GEM Detectors for COMPASS

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Solid State Detectors Seminar

Outline

- The COMPASS experiment
- Gas Electron Multiplier basics
- Discharge studies
- Design of COMPASS GEM detectors
- Construction
- Quality control
- Readout electronics
- Performance in the beam
- Summary and Outlook

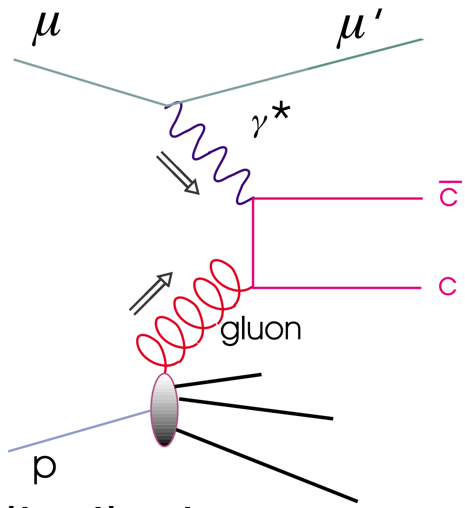
The Physics Program

CO mmon M uon and P roton A pparatus for S tructure and S pectroscopy

Muon beam

- Gluon polarization $\Delta G/G$

Photon-gluon fusion

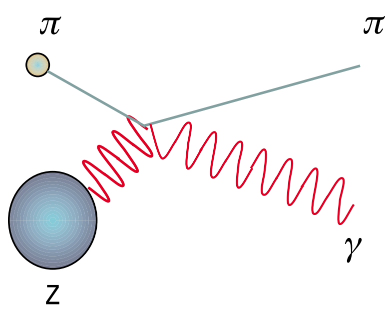


- Longitudinal and transversal spin distribution
- Polarization of Λ and $\overline{\Lambda}$

Hadron beam

- Study of charm hadrons
- Study of hadron structure with virtual photons

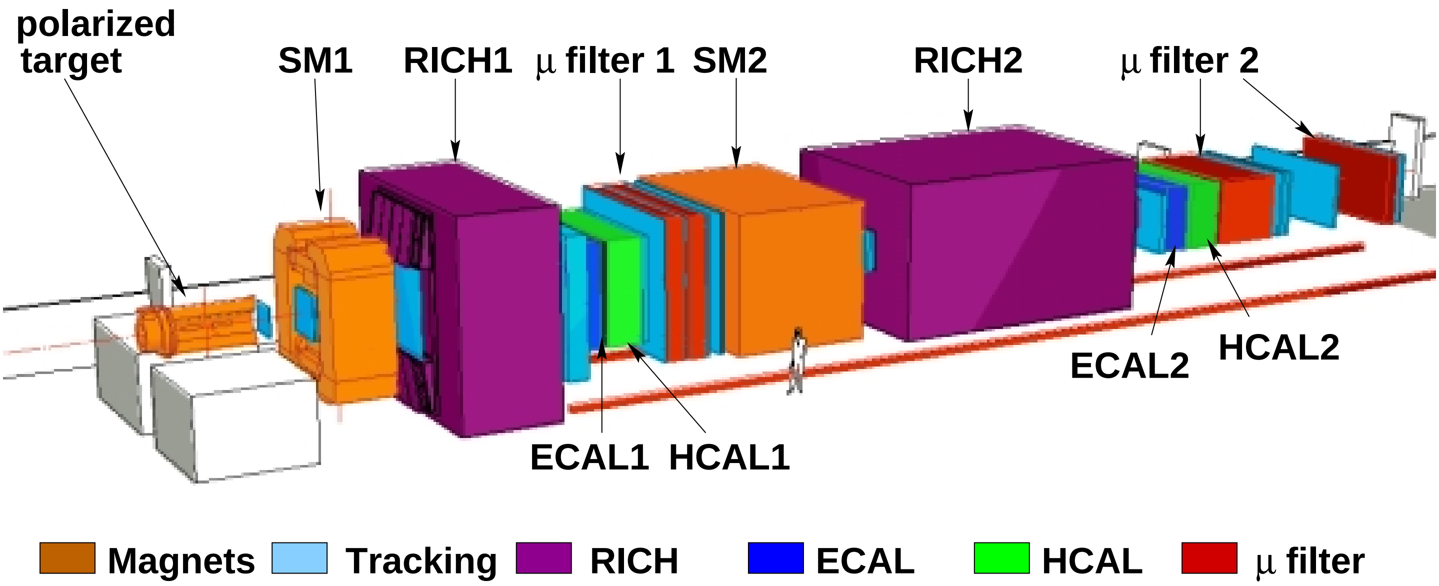
Primakoff scattering



- Exotic hadrons (glueballs, hybrids)

The Spectrometer

Fixed target experiment at the SPS of CERN



Target:	Polarized ^{6}LiD, liquid hydrogen, active charm target	
Tracking:	large area	small area
before SM1	Drift chambers	Micromegas, Si, SciFi
after SM1	Straws, MWPC	GEM, Si, SciFi
Particle Id:	2 RICH with MWPC + CsI photocathode pads	
	RICH 1	C_4F_{10}
	RICH 2	C_2F_6 + Ne
Calorimetry:	electromagnetic, hadronic	
	ECAL	lead glass + $PbWO_4$
	HCAL	lead/scintillator
Muon Id:		
	Muon filter walls	concrete + iron
after walls	Drift tubes ($\phi\,3\,\mathrm{cm}$)	
after 2nd wall	Scintillator hodoscopes	

Tracking

Beam parameters	Muon beam μ^+,μ^-	Hadron beam p, K, π
$x \times y$ (RMS) (mm^2)	7.8×7.8	1.5×1.1
$x' \times y'$ (RMS) (mrad)	0.4×0.8	0.29×0.48
Momentum (GeV/c)	100–200	270–300
Flux (per spill)	1.8×10^8	10^8

Trigger rates

Muon program $10\,\mathrm{kHz}$

Hadron program $10 - 100\,\mathrm{kHz}$

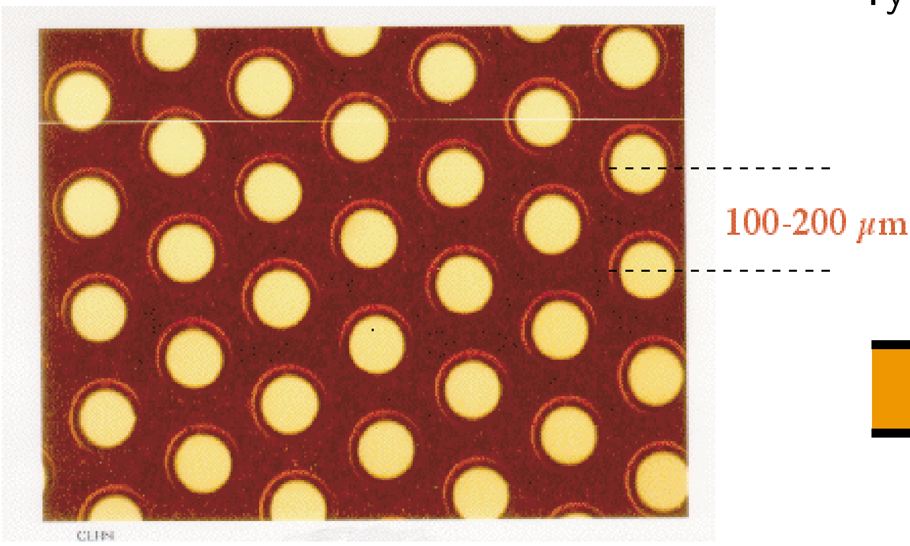
Requirements for Small Area Trackers

- High rate capability
- High spatial resolution
- Large active area
- "Massless detectors"

$\Rightarrow$ Micropattern gas detectors

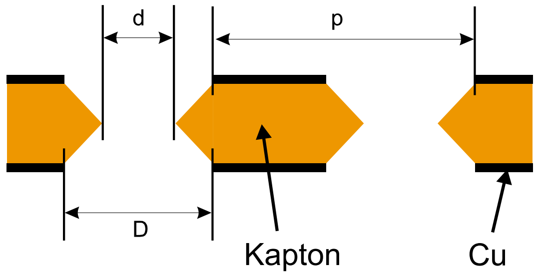
Micromegas	12	muon program
GEM	20	hadron + muon program

GEM – Principle



Typical dimensions:

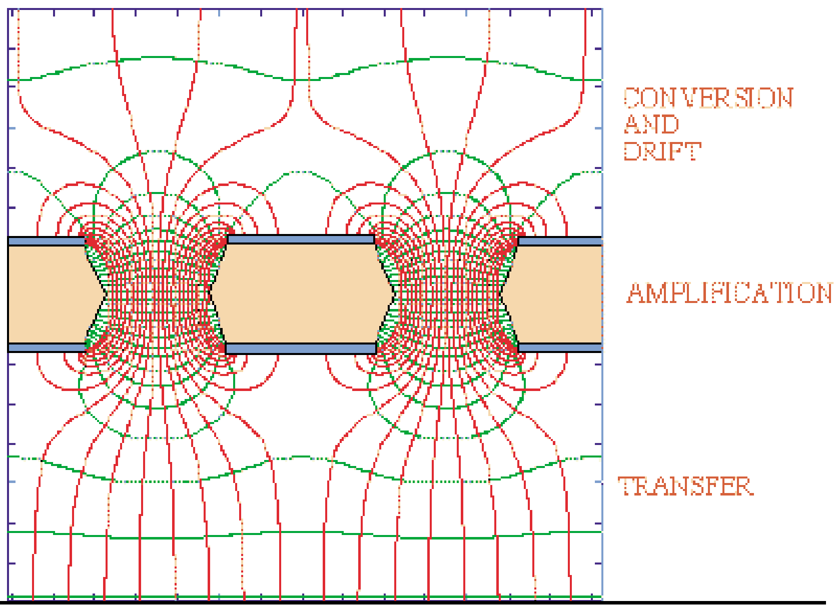
$$
\begin{aligned}
D &= 70\,\mu\mathrm{m}\\
d &= 60\,\mu\mathrm{m}\\
p &= 140\,\mu\mathrm{m}
\end{aligned}
$$



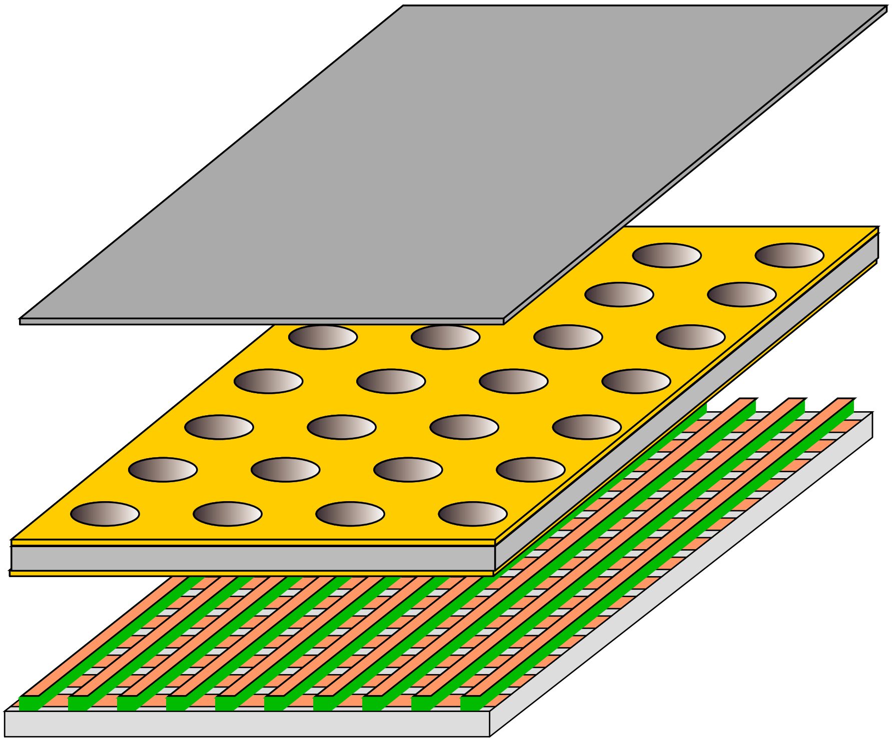
Gas Electron Multiplier [F. Sauli, NIM A386, 531 (1997)]

- Thin polymer (Kapton) foil, typ. $50\,\mu\mathrm{m}$ thick
- Metal-clad on both sides, typ. $5\,\mu\mathrm{m}$ Cu
- Perforated by large number of holes, typ. $10000/\mathrm{cm}^2$: photolithography + etching process
- $\Delta U \sim 500\,\mathrm{V}$ between electrodes $\Rightarrow$ high electric field inside holes:

Proportional avalanche multiplication



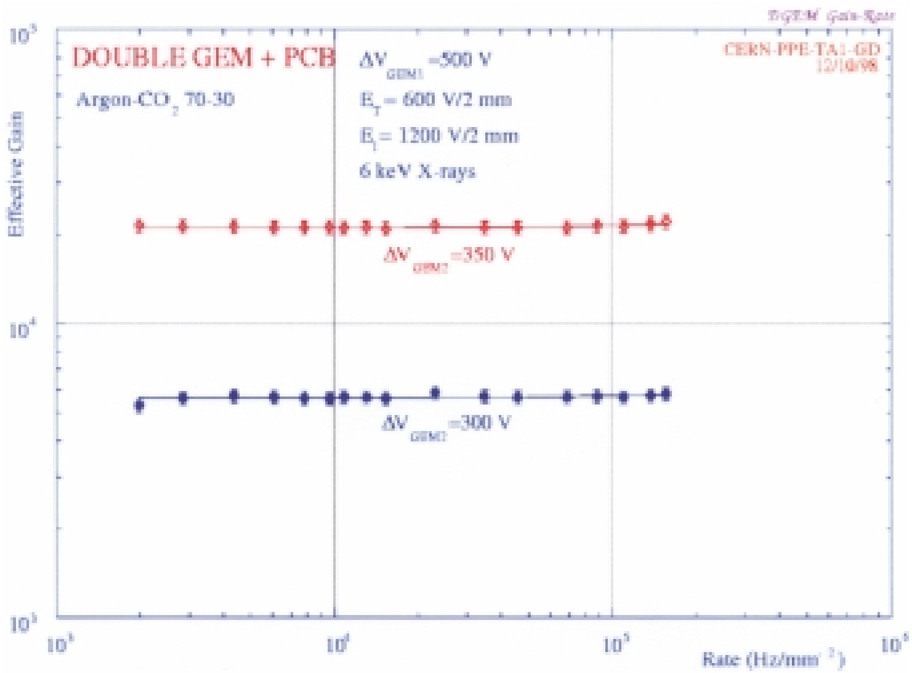
GEM-based Detector



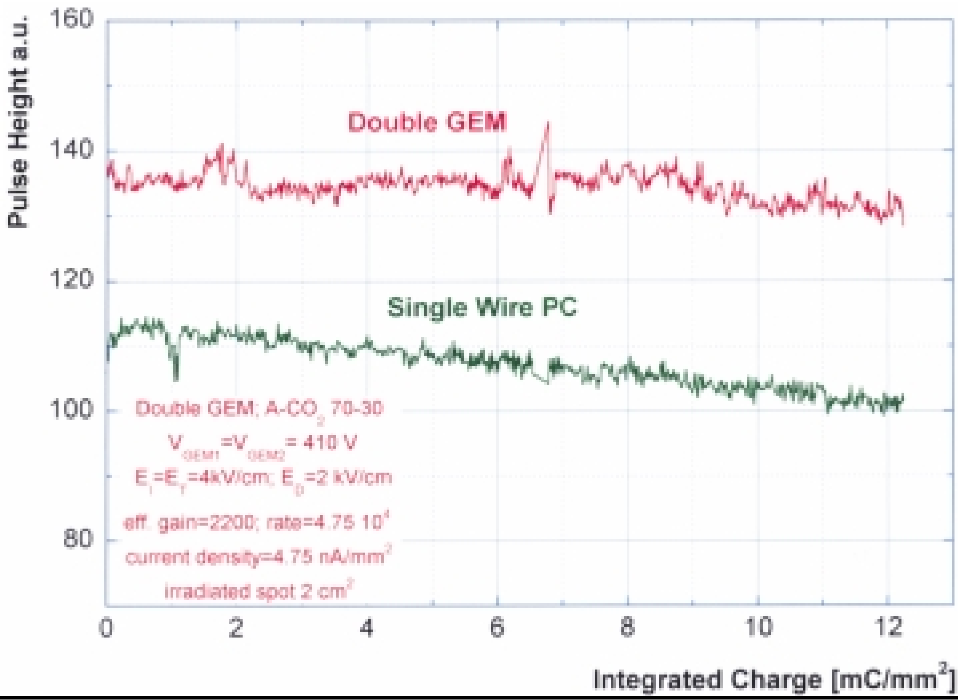
- Gain is a property of GEM foil
  ⇒ little dependence on external fields (mechanical tolerances!)
- Signal on readout electrode entirely due to electron collection
- No slow ion tail, no ion feedback
- Possibility to cascade several GEM foils ⇒ higher gain
- Separation of gas amplification and readout stage
  ⇒ high flexibility!
- Readout electrodes remain on ground potential

GEM Detectors - Properties

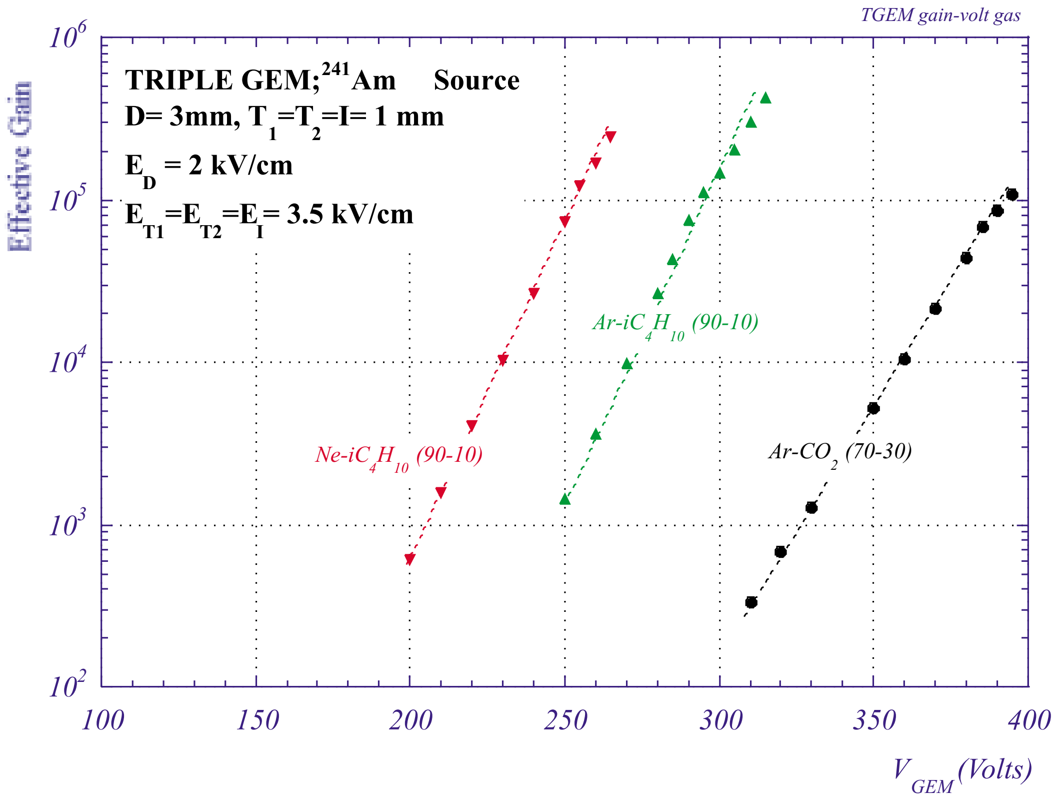
High rate capability $> 10^5\,\mathrm{Hz/mm^2}$



No aging observed up to $10\,\mathrm{mC/mm^2}$



Choice of Gas Filling



Requirements for use in high rate HEP applications:

- Non-polymerizing (aging!)
- Large drift velocity
- Low diffusion
- High gain at low operating voltages
- Non-flammable

$\Rightarrow$ Ar/CO_2 (70%/30%)

Gas Discharges

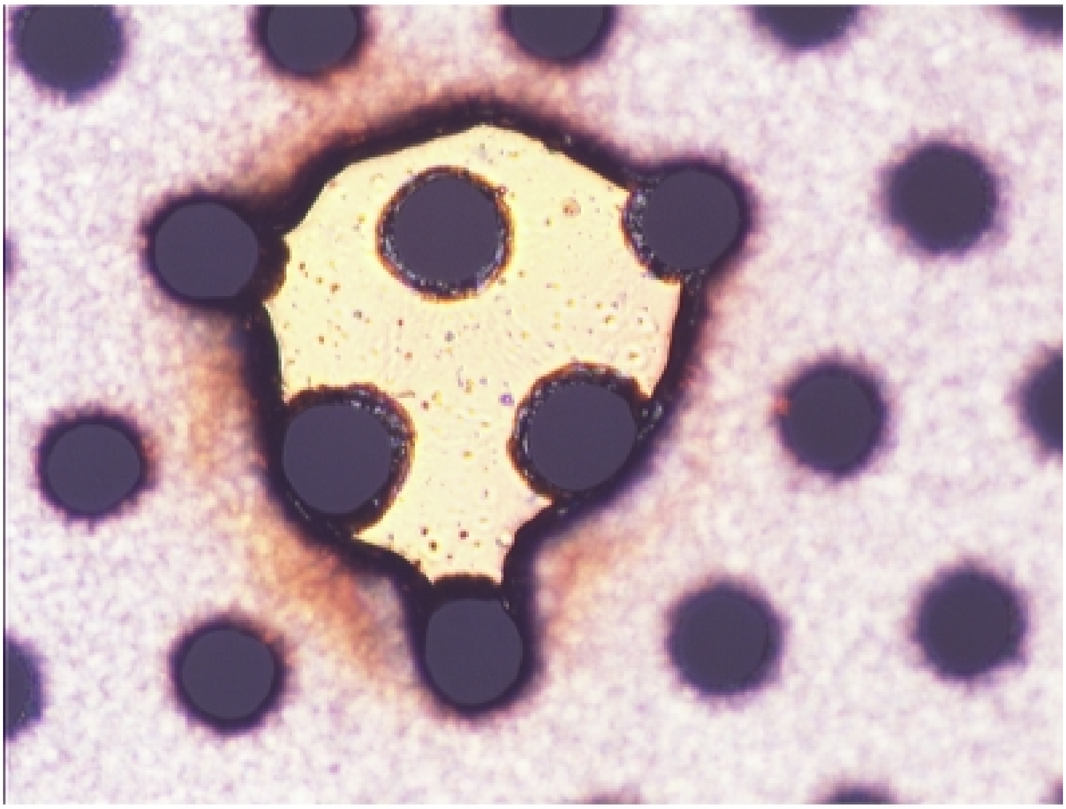
- Due to manufacturing defects ⇒ QC
- Due to nuclear interactions on exposure to heavily ionizing tracks

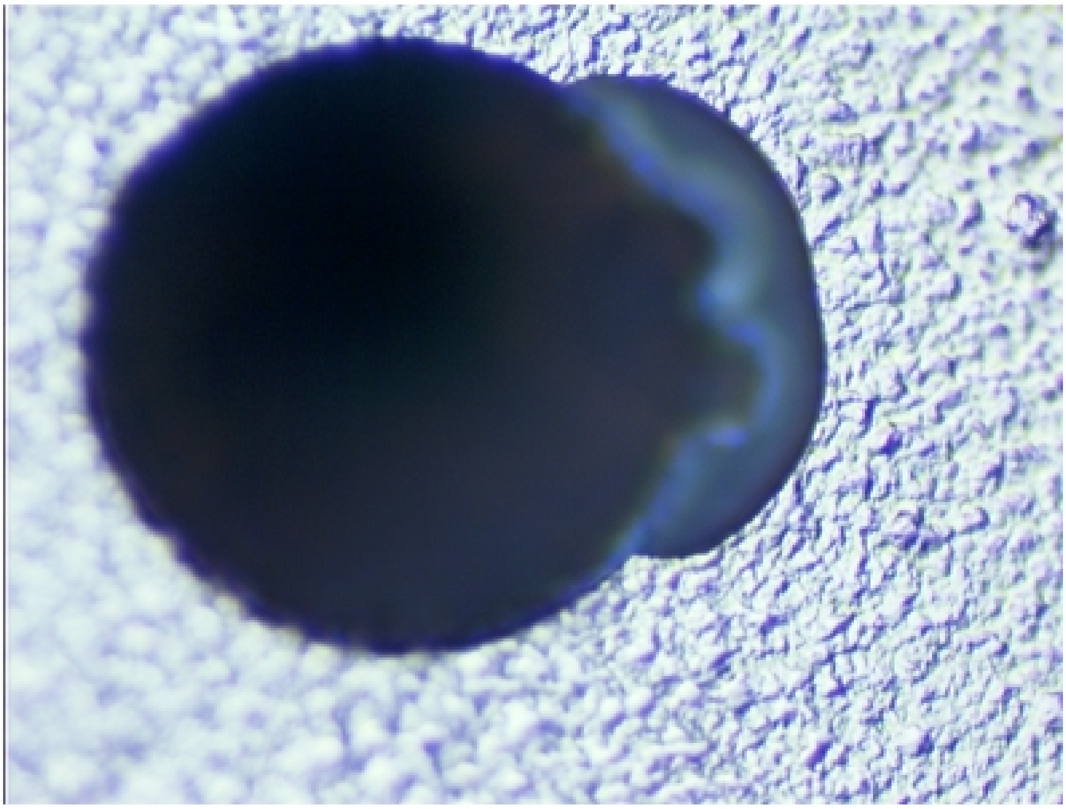
Systematic investigation of

- Probability of discharge
- Energy/charge released in a discharge

⇒ Strategies to optimize GEM detectors for successful operation under harsh COMPASS conditions

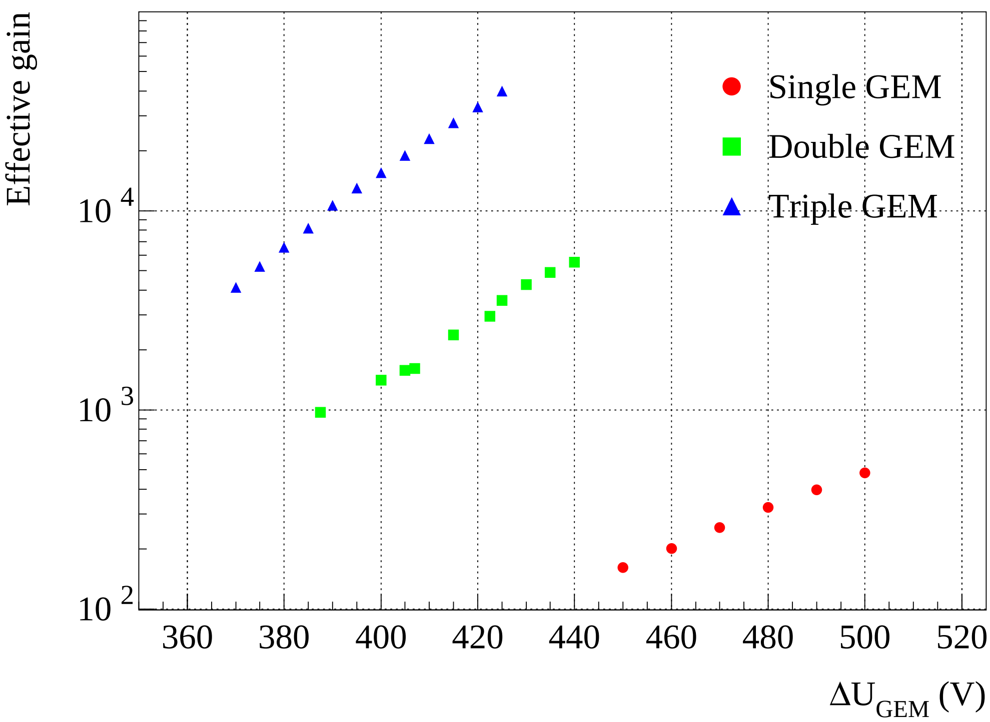
Defects in GEM Foils

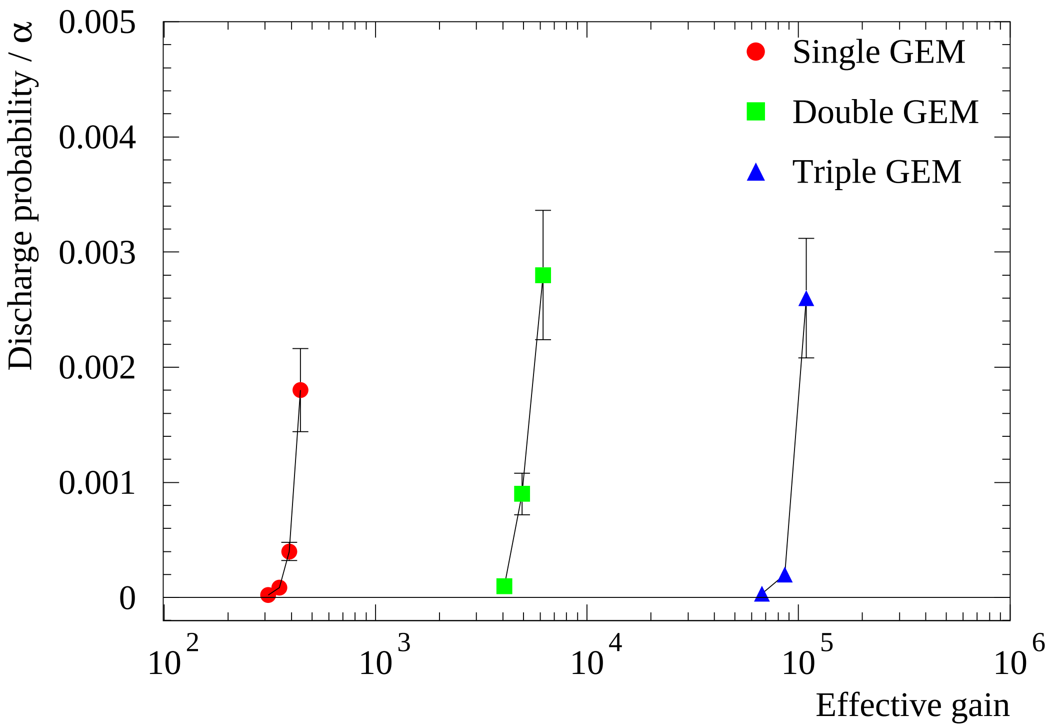




Discharge Probability

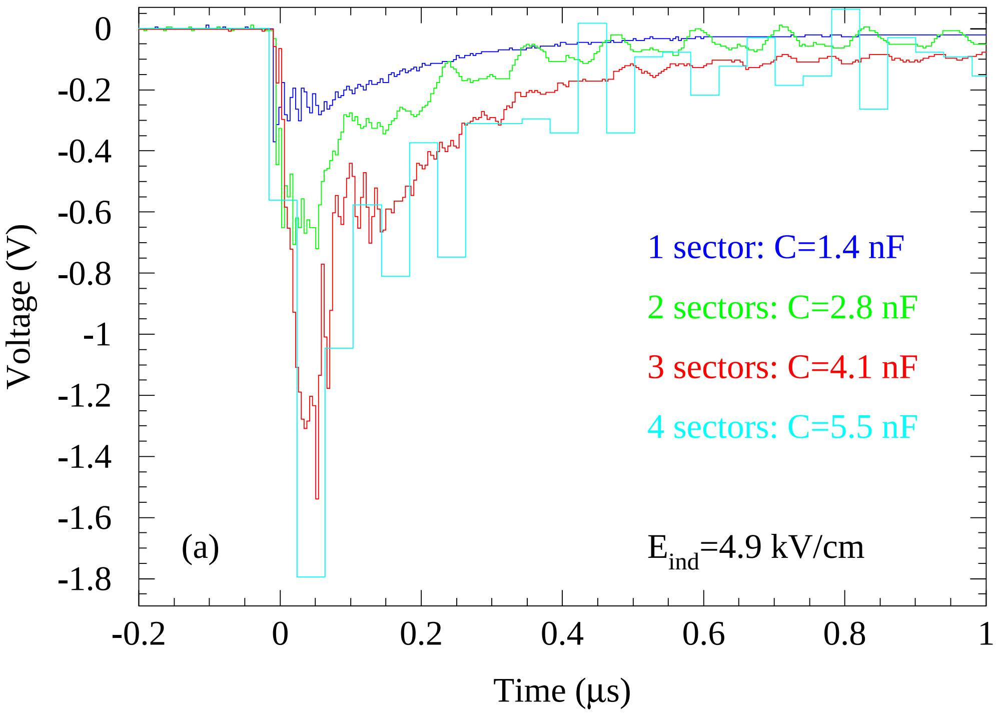
$10 \times 10\,\text{cm}^2$ GEM, $5.5\,\text{MeV}$ α (^{241}Am)

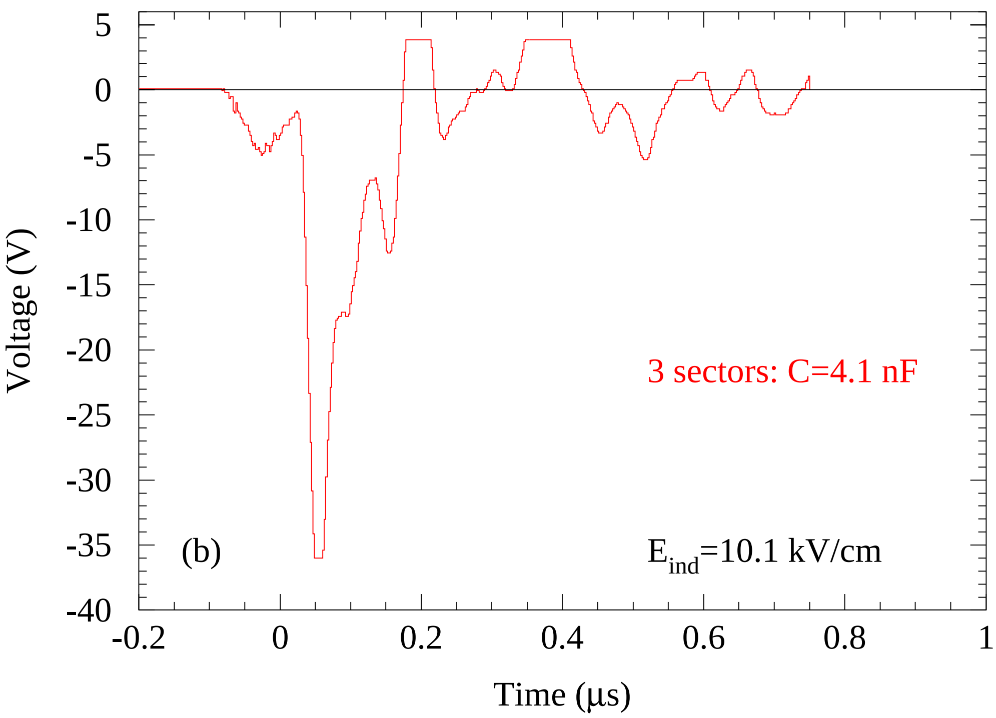




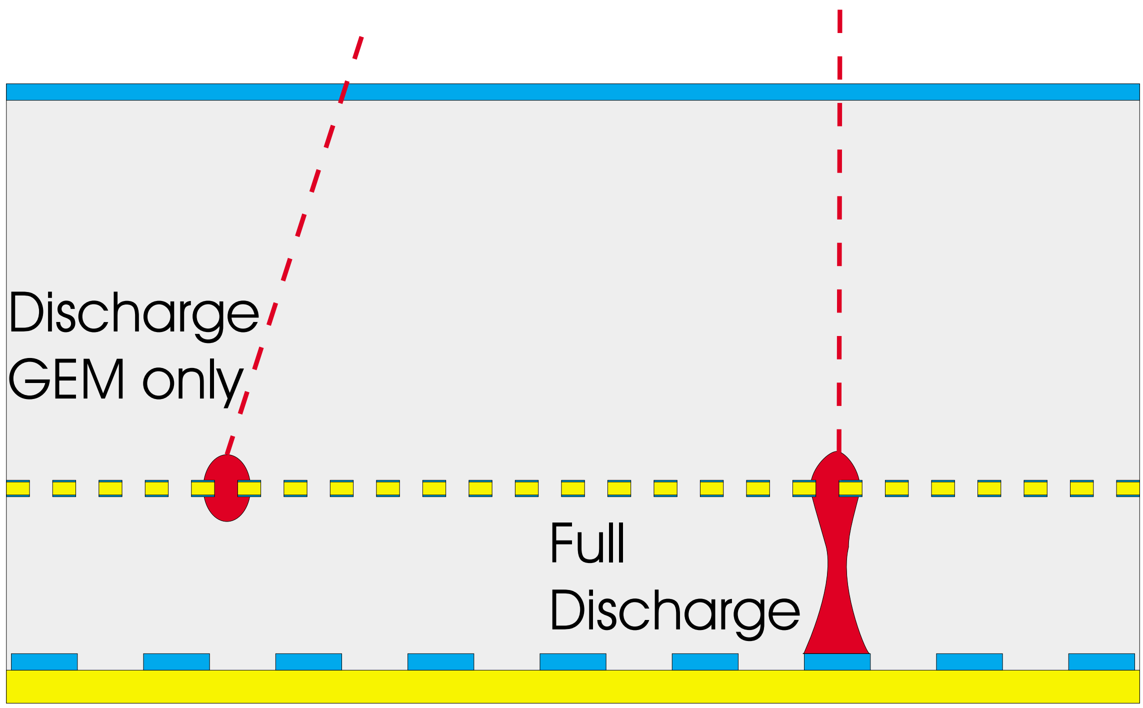
Discharge Energy I

$10 \times 10\,\mathrm{cm}^2$ DGEM, sectorized, $5.3 - 8.8\,\mathrm{MeV}$ α (^{228}Th)





Discharge Energy II



Discharges in GEM only

- Charge released depends on capacitance between electrodes
- Fraction of charge collected depends on induction field
- Duration $\sim 200\,\mathrm{ns} \Rightarrow Q \sim 2.5 - 10\,\mathrm{nC}$

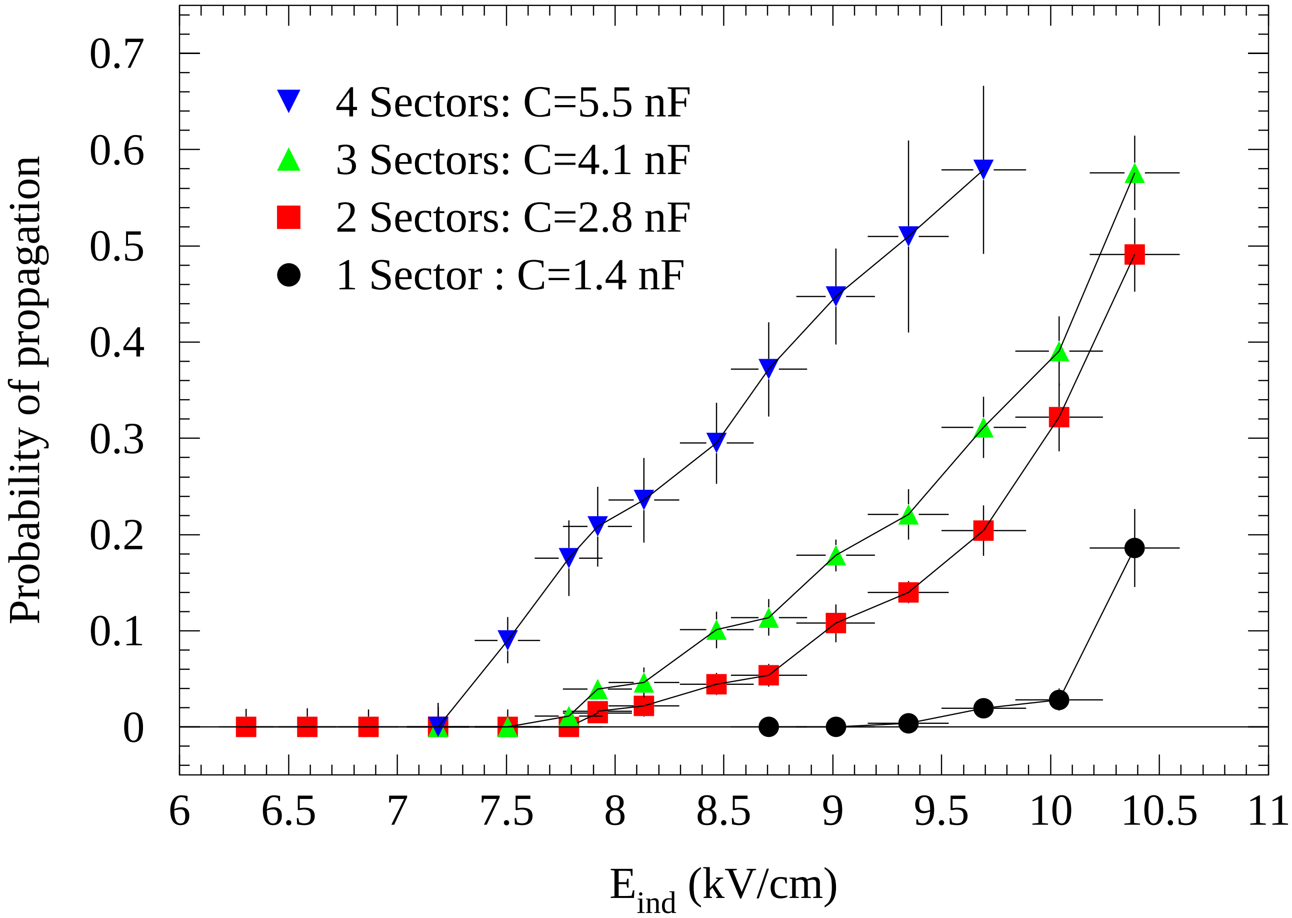
Full discharges to readout strips

- Charge released determined by capacitance and potential difference between readout and lower GEM electrode ($C \sim 60\,\mathrm{pF}$ for $10 \times 10\,\mathrm{cm}^2$ GEM; $\Delta U \sim 800 - 2000\,\mathrm{V}$)
- Charge $Q \sim 50 - 120\,\mathrm{nC}$, current $I \sim 1\,\mathrm{A}$

$\Rightarrow$ Protection of FE chip necessary!

Probability of Full Discharges

$10 \times 10\,\mathrm{cm}^2$ DGEM, sectorized, $5.3 - 8.8\,\mathrm{MeV}\ \alpha$ (^{228}Th)

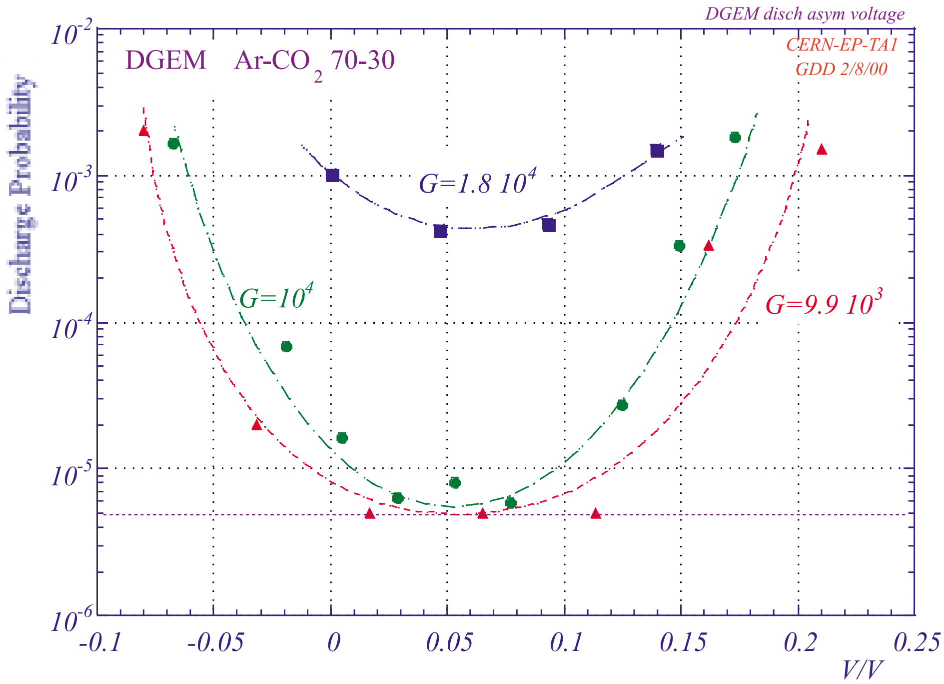


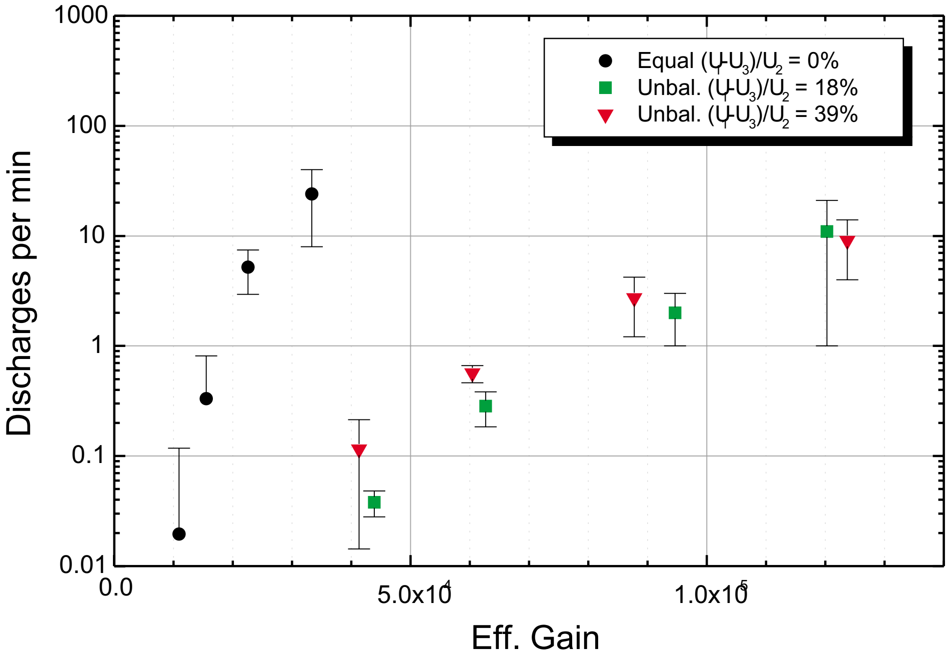
- Probability of propagation depends on $E_{\rm ind}$ and energy of primary discharge (GEM capacitance)

$\Rightarrow$ Can be decreased by decreasing sector size:

13 sectors instead of 5

Sharing of Gain

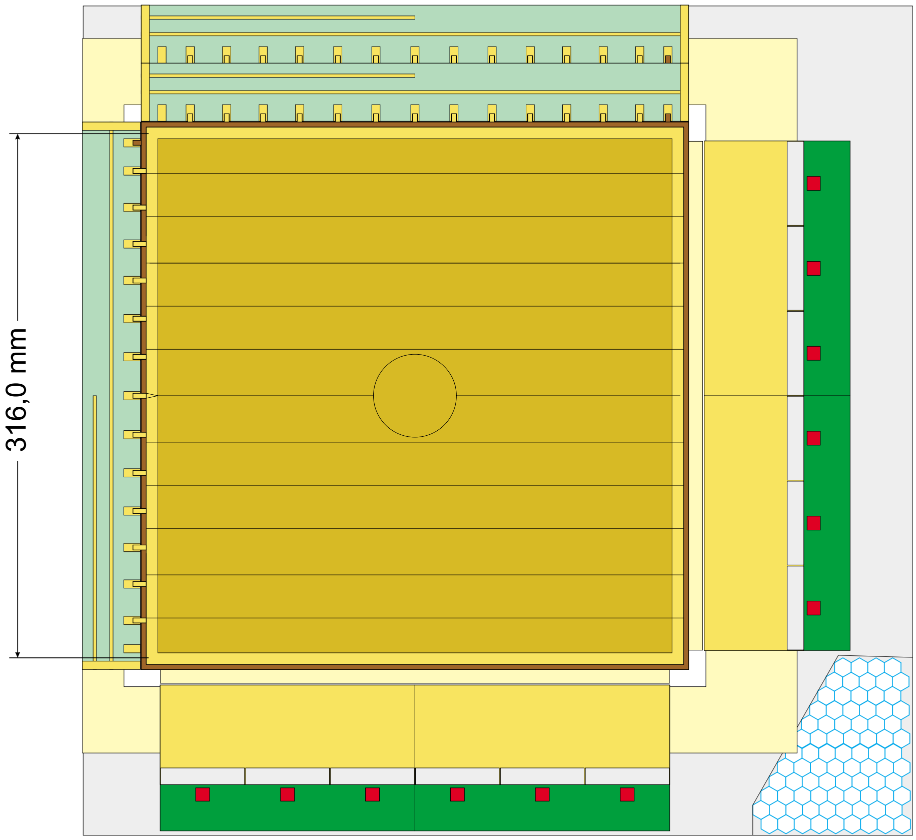


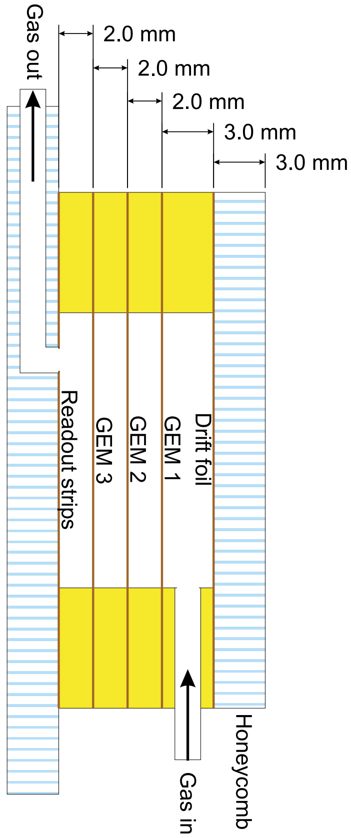


Asymmetric gain sharing between GEMs

$\Longrightarrow$ probability of discharges lower by 2 orders of magnitude at given gain

COMPASS GEM design I





Triple GEM: Probability of discharge at given gain lower by more than one order of magnitude compared to DGEM

Sectorized foils: Decrease energy stored in GEM foils

- Charge released in a GEM discharge smaller
- Probability of propagating discharge lower

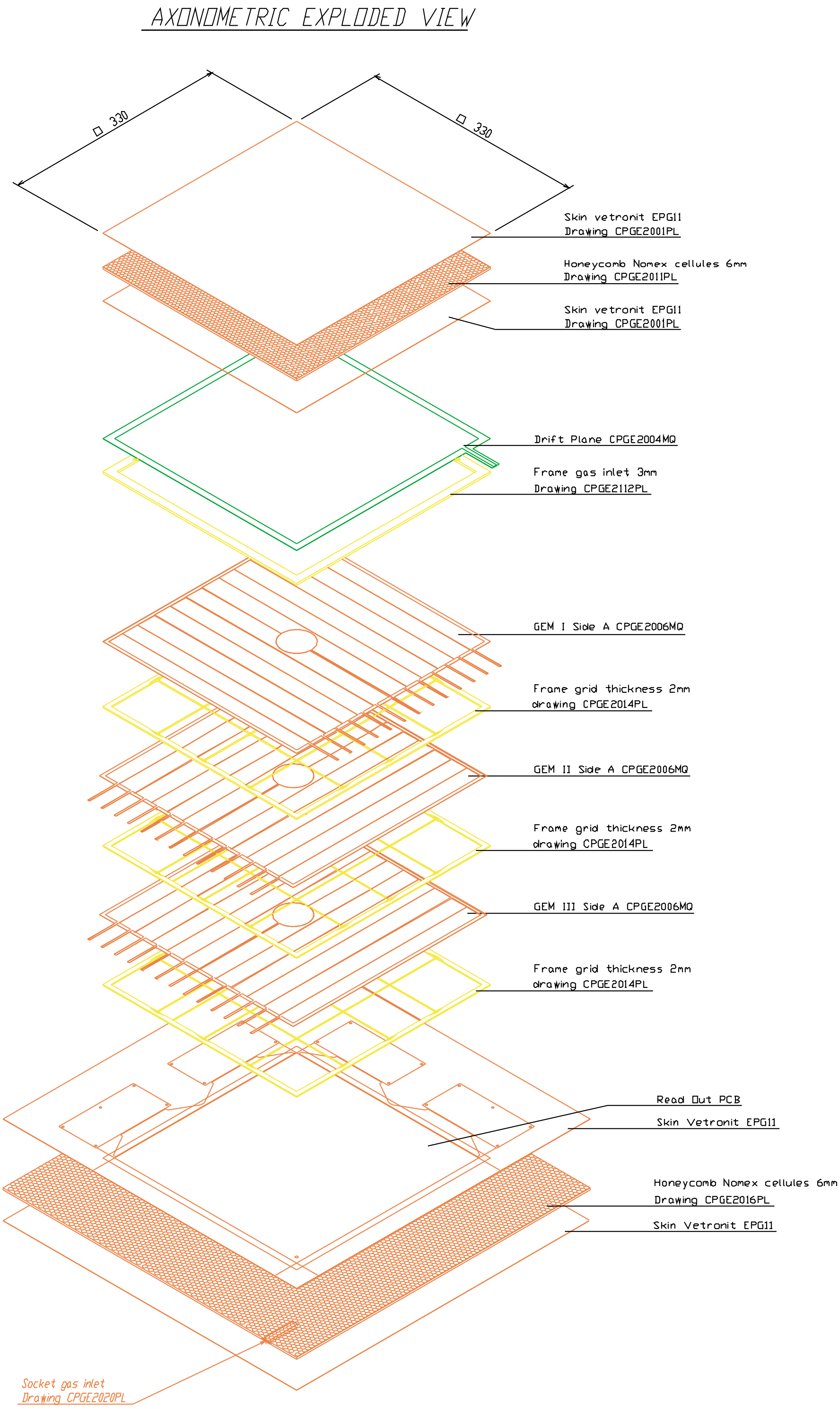
"Beam killer": Central area of $5\,\mathrm{cm}\ \phi$ can be deactivated

Readout: 2-dim, 2×768 strips, $400\,\mu\mathrm{m}$ pitch

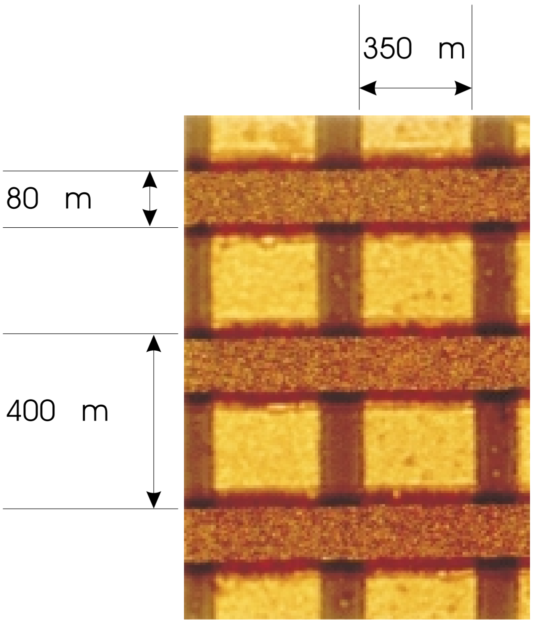
$\Rightarrow$ Active area $30.7 \times 30.7\,\mathrm{cm}^2$

Thickness of detector: $15\,\mathrm{mm}$

COMPASS GEM design II



Two-dimensional Readout



Production process [A. Gandi, R. de Oliveira, CERN-EST]

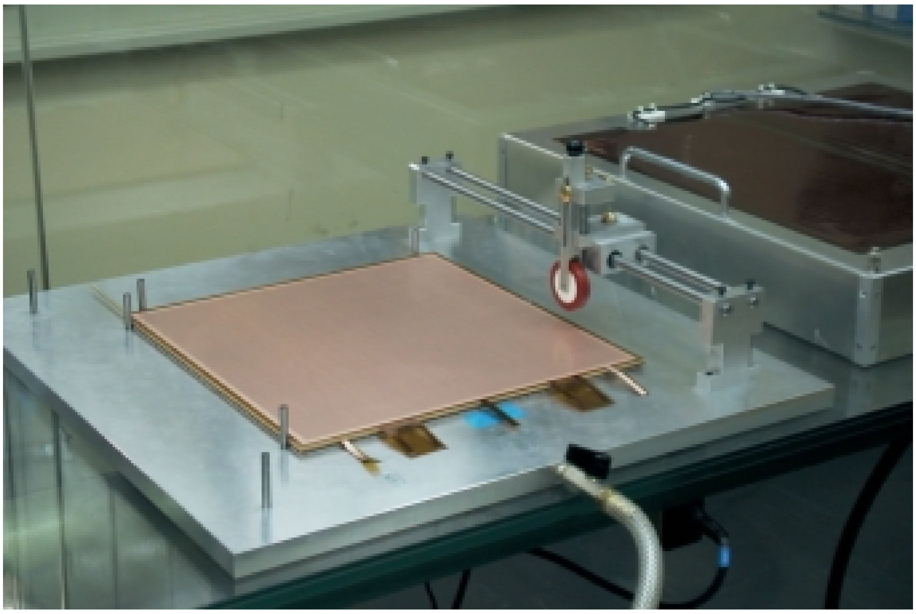
- Two orthogonal sets of parallel Cu strips, engraved on two sides of Cu-clad Kapton foil ($50\,\mu\mathrm{m}$ thin):
  - $80\,\mu\mathrm{m}$ width on upper side
  - $350\,\mu\mathrm{m}$ width on lower side
  - $400\,\mu\mathrm{m}$ pitch
- Gluing of Kapton foil onto a thin insulating support (fiber glass)
- Chemical removal of Kapton in the interstices between the strips on the upper side
  $\Rightarrow$ Bottom layer of strips is opened to charge collection
- Charge sharing $1 : 1$ between upper and lower layer achieved by adjusting strip widths

Construction of GEM detectors

- Carried out by K. Dehmelt [Univ. Mainz] and M. van Stenis [CERN-EP/TA1] in TA1 cleanroom: class < 10000, humidity $+$ temperature controlled
- Protective clothing: overall, shoe-covers, hair-covers, facial masks, gloves

Construction – Tools & Materials

Tools: designed by M. Delattre and M. van Stenis



- Alignment plate and gluing tool
- Heating cover with N_2 flow
- HV test box with N_2 flow

Materials:

Glue:	ARALDIT AY103 + HD991 (ratio 10:4)
Support:	$2 \times 125\,\mu m$ Stesalit on $3\,mm$ Honeycomb Nomex
Drift foil:	$5\,\mu m$ Cu on $50\,\mu m$ Kapton
GEM foils:	$2 \times 5\,\mu m$ Cu on $50\,\mu m$ Kapton
Frame:	$3\,mm$ Stesalit
Spacer grid:	$2\,mm$ Vetronite
Sealant:	Polyurethane Nuvovern LW (2 comp.)
Strip PCB:	$2 \times 5\,\mu m$ Cu on $50\,\mu m$ Kapton, $60\,\mu m$ NoFlow glue, $120\,\mu m$ Stesalit
Shielding	$5\,\mu m$ Aluminum

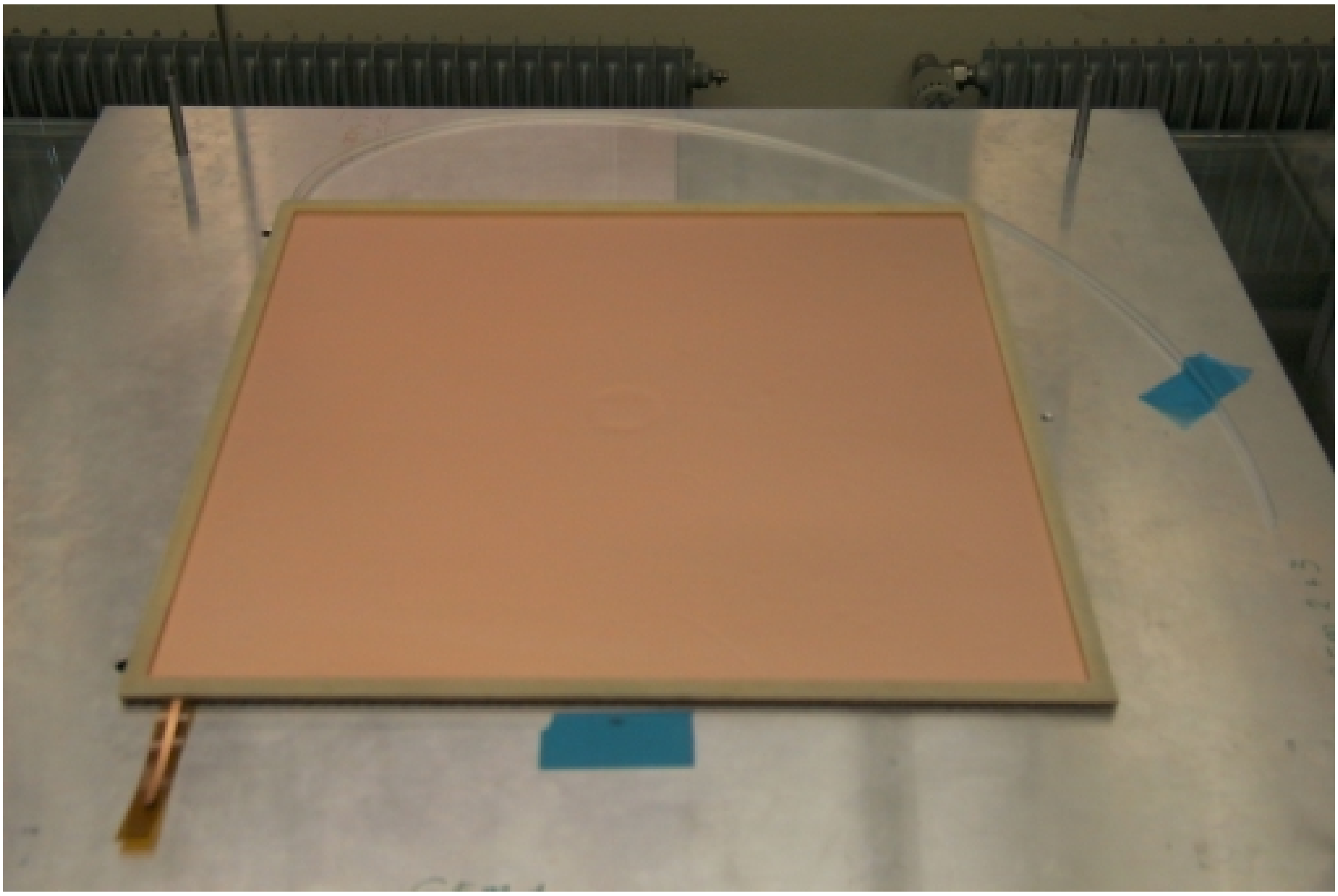
Triple GEM Material Budget

Part	Material	$^0/_{00}$ of X_0
GEM	Cu: $6 \times 5\,\mu\mathrm{m}$ ($X_0 = 14.3\,\mathrm{mm}$) $\times 0.8$	1.68
	Kapton: $3 \times 50\,\mu\mathrm{m}$ ($X_0 = 286\,\mathrm{mm}$) $\times 0.8$	0.42
		Total: 2.1
Drift	Cu: $5\,\mu\mathrm{m}$	0.35
	Kapton: $50\,\mu\mathrm{m}$	0.17
		Total: 0.52
Grid	G10: $3 \times 2\,\mathrm{mm}$ ($X_0 = 194\,\mathrm{mm}$) $\times 0.008$	Total: 0.25
PCB	Cu (80 $\mu\mathrm{m}$ strips): $5\,\mu\mathrm{m} \times 0.2$	0.07
	Cu (350 $\mu\mathrm{m}$ strips): $5\,\mu\mathrm{m} \times 0.75$	0.26
	Kapton: $50\,\mu\mathrm{m} \times 0.2$	0.03
	G10: $120\,\mu\mathrm{m}$	0.62
	NoFlow Glue: $60\,\mu\mathrm{m}$ ($X_0 = 200\,\mathrm{mm}$)	0.30
		Total: 1.28
Shield	Al: $5\,\mu\mathrm{m}$ ($X_0 = 89\,\mathrm{mm}$)	Total: 0.06
		Total: 4.21
HC	NOMEX: $2 \times 3\,\mathrm{mm}$ ($X_0 = 13125\,\mathrm{mm}$)	Total: 0.46
Skins	G10: $4 \times 120\,\mu\mathrm{m}$	Total: 2.47
		Total: 7.14

Construction Steps I

Assembly starts from drift side:

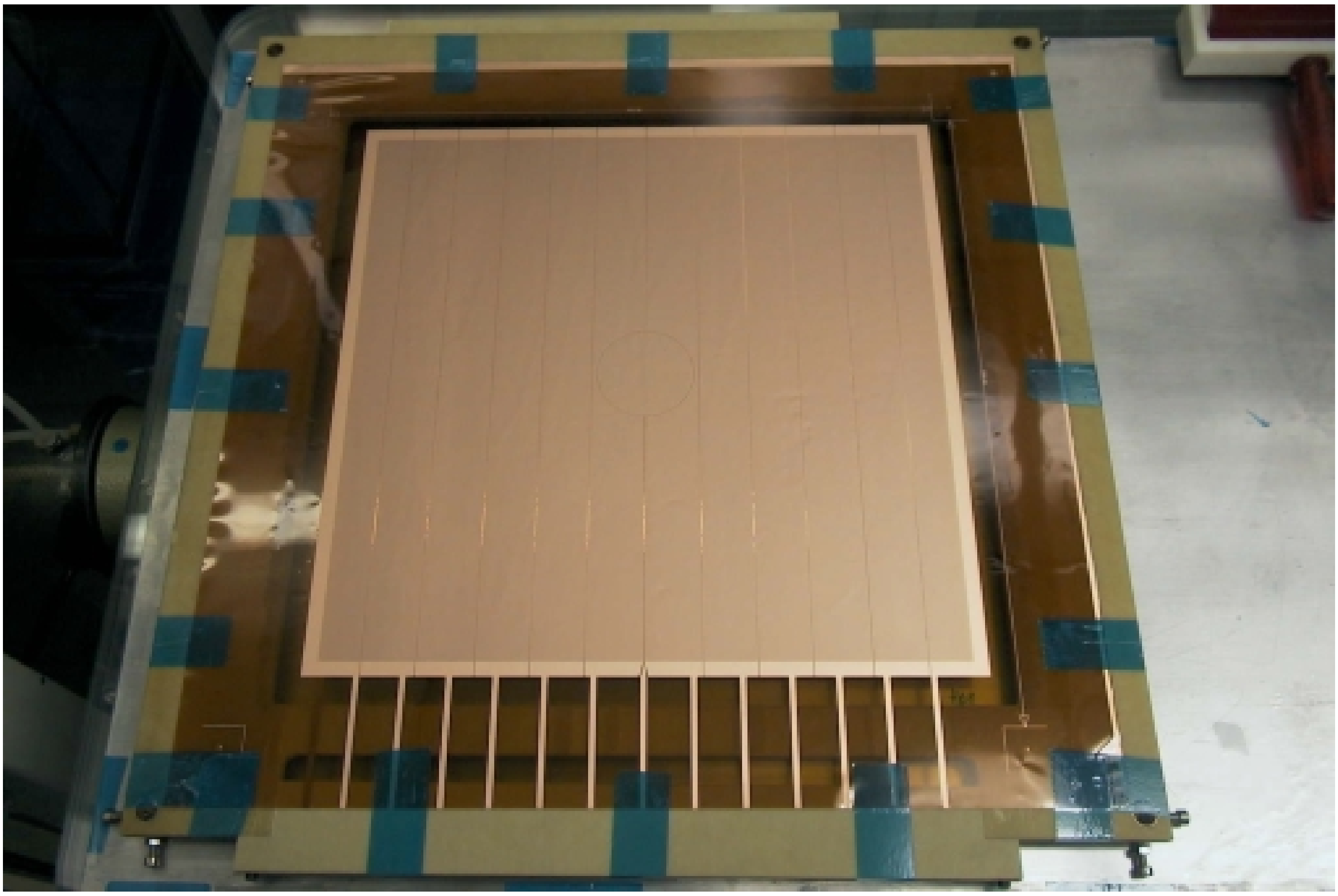
- Glue Stesalit skins onto honeycomb ($330 \times 330\,\mathrm{cm}^2$)
- Glue drift foil onto honeycomb sandwich
- $3\,\mathrm{mm}$ frame with gas distribution channels
  - Seal with Polyurethane
  - Clean in ultrasonic bath
  - Test for HV stability (up to $5\,\mathrm{kV}$)
  - Glue gas input pipe
- Glue frame onto drift foil



Construction Steps II

Pre-tension GEM foil

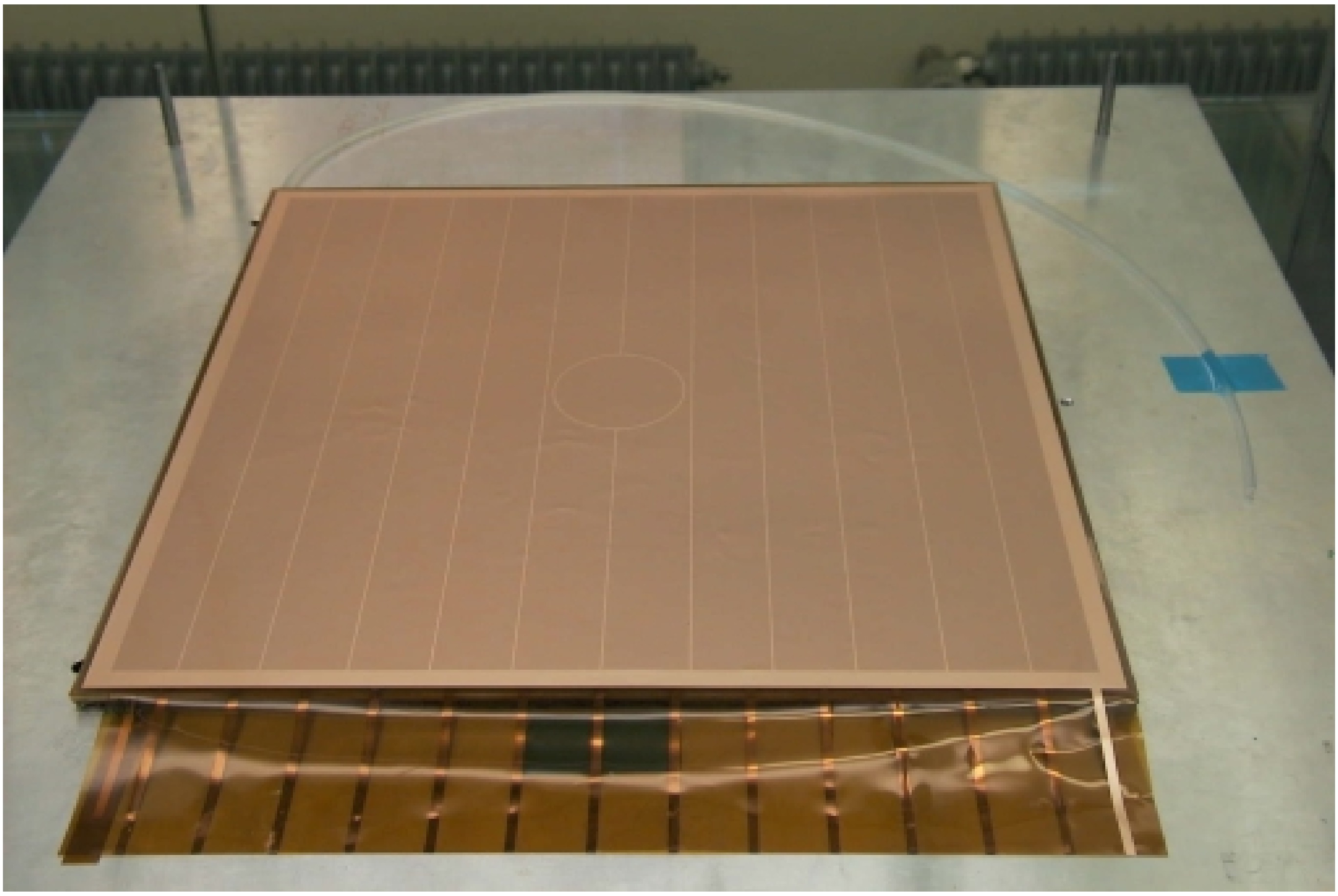
- Stretch GEM foil over transfer frame
- Glue GEM foil onto transfer frame
- HV test



Construction Steps III

Glue GEM foil

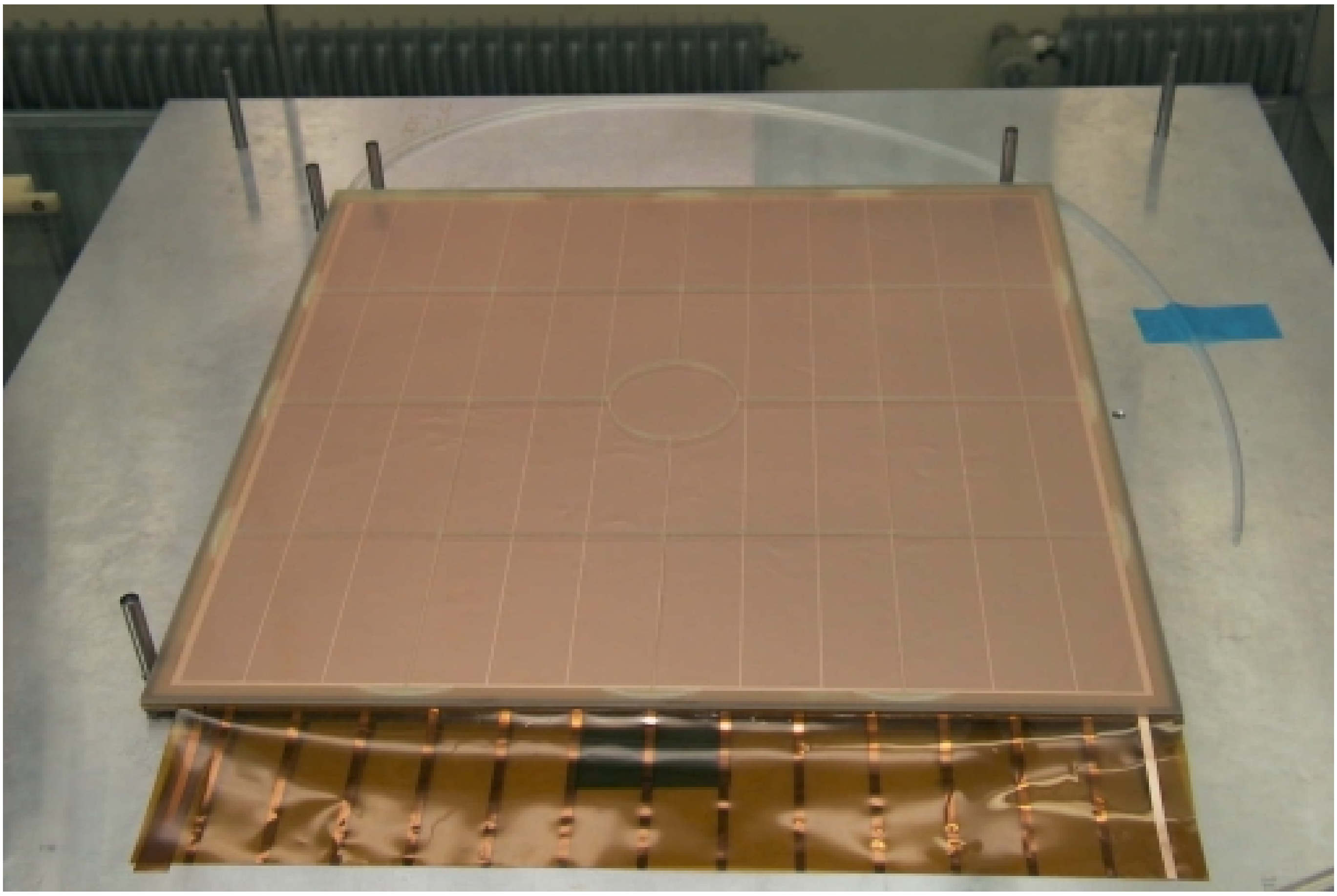
- Mount drift honeycomb on alignment plate, fix with vacuum
- Apply glue to the frame using gluing wheel
- Align GEM on transfer frame to honeycomb using pins
- Apply weight to the transfer frame to stretch GEM
- Cut out GEM from transfer frame
- HV test



Construction Steps IV

Glue spacer grid

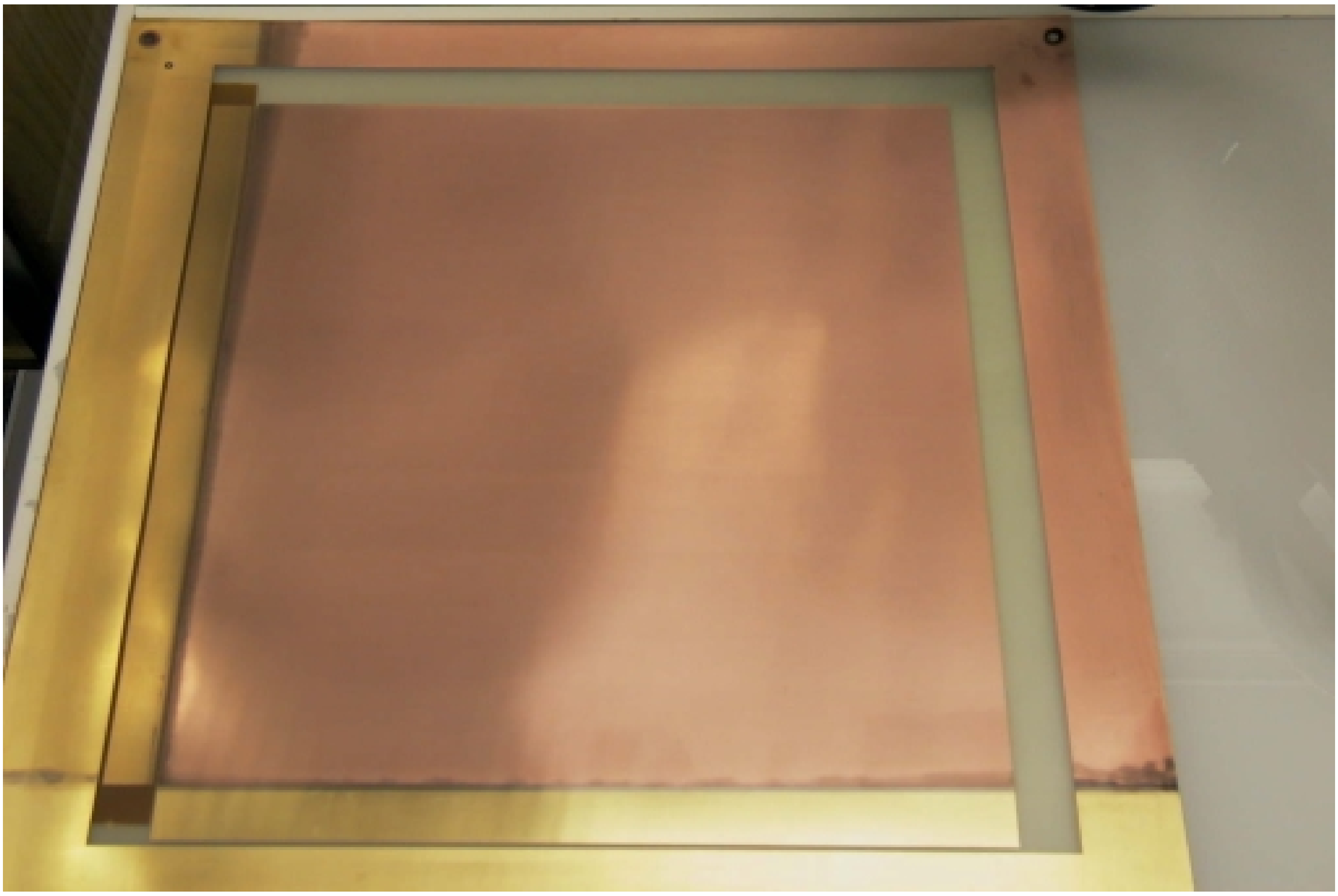
- Apply glue to the spacer grid using gluing wheel
- Mount drift honeycomb on alignment plate, fix with vacuum
- Align spacer grid to honeycomb using pins
- Apply weight to the spacer grid
- HV test



Construction Steps V

Large honeycomb, Strip PCB

- Insert gas outlet piece into honeycomb
- Glue Stesalit skins onto honeycomb ($500 \times 500\,\mathrm{cm}^2$)
- Strip PCB:
  - Measure strip pitch and deviation from parallelism
  - Check for shorts

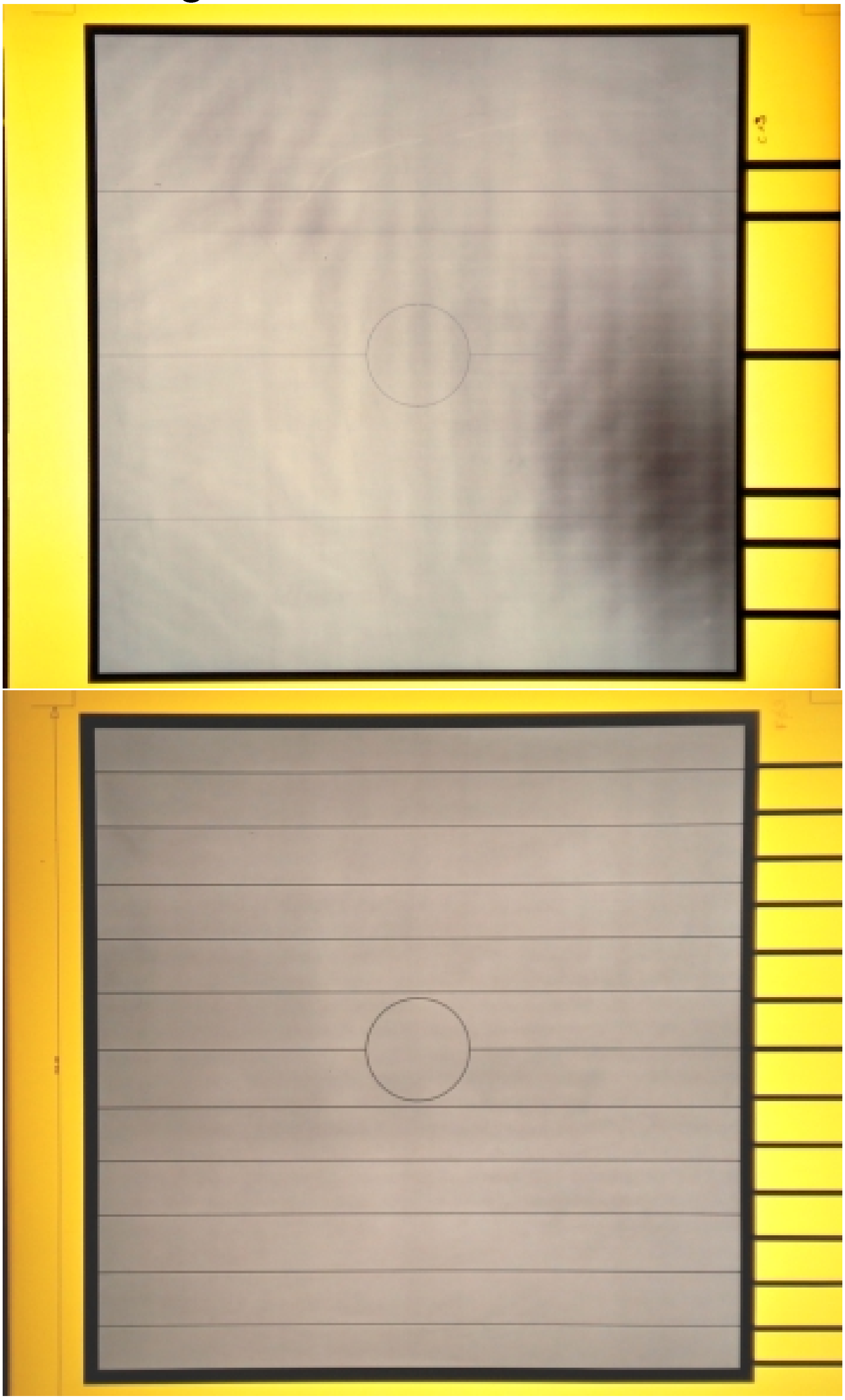


- Glue strip PCB onto honeycomb sandwich
- Close detector by gluing drift stack onto large honeycomb using alignment pins inserted into large honeycomb

GEM quality control I

Optical transparency

⇒ relative alignment of holes in two Cu electrodes

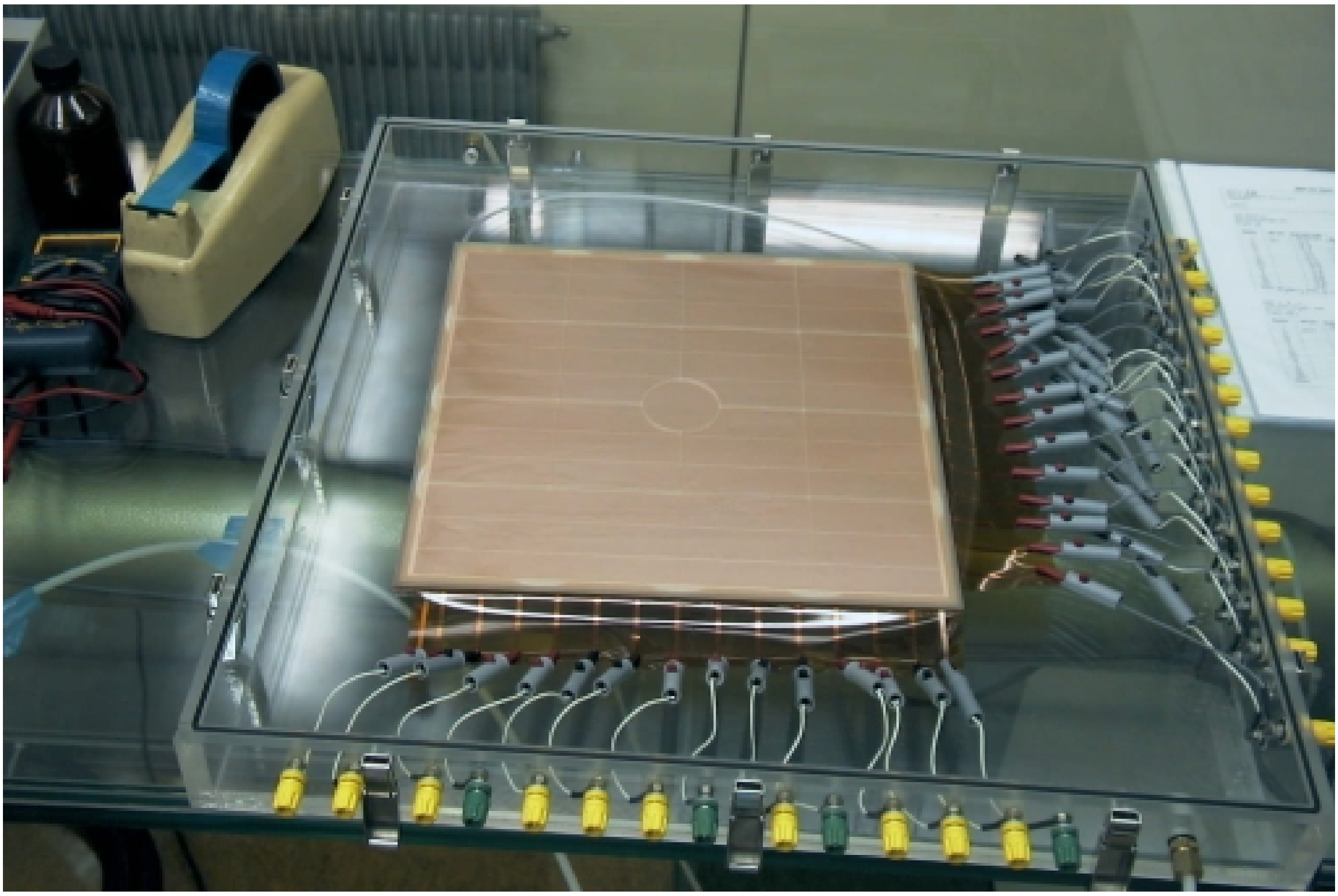


GEM quality control II

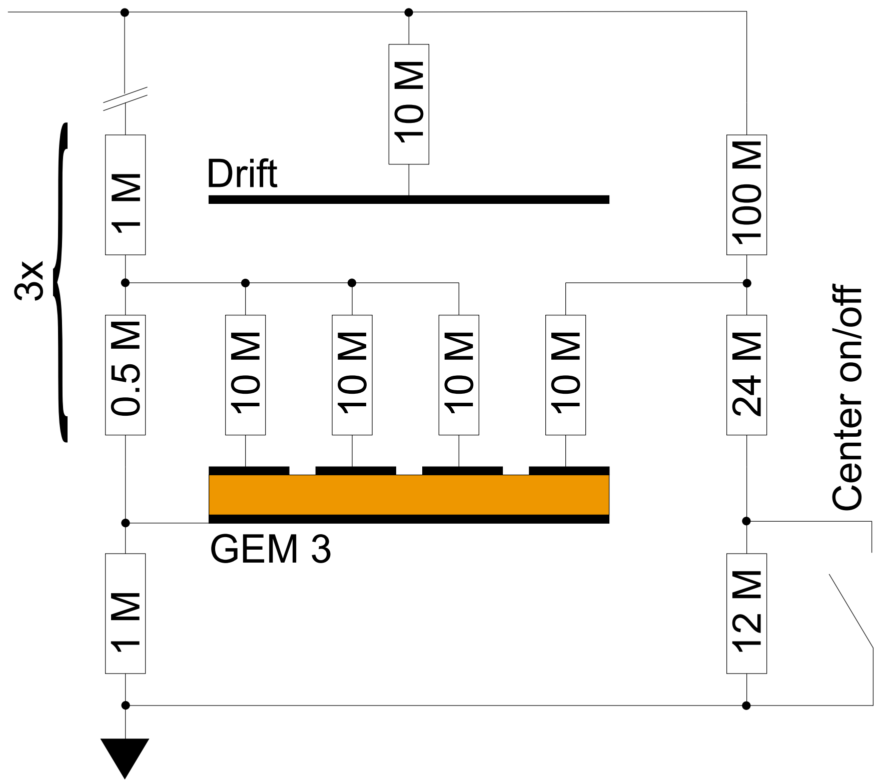
HV test:

- up to $600\,\mathrm{V}$ before mounting
- up to $550\,\mathrm{V}$ after each gluing step

$\Rightarrow$ monitor leakage currents of sectors, shorts



HV Distribution



- Resistor network instead of individual power supplies
- Main chain defines fields between foils and gain in GEM
- Individual protection resistors on upper GEM side: $10\,\mathrm{M}\Omega$ $\Rightarrow$ Most of the potential drop on upper side in case of discharge! Limitation: max. $5\,\mathrm{V}$ potential drop under exposure to high intensity beam ($10^8\,\mathrm{s}^{-1}$, $G = 5 \cdot 10^3$)
- Operational even with permanent short in one sector: small drop of potential in remaining sectors can be compensated by slightly increased HV
- Room for improvement: sectorization on both sides of the GEM foils

Detector Quality Control

Gas leak test (pure CO_2)

HV distribution boards:

- Chemical cleaning of boards after assembly of resistors
- Coating of boards with HV-proof varnish
- Test of each individual board before mounting

HV stability:

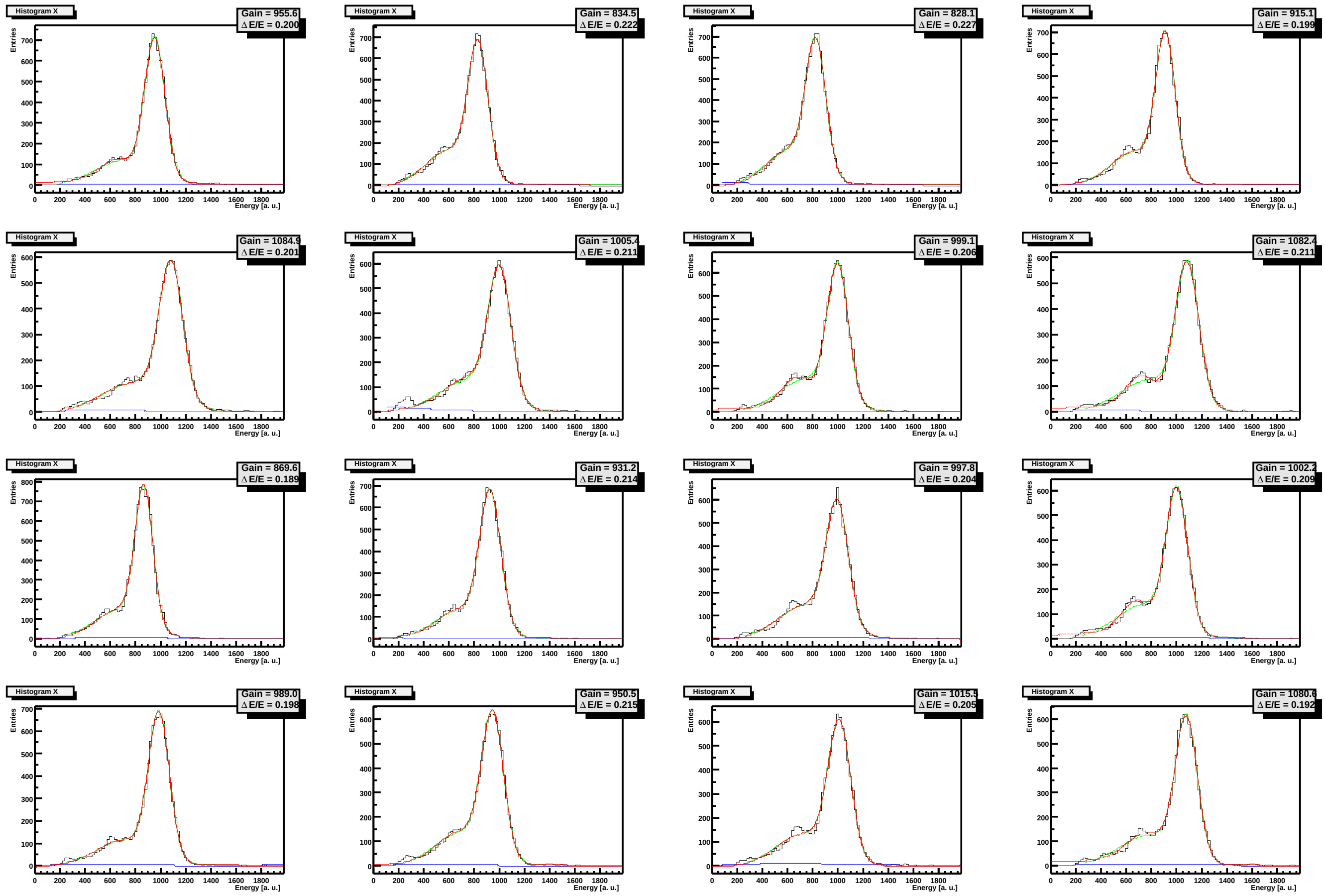
- Test of each individual GEM foil before mounting HV boards (pure CO_2)
- Test for external discharges at nominal voltage (pure CO_2)
- Test for internal discharges at nominal voltage (Ar/CO_2)

Detector performance:

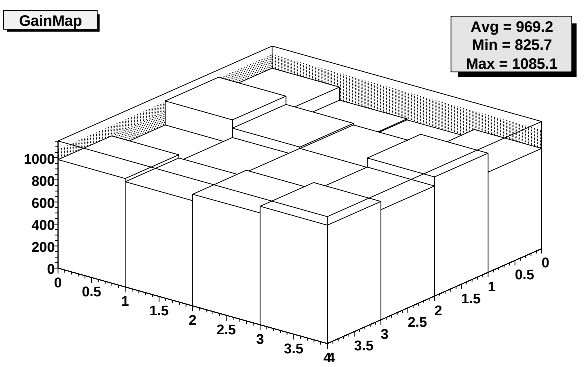
- Check for shorts in readout circuit
- Gain map with $8.9\,\mathrm{keV}$ X-rays, using standard laboratory preamplifier/amplifier

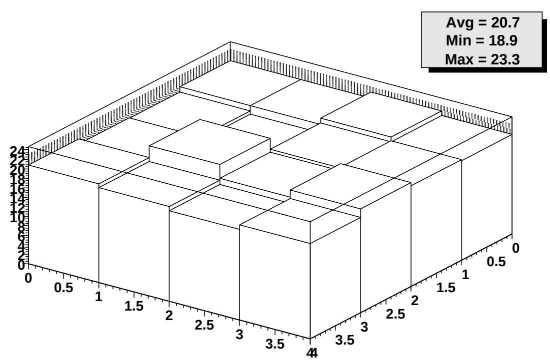
Uniformity of Gain and Resolution

Cu X-ray spectra (8.9 keV) in 4 × 4 points over each detector for both strip layers



Maps of relative gain and energy resolution



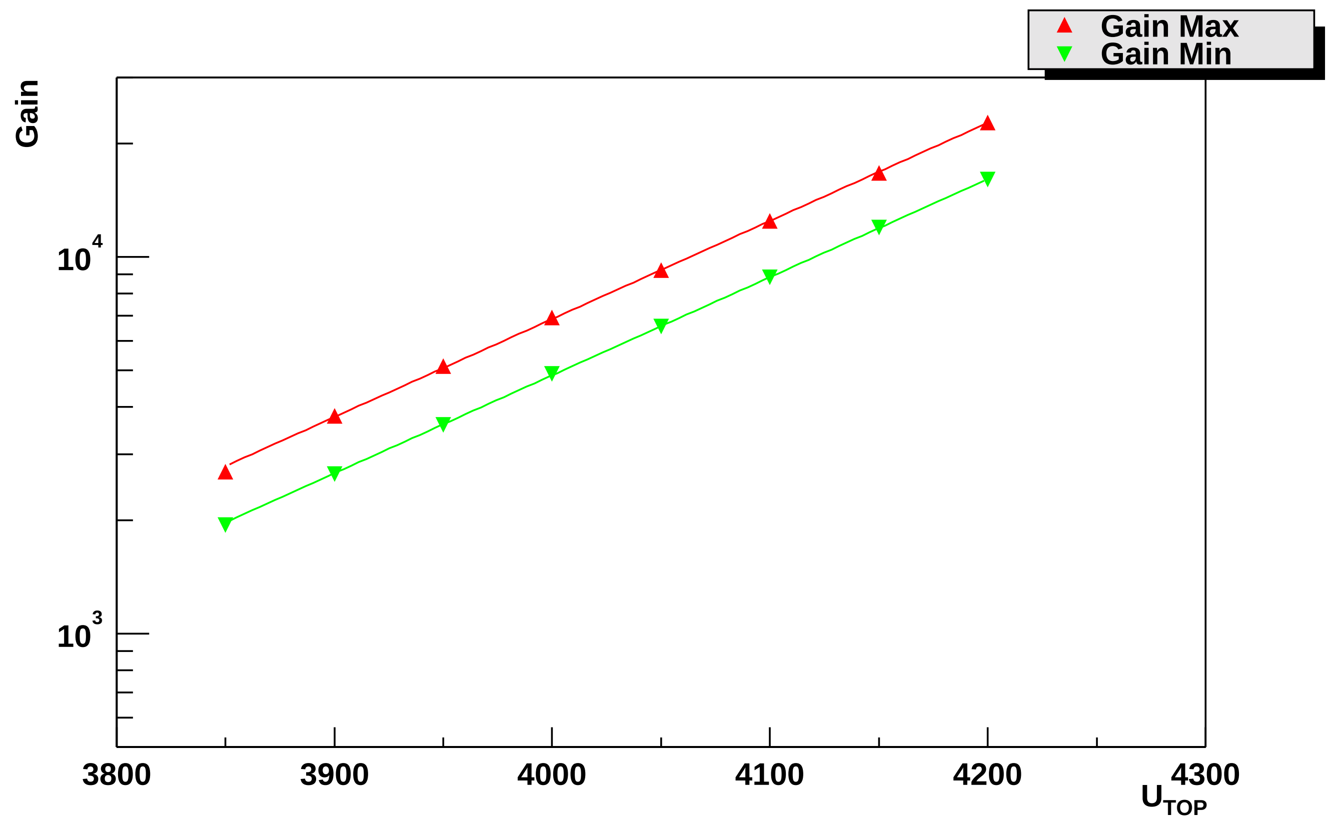


Gain Calibration

Effective gain: measure current on readout strips I as a function of count rate R under irradiation with $8.9\,\mathrm{keV}$ X-rays

$$G = \frac{I}{e_0 N R}, \qquad e_0 N: \text{ primary charge}$$

Gain calibration at points with maximum and minimum gain



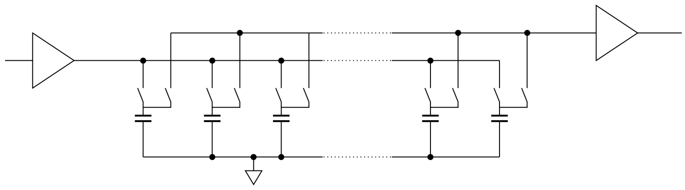
TGEM11

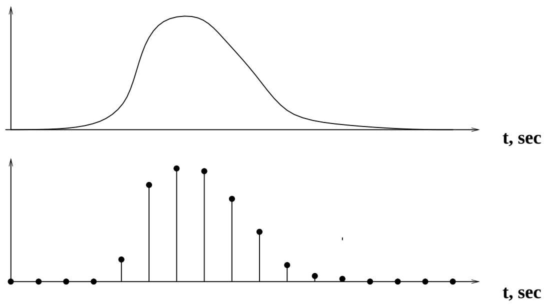
GEM Readout

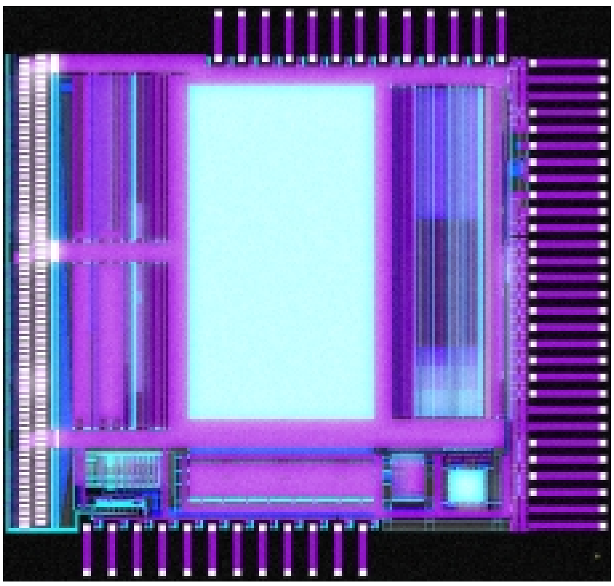
"Deadtime-less" frontend electronics ⇒ Pipeline

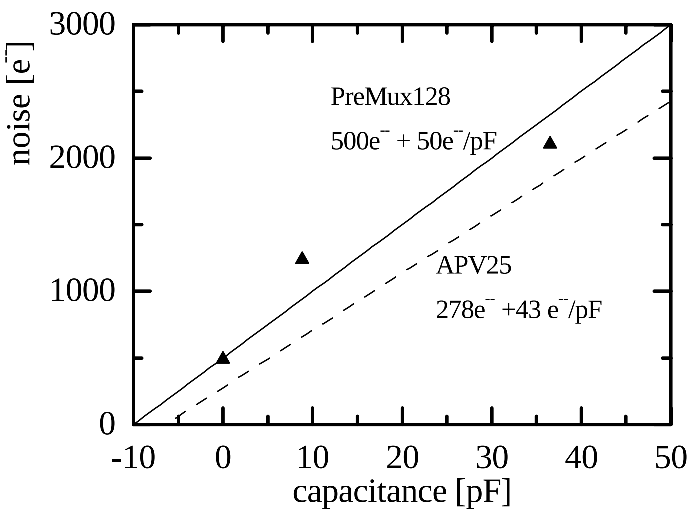
APV25-S0: CMS Si microstrip tracker FE chip

- Analogue pipeline ASIC fabricated in $0.25\,\mu\mathrm{m}$ CMOS technology
- Preamplifier + shaper ($50\,\mathrm{ns}$ peaking time)
- 192 memory cells / channel
- Samples written at $40\,\mathrm{MHz}$
- FIFO depth 31 events ⇒ Latency up to $4\,\mu\mathrm{s}$
- MUX output





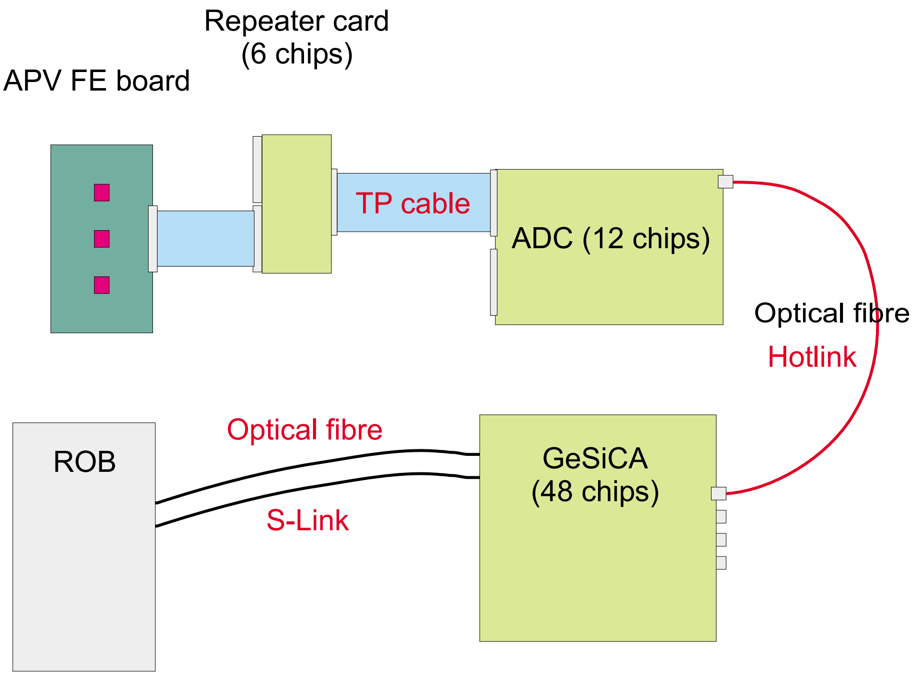




Front-end Electronics

FE-card: 3 APV chips, glass pitch adapter, $220\,\mathrm{pF}$ capacitors, BAV99 double diodes for input protection

Readout chain: designed and built by I. Konorov (TU München)



COMPASS SAT – Beam Tests

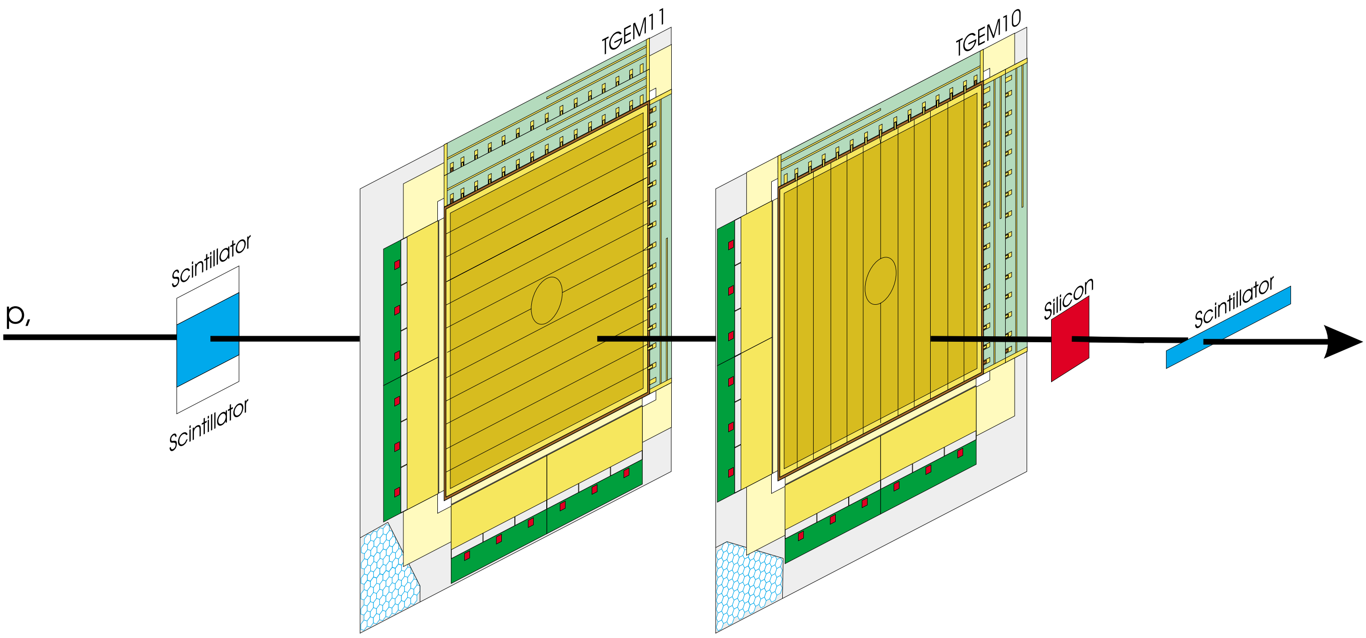
CERN PS-T11: $10^6\, p, \pi/$spill, $3.6\,\mathrm{GeV}/c$

3 triple GEM detectors:

- 2 fully equipped with electronics (3072 channels)
- 1 half equipped with electronics (768 channels)

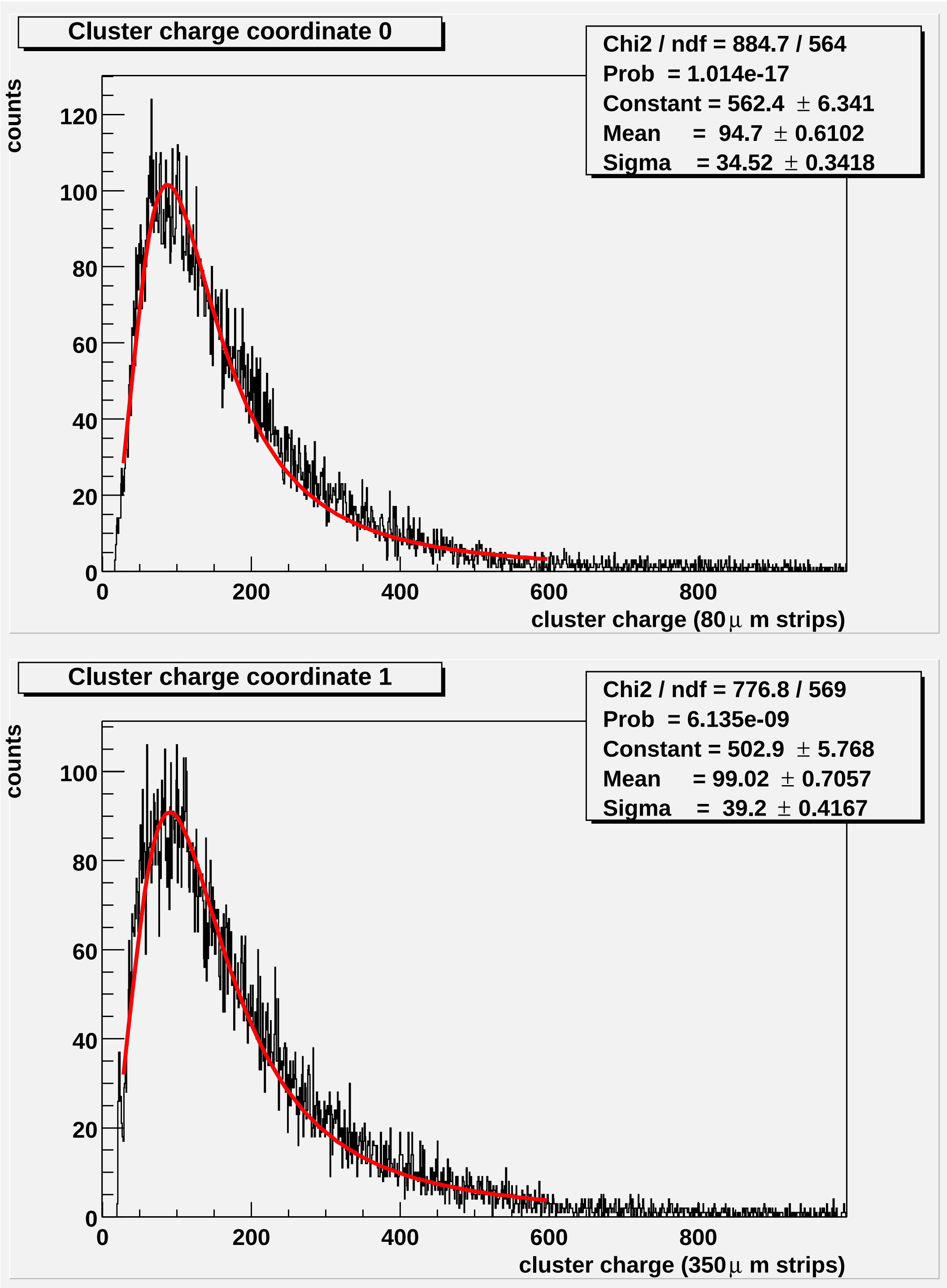
1 Si microstrip detector:

- $5 \times 7\,\mathrm{cm}^2$, double-sided, $300\,\mu\mathrm{m}$ thick
- $50\,\mu\mathrm{m}$ strip pitch (2304 channels)



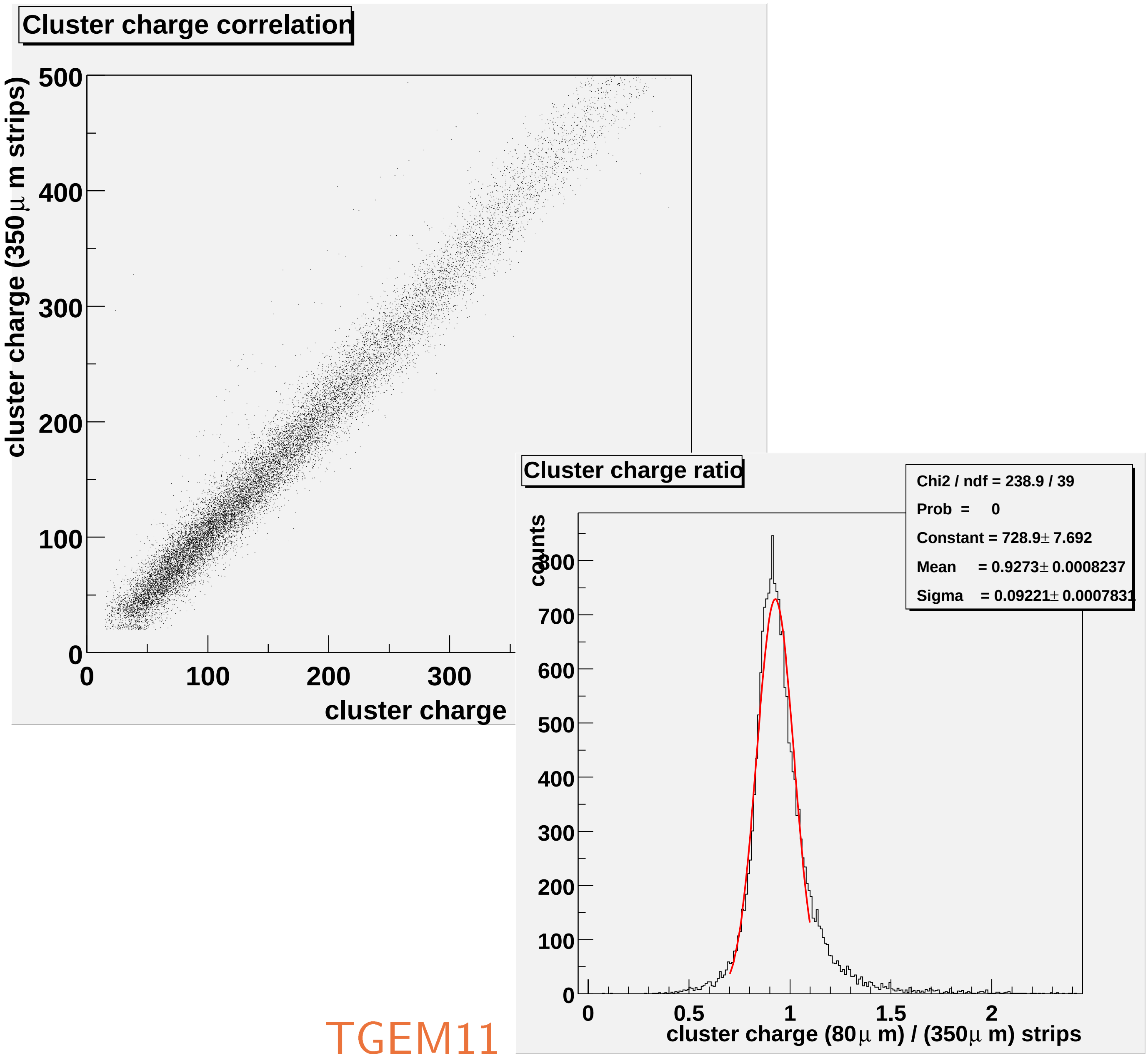
Cluster Amplitudes

Single cluster, $U_0 = 4050\,\mathrm{V}$ $(G \sim 8000)$ TGEM11



- Strip noise: $1050\,\mathrm{e}^-$ $(80\,\mu\mathrm{m})$, $1250\,\mathrm{e}^-$ $(350\,\mu\mathrm{m})$

Cluster Amplitude Correlation

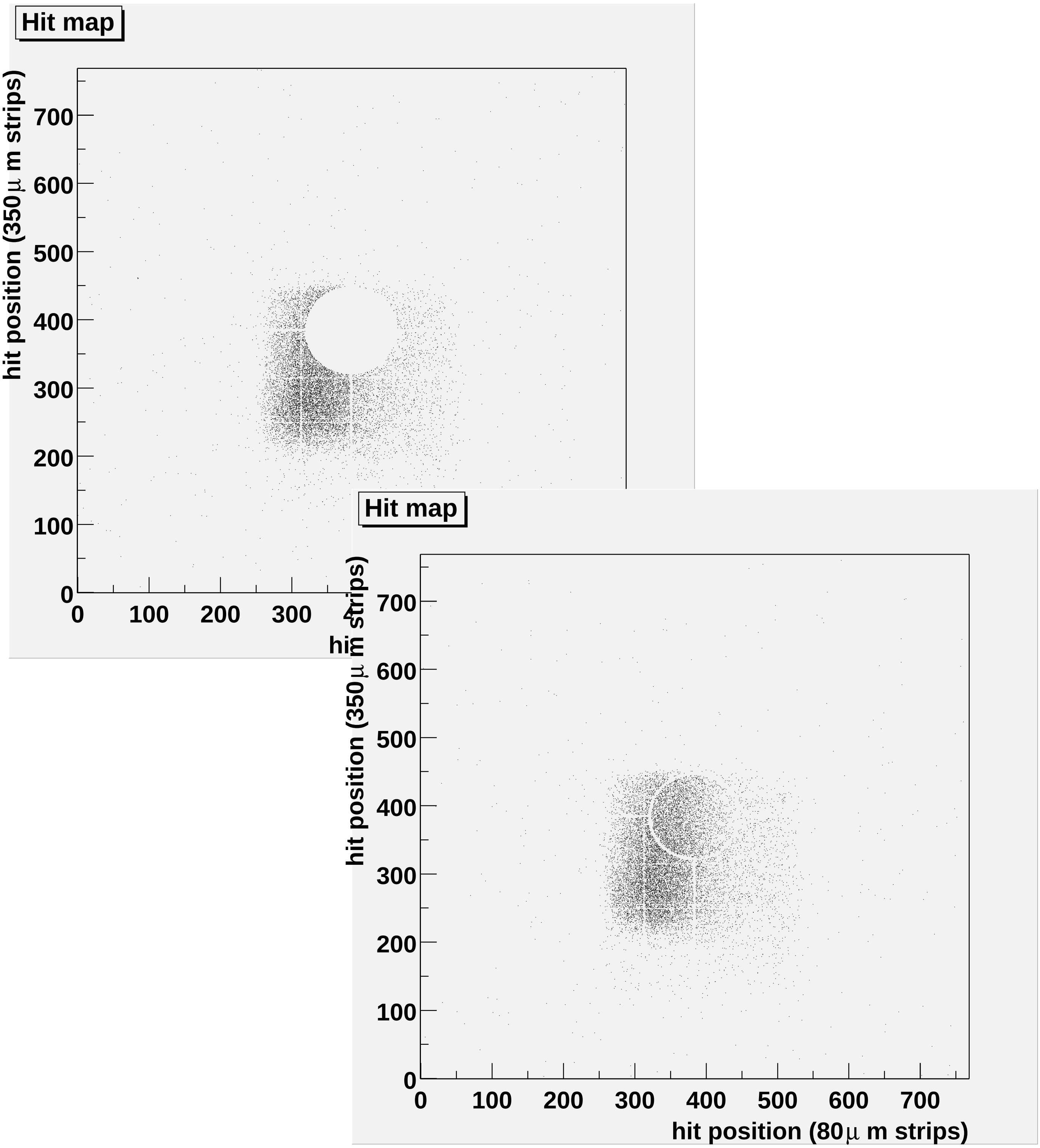


TGEM11

- Charge sharing between strip planes ~ 1
- Narrow correlation between amplitudes: $\sigma = 0.09$

$\Rightarrow$ Resolve hit ambiguities

Hit Map

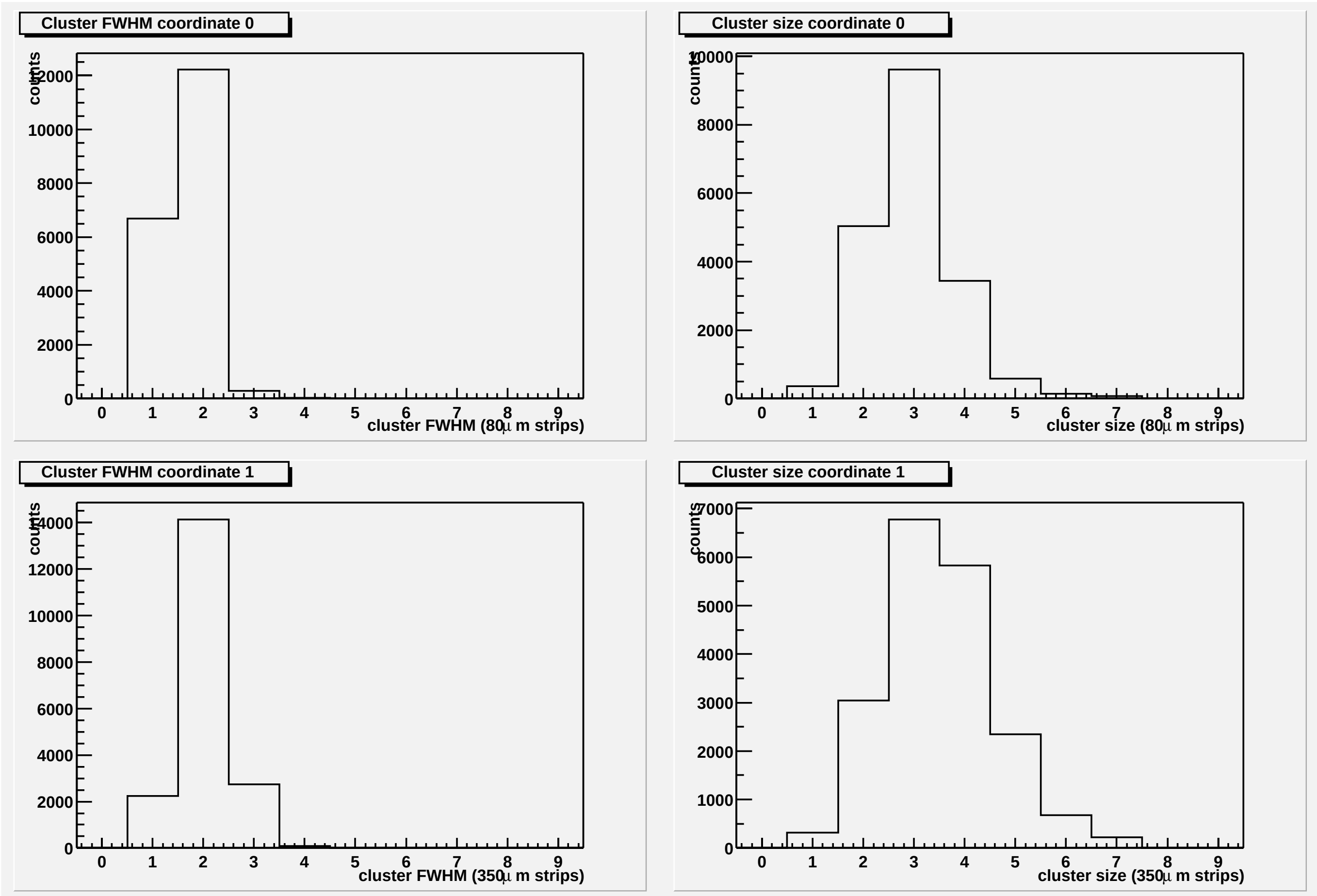


- Image of scintillator used for triggering clearly visible
- Deactivation of central part works efficiently
- Inactive regions underneath spacer grid

Cluster Size

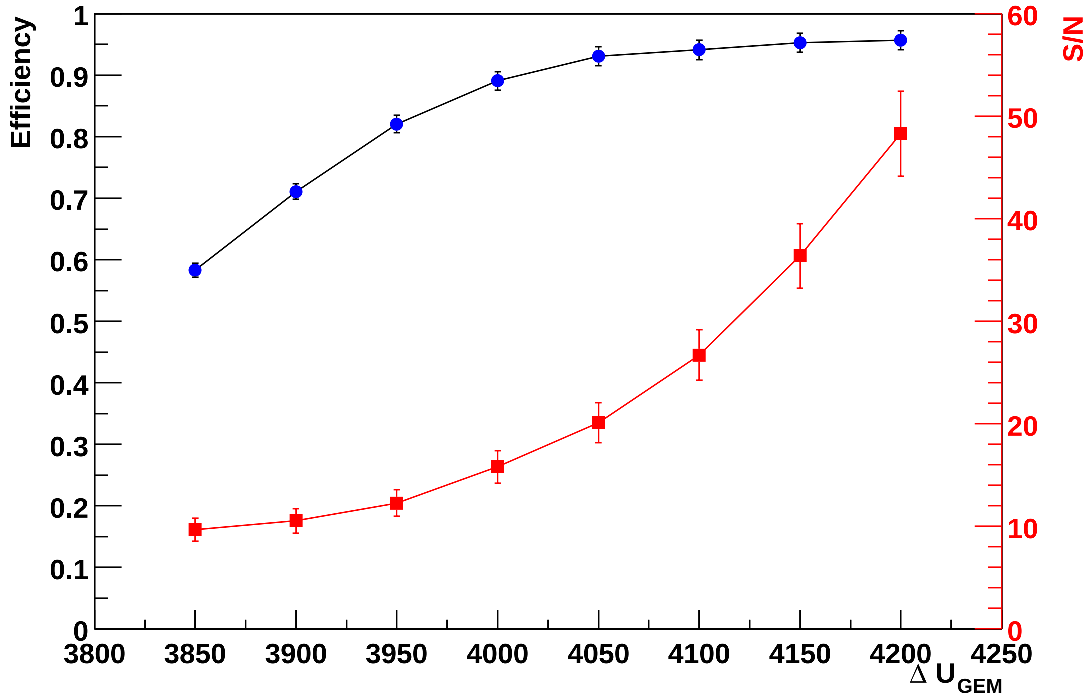
Cluster:

- strip amplitude $> 3\sigma_i$
- cluster amplitude $> 5\sqrt{\sum_i \sigma_i^2}$

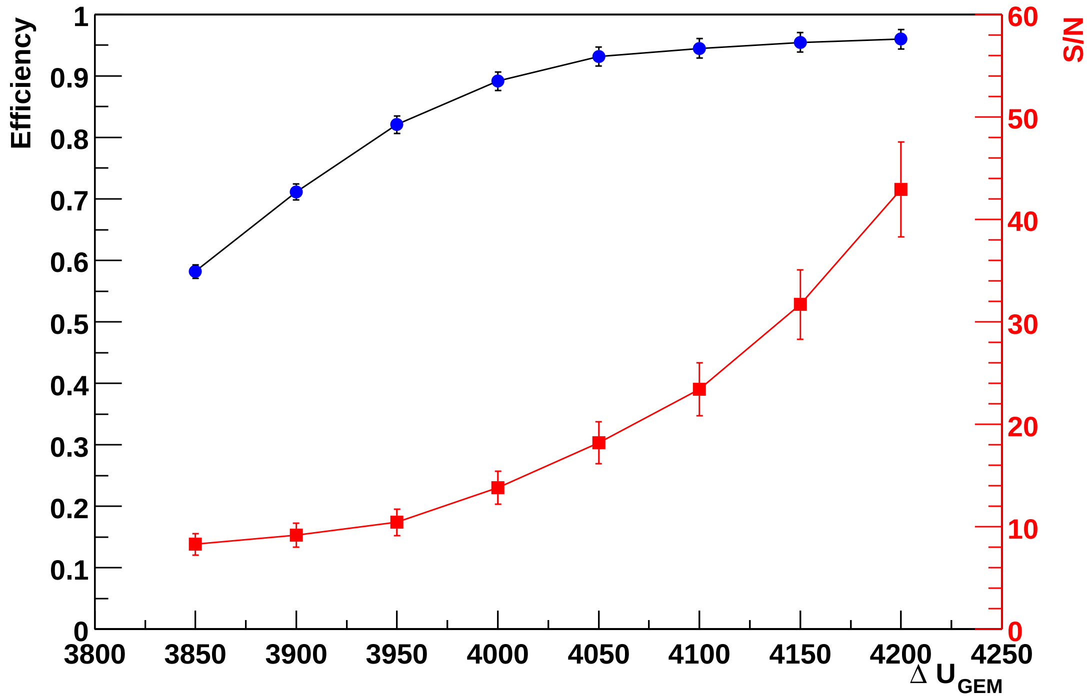


Efficiency

$80\,\mu$m strip layer: TGEM11

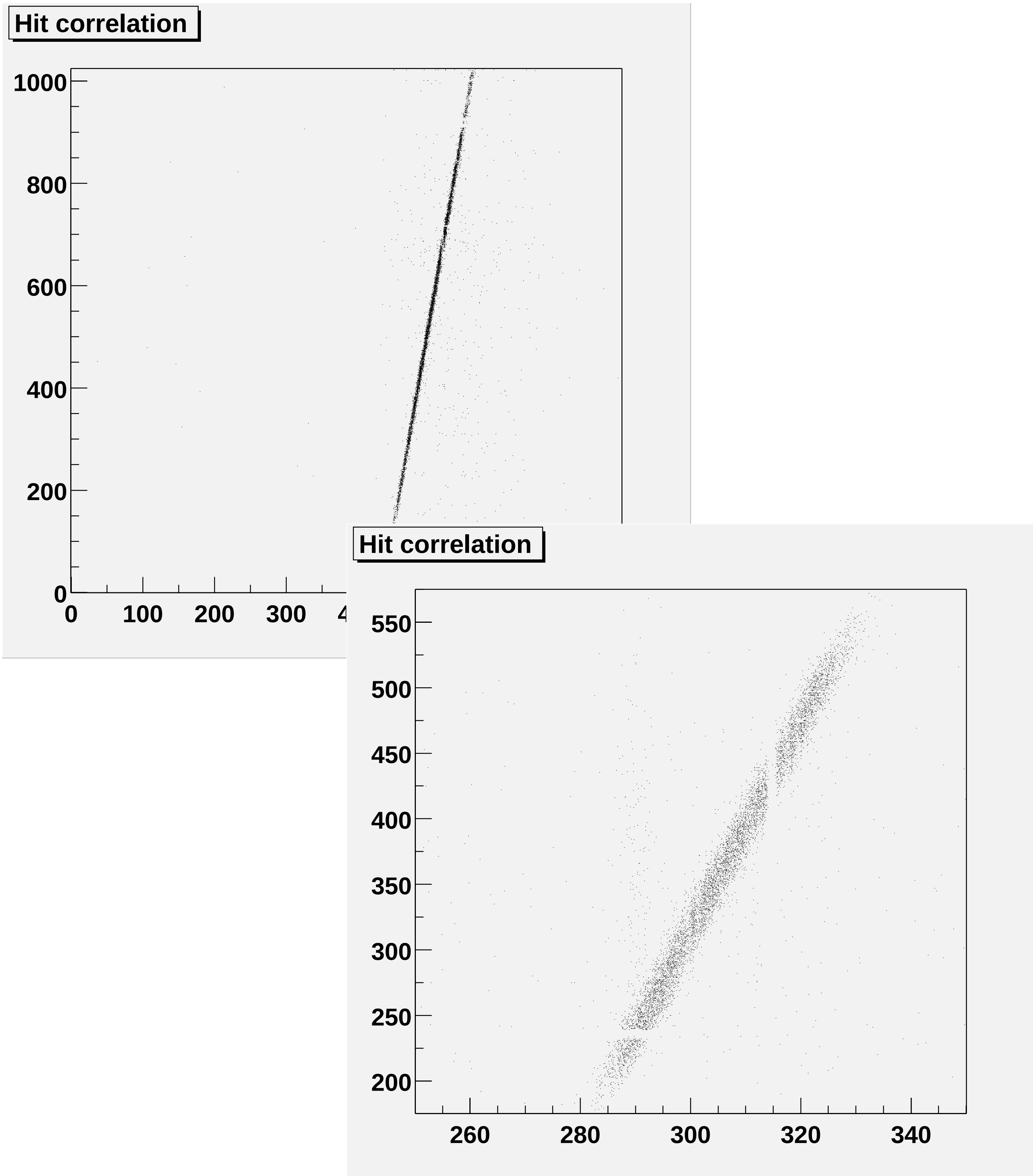


$350\,\mu$m strip layer:



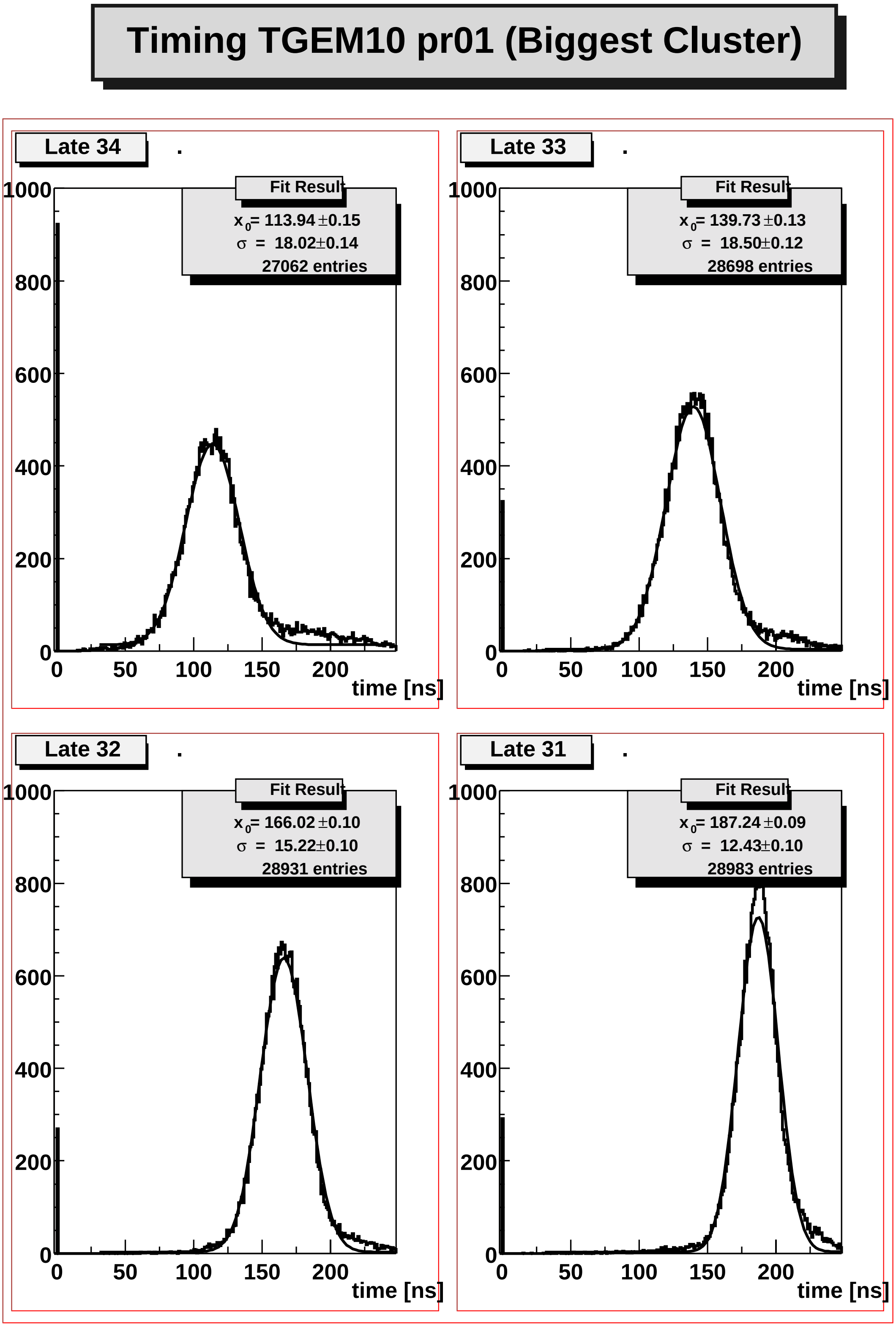
Hit Correlations

TGEM11 — SIL6, two projections



Time Resolution

APV25: 3-sample readout, rising edge of signal



Summary

GEM detectors meet requirements for tracking devices in modern HEP experiments:

- high rate capability
- no aging observed
- large active area
- thin, little material
- cheap

COMPASS adopted GEM detectors for SAT:

- $31 \times 31\,\mathrm{cm}^2$ active area
- 2-dimensional projective readout

Optimization

- triple GEM amplification
- sectorization of GEM foils
- asymmetric gain sharing
- input protection for FE chip APV25 S0

Beam test of COMPASS GEM detectors

- no loss of electronic channels
- low noise
- efficiency plateau reached at gain ~ 8000, $S/N \sim 18$
- narrow correlation of pulse heights
- time resolution $< 15\,\mathrm{ns}$

Outlook

Production of GEM detectors for COMPASS

- Ongoing at CERN-EP/TA1
- 9 detectors of final design assembled
- test procedures for QC of components and detectors defined

Goal for 2001: 14 detectors (70 % of total)

The Group

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