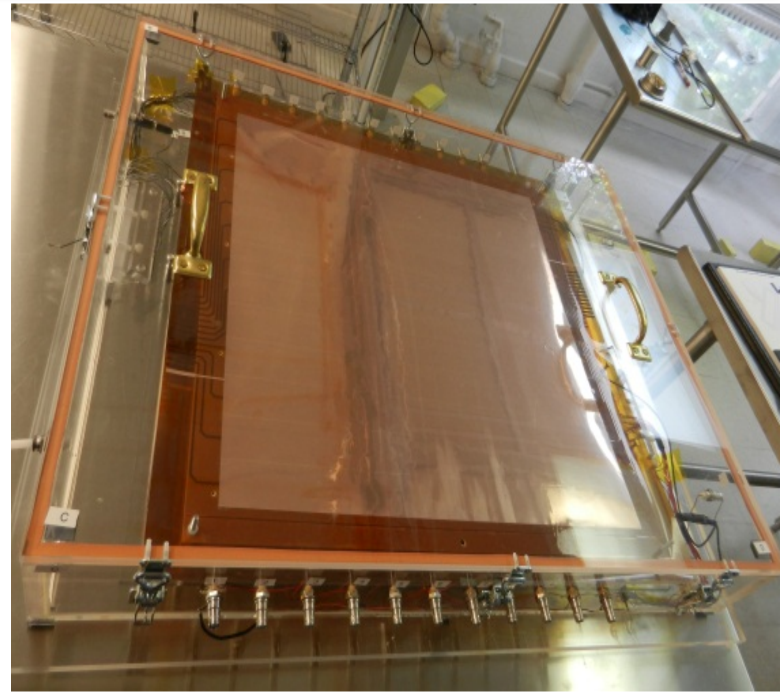


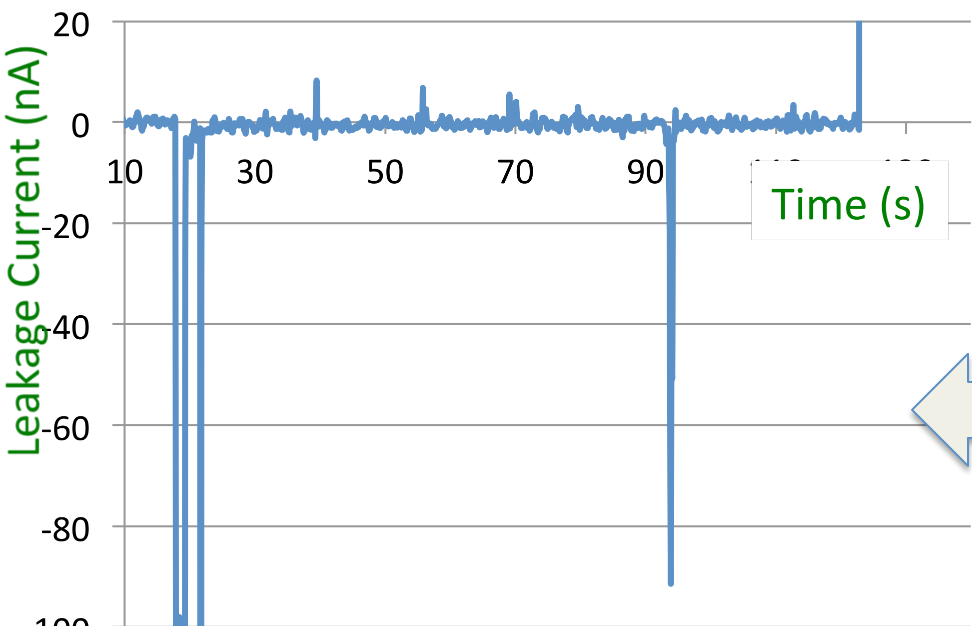
Honeycomb support board (CERN PCB workshop)



Foil testing and Leakage Current Measurement

- Rapid HV ramp-up to 550 V –causes quick burn-up of dust without polymerization or damage to foil.
- At 550 V: the initial current is a few of μA (re: capacitance of the sector).
- Then quickly drops and stabilizes to less ~ 1 nA leakage current: far better than the 5 nA requirement.
- Initially a few μA level sparks; spark rate slows down to quickly after that.

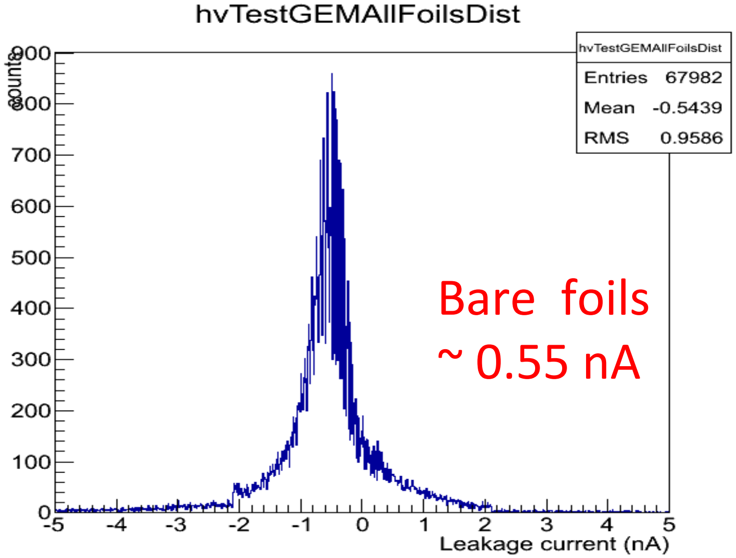


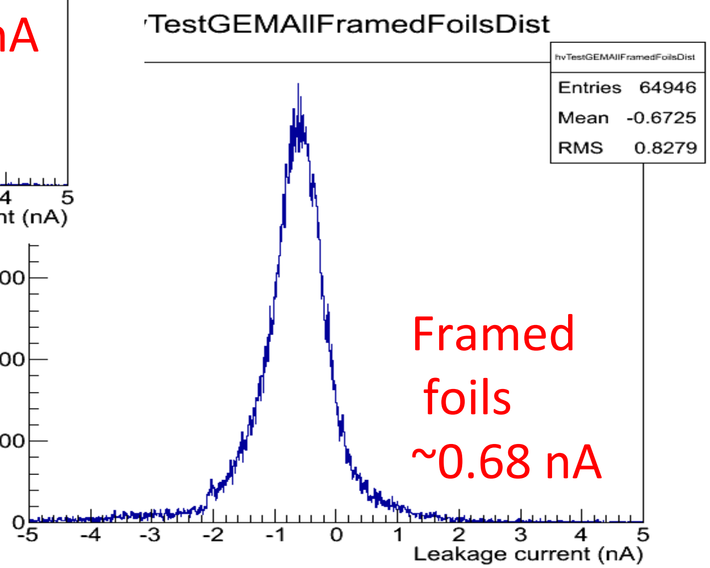


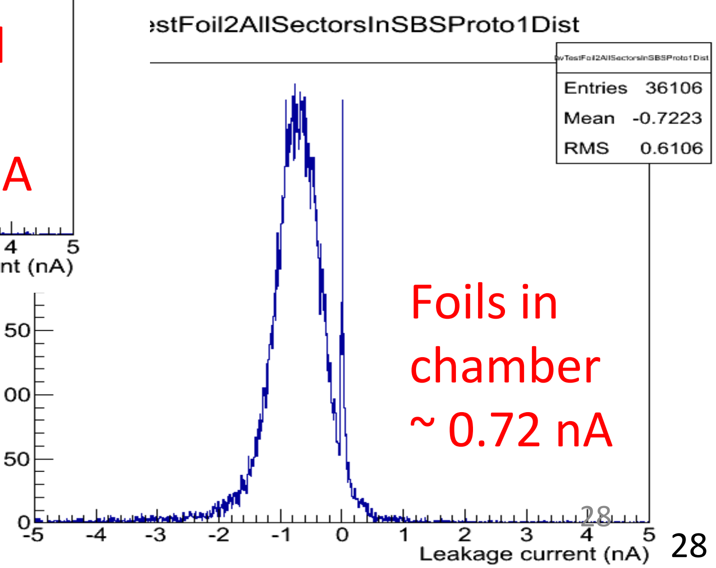
- The current drawn by the GEM foil measured using a picoammeter (through a Labview interface and saved into a text file.)
- the ~ 100 nA spike associated with someone moving near the HV test box.

Foil testing and Leakage Current Results

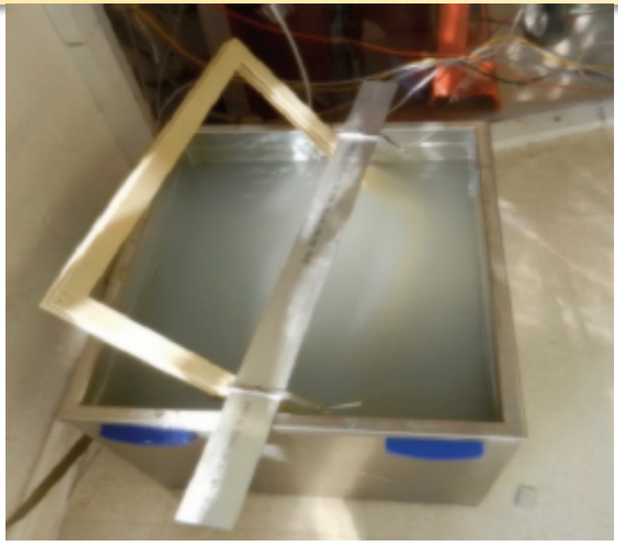
- Distribution of leakage current for all 72 sectors of a GEM chamber (24 sectors per foil x 3 foils)
- Current for 550 V in N_2 for bare, framed foils and in chamber
- Each sector tested for 120 s.
- PMP key performance parameter for accepting a foil: Leakage current < 5 nA



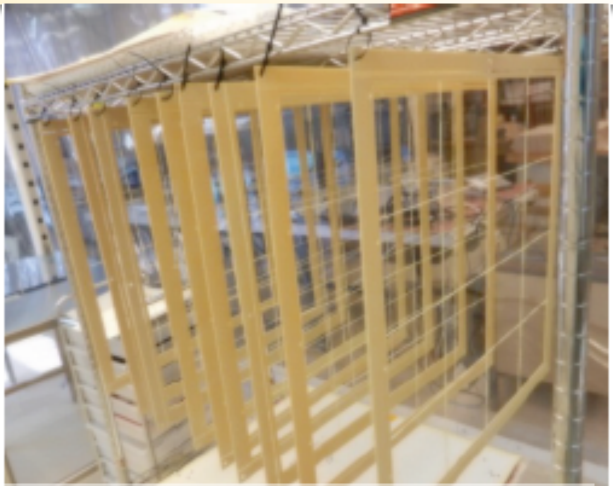




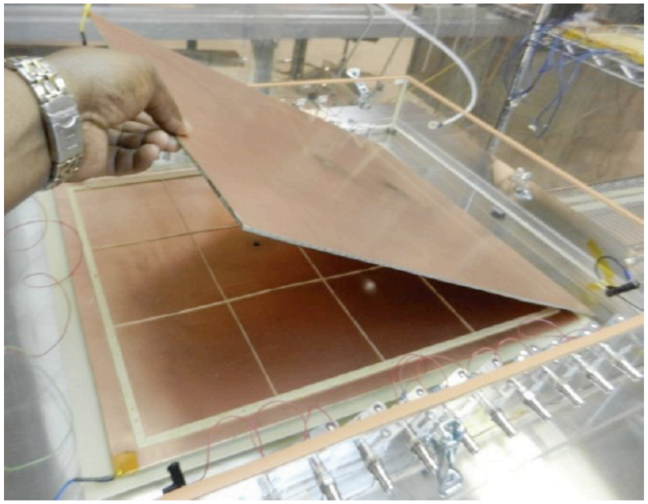
Preparation of the frames



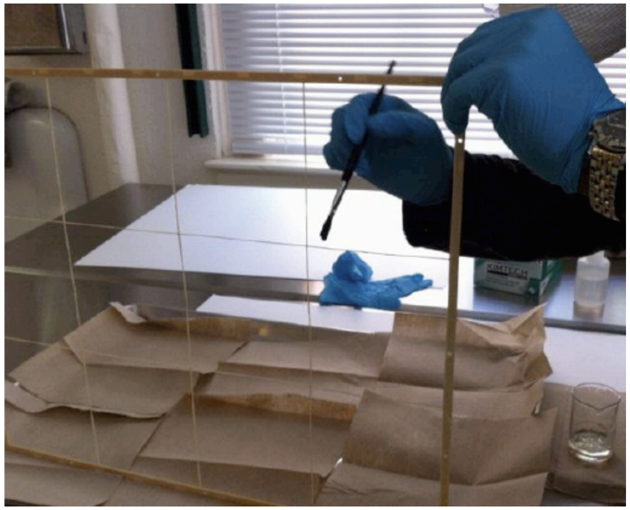
Spacers sanded, then frames cleaned in Ultra-sonic bath with demineralized Water



Dried for 4 days under a filter hood .

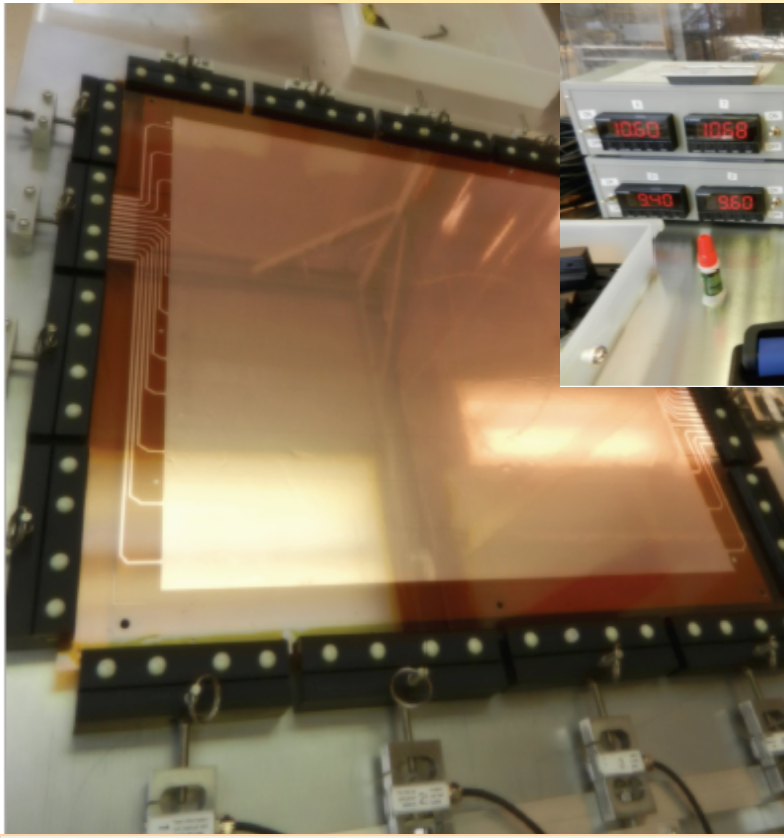


Loading the frame into the dry N2 box for testing at 4000 V



Machined surfaces sealed with a layer of polyurethane (Nuvovern LW) to prevent surface irregularities, residual fibers or sharp edges in the active area of the chamber

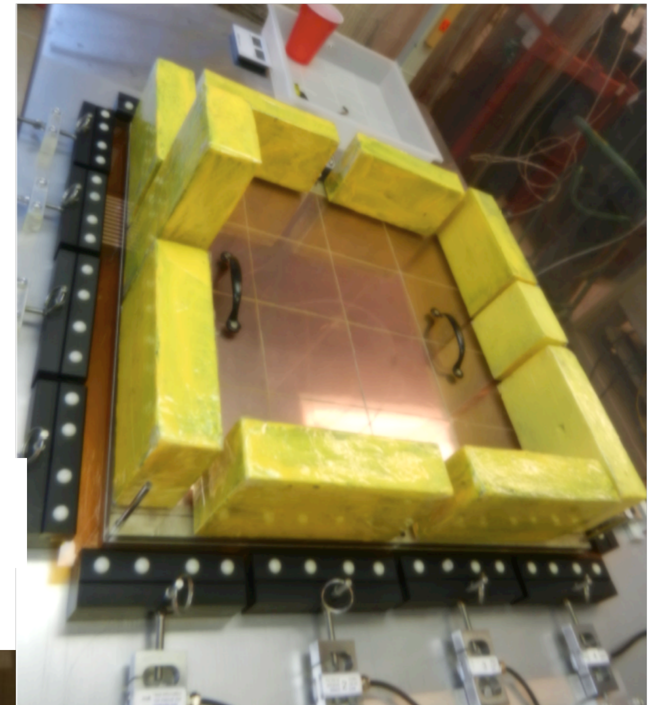
Foil Stretching and Glueing

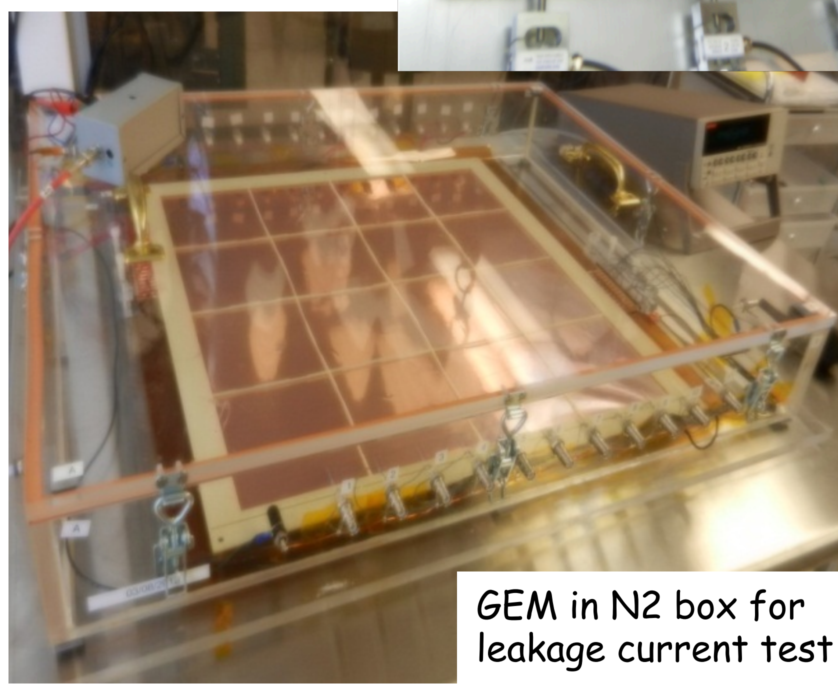


50 cm x 50 cm GEM stretcher at Uva

- Stretcher concept from LNF / Bencivenni et al. and INFN.
- Stretching time ~ 1 hours
- Foil Tension: T ~ 0.3 kg/cm

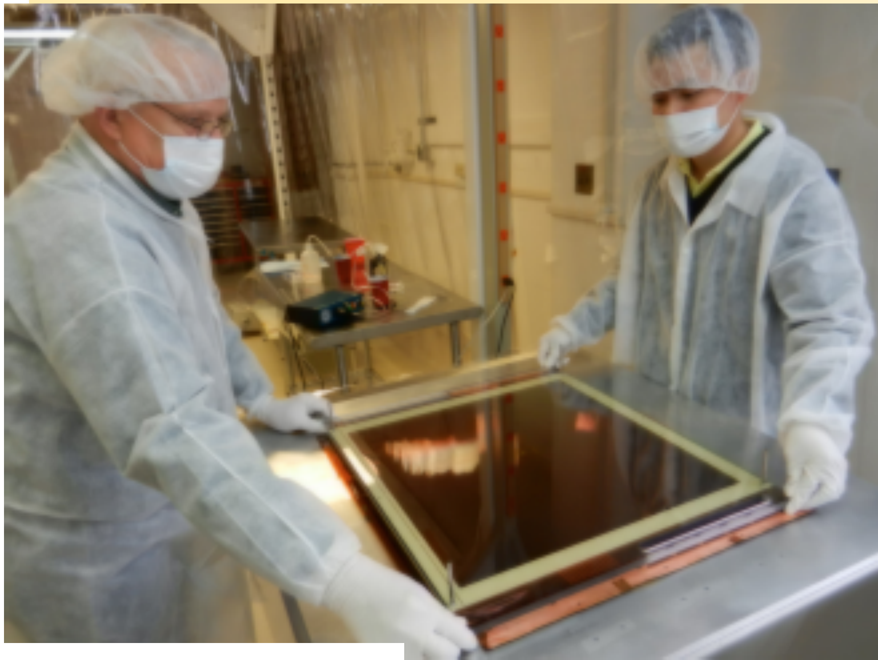
Frame glued on.
Overnight drying.



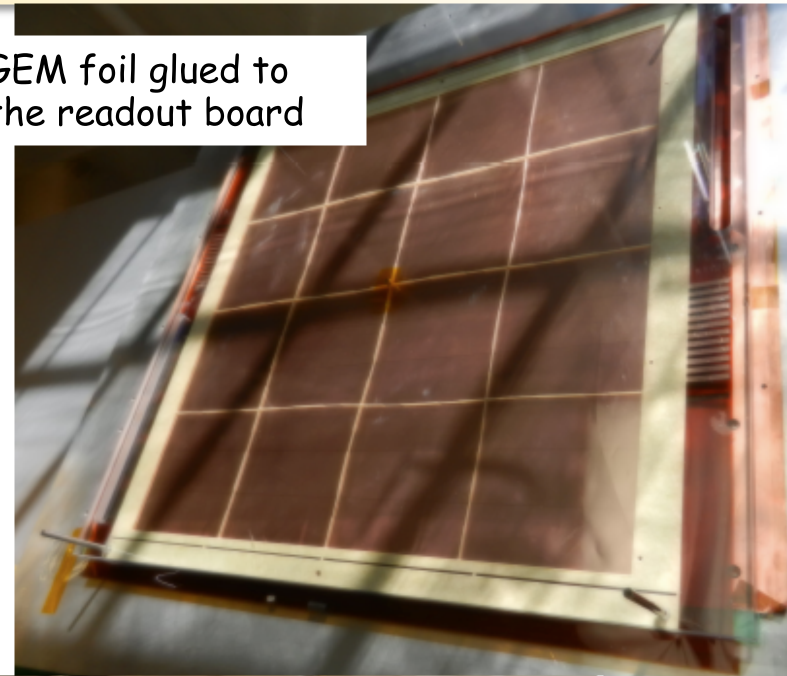


GEM in N2 box for
leakage current test

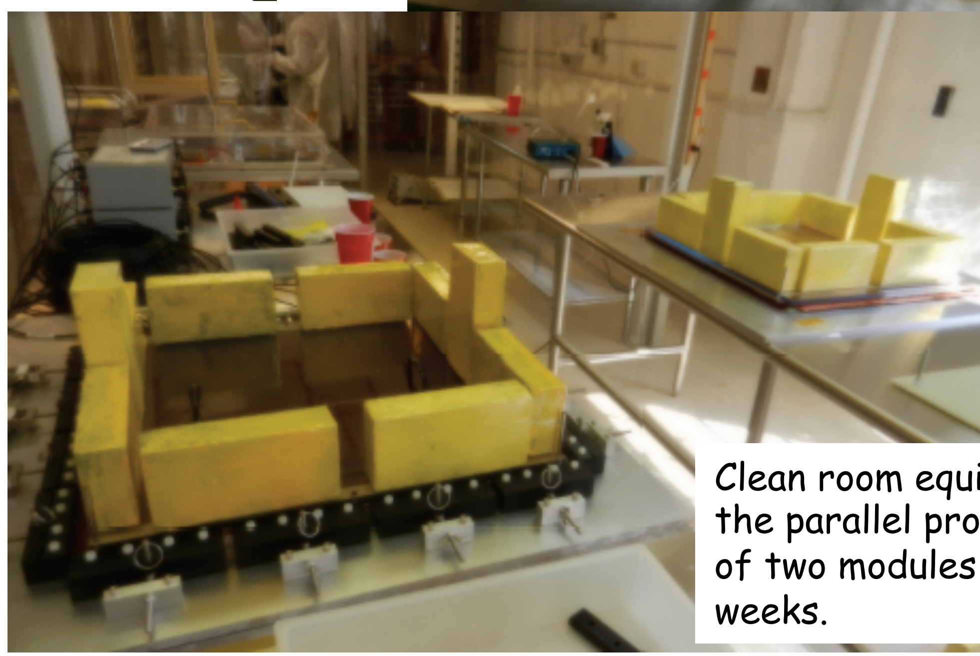
Final Assembly



Four large dowel pins at the corners used to align the frames to within 100 μm



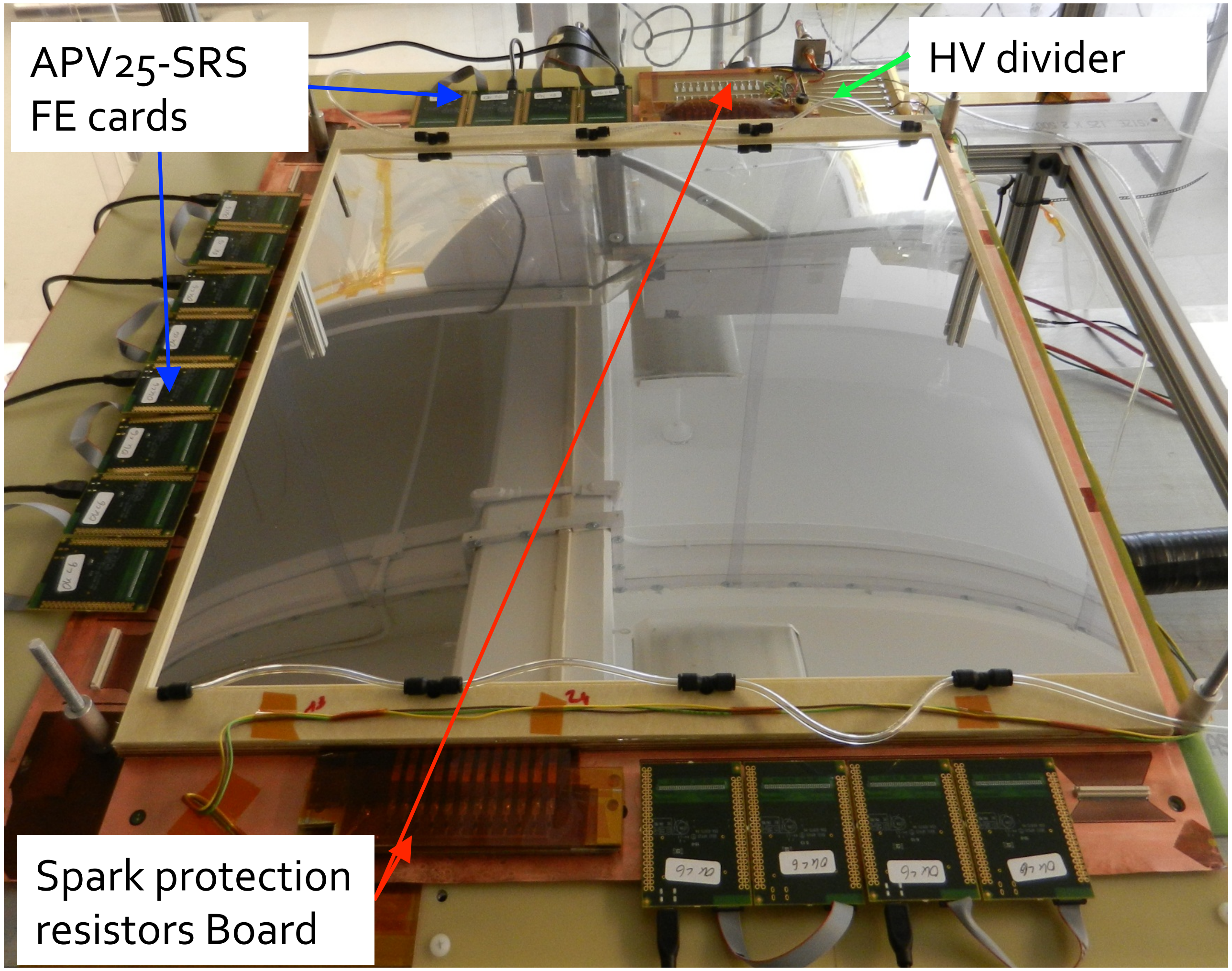
GEM foil glued to the readout board



Clean room equipped for the parallel production of two modules in 3 weeks.

SBS GEM module

❑ 4 full size modules completed at Uva: all fully operational.

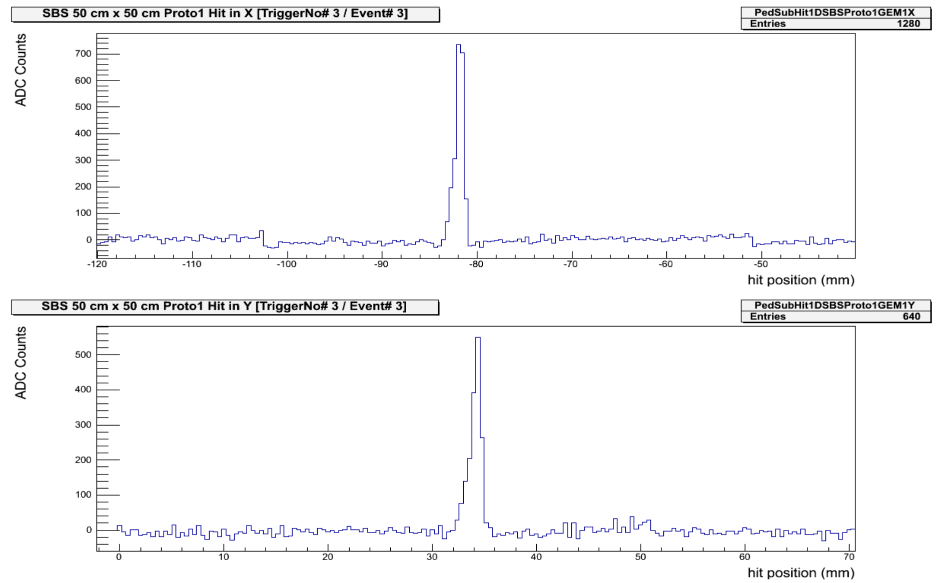


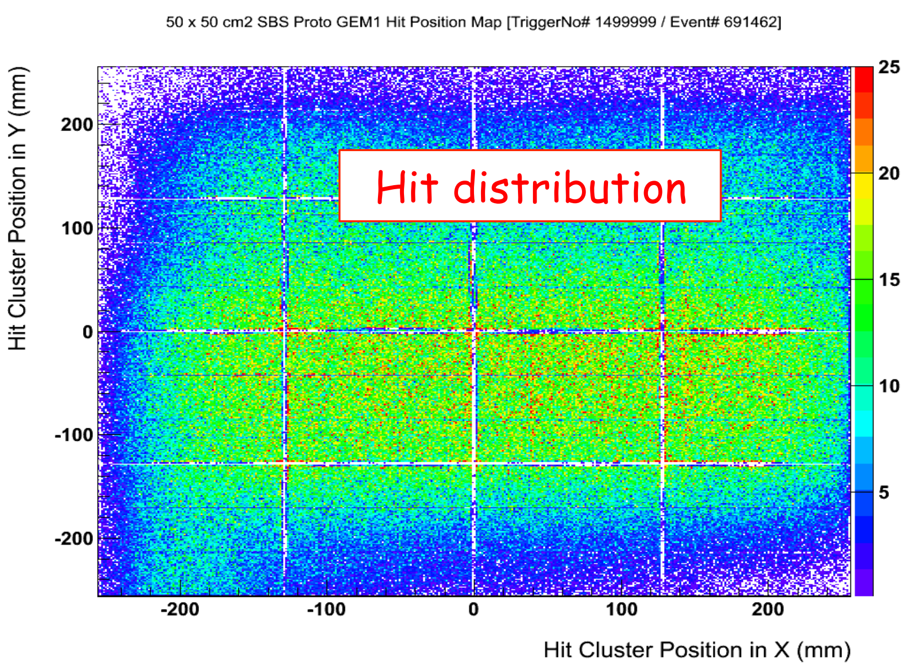
SBS Back Tracker
Prototype II

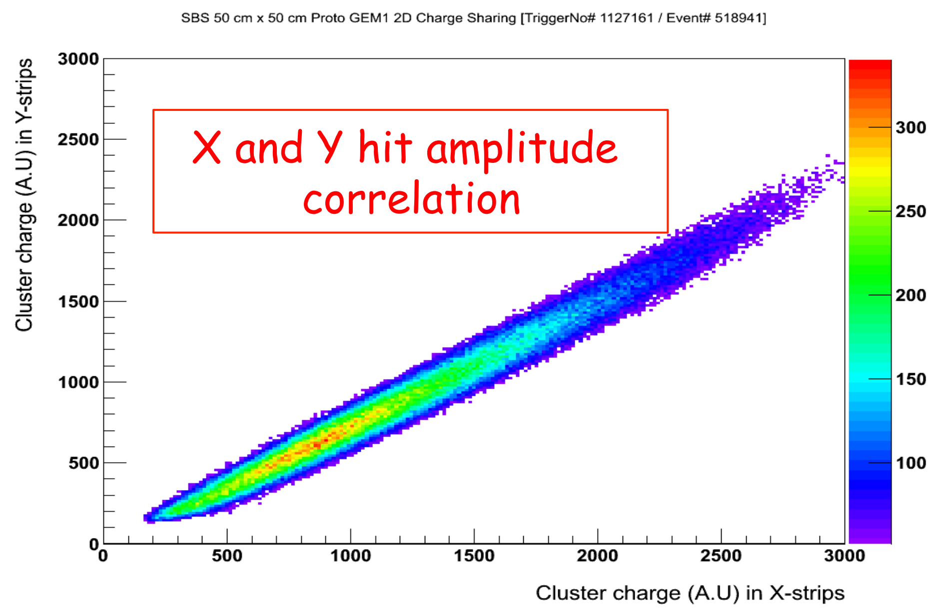
SBS GEM module full-size prototype results

- Bench test with cosmics: acceptance limited by trigger scintillators
- Gas: Argon/CO2 – 70:30, HV: 4300 V (a gain of ~8000)
- S/N ratio is ~ 25:1 on average
- Clean X-Y ADC correlation: critical for multi-hit tracking

2D X/Y strips hits event on prototype I







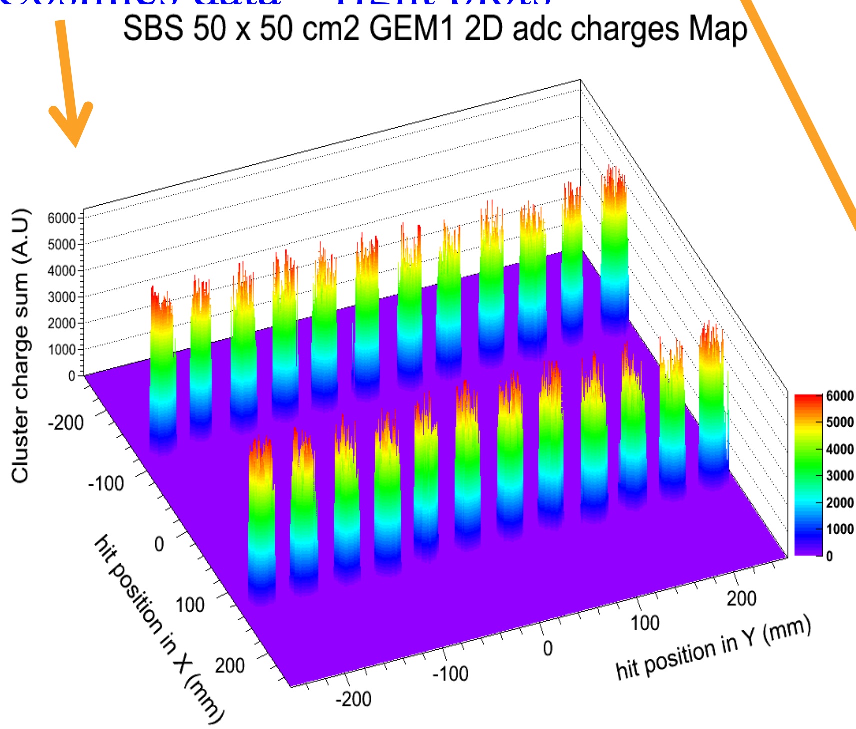
SBS Prototype I: Gain uniformity

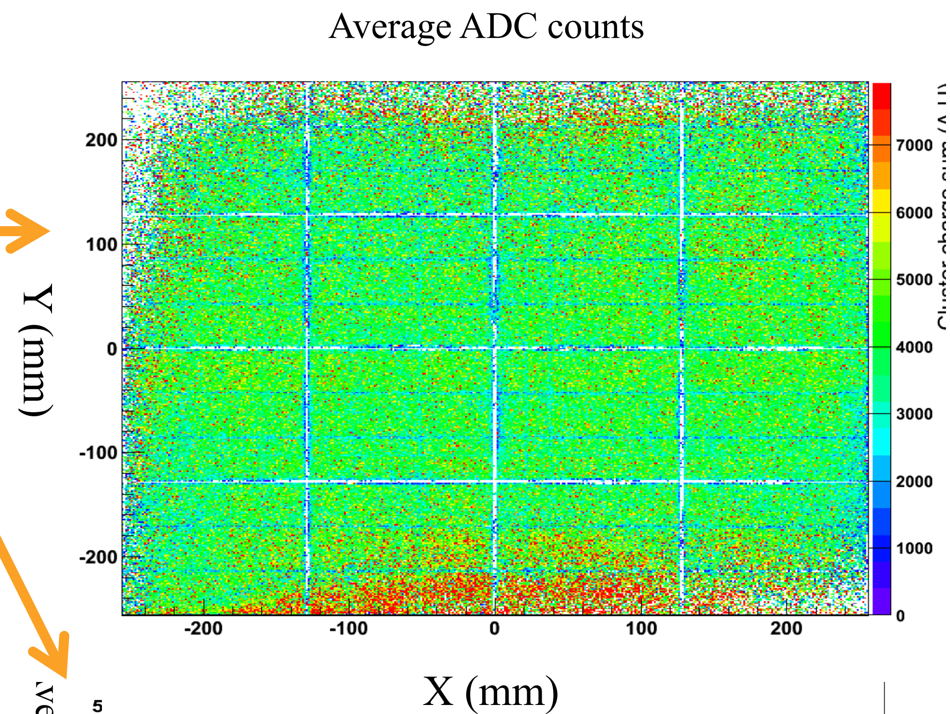
Average ADC count per bin over a large number of events

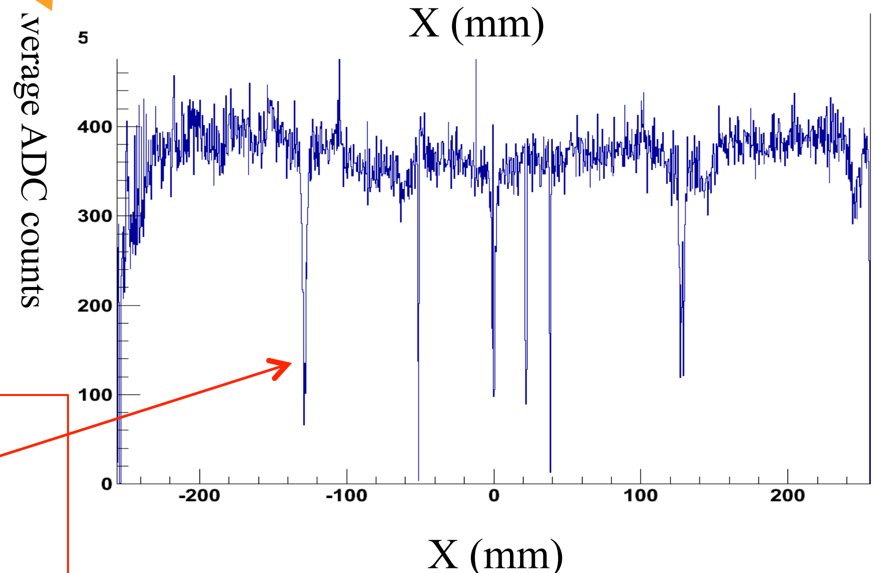
=

Σ_N (ADC counts) / N_{hits}

- Cosmics data – right plots
-

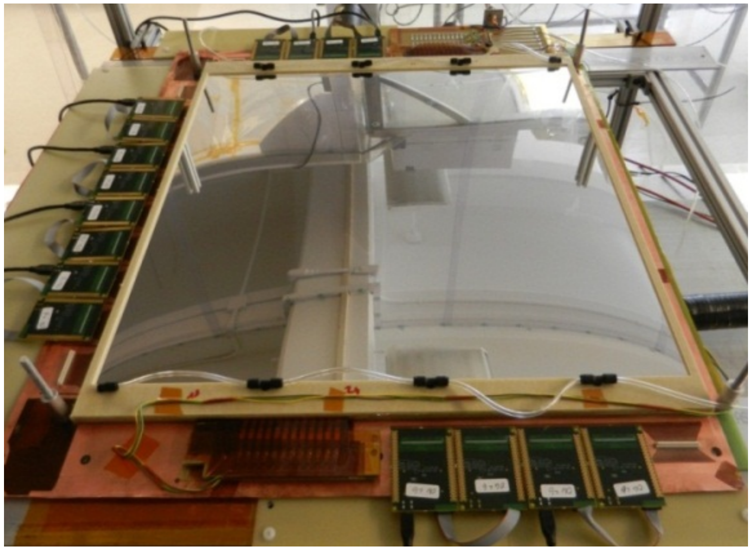


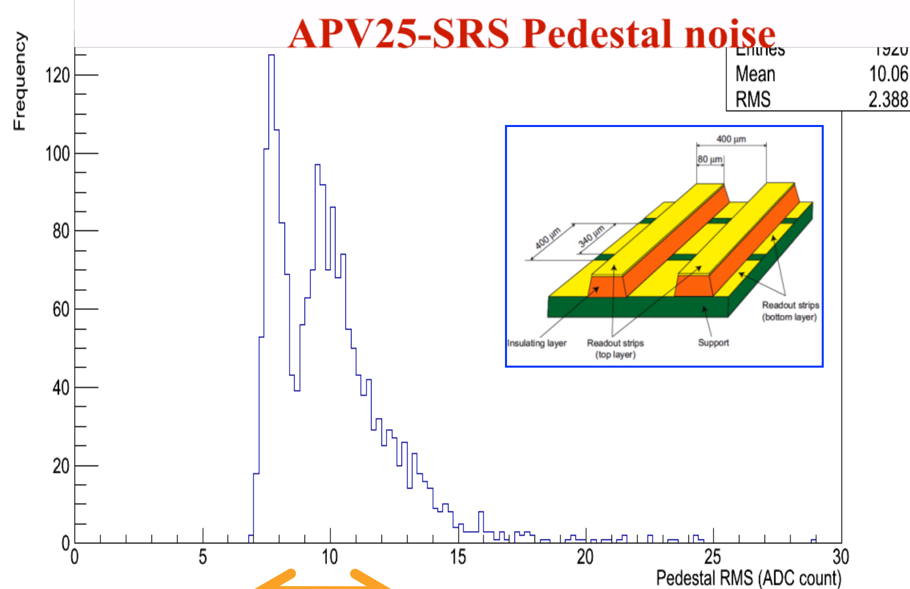




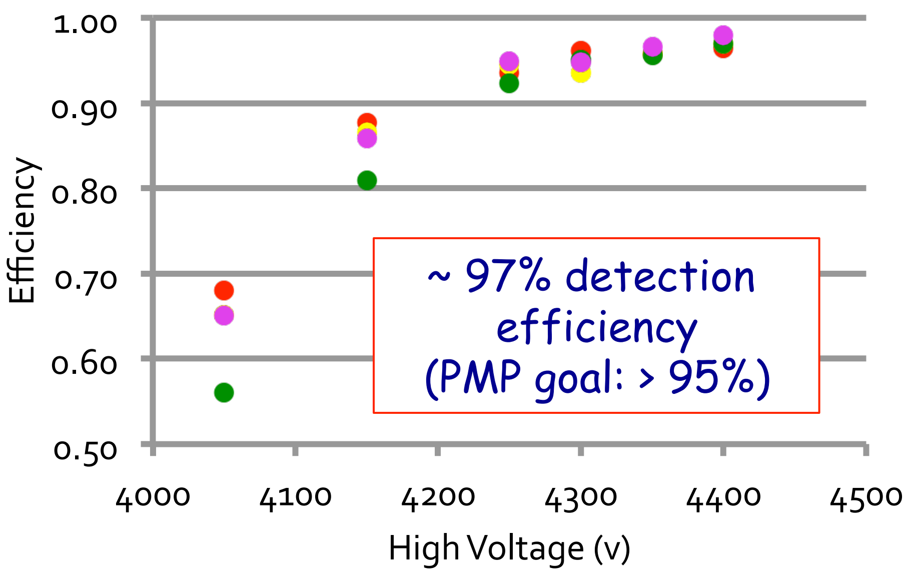
- ❑ Efficiency drops at the spacers: causes about 2.5% drop in overall efficiency.
- ❑ A 50 x 60 module just completed with no spacers: testing underway.

SBS GEM module full-size prototype results





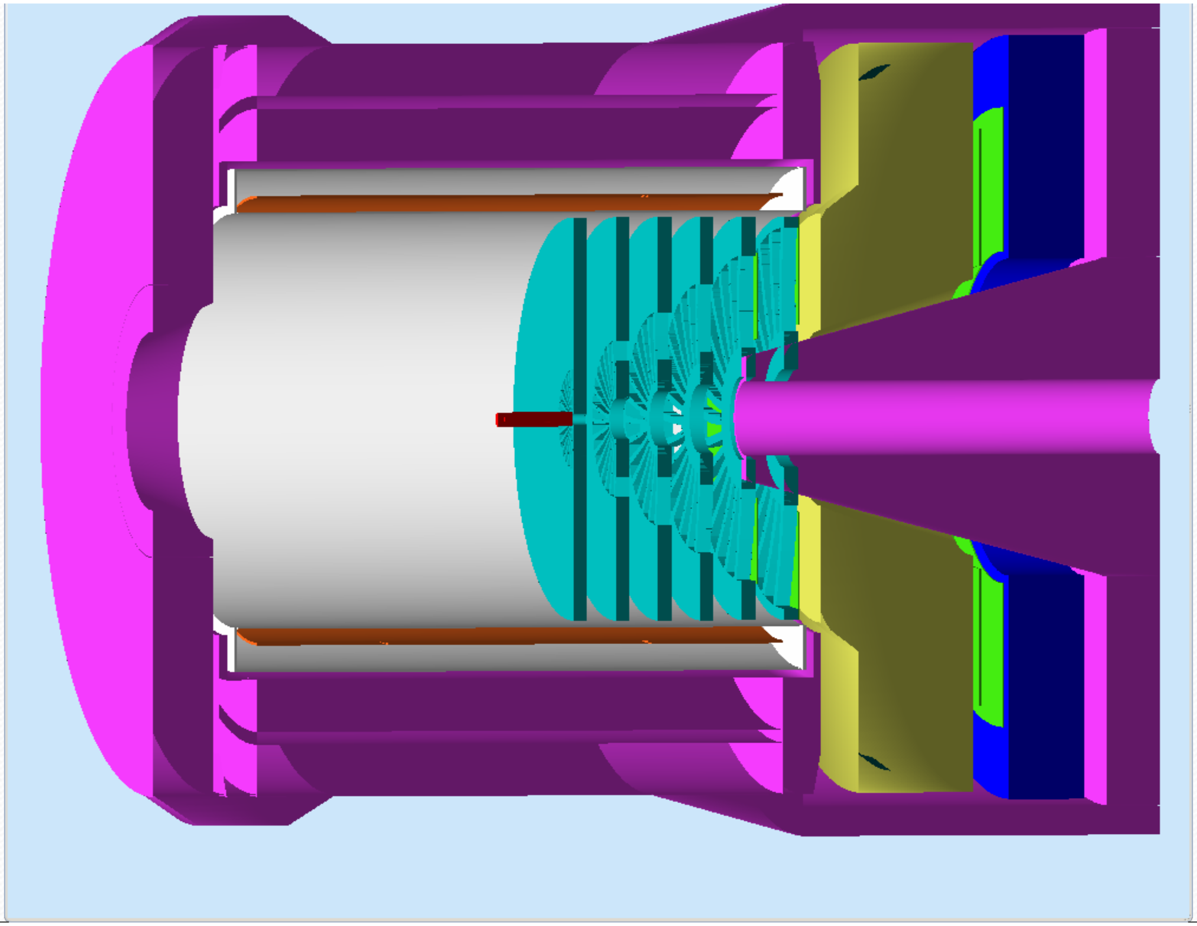
~ 1600 e- to 2750 e-
With a gain of 8000 the average signal per strip will be ~ 50,000 e-



~ 97% detection efficiency
(PMP goal: > 95%)

GEM chambers for Hall A SoLID spectrometer

Solenoidal Large Intensity Device for Precision Study of Nucleon Structure and Test of Standard Model



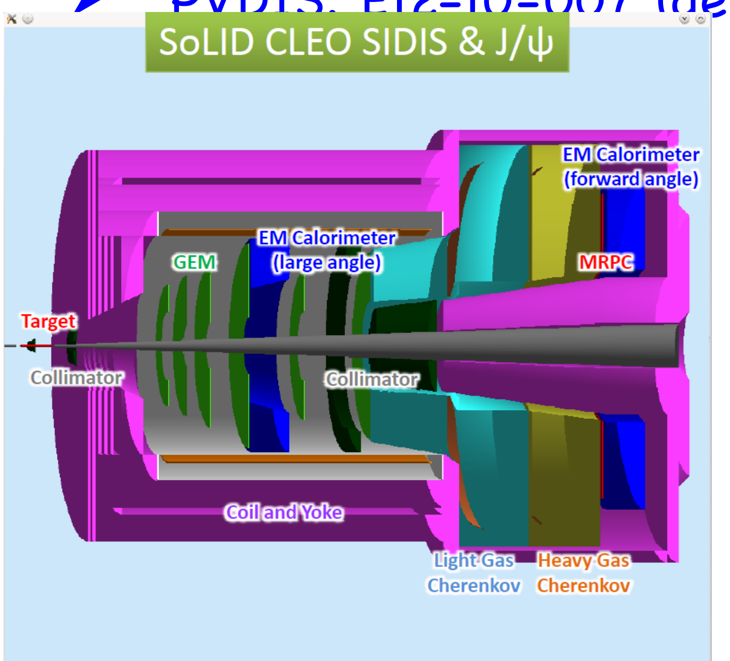
Physics Program for SoLID

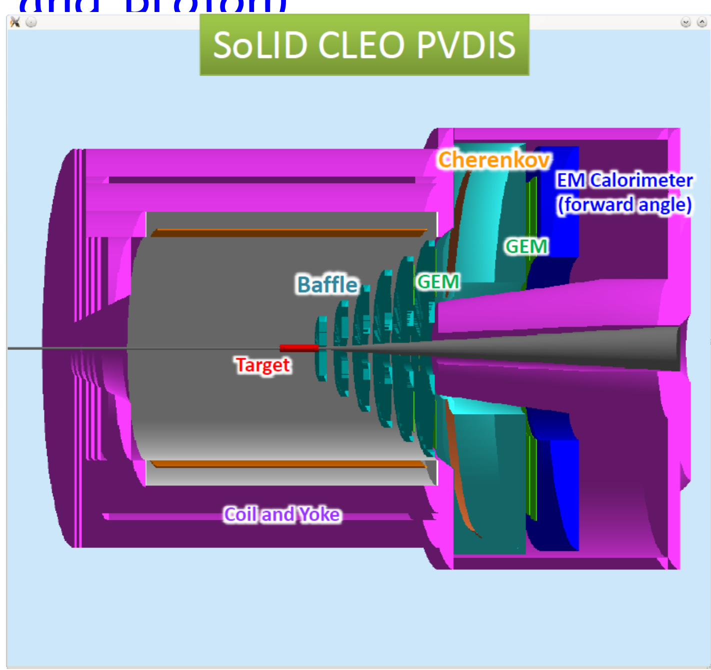
•SoLID: large acceptance, capable of handling high luminosity (up to~10^{39} with baffle, up to ~10^{37} without baffle)

- ➢ Ideal for precision Inclusive-DIS (PVDIS) and SIDIS experiments
- ➢ Excellent for selected exclusive reactions (ex. J/Ψ)

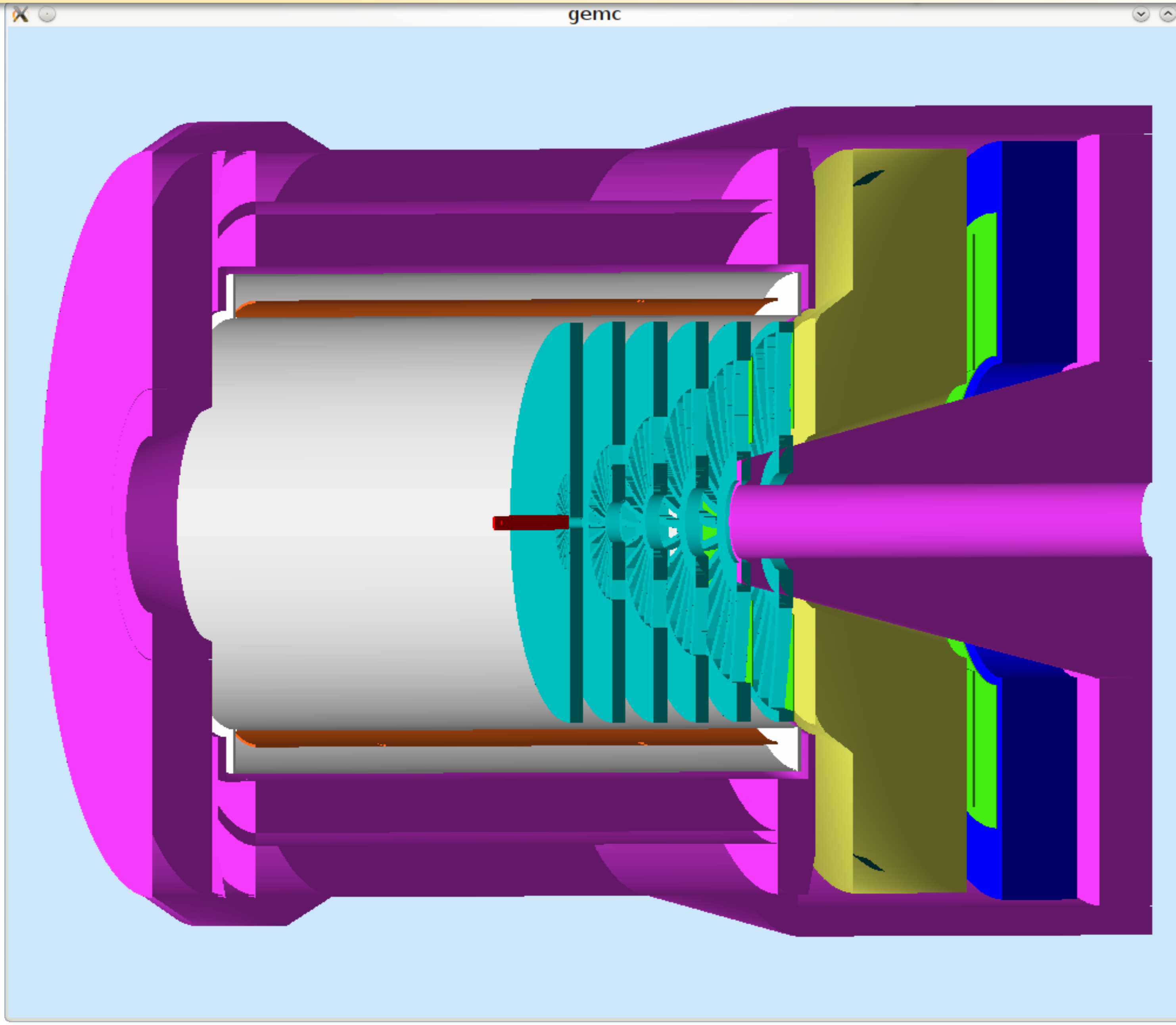
• Five high impact experiments approved:

- ➢ SIDIS: E12-10-006 (^{3}He-T), E12-11-007 (^{3}He-L), E12-11-108 (proton-T)
- ➢ PVDIS: E12-10-007 (deuteron and proton)



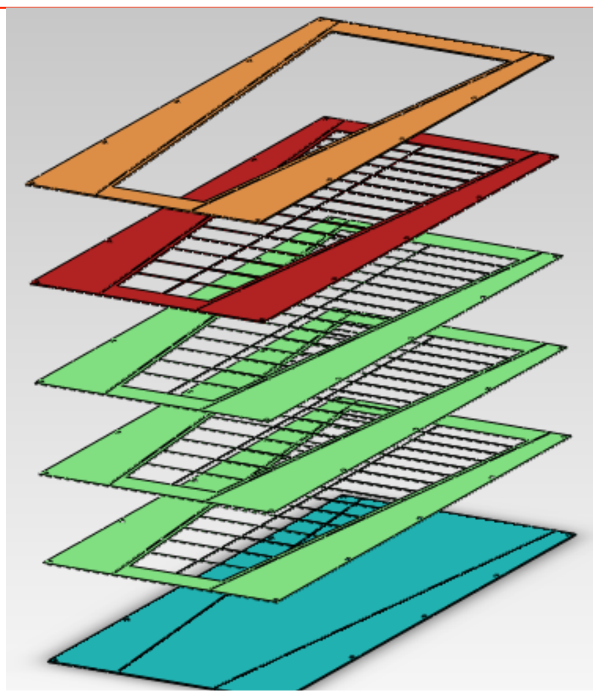


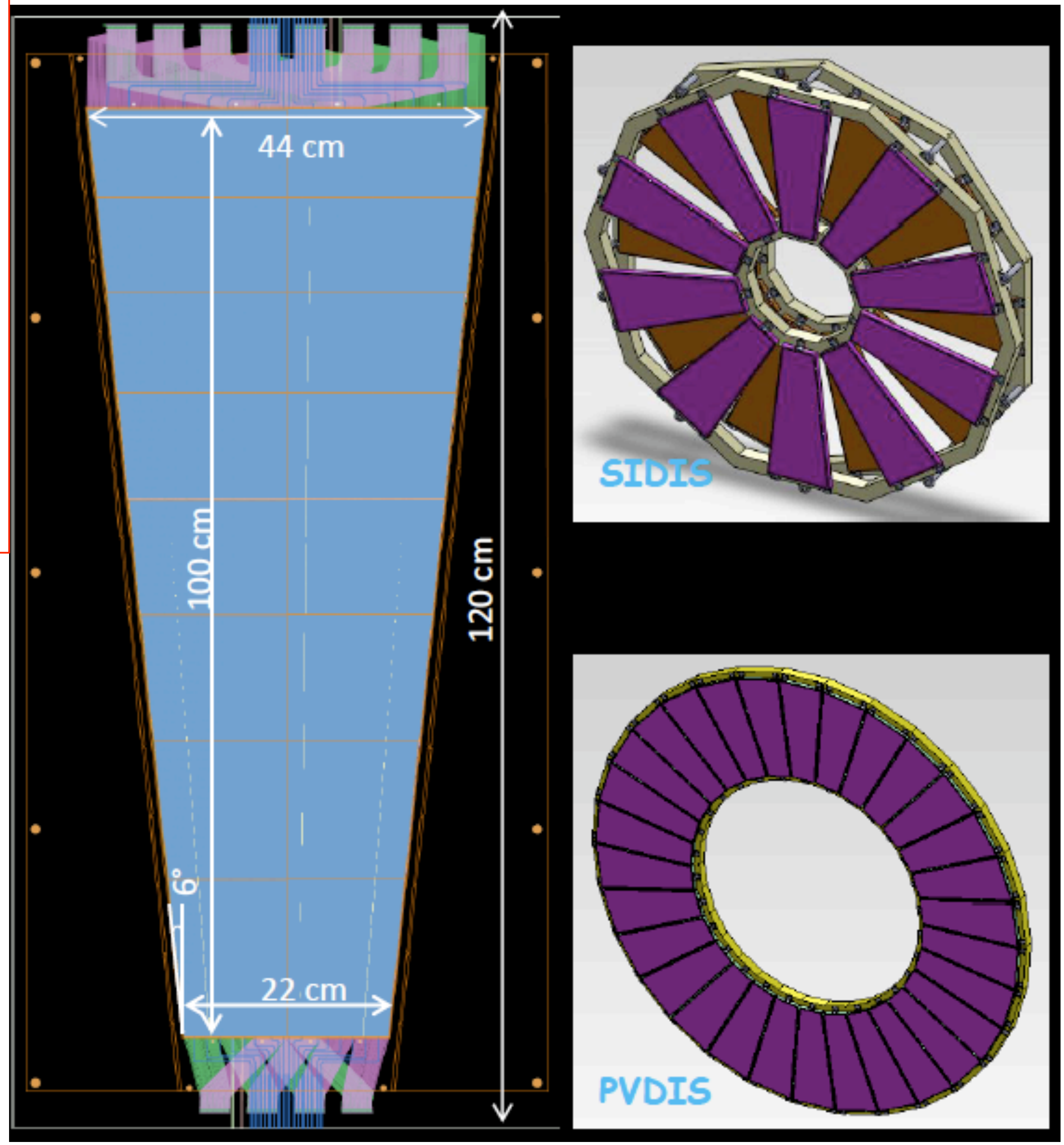
GEM chambers for Hall A SoLID spectrometer



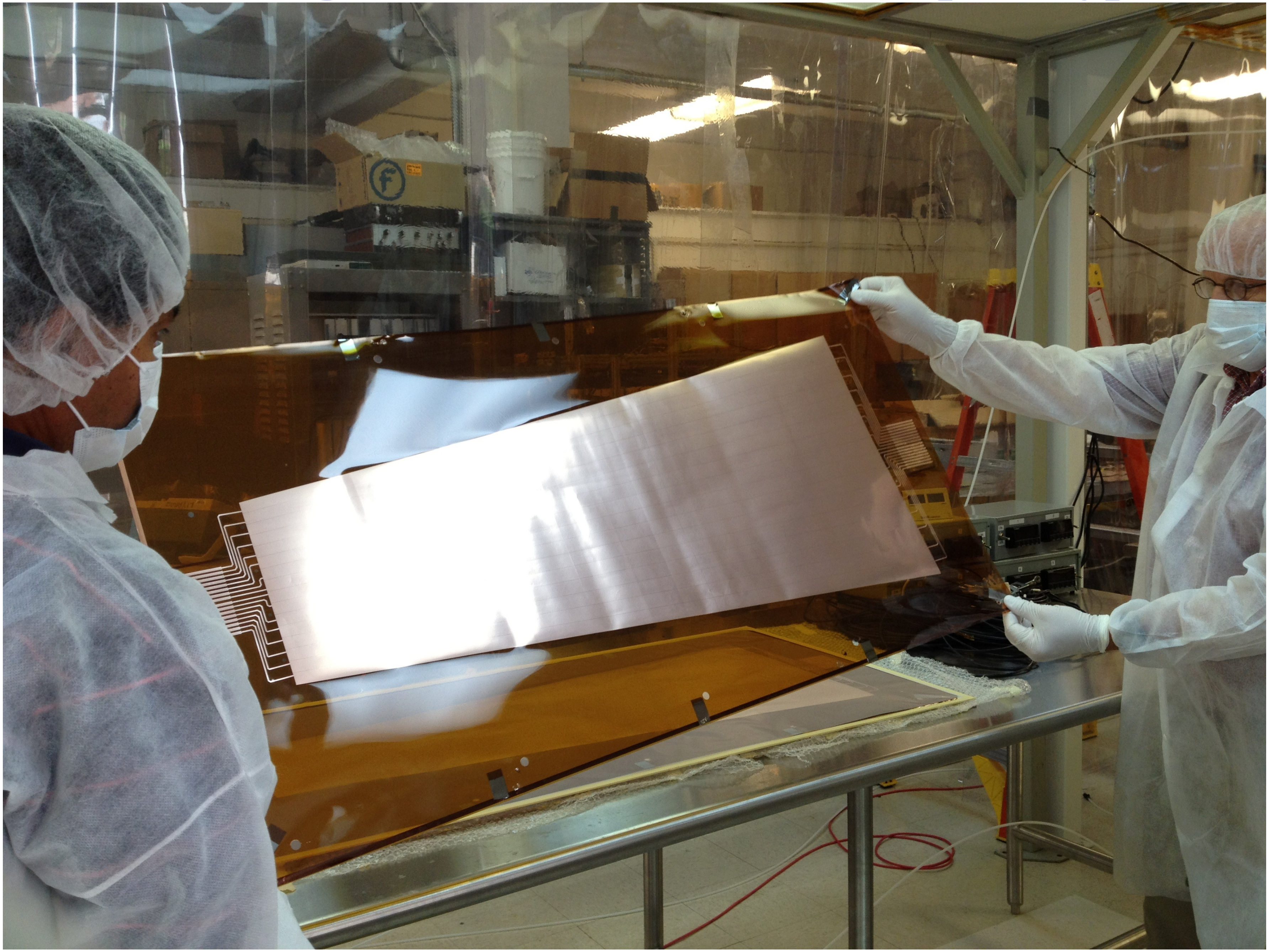
SoLID-EIC GEM Tracker R&D

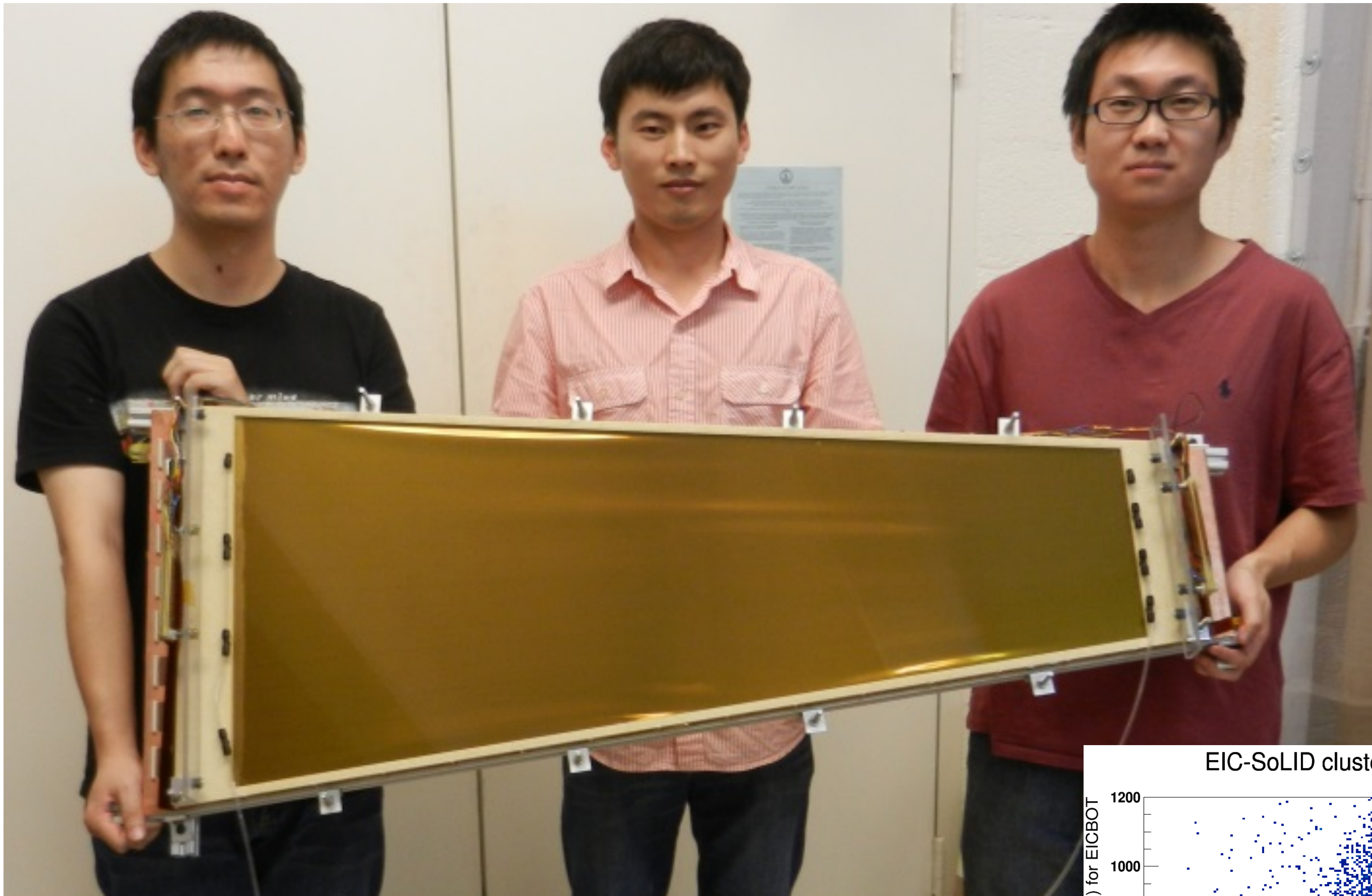
- SoLID requires 150 GEM modules with a total active area of ~ 35 m^2
- Twice the size of SBS tracker
- Requirements similar to a future EIC forward tracker
- UVa group is conducting large GEM R&D towards SoLID GEMs
- The first prototype fabrication is underway.

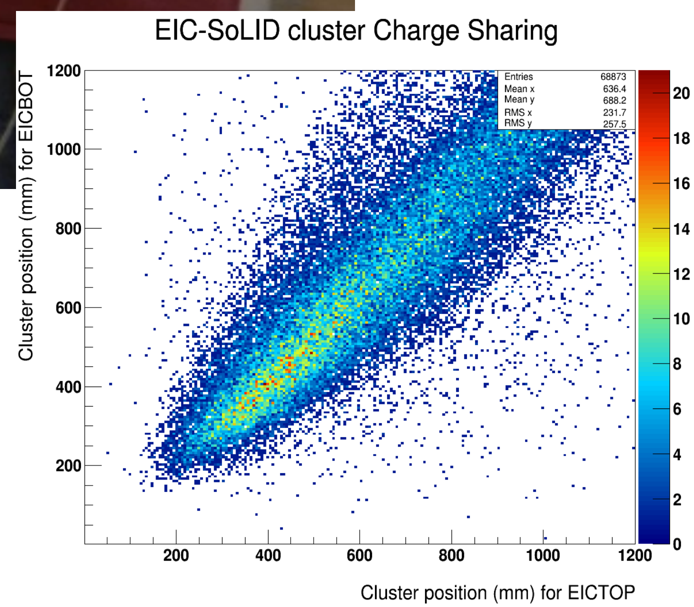




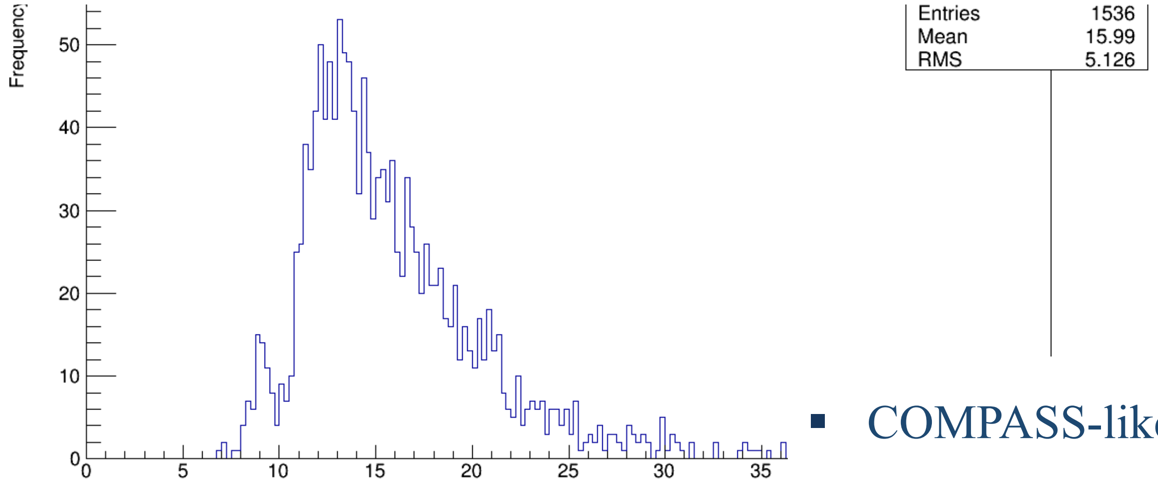
The 1 m long GEM foil for SoLID-EIC prototype GEM

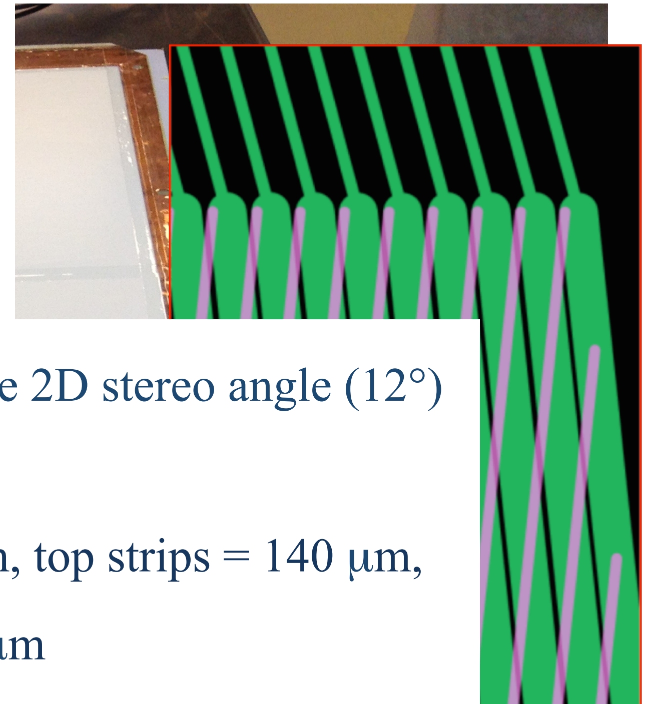


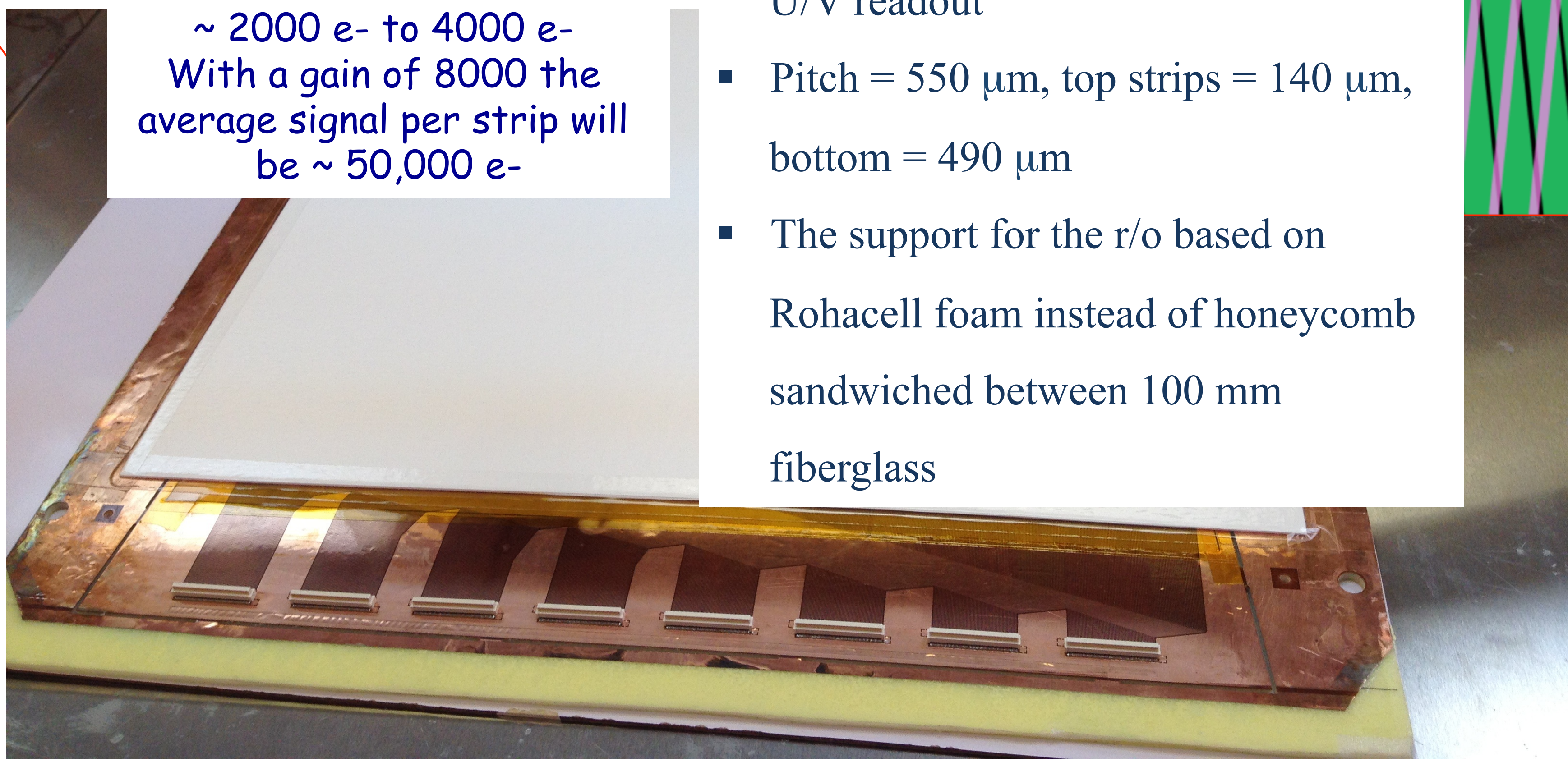



EIC-SoLID cluster Charge Sharing
Entries 68873
Mean x 636.4
Mean y 688.2
RMS x 231.7
RMS y 257.5
Cluster position (mm) for EICBOT
Cluster position (mm) for EICTOP
200
400
600
800
1000
1200
0
2
4
6
8
10
12
14
16
18
20

The U/V COMPASS-like readout board



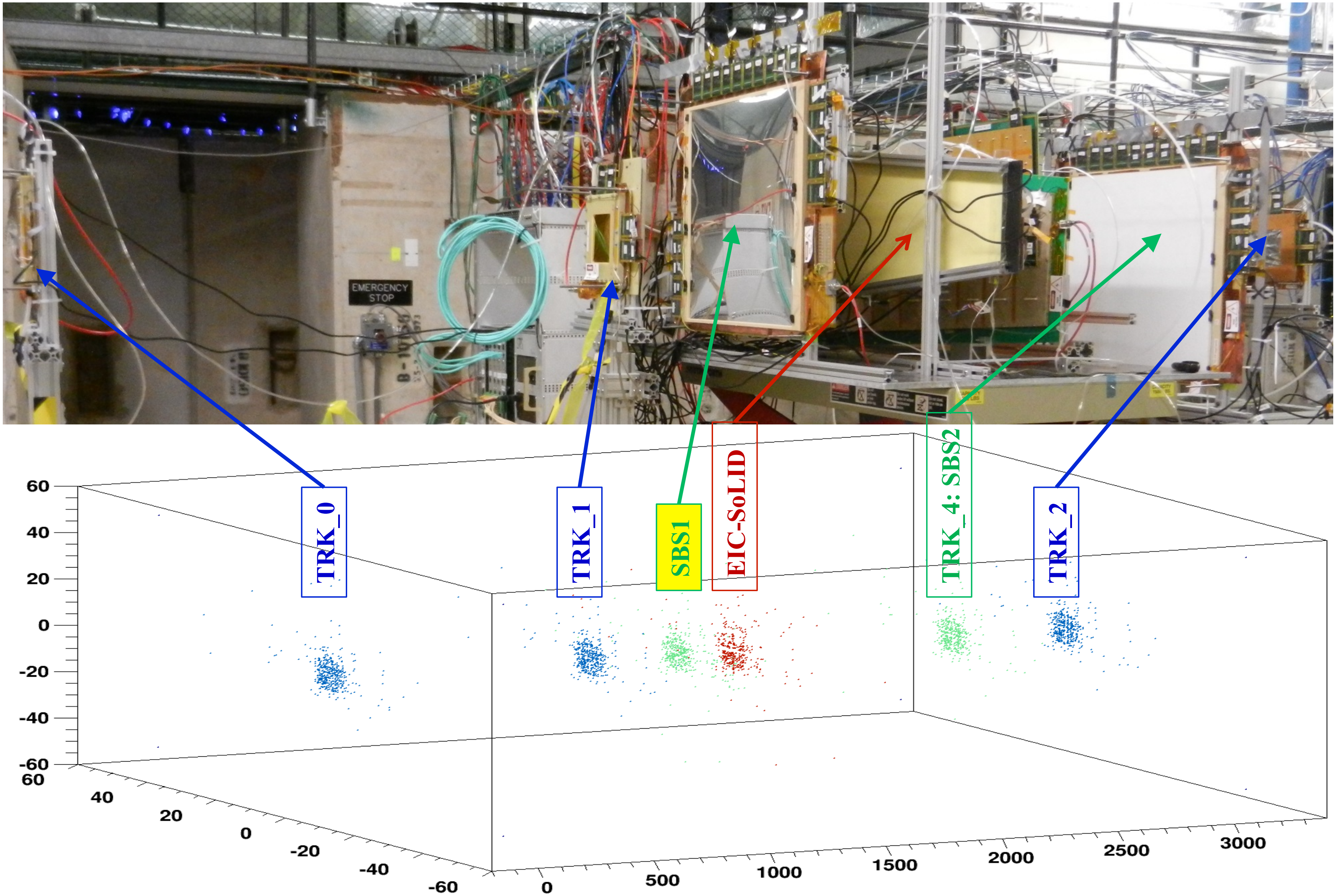




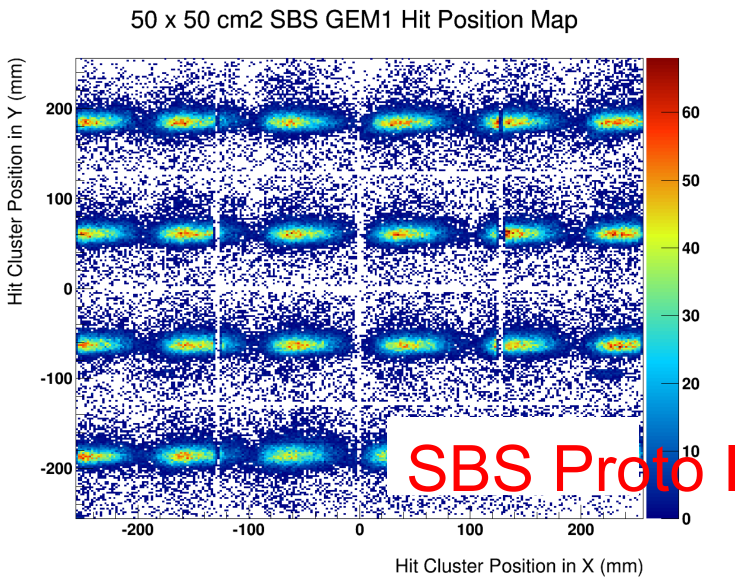
~ 2000 e- to 4000 e-
With a gain of 8000 the average signal per strip will be ~ 50,000 e-

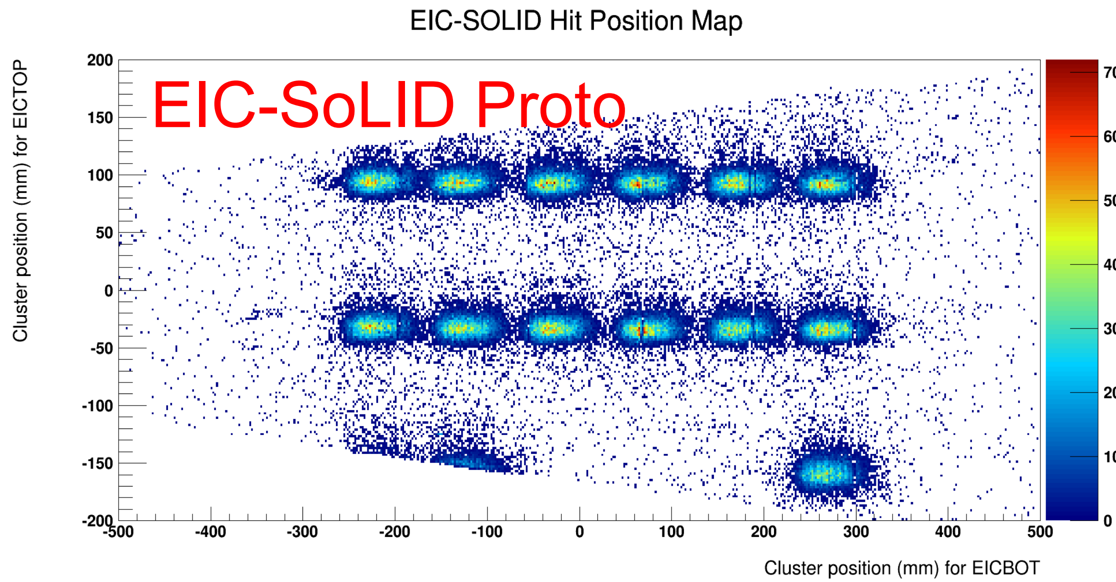
- COMPASS-like 2D stereo angle (12°) U/V readout
- Pitch = 550 μm, top strips = 140 μm, bottom = 490 μm
- The support for the r/o based on Rohacell foam instead of honeycomb sandwiched between 100 mm fiberglass

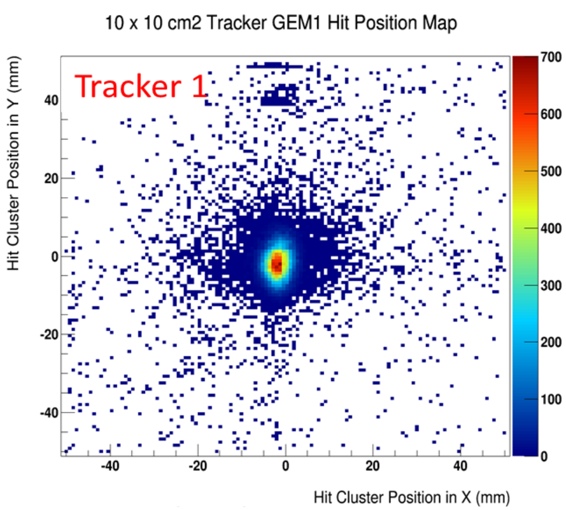
Large Size GEMs in MT6-2B @ FTBF (Fermilab)

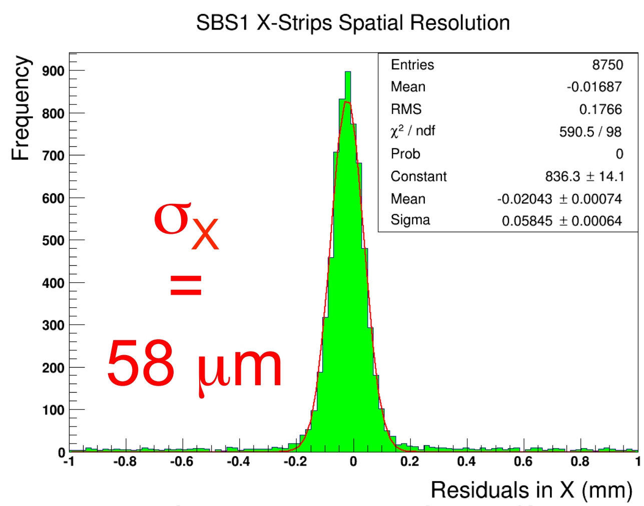


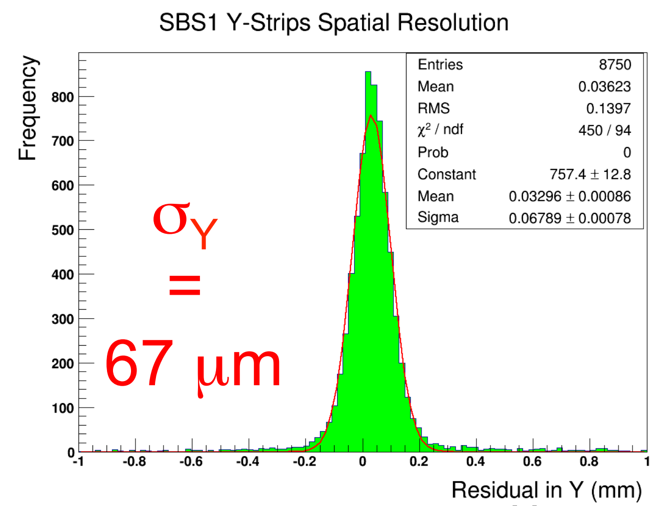
Preliminary Results with Fermilab Test Beam



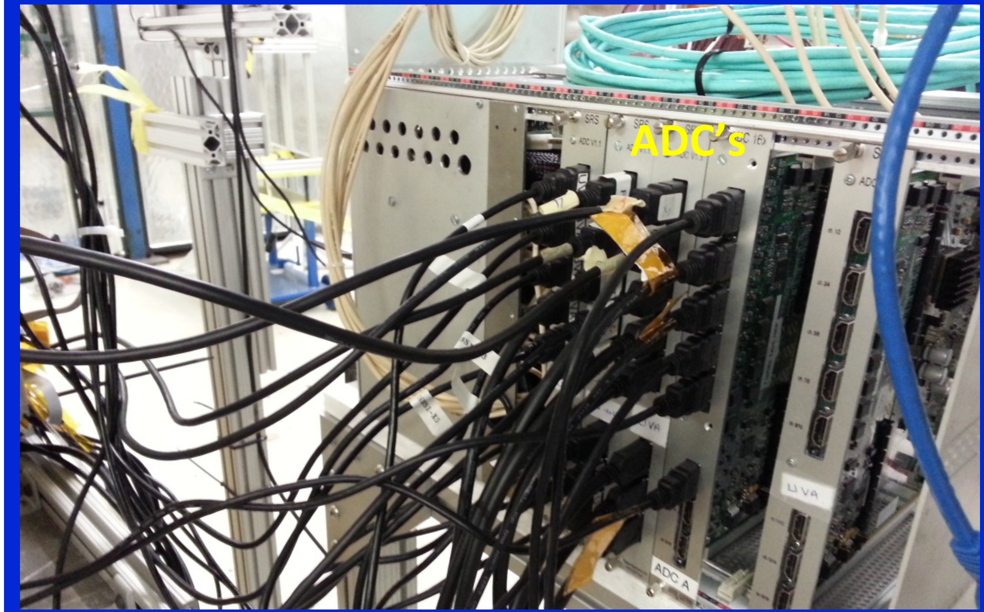




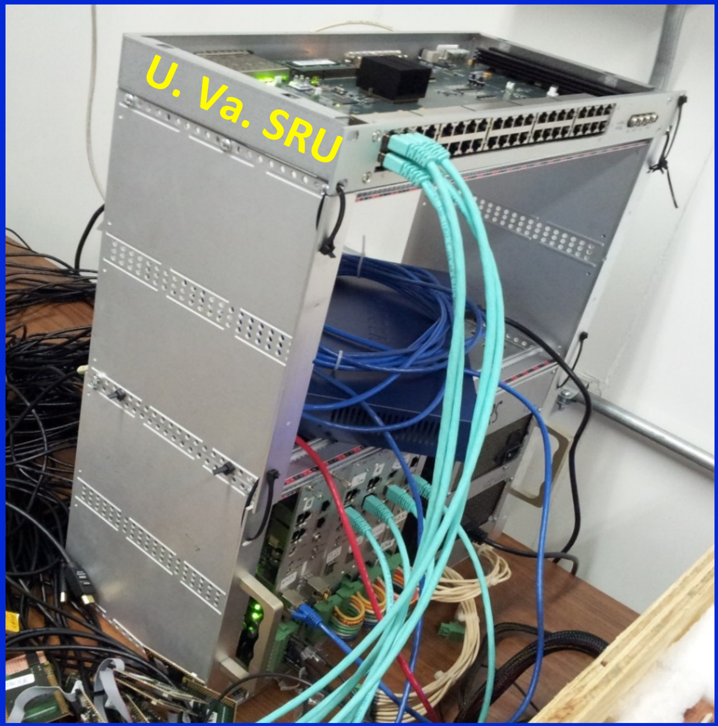




SRS Readout With DATE @ FTBFL (FNAL)

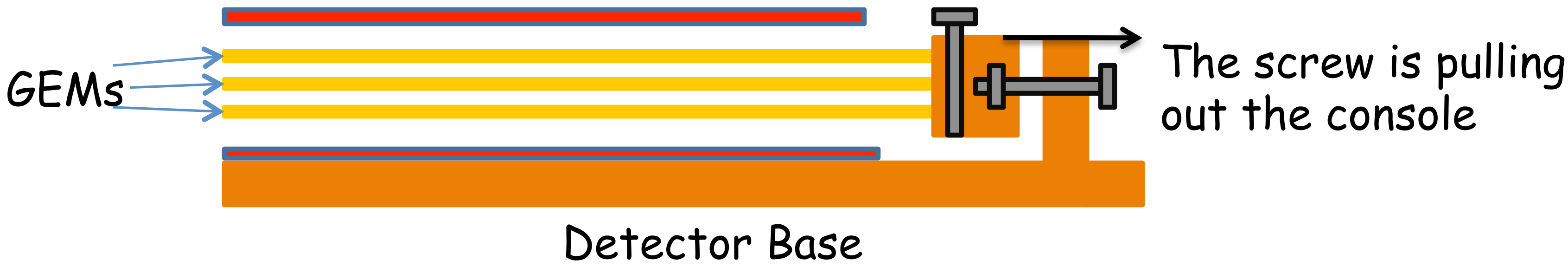


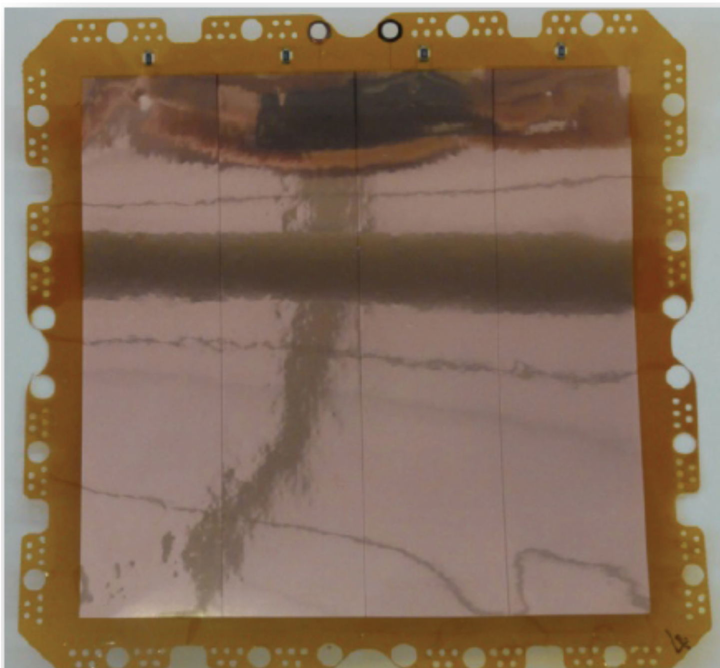
- Beam structure: 1min cycle, 4s spills 10k to 35k particles/spill
- 64 APV25 with SRS+SRU+ 4FEC/ADC combos
- DAQ rate is up to 400 Hz (average over 4s spill)
- Using 3,6 and 9 time slices (25ns) for digitization
- Trigger: coincidence of 3 scintillators

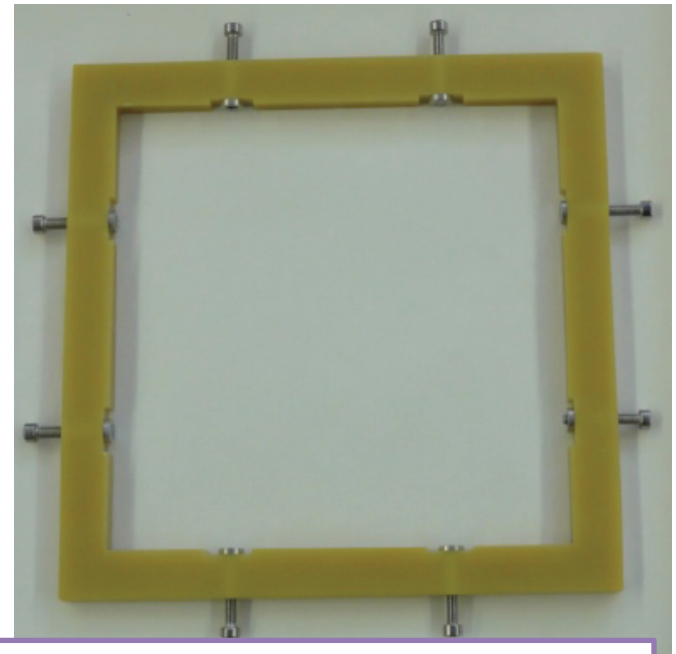


New developments and Future Directions

No-Stretch No-spacer GEMs from CERN



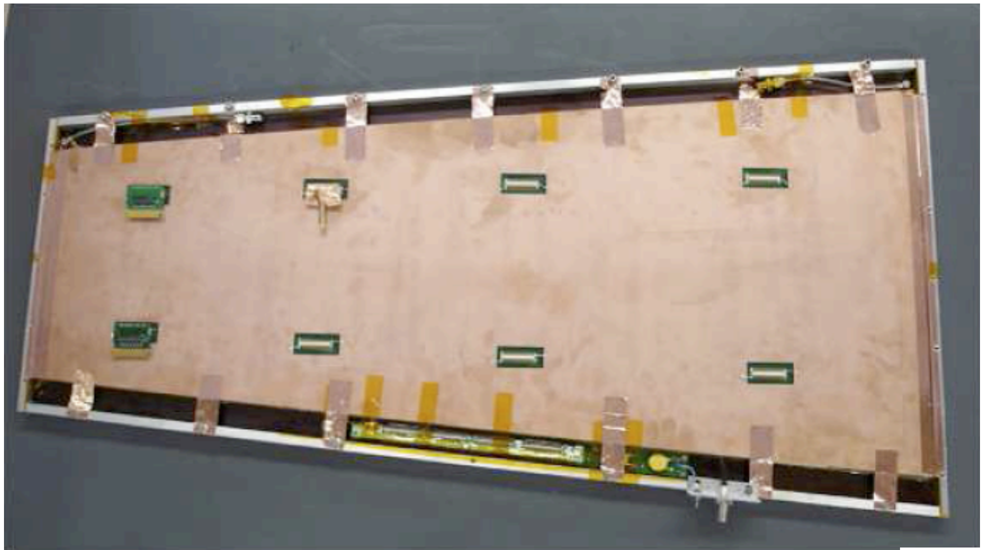


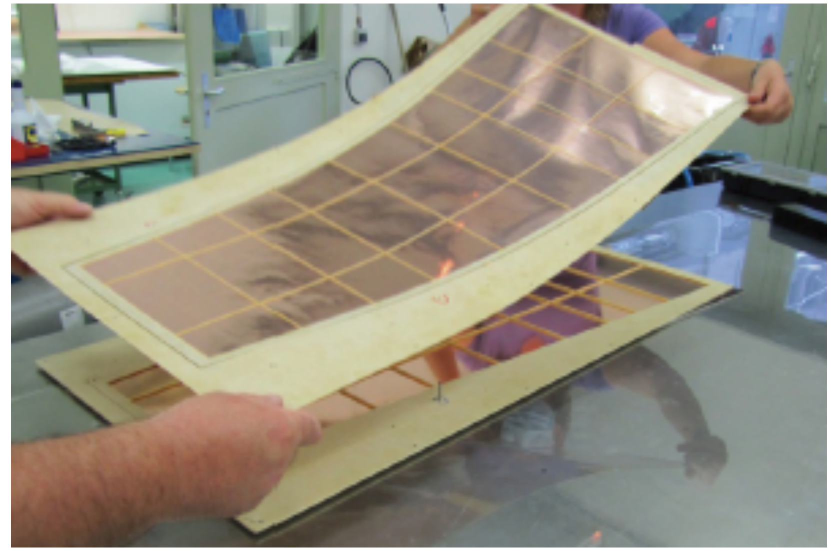


Already tested for 30 cm x 30 cm foils
Reduces the assembly time from ~ 10 days to few hours.

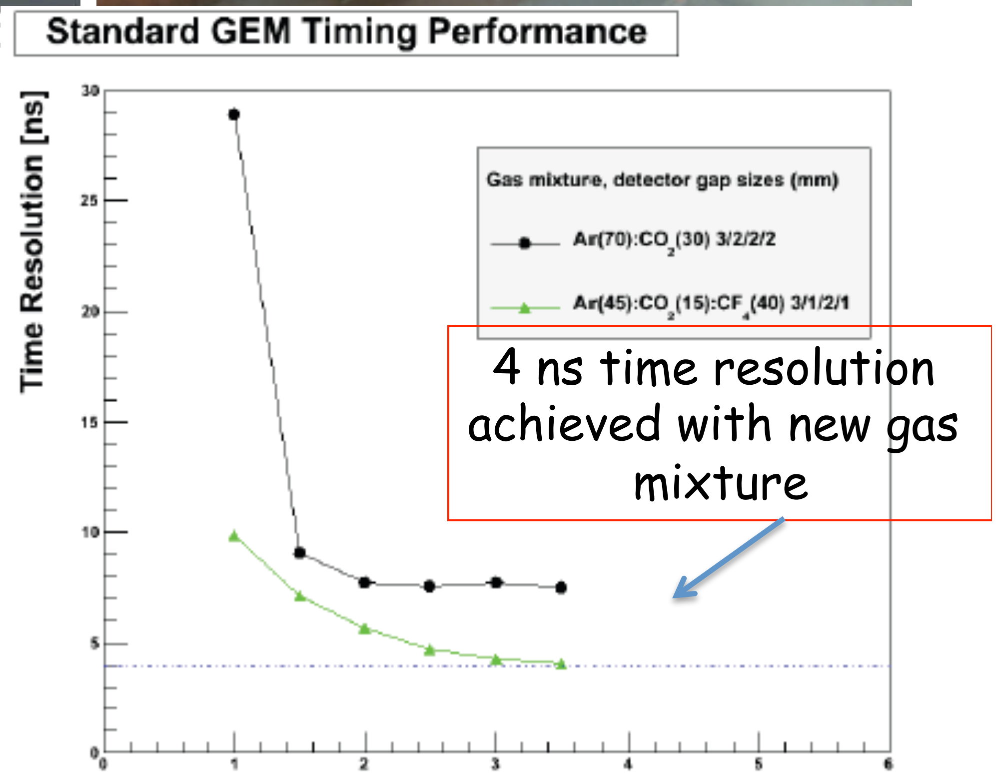
Issue: material at the edges

Timing GEMs for Trigger



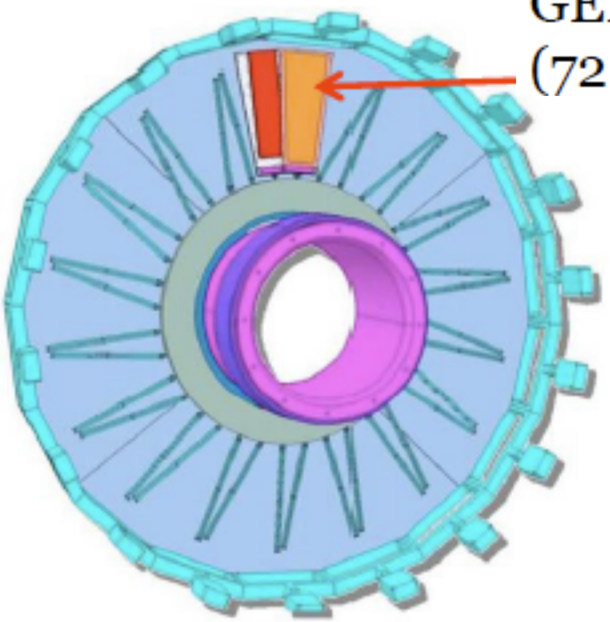


Large prototype GEM module for CMS
99 cm x (22 – 45.5) cm



CMS high-eta GEM tracker proposal

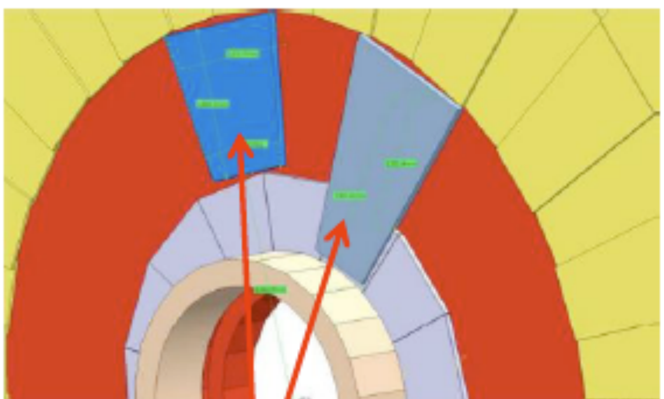
GE1/1 detectors
(72 chambers)



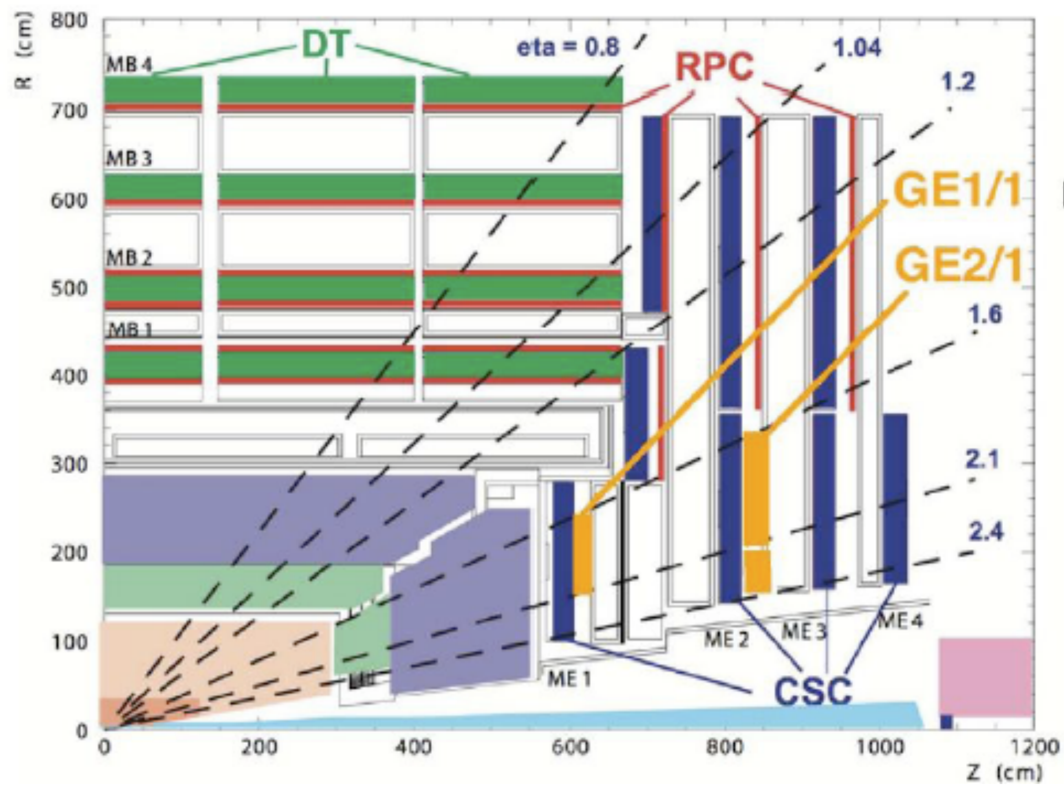
GEM s for triggering and tracking

- Proposal to cover the $1.6 < |\eta| < 2.4$ region with GEMs.
- GEMs for
- 240 GEM chambers

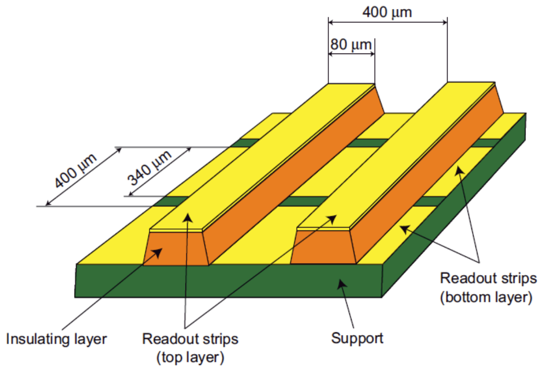
Total active area covered ~ 300 m^2

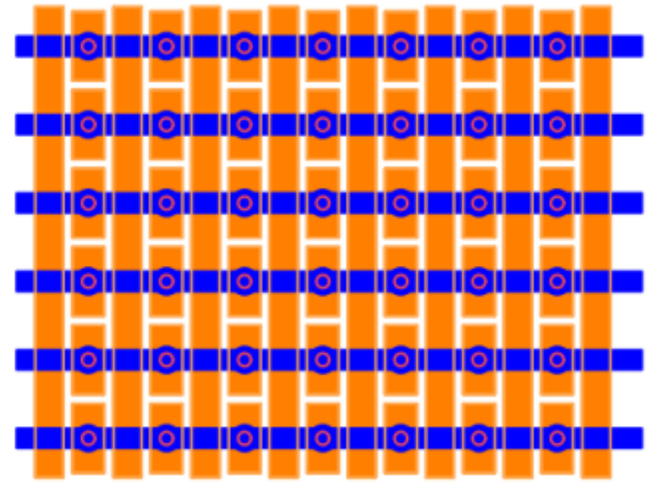


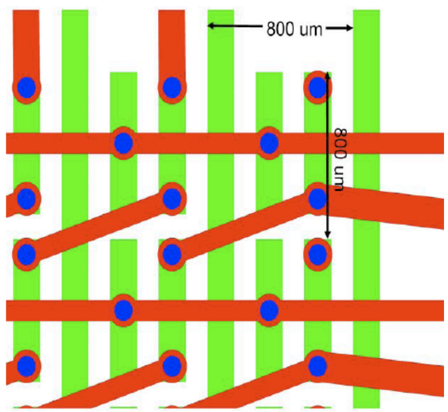
GE2/1 detectors
(144 chambers)



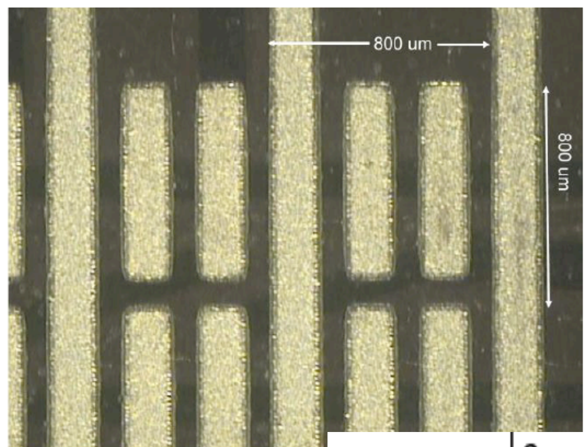
Different Readout Schemes.

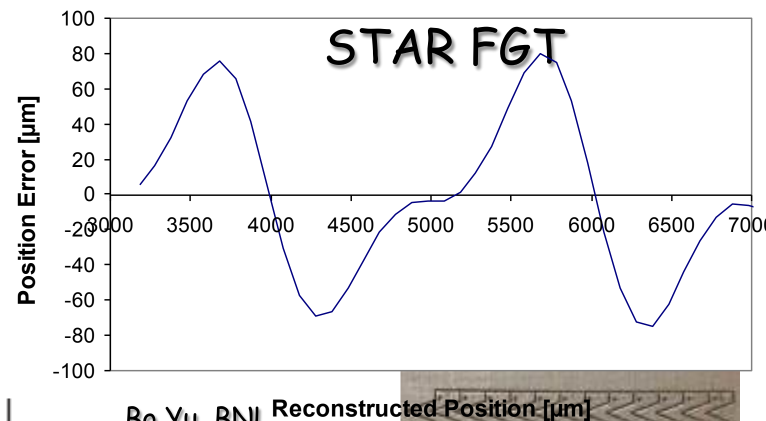






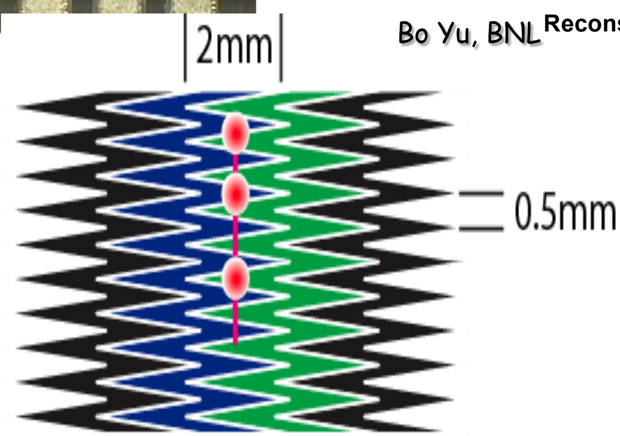
Detail in circled area above
Green = top side, red = bottom side



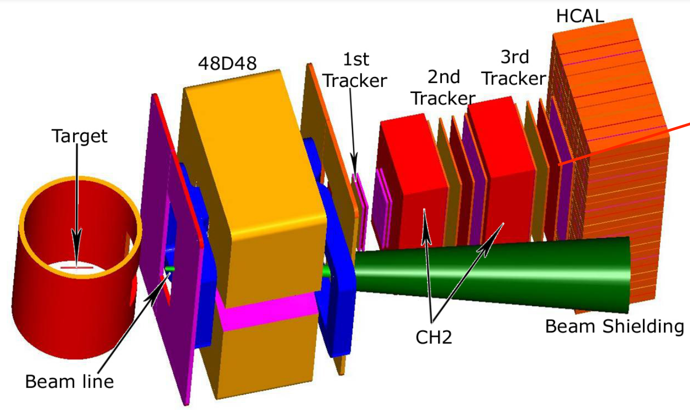


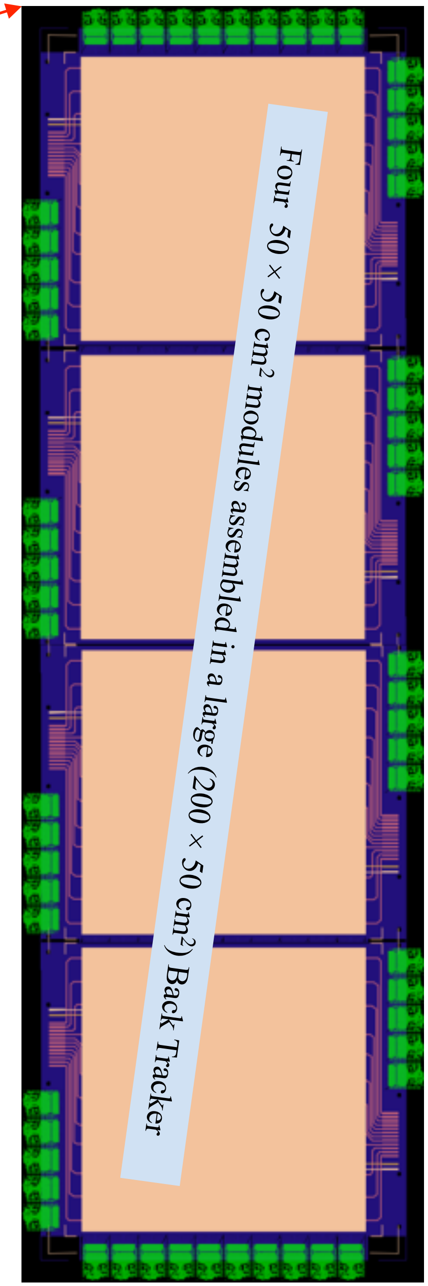
Bo Yu, BNL

SBU, Yale, FIT



Towards very large GEM chambers

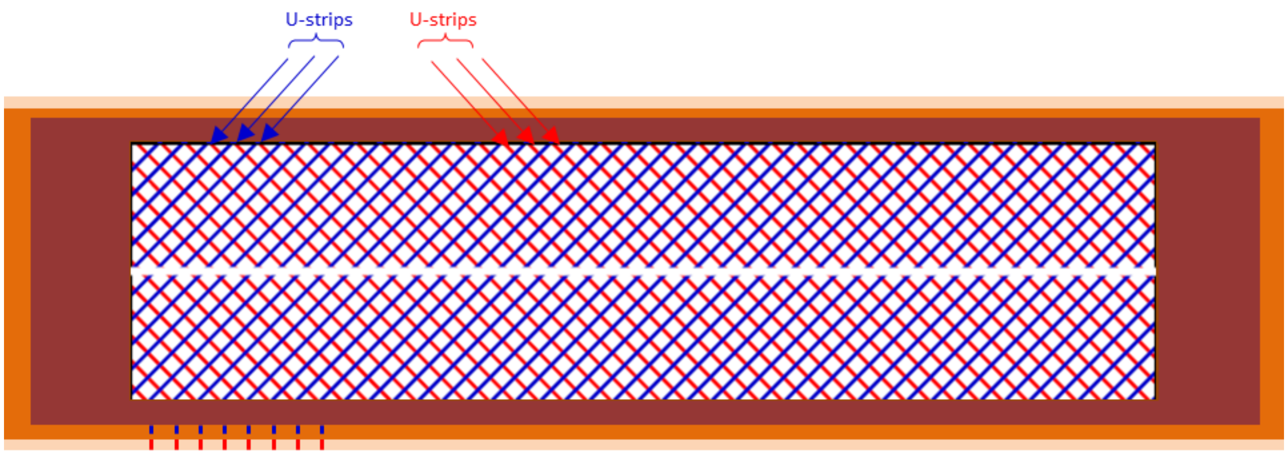




- Rui de Oliveira's group at CERN now has the technical feasibility to produce 50 cm x 200 foils.
- Jefferson lab-UVa collaboration has the expertise, infra-structure and capability to build such a GEM chamber
- Would be a breakthrough in large area tracking technology.
- Size ideally matched for nuclear physics detectors: Huge boost to future experiments.
    - Cover large areas with no dead zones.
- Link to industrial applications beyond nuclear physics: National security, Radiation detection, Medical Physics

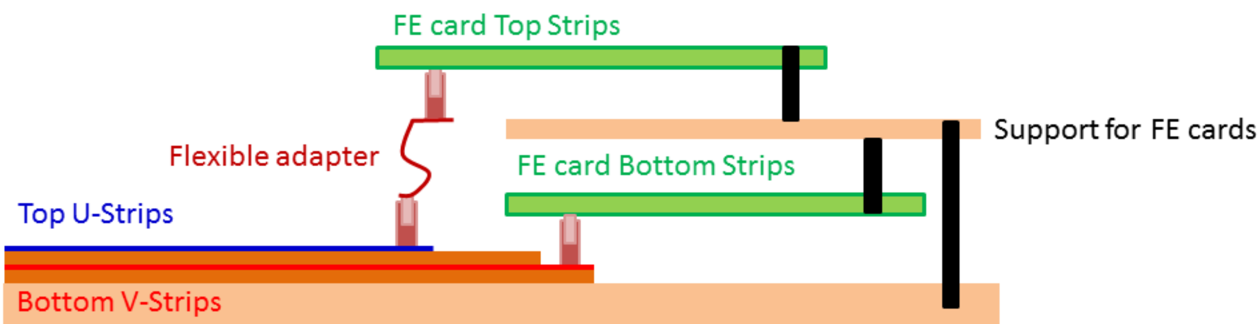
Proposed Large Area GEM chamber

Top view of the 2d 45° readout



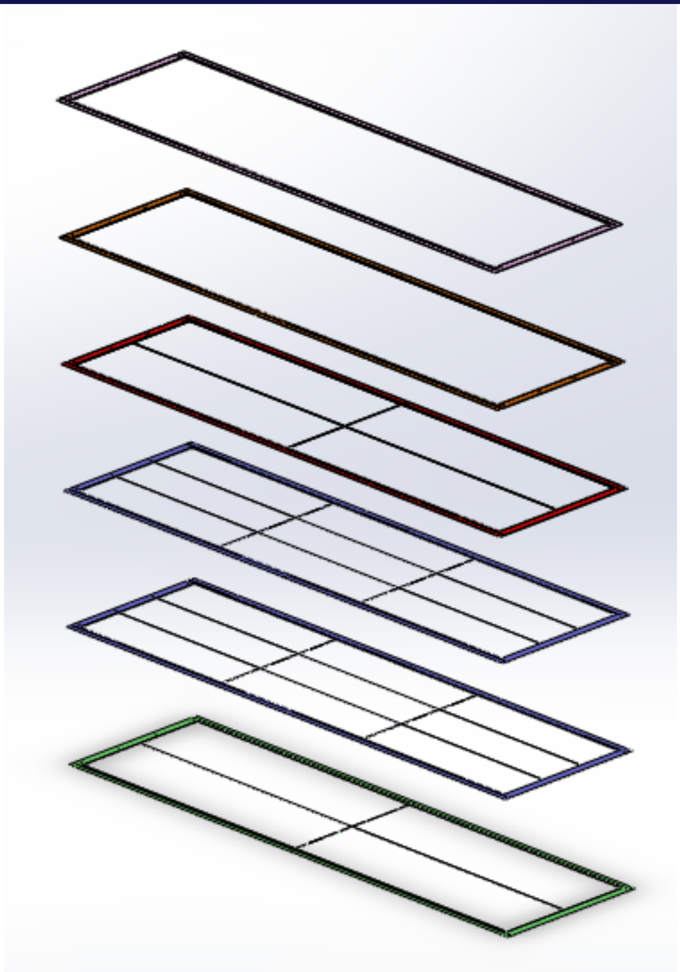
- 200 cm x 50 cm active area.
- Base frame with wide sides
- U-V readout from both sides
- 400 micron strip pitch.
- longest strip is ~ 35 cm

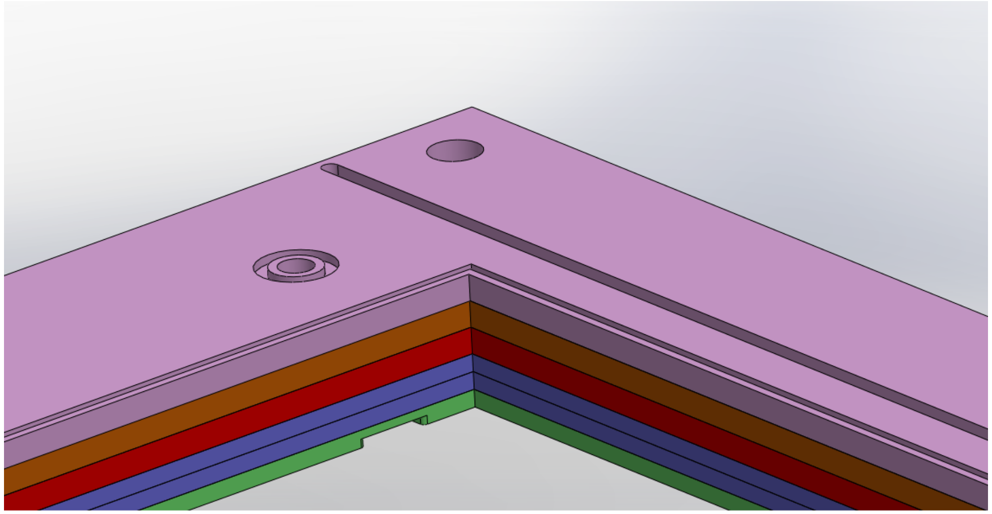
Cross section view with FE cards

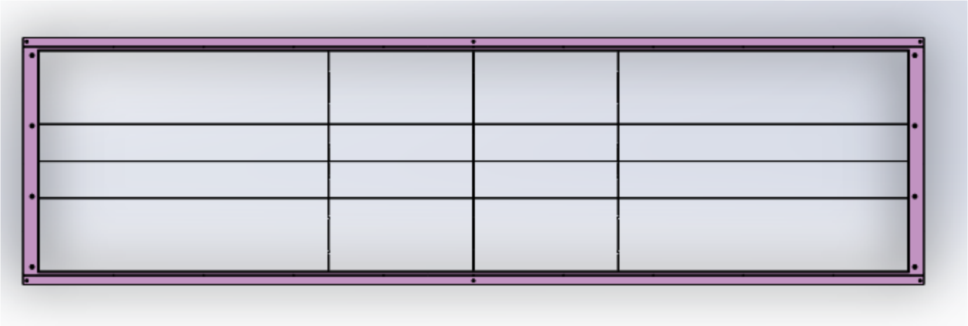


- Readout cards in two layers.
- Readout: 18 k of APV-25 based SRS electronic channels

Frame design underway







- Design/mechanical studies underway within Solidworks to evaluate:
- Evaluate stress on frames
- Foil deformations
- Gas flow.
- Frame assembly techniques

Conclusion

- GEM: cost effective solution for high resolution tracking in hostile environments.
- Major developments in the last few years.
- Now technology ready for large scale projects.