GEM Detectors for SoLID

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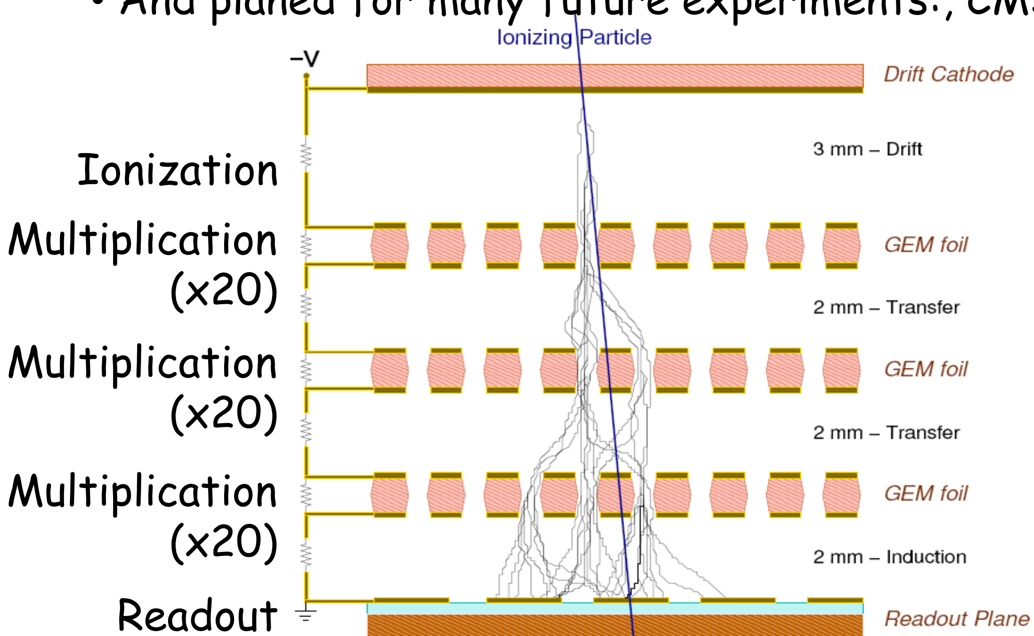
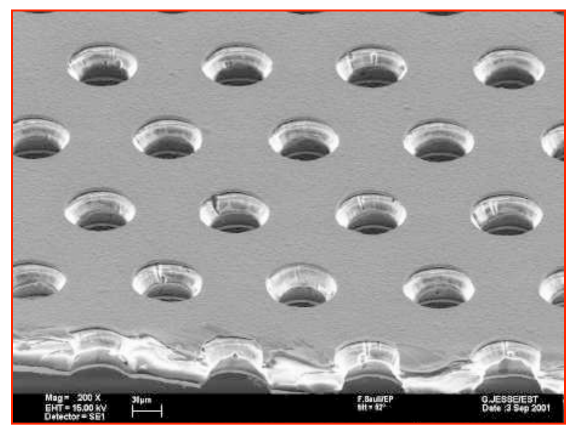
Why GEMs ?

- SoLID concept leads to high rate in trackers: and requires good resolution.
- Gas Electron Multiplier (GEM) detectors provide a cost effective solution for high resolution tracking under high rates over large areas.

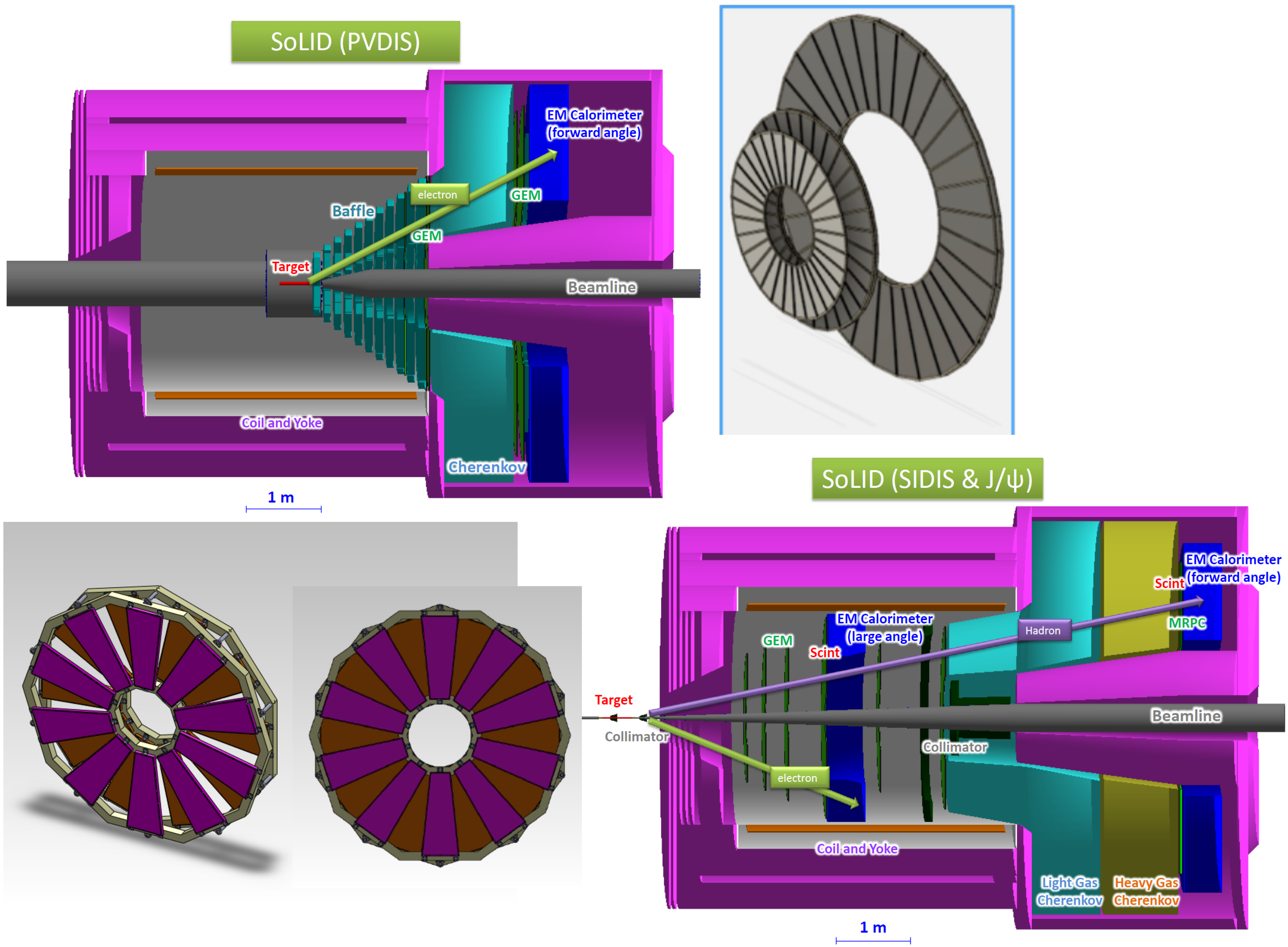
  - Rate capabilities higher than many MHz/cm^2
  - High position resolution (< 75 μm)
  - Ability to cover very large areas (10s – 100s of m^2) at modest cost.
  - Low thickness (~ 0.5% radiation length)
  - Already Used for many experiments around the world: COMPASS, Bonus, KLOE, TOTEM, STAR FGT, ALICE TPC, pRad etc.
  - And planed for many future experiments:, CMS upgrade, SoLID, Moller, P2 @ Mainz



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



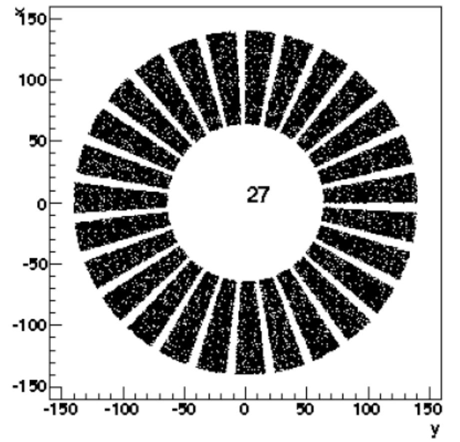
Novel technology: F. Sauli, Nucl. Instrum. Methods A386(1997)531

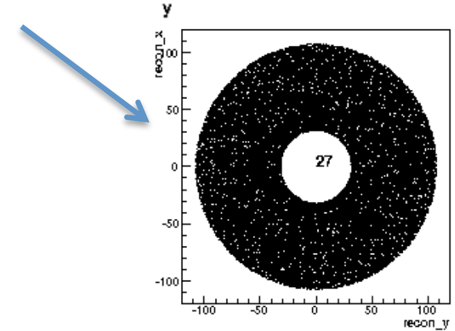

SoLID (PVDIS)
EM Calorimeter
(forward angle)
electron
GEM
Baffle
GEM
Target
Beamline
Coil and Yoke
Cherenkov
1 m
SoLID (SIDIS & J/ψ)
EM Calorimeter
(forward angle)
Scint
MRPC
Hadron
EM Calorimeter
(large angle)
GEM
Scint
Target
Collimator
Beamline
Collimator
electron
Coil and Yoke
Light Gas
Cherenkov
Heavy Gas
Cherenkov
1 m

SIDIS GEM full configuration

- Six locations instrumented with GEM:
- PVDIS GEM modules can be re-arranged to make all chamber layers for SIDIS. – move the PVDIS modules closer to the axis so that they are overlapping with each other

Plane	Z (cm)	R_I (cm)	R_O (cm)	Active area (m^2)	# of channels
1	-175	36	87	2.0	24 k
2	-150	21	98	2.9	30 k
3	-119	25	112	3.7	33 k
4	-68	32	135	5.4	28 k
5	5	42	100	2.6	20 k
6	92	55	123	3.8	26 k
total:				~20.4	~ 161 k





- More than enough electronic channels from PVDIS setup.
- The two configurations will work well with no need for new GEM or electronics fabrication.

PVDIS GEM full configuration

- Instrument five locations with GEMs:
- 30 GEM modules at each location: each module with a 12-degree angular width.

Location	Z (cm)	R_{min} (cm)	R_{max} (cm)	Surface (m^2)	# chan
1	157.5	51	118	3.6	24 k
2	185.5	62	136	4.6	30 k
3	190	65	140	4.8	36 k
4	306	111	221	11.5	35 k
5	315	115	228	12.2	38 k
Total				$\approx$ 36.6	$\approx$ 164 k

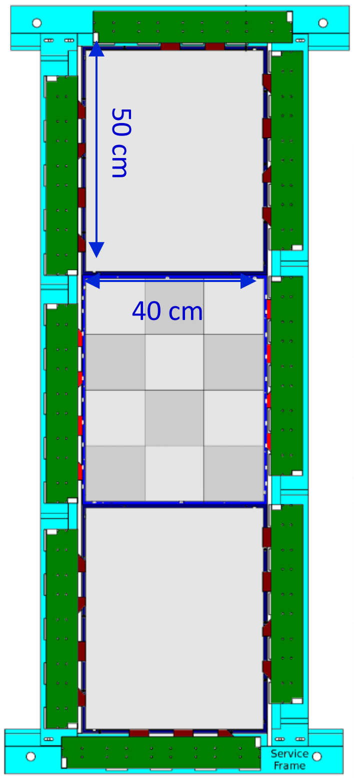
- The high occupancy at location 1 will require splitting each readout strip into two channels: this will add another 12 k channels
- Total number of channels needed: ~ 176 k
- With ~ 15% spares (to account for losses during production etc.) need to plan for

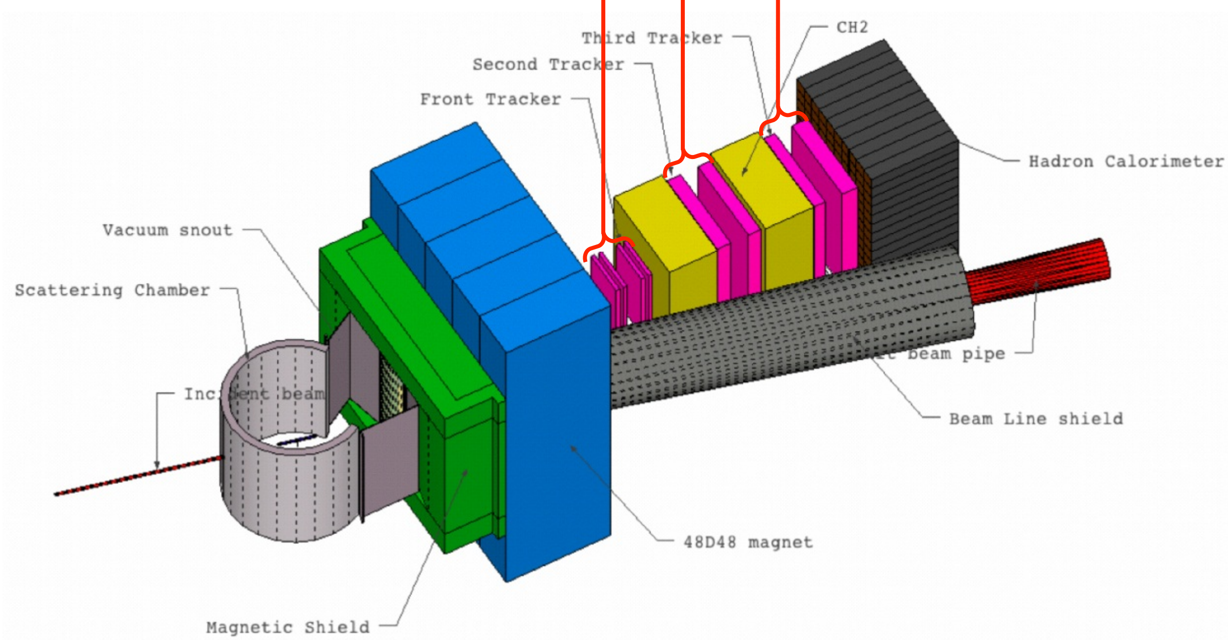
200 k channels

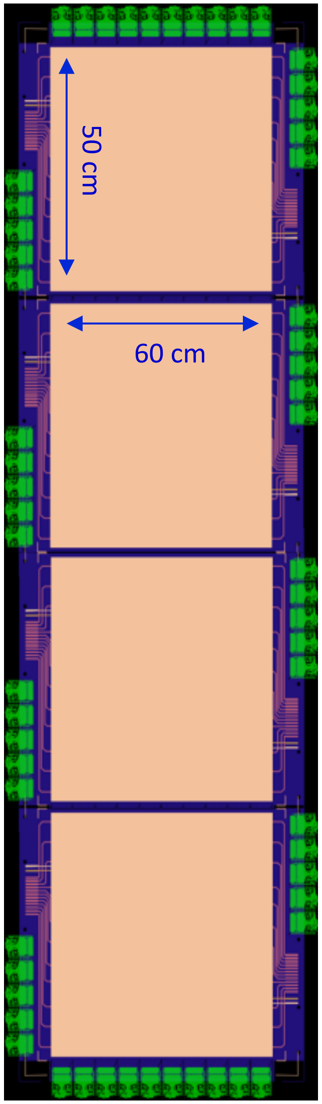
GEM plans for SoLID based on recent work for SBS

- Front Tracker:
- 6 GEM Layers (150 × 40 cm^2)
- Each layer = 3 GEM modules (50 × 40 cm^2)
- R&D and Production by INFN Roma, Catania

- Back Tracker
- 11 GEM Layers (200 × 60 cm^2)
- Each Layer = 4 GEM modules (50 × 60 cm^2)
- R&D and Production @ University of Virginia







Proton arm layout for GEp (5) experiment

Total Area ~ 16 m^2

SBS GEM Production at UVa is complete:

- Completed building 49 modules (plan was to build 48) and tested.
- 46 tested modules and all work per specs.
- GEM foils and readouts from CERN: GEM frames from Resarm in Belgium
- All assembly done in clean-room at UVa.
- Foils from CERN very high quality; over 90% yield; mostly on-time delivery.
- Foil QA at every step extremely important.
- Production design and prototyping process takes at least about 1 year.
- The GEM foil ordering process has a long lead time, need at least ~ 1 year to get started.
- In production mode: ~ 2 modules per month.
- Could be increased to two parallel assembly lines, yielding ~ 4 modules/ month.

Experience for SoLID geometry and size GEMs gained from two EIC GEM prototypes

All readout connections to the outer edge of the circle:

Large & Low-mass Forward Tracker GEM for EIC R&D

Common GEM foil design:

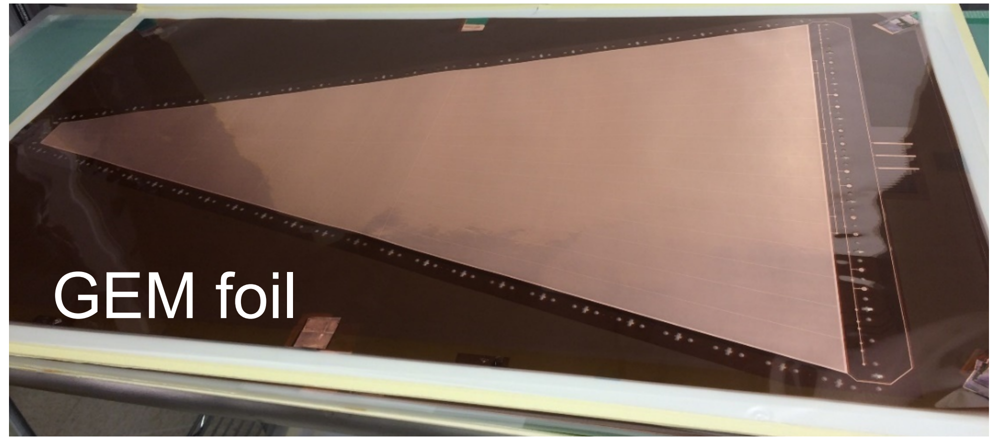
- (Univ. of Virginia, Florida Tech, and Temple U.)
- All connections (HV, gas flow structure and FE cards) are made on outer radius end.

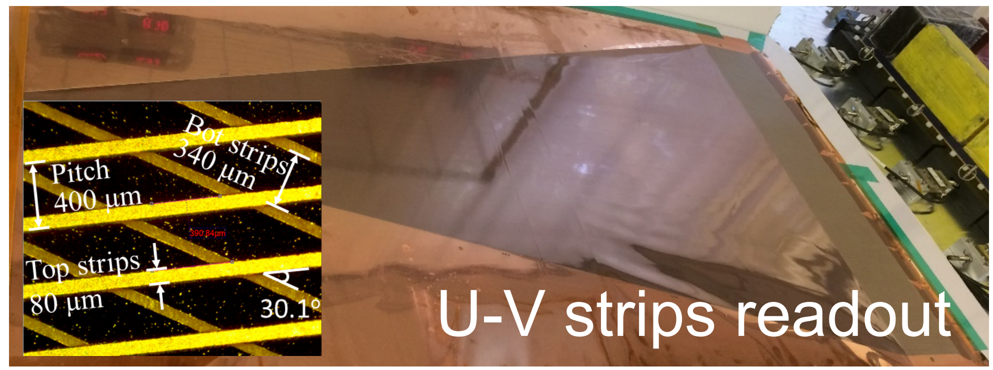
2D U-V strips readout (R/O)

- Spatial resolution improvement
- All readout electronics on outer radius end.
- No connectors or metallized vias on R/O

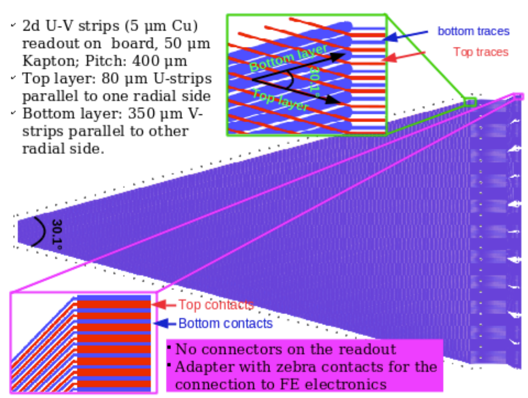
Double-sided zebra connection

- Large density of electronics channels read out on side of the detector (outer radius)
- No electronics on side or inner radius, no multiple scattering or radiation damage issues
- No connectors or metallized vias on R/O

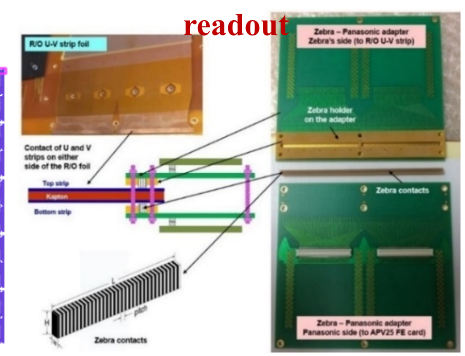




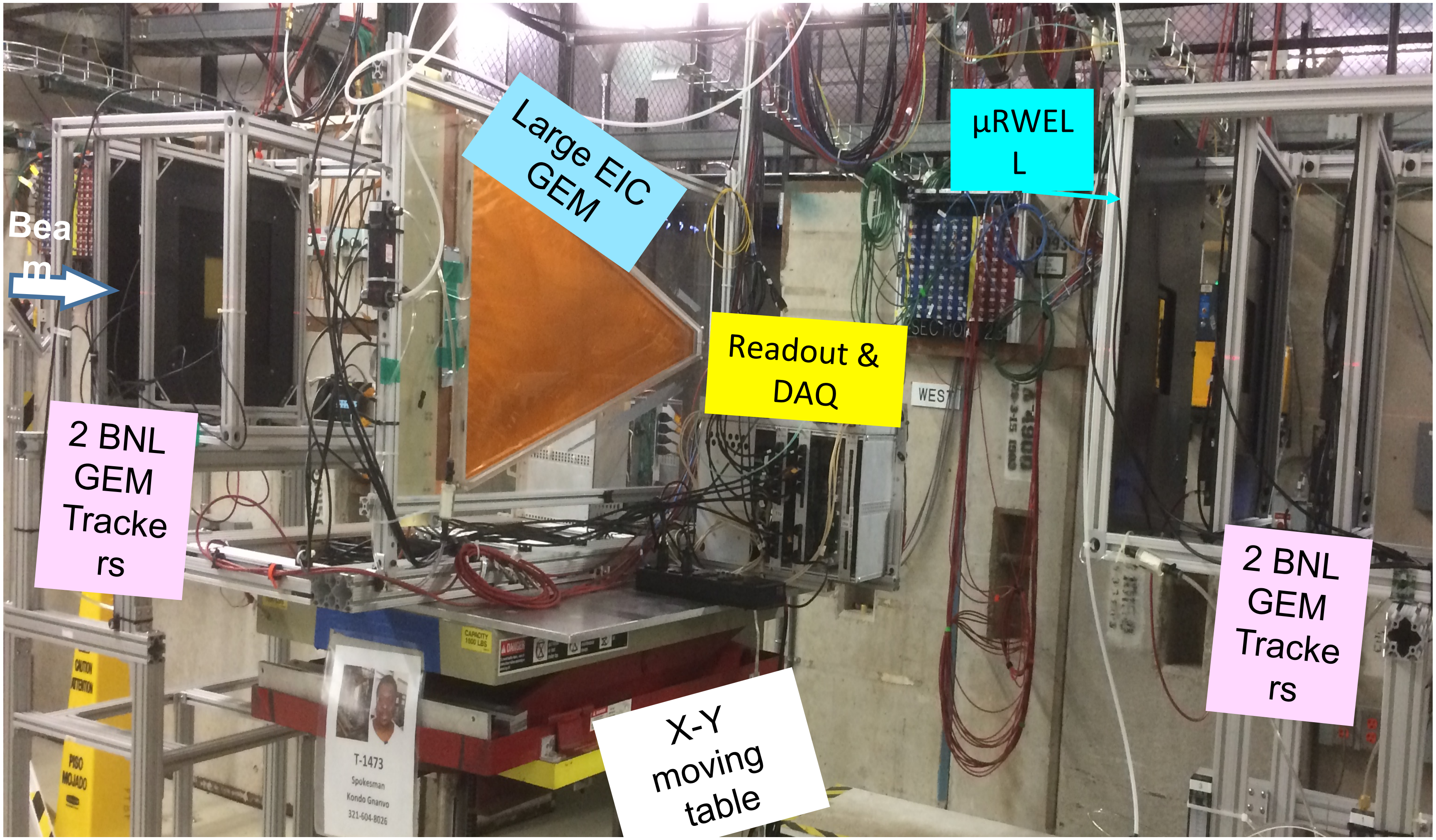
Design of EIC-Proto II 2D U-V strips readout board

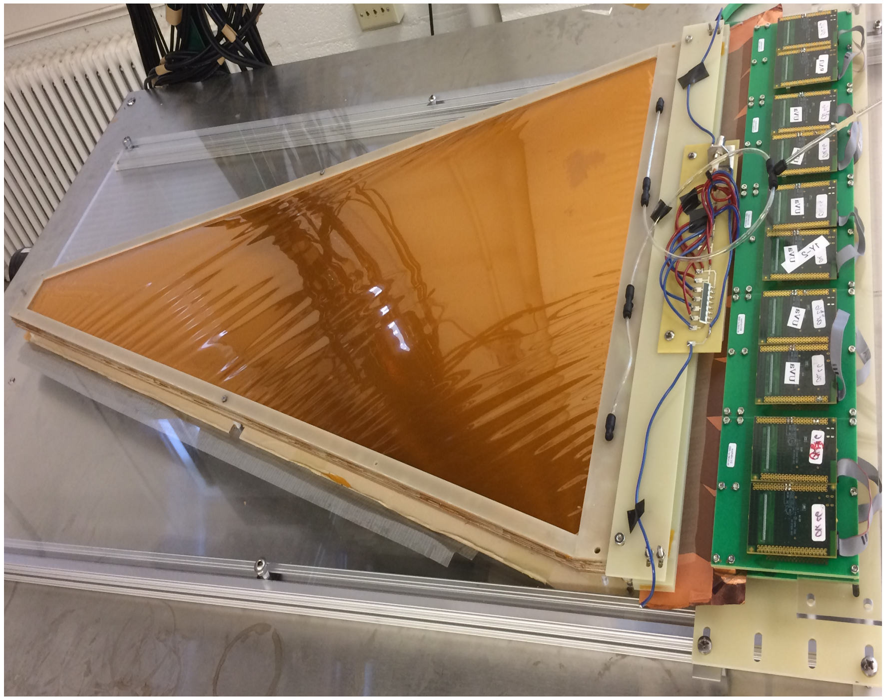


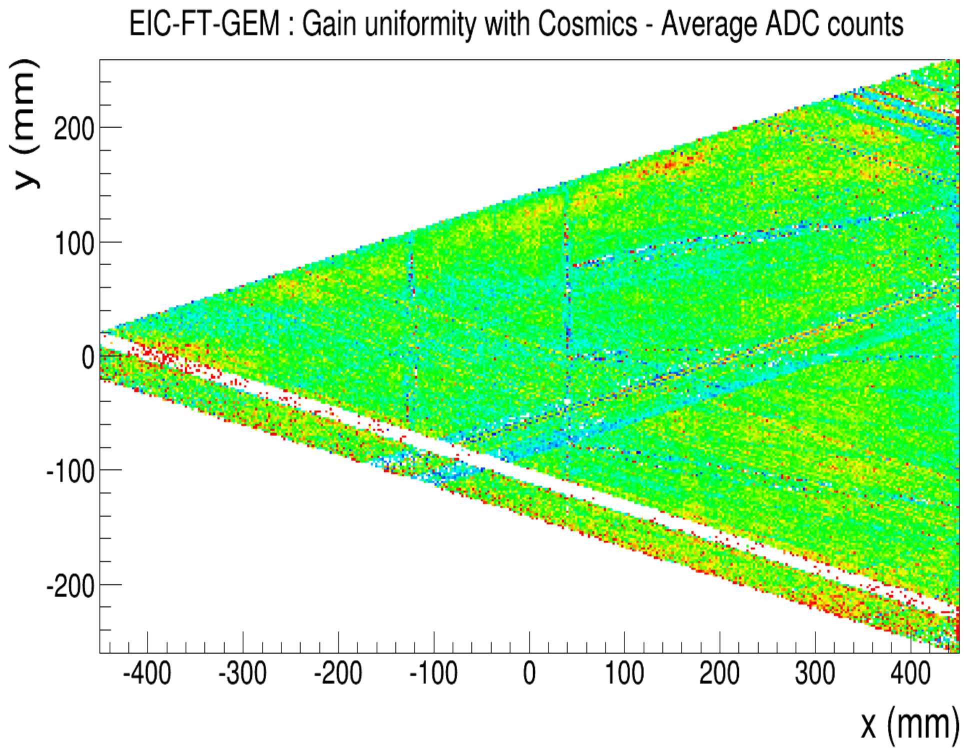
Principle of double-sided zebra connection on flexible PCB readout

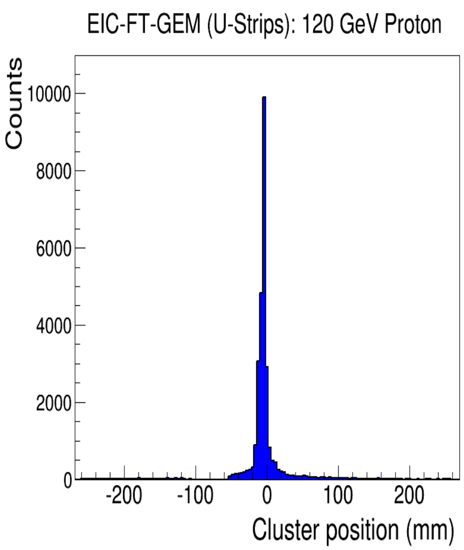


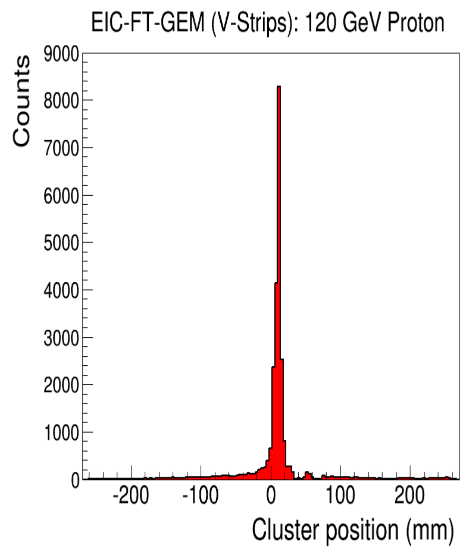
Large GEM Setup in MT6.2b Area at the FTBF (June-July 2018)

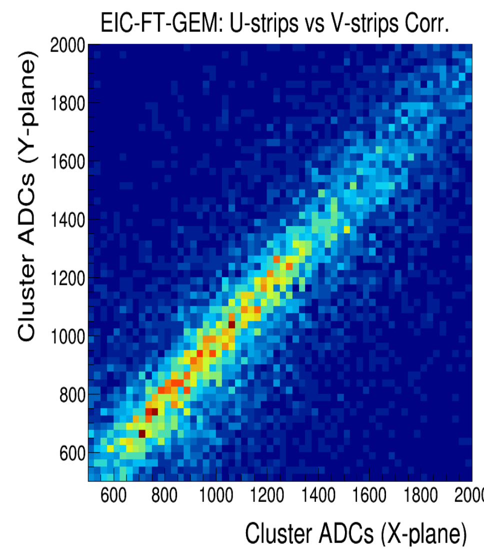


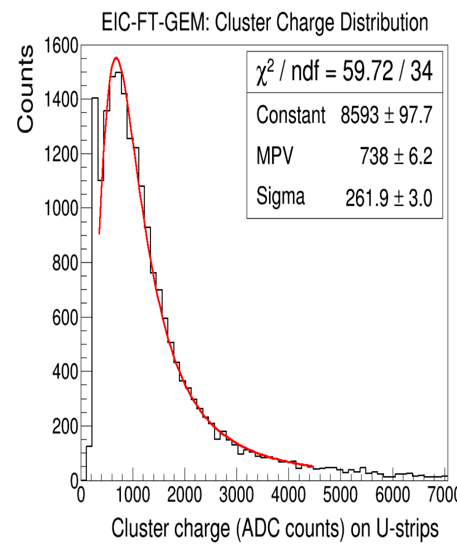



EIC-FT-GEM : Gain uniformity with Cosmics - Average ADC counts
y (mm)
200
100
0
-100
-200
-400
-300
-200
-100
0
100
200
300
400
x (mm)


EIC-FT-GEM (U-Strips): 120 GeV Proton
Counts
10000
8000
6000
4000
2000
0
-200
-100
0
100
200
Cluster position (mm)


EIC-FT-GEM (V-Strips): 120 GeV Proton
Counts
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-200
-100
0
100
200
Cluster position (mm)


EIC-FT-GEM: U-strips vs V-strips Corr.
Cluster ADCs (Y-plane)
2000
1800
1600
1400
1200
1000
800
600
600
800
1000
1200
1400
1600
1800
2000
Cluster ADCs (X-plane)


EIC-FT-GEM: Cluster Charge Distribution
χ^2 / ndf = 59.72 / 34
Constant 8593 ± 97.7
MPV 738 ± 6.2
Sigma 261.9 ± 3.0
Counts
1600
1400
1200
1000
800
600
400
200
0
0
1000
2000
3000
4000
5000
6000
7000
Cluster charge (ADC counts) on U-strips

Plan for electronics

- Need 200 k chan.
- The plan has been to use AVP-25 electronics.
  - Used for SBS
  - Already developed.
  - Lot of expertise at Jlab
  - Cheap
  - Unfortunately APV-25 chip is now extinct.
- Reuse APV-25 electronics from SBS :
  - SBS has a total of ~ 160 k of APV-25 (120 k chans. owned by Jlab (from UVa) ~ 40 k owned by INFN).
  - Assuming that at least ~ 66% survival rate after SBS run, we will have ~ 105 k of APV electronics for SoLID
- Need another ~ 100 k channels: need to find a suitable readout chip for these
- SAMPA chip is not rad-hard: will not work for SoLID
- VMM is a good choice: but need to develop direct mode readout.
  - Assume $ 75 k for pre-R&D work
  - Assume $ 200 engineering design and development of readout system
  - $ 4/chan for fabrication costs.

Alternate Chip Options

- VMM3: Developed by BNL for ATLAS
  - Good
    - digital output with on board zero suppression
    - High rates
    - suitable for large detectors,
  - Bad
    - single sample; does not allow pileup correction or time based background rejection
  - The direct readout mode (with fast ~ 200 ns reset time) may work well for SoLID.
  - Only 6-bit ADC in this mode.
  - Need to understand and evaluate the VMM chip for SoLID with pre-R&D work
  - Important to get a collaborator to take over the project.

Alternate Chip Options: VMM

SRS
Scalable Readout System

APV (ANALOGUE)

APV (250 nm CMOS)

- Pipeline depth: max. 192 clocks
- Trigger latency: max. 3 us
- Noise: < 500 e- intrinsic >750..1400 e- on detector
- dynamic range: 25 fC
- Detector capacity: 18… < 60pf
- ADC ext. 4096/1000 [counts/baseline]
- Gain: fixed CSA gain 100uA/mip, 5 output signal gains (in step of 20%)
- Timing jitter : ½ (1/fc) [+- 12ns]
- Shaping times: 50 ns adjustable to 80 ns
- max readout rate: 7 kHz

VMM (DIGITAL)

VMM (130nm CMOS)

- Pipeline depth: 64 digital frames (peak)
- Trigger latency: (self triggered) or L0 (12.8us)
- noise : < 400 e- on 10x10 detector reported
- dynamic range: expect >> 25 fC
- Detector capacity: 30pF …. < 1nF
- ADC: embedded, 10 bit
- Gains: 8 CSA gains [0.5..16mV/fC]
- Timing jitter: 20 bit t-stamp, 1ns resolution
- Shaping times: 4 [25… 200ns]
- max readout rates: estimated 4 MHz/ch

Budget Estimates

Activity Name	Costed Labor (PW)	Contrib Labor (PW)	Total Labor (PW)	Labor Cost ($K)	Procurement Cost ($K)	Total Cost ($K)
GEM	**632.00**	**40.00**	**672.00**	**$1,605.28**	**$2,194.00**	**$3,799.28**
GEM Modules	**484.00**	**0.00**	**484.00**	**$1,229.36**	**$1,464.00**	**$2,693.36**
GEM foils			0.00	$0.00	$620.00	$620.00
GEM readout planes			0.00	$0.00	$464.00	$464.00
GEM cathode foils			0.00	$0.00	$100.00	$100.00
GEM module frames			0.00	$0.00	$230.00	$230.00
GEM module supplies			0.00	$0.00	$40.00	$40.00
GEM module tooling			0.00	$0.00	$10.00	$10.00
GEM module assembly	484.00		484.00	$1,229.36		$1,229.36

- Main items: materials for 150 GEM modules.
  - 450 GEM foils from CERN shop.
  - 150 2-D readout boards from CERN shop
  - 150 GEM frame sets from Resarm
  - Technician manpower for GEM assembly: ~ 12 FTYE.

- All estimates based on recent lab experience from SBS GEM module production.

Budget Estimates

Activity Name	Costed Labor (PW)	Contrib Labor (PW)	Total Labor (PW)	Labor Cost ($K)	Procurement Cost ($K)	Total Cost ($K)
GEM Readout	**0.00**	**0.00**	**0.00**	**$0.00**	**$430.00**	**$430.00**
VMM electronics channels			0.00	$0.00	$400.00	$400.00
VMM electronics cables			0.00	$0.00	$30.00	$30.00
GEM high voltage	**0.00**	**0.00**	**0.00**	**$0.00**	**$80.00**	**$80.00**
HV power supplies			0.00	$0.00	$70.00	$70.00
HV power cabling			0.00	$0.00	$10.00	$10.00
GEM gas system	**0.00**	**0.00**	**0.00**	**$0.00**	**$30.00**	**$30.00**
GEM Gas plumbing			0.00	$0.00	$30.00	$30.00
GEM mechanical support	**16.00**	**0.00**	**16.00**	**$40.64**	**$90.00**	**$130.64**
GEM mechanical support wheels	16.00		16.00	$40.64	$90.00	$130.64
Transport and travel			0.00	$0.00	$100.00	$100.00
Installation and Testing	132.00		132.00	$335.28		$335.28
Management		40.00	40.00	$0.00		$0.00

- All estimates based on recent lab experience from SBS GEM module production.

Time Line for engineering design and prototyping

	Task	FY21				FY22			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.1.4	**GEM Design and Prototyping**								
1.1.4.1	**GEM Module design**								
1.1.4.1.1	GEM Module component design and prototyping								
1.1.4.1.1.1	GEM Module component design for level 1 prototypes								
1.1.4.1.1.2	GEM Module component procument for level 1 prototypes								
1.1.4.1.1.3	GEM Module level 1 prototype fabrication and testing								
1.1.4.1.1.4	GEM Module component design for level 2 prototypes								
1.1.4.1.1.5	GEM Module component procument for level 2 prototypes								
1.1.4.1.1.6	GEM Module level 2 prototype fabrication and testing								
1.1.4.1.1.6	GEM Module final engineering design								
1.1.4.1.2	GEM fabrication tooling design and prototyping								
1.1.4.1.1.1	GEM fabrication tooling: level 1 design and fabrication								
1.1.4.1.1.2	GEM fabrication tooling: level 2 design and fabrication								
1.1.4.1.1.3	GEM fabrication tooling: final engineering design								
1.1.4.2	**GEM Readout design**								
1.1.4.2.1	VMM electronics level 1 prototype design, fabrirication								
1.1.4.2.2	VMM electronics level 1 prototype testing								
1.1.4.2.3	VMM electronics level 2 prototype design, fabrirication								
1.1.4.2.4	VMM electronics level 2 prototype testing								
1.1.4.2.5	VMM electronics final engineering design								
1.1.4.5	**GEM mechanical support design**								
1.1.4.5.1	GEM mechanical support wheels design								
1.1.4.5.2	GEM mechanical support cable support design								
1.1.4.5.3	GEM mechanical support: 1 sector prototype fabrication								
1.1.4.5.4	GEM mechanical support final engineering design								
1.1.4.6	Transport and travel								
1.1.4.8	Management								

Time Line forFabrication

Risks and Mitigation strategies

- On time availability of GEM foils.
  - Since this is a very large order of GEM foils, and since CERN has been the only supplier of GEM foils of this size, there is the risk of delays in GEM foil availability.
- Mitigation strategies:
  - Please the orders for the whole need well in advance (at least 1 year or more) to allow CERN shop to plan the delivery.
  - Now there are several companies around the world working with CERN on large GEM foils: need to engage them early and evaluate their foils.

- All Working with these companies, CERN shop is now completing a very large foil order for CMS upgrade project. This shows that advanced planning and early coordination with CERN, risks could be minimized.

Risks and Mitigation strategies

- The fabrication timeline may be too ambitious for one group to complete on time.
  - Based on SBS experience, it seems that the UVa group could build up to about 40-50 modules/year, but a more conservative and safe goal would be about 35-40 per year. This will require longer than anticipated in the plan.
  - Mitigation strategies:
    - Work with partner institutions with GEM experience to distribute the production to more locations. Work with these institutions from prototyping stage to build readiness.
    - Work with groups at Temple U and Hampton U.

Risks and Mitigation strategies

- Suitability of VMM electronics for high rate operation needed for SoLID ?
  - The standard operating mode of VMM looks too slow for SoLID conditions
- Mitigation strategies:
  - The direct readout mode of VMM appears to work as needed. Evaluate and characterize the chip in this mode as part of pre R&D. If SoLID rate needs are not met, look for alternate solutions.

EH&S considerations

Conclusions

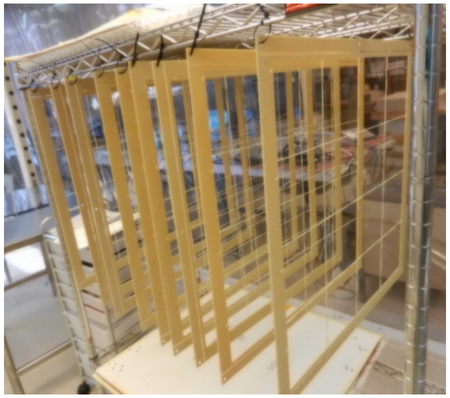
Backup

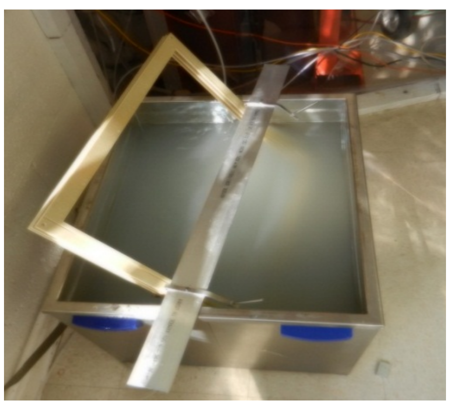
SBS GEM module technical requirements

All GEM modules were constructed such that:

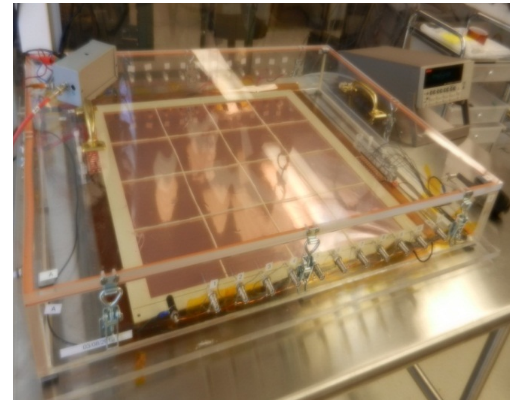
- all foils have an average dark current of less than 5 nA for each 20 x 5 cm^2 sector at 550 V across the foil.
- a gain of at least 5000 at the operational voltage in a gas mixture of 70% Argon and 30% CO_2
- a track efficiency of at least 95%, averaged over the module, in cosmic tests
- a position resolution of $\sigma < 100\ \mu m$.
- A timing resolution of $\sigma < 25$ ns.

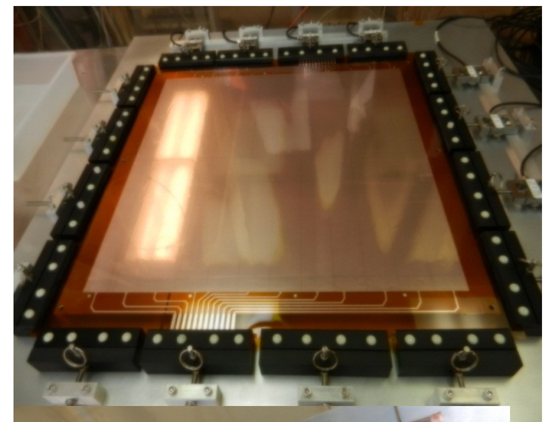
UVa GEM Lab

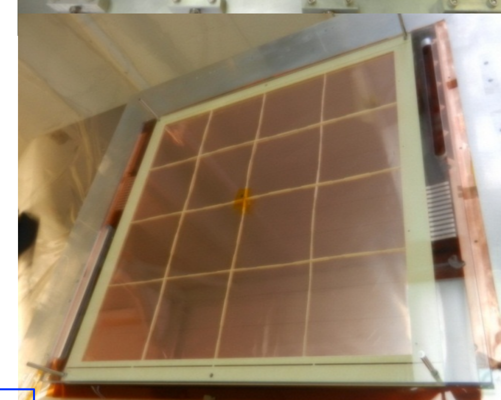




Large area (3 × 7 m^2) class 1000 Clean Room



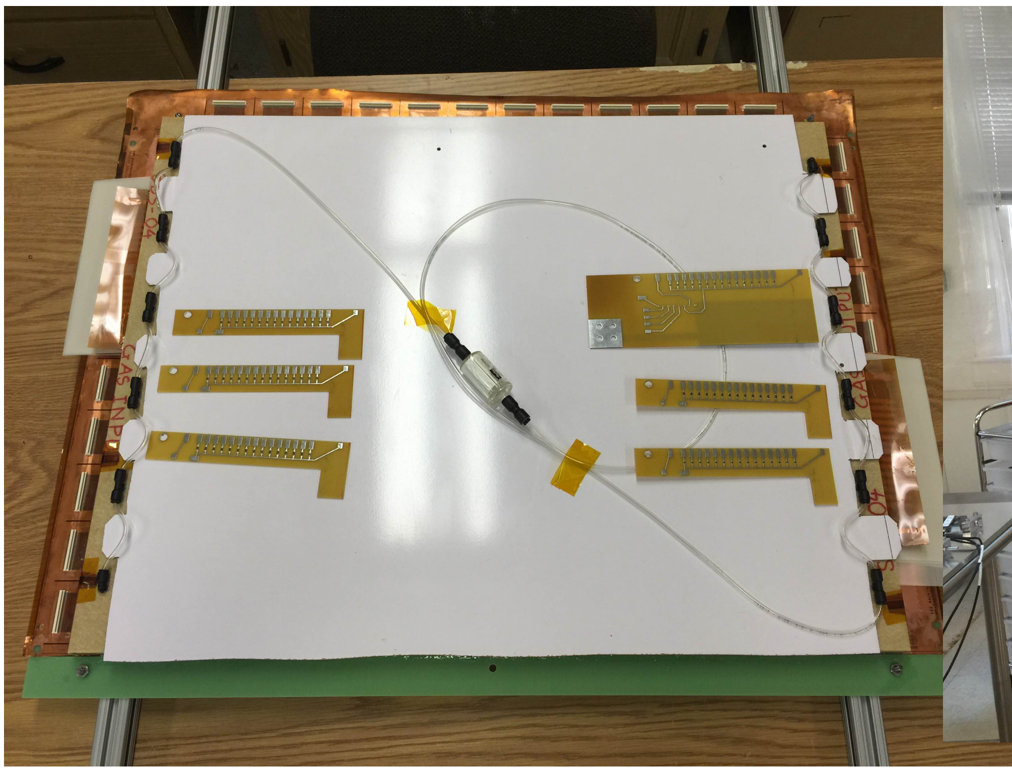




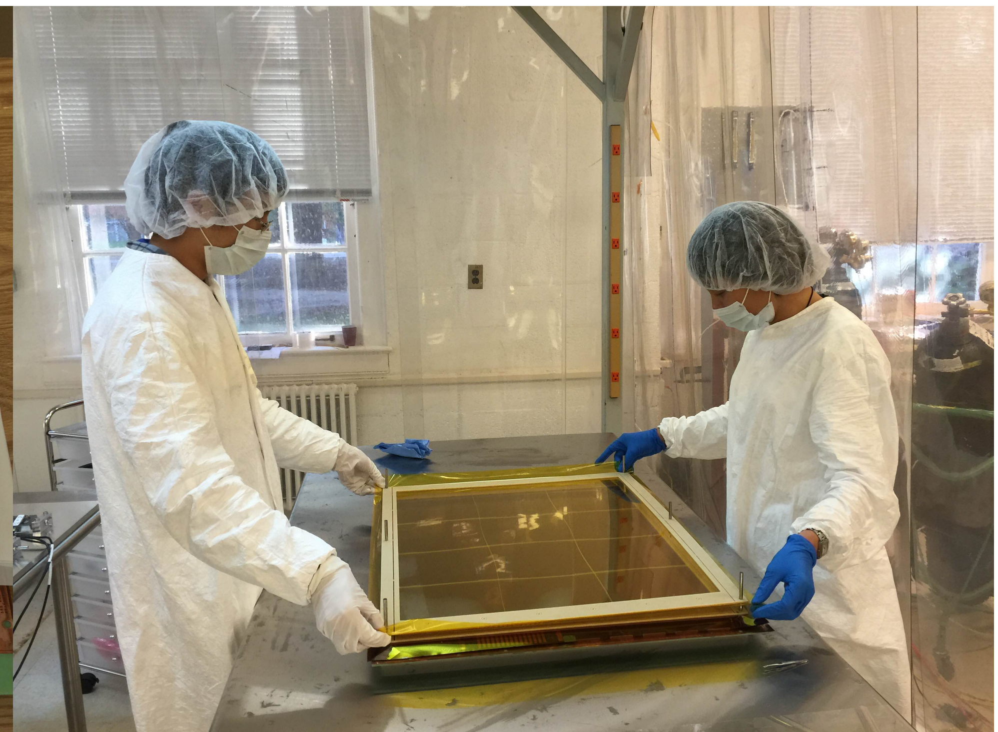
Team members: NL, Dr. Kondo Gnanvo, Dr. Vladimir Nelyubin, and Dr. Huong Nguyen

SBS Production

- First module constructed in May 2014
- After some delays waiting for foils/frames, production ramped up to expected rate now – 2 modules/month



Module #4 prepared for testing



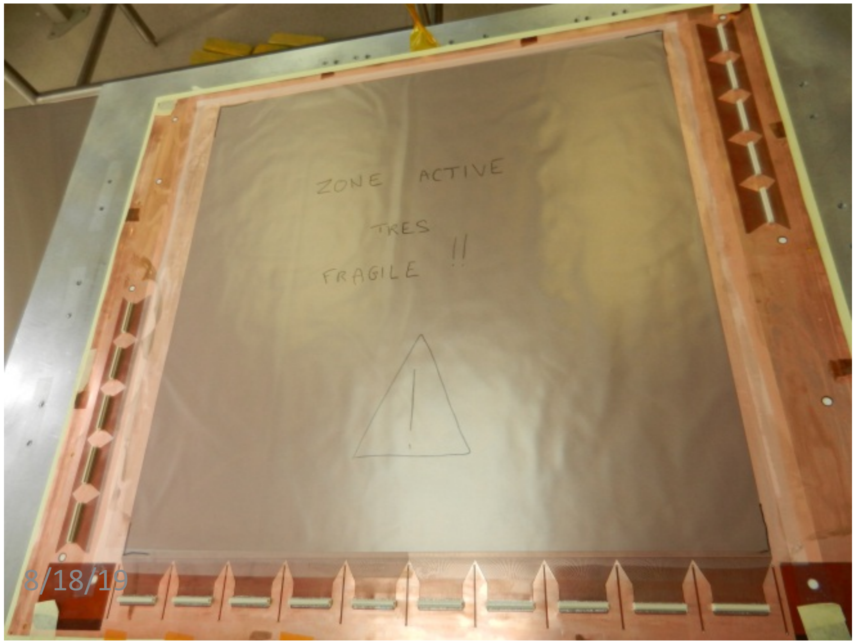
Top window glued on module #5

Large Tracker GEM module: components

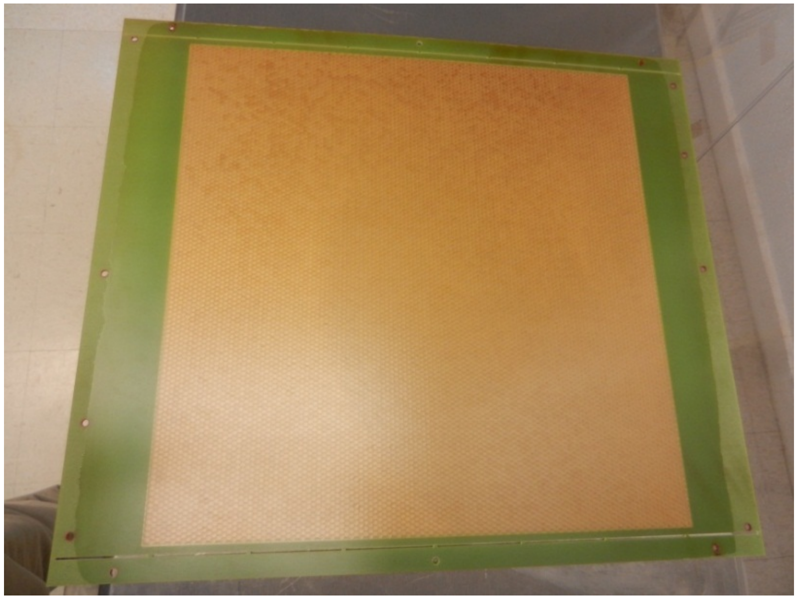
GEM foil (CERN PCB workshop)

Support frame with spacers (RESARM Belgium)

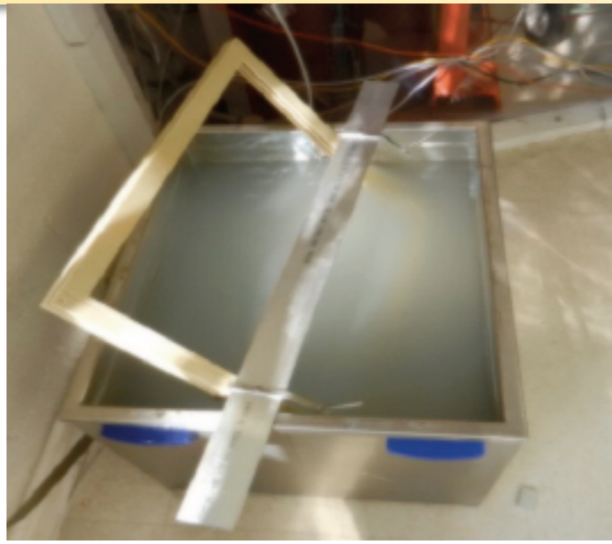
Flexible 2D readout board (CERN PCB workshop)



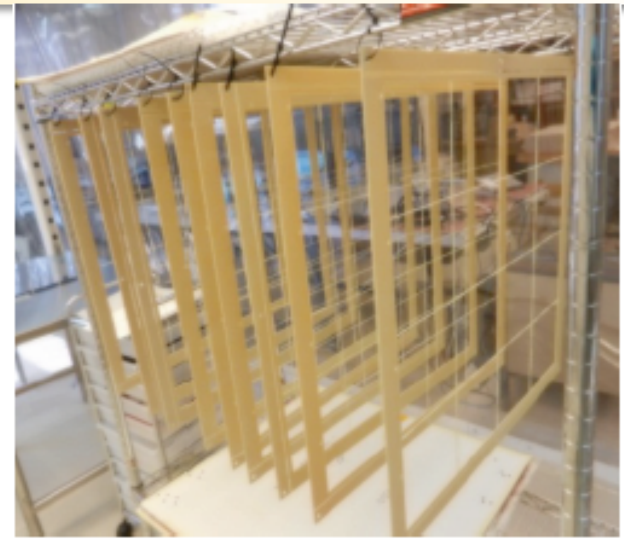
Honeycomb support board (CERN PCB workshop)



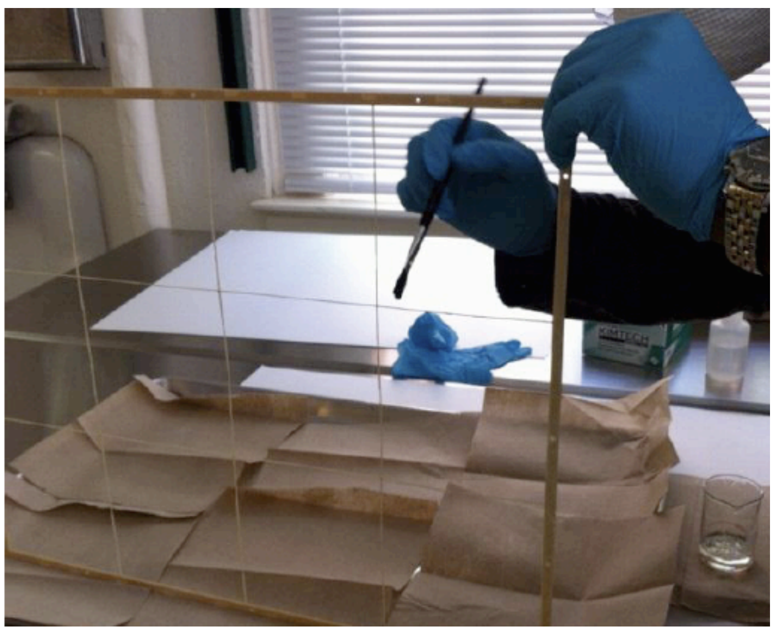
Preparation of the frames



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



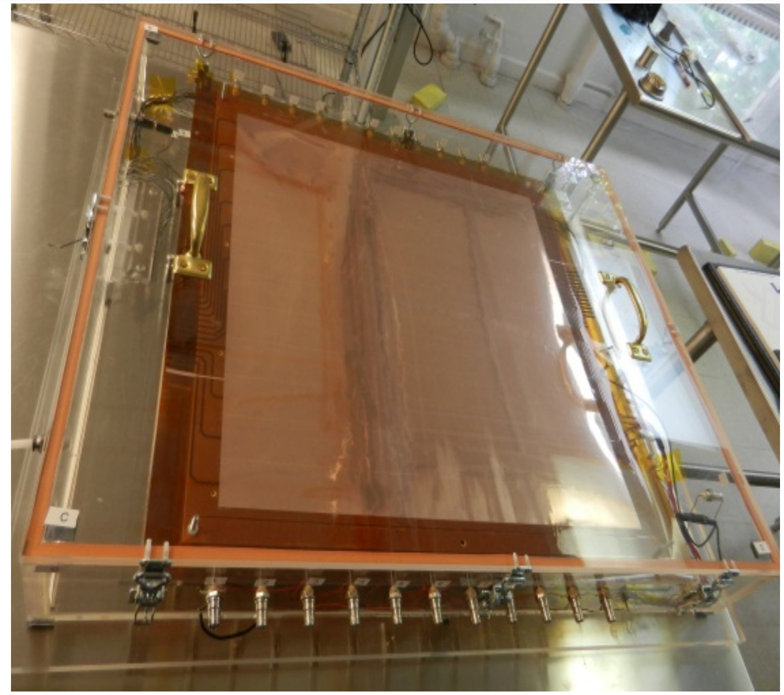
Dried for 4 days under a filter hood .

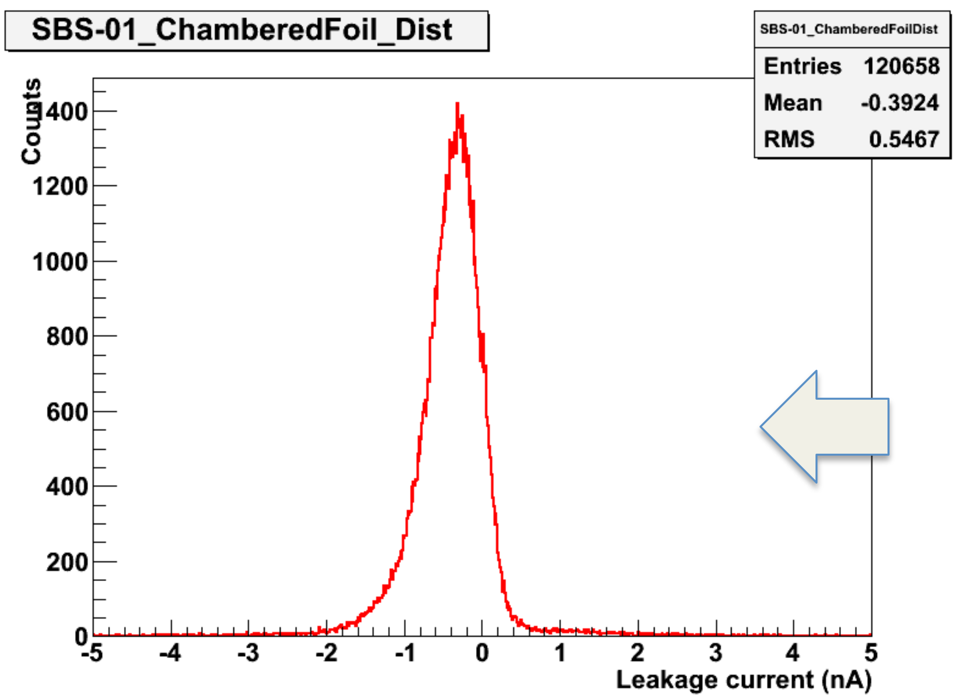


Machined surfaces sealed with a layer of polyurethane (Nuvovern LW) to prevent surface irregularities, residual fibers or sharp edges in the active area of the chamber

GEM foil quality assurance

- Rapid HV ramp-up to 550 V.
- 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.
- The test is done for raw foils, framed foils and foils in chamber





If the test indicates that a foil is bad: send back to CERN

Distribution of leakage current for all 90 sectors of a GEM chamber (30 sectors per foil x 3 foils)

Each sector tested for 120 s.

PMP key performance parameter for accepting a foil: Leakage current < 5 nA

SBS GEM module production workflow

Working on 4 chambers at a given time:

- Building module # n in the clean room
- Out of the clean room final steps (soldering, gas sealing etc.) on module # n-1
- Testing module # n-2 on test stand.
- Preparing frames for module # n+1.

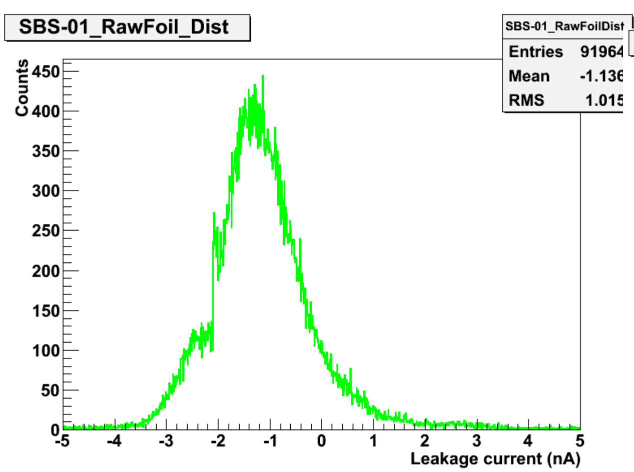
  Prototype meets SBS design requirements stated in the PMP
- Will be hiring a technician to keep the momentum as the students move on

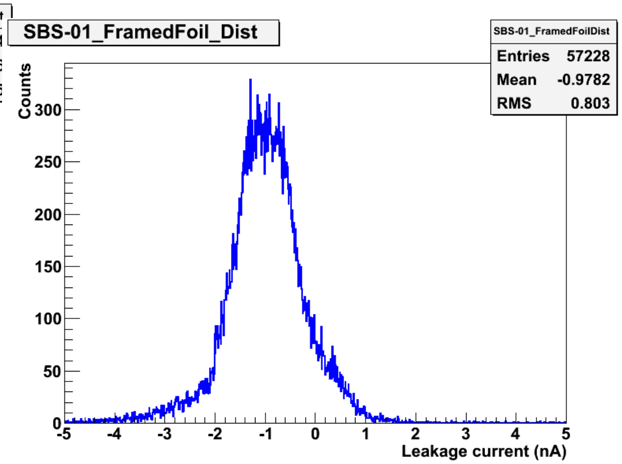
~ 2 Modules per month.

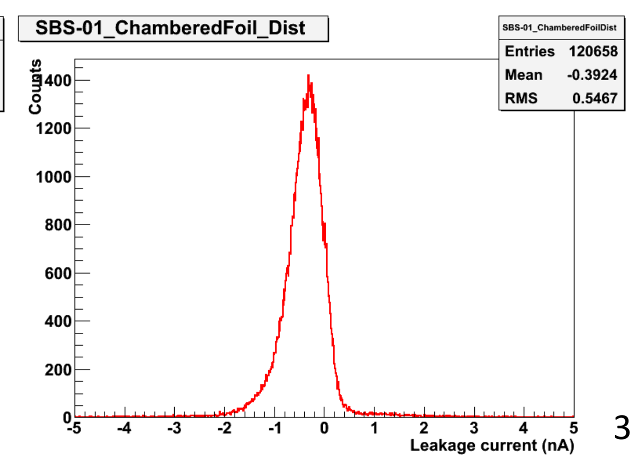
Day	Task	Man power
	Preparation (in parallel to the fabrication of the previous module)	
-8	Glue spacers on the gas window frame	A,B
-7	Sand a set of frames and clean in Ultra-sonic bath	A,B
-6	Remove from US bath and hang in clean shelf to dry	A,B
-2	Apply varnish sealant on the frame and hang to dry	A,B
-1	Inspection and electronic pedestal test of the readout board	A,B,C,D
	Module Fabrication - In clean room work	
1	Test all sectors of 2 GEM foils . If bad sector found, set the foil aside and move to the next foil; continue till two good foils found	A,B
2	Stretch and glue foil #1	A,B
2	Glue readout to the base	A,B
2	Test all sectors of foil # 3	A,B
3	Glue empty frame on to readout	A,B
3	Remove from stretcher and test framed foil # 1	A,B
3	Stretch and glue foil # 2	A,B
4	Glue framed foil # 1 in chamber	A,B
4	Remove from stretcher and test framed foil # 2	A,B
5	Stretch and glue foil # 3	A,B
5	Glue framed foil # 2 in chamber	A,B
6	Remove from stretcher and test framed foil # 3	A,B
6	Stretch and glue Cathode foil	A,B
7	Glue framed foil # 3 in chamber	A,B
7	Remove from stretcher and store Cathode foil	A,B
7	Stretch and glue top gas window	A,B
8	Glue Cathode frame in chamber	A,B
8	Remove from stretcher and store top gas window	A,B
8	Stretch and glue bottom gas window	A,B
9	Glue top gas window on chamber	A,B
9	Remove from stretcher and store bottom gas window	A,B
10	Glue top frame on chamber	A,B
11	Glue bottom gas window on chamber	A,B
12	Glue bottom frame on chamber	A,B
13	Glue gas connectors and close gas inputs and outputs	A,B
	Module Fabrication - Out of clean room work	
14	Install covers and move the chamber out of the clean room	A,B
15	Remove supporting frame parts and extra foil	A,B
16,17	Seal the chamber with sealant	A,B
18,19	Connect chamber to N_2 and test all sectors	A,B
20,21	Solder HV dividers	A,B
22	Mount chamber on test stand and connect chamber to Ar/CO_2	C
	Chamber testing	
23,...	Start chamber testing with cosmics	C,D

GEM foil quality assurance

- Visual inspection of the foil upon arrival from CERN. If there is any sign of damage:
    - inspect the area under the microscope. If damage is confirmed, set the foil aside and return to CERN.
    - If there are minor issues such as local discoloration, spots etc. refer the foil or sector for microscope and special attention during high voltage testing
- High voltage testing of all sectors at three different stages: in the raw foil, in the framed foil and the foil in the module.
    - require leakage current to be less than 5 nA: if raw foil fails test, set the foil aside and return to CERN.

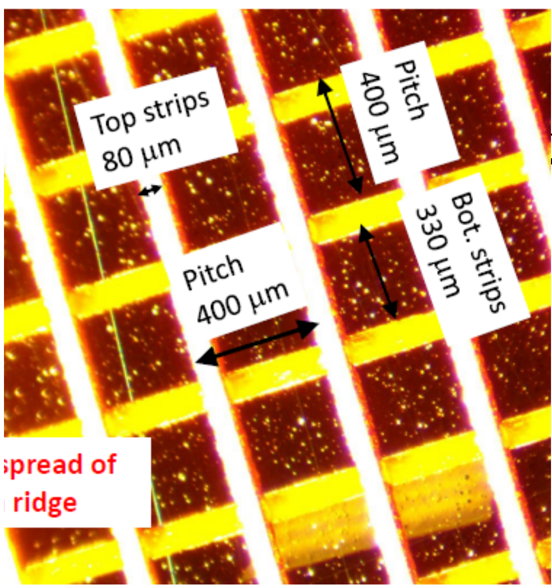




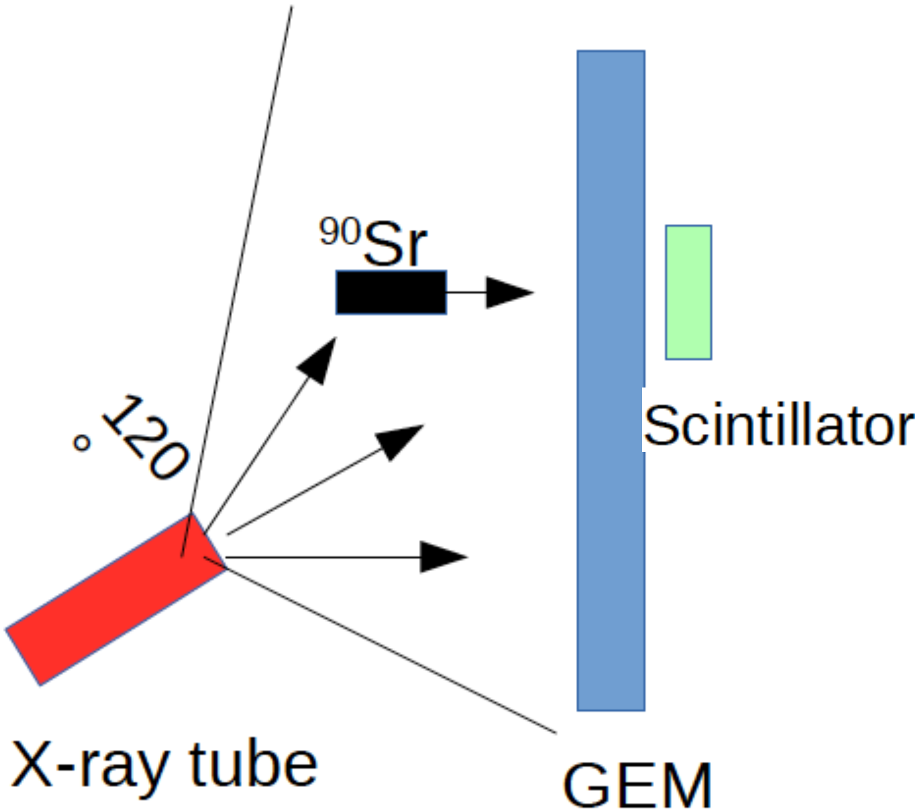


Readout foil quality assurance

- Visual inspection upon arrival from CERN:
  - Check sensitive area and all connectors. Note any areas with possible issues for inspection under microscope.
- Inspection of readout strips under the microscope:
  - measure the readout strip width and strip pitch for both directions. Ensure that no Kapton is extending out from under the top readout strip layer.
  - If observations are not within specs, set the readout aside and return to CERN.
- Electronic pedestal noise test of the readout board:
  - Connect all connectors of the readout board to the APV-25 readout system and take pedestal data. Ensure that all channels have pedestal RMS values of 50 channels or less.

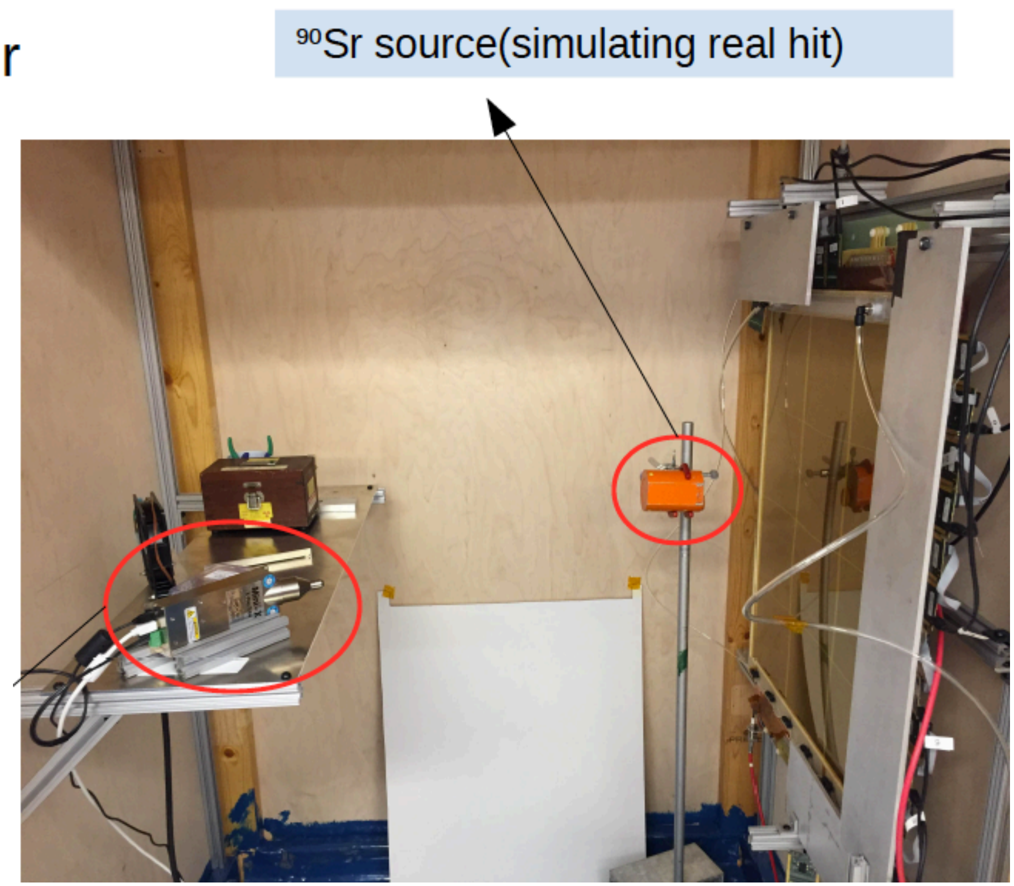


Testing the modules



X-ray generator specification:

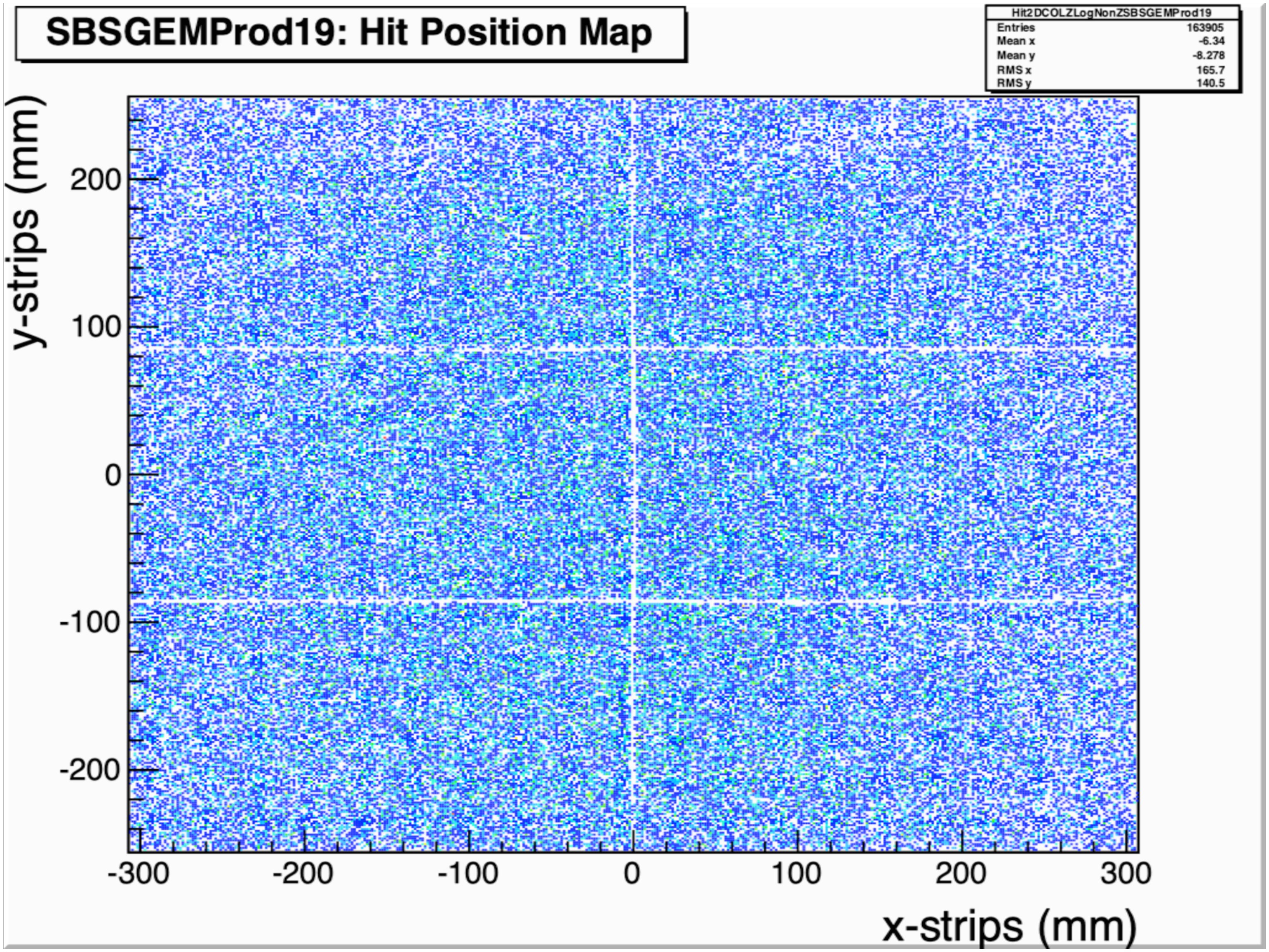
- Photon energy range: up to 50 keV
- Output flux: 100 MHz/cm^2 on the surface of GEM (conversion rate ~0.5% to electrons for ionization to happen)
- Angular distribution: uniform within 60°



This setup provides:

- Charge deposition in GEM: up to 3.4x10^{11} e$^-$/cm^2/s , equivalent to ~7MHz/cm^2 MIP.

Production module Test Results



Alternate Chip Options: VMM: SRS version