GEM detectors and some of their applications

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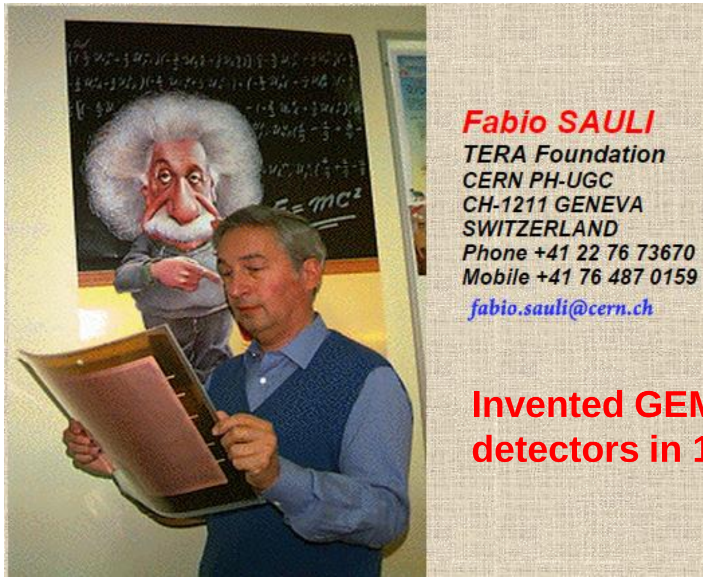
01/06/2016

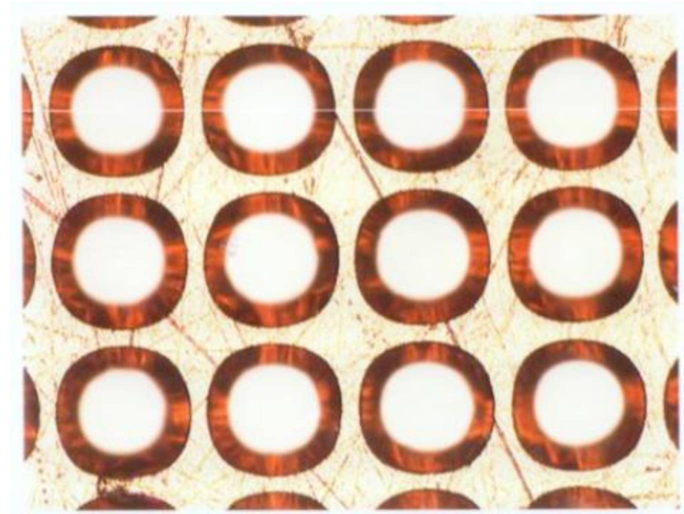
Overview

- Introduction of Gaseous Electron Multiplier (GEM) detectors
  - ✓ Brief history
  - ✓ Operating principle and basic performances
  - ✓ Availability from industry
- Applications of GEMs in Europe (mainly at CERN):
  - ✓ HERA-B, COMPASS, and LHCb
  - ✓ Compact Muon System (CMS), TOTEM
  - ✓ KLOE-2, ALICE
- Applications of GEMs in the US:
  - ✓ SBS, SoLID at JLab
  - ✓ PHENIX, RHIC, and Electron Ion Collider (EIC) at BNL
- Other applications (muon tomography, radiography, double-phase detection, astrophysics observations)
- Summary

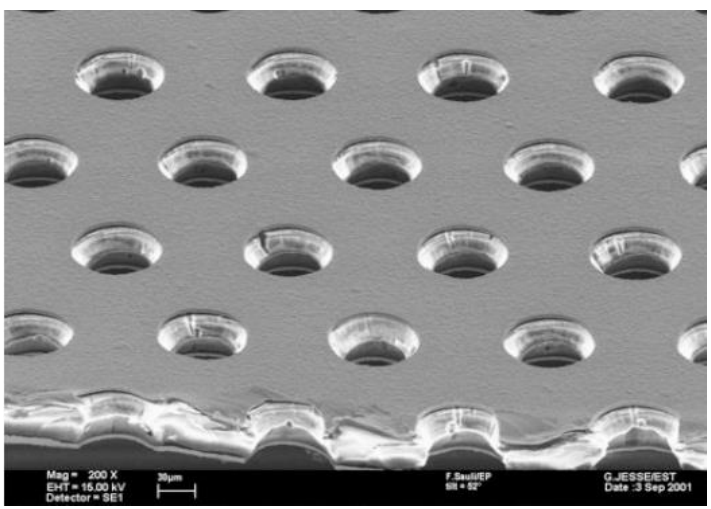
GEM detectors -- invention



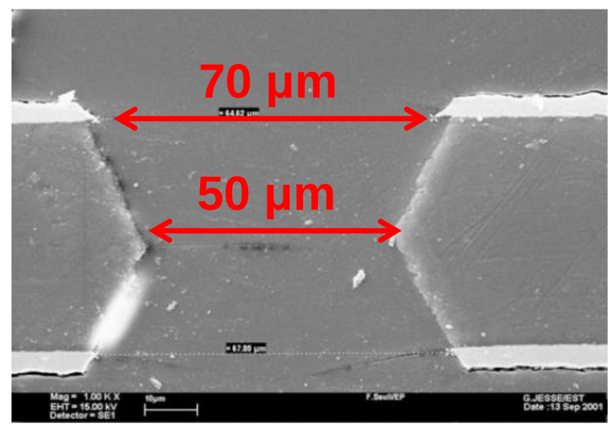
Invented GEM detectors in 1997.



Close view of the first GEM foil, with holes 140 µm apart on a 50 µm thick, copper coated polymer foil.



Microscopic picture of a "standard" GEM: 70 µm hole diameter at 140 µm pitch in a triangular pattern.



A section through a hole with a **double-conical** shape.

GEM foil producing procedures

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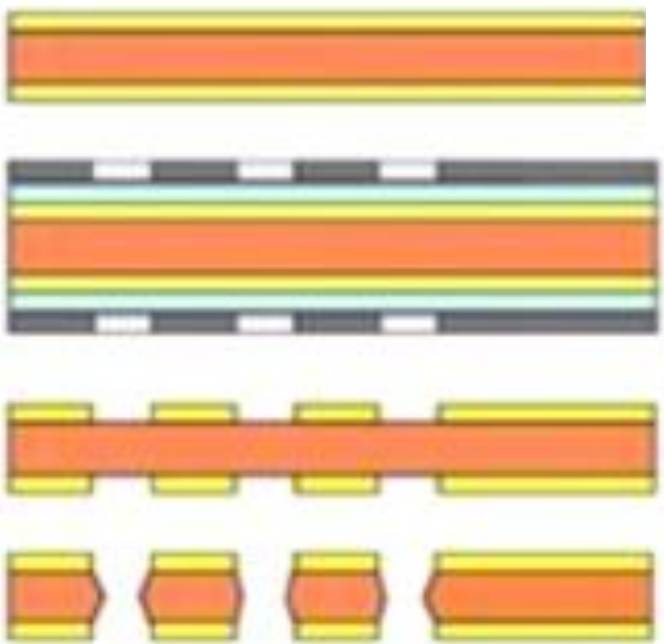
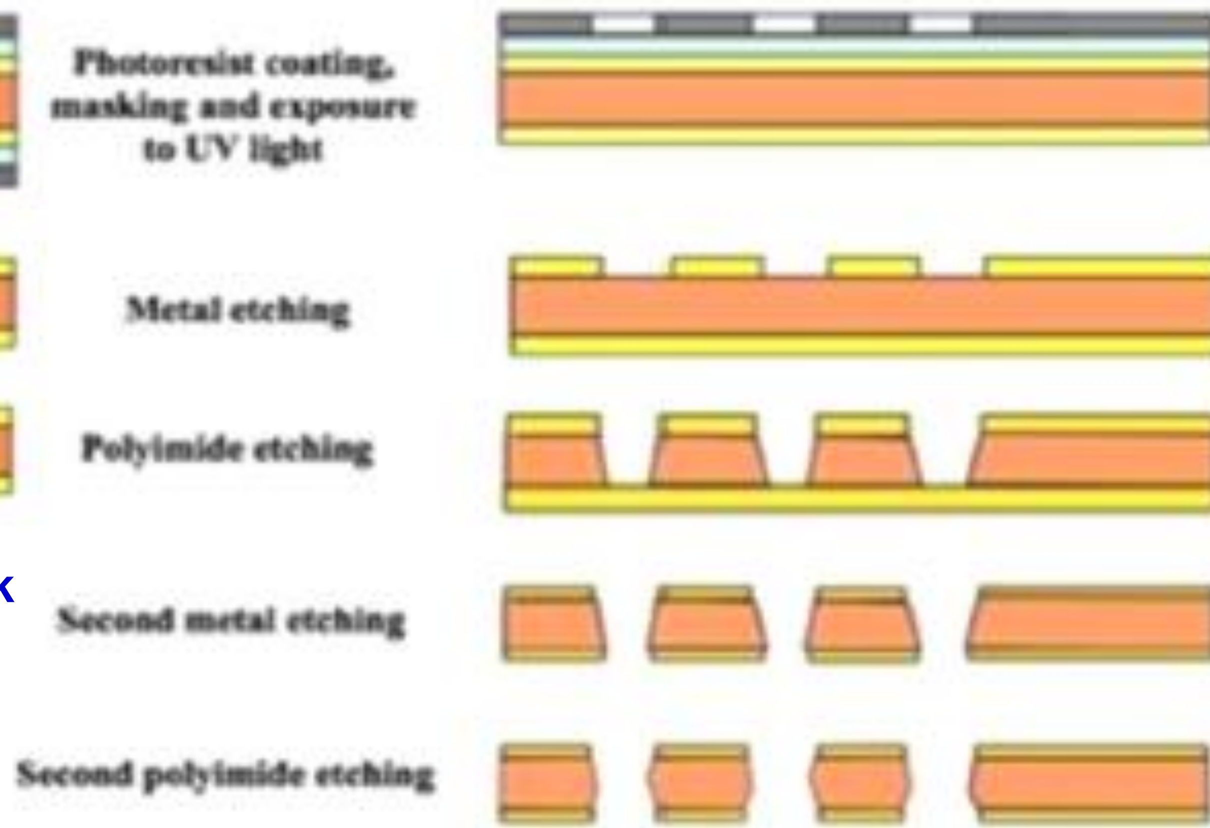
50 µm **Kapton/apical** foil, with 5 µm copper on both surfaces

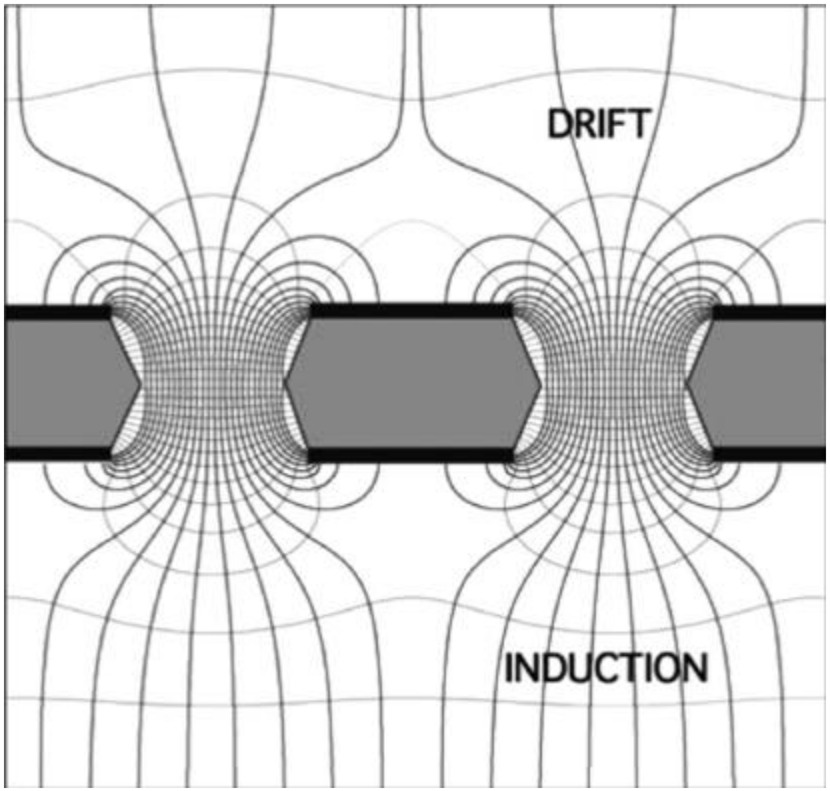


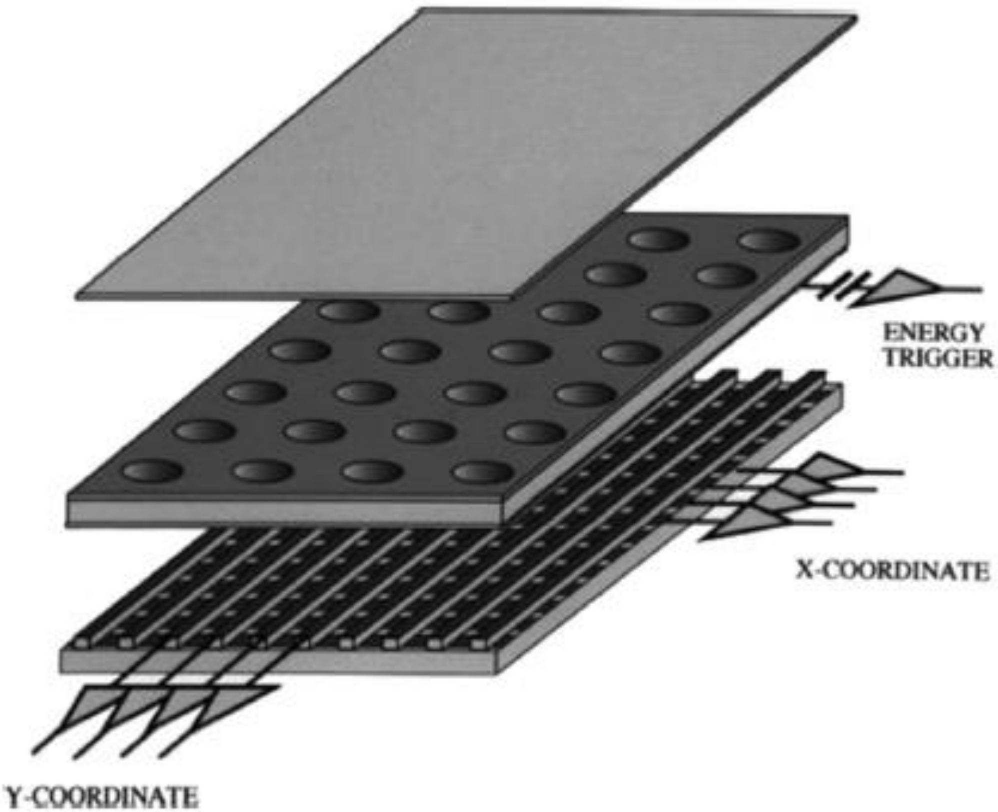


Older technique: **double-mask** manufacturing

Newer technique: **single-mask**

GEM detectors
-- operating principle



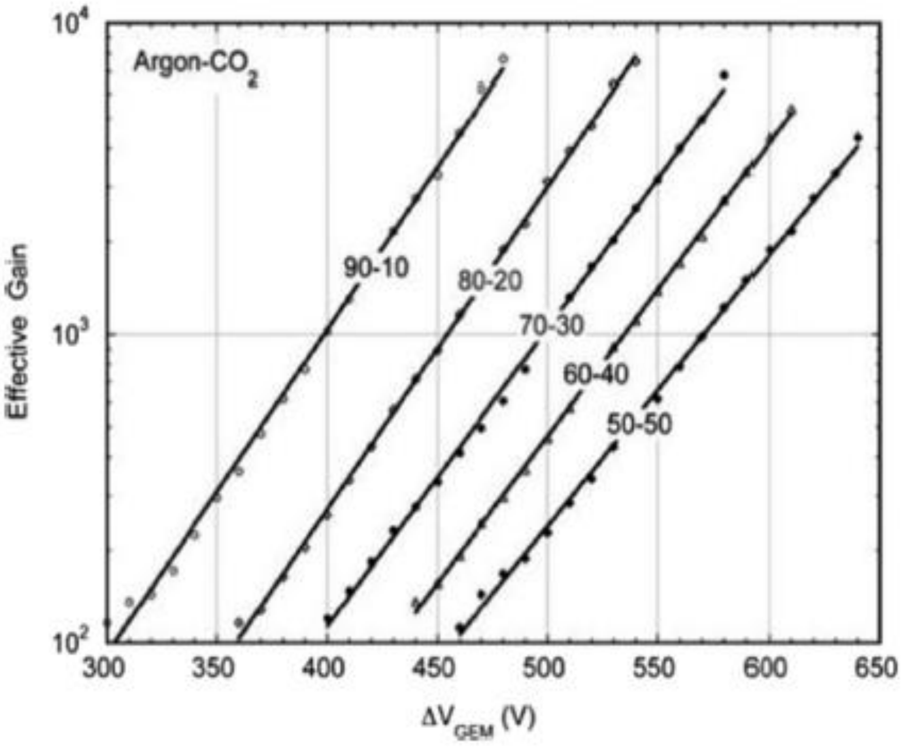


Field simulation of a single-layer GEM detector in GARFIELD

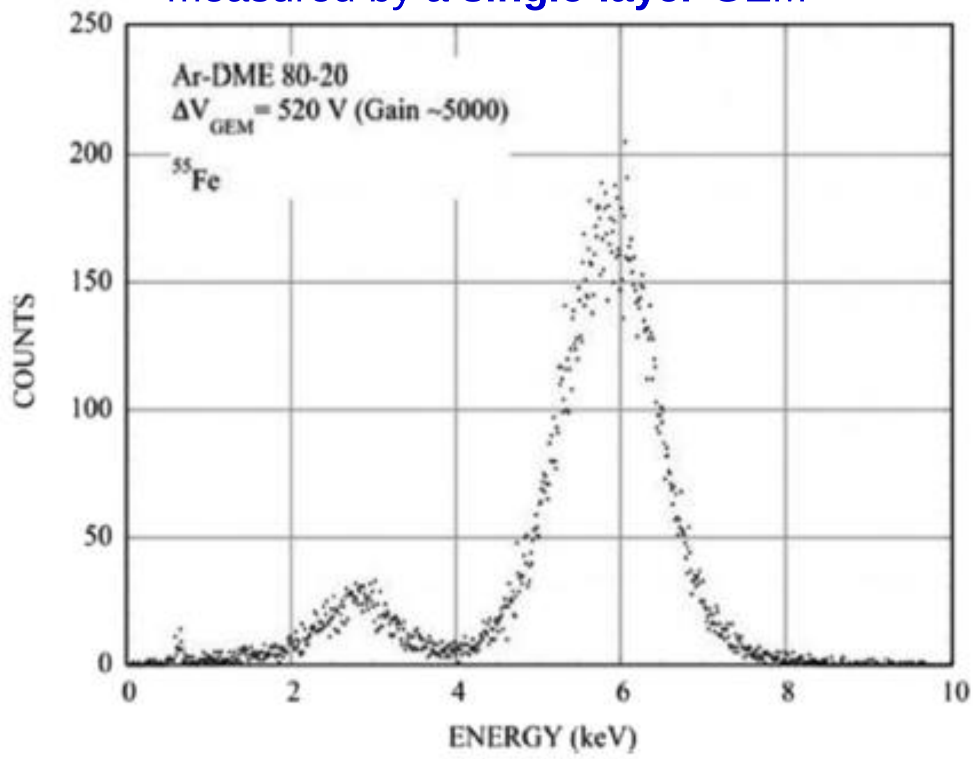
Schematics of a single-layer GEM detector with Cartesian reading out strips.

Performances of a single-layer GEM detector

Effective gain of a **single-layer** GEM



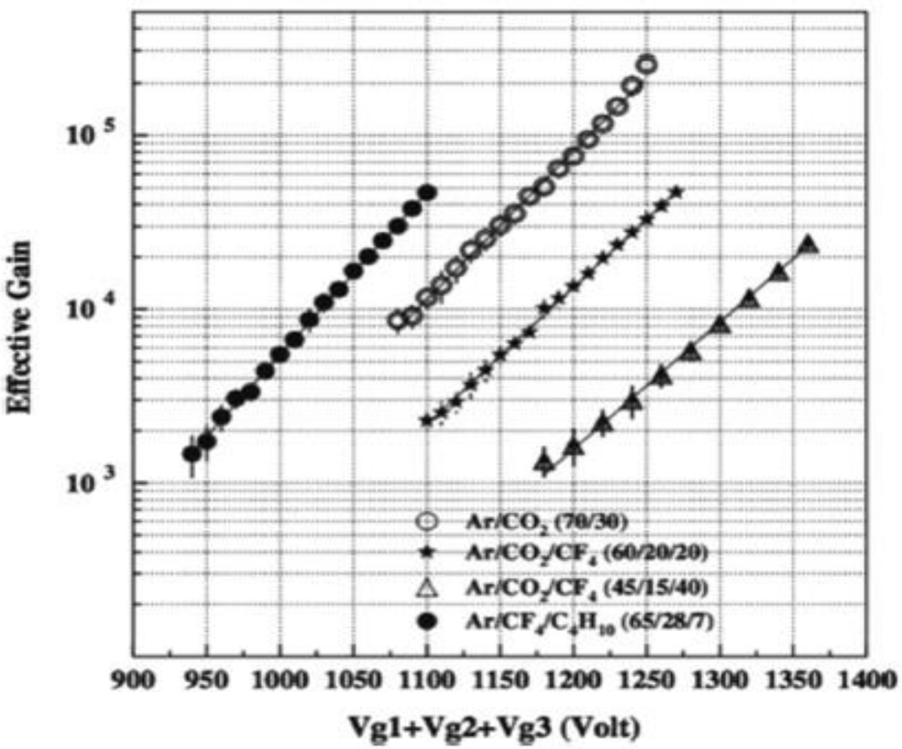
Spectrum for 5.9 keV X rays measured by a **single-layer** GEM



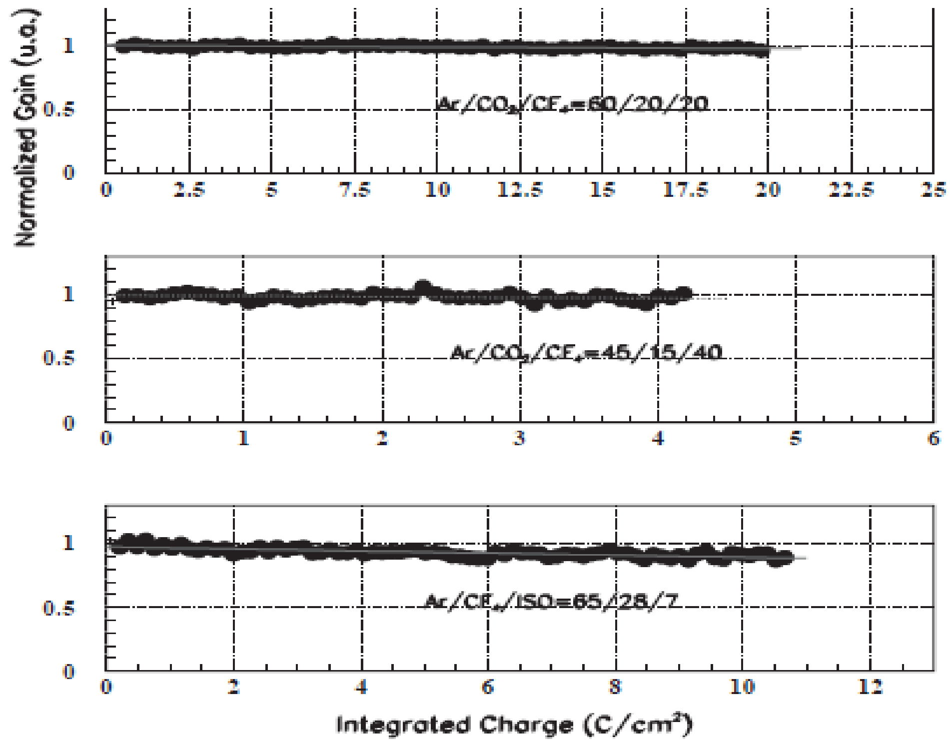
- A single layer GEM (small area) can reach an effective gain of 10^3 in normal Ar-based gas mixtures.
- And its energy resolution is ~17% FWHM (for 5.9 keV X rays).

Performances of triple-GEM detectors

Effective gain of a **triple-GEM** in Ar based gases



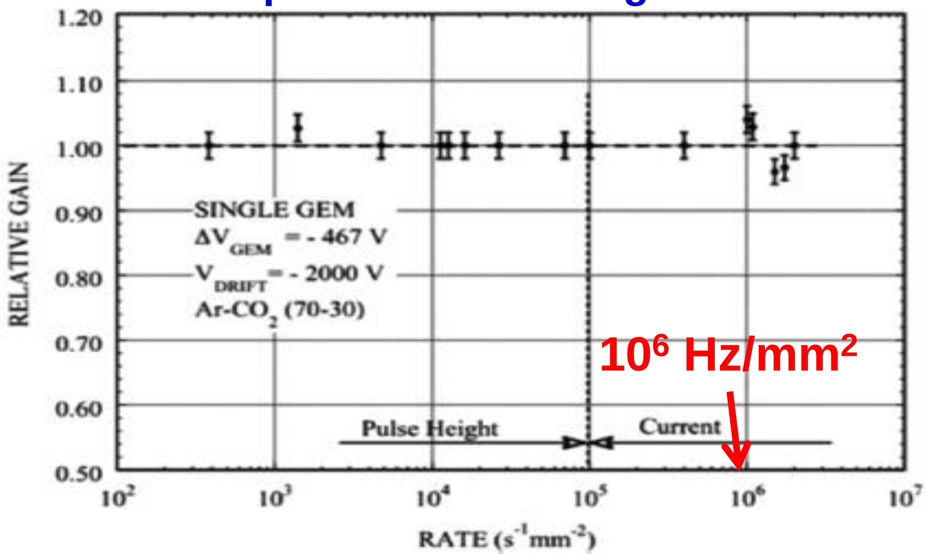
Long term stability of a **triple-GEM** detector



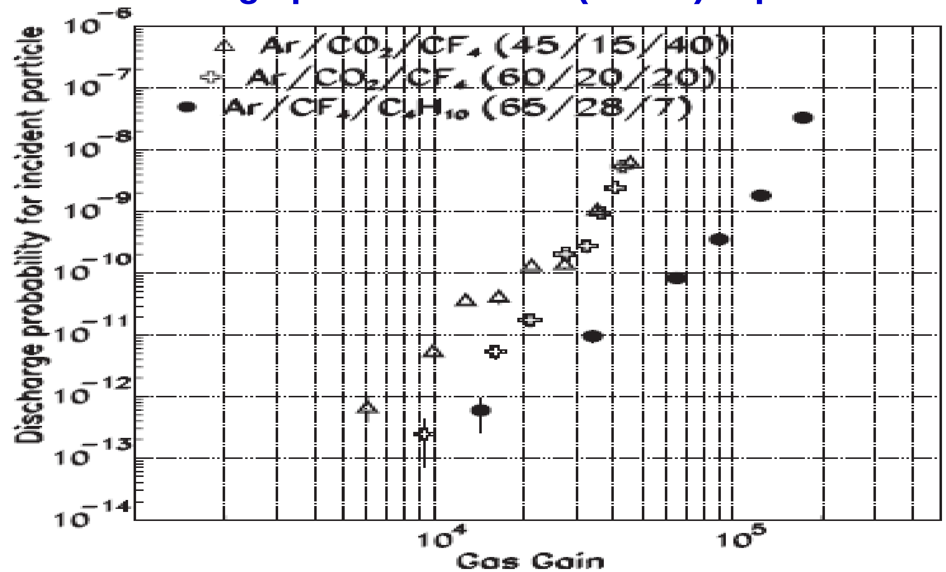
- With a multi-GEM-layer structure (up to 5 layers), very high total effective gain (up to 10^6, in some gases) can be attained with each GEM layer working at very lower gain (therefore much less prone to discharges).
- Usually a **triple-GEM** configuration gives enough gain and good long term stability (<u>no obvious aging problem</u>).

Rate capability and discharge probability of GEMs

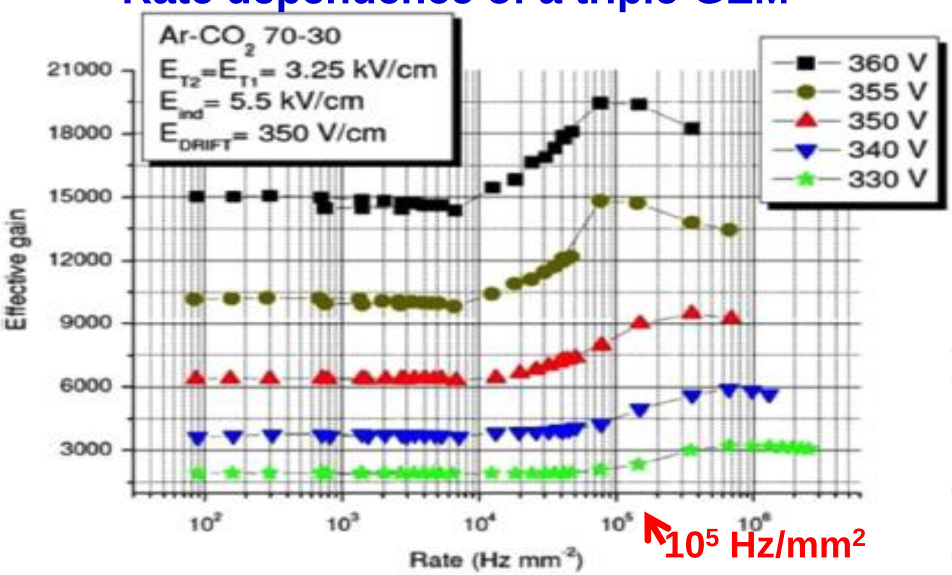
Rate dependence of a single GEM



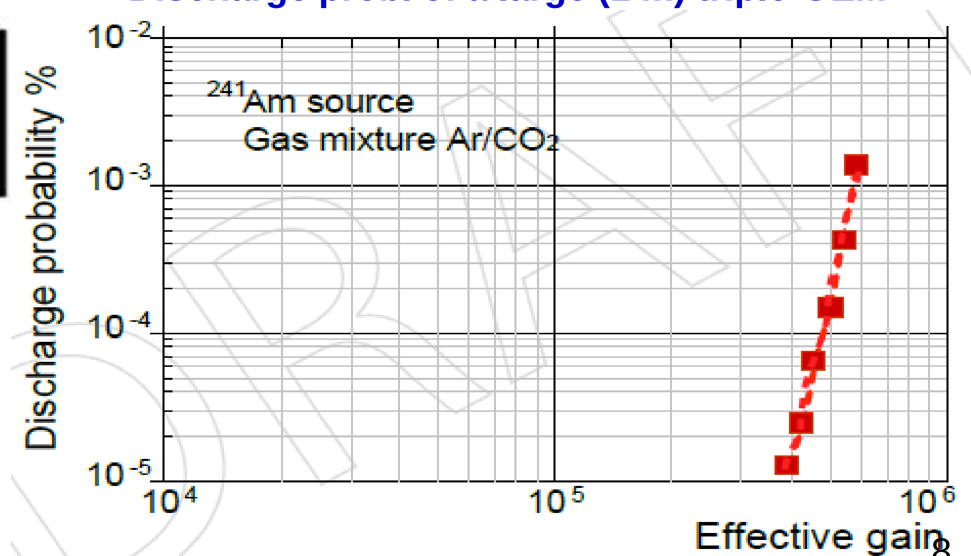
Discharge prob. of a small (30 cm) triple-GEM



Rate dependence of a triple-GEM

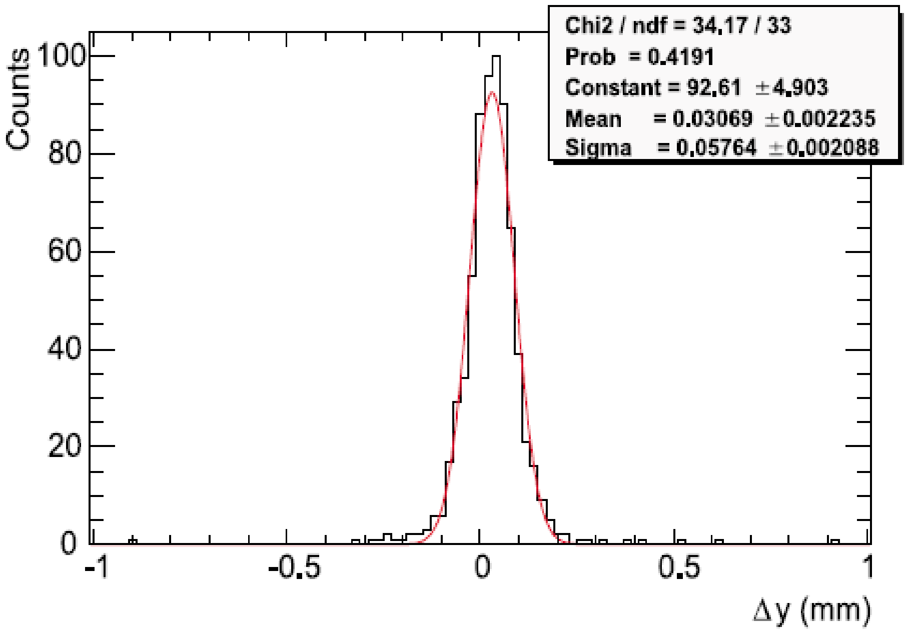


Discharge prob. of a large (1 m) triple-GEM

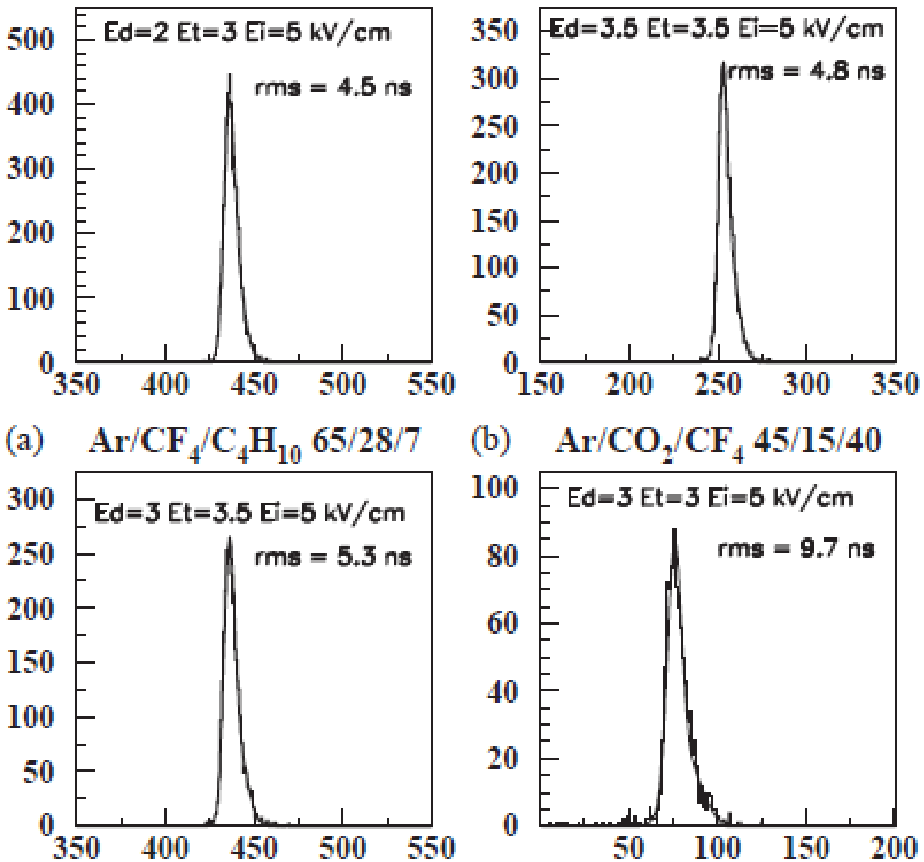


Spatial and timing resolutions

Residual distribution of a triple-GEM



- Spatial resolution of a GEM detector depends on readout strips that are applied. A typical resolution is ~70 μm.
- The above result is from a GEM prototype (30cm by 30cm) for the COMPASS experiment. The readout strips have a pitch of 400 μm. Spatial resolution reached **~46 μm** after deconvoluting uncertainties.



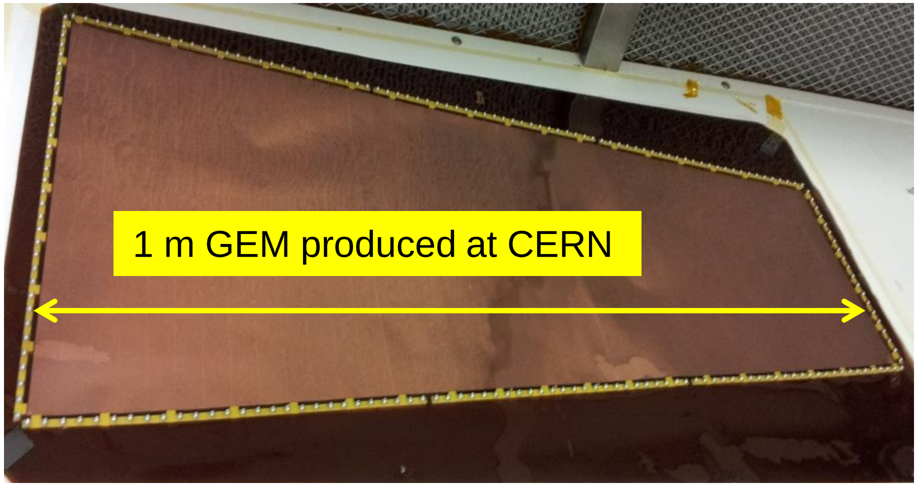
(a) $Ar/CF_4/C_4H_{10}$ 65/28/7 (b) $Ar/CO_2/CF_4$ 45/15/40

(c) $Ar/CO_2/CF_4$ 60/20/20 (d) Ar/CO_2 70/30

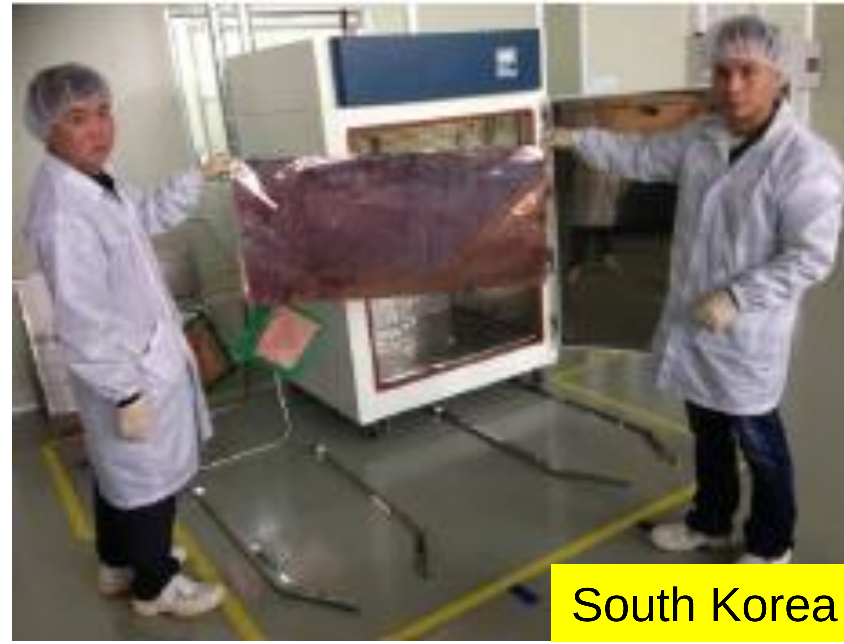
Timing res. of triple-GEM detectors **< 10 ns**.

GEM foil manufacturers

- **CERN workshop**, the main GEM foil provider (from Rui De Oliveira).



- **South Korea**, has produced 10cm GEM foils, to be tested at CERN. On the way to producing 1-m long GEM foils.


South Korea

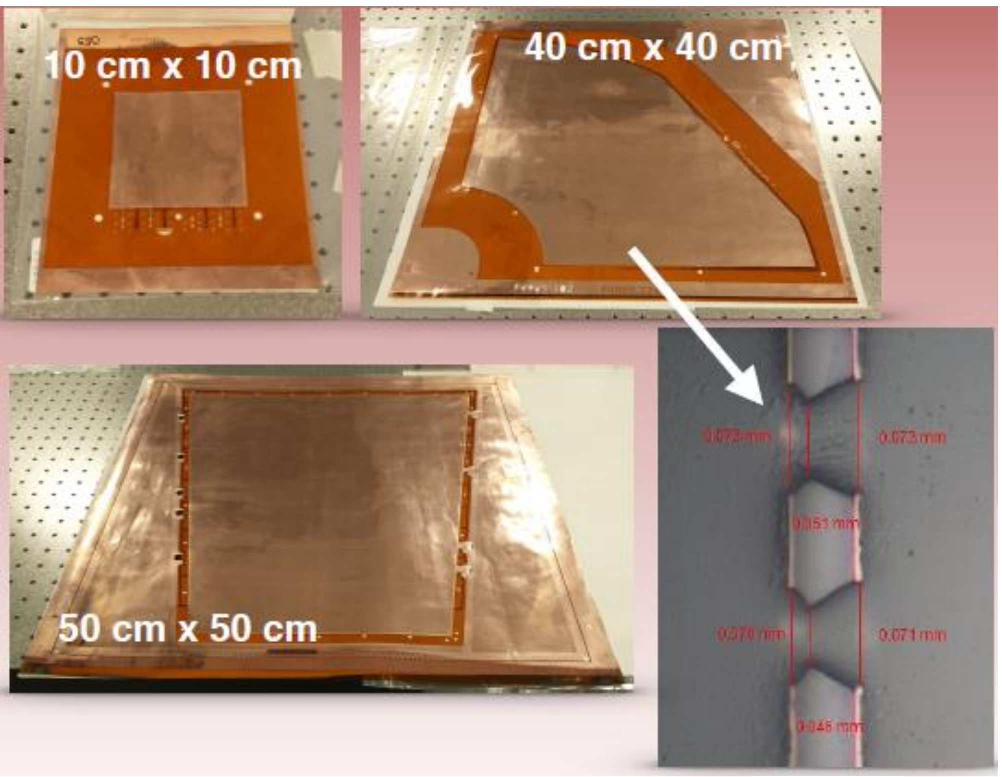
- **India**, plans on producing 10 cm and 30 cm GEMs.

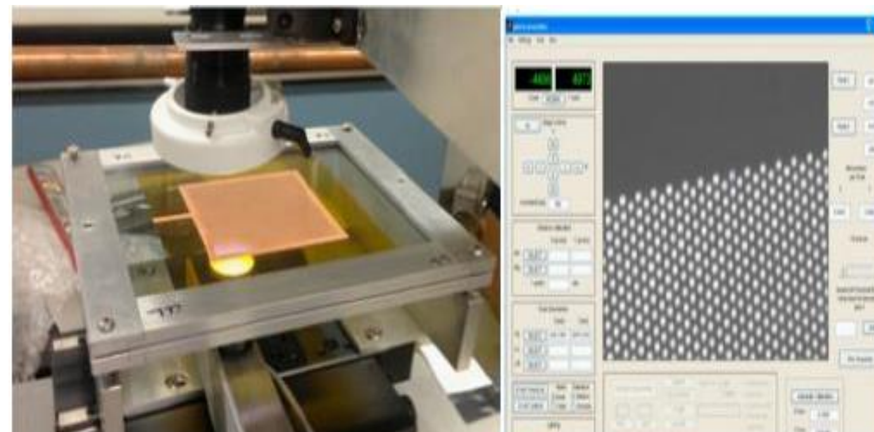

India (tank for 30 cm GEM etching)

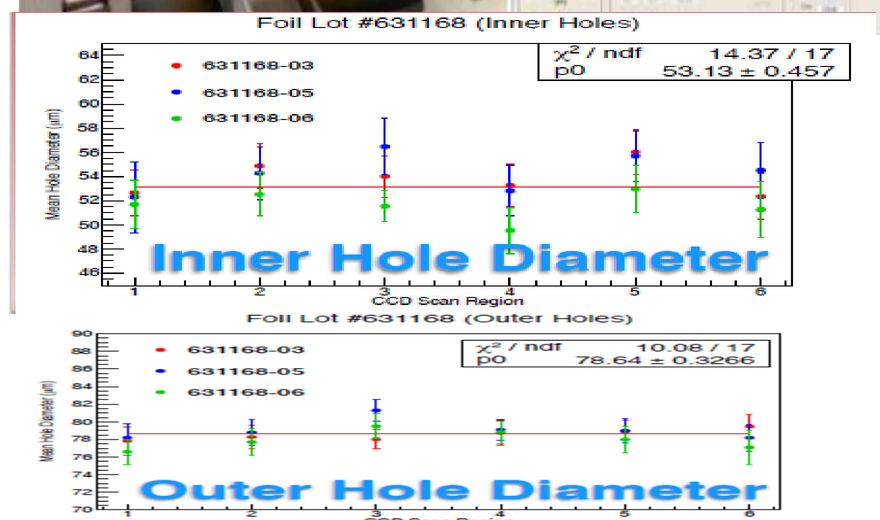
- **China** is also interested in making GEM foils. A 30 cm GEM foil was successfully produced.

GEM foil manufacturers

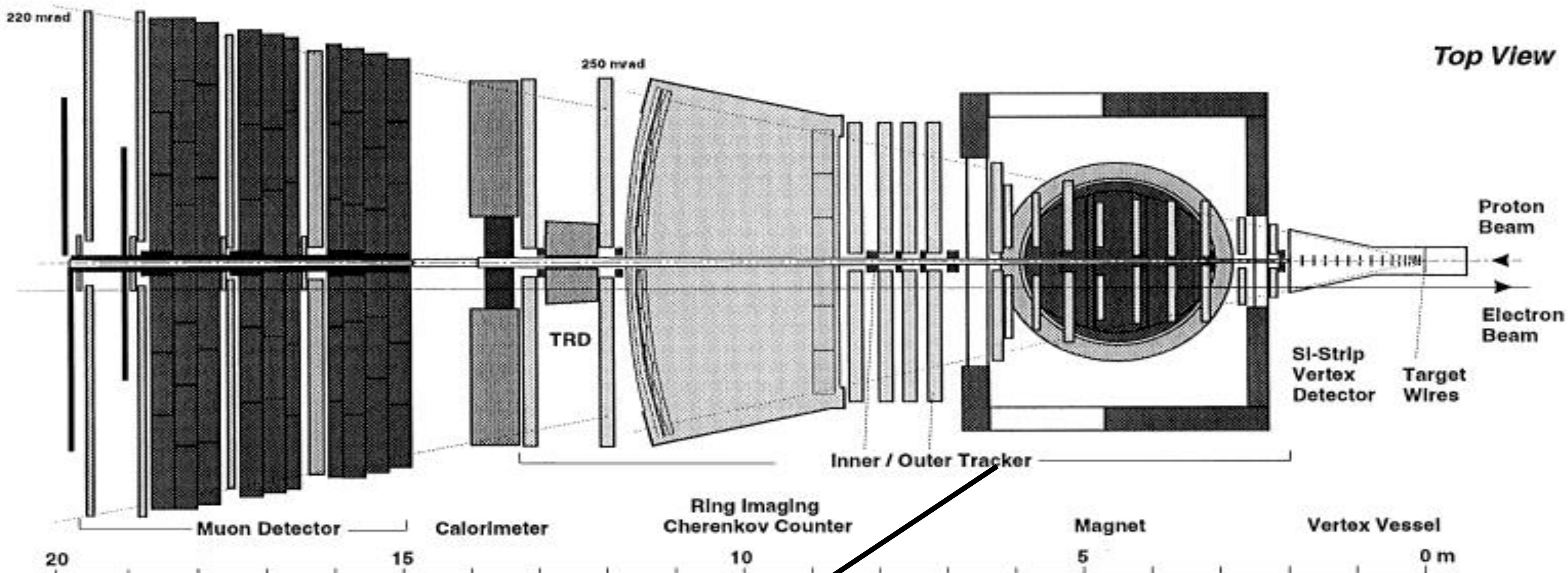
- **Tech-Etch Inc. in the US**, is able to provide up to 50 cm (single-mask) GEM foils.
- B. Surrow et al. at **Temple University** are capable of scanning GEM holes with CCD camera setup.
- By now the foils' electrical characters and hole uniformity are measured to be very good. Detector performances with the foils will be tested this year.



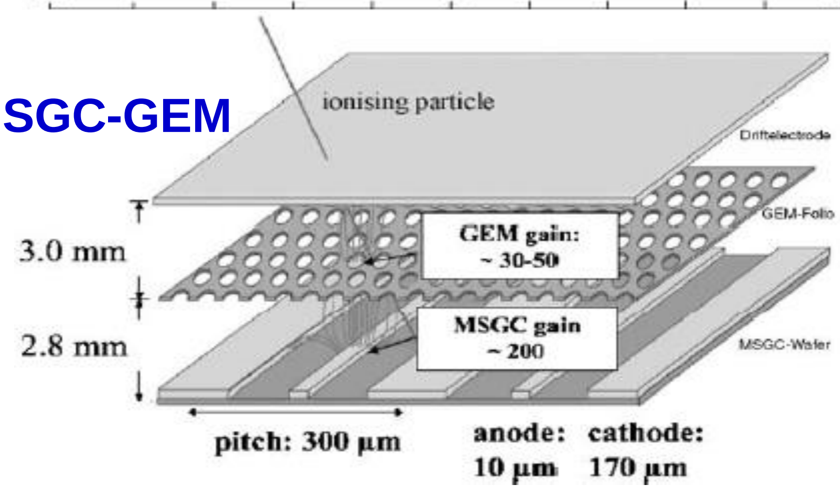


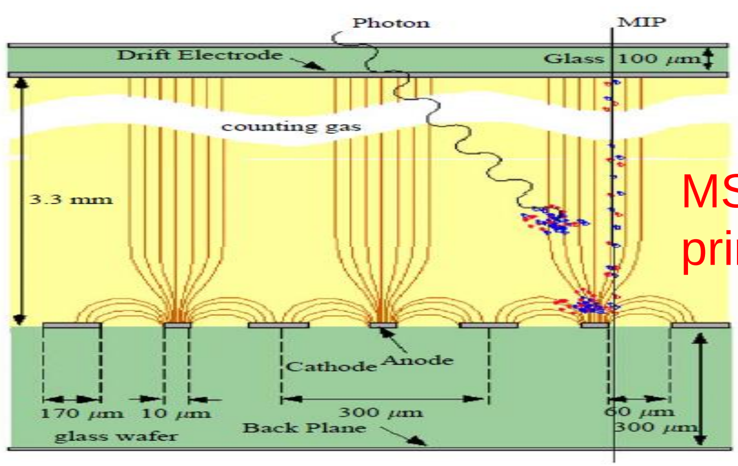


The HERA-B detector at DESY. The inner tracking system started commissioning in June 1999.



MSGC-GEM

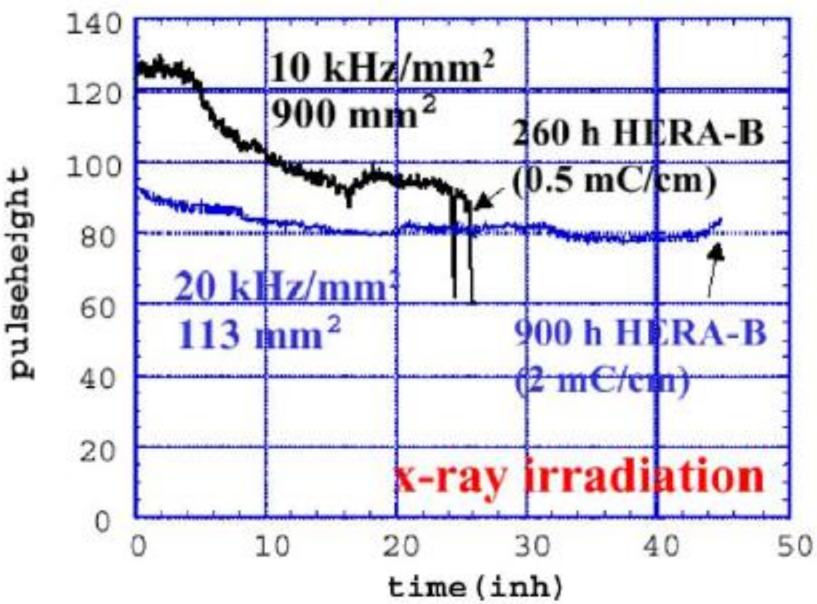




MSGC principle

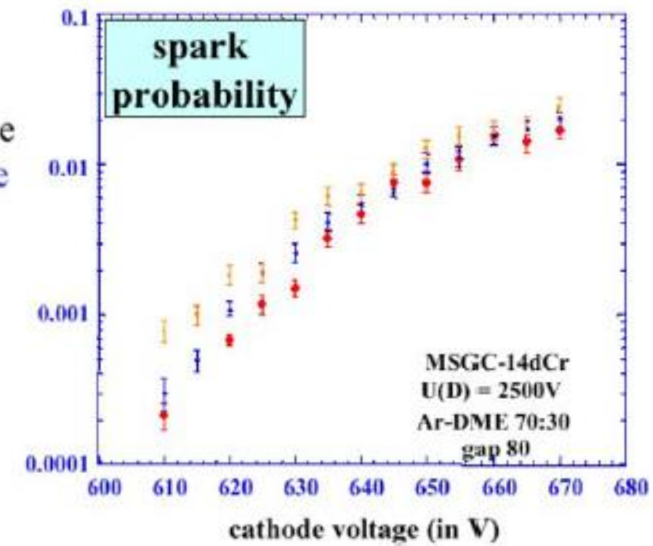
GEM applications: HERA-B Inner tracker

- It showed some aging problem and discharges to the MSGC-GEM detectors



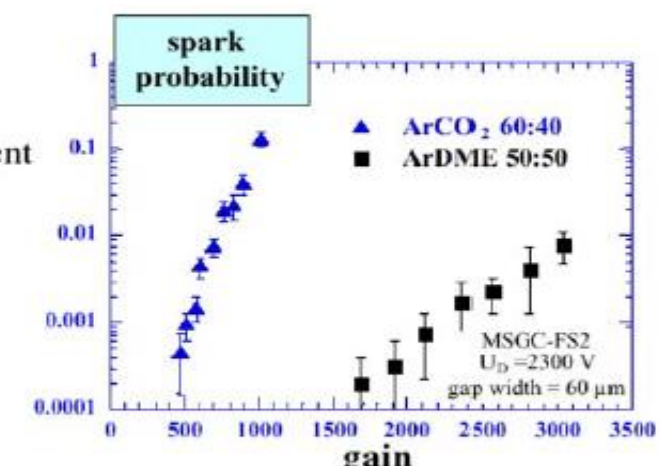
- This is an earlier application of GEMs. Problems are mainly due to MSGC detectors, also people gained experience by applying GEM detectors at such an experiment.

• strong dependence on cathode voltage



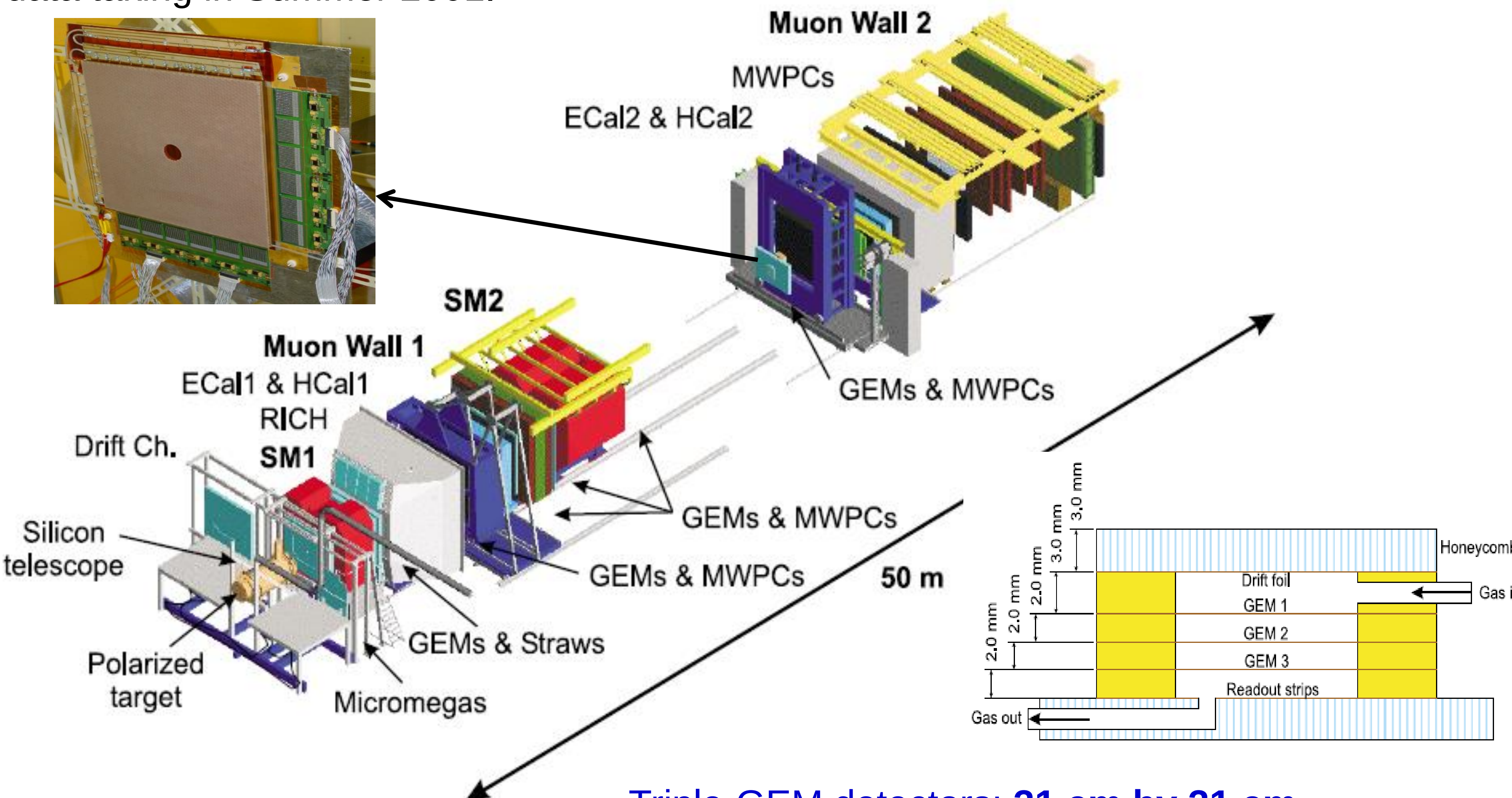
• gas dependent

(ArDME much better than e.g. $ArCO_2$)



GEM applications: COMPASS tracker

COMPASS (COmon Muon and Proton Apparatus for Structure and Spectroscopy) has been installed at the Super Proton Synchrotron accelerator (SPS) at CERN and began data taking in Summer 2001.



Triple-GEM detectors: **31 cm by 31 cm**

GEM applications: COMPASS tracker

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Table 2
Material budget for a triple-GEM detector in the active area

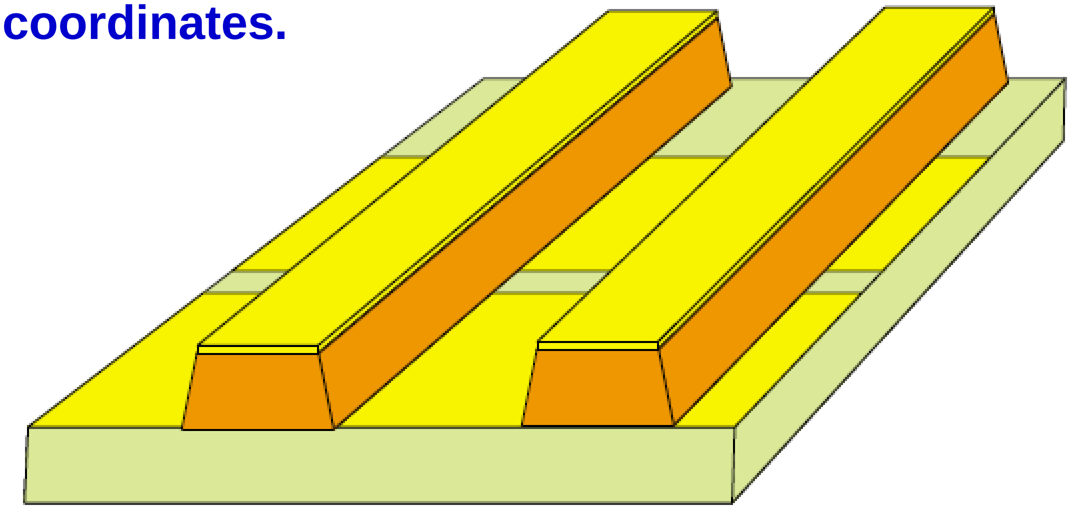
Part	Details	‰ of X_0
3 GEMs	$6 \times 5\,\mu m$ copper (0.7)	1.68
	$3 \times 50\,\mu m$ kapton (0.7)	0.42
		Total: 2.10
1 Drift	$5\,\mu m$ copper	0.35
	$50\,\mu m$ kapton	0.17
		Total: 0.52
3 Grid spacers	$3 \times 2\,mm$ fiberglass [0.008]	0.25
1 Readout board	$80\,\mu m$ strips: $5\,\mu m$ copper [0.2]	0.07
	$340\,\mu m$ strips: $5\,\mu m$ copper [0.85]	0.26
	$50\,\mu m$ kapton [0.2]	0.03
	$120\,\mu m$ fiberglass	0.62
	$60\,\mu m$ epoxy	0.30
		Total: 1.28
1 Shielding	$10\,\mu m$ aluminum	0.11
2 Honeycombs	$2 \times 3\,mm$ Nomex	0.46
4 Fiberglass foils	$4 \times 120\,\mu m$ fiberglass	2.47
		Total: 7.19

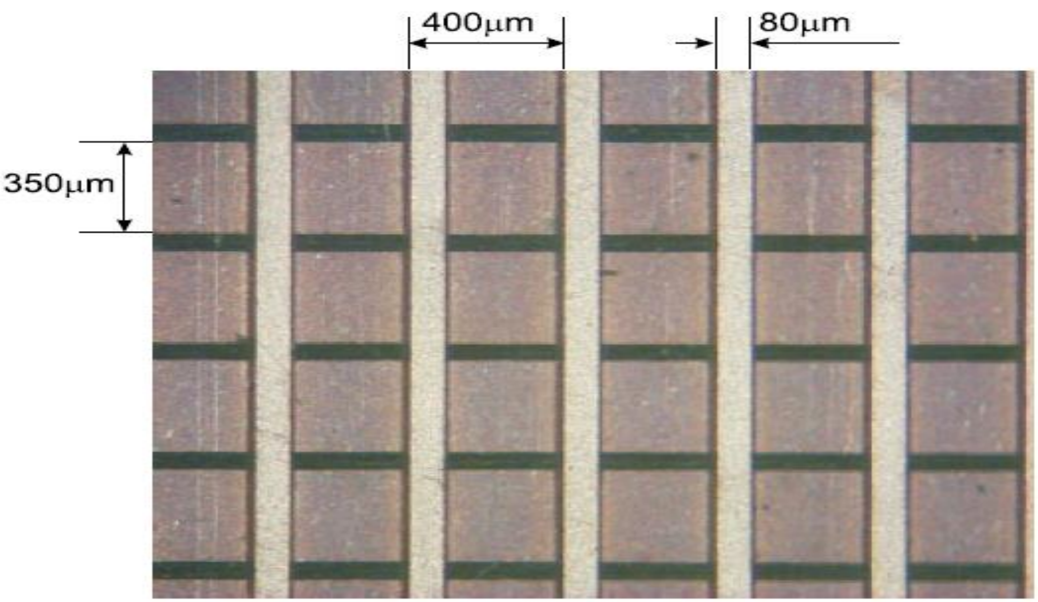
For some components, the fractional filling factor is given in brackets.

Material budget is a key factor for tracking-purpose detectors.

GEM applications: COMPASS tracker

2-D readout strips, 400 µm pitch in both coordinates.





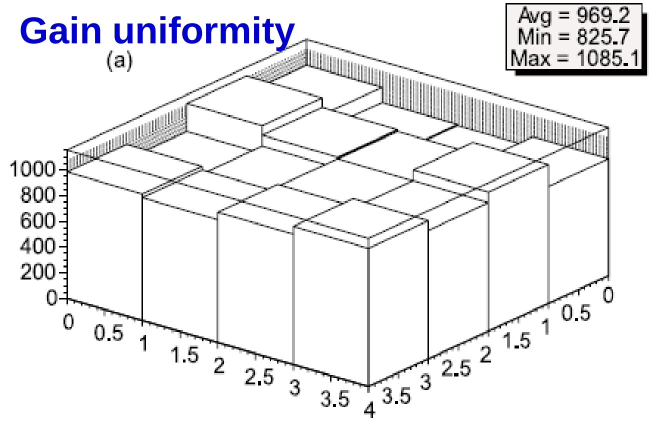
APV25 chip (128 ch./chip)

A COMPASS GEM detector has 128*6=**768 strips in each direction**,

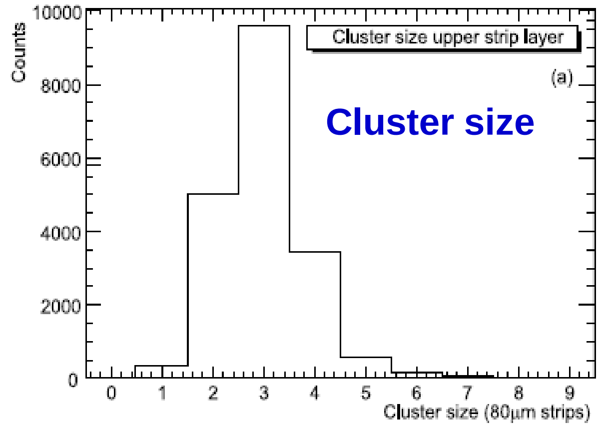
A detector needs **12 APVs** for reading out.

GEM applications: COMPASS tracker

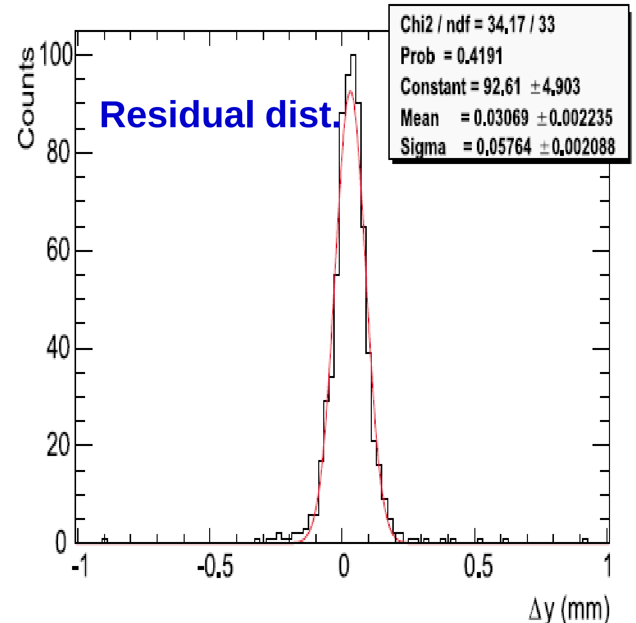
Gain uniformity



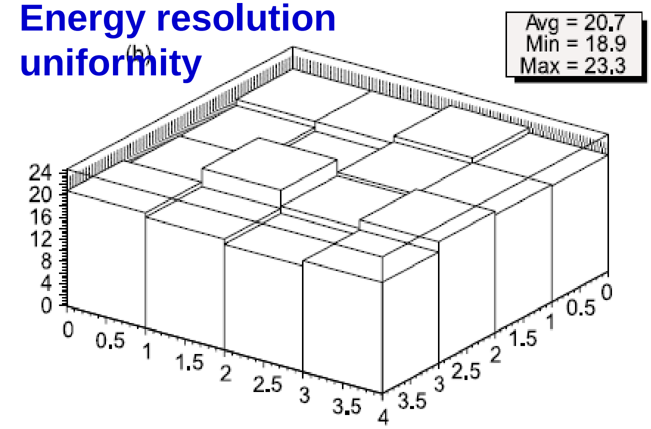
Cluster size

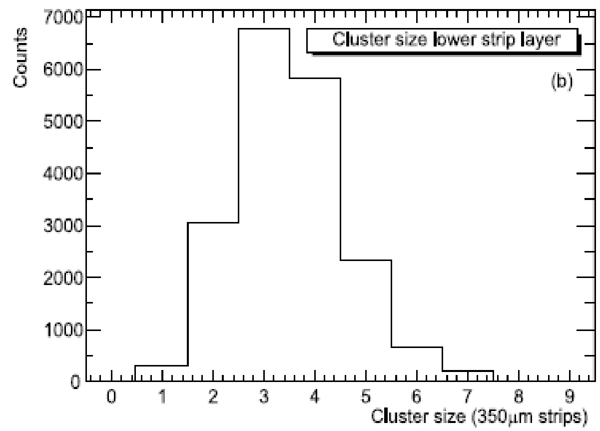


Residual dist.



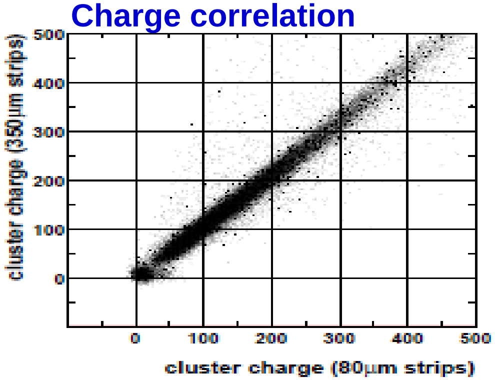
Energy resolution uniformity

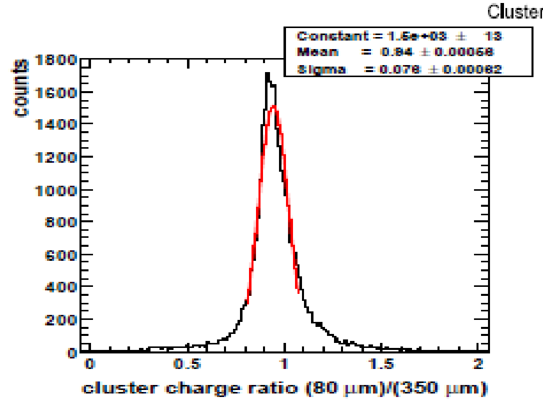




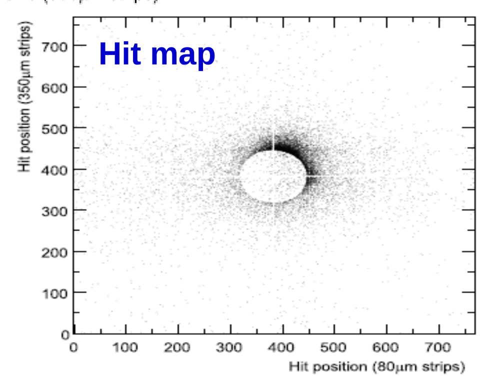
GEMs at COMPASS experiment became very successful.

Charge correlation

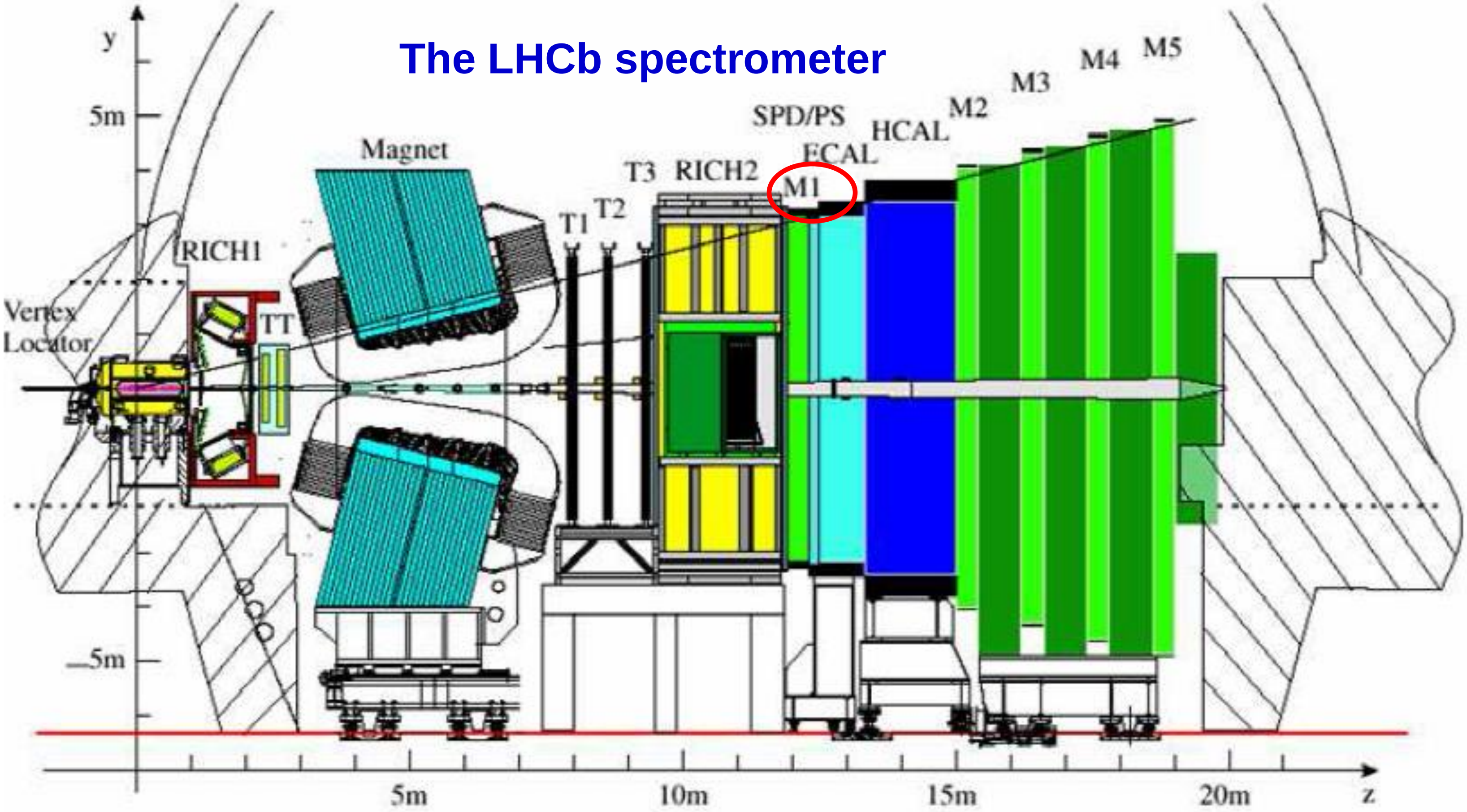




Hit map

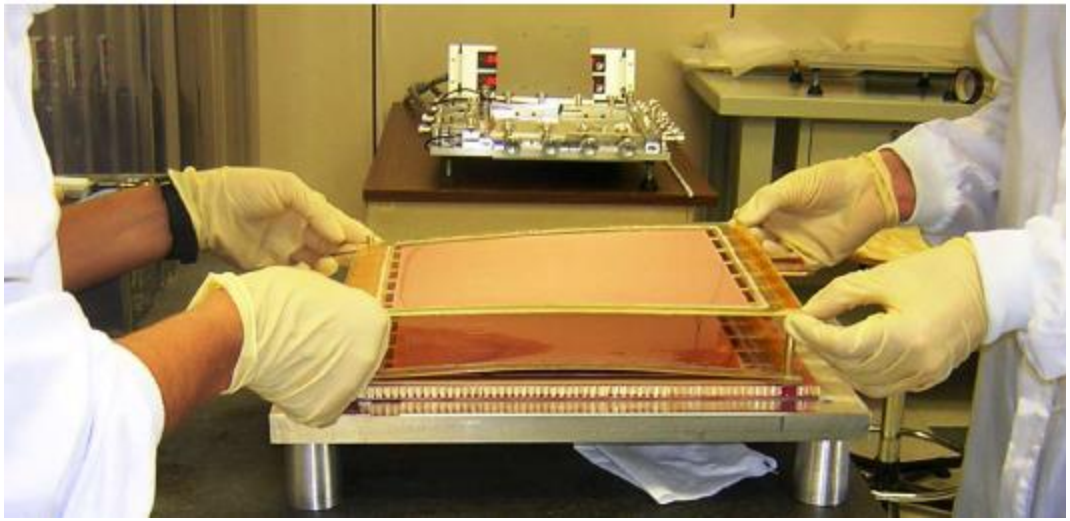


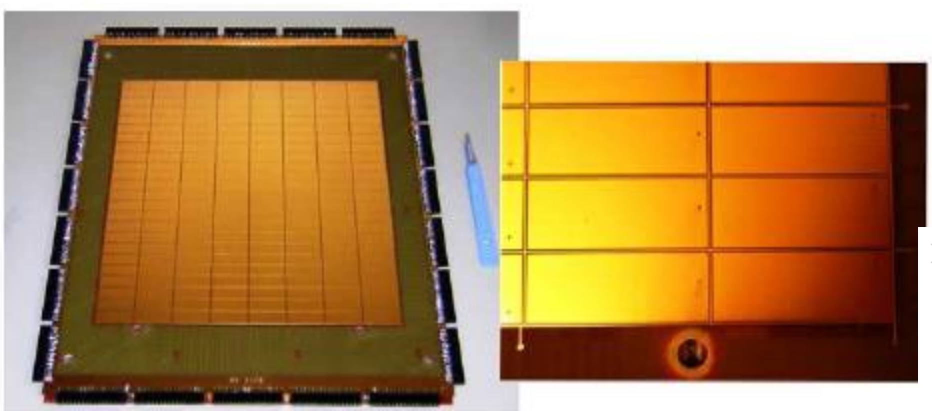
GEM applications: LHCb Muon Level 0 Trigger



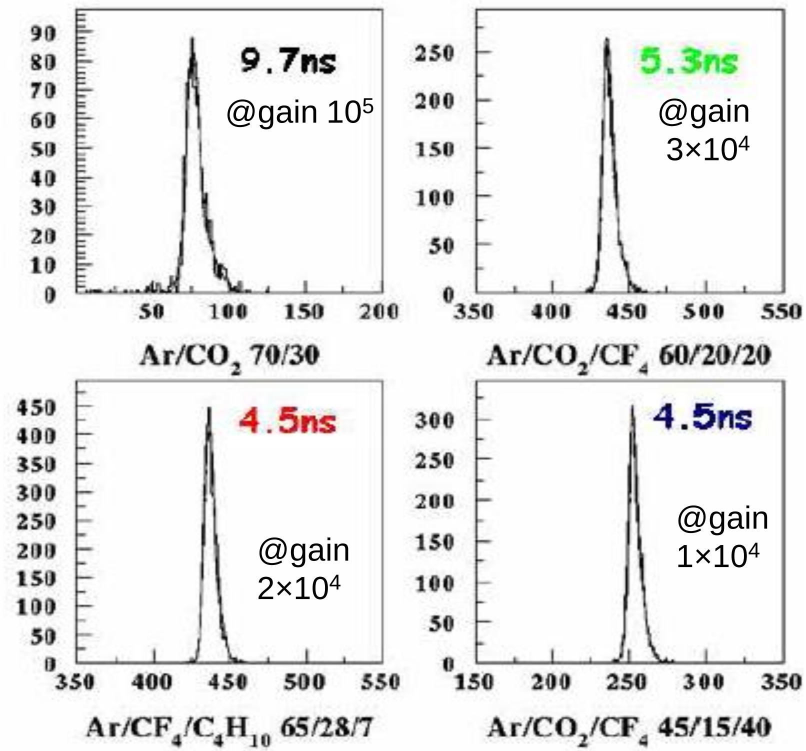
Triple-GEM in the inner region of the first muon station (M1R1)

GEM applications: LHCb Muon Level 0 Trigger

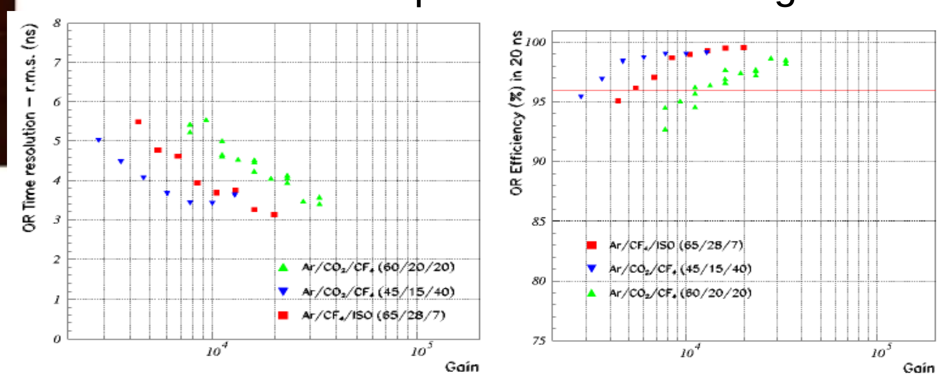




Triple-GEM with an area of 20cm by 24 cm,
Readout: 8*24 gold-plated pads
(size 25 mm by 10 mm).



Time responses in different gases.



Efficiency >96% in a 20 ns window.

GEM applications: CMS Muon Upgrade at LHC

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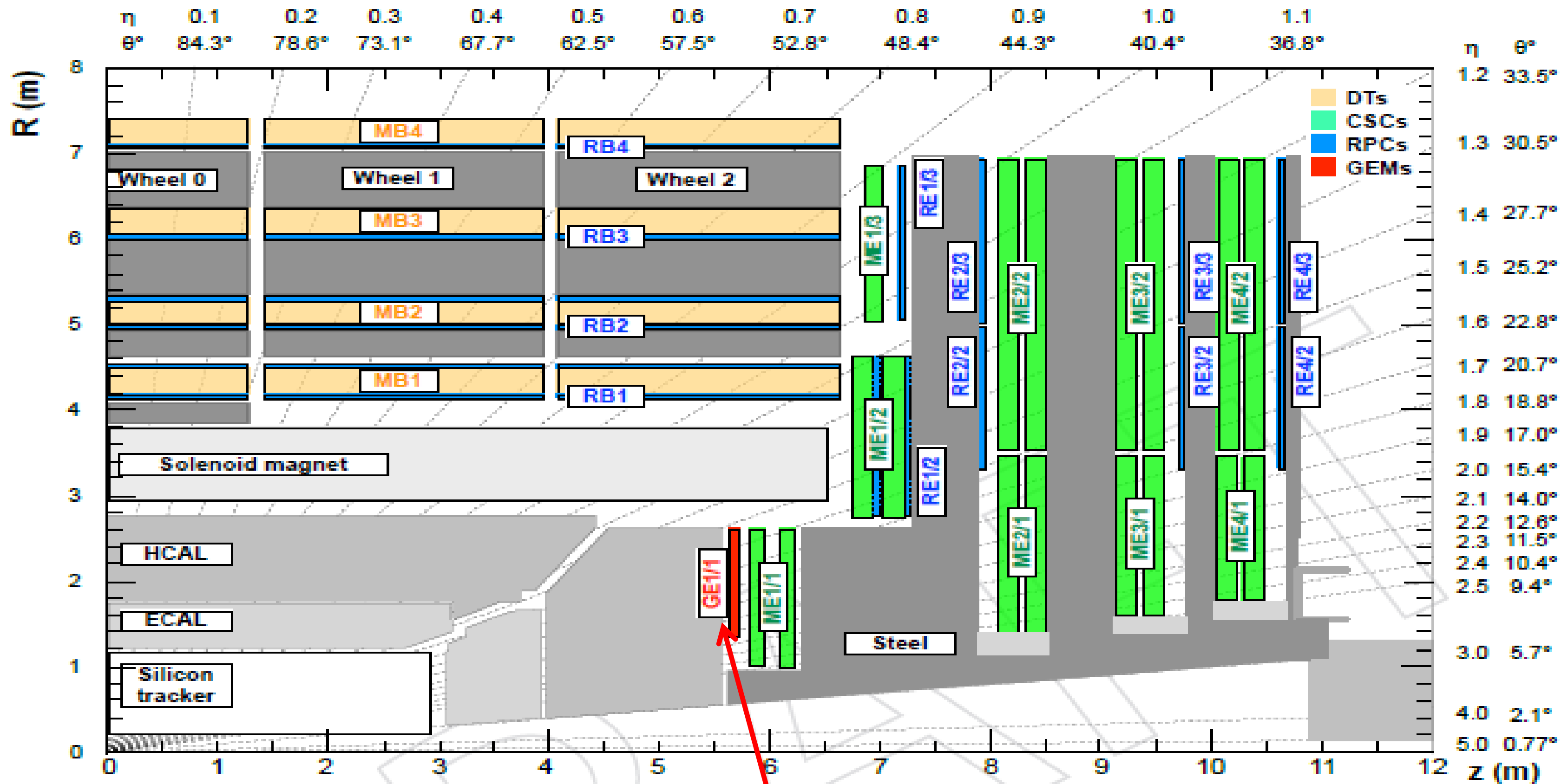
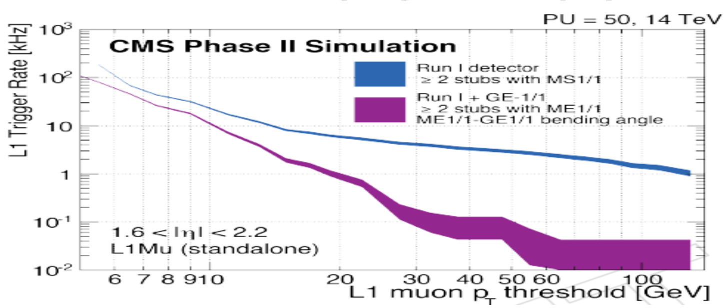
A quadrant of R-z cross section of the CMS detector.

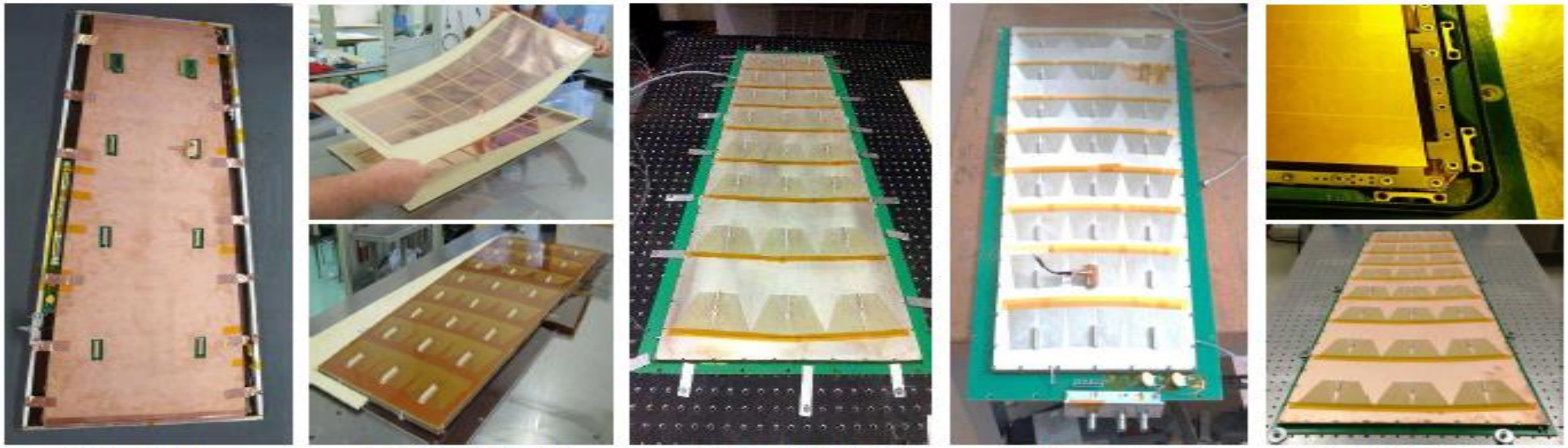




Trigger rate is expected to be reduced with the help of GEMs in the GE1/1 region

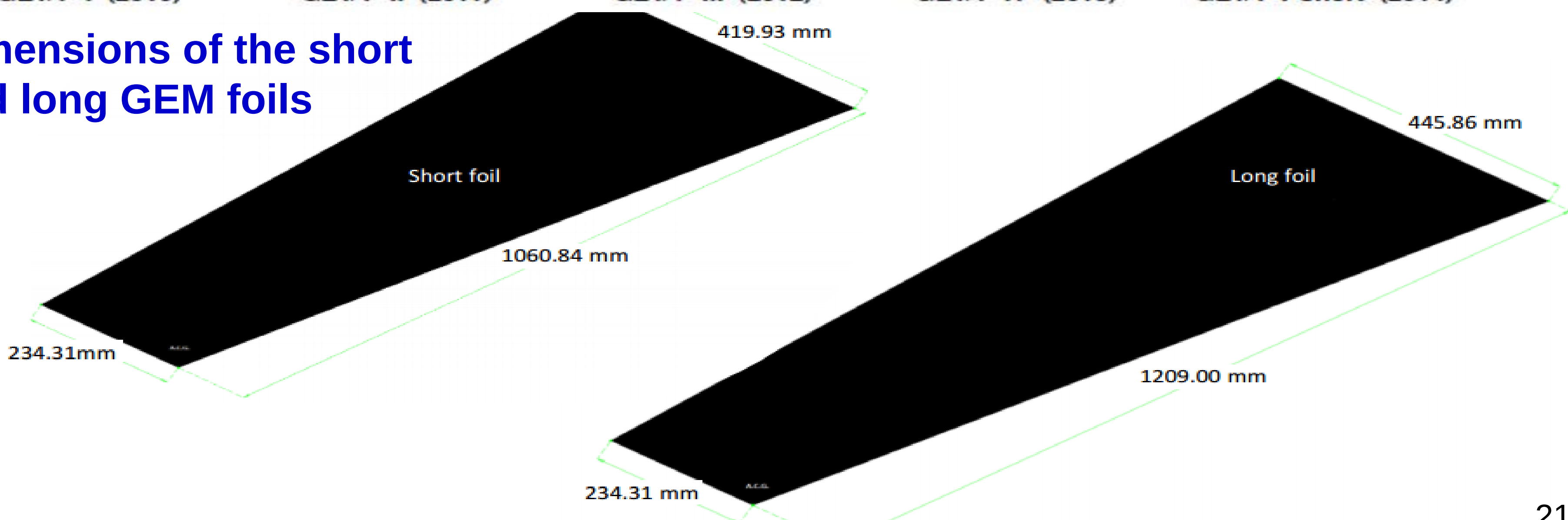
GEM applications: CMS Muon Upgrade at LHC

Generations of the GE1/1 GEM chambers: <u>short</u> (1 m long) chambers. Chamber opening angle 10 degrees.



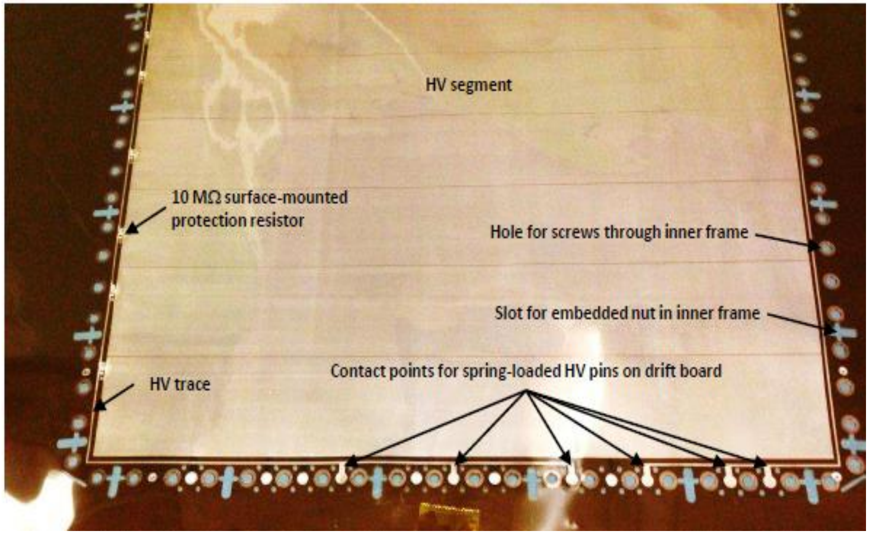
GE1/1- I (2010) | GE1/1- II (2011) | GE1/1- III (2012) | GE1/1- IV (2013) | GE1/1-V-short (2014)

Dimensions of the short and long GEM foils

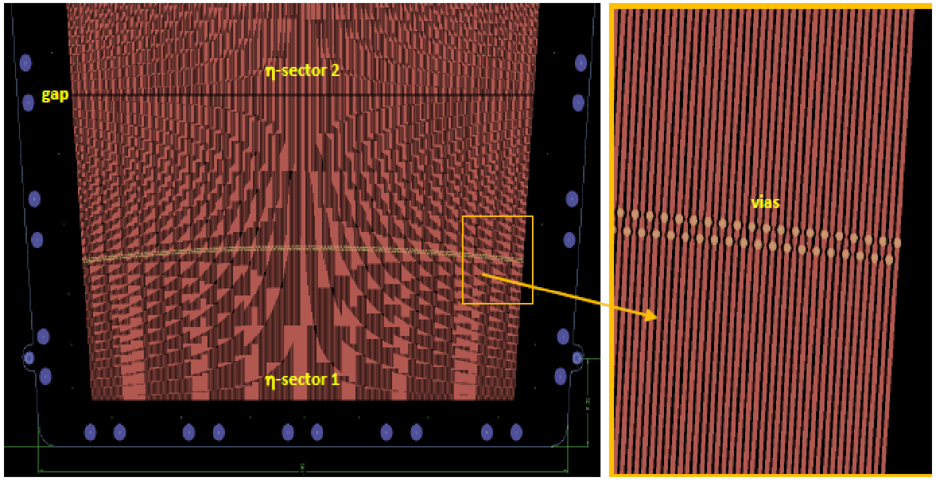


GEM applications: CMS Muon Upgrade at LHC

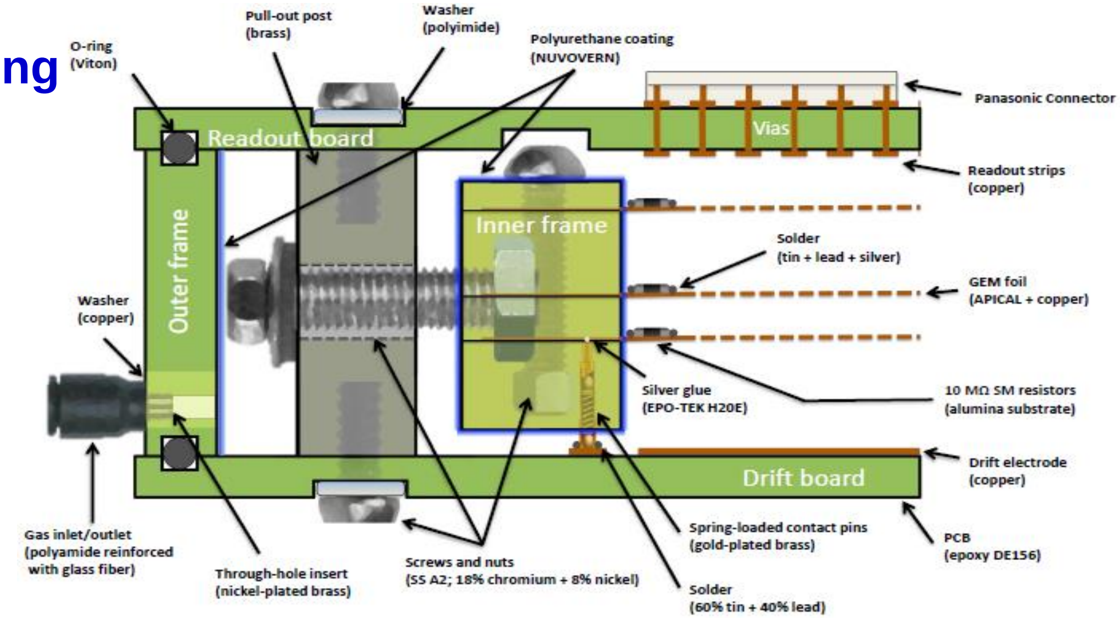
Details of a GEM foil.



Readout strips, with a pitch of 463 μrad in azimuthal direction. Strip length ~12 cm, **total channels 128*3*8 for a short GEM**.

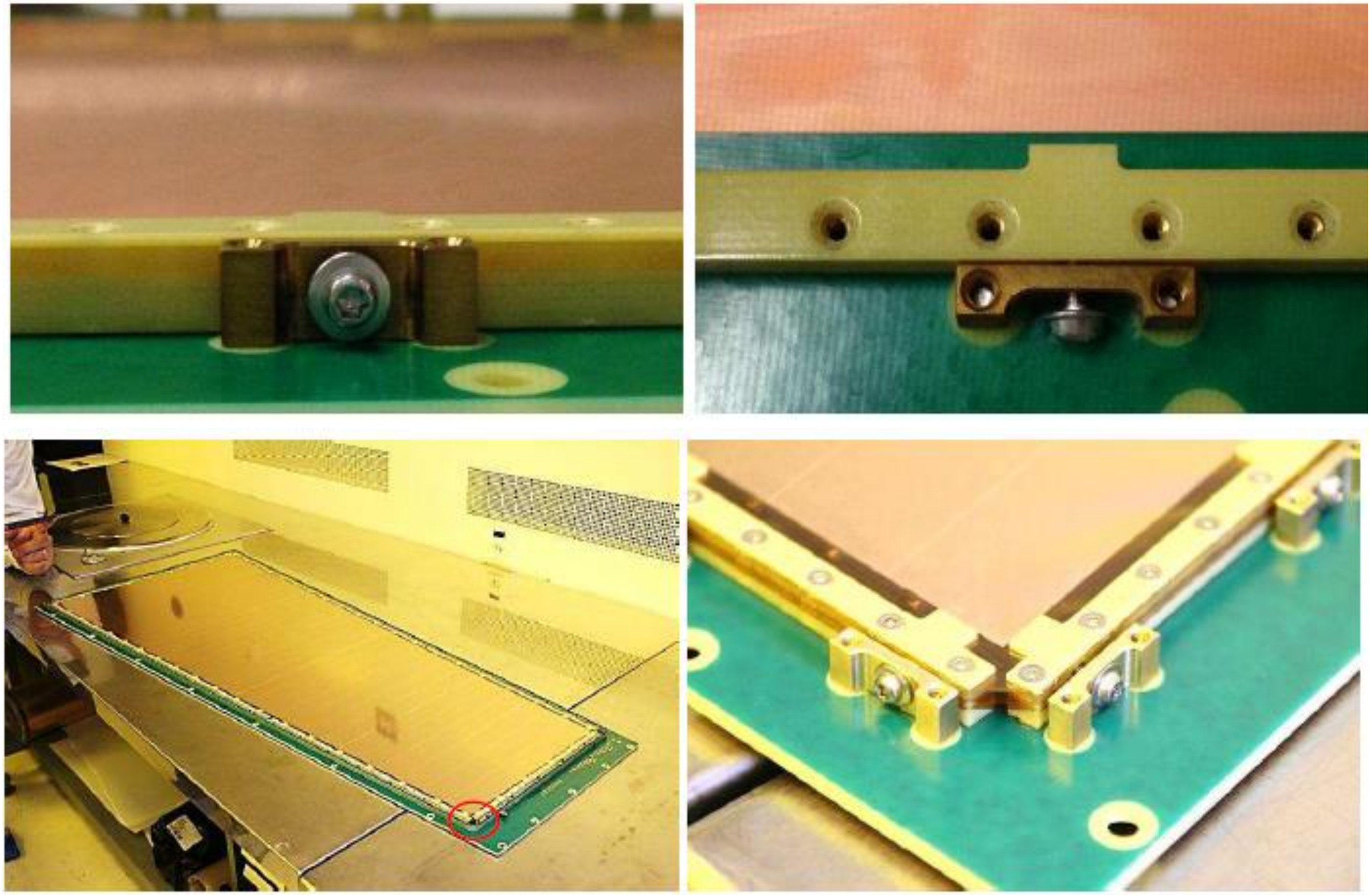


Mechanical stretching of a GEM detector.



GEM applications: CMS Muon Upgrade at LHC

Detector assembly



GEM applications: CMS Muon Upgrade at LHC

Mass assembly/testing sites:

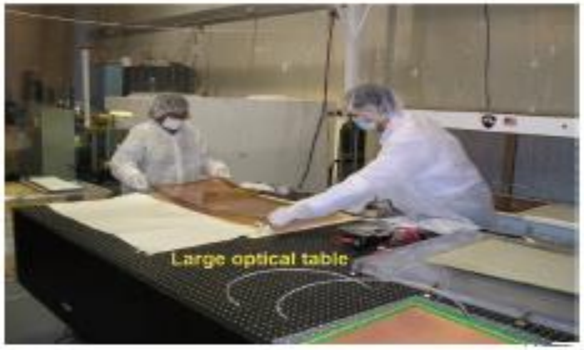
- ✓ CERN,
- ✓ U. Of Gent,
- ✓ INFN-Bari,
- ✓ INFN-LNF,
- ✓ Florida Tech,
- ✓ India BARC


(a) BARC


(b) INFN-Bari


(c) CERN

(d) UGent

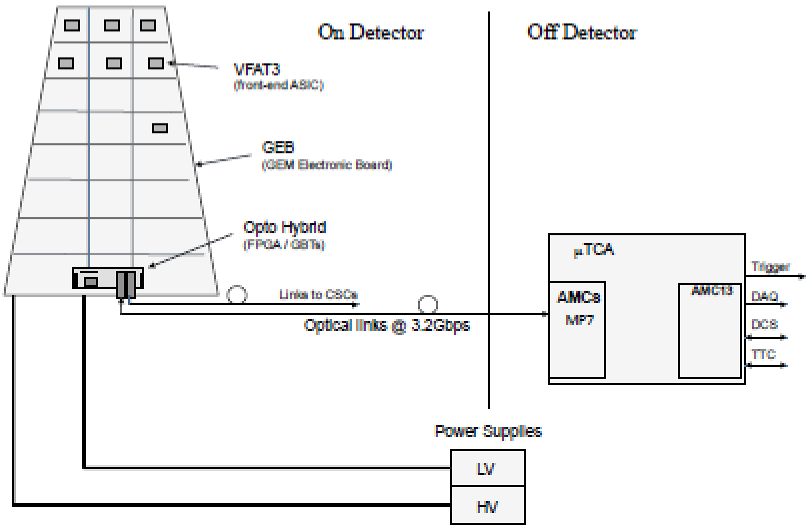


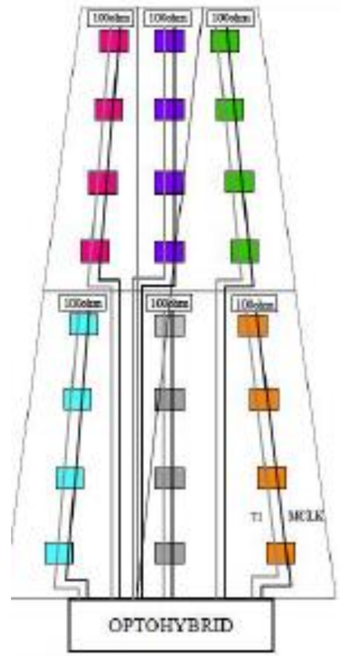
(e) FIT

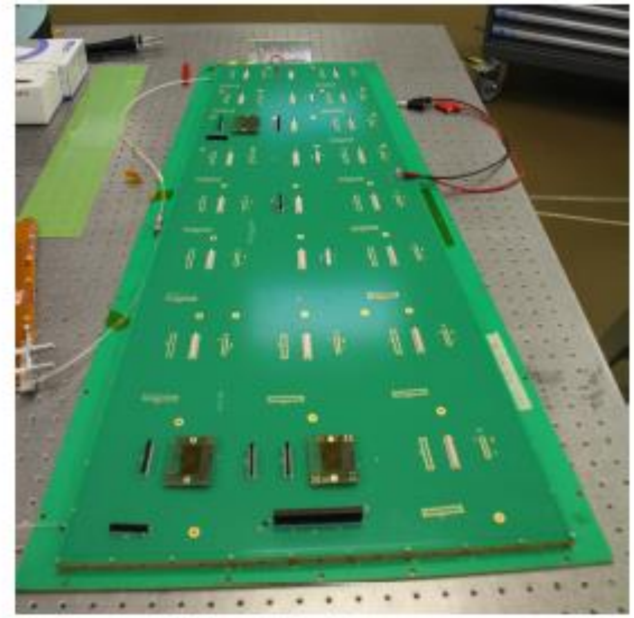

(f) INFN-LNF

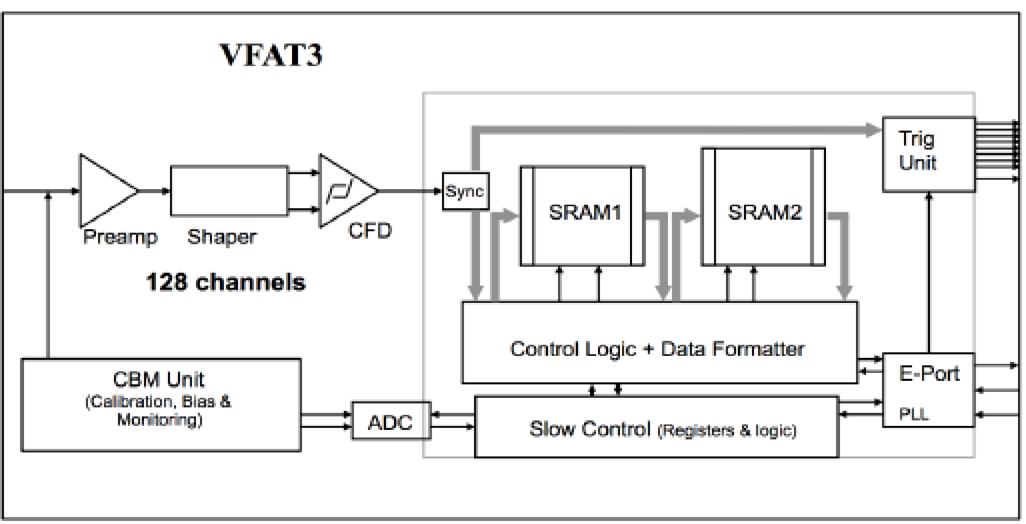
GEM applications: CMS Muon Upgrade at LHC

Electronics system:
Binary VFAT3 chips (128 ch./chip)





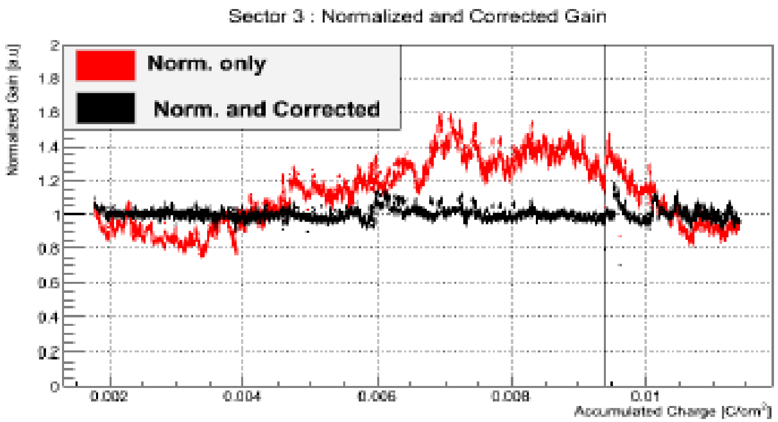


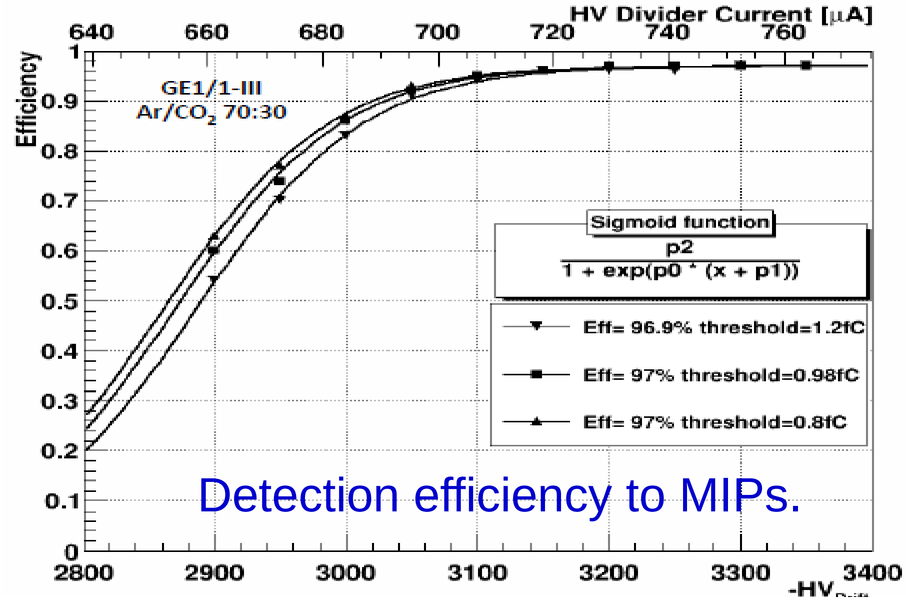


An opto-Hybrid board (for data transferring/receiving) plugs into a GEB (GEM Electronic Board) board which is mounted on the back of an readout board.

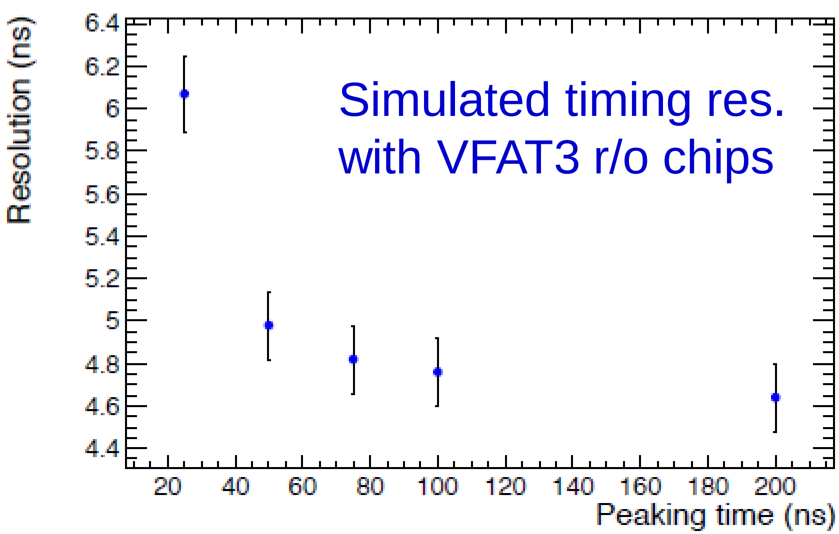
GEM applications: CMS Muon Upgrade at LHC

Long-term stability in a sector on a prototype

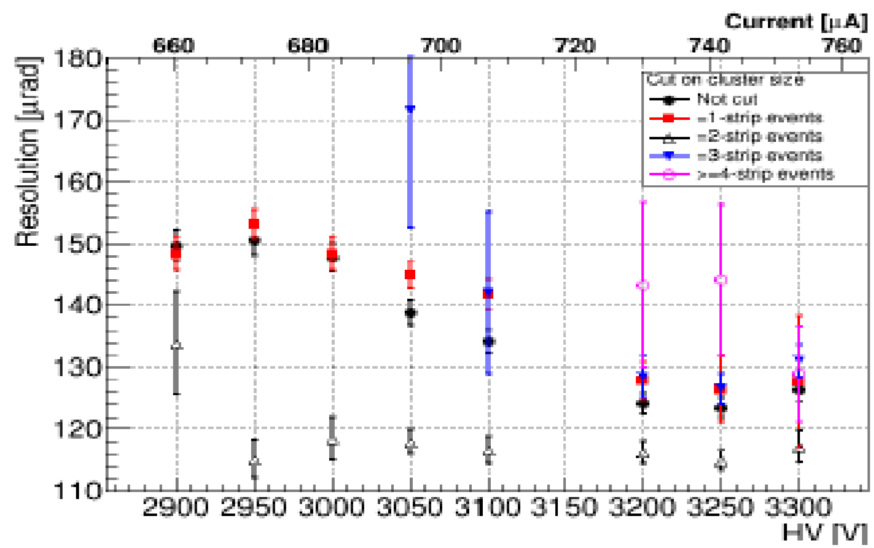




Detection efficiency to MIPs.



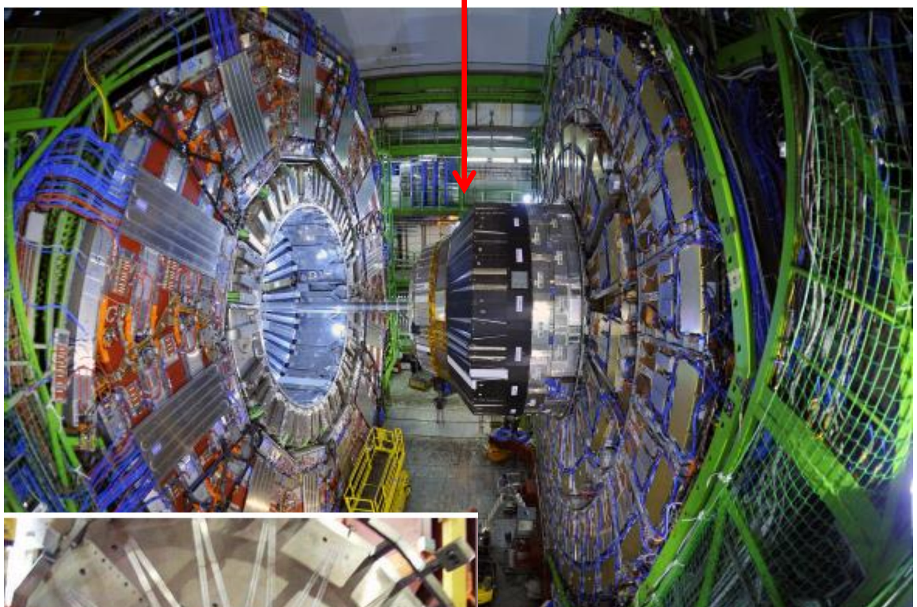
Simulated timing res. with VFAT3 r/o chips



Spatial res. Measured by (analog) APVs

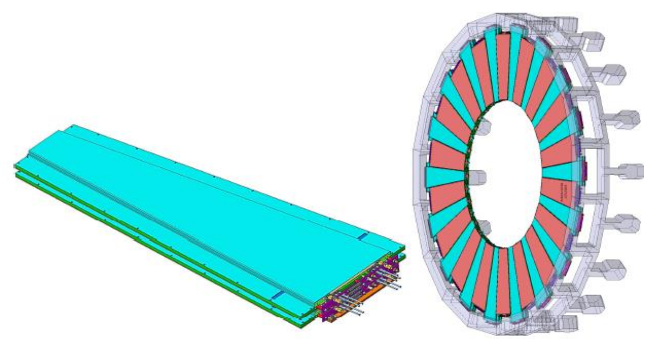
GEM applications: CMS Muon Upgrade at LHC

36 GE1/1 super GEM chambers to be installed here during the long shutdown of LHC in 2017/2018.

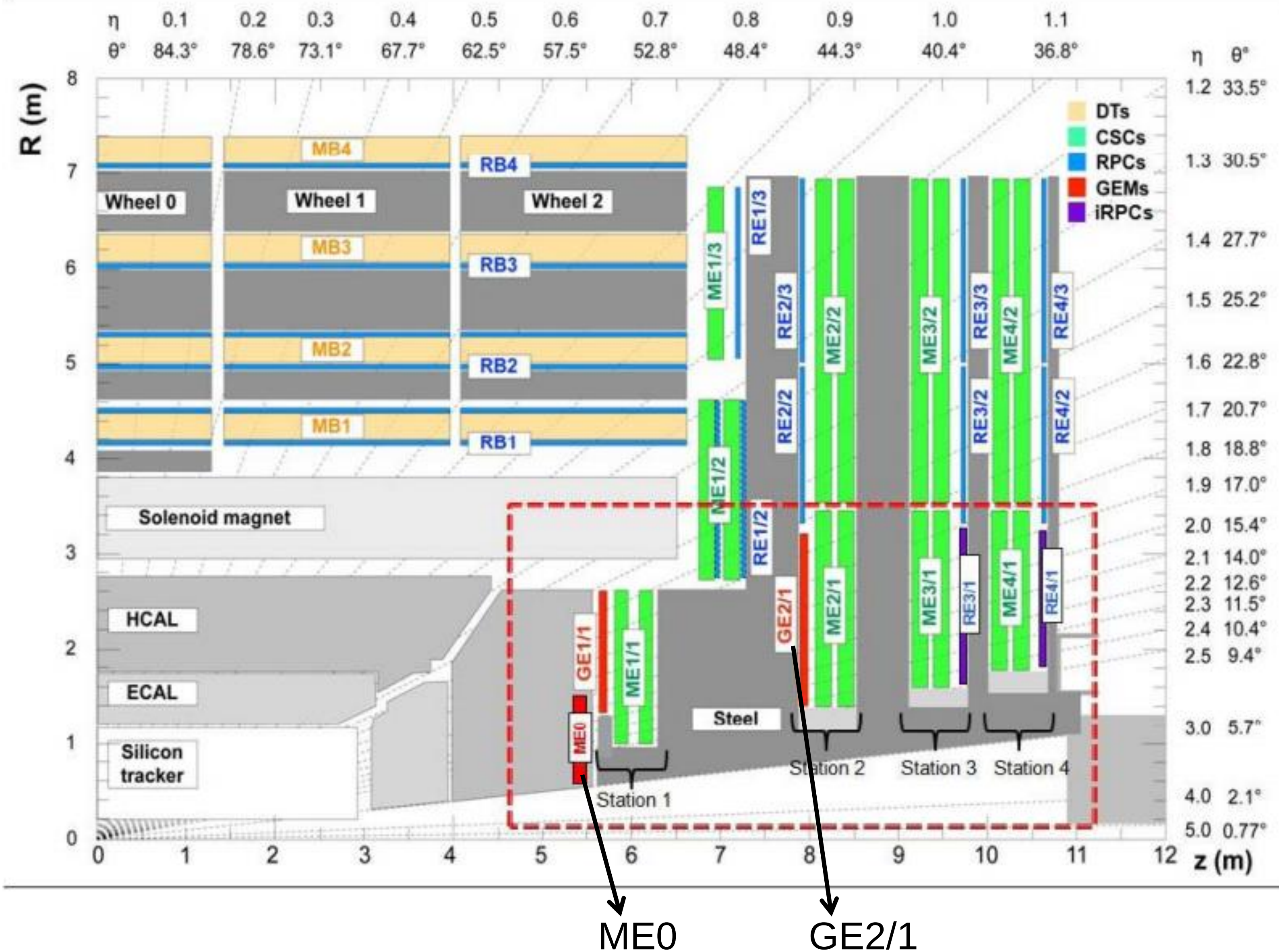


Back flange showing the GE1/1 chamber support rails.

A slot for a superchamber (a pair of GEM chambers).



GEM applications: CMS Muon Upgrade (Phase 2)



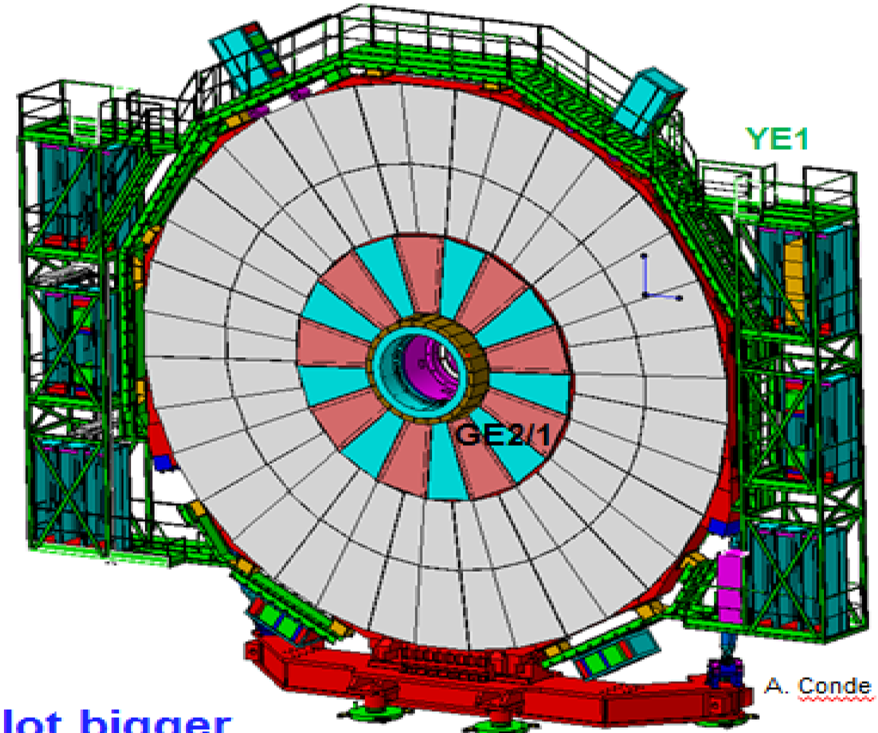
GEM applications: CMS Muon Upgrade (Phase 2)

GE2/1 Overview

Main motivation: Allows triggering on muons coming from highly displaced secondary vertices (due to new long-lived particles, e.g. a dark photon) that future track trigger cannot find beyond a few cm of displacement L_{xy} .

Current *baseline* design:

- Triple-GEM detector
- 72 trapezoidal chambers (20.15°)
- All chambers same size
- 1.9 m long
- 1.2 m wide (at wide end)
- ~ 3.5 × size of GE1/1
- 36 overlapping superchambers (SC) with 2 chambers per SC
- Radial readout strips
- 12-15 η-segments for readout strips
- 9,000 - 12,000 r/o channels per chamber; 650k - 860k ch. total



Concept very similar to GE1/1 – but a lot bigger…

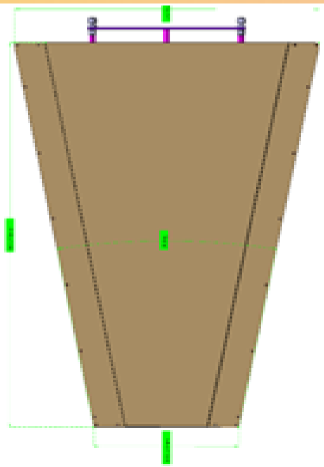
GEM applications: CMS Muon Upgrade (Phase 2)

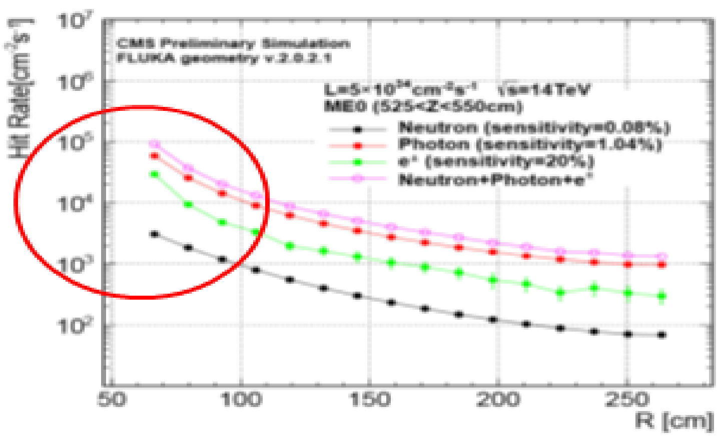
Florida Tech

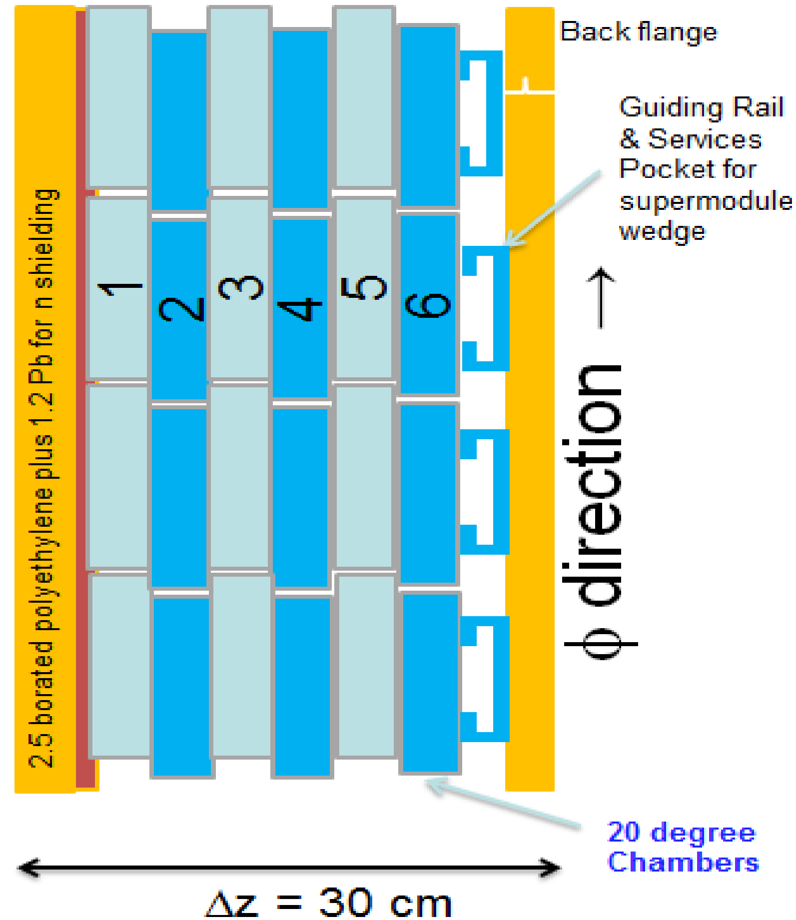
GE0 Baseline Design

Florida Tech

- Triple-GEM detector to provide muon ID (tag) in highest eta region
- Size similar to GE1/1-S, but 20.1° trapezoids; 216 ch.
- More layers than GE1/1 & GE2/1 to reject gamma & neutron backgrounds and to cope with ~100 kHz/cm^2 hit rates:







GEM applications: TOTEM at LHC

Total Cross-section, Elastic Scattering and Diffraction Dissociation at LHC

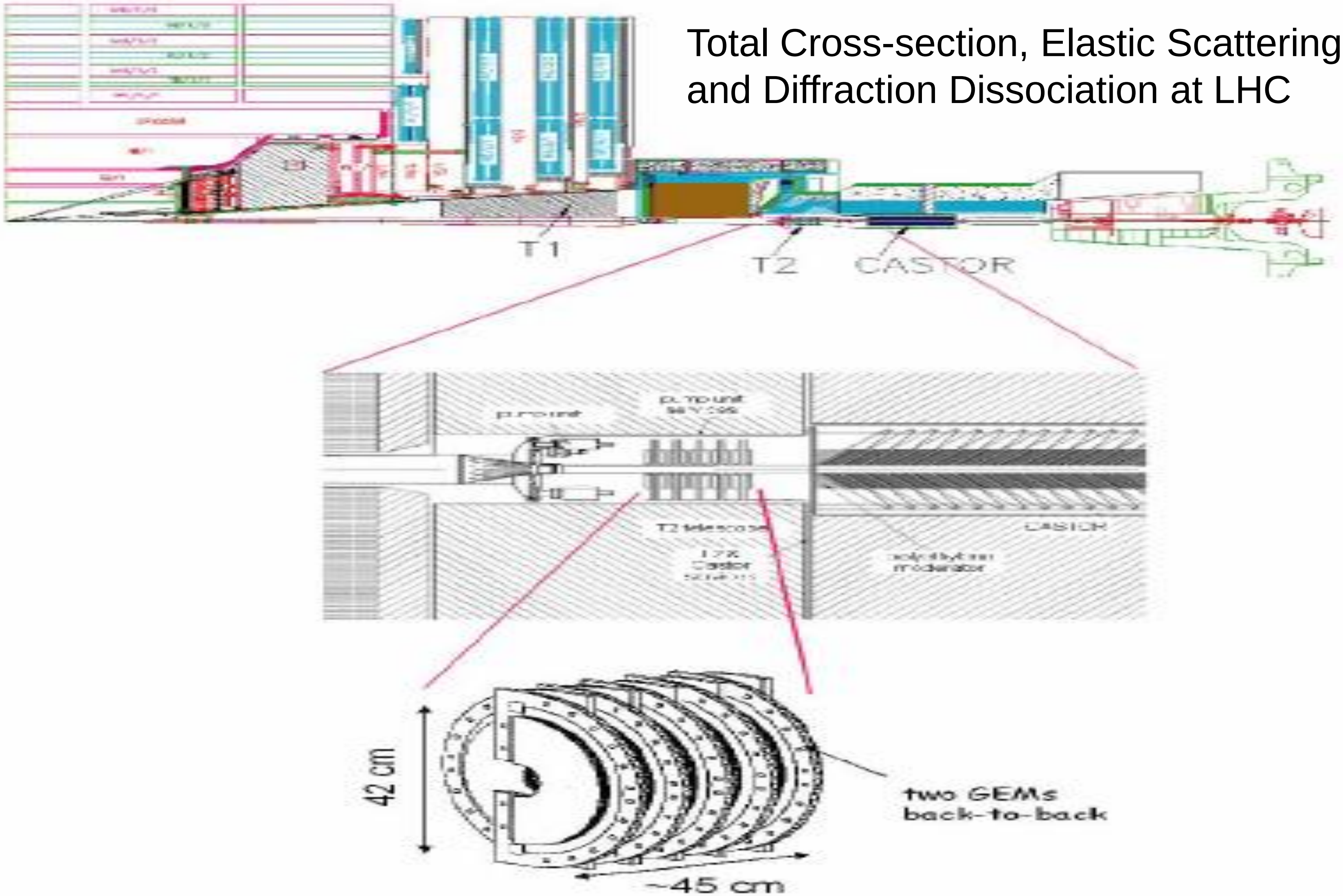


Fig. 1. TOTEM detectors are installed in the CMS forward region (above), location of the T2 telescope within the shielding of CMS (middle) and 20 GEM detectors in back-to-back configuration (below).

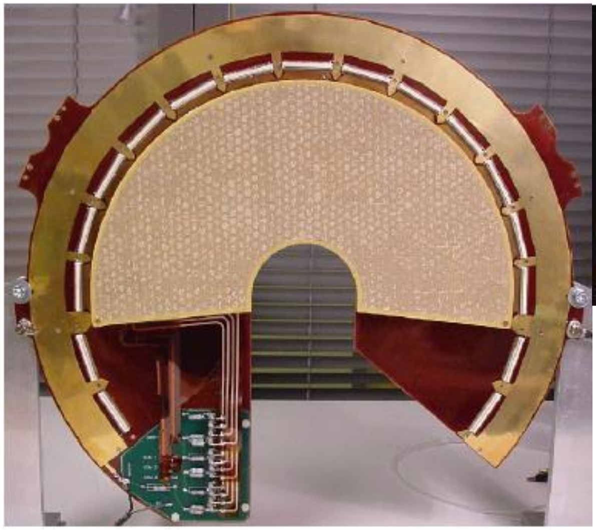
GEM applications: TOTEM at LHC

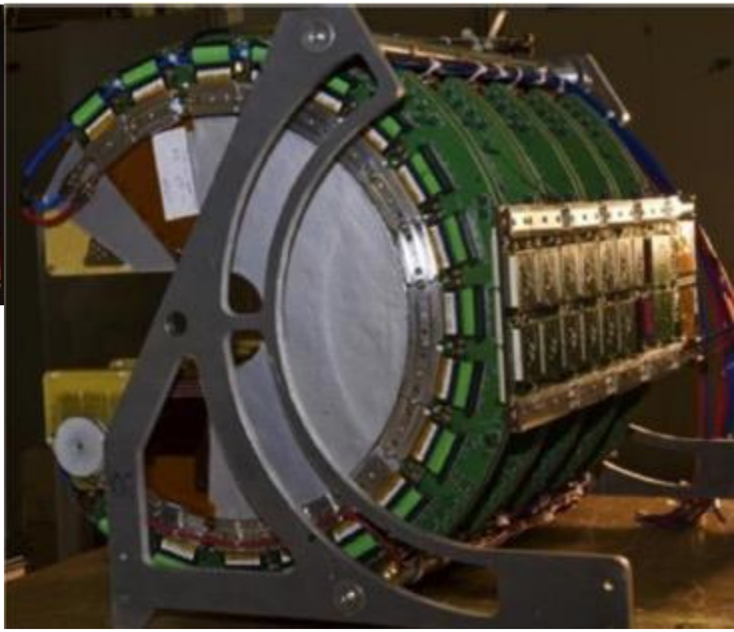
2.2.1 The TOTEM Triple GEM

A gaseous detector based on GEM (gas electrons multiplier) technology is typically characterized by:

-high rate capabilities ($> 10^5 Hz/mm^2$);
-radiation hardness;
-good time ($< 10ns$) and spatial ($< 60\mu m$) resolution;
-active area up to $10^3 cm^2$;
-reduced constraints on the detector shape;
-readout fully decoupled from amplification (very interesting aspect because it allows an independent optimization of the functional parts of the chamber).

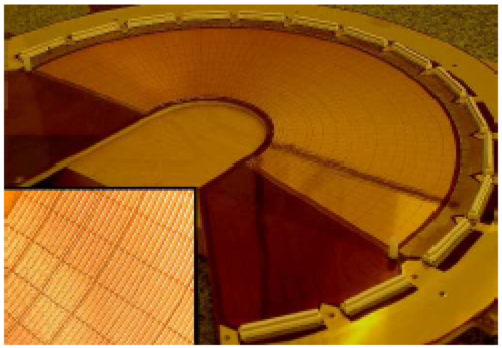
All these properties are compatible with the TOTEM requirements for the telescope $T2$. The collaboration has decided therefore to realize its inelastic telescope with a GEM detector, based on the successfully triple GEM of COMPASS [30].

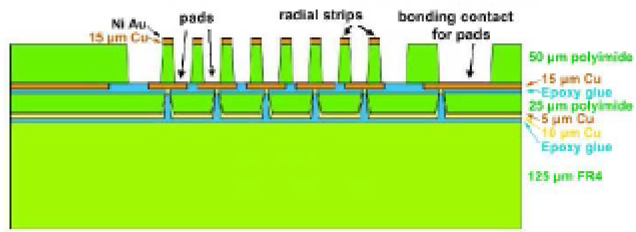


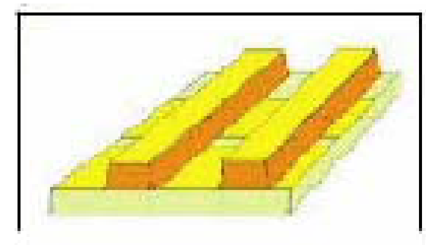


GEM applications: TOTEM at LHC

512 concentric strips measuring radial coordinates of traversing particles;
A matrix of 1560 pads give azimuthal coordinates, delivering trigger info.







COMPASS-like readout structure

Figure 2.14: Left:The readout plane is realized on a printed circuit board covered by polyimide foil with the pattern of strips and pads shown in fig. 2.3. The readout board contains 2×256 concentric strips for the radial coordinates and a matrix of 1560 pads for azimuthal coordinates and for the T2 local trigger. The width and spacing of the strips are 80 and $400\mu m$ respectively. To reduce the occupancy, the strips are divided into two parts. The pads are divided into 65 radial sectors each containing 24 pads with sizes ranging from $2 \times 2\,mm^2$ in the internal side (the one that is close to the vacuum chamber of the beam pipe) to $7 \times 7\,mm^2$ on the external side. The charge collected is read at the outer edge of the readout board where 17 high density $130pins$ connectors are foreseen. In the corner a view of the strips and pads is shown and a complete description of the readout pattern is given in fig. 2.3. A measurement of strips and pads capacitance is shown in fig. 2.18. Right: Detailed view of the strips and pads structure with dimensions and materials used. The strips lie on top of the pads and are isolated from the pads by a thin layer of polyimide, which is removed between the strips by wet etching.

GEM applications: TOTEM at LHC

Front-end electronics

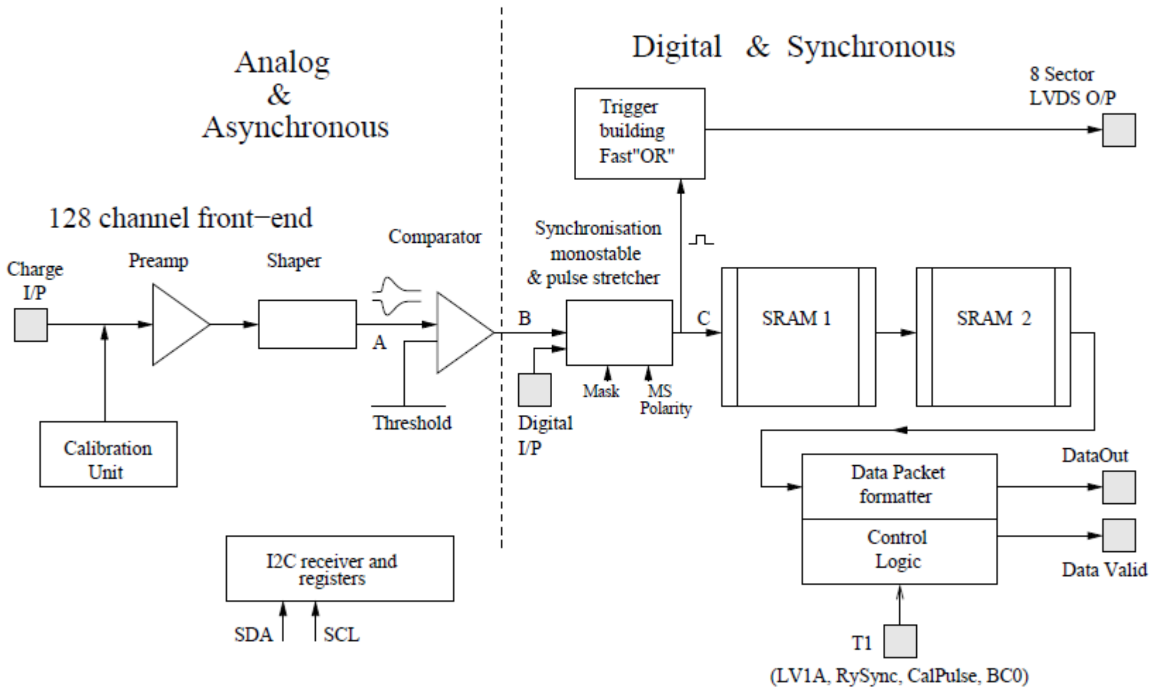
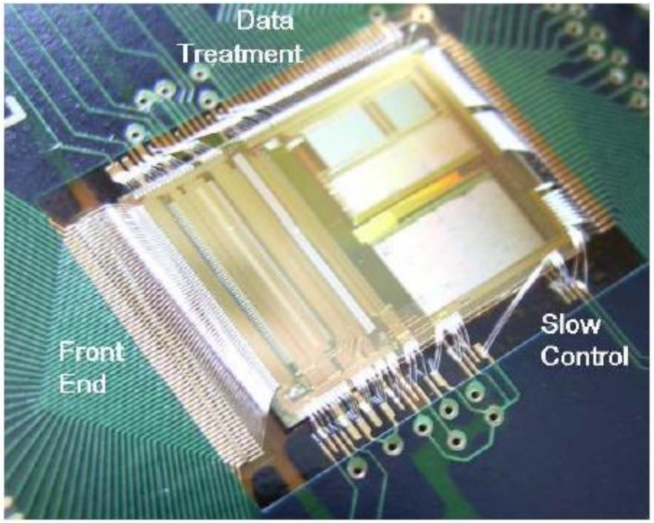
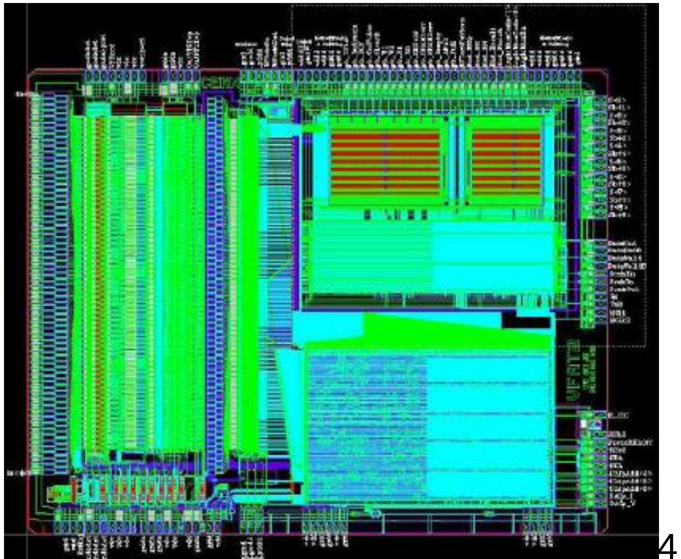


Diagram of a VFAT2





GEM applications: TOTEM at LHC

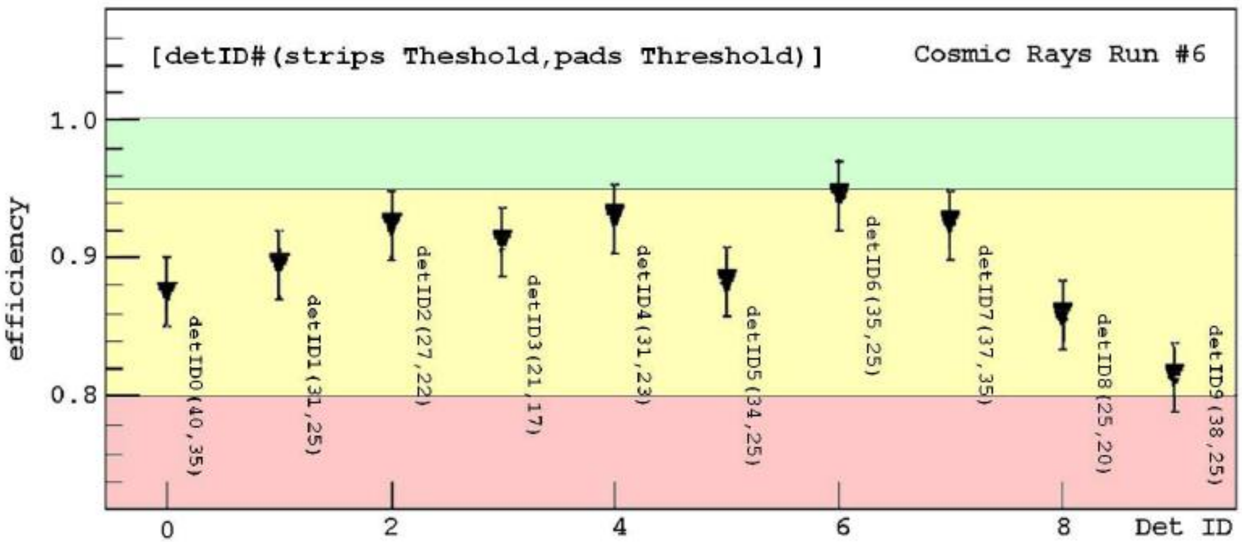
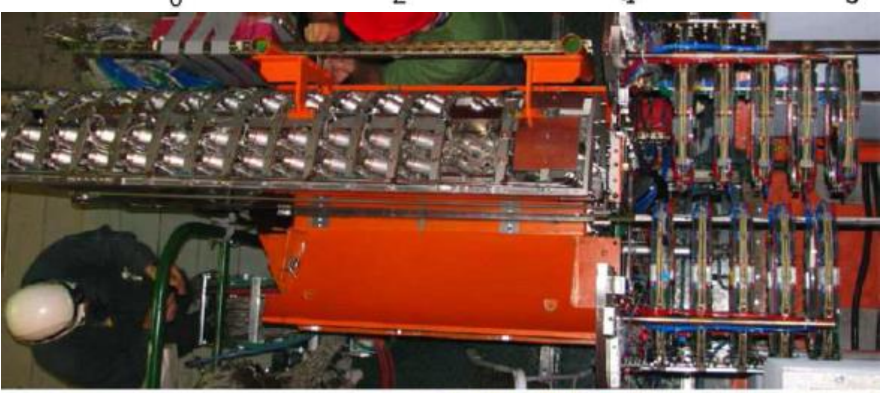
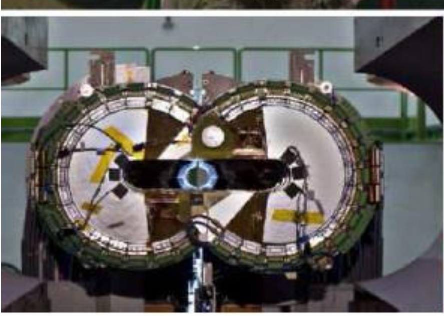
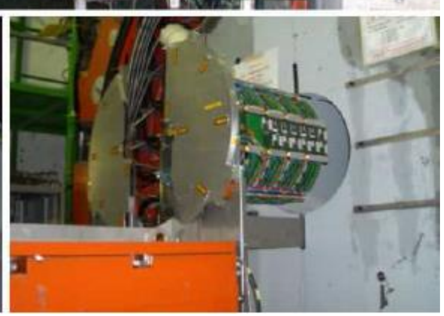


Figure 5.26: Cosmic Rays Efficiency Measurement: HV=$-4.2kV$, MSPL=3clk, Threshold on the plot. The three regions used to validate the status of the quarter are also shown.







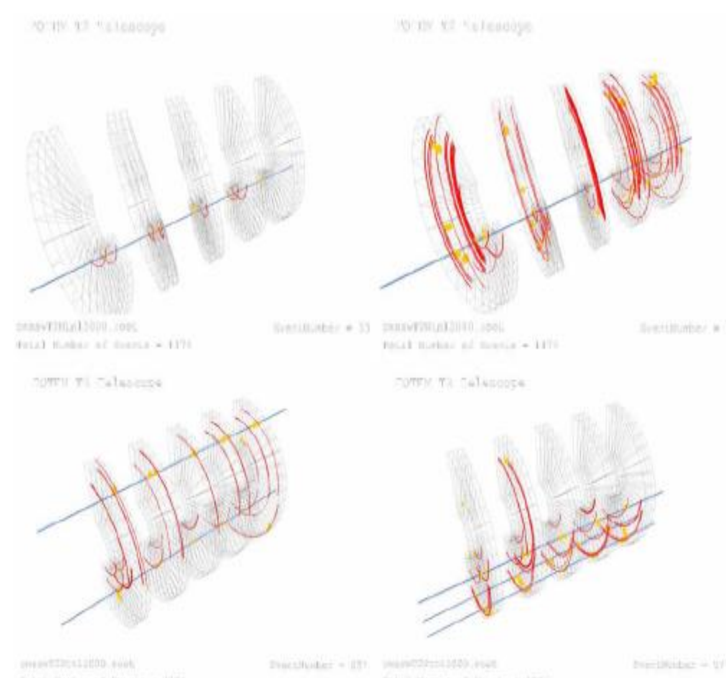
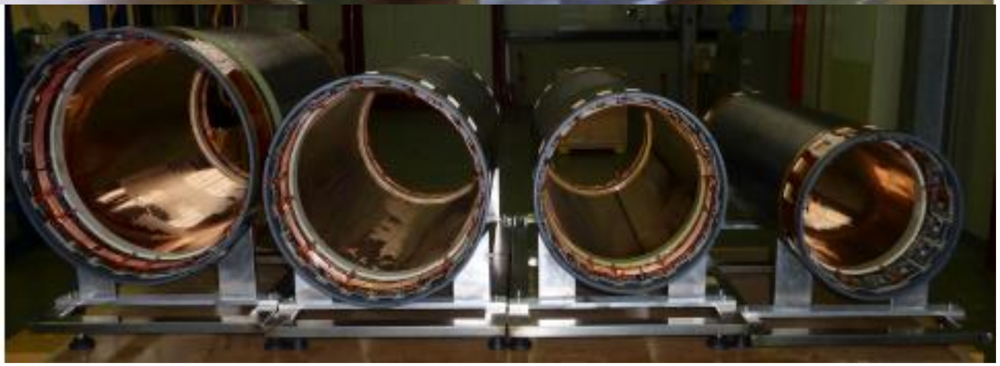


Figure 5.51: Four event of the 2009 LHC runs. One quarter is displayed. Detectors shape, hit pads (yellow blocks), hit strips (red lines) and reconstructed tracks (blue lines) are shown.

GEM applications: Inner Tracker at KLOE-2 experiment



- **Four layers of cylindrical triple-GEMs, 70 cm long;**
- **Very low mass detector!**

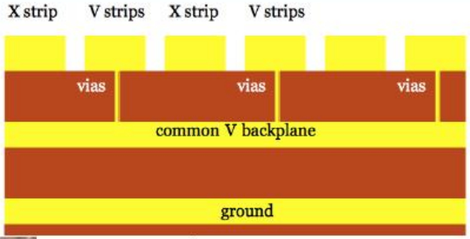
The electrodes of the IT

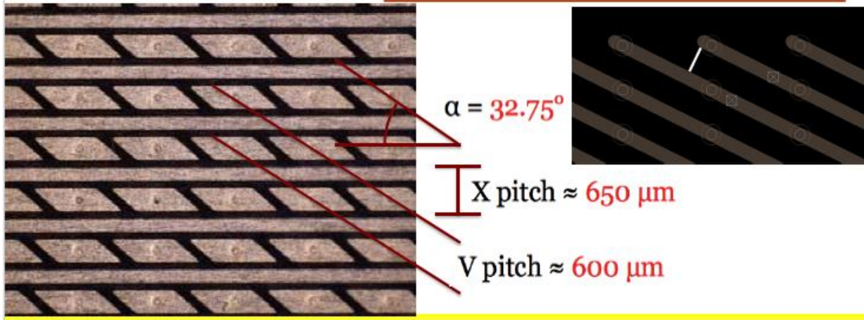
- Every layer of the Inner Tracker is a triple-CGEM composed by a cylindrical anode, 3 CGEM and a cylindrical cathode
- The dimensions of the electrodes required a **new production technique**
- The CERN TE-MPE-EM workshop (Rui de Oliveira) produced large area GEM foils (up to **350 x 700 mm^2**) using the single-mask technique (**first time for an experiment**)
- Every GEM foil is divided in 40 HV sectors (**1.5 x 70 cm^2**) on the top side and 4 HV sectors on the bottom side in order to reduce the energy of discharges
- Each cylindrical electrode is realized with the wrapping technique developed at LNF

G. Morello on behalf of KLOE-2 IT group 5

The readout of the IT

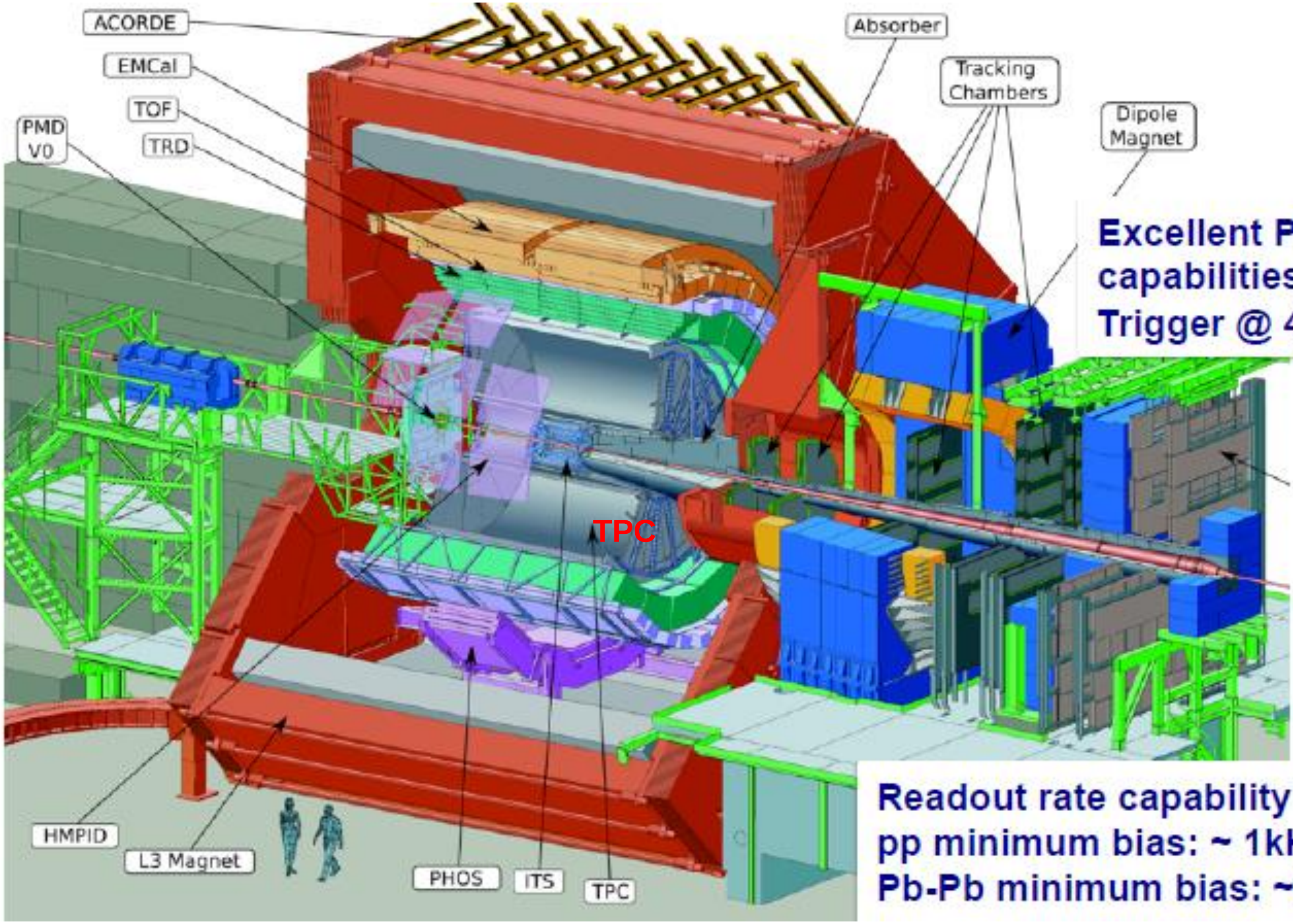
The readout of the IT is a flexible kapton/copper circuit.
The 2-dimensional view is given by the X-strips (parallel to the axis of the CGEM) and V pads connected by vias to a common backplane





G. Morello on behalf of KLOE-2 IT group 6

GEM applications: ALICE TPC



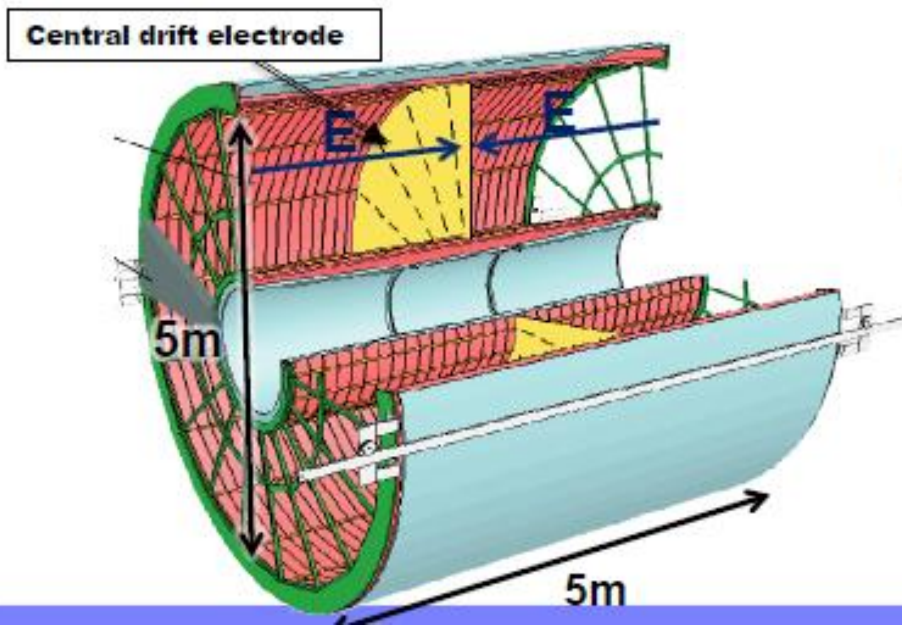
Excellent PID capabilities
Trigger @ 40 MHz

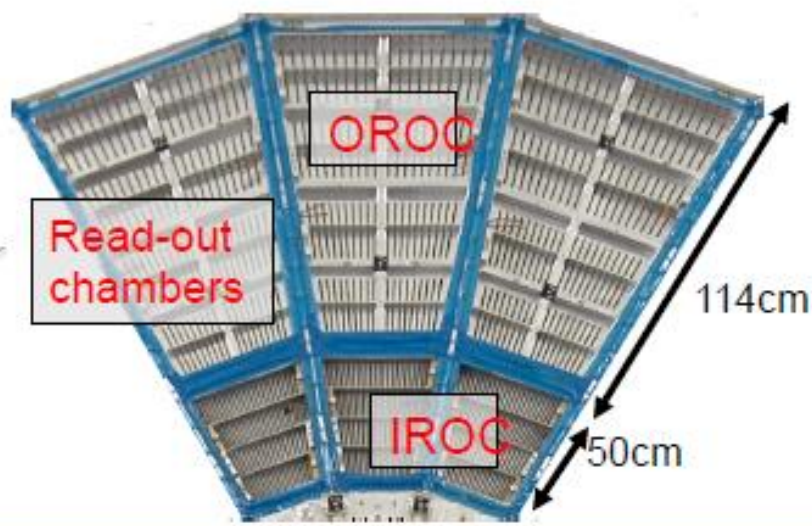
Readout rate capability
pp minimum bias: ~ 1kHz
Pb-Pb minimum bias: ~500 Hz

GEM applications: ALICE TPC

- Diameter: 5 m, length: 5 m
- Acceptance: $|\eta| < 0.9$, $\Delta\phi = 2\pi$
- Gas: Ne-CO_2 (90-10) in Run1
- Drift field = 400V/cm
  - Diffusion: $\sigma_T \approx \sigma_L \approx 0.2$ mm/$\sqrt{\text{cm}}$
  - $v_d \approx 2.7$ cm/μs, max. drift time: 92 μs

- **Read-out Chambers: Total = 36 x 2**
  - **outer (OROC): 18 x 2**
  - **inner (IROC): 18 x 2**
- **Pad sizes: 4 x 7.5 mm², 6 x 10 (15) mm²**
- **Channel number: 557 568**
- **In Run1 & Run2: MWPC + gating grid operation**
  - **Rate limitation: few kHz**

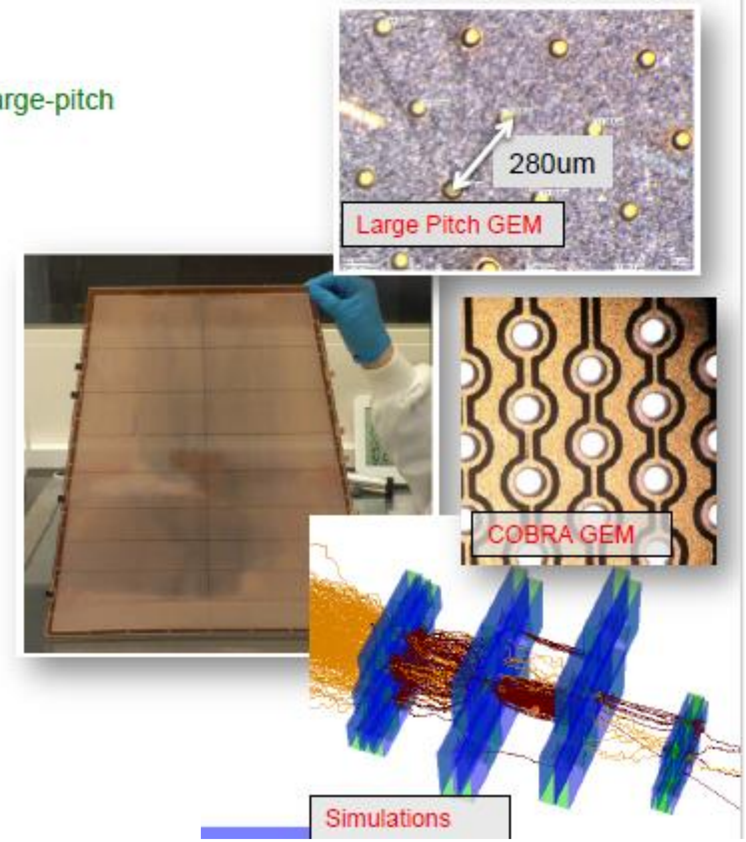




GEM applications: ALICE TPC

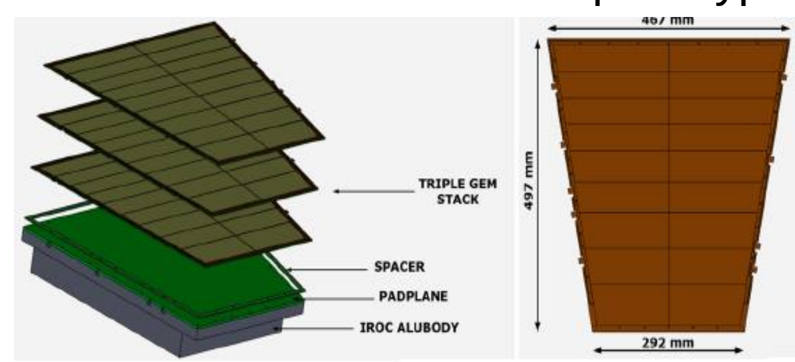
- Extensive studies started in 2012
  1. technology choice
     - Baseline: Stacks of standard (S) and large-pitch (LP) GEM foils
     - 2 GEM + MicroMegas (MMG)
     - COBRA-GEM
  2. ion backflow
  3. gain stability
  4. discharge probability
  5. large-size prototype
     - single mask technology
  6. electronics R&D
  7. garfield simulations
  8. physics and performance simulations
- Collaboration with RD51 at CERN

(e.g. meeting this week @ CERN…)



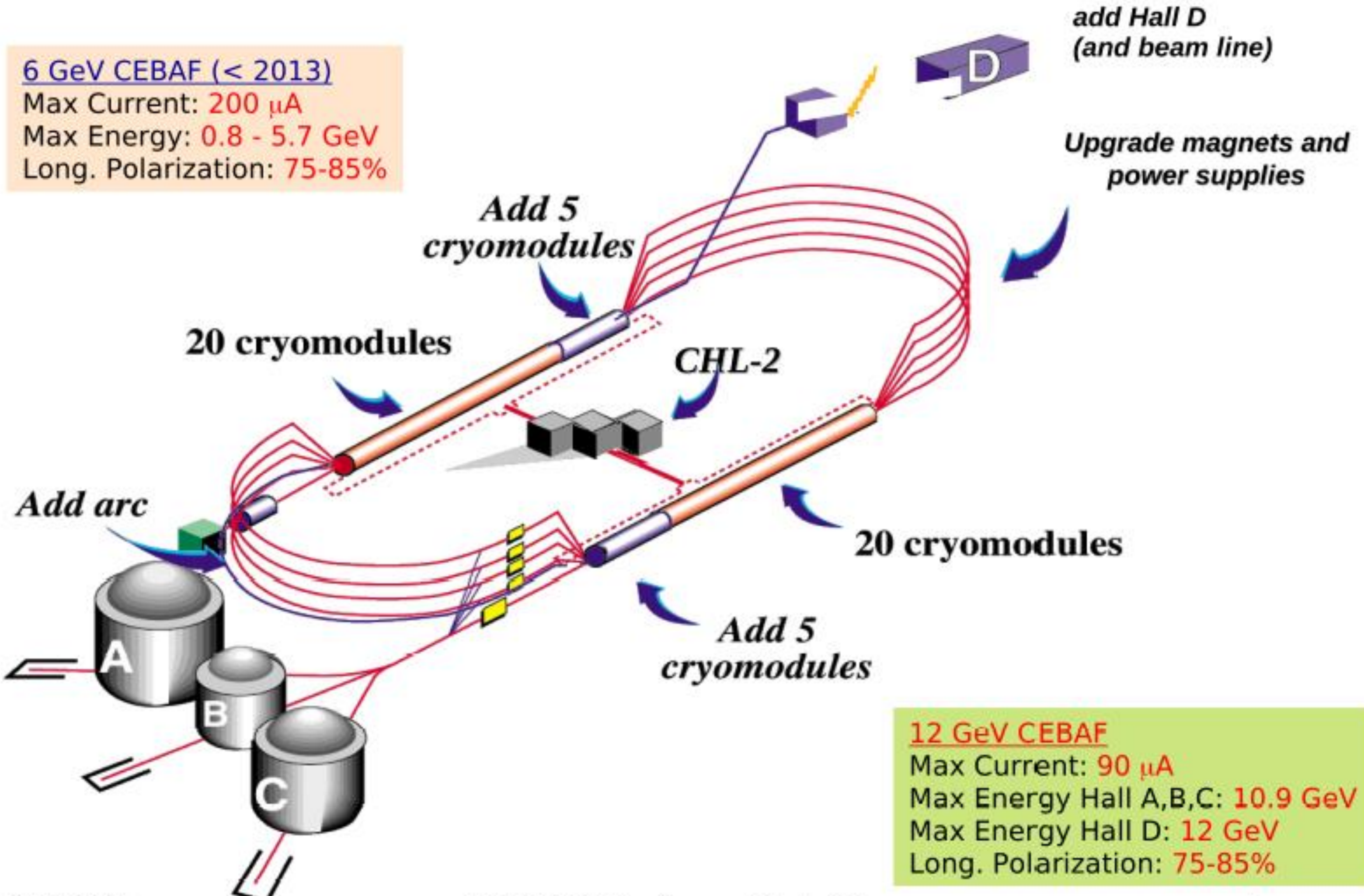
- Advantages:
  – reduced ion backflow (IBF)
  – high rate capability
  – no long ion tail
- Requirements for read-out system:
  – **IBF < 1% at gain 2000**
  – **d*E*/d*x* resolution < 12% for ^{55}Fe**
  – **Stable operation under LHC conditions**

A prototype



GEM applications: GEM trackers for SBS at JLab

The 12 GeV upgrade of CEBAF accelerator @ JLab



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GEM applications: GEM trackers for SBS at JLab

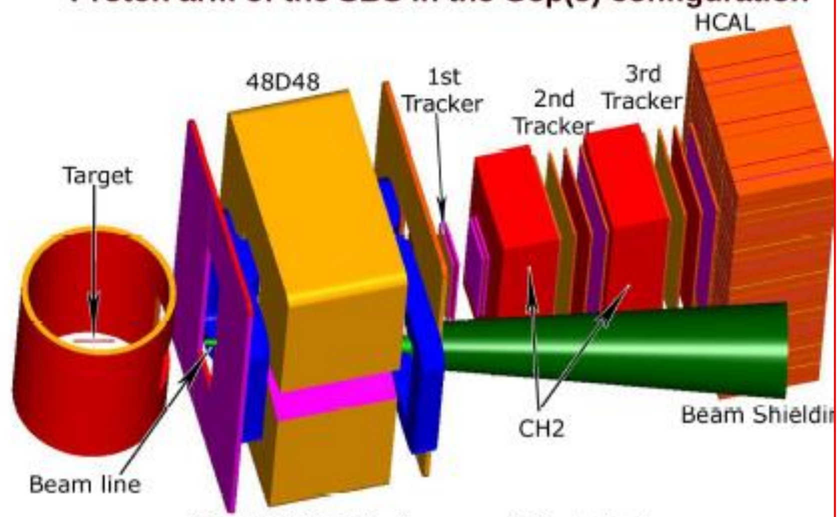
Florida Tech

Requirements for the Super Bigbite Spectrometer (SBS)

Experiments	Luminosity $(s \cdot cm^2)^{-1}$	Tracking Area (cm^2)	Resolution		
			Angular (mrad)	Vertex (mm)	Momentum (%)
GMn - GEn	up to $7 \cdot 10^{37}$	40x150 and 60x200	< 1	<2	0.5%
GEp(5) **Most demanding**	**up to $8 \cdot 10^{38}$**	40x150, 60x200 and 80x300	<0.7 ~1.5	~ 1	0.5%
SIDIS	up to $2 \cdot 10^{37}$ **High rate**	40x150 and 60x200 **Large area**	~ 0.5 **Spatial resolution < 100 microns**	~1	<1%

- Large luminosity
- Large acceptance
- Forward angles
- Re-configurable detectors
- Polarized Proton Target

Proton arm of the SBS in the Gep(5) configuration

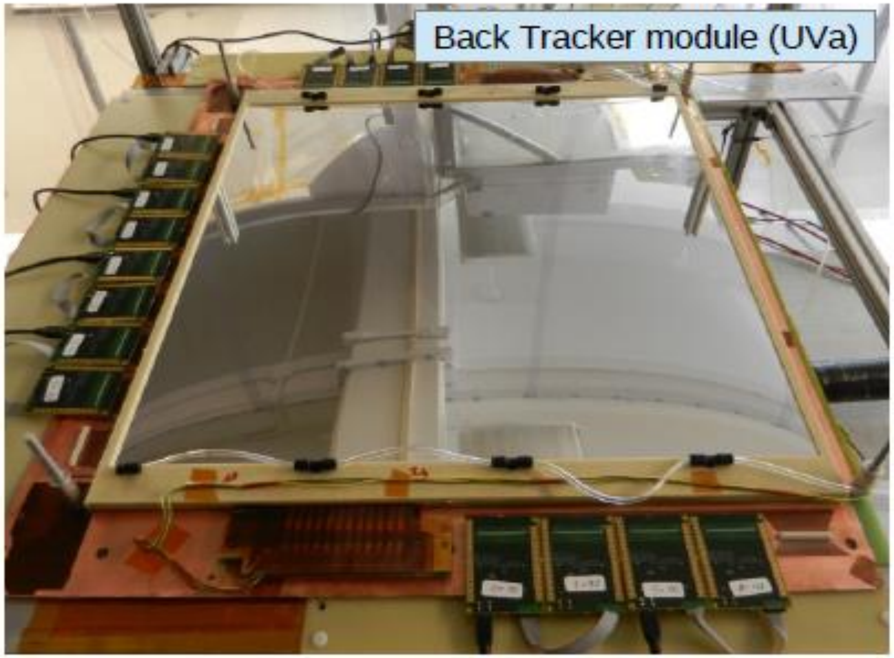


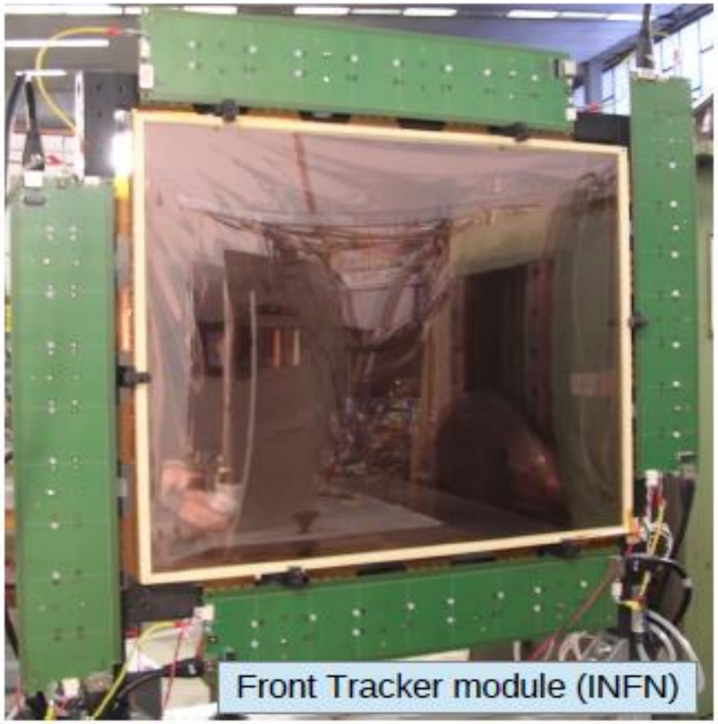
- Front Tracker (FT): Track of the recoil protons
  - 1st tracker: 6 GEM layers, active area of 150×40 cm^2
  - Each layers: vertical stack of 3 GEM modules (50×40 cm^2)
  - Total production of 18 modules
- Back Tracker (BT): Proton Polarimetry
  - Polarization of the recoil protons
  - 2nd & 3rd Trackers: 10 layers, active area of 200×60 cm^2
  - Each layer: vertical stack of 4 GEM modules (60×50 cm^2)
  - Total production of 40 (+ 5) modules

Florida Tech

SBS GEM modules

- Spatial resolution < 0.1 mm; high radiation tolerance
- Lightweight triple-GEM detectors (0.7% radiation length)
- Readout layer: 2D x/y strip ala COMPASS (0.4 mm pitch)
- APV25-based electronics with VME64x modules (total channels > 120K channels)





K. Gnanvo et al. Nucl. Inst. and Meth., A782, 77-86 (2015)

GEM applications: GEM trackers for SBS at JLab

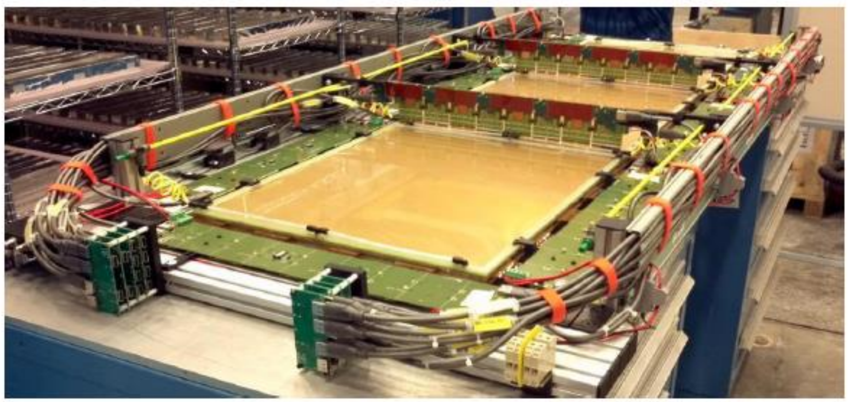
Florida Tech

Production Status

Carbon fiber Holding frame
More compact and more rigid option
minimize thermal deformation

Front Tracker GEMs

- 18 modules to be completed by mid 2017
- 8 modules already assembled with 4 tested
- One full layer integrated with APV25 cards @ JLab
- 4 layers expected by end 2016



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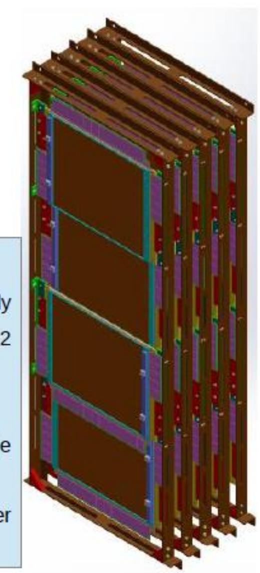
Production Status

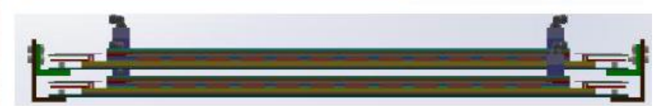
Back Tracker GEMs

- 45 modules to be completed by mid 2017
- Production rate of 2 modules / month
- 19 modules successfully tested as of Oct. 2015

Holding frame:

- 4 modules: 2 modules sitting directly on the frame (bottom plane), other 2 modules on L-shape (top plane)
  - This minimizes dead area
  - And allow easy replacement of the modules and of the FE cards
- The holding frames are under production @ JLab





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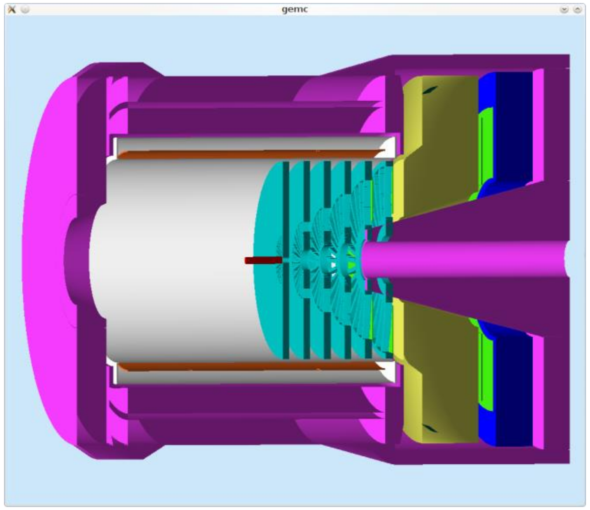
GEM applications: GEM trackers for SOLID at JLab

Tracking needs for SoLID (PVDIS)

SOlenoidal **L**arge **I**ntensity **D**evice

- Rate: from 100 kHz to 600 kHz (with baffles), GEANT4 estimation
- Spatial Resolution: ~0.2 mm (sigma)
- Total area: ~37 m^2 total area (30 sectors x 5 planes, each sector covering 12 degree)
- Need to be radiation and magnetic field tolerant



PVDIS GEM configuration

- Instrument locations 1,2,3,4, and 5 GEM:
- 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

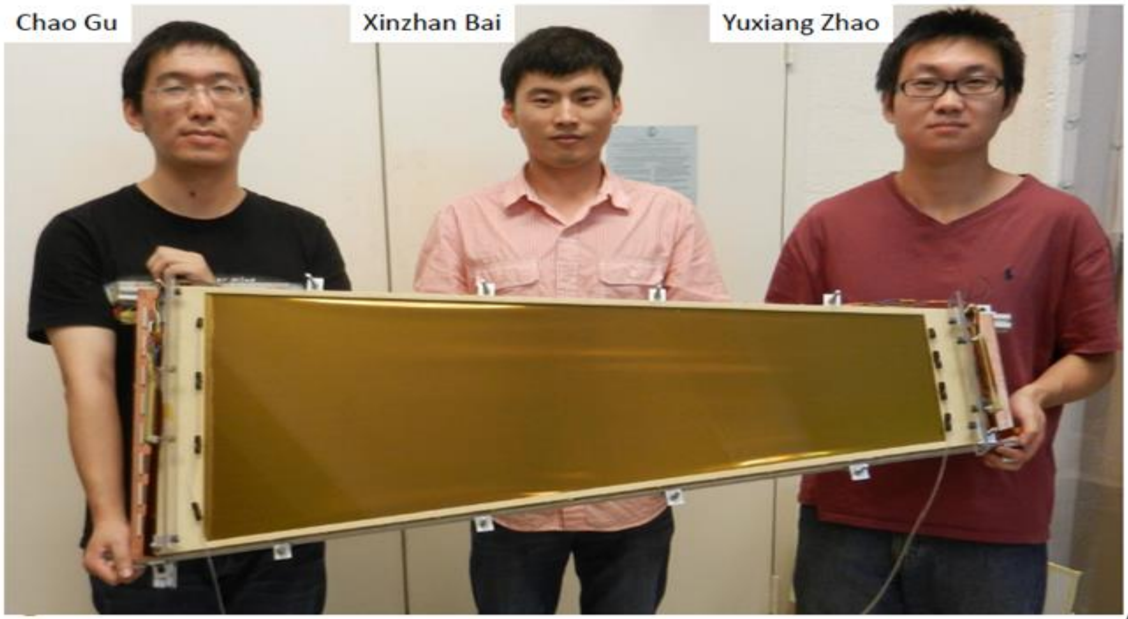
Largest GEM module size required: 113 cm x (21-44) cm

With ~5% spares, we will need about 170 k readout channels.

GEM applications: GEM trackers for SOLID at JLab

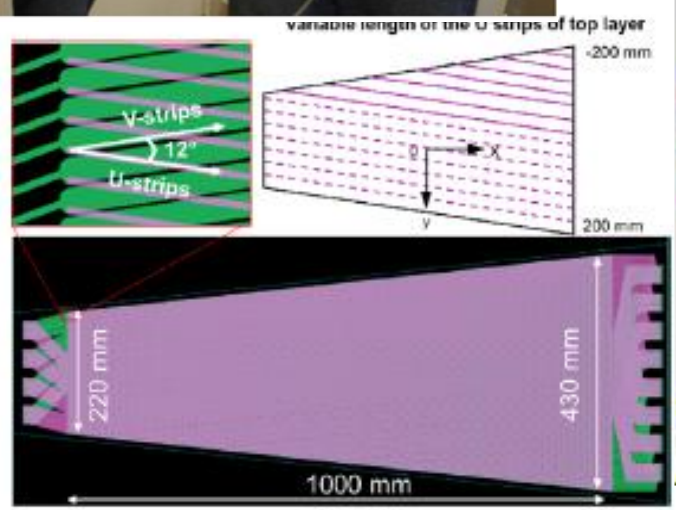
The first prototype

The "real" SoLID-GEM Chinese collaboration

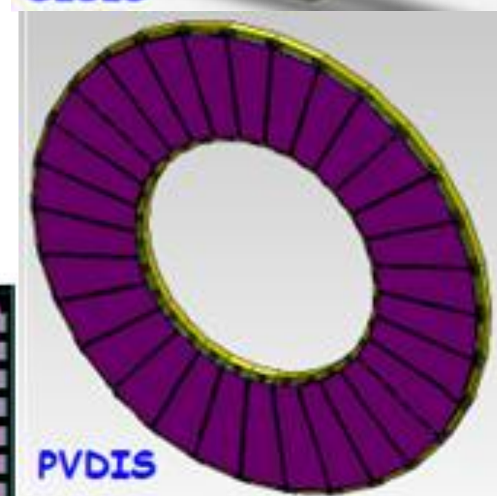


(a)

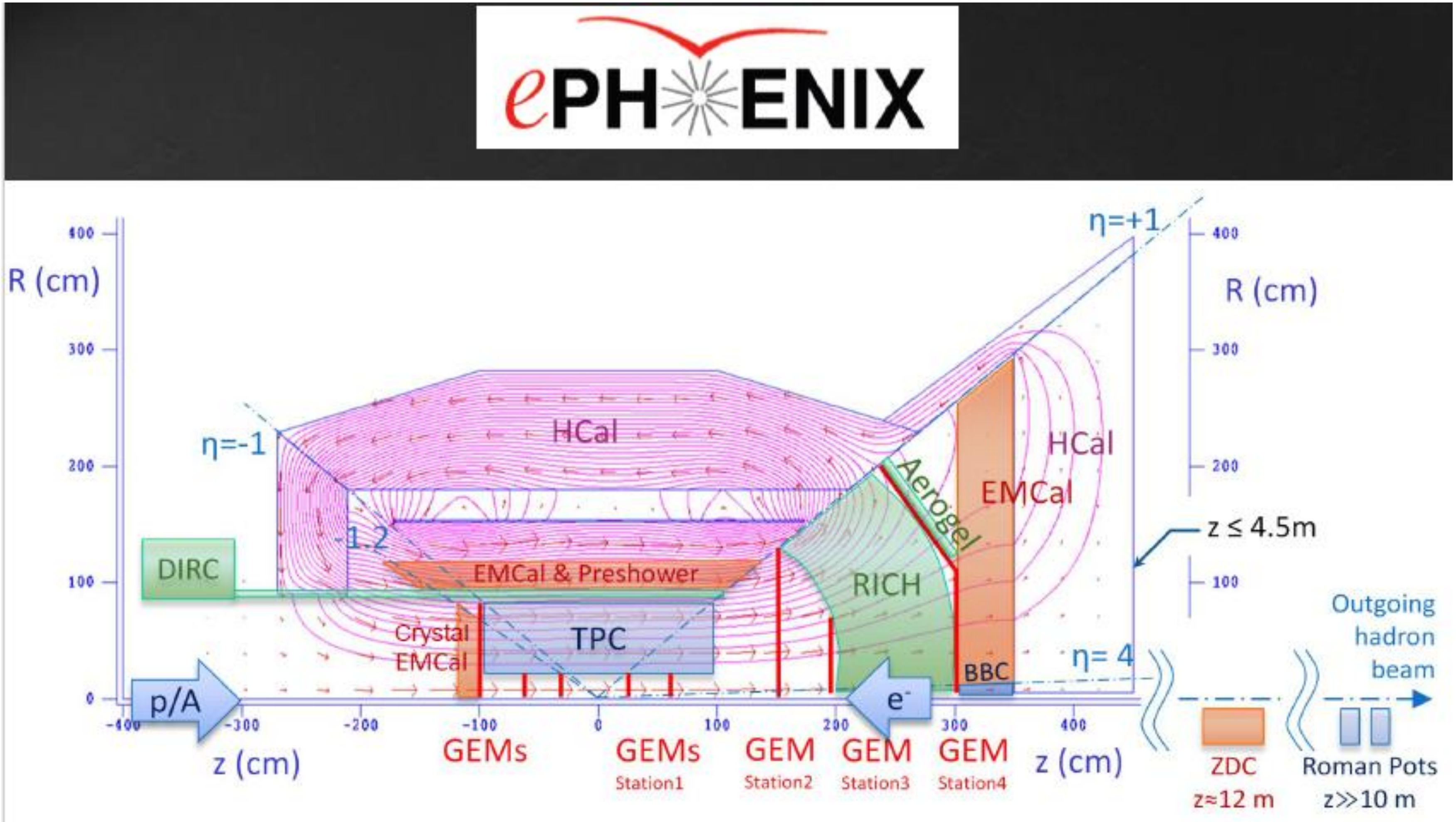
GEM foil



2D U-V strip readout



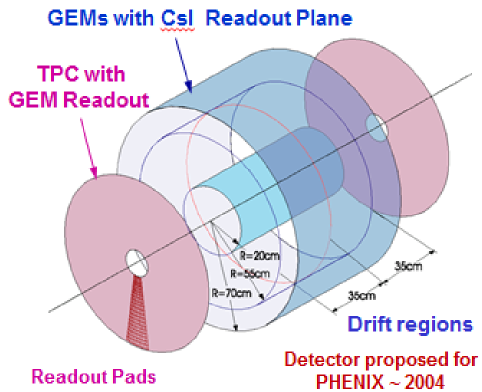
GEM applications: Forward Tracking, TPC for RHIC, ePHENIX, Electron Ion Collider



GEM applications: Forward Tracking, TPC for RHIC, ePHENIX, Electron Ion Collider

Florida Tech

Particle ID Using the Central TPC



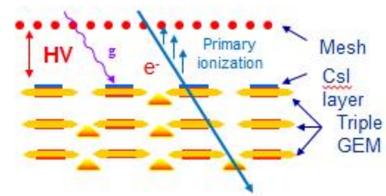
- TPC provides momentum measurement and particle id through dE/dx. Use ionization in gas volume to measure track trajectory.
- Use Cherenkov light produced in the *same* gas volume to identify electrons
  ⇒ HBD concept

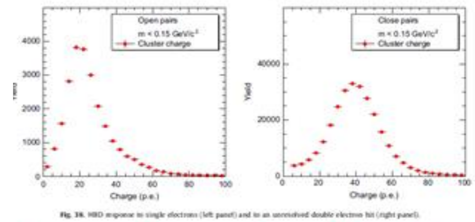
  Acts as a threshold counter (no other particle id)

- Gas must be transparent to UV light ⟶ CF_4 (like HBD)
- Want fast drift velocity (⟶ CF_4 or mixtures containing CF_4)
- Photosensitive GEM must operate near the HV plane of the field cage. Field cage must be optically transparent on its outer radius and take up minimal radial space.

The PHENIX HBD

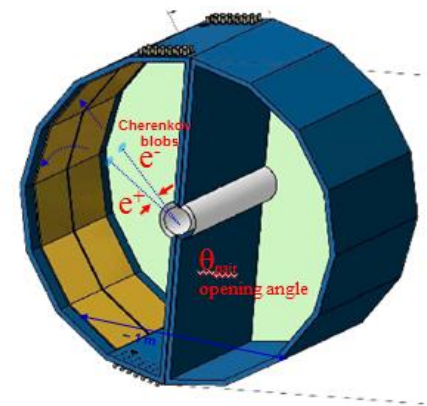
Proximity Focused Windowless Cherenkov Detector





Discriminated between single and double electrons using pulse height from Cherenkov light

Radiator gas = Working gas
Gas volume filled with pure CF_4 radiator



W.Anderson et al., NIM A646 (2011) 35-58

N_0 = 322 cm^{-1}

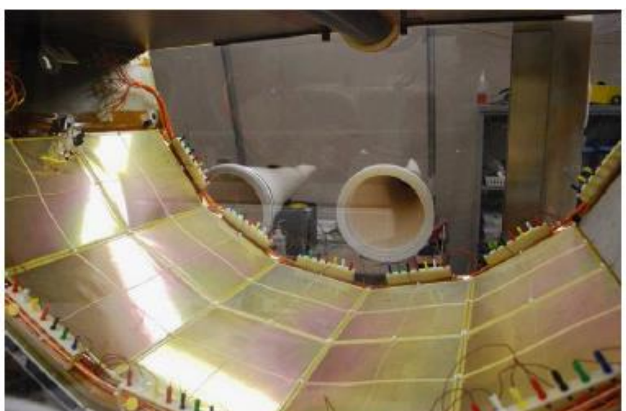


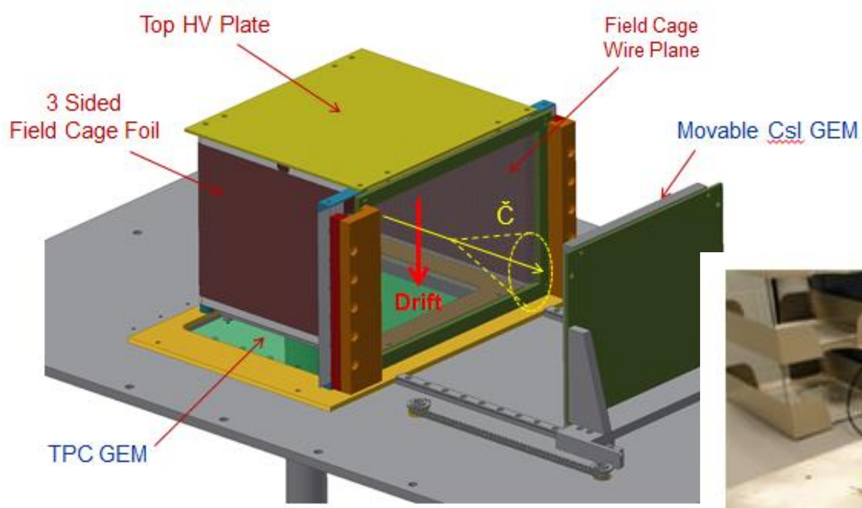
Fig. 11. A complete HBD in the glovebox following installation of all photocathodes and meshes. The lucite device in the upper left is the scintillation cube, placed outside the acceptance of PHENIX and used to monitor quantum efficiency in situ and over time (see Section 3.6).

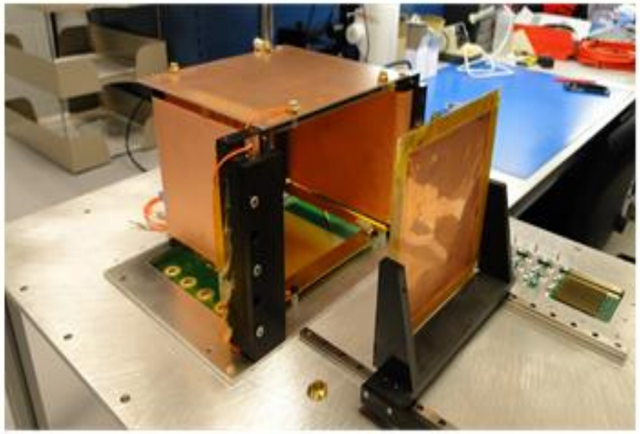
Table 1
Design parameters of the HBD.

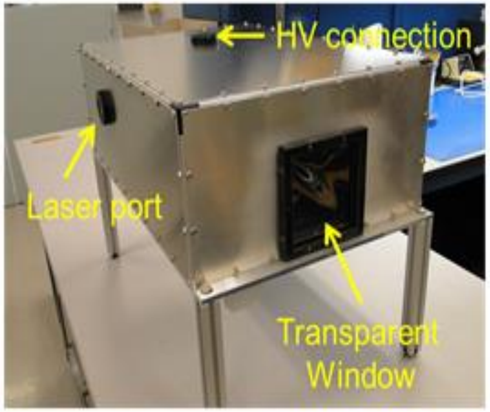
Acceptance	$\|\eta\| \le 0.45$, $\Delta\phi = 135°$
GEM size ($\phi \times z$)	23×27 cm^2
GEM supporting frame and cross ($w \times d$)	Frame: 5×1.5 mm^2, cross: 0.3×1.5 mm^2
Hexagonal pad side length	$a = 15.5$ mm
Number of pads per arm	1152
Dead area within central arm acceptance	7%
Total radiation length within central arm acceptance	2.40%
Weight per arm (including HV and gas connectors)	< 10 kg

GEM applications:
Forward Tracking, TPC for RHIC, ePHENIX, Electron Ion Collider

3D Detector Model







- Three sided field cage allows for installation of a fourth foil side or a wire frame that allows passage of Cherenkov light to the photosensitive GEM detector
- Photosensitive GEM is mounted on a movable stage to allow varying its position relative to the TPC detector

Quintuple-GEM based RICH detector

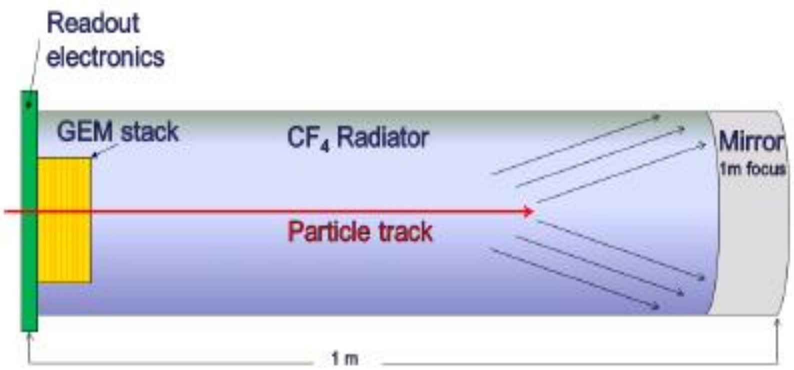
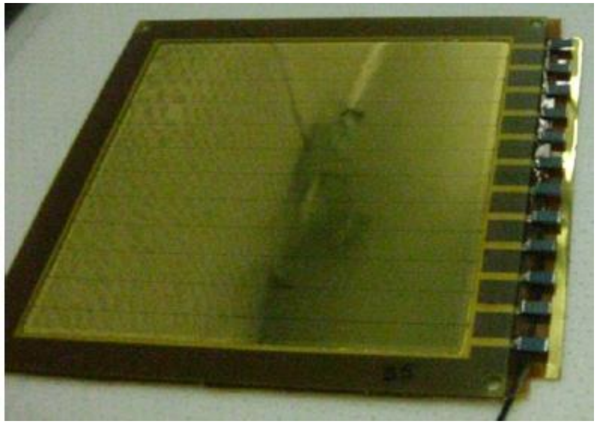
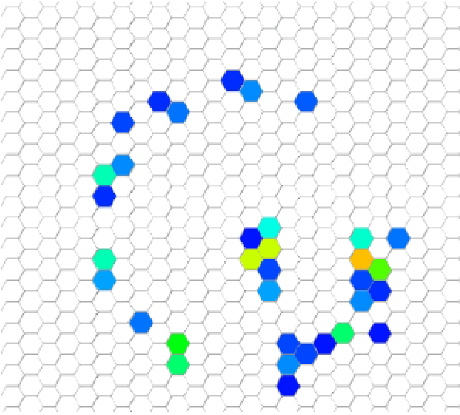
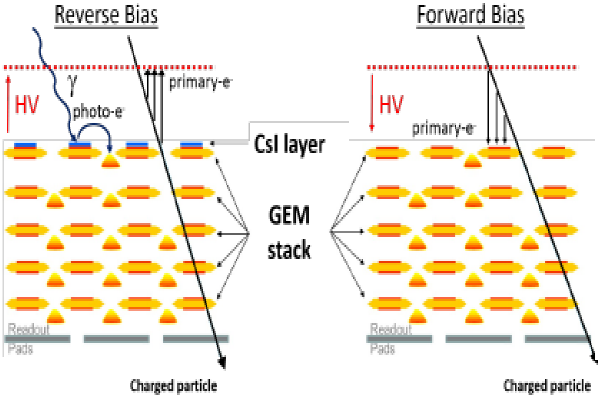


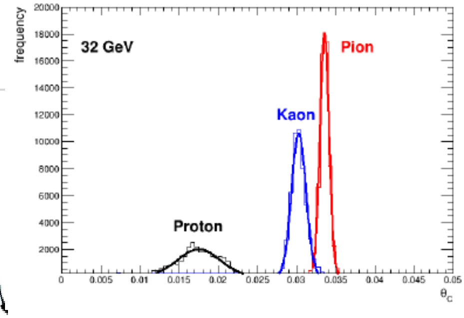
Fig. 3: Schematic diagram of the RICH detector prototype setup.

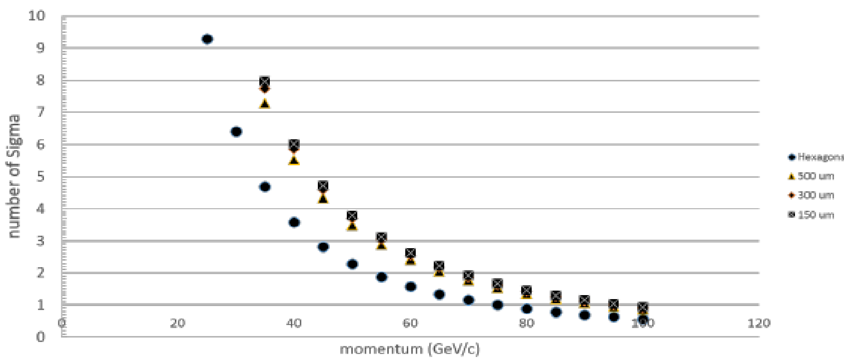
Fig. 4: Photograph of the RICH detector prototype setup.





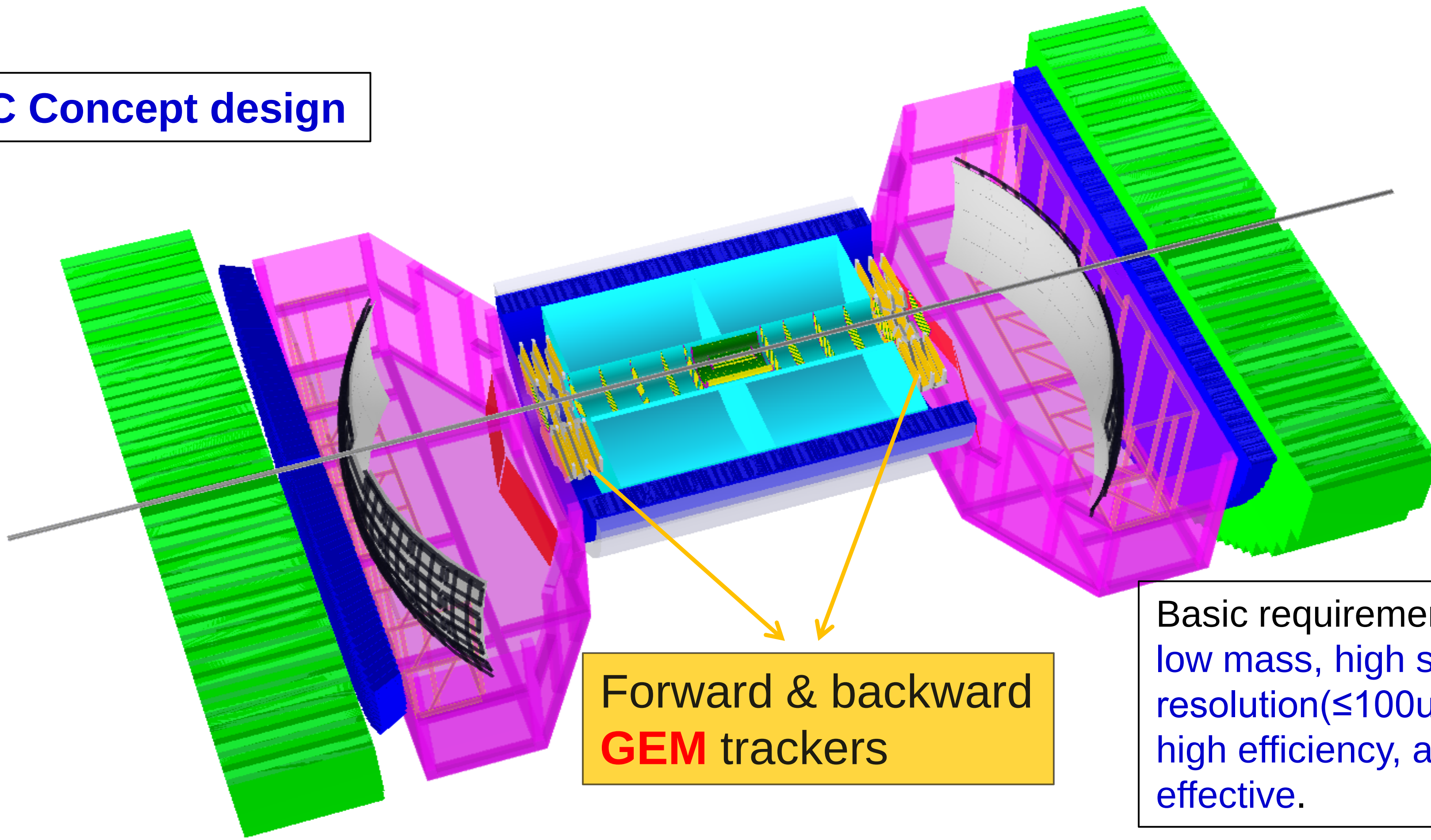






GEM applications: Forward Tracking, TPC for RHIC, ePHENIX, Electron Ion Collider

EIC Concept design

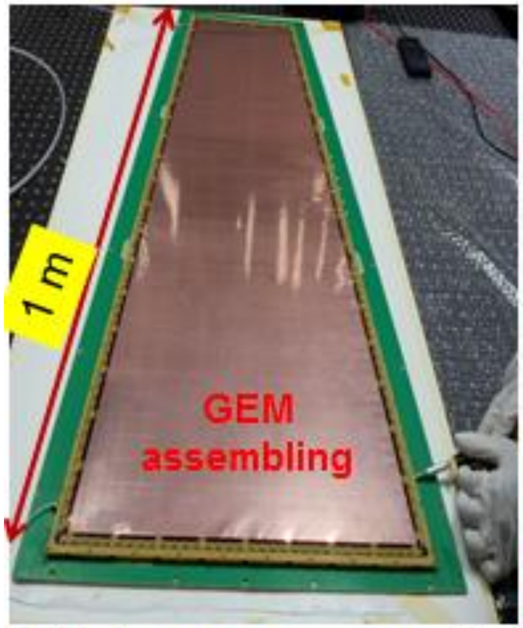


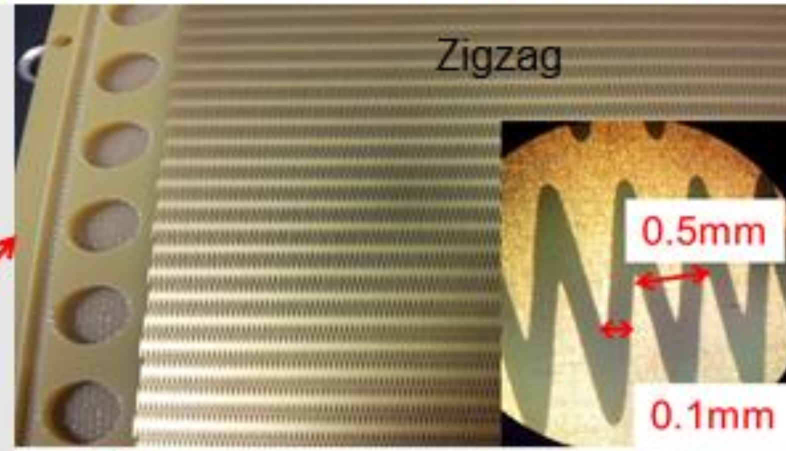
Forward & backward **GEM** trackers

Basic requirements:
low mass, high spatial resolution(≤100um), high efficiency, and cost effective.

GEM applications: Forward Tracking, TPC for RHIC, ePHENIX, Electron Ion Collider

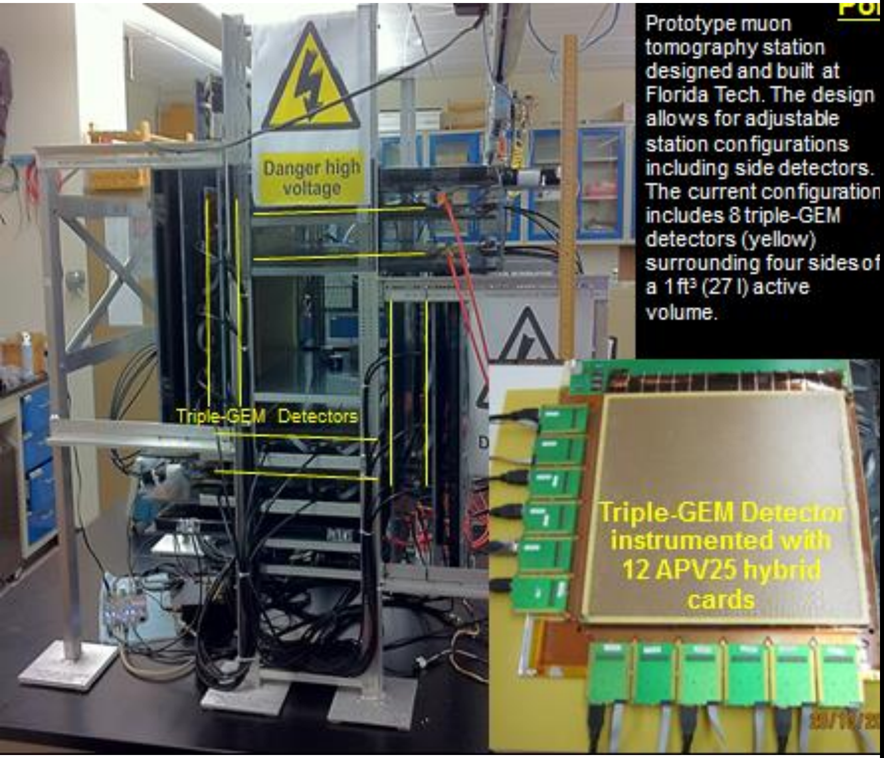
- **The FIT group** has assembled and tested a 1-m long triple-GEM detector equipped with **zigzag read strips**. Using of zigzag strips reduces channel number and cost!

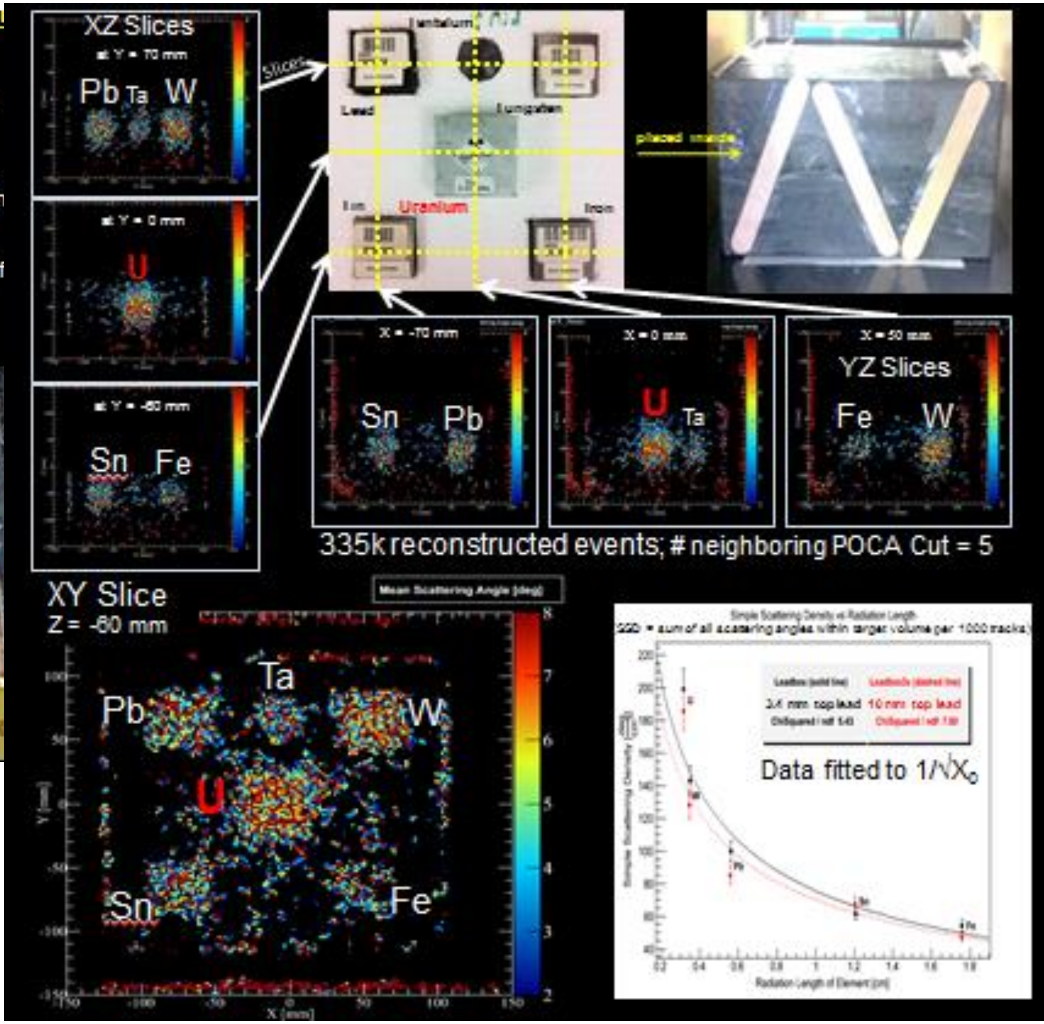




GEM detector was assembled using the **mechanical stretching method** pioneered by the CMS GEM collaboration.
Zigzag strips run radially, at radius from ~1.6 m to 2.6m, strip angle pitch 1.37 mrad. An angular resolution of ~190 urad (or 369 um at R=1.87m) was achieved for this prototype.

Ref. **NIMA 811 (2016) 30-41**





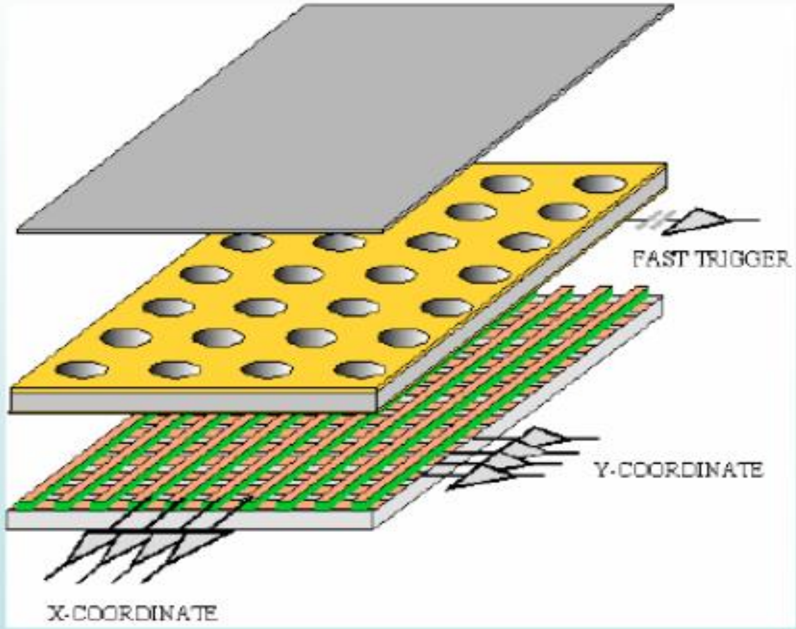
Muon Tomography System at Florida Tech, 8 triple-GEM detectors (30 cm by 30 cm).

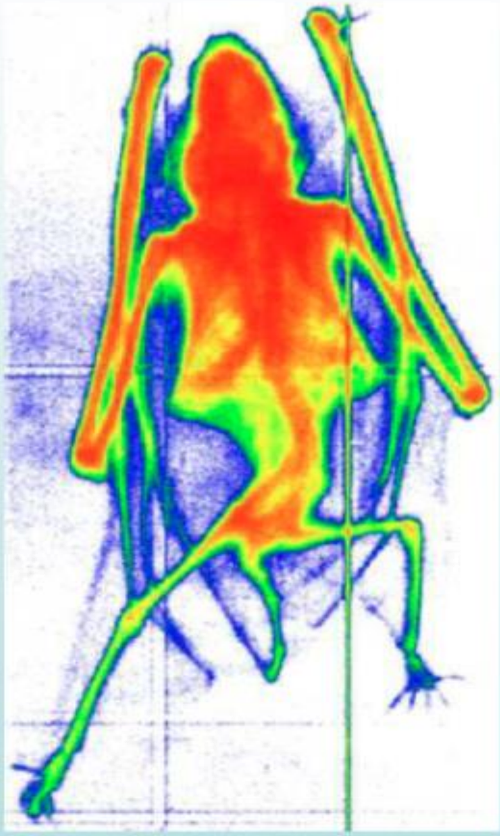
Other GEM applications: Irradiation Imaging

DIGITAL RADIOGRAPHY WITH GEM DETECTORS:

QuickTime™ and a
GIF decompressor
are needed to see this picture.

2-D READOUT





RADIOGRAPHY OF A SMALL MAMMAL (A BAT)

Other GEM applications: Neutron detectors

Fast neutron detection

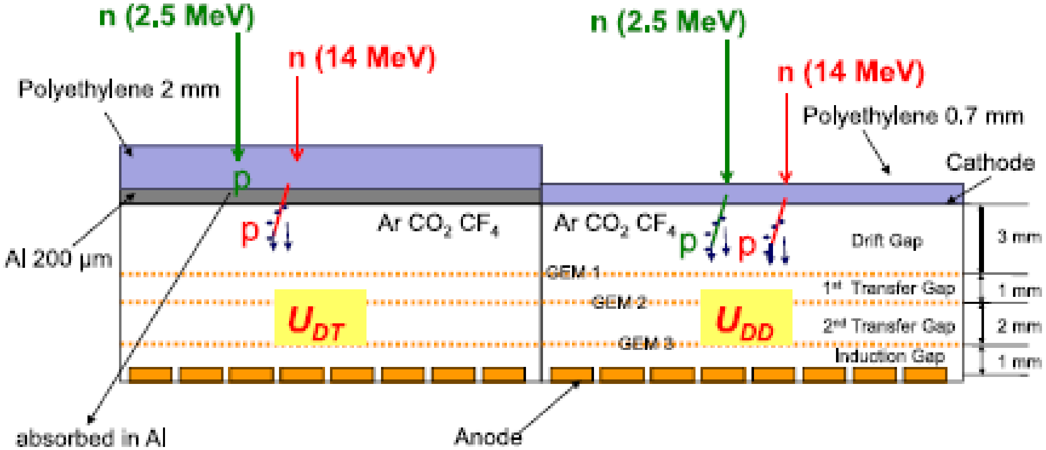
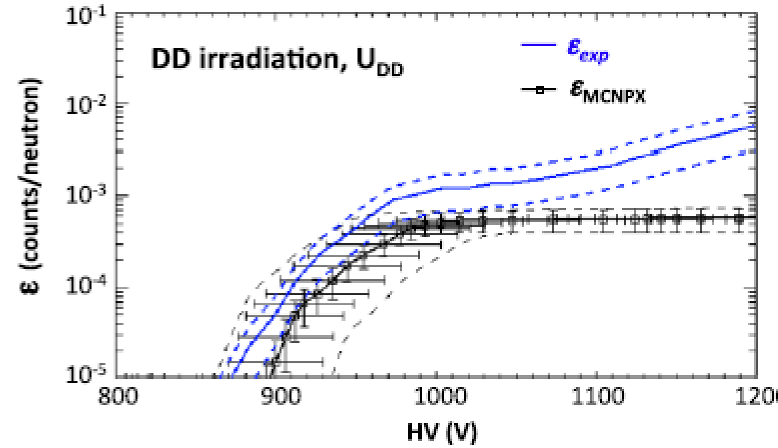
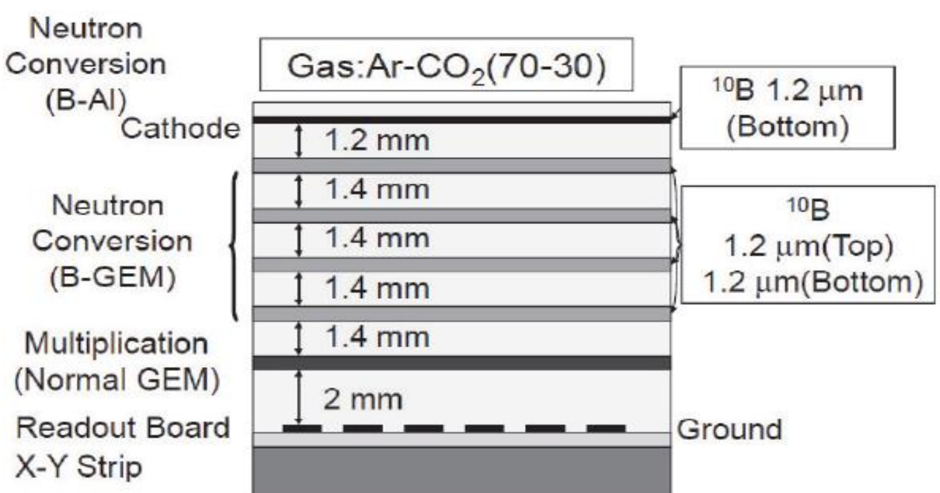
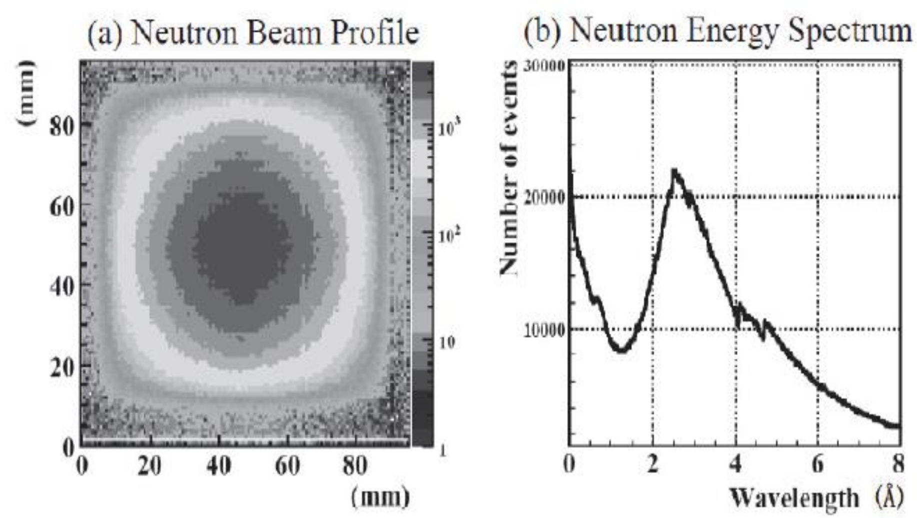


Fig. 1. Scheme of the triple-GEM neutron detector.



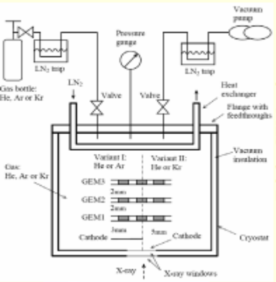
Thermal neutron detection

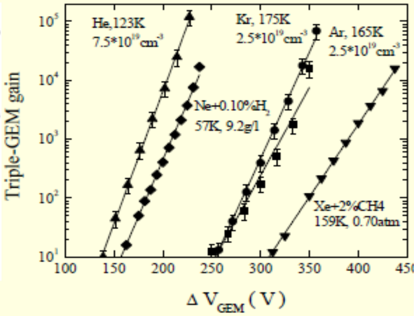




Other GEM applications: Two phase avalanche detectors

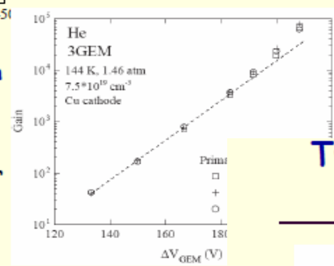
Gaseous cryogenic avalanche detectors based on GEMs





3GEM operation at cryogenic T at different fluxes
- No charging-up effects were observed in He, even at fluxes as high as 10^6 e/mm^2 s

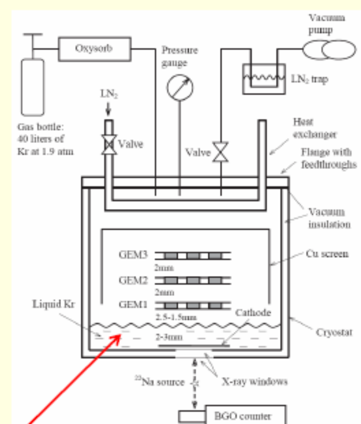
3GEM operation at cryogenic T in different gases
- Rather high gains are reached at cryogenic T: the maximum gain exceeds 10^5 in He and 10^4 in Ar, Kr and Xe+CH$_4$



Experimental setup
- Operated in He, Ar, Kr and Xe
- 2.5 l cryogenic chamber

Alexei Buzulutskov, Detector Development Symposium, SLAC, Apr 6, 2006

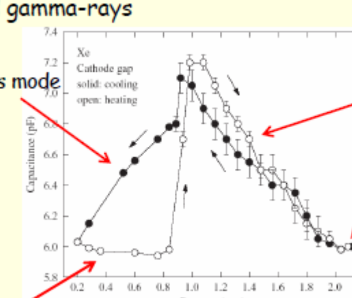
Two-phase avalanche detectors based on GEMs: experimental setup



Liquid layer thickness 3-12 mm

- *Developed at Budker Institute*
- 2.5 l cryogenic chamber
- Operated in Ar, Kr and Xe
- Liquid thickness 3-11 mm
- Liquid purity: electron drift path about 10 mm in Ar, 3 mm in Kr and 1 mm in Xe
- 3GEM+PCB assembly inside
- Irradiated with pulsed X-rays, beta-particles and gamma-rays

Solid-gas mode



Liquid-gas mode

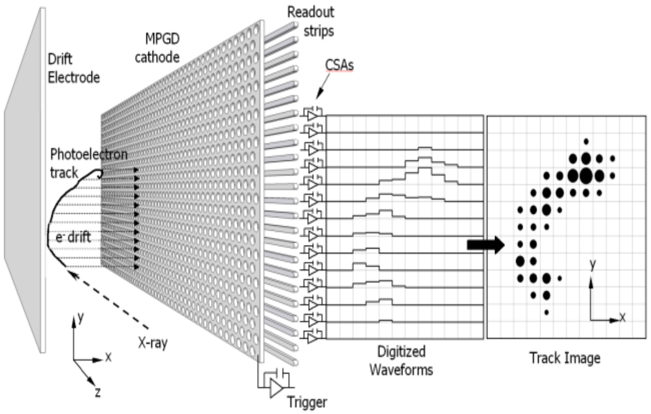
Gaseous mode

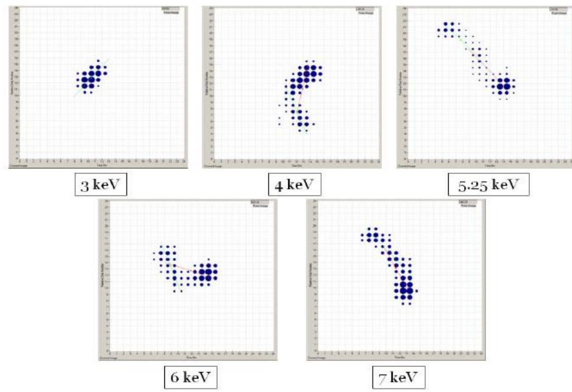
Gaseous mode

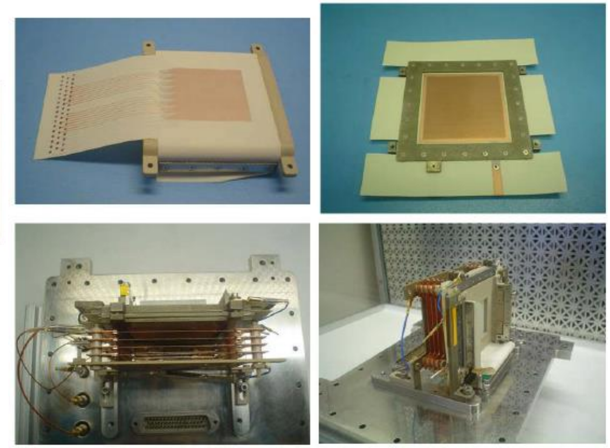
Cathode gap capacitance as a function of pressure in Xe during cooling-heating procedures

Alexei Buzulutskov, Detector Development Symposium, SLAC, Apr 6, 2006 8

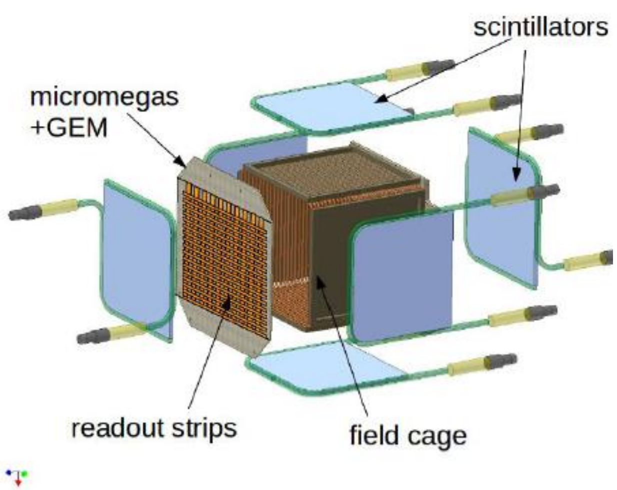
Negative Ion TPC X-ray polarimeter







TPC for High-energy Astrophysics and Polarimetry from MeV to GeV



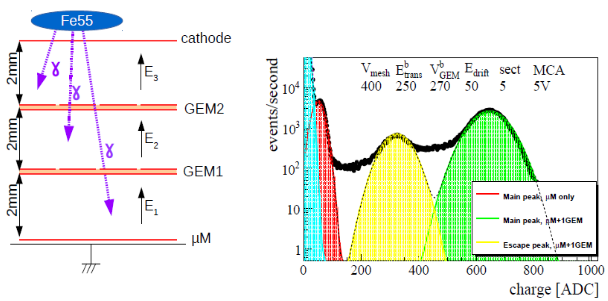


Figure 3: Left: layout of the test setup, with one micromegas and two GEMs. By applying a null or inverted voltage to the top GEM, we only observe conversion in the two lower regions. Right: example of measured ^{55}Fe spectrum with amplification with one micromegas and one GEM. We see the main peak (5.9 keV) after amplification with only the micromegas (in red) or with both micromegas and GEM (in green). The escape peak is only visible with full amplification (in yellow).

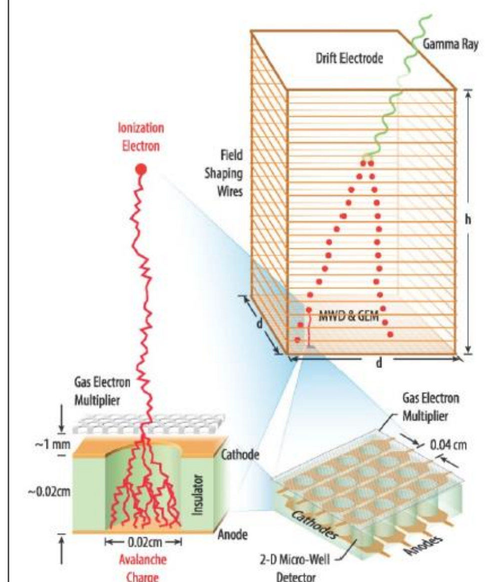


Figure 2 - Schematic of the 3-DTI TPC technology showing how electron-positron pairs are tracked in 3-D. Components of the time projection chamber, micro-well detector plus GEM, and an avalanche in a single well are identitifed.

A Pair Production Telescope for Medium-Energy Gamma-Ray Polarimetry

Summary

- GEM detectors have been successfully applied in many aspects of fields.
- It is anticipated that GEM detectors, as well as other Micro Pattern Gaseous Detectors (MPGDs) will be continued used in future experiments.
- Glad to see that Chinese groups are involved in GEM foil manufacturing and in different applications!

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Disclaimer: this reference list may be not complete in the sense of reflecting all GEM related studies and applications, the speaker hereby respect and thanks to all the hard work that has been done by others on GEM detectors.

Thank you for your attention!