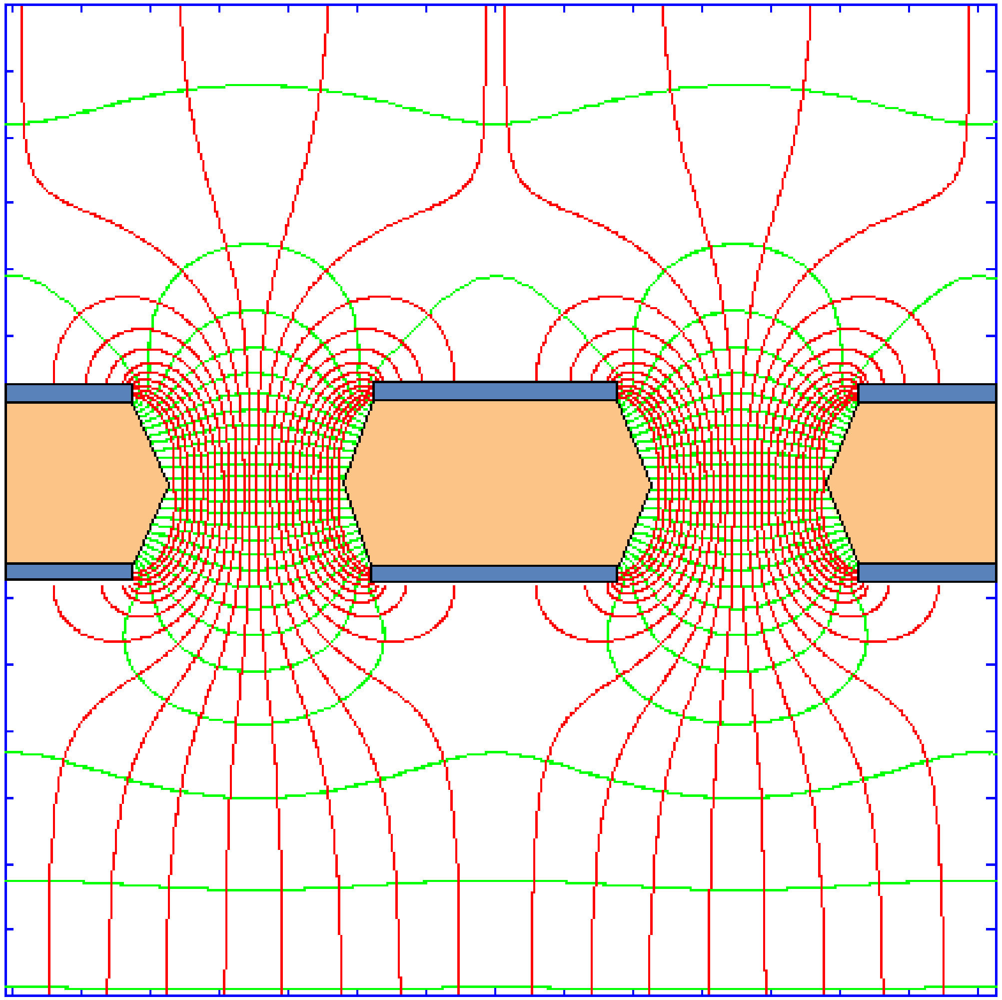
GEM
GAS ELECTRON MULTIPLIER

Development and Applications

Fabio SAULI , CERN Geneva Switzerland

Gas Electron Multiplier - GEM

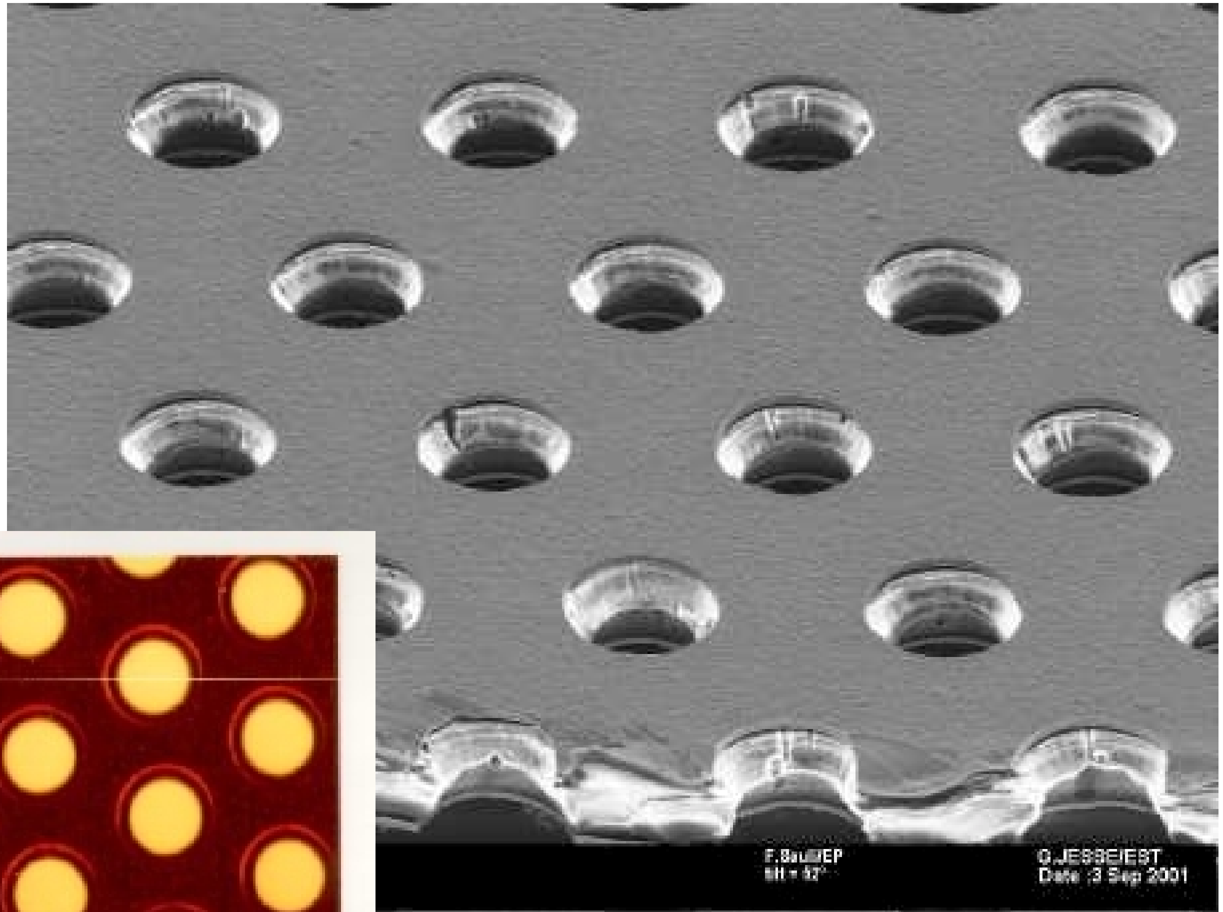
A thin polymer foil, metal-coated on both sides, is chemically pierced by a high density of holes. On application of a voltage gradient, electrons released on the top side drift into the hole, multiply in avalanche and transfer the other side.
Proportional gains above 10^3 are obtained in most common gases.

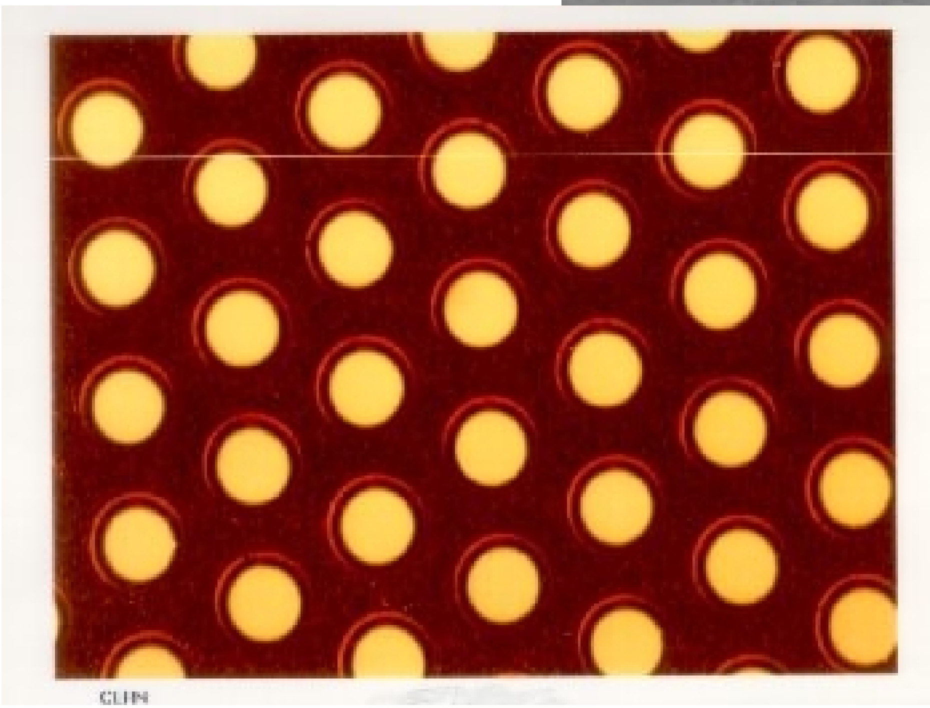


F. Sauli, Nucl. Instrum. Methods A386(1997)531

GEM Foil

Manufactured with printed circuit technology developed at CERN by A. Gandi and R. De Oliveira

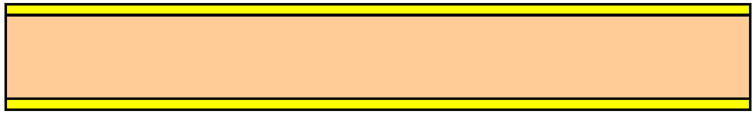




Typical geometry:
5 µm Cu on 50 µm Kapton
70 µm holes at 140 mm pitch

GEM Manufacturing

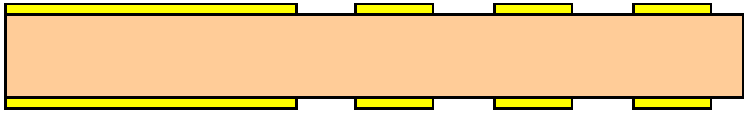
Basic material: Cu-plated Kapton foil:



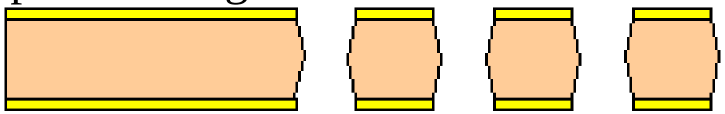
GEM

2-D Readout board

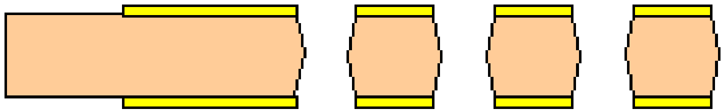
Copper etching



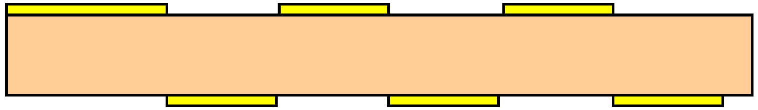
Kapton etching



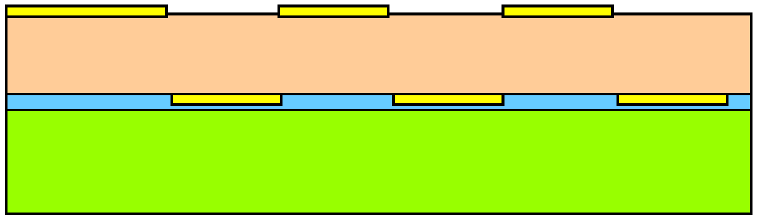
Edge finish



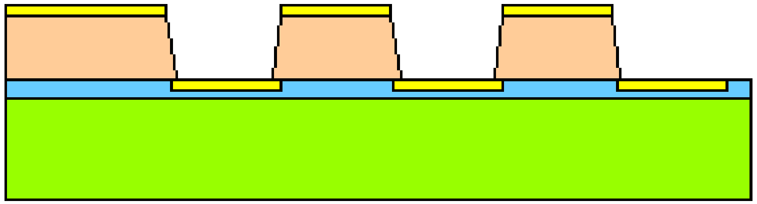
Copper etching



Gluing on support

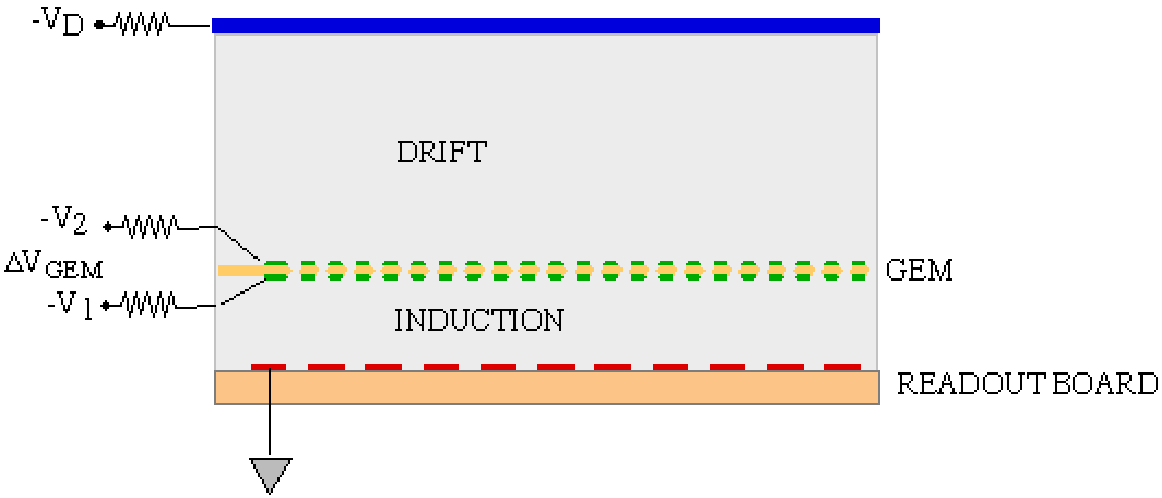


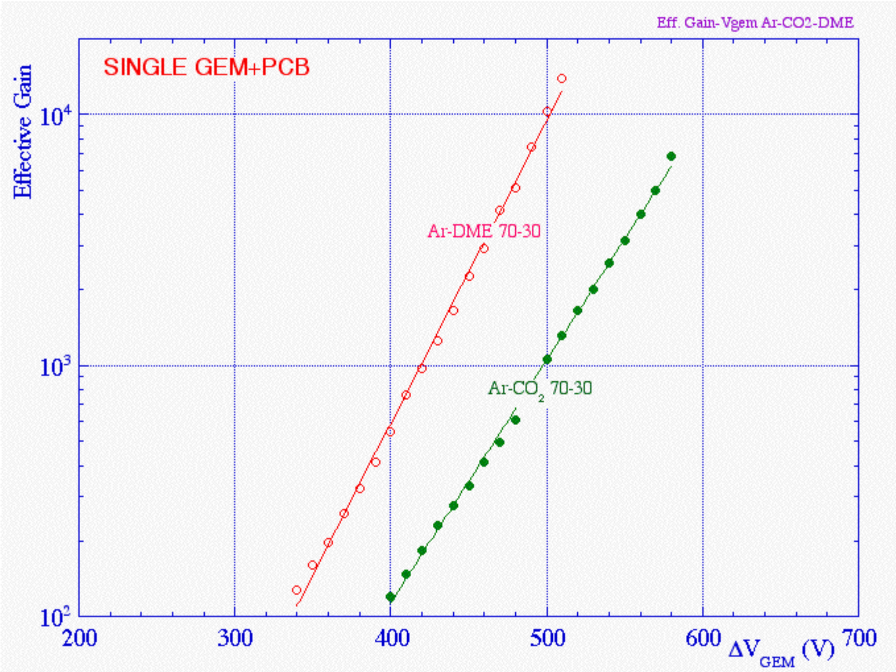
Kapton etching

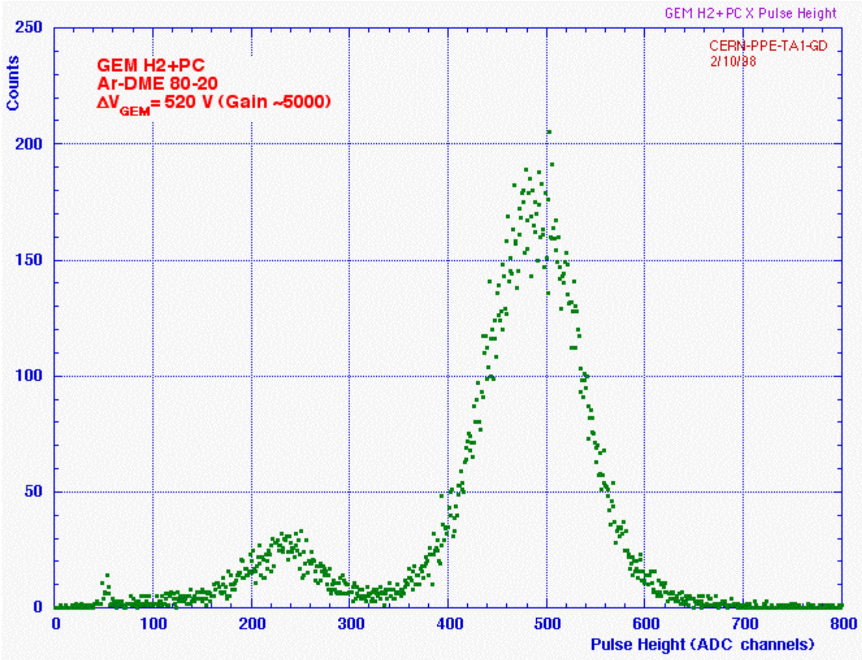


Single GEM + PCB

Electrons multiplied and transferred into the induction gap are collected and detected on a patterned printed circuit board (pads, strips…)



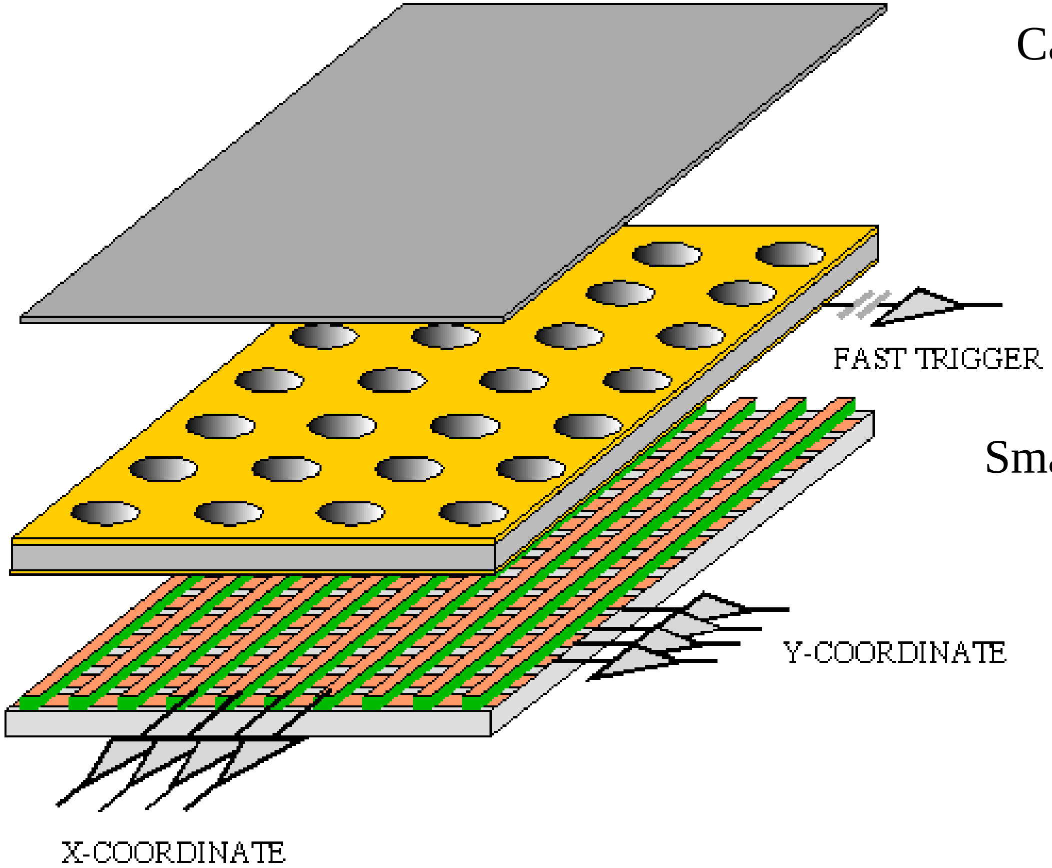




R. Bouclier et al, Nucl. Instr. and Meth.A396(1997)50

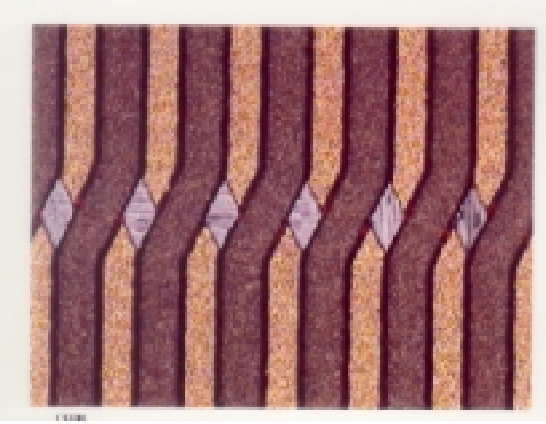
2-Dimensional Readout

The electron charge is collected on strips or pads on the readout board. A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.

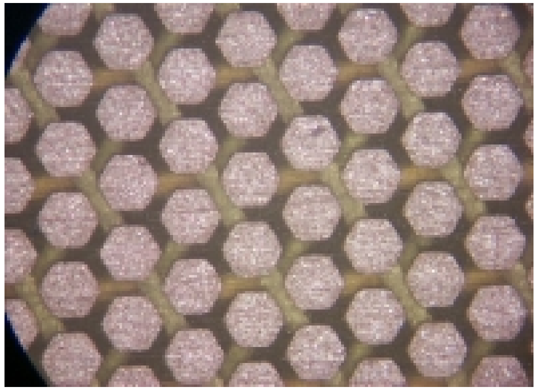


Cartesian

Small angle



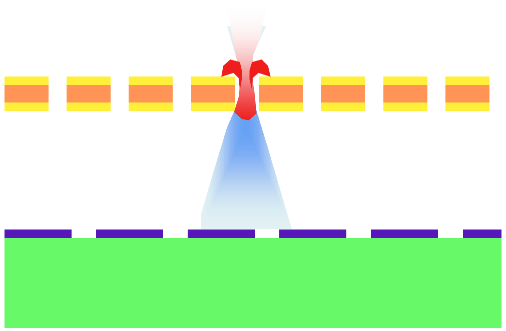
Pads



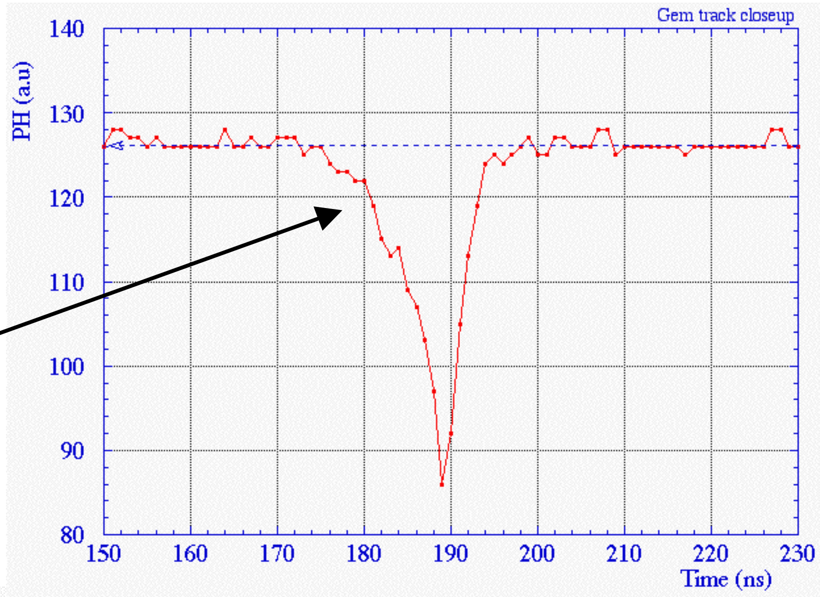
A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

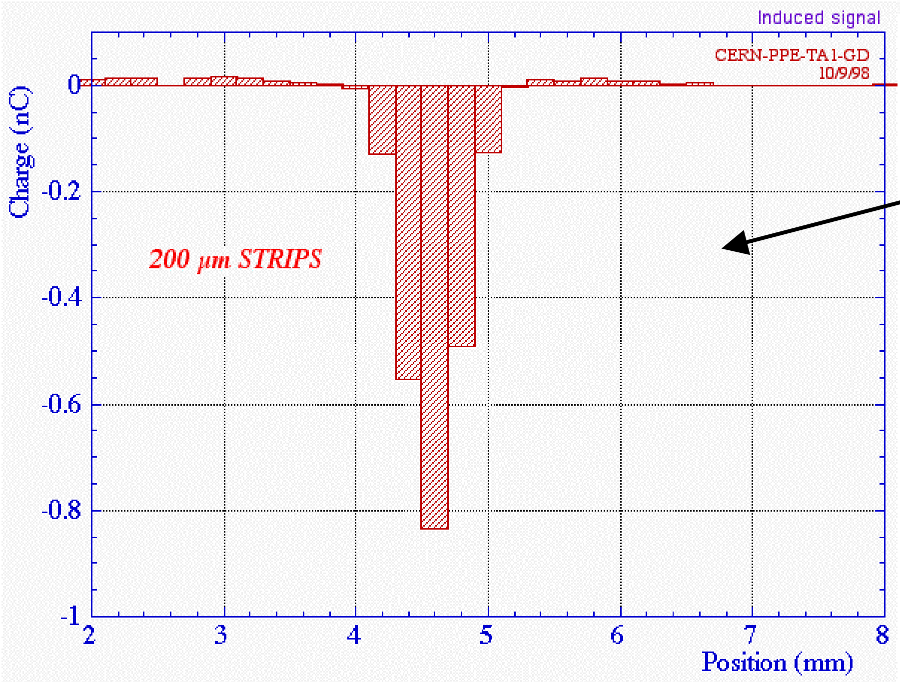
Fast electron signal

The total length of the detected signal corresponds to the electron drift time in the induction gap:



Full Width 20 ns
(for 2 mm gap)





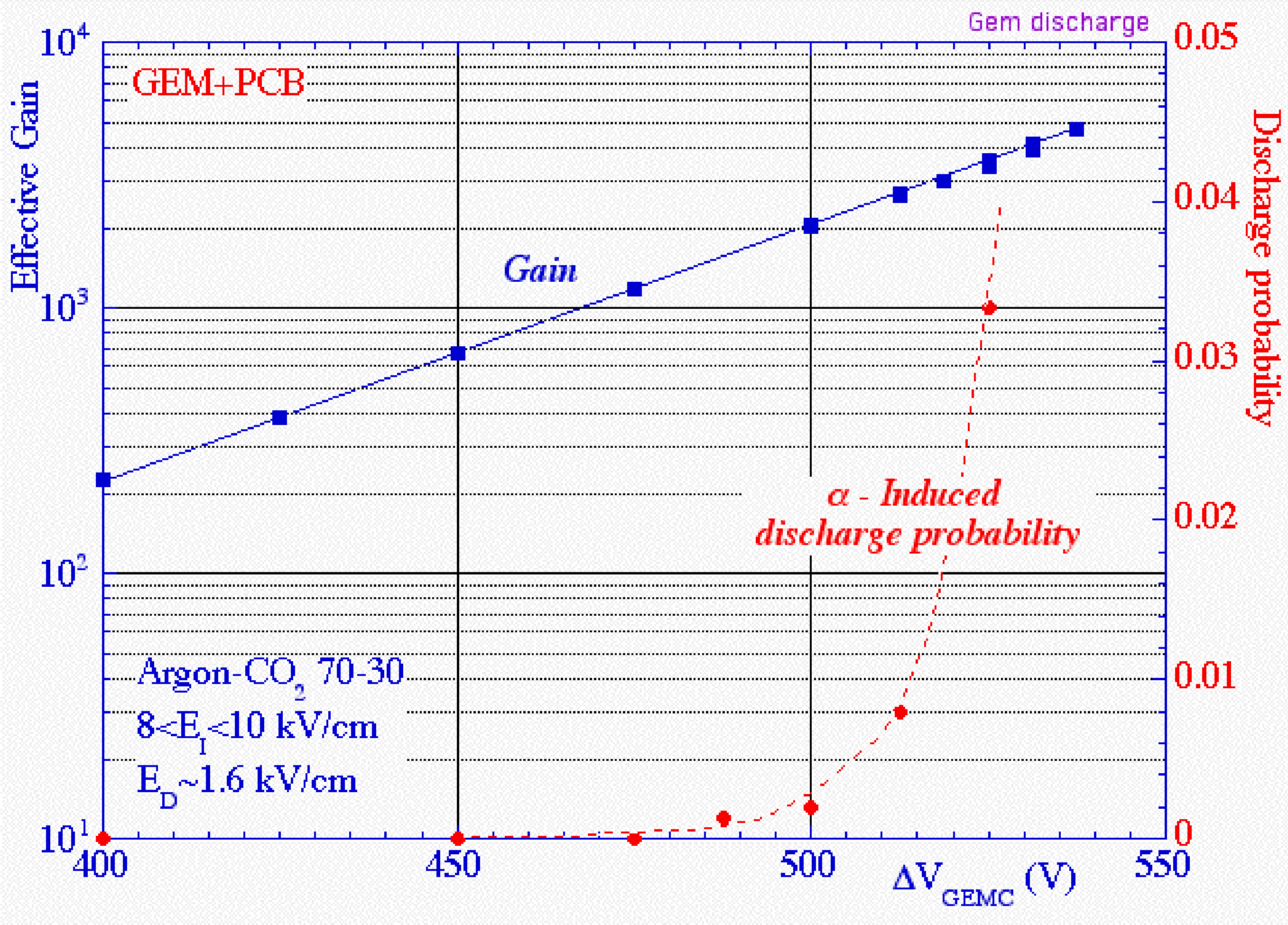
Induced charge profile on strips
FWHM 600 μm

F NO POSITIVE ION TAIL
Very good multi-track resolution

Micro-Pattern Gas Detectors: Discharge problems

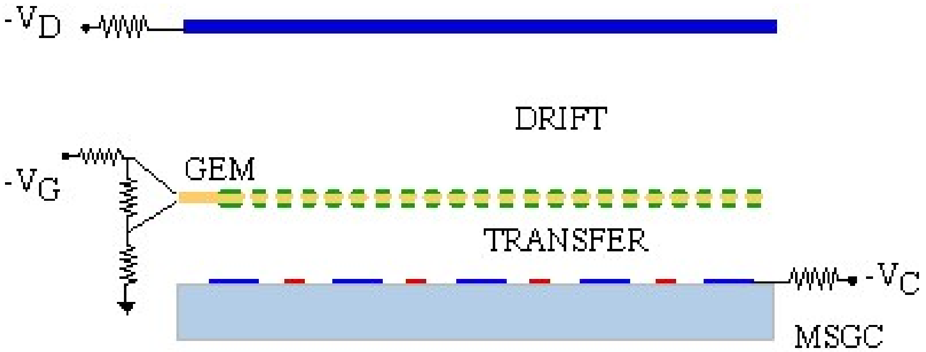
Exposed to heavily ionizing tracks (alpha particles) all micro-pattern detectors discharge at low gains

A similar behavior is observed for MSGCs, PPAC, GEM, MGC, µM,…

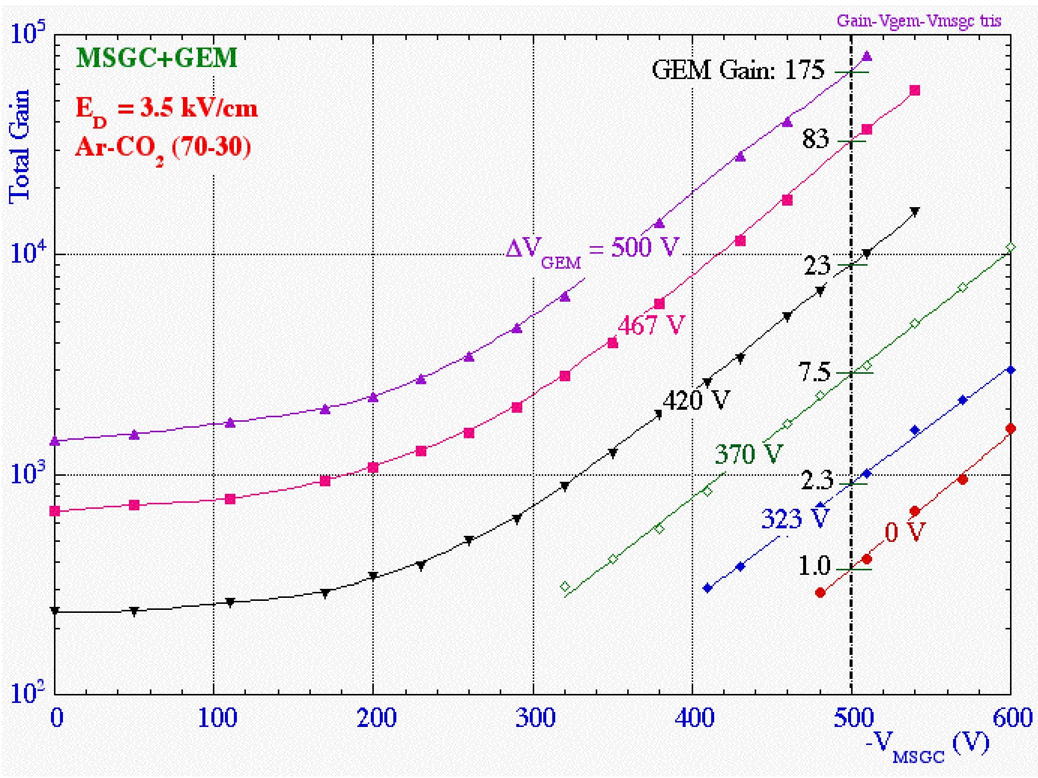


A. Bressan et al, Nucl. Instr. and Meth. A424(1999)361

Micro-Strip Gas Chamber + GEM



Addition of GEM over the MSGC allows to largely increase the gain before discharge:



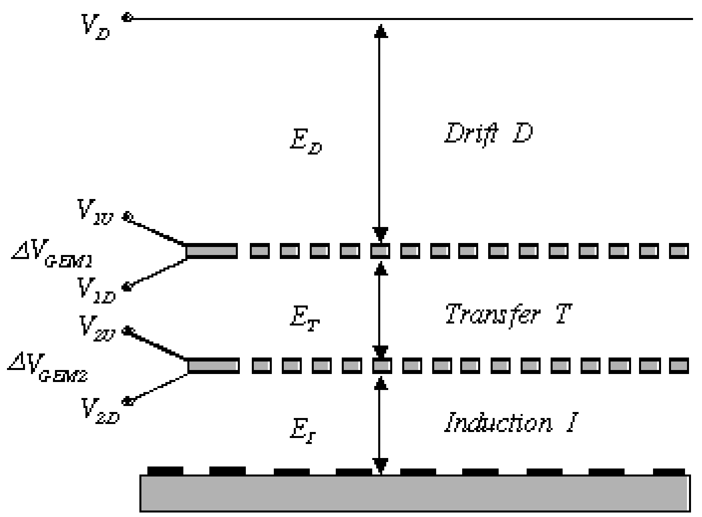
Solution adopted by the HERA-B tracker
~ 200 large size MSGC+GEM detectors built and operational

T. Zeuner, Nucl. Instr. and Meth. A446(2000)324

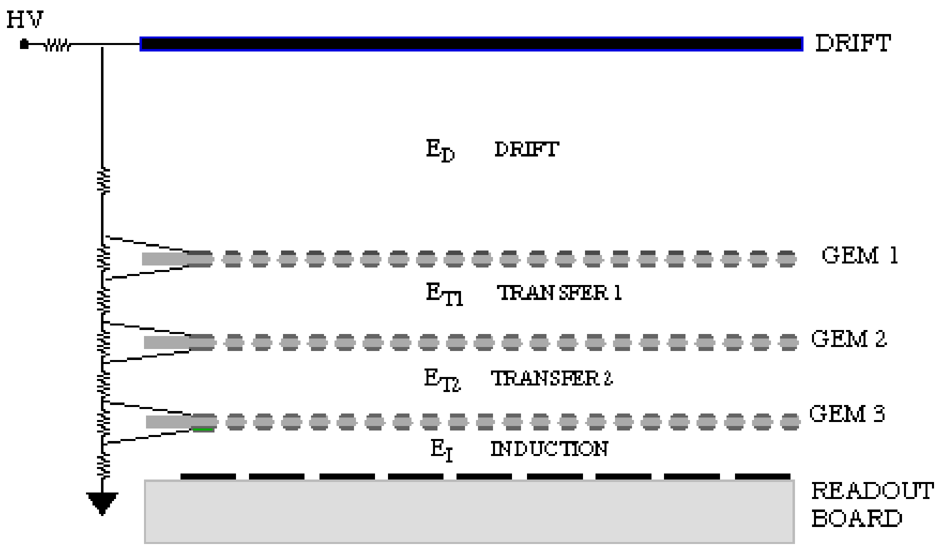
Multiple GEM Structures

Cascaded GEMs permit to obtain larger gains

Double GEM



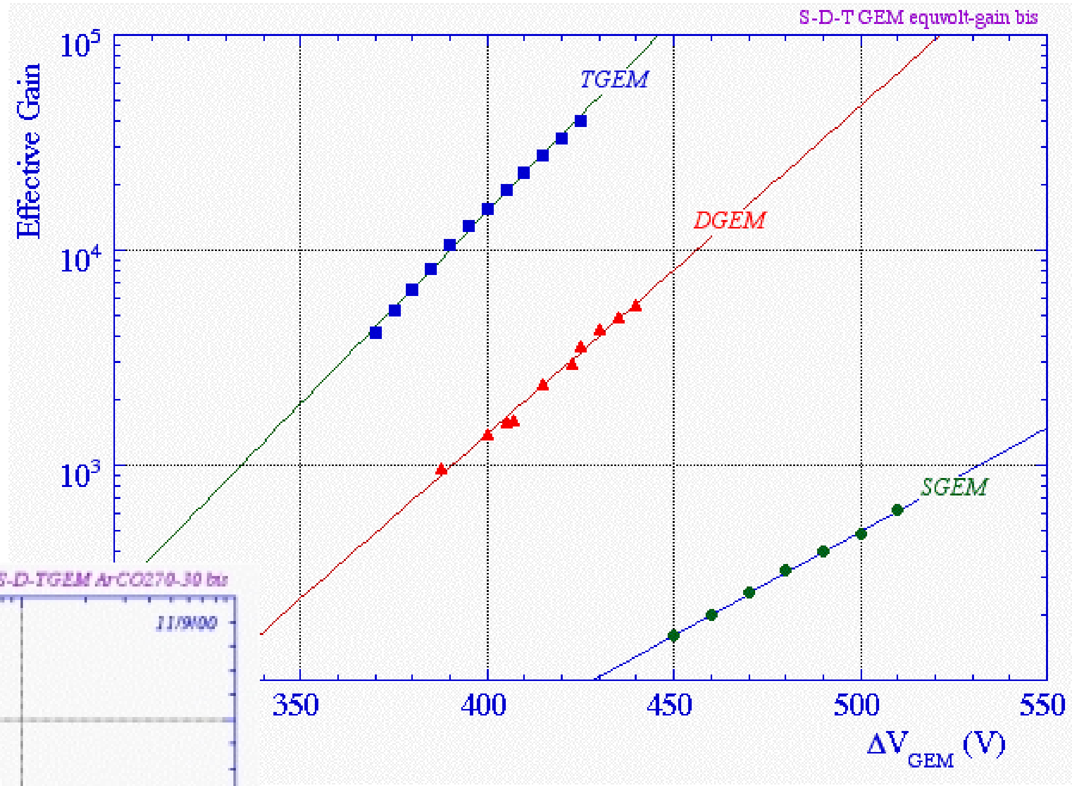
Triple GEM

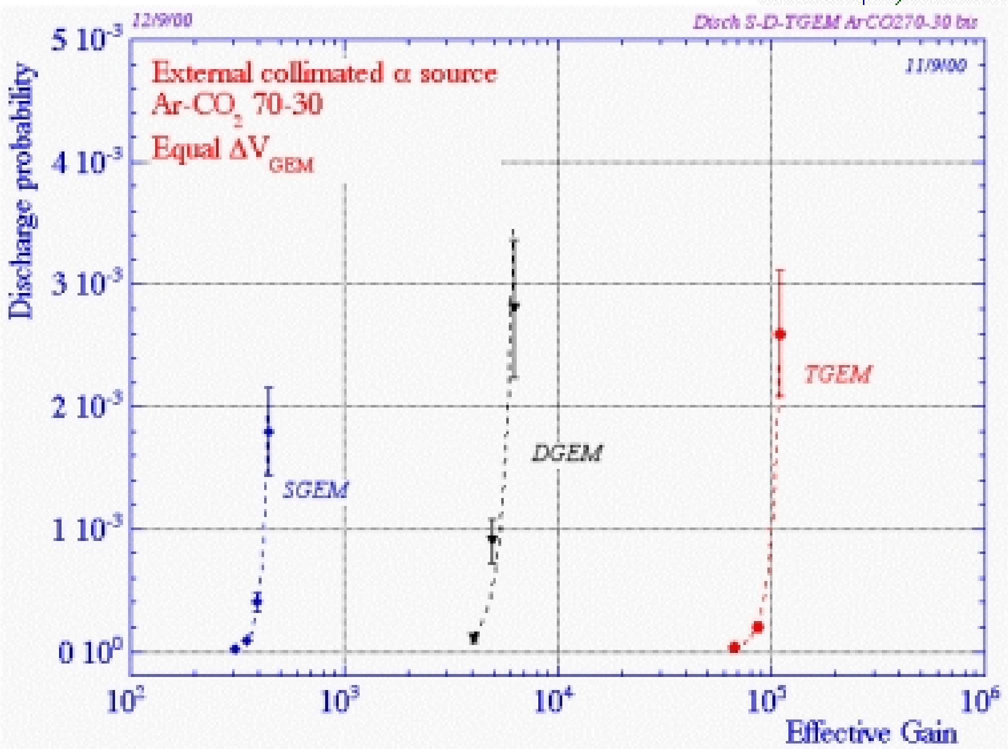


C. Buttner et al, Nucl. Instr. and Meth. A 409(1998)79
S. Bachmann et al, Nucl. Instr. and Meth. A 443(1999)464

S-D-TGEM Gain and Discharge

Multiple structures provide equal gain at lower voltage
The discharge probability on exposure to α particles is strongly reduced



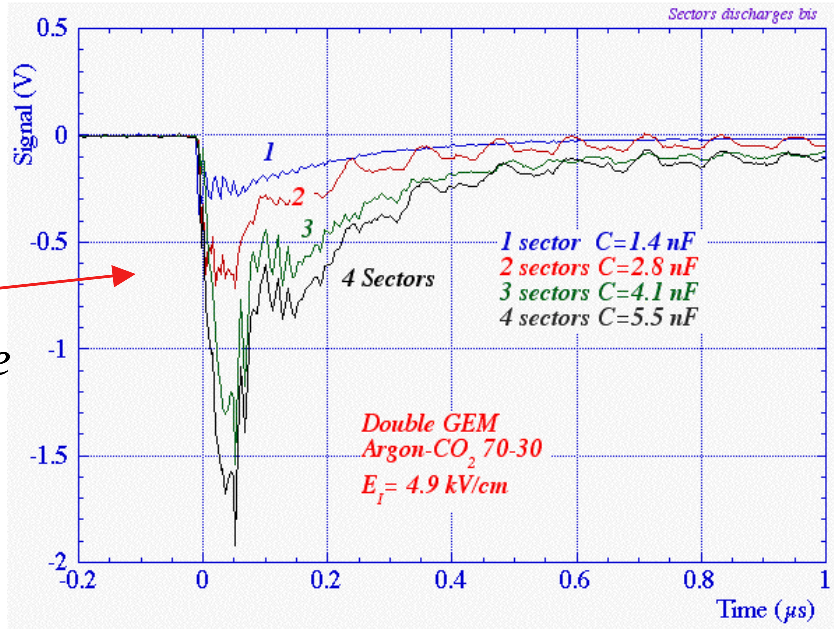


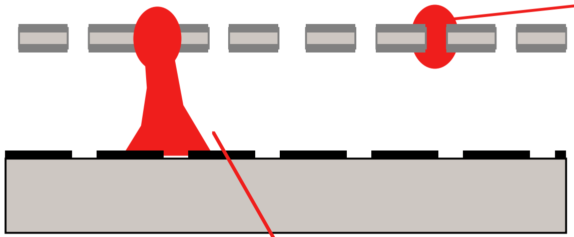
For a gain of 8000 (required for full efficiency on minimum ionizing tracks) in the TGEM the discharge probability is not measurable.

S. Bachmann et al, CERN-EP/2000-151

Discharge energy

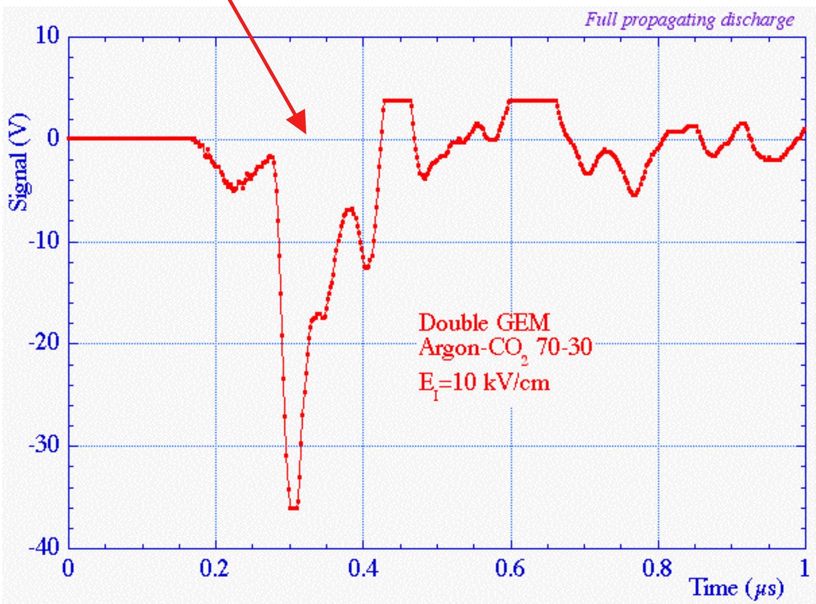
Discharges can be limited to GEM or propagate to the readout board. In the first case, the energy depends on the GEM capacitance.





GEM discharge

Propagating discharge



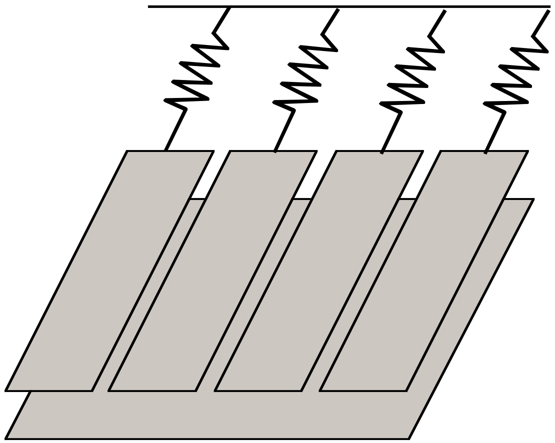
The energy of a full propagating discharge is 30 to 50 times larger than a GEM discharge

S. Bachmann et al, CERN-EP/2000-151

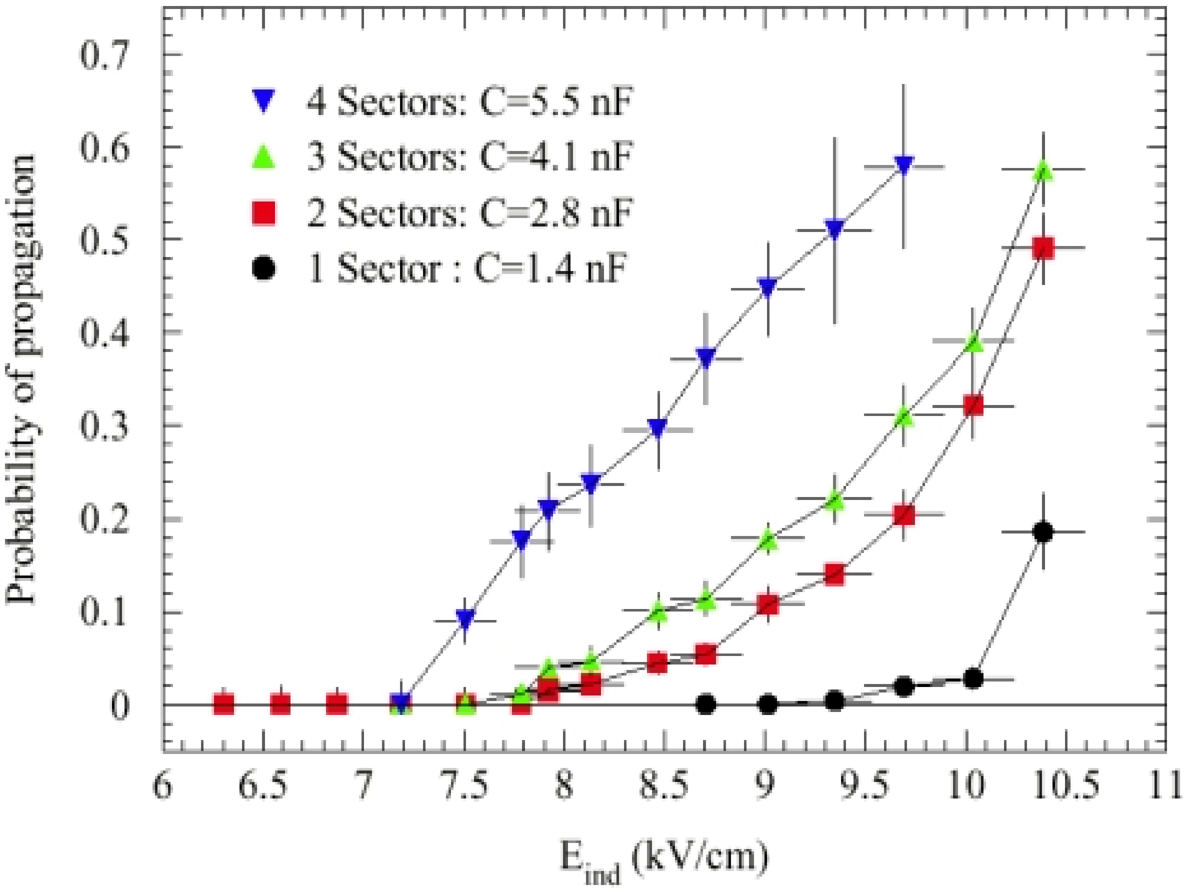
Propagating discharge probability

The full discharge propagation probability depends on the induction field and on the energy (capacitance) of the primary GEM discharge:

Segmented upper GEM electrode



Lower GEM electrode

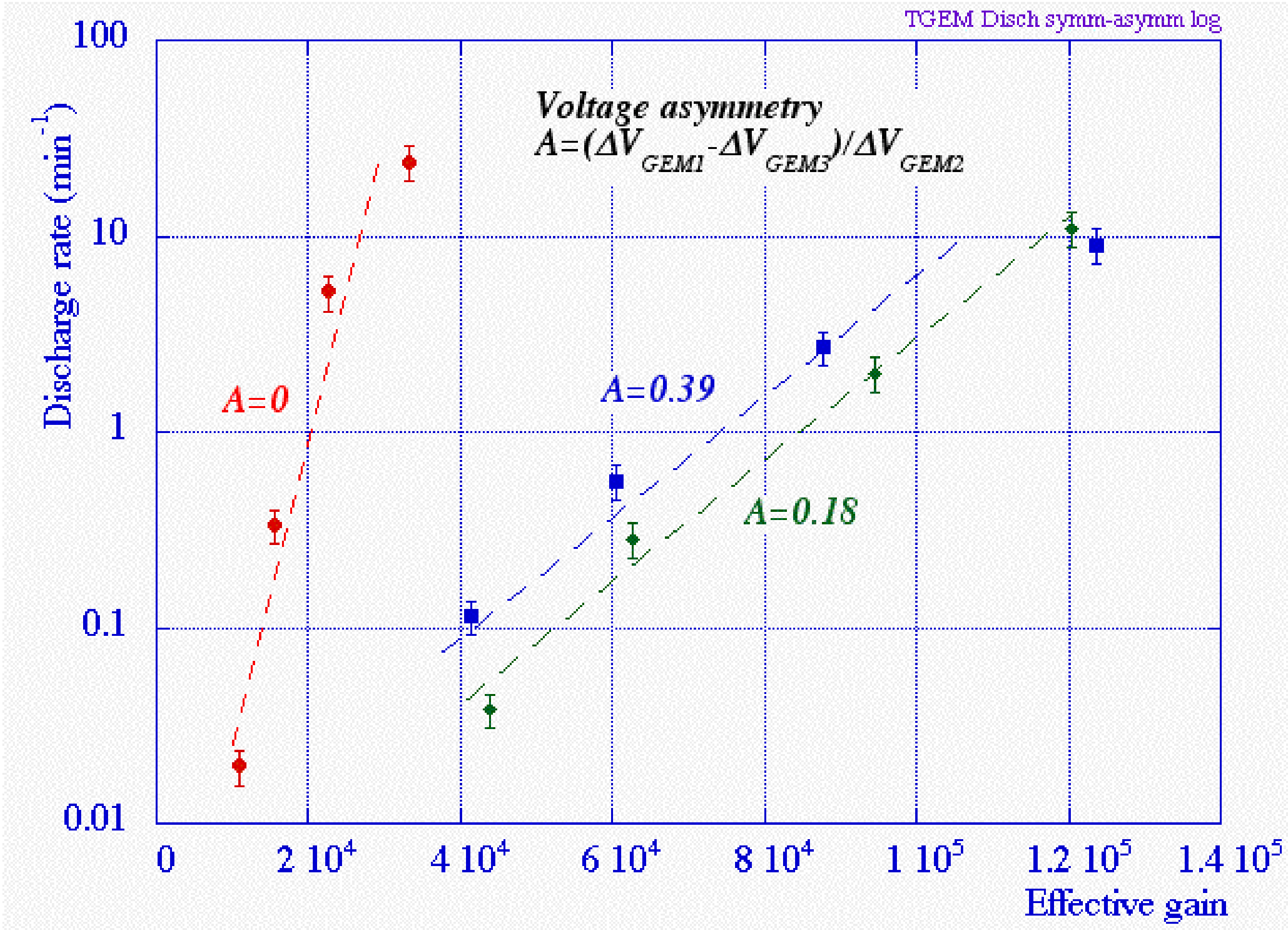


- GEM sectorization reduces discharge energy and propagation probability
- Operation at low induction fields (< 5 kV/cm)

Asymmetric gain sharing

Higher (lower) gain on first (last) GEM largely reduces discharge probability:

COMPASS
Triple-GEM

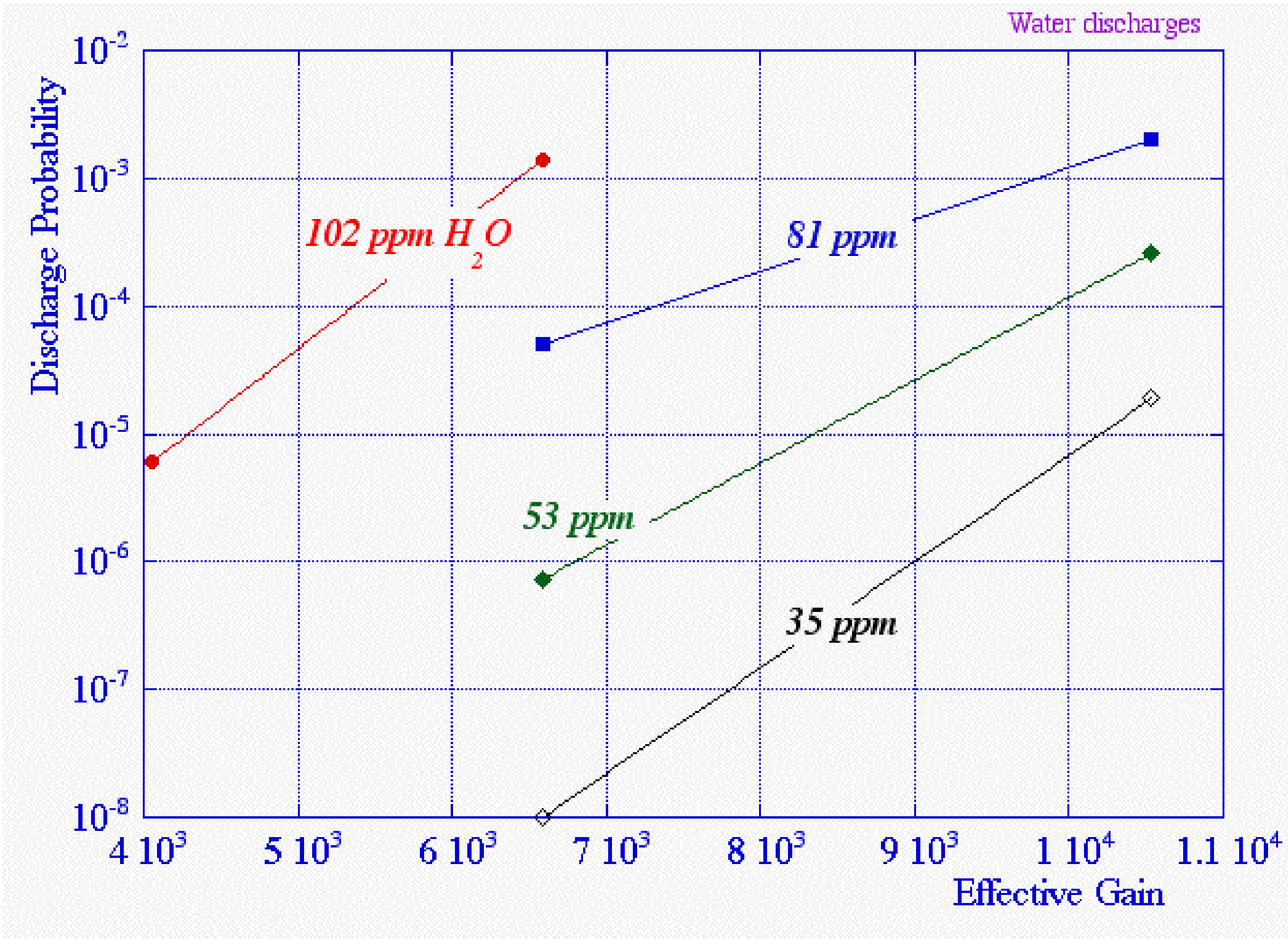


• With asymmetric gain sharing, the discharge probability is lower by ~ 2 orders of magnitude at a given gain!

Influence of water content

The probability of α-induced discharges depends strongly from water content:

Double GEM
10 x 10 cm^2

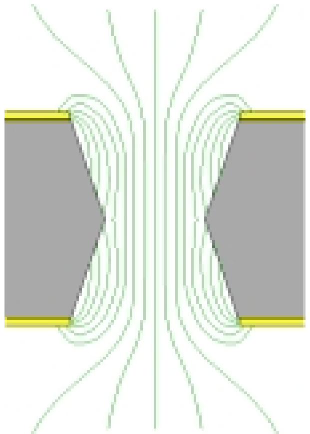


• Use Only metal gas pipes in the experiment (measured water content < 50 ppm)

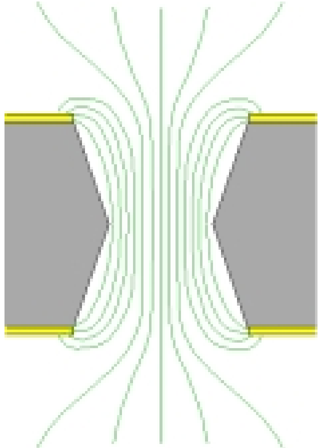
Charging up

Due to the slight double-conical shape of the holes, consequence of the chemical manufacturing, charges can deposit on the insulator and dynamically modify the gain.

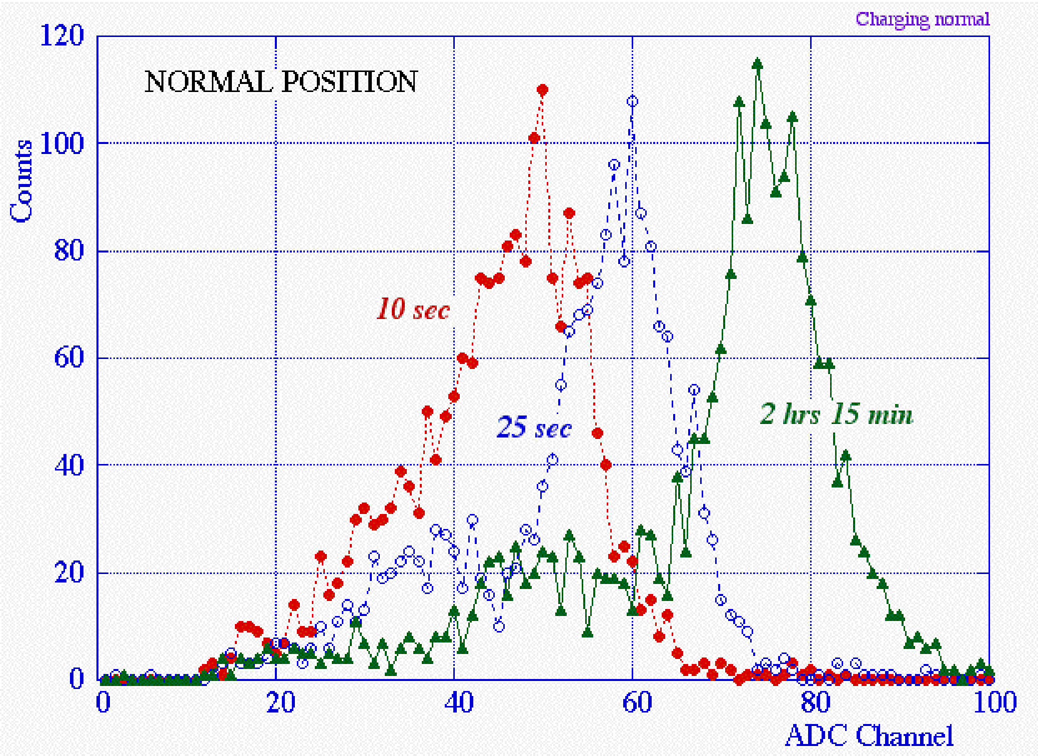
Ions and electrons accumulate on the insulator; equilibrium is reached when no field line enters the dielectric:



Due to the increase of field in the hole, the gain increases with charging up until equilibrium is reached.

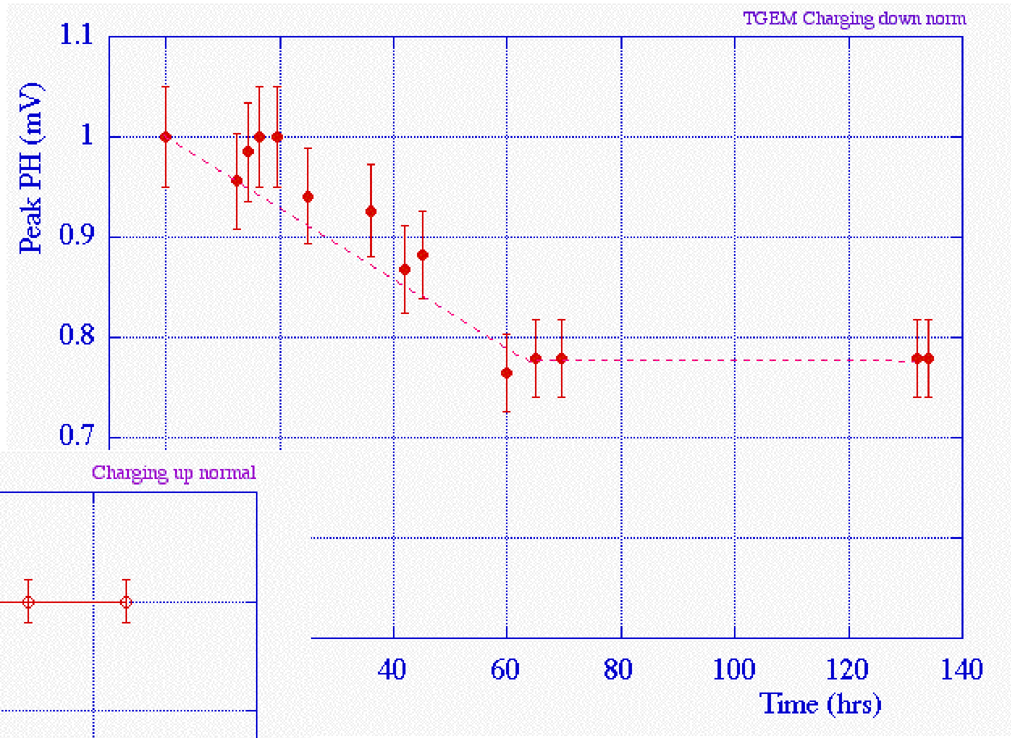


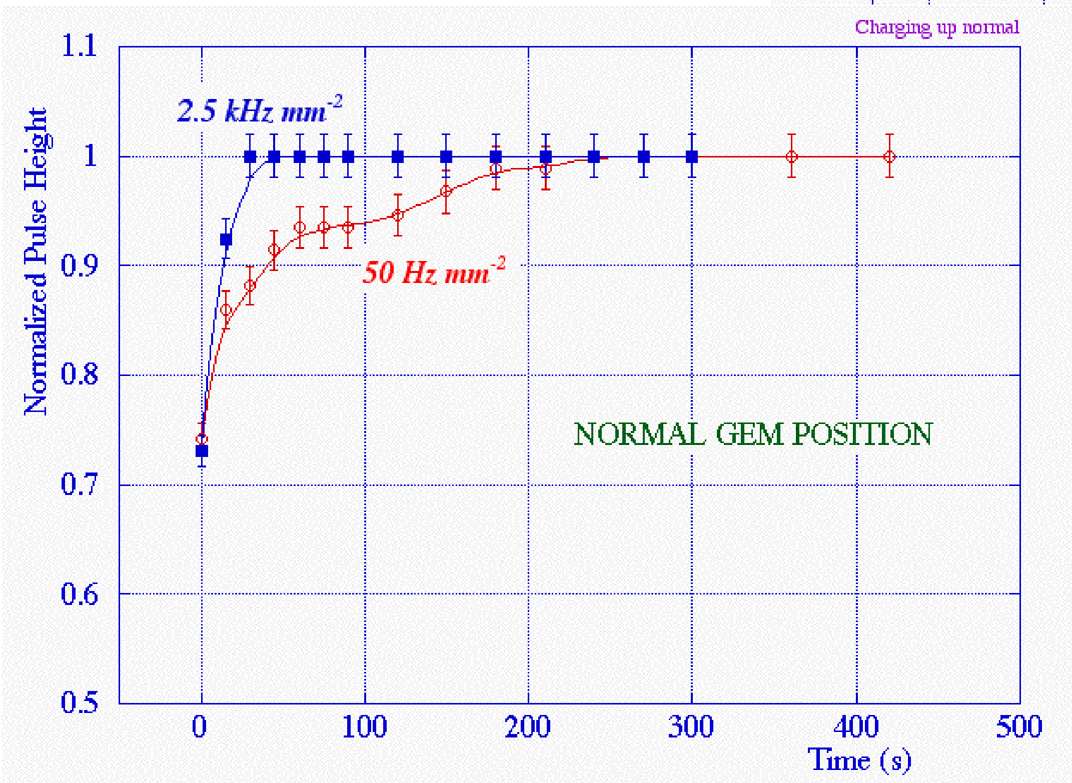
Time evolution of pulse height spectra for 9 keV X-rays:



Charging up - Charging down

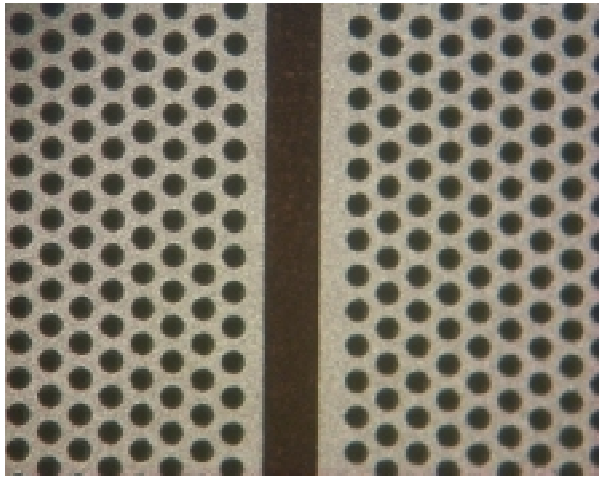
Charging up depends on irradiation rate, but the gain saturates at the same value:





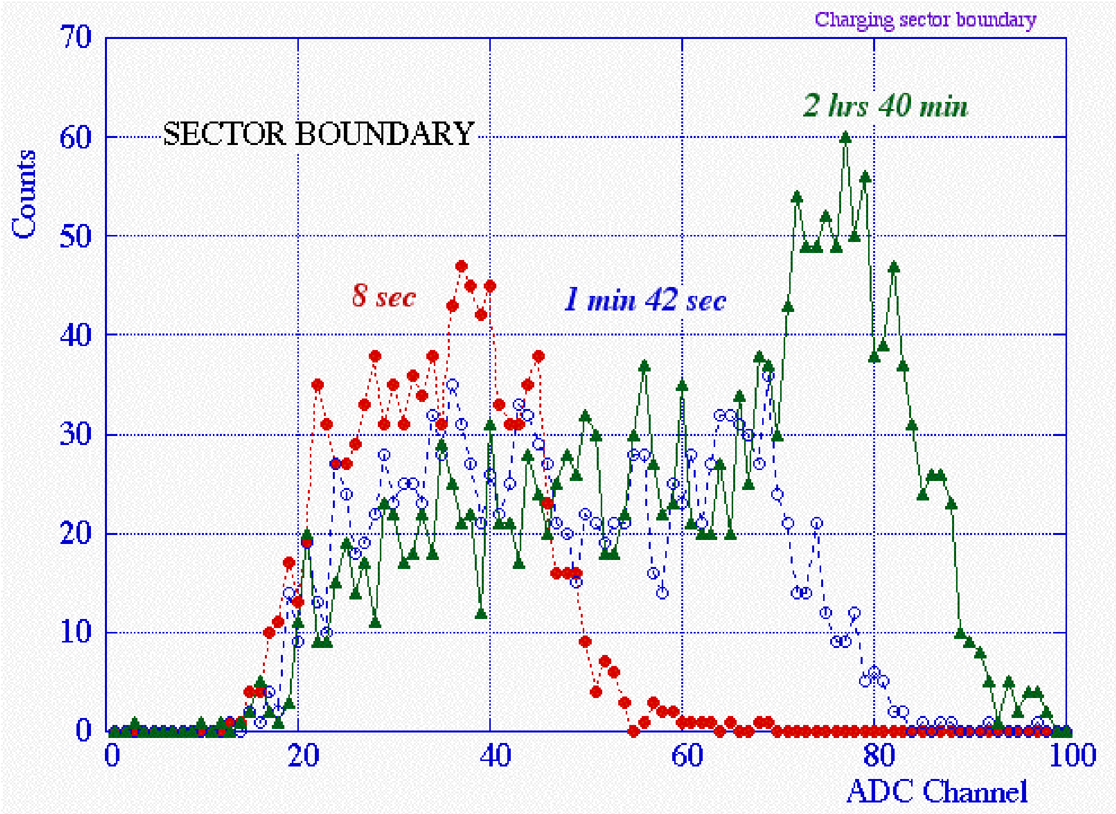
Removing the source, charging down takes several days

Sector boundary charging

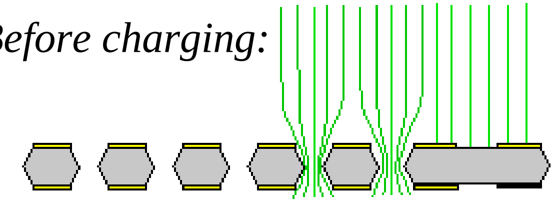


Charging under irradiation of the insulating gap (partially) restores collection efficiency.

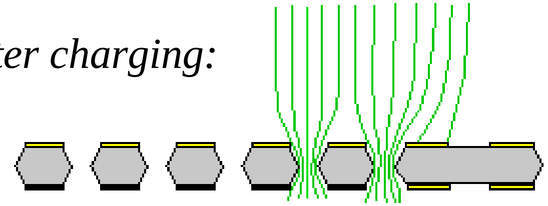
Pulse height spectra for 9 keV X-rays in the sector boundary region:



Before charging:



After charging:

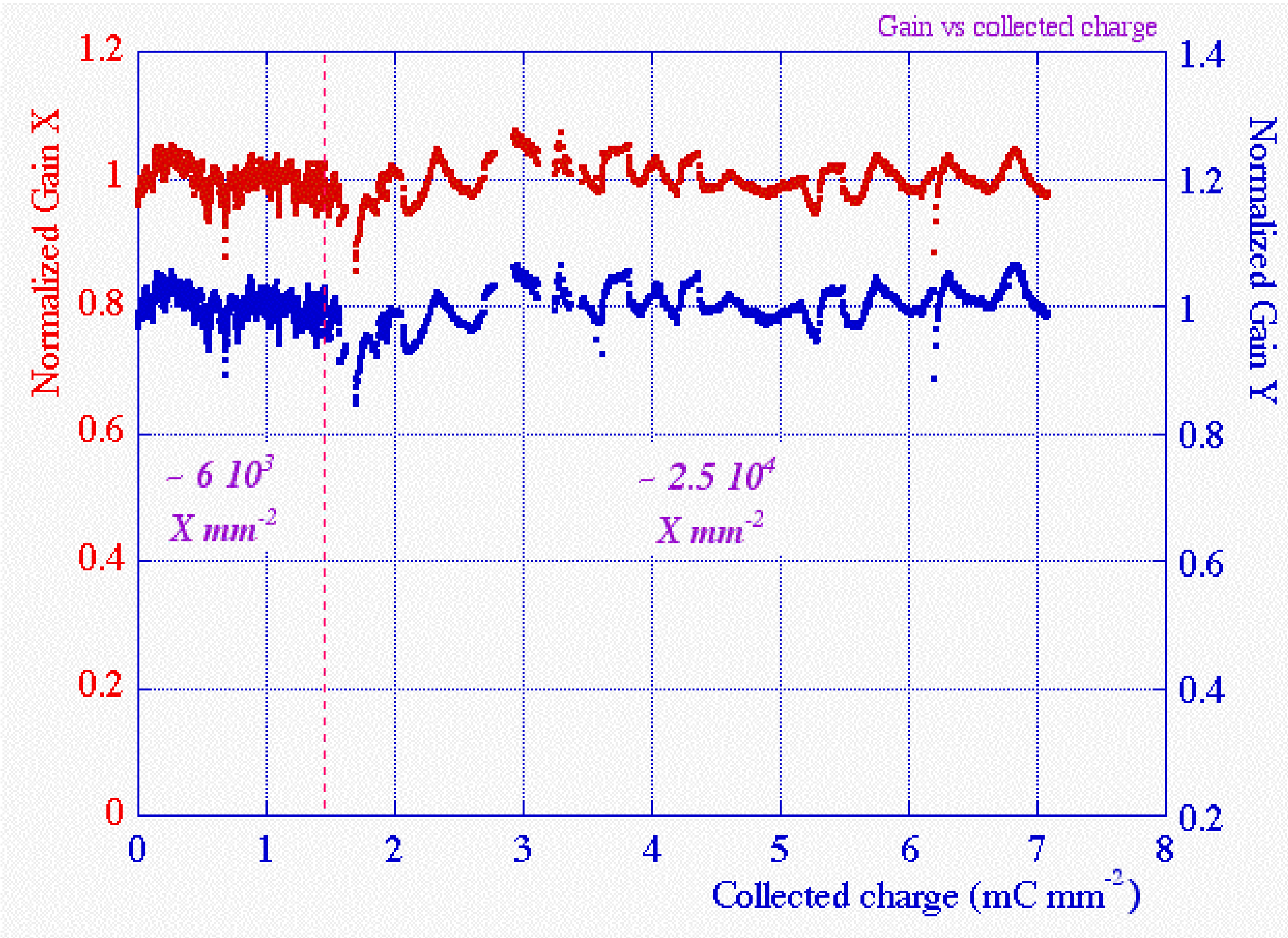


Aging

GEM detectors are rather insensitive to aging under sustained irradiation

- Larger area available to polymer deposits
- Avalanche growth mostly on the hole's center (far from electrodes)

Gain as a function of collected charge, measured on a production TGEM COMPASS chamber

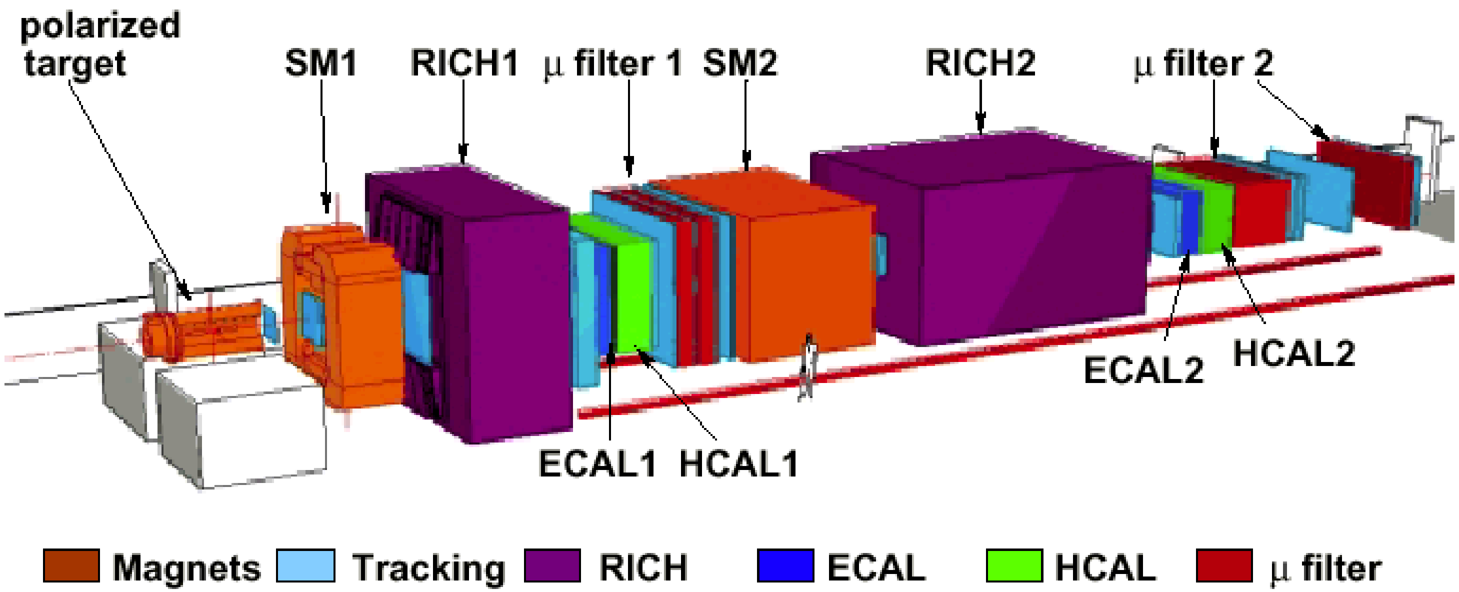


C. Altunbas et al, DESY Aging Workshop (Nov. 2001) Subm. Nucl. Instr. and Meth.

COMPASS

Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Beam on Target: 2.10^8 Hadrons/spill
10^8 Muons/spill



COMPASS, CERN/SPSLC 96-14 (1996)

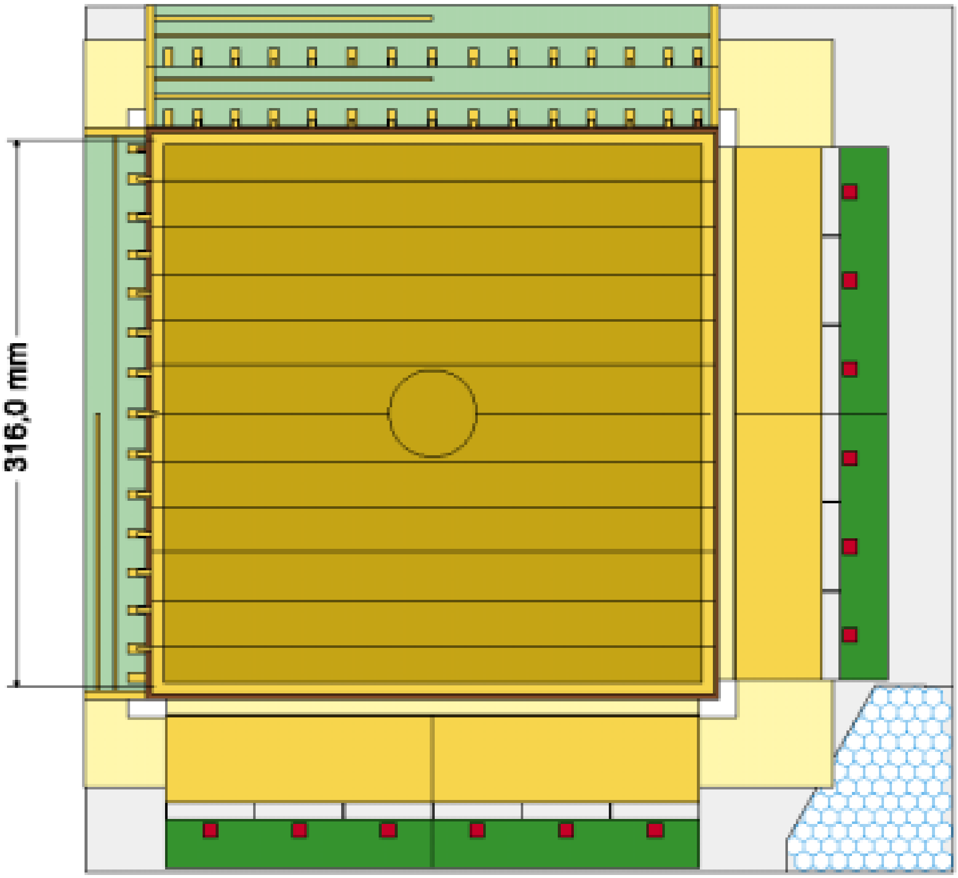
Requirements for the Small Area Tracker:
High Rate and Multi-Particle Capability
Good Space Resolution
Large active area
Low mass

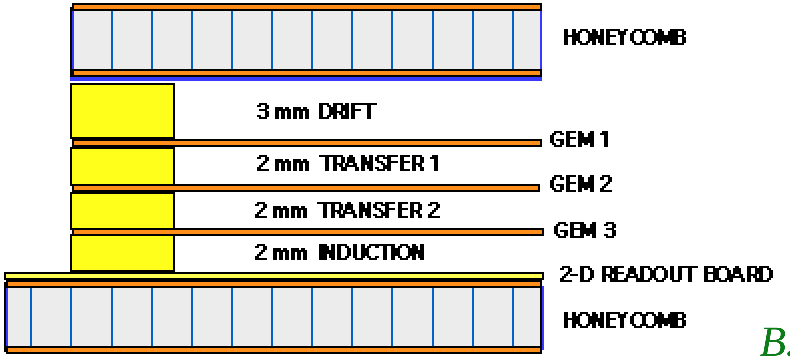
☞

20 Triple-GEM detectors
31 x 31 cm^2 active
2-Dimensional Read-out
Segmented

COMPASS Triple-GEM Detector

- Active Area 30.7 x 30.7 cm^2
- 2-Dimensional Read-out with
  2 x 768 Strips @ 400 μm pitch
- 12+1 sectors GEM foils
  (to reduce discharge energy)
- Central Beam Killer 5 cm Ø
  (remotely controlled)
- Total Thickness: 15 mm
- Honeycomb support plates
  (Low Mass)



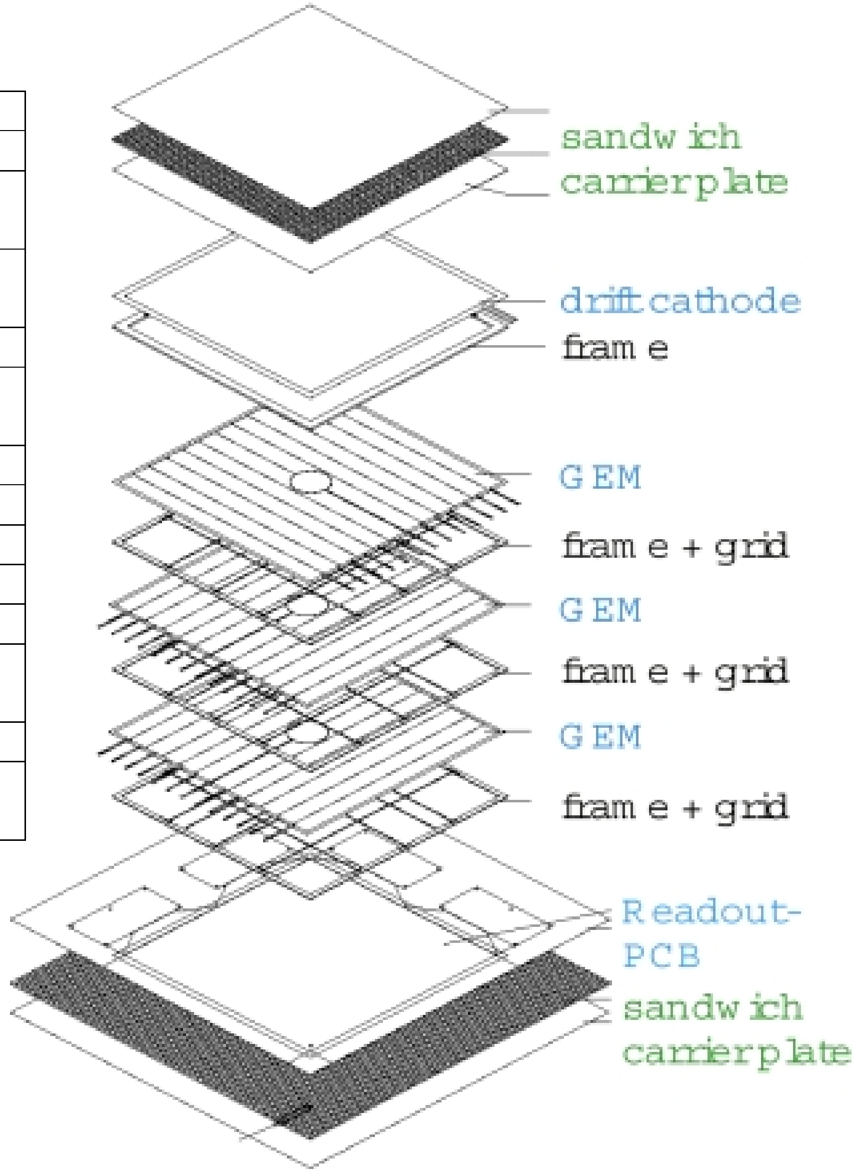


A succession of thin frames holding GEMs is glued on on light honeycomb supporting plates

B. Ketzer et al, IEEE Trans. Nucl. Sci. NS-48(2001)

COMPASS Triple-GEM Construction

Material	Details
Assembly Glue	ARALDIT AY103 + HD991 (ratio 10:4)
Frame & grid spacer conditioning	Polyurethane (2 component) Nuvovern LW
Honeycomb Sandwich structure	Stesalit (125 mm)-Honeycomb Nomex (3 mm)-Stesalit (125 µm)
Shielding	Aluminium (10 µm)
GEM foils (50 mm)	50 µm thick kapton, 5 µm copper, 70 µm hole diameter., 140 µm pitch
Drift	5 µm Cu on 50 µm kapton
Drift Frame	3 mm thick Stesalit
Spacers	Fibreglass grids 2 mm thick
Gas pipes	PP tube (3 mm diameter)
Gas outlet	Fibreglass + fitting
PCB	Active area 30.7 x 30.7 cm^2, 2-dim 2x 768 strips, 400 µm pitch
HV boards	Custom made
HV protection and sealant	R4-3117

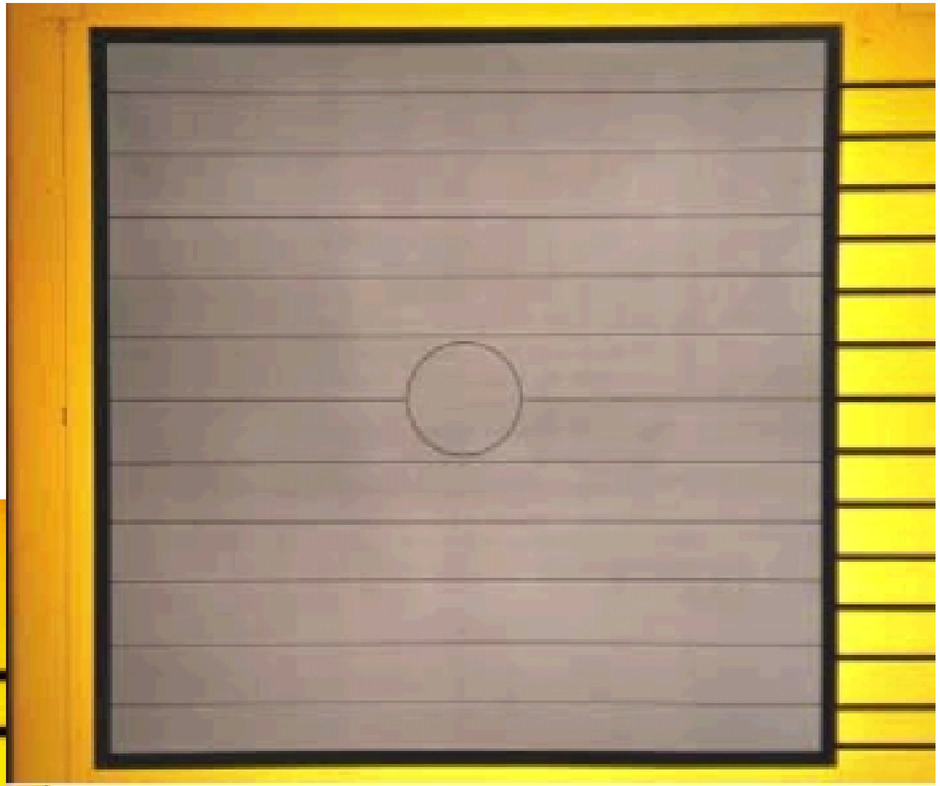


Total material in active area ~ 0.7% X_0

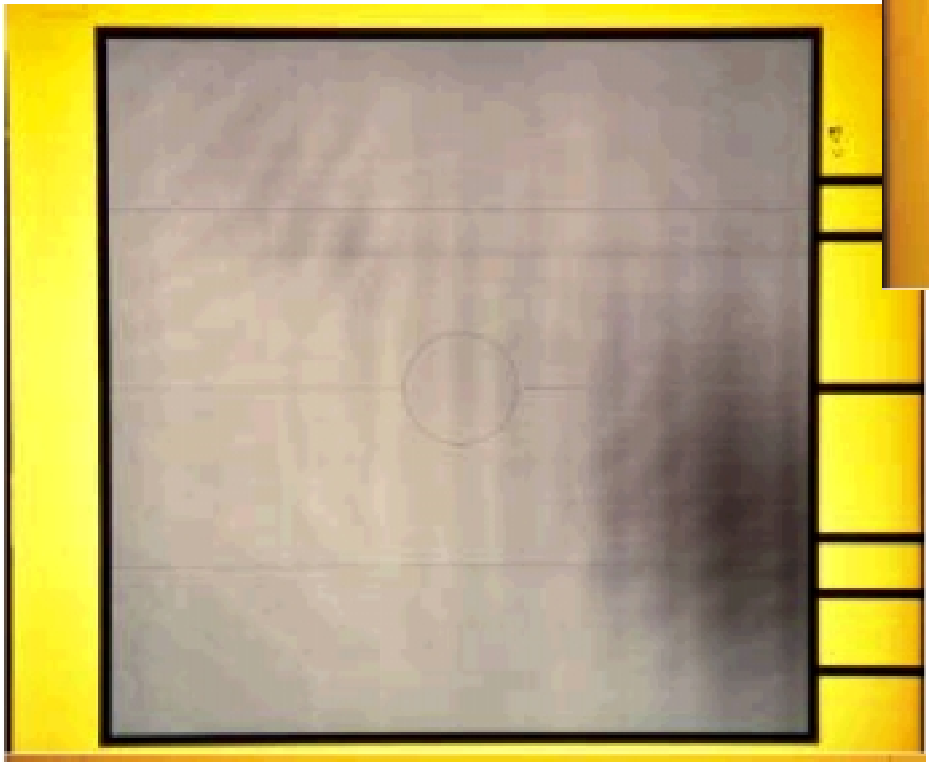
C. Altunbas et al, Construction, test and commissioning of the Triple-GEM tracking detector for COMPASS, in preparation (Nov. 2001)

GEM foils production and test

~ 80 GEM foils, 30.7 x 30.7 cm^2 active have been produced. (Nov. 2001).
Before assembly, each foil is optically inspected (uniformity of transparency) and HV tested (up to 550 V in N_2)



Good GEM

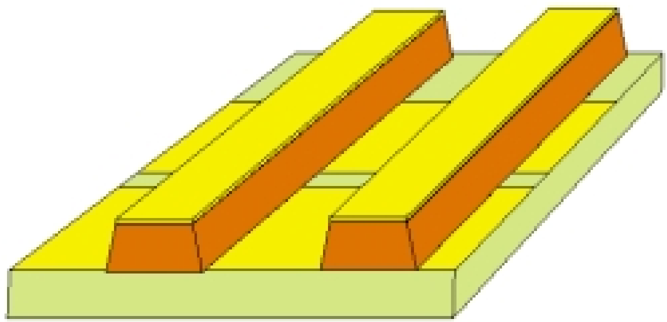


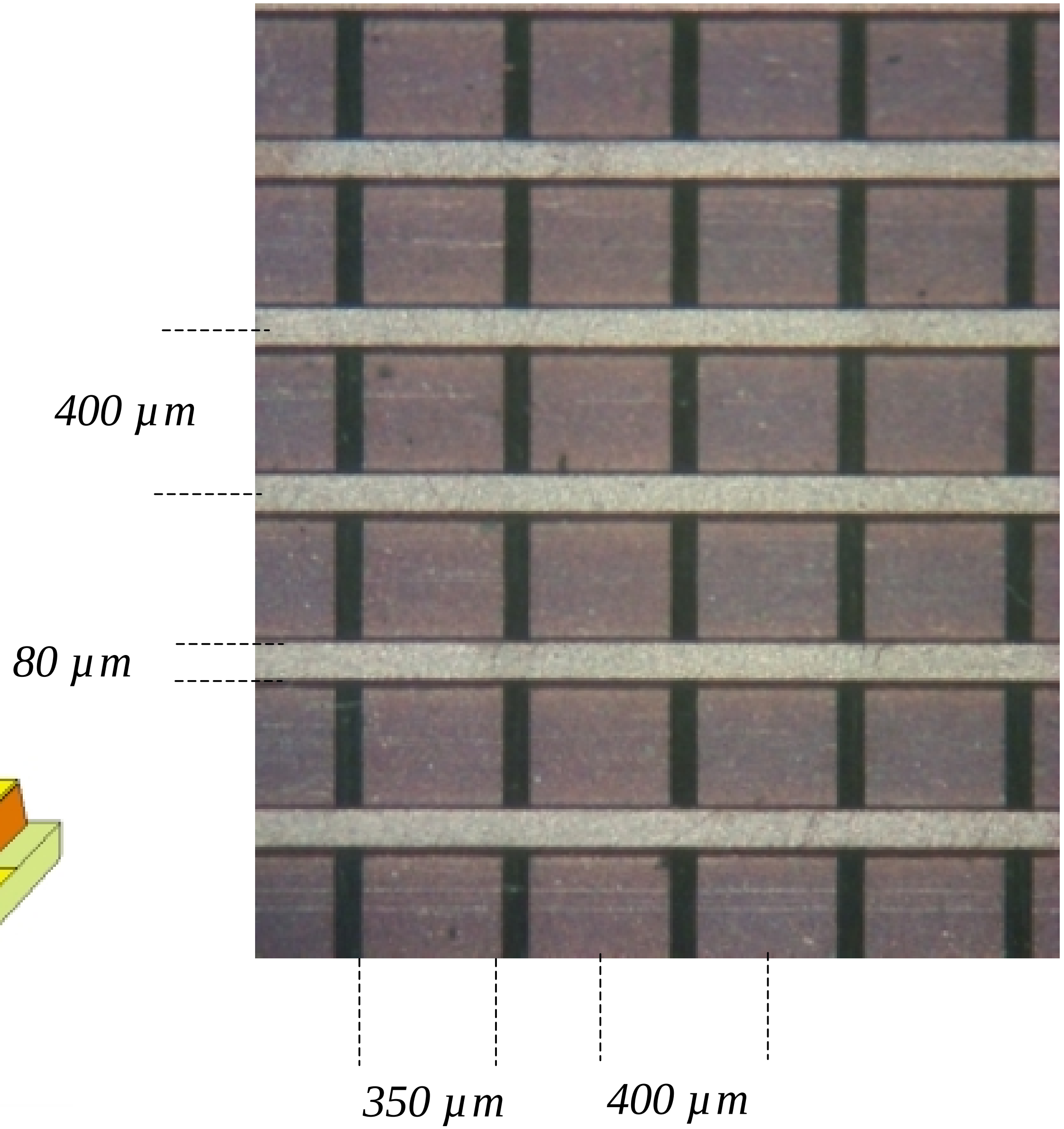
Bad GEM
(narrower holes on lower right side)

2-Dimensional Read-out Board

Two orthogonal sets of parallel strips at 400 µm pitch engraved on 50 µm Kapton
80 µm wide on upper side,
350 µm wide on lower side
(for equal charge sharing)

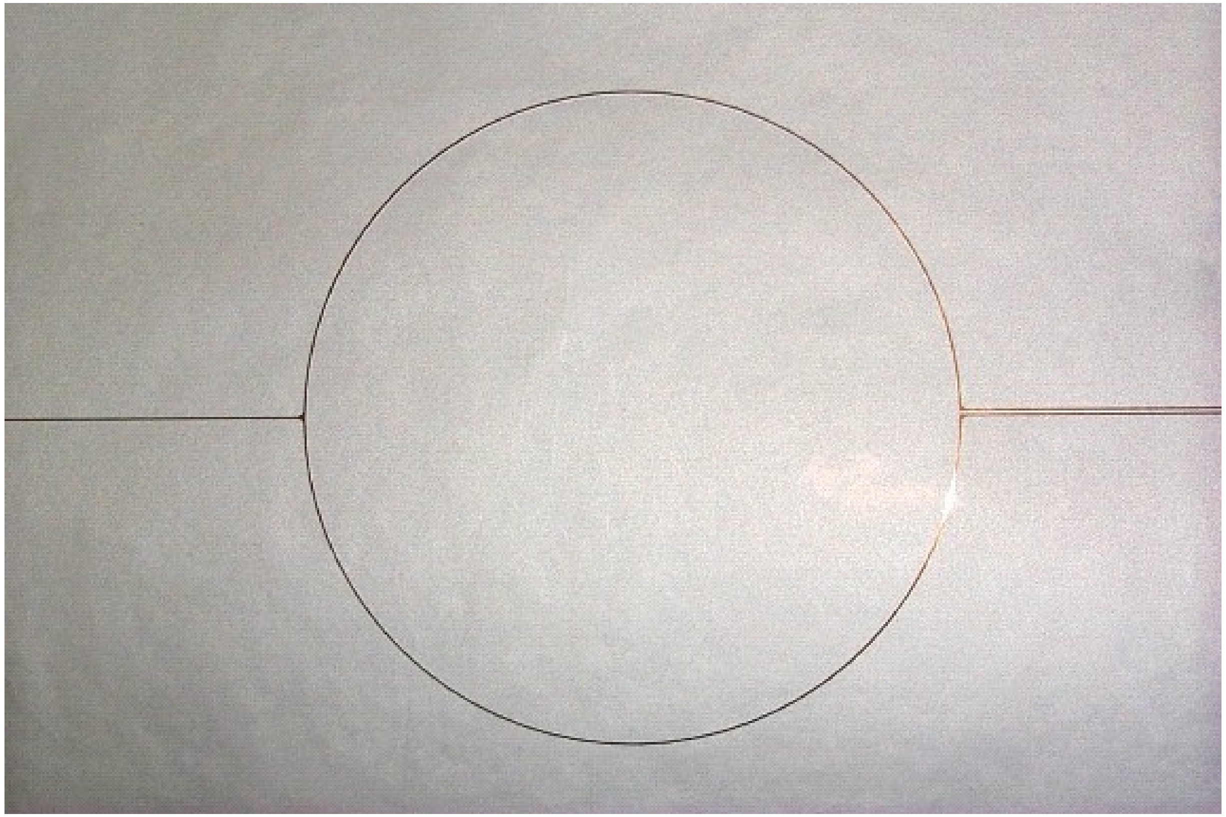
Technology developed by A. Gandi and R. De Oliveira, CERN-EST





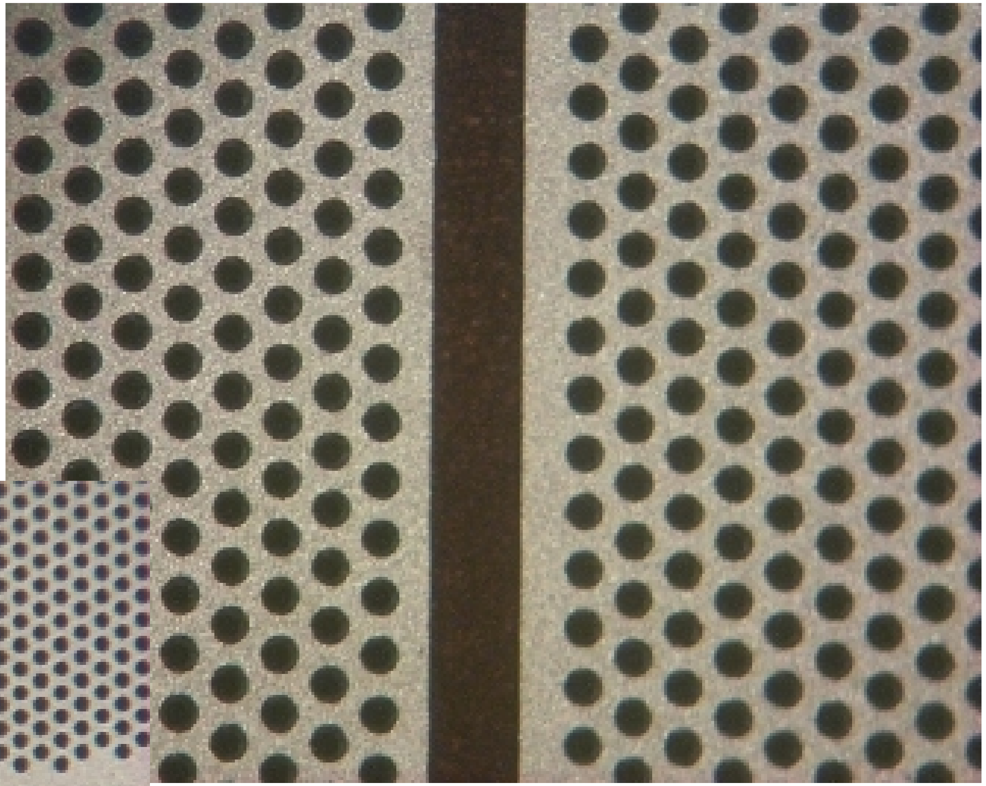
Beam killer

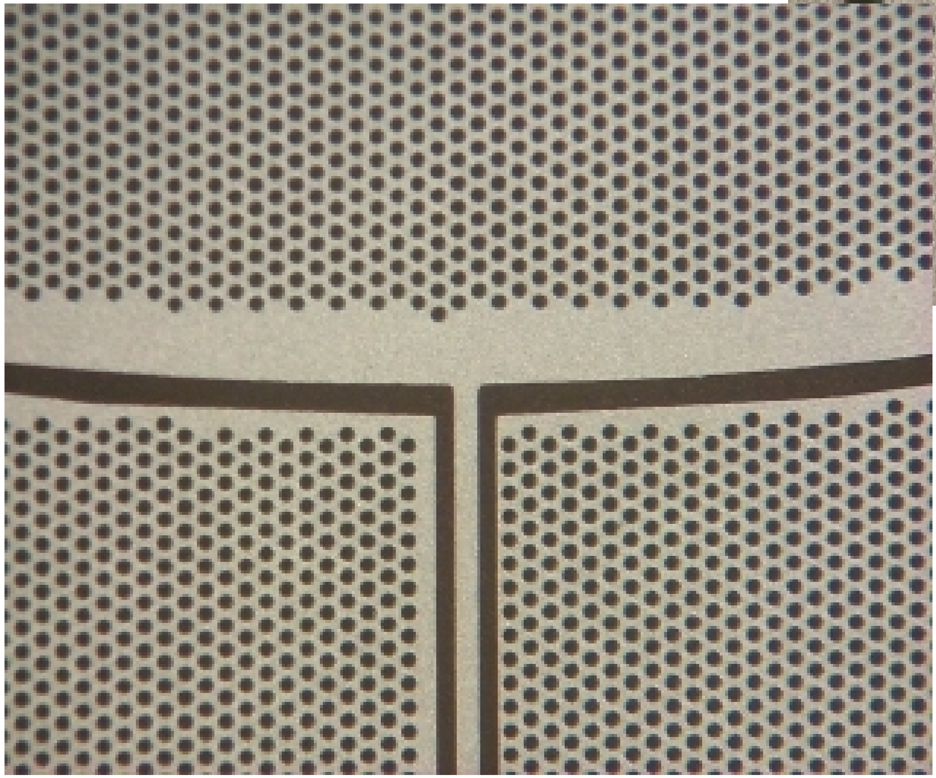
A central sector on each GEM, 5 cm in diameter, is independently powered. Application of a lower potential (by ~ 200 V) on the sector completely kills detection of the main unscattered beam.



Sectors separation

200 µm sector separation (three hole rows removed)





Voltage connection to the beam killer

Triple GEM Detector Manufacturing

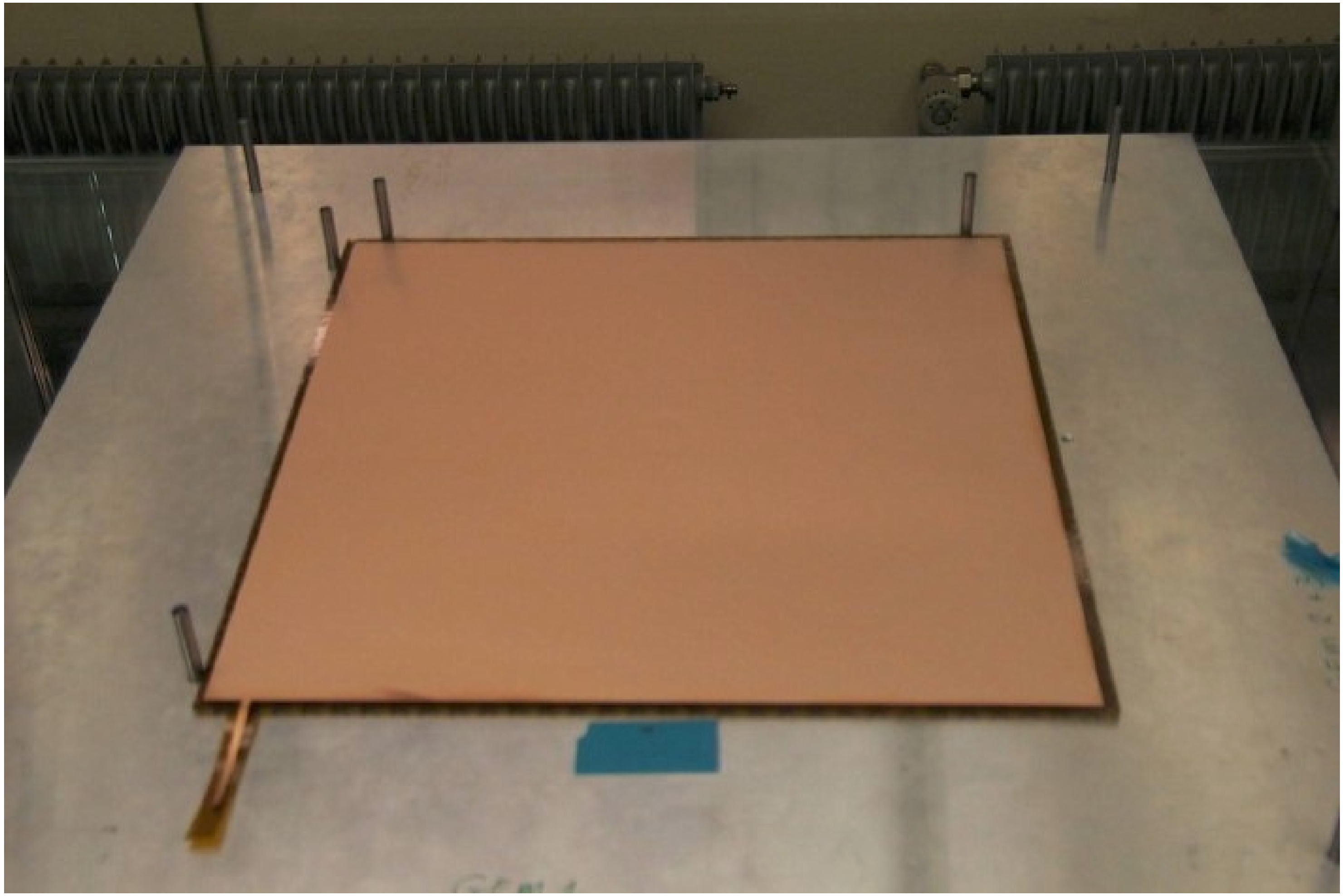
All manufacturing is done in a Clean Room, using protection suits, masks and gloves.

Loading frames with Epoxy before mounting electrodes:

Triple GEM Detector Manufacturing

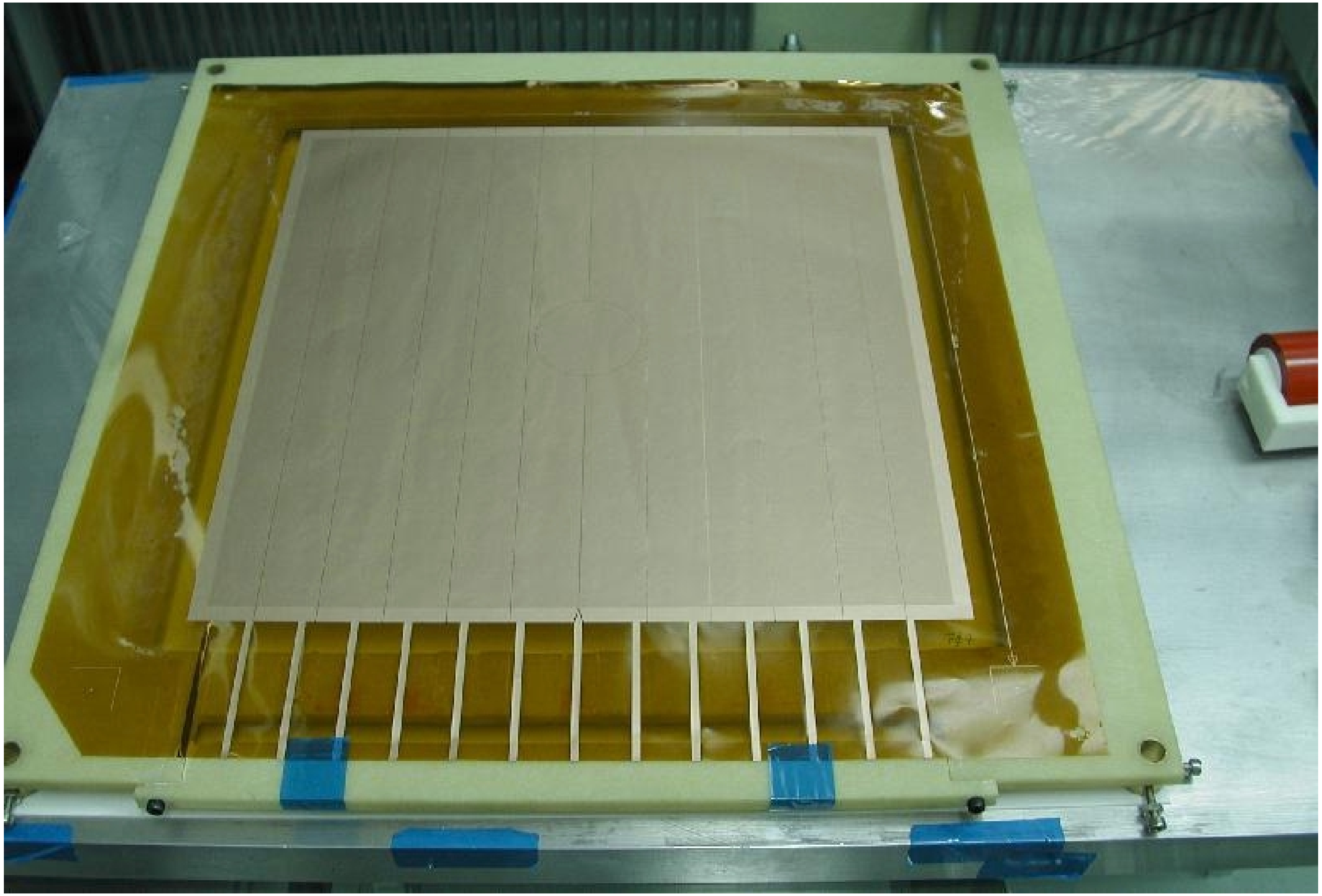
Assembly done on a mounting table with precision positioning pins

Gluing the Drift Electrode on the small Honeycomb Plate:



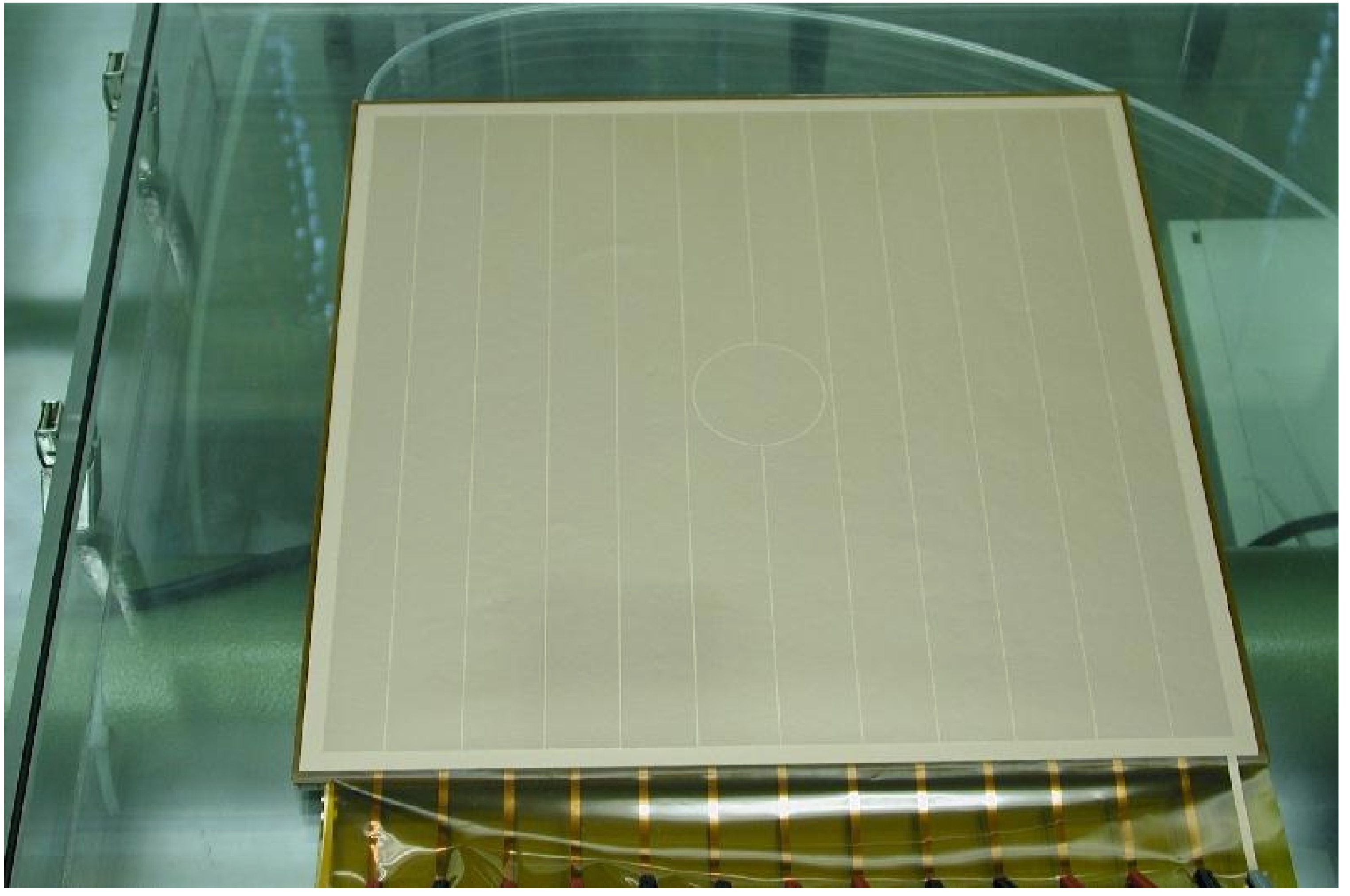
Triple GEM Detector Manufacturing

Pre-tensioning GEM foils on transfer frame:



Triple GEM Detector Manufacturing

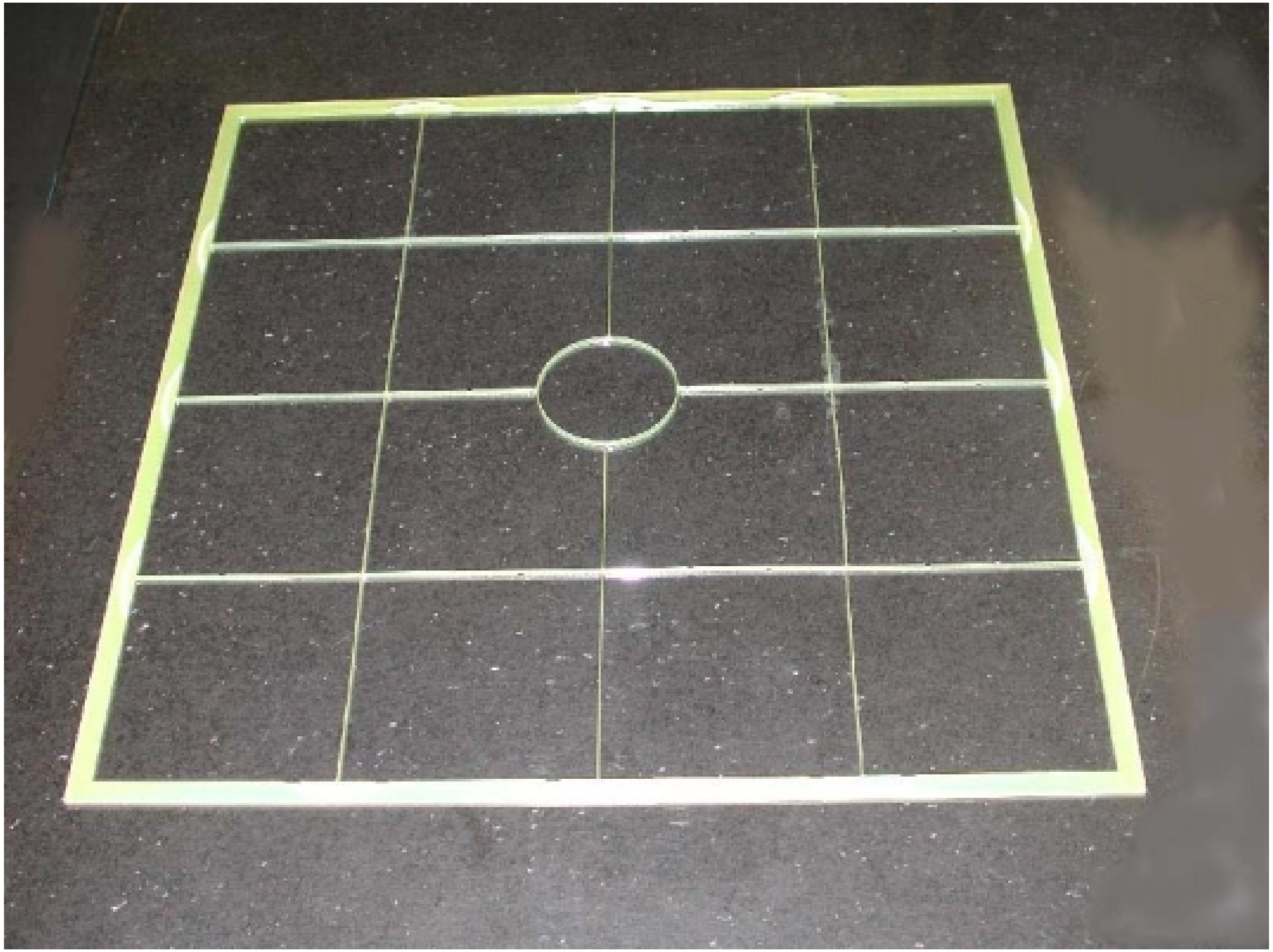
First GEM glued to drift frame:



Triple GEM Detector Manufacturing

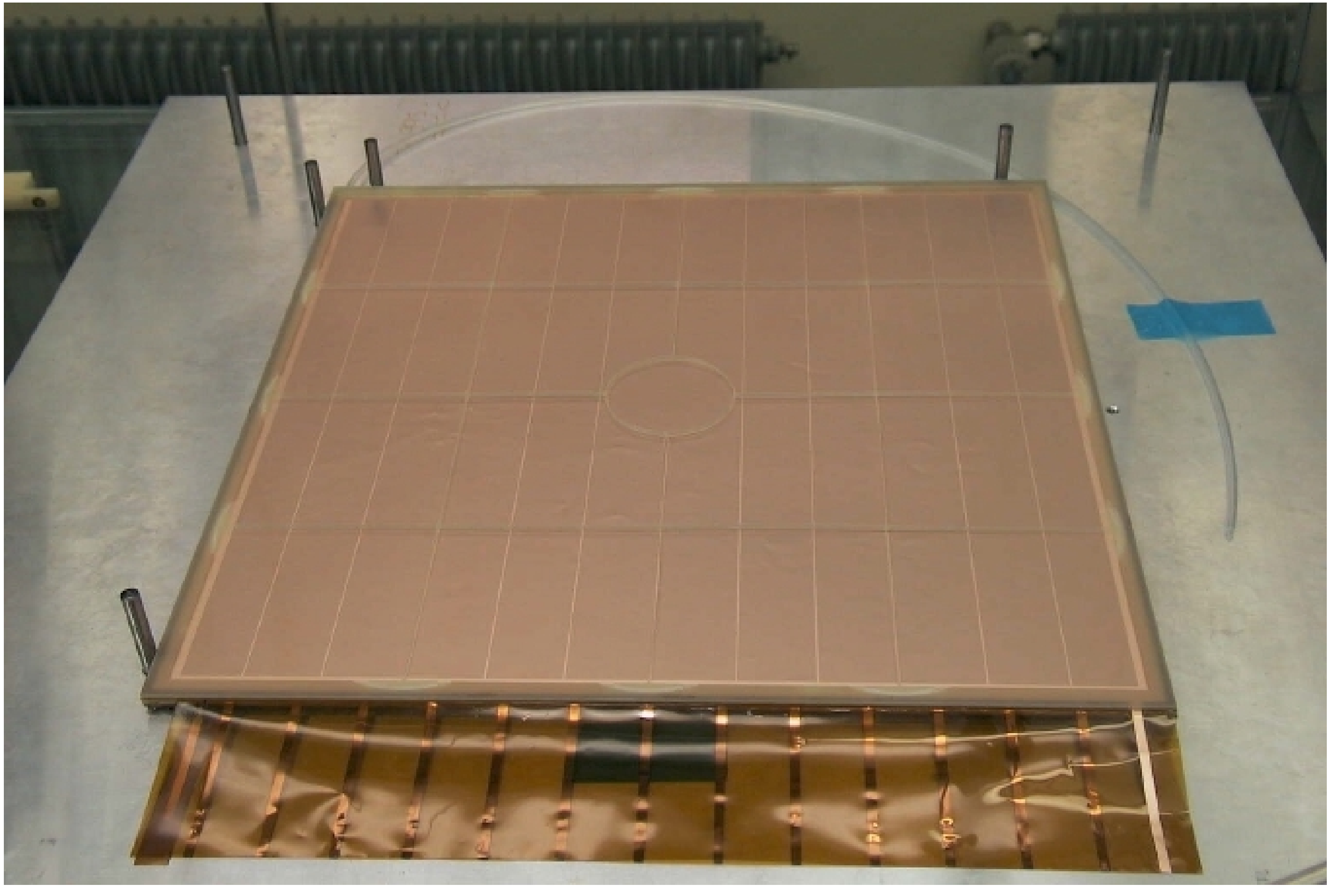
Spacer Grid:

Cut from a 2 mm thick fibreglass plate with thin (~300 μm) gap-restoring strips:



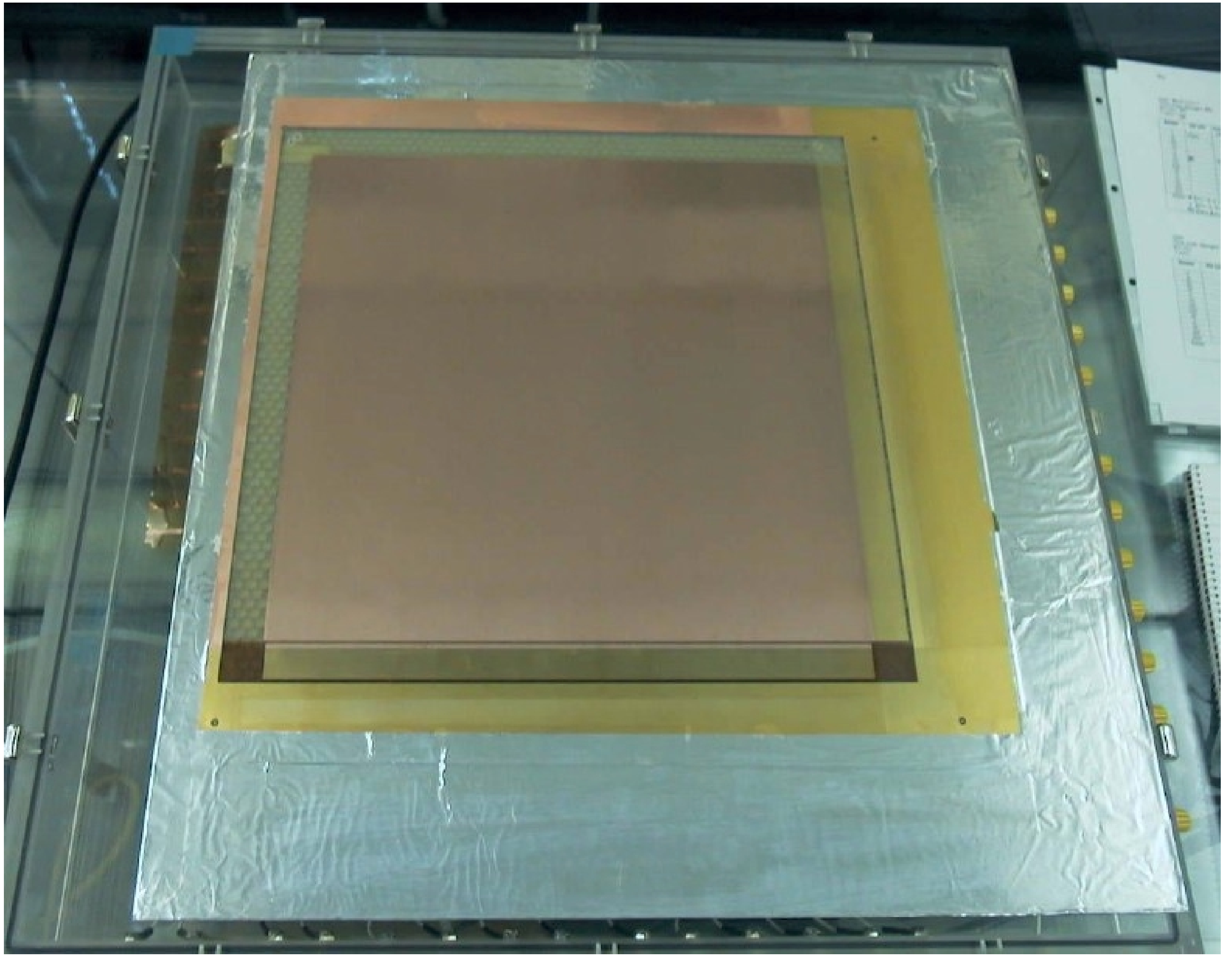
Triple GEM Detector Manufacturing

Spacer grid glued to assembly



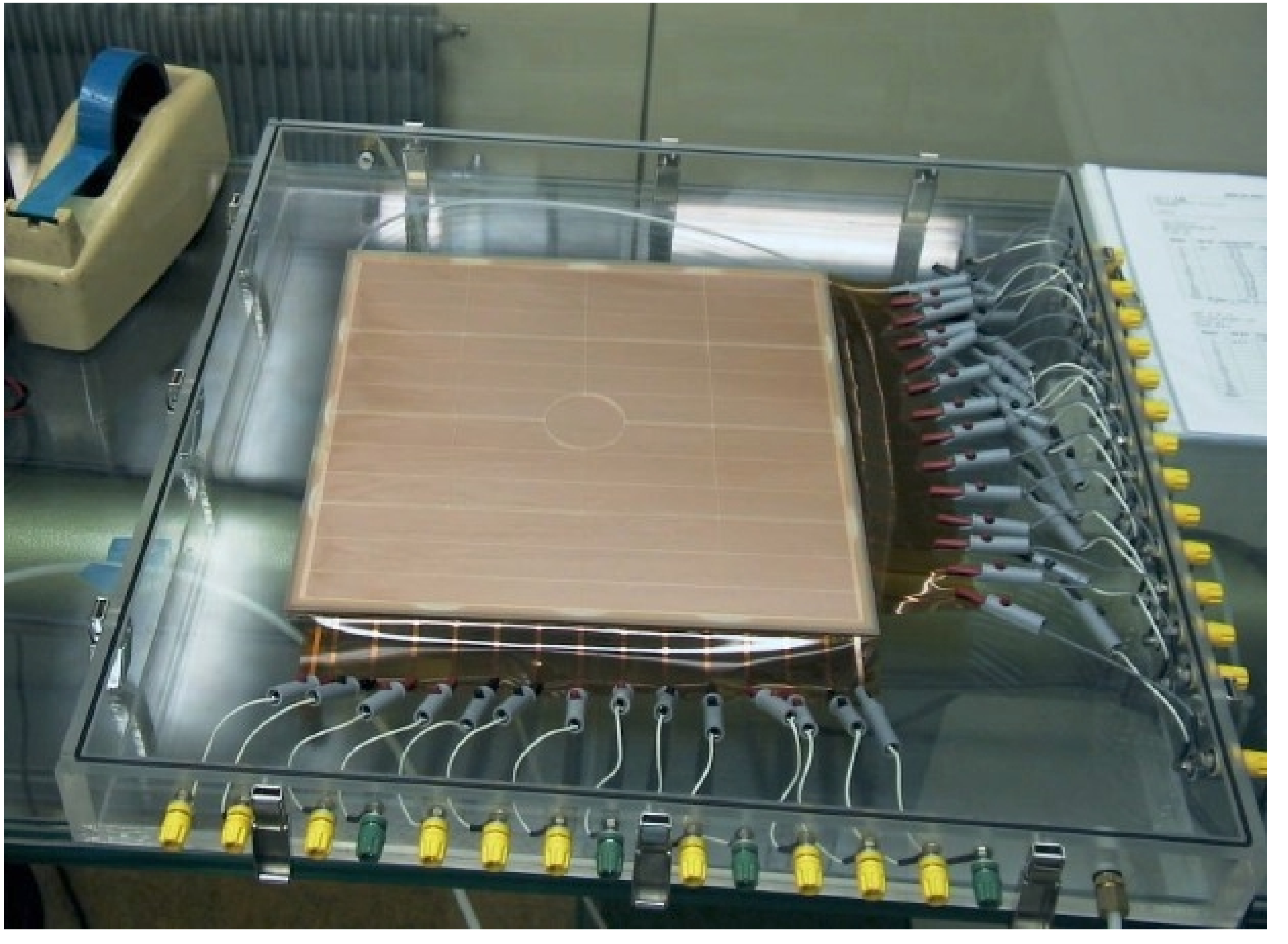
Triple GEM Detector Manufacturing

2-D read-out board glued to large honeycomb plate:



Quality control

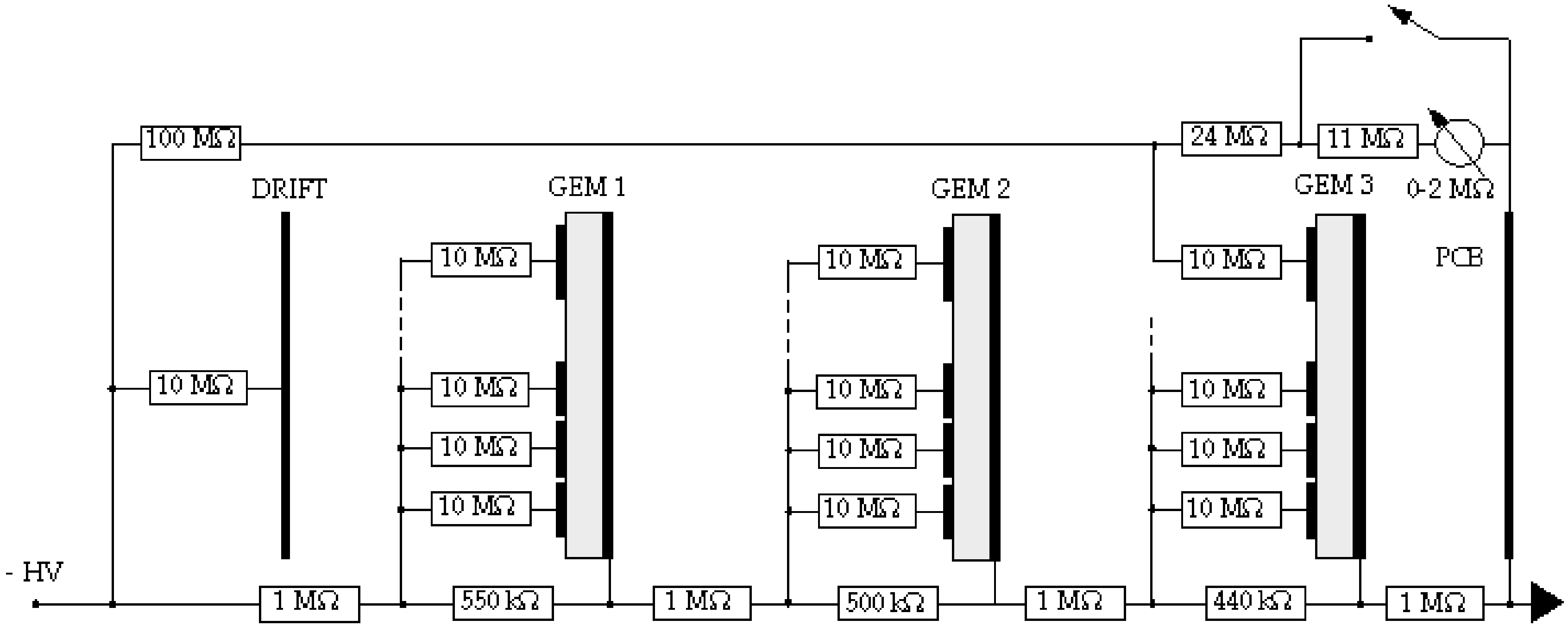
Before mounting, and at each assembly step, all GEM foils are HV tested in a N_2 gas box (requirement: less than 5 nA at 550 V)



High Voltage distribution

Resistive chain with single power supply.

- Asymmetric voltage to GEMs
- Individual sectors protection resistor
- Remote controlled switch to activate beam killer



In case of a sector short, the voltage distribution is slightly modified, and the gain decreased by ~ 10% (can be compensated by an increase in HV)

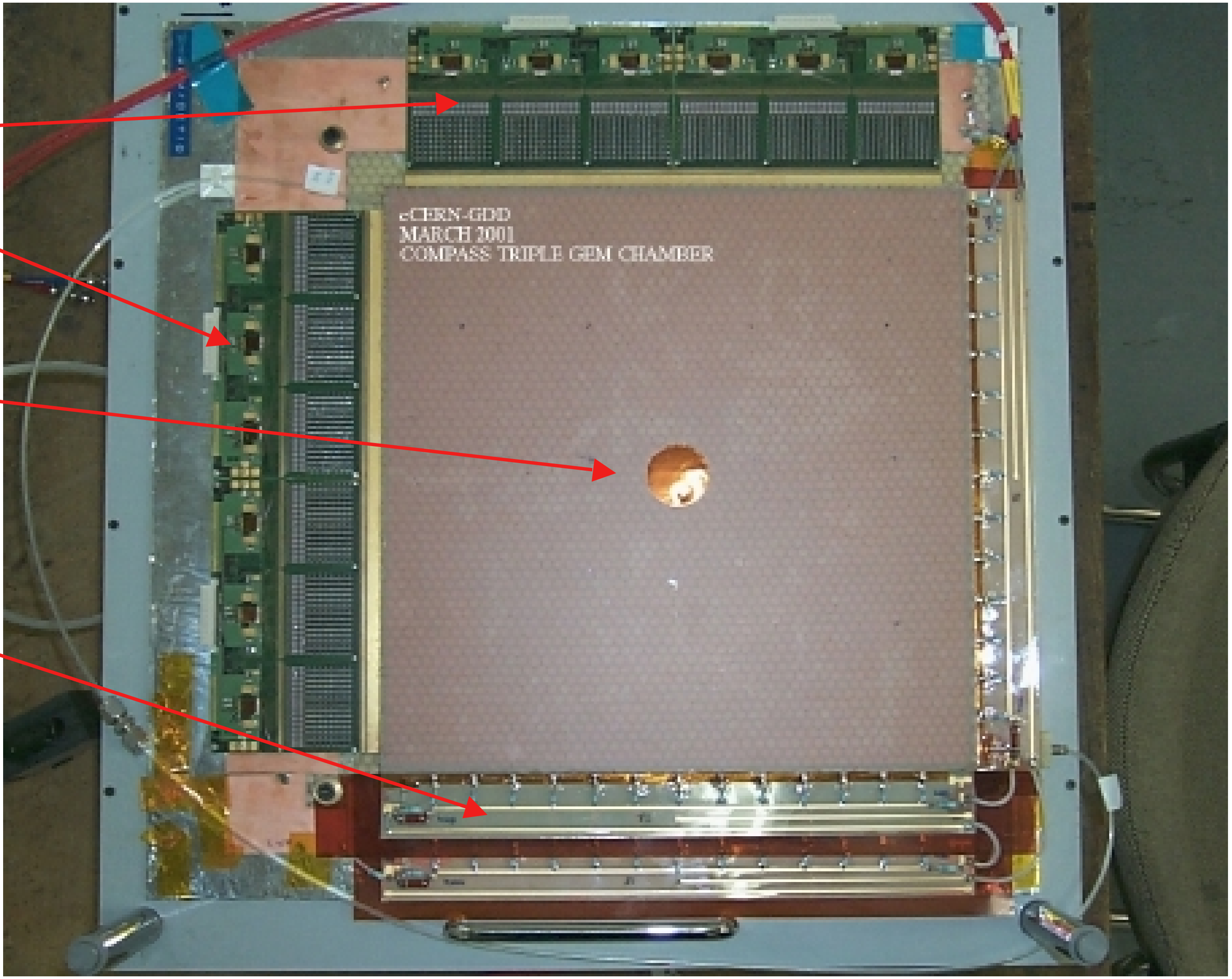
Completed COMPASS Triple-GEM Chamber

30.7 x 30.7 cm^2 active
2-D readout

Readout Cards

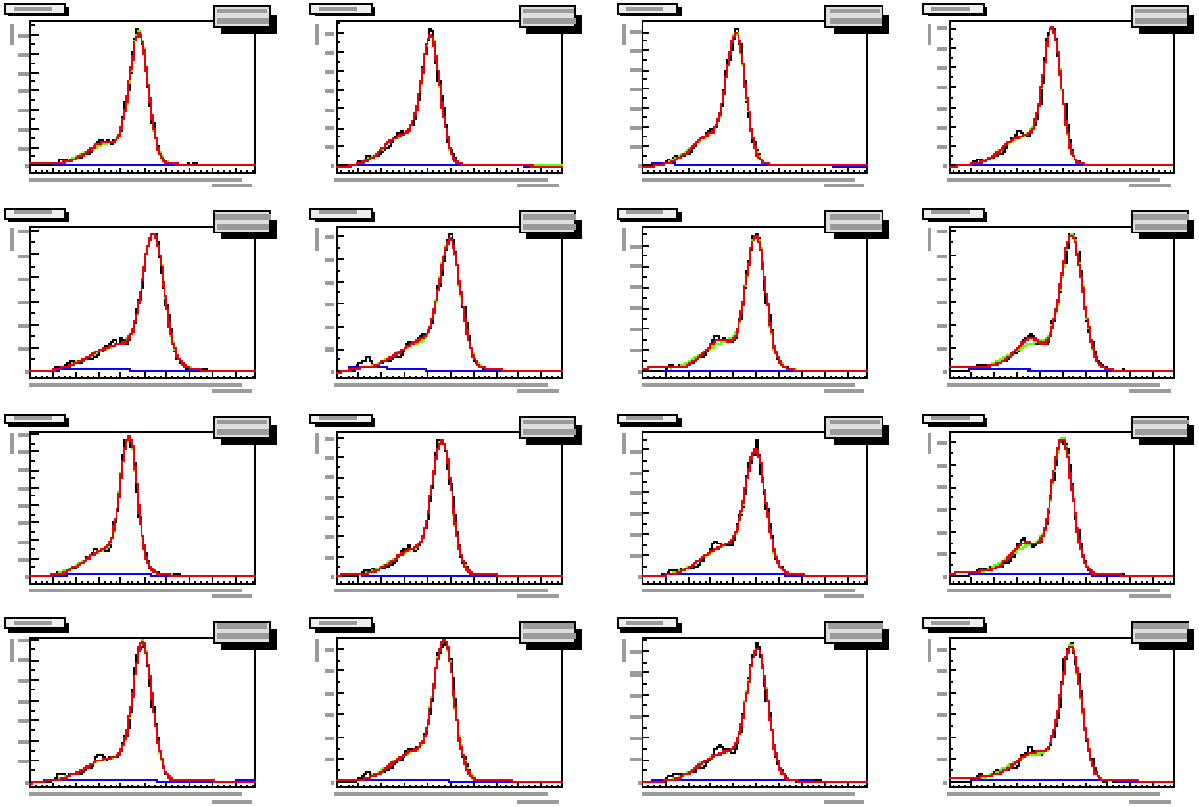
Lower mass cut

HV distribution

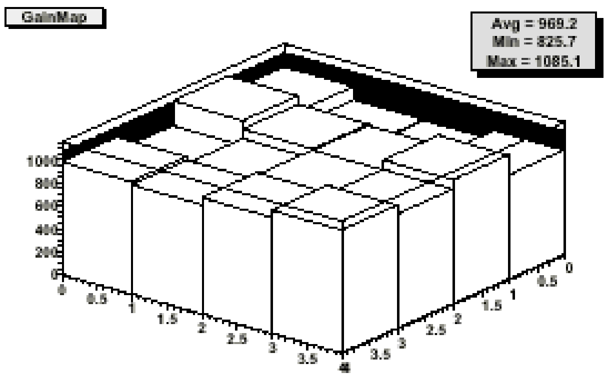


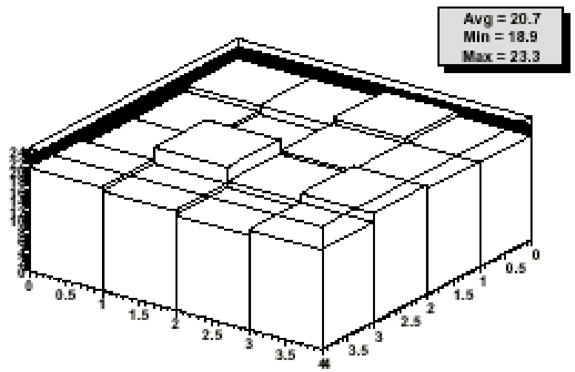
Quality control: gain map

X-rays Pulse Height spectra are recorded on 16 positions across each detector, in both x- and y-projections



TGEM 11
2-D distributions of gain and energy resolution:

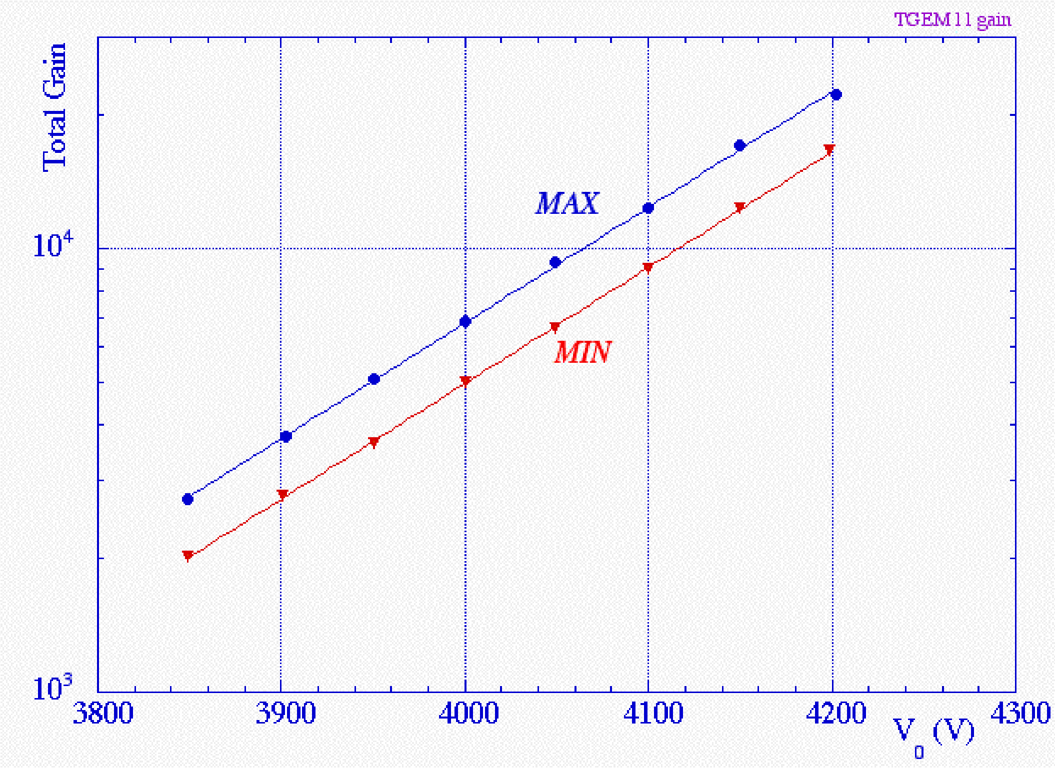


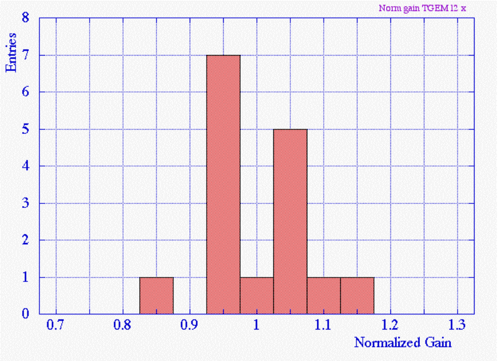


Quality control: gain summaries

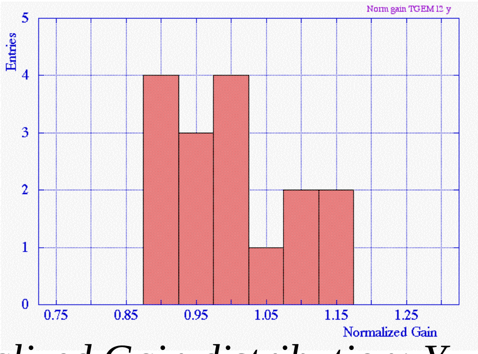
On each detector, the absolute gain is measured on 16 positions across the area

TGEM 11
Points of extreme gain values (30% difference):

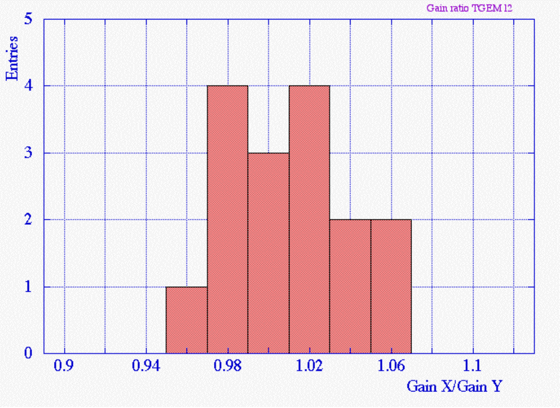




Normalized Gain distribution: X



Normalized Gain distribution: Y

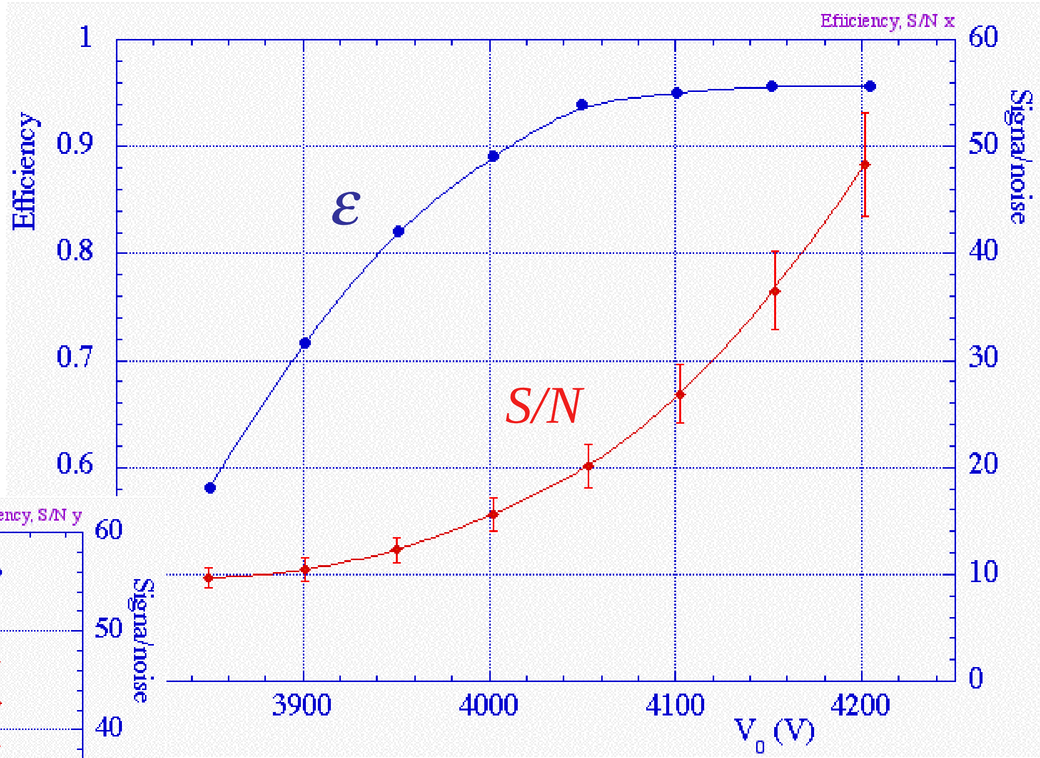


Gain ratio X/Y

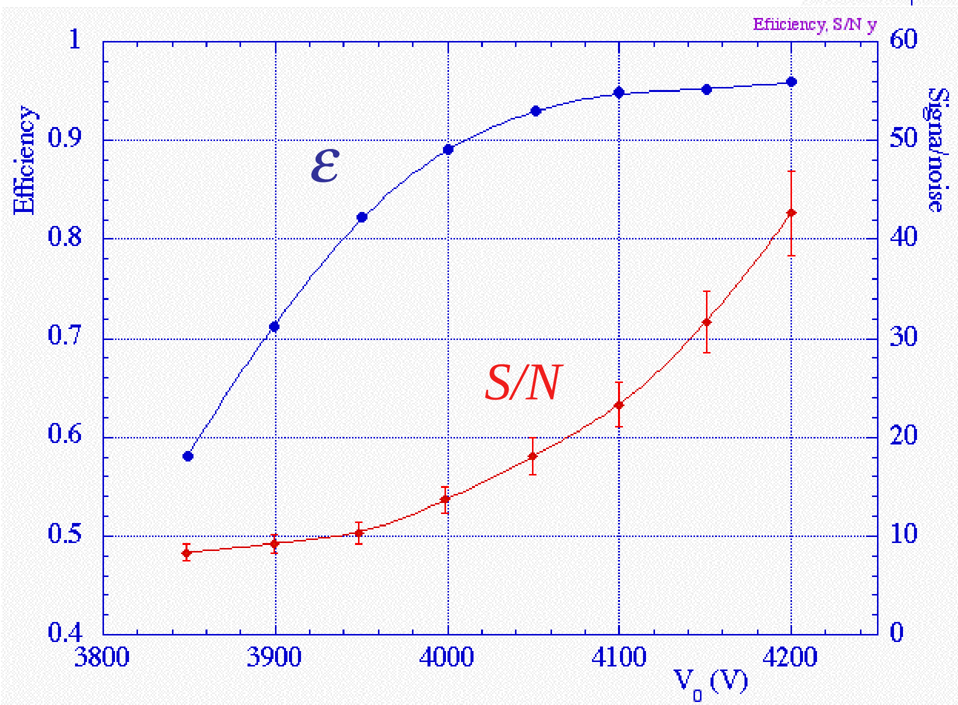
Triple GEM Efficiency in beam

Efficiency and signal/noise are measured for minimum ionizing tracks over a wide area of the detector (~ 100 cm^2)

X-coordinate (80 µm strips):



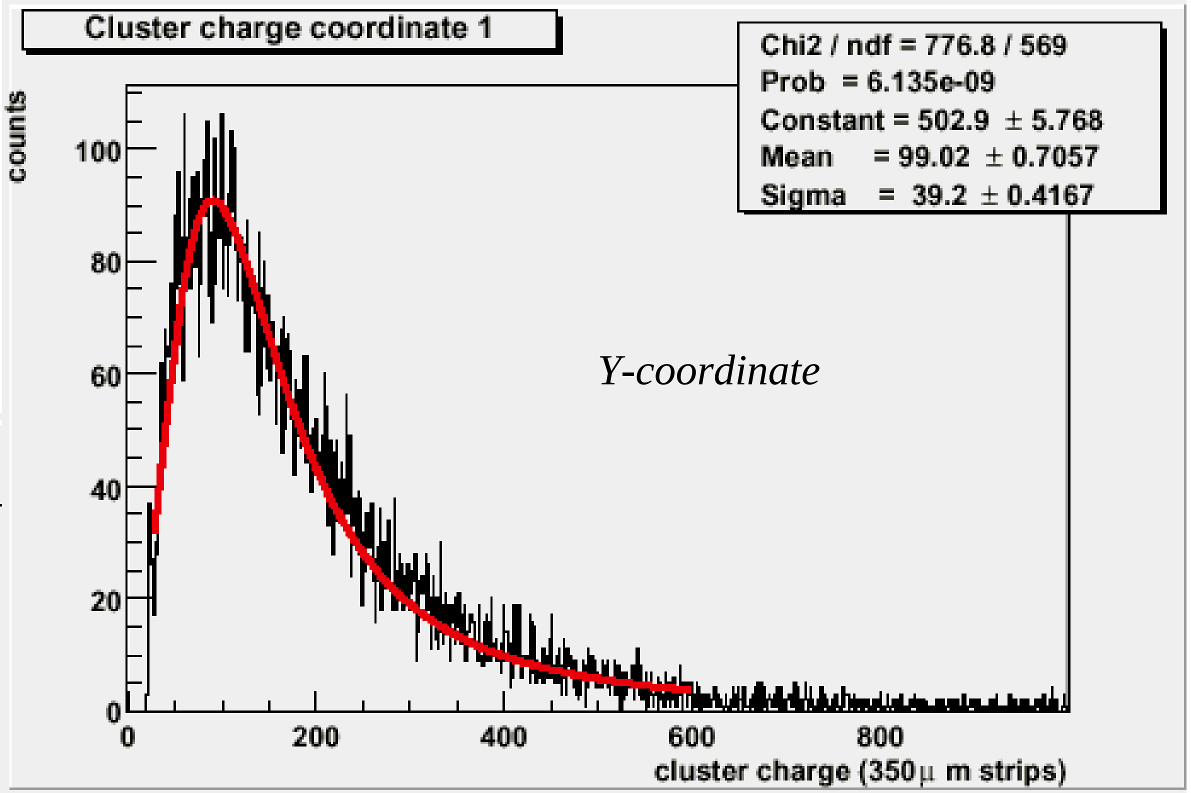
Y coordinate (350 µm strips):

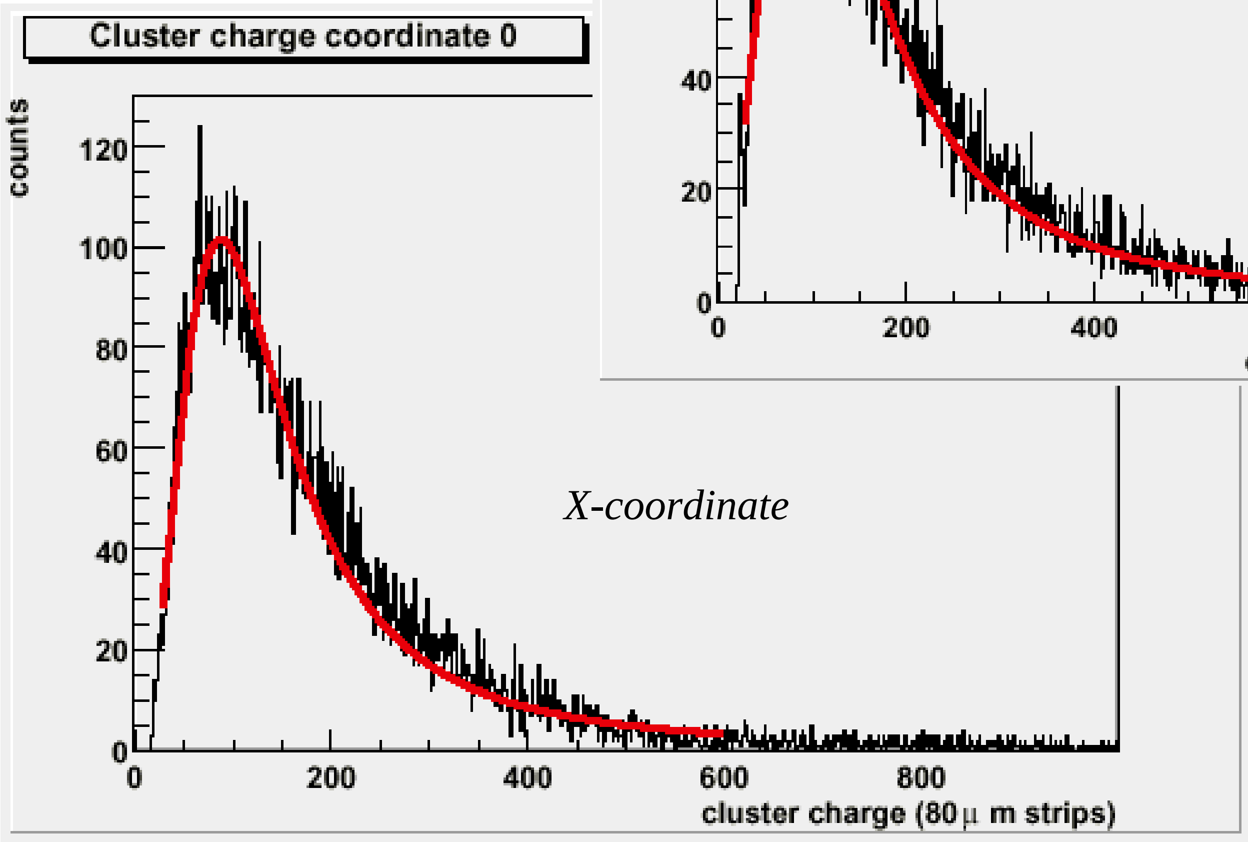


Full efficiency is reached for a gain of 4000 on each coordinate (8000 total)

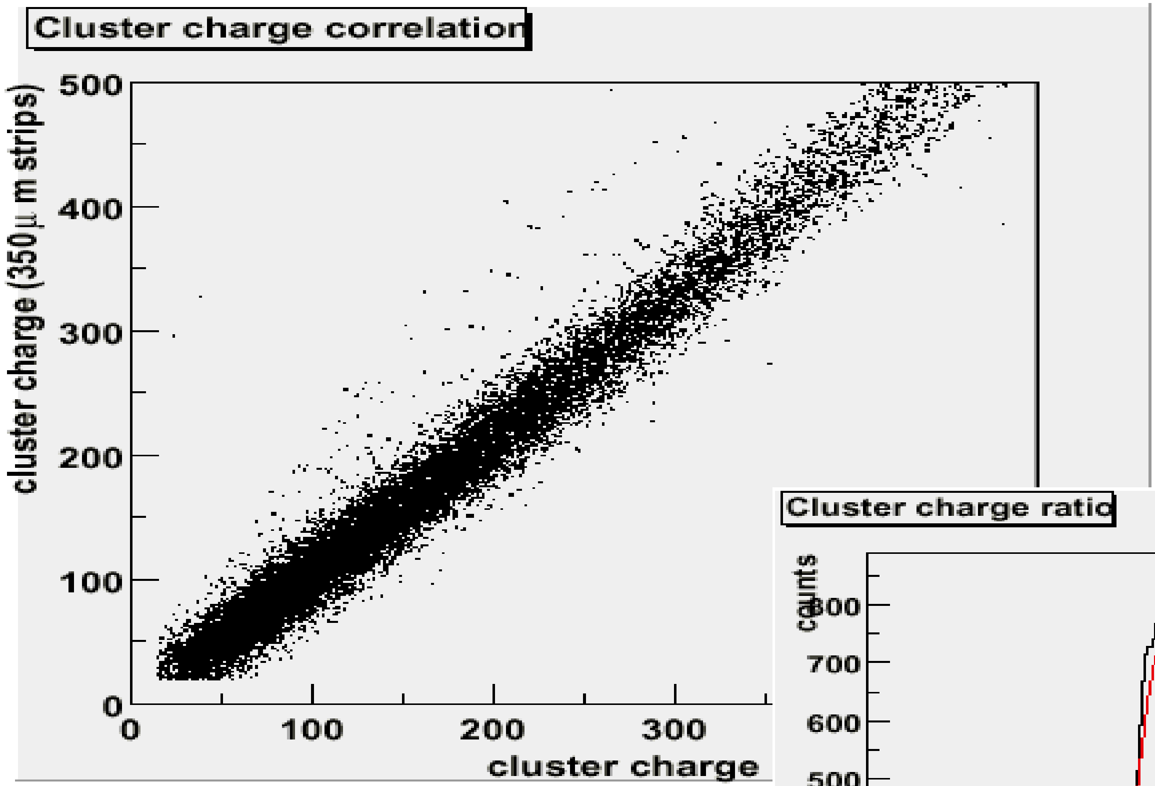
Pulse height spectra

Beam measurements
TGEM 11
Total gain 8000

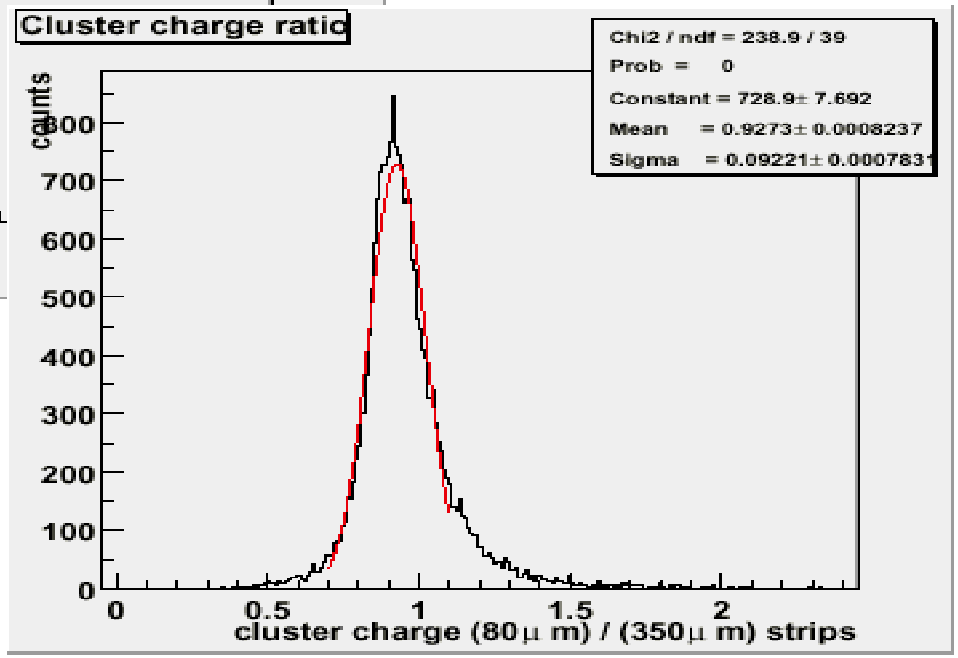




Cluster charge correlation



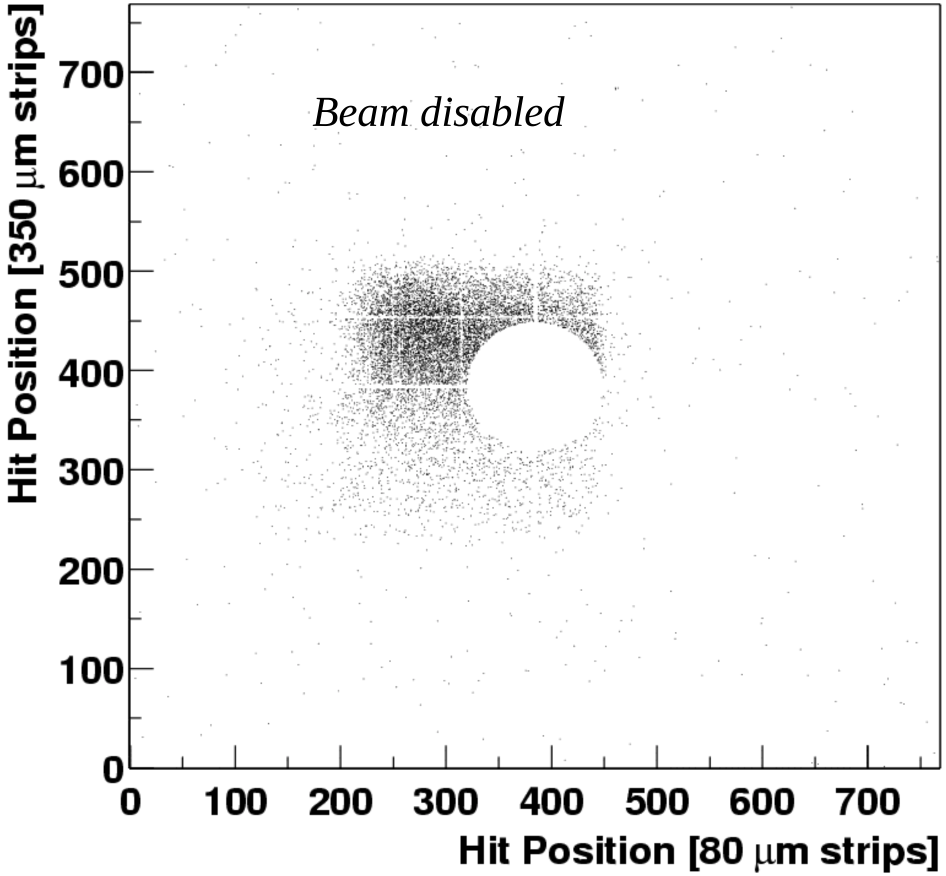
Very good correlation, used for multi-track ambiguity resolution

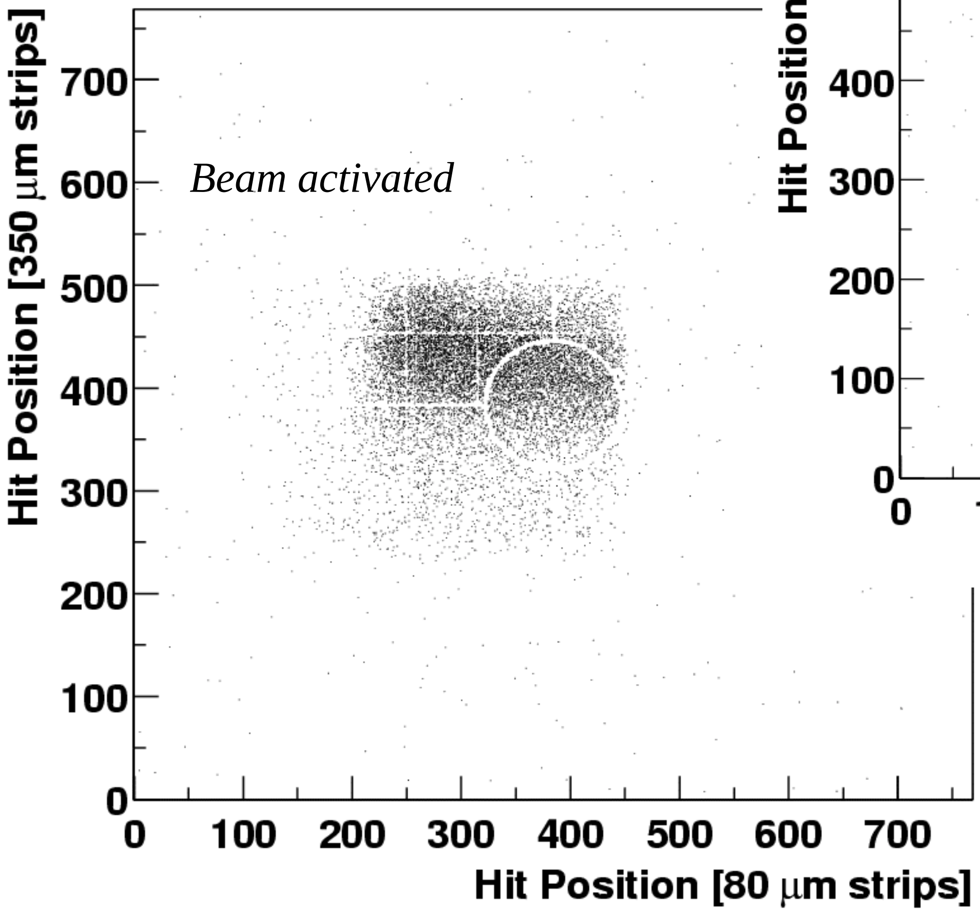


X-Y Cluster charge correlation
rms ~ 10%

Beam killer

The central beam area can be remotely activated for calibrations and alignments. Disabled during high intensity runs.

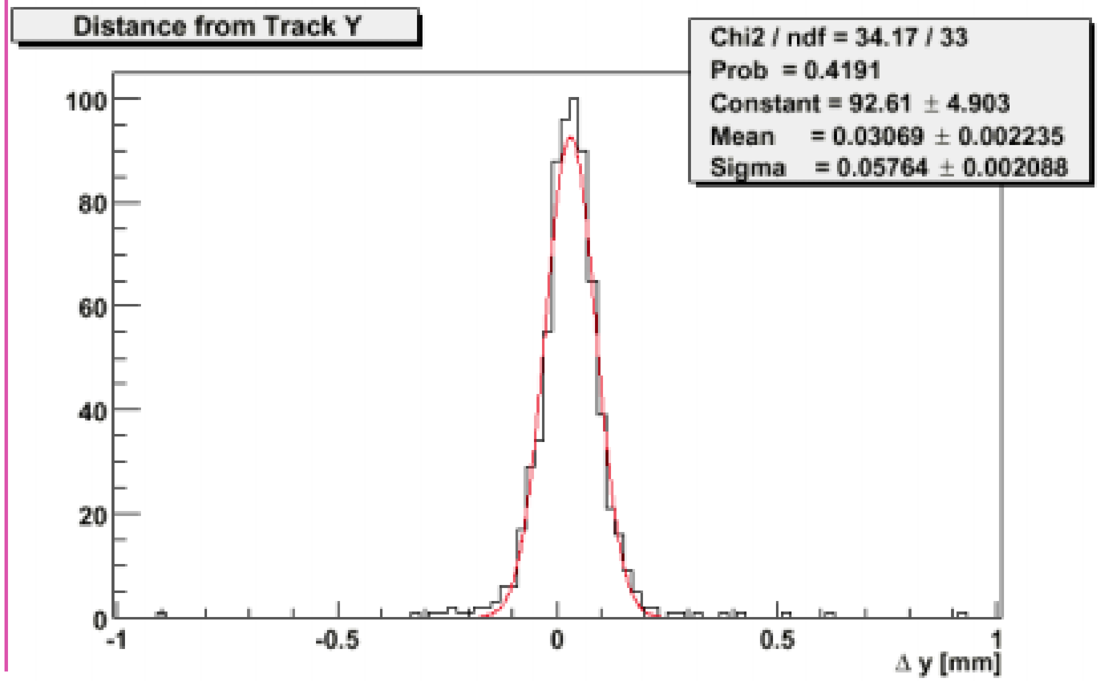


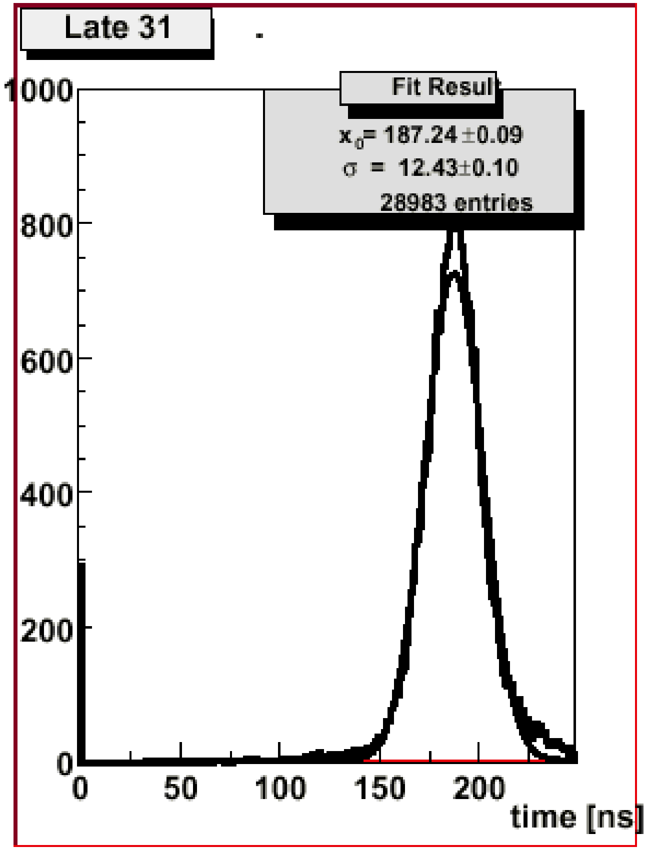


The integrated loss of efficiency around spacers is ~ 2 %

Space and time resolution

Space resolution: tracks fit with two TGEM and one Silicon micro-strip
After deconvolution s = 46±3 μm

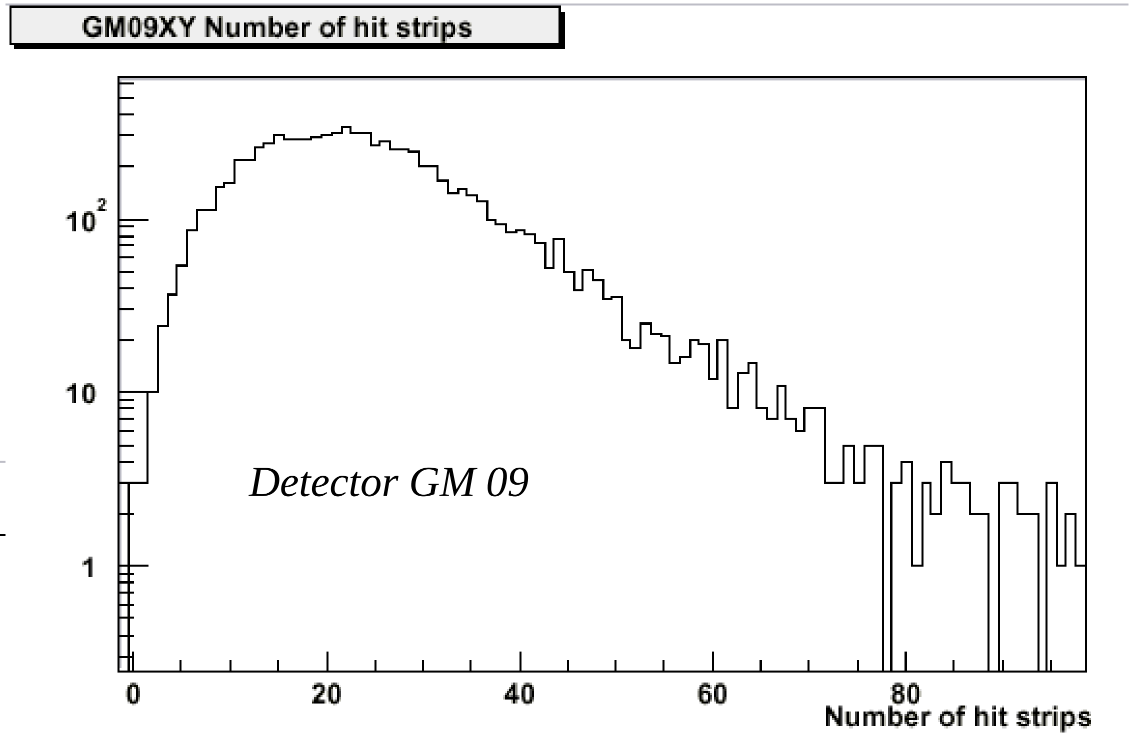


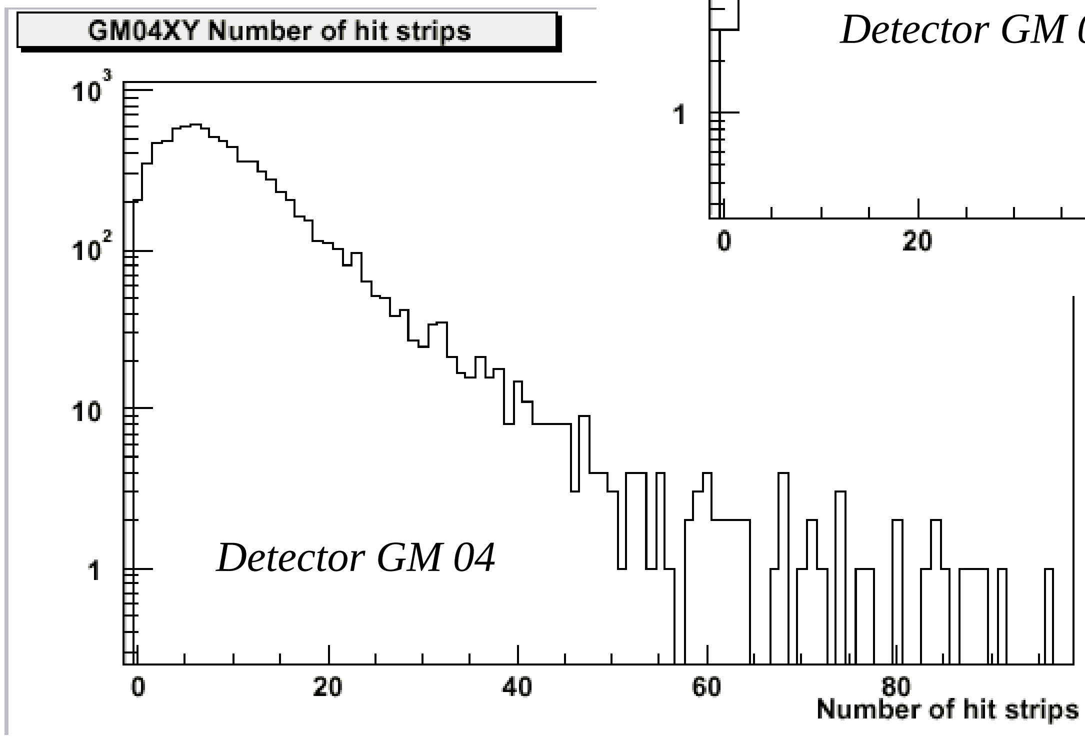


Time resolution: computed from charge signals in three consecutive samples (at 25 ns intervals)

Multiplicity-Full beam runs

Full COMPASS run
2.1 10^8 μ/spill
3 σ cut on strip's charge



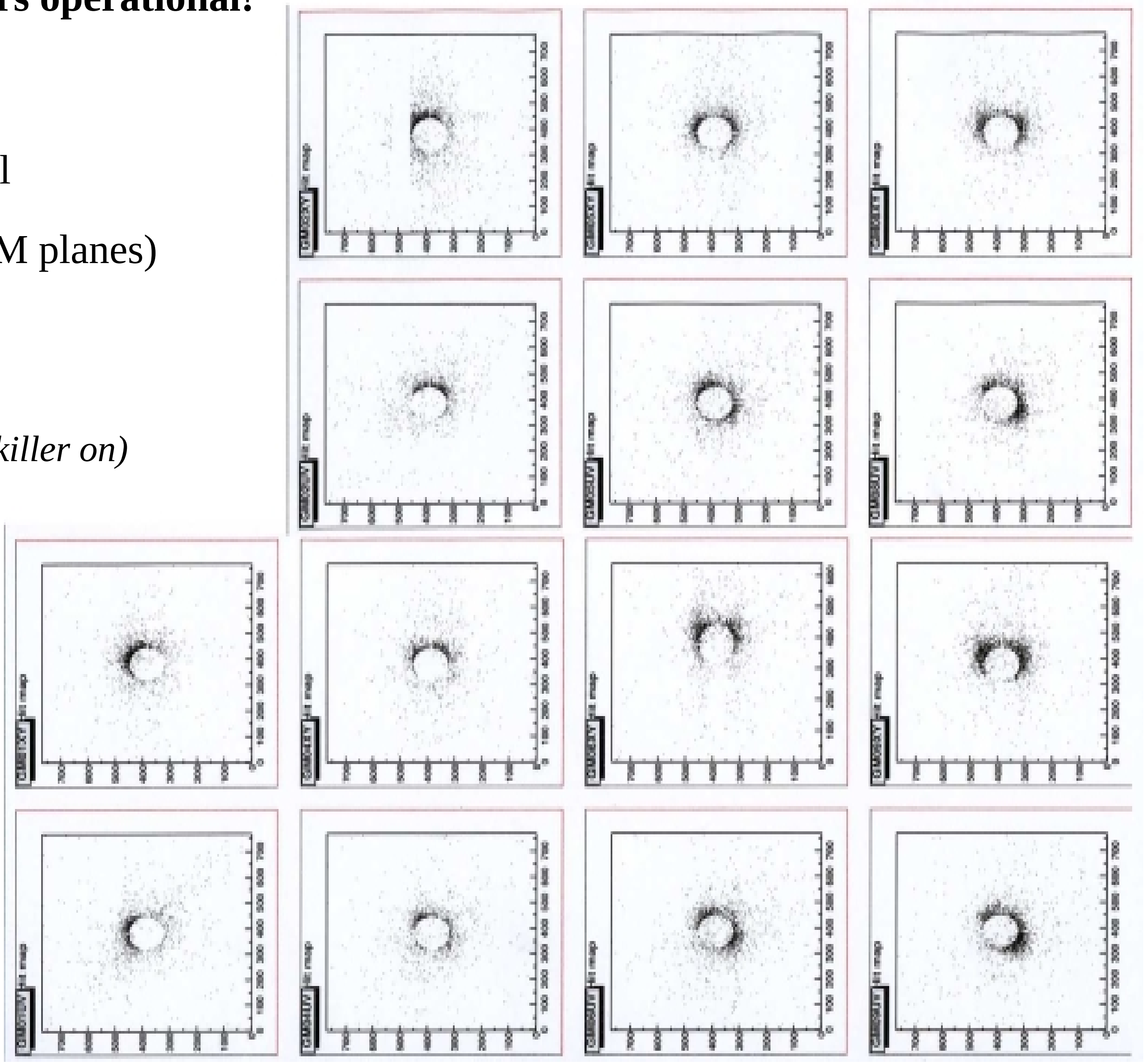


14 COMPASS chambers operational!

October 15, 2001:
14 TGEM chambers
installed and operational

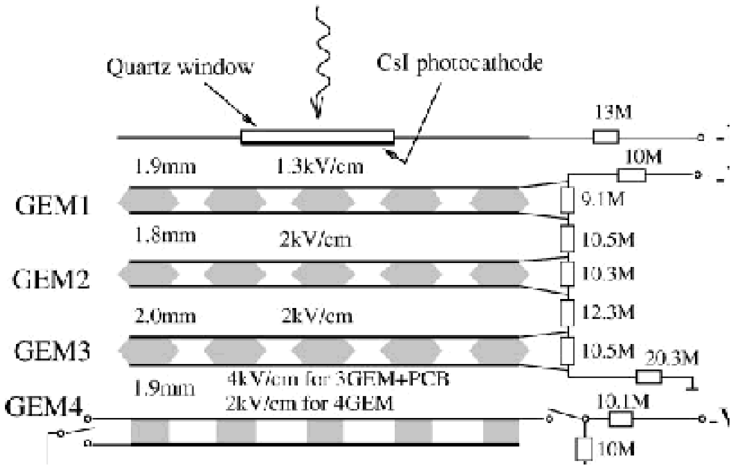
(Total detector: 20 TGEM planes)

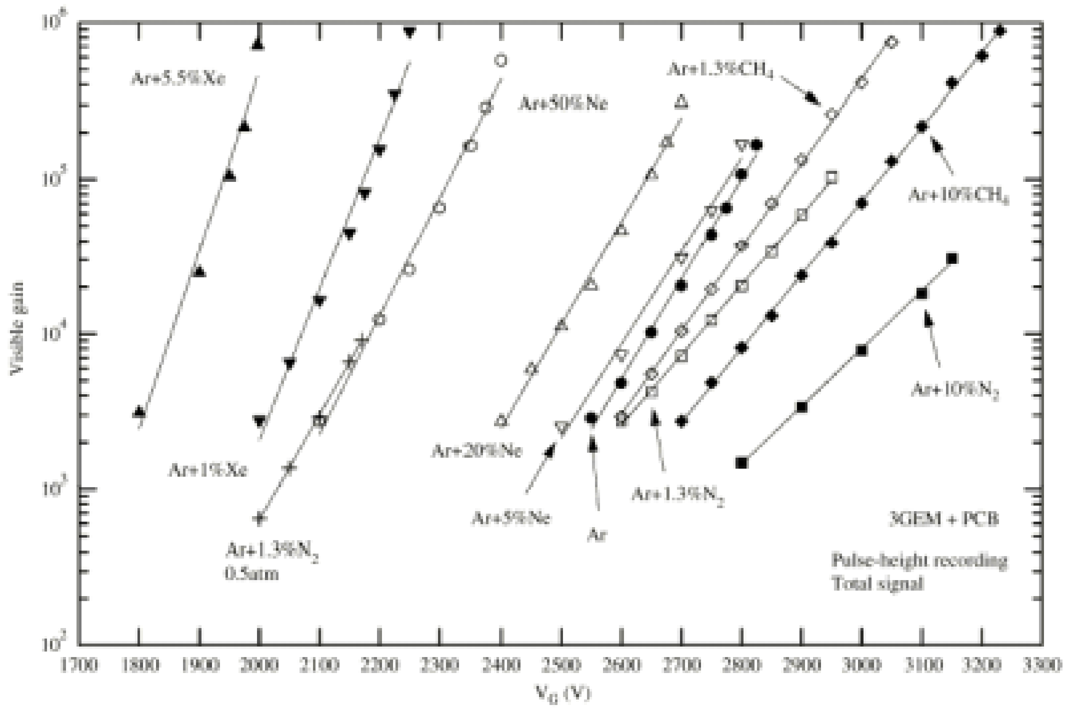
High intensity μ beam
2-D scatter plots (beam killer on)



Multi-GEM for photon detection

Multiple GEM detectors permit to achieve very large gains (10^6) in photocathode-friendly pure noble gases and poorly quenched mixtures.
Reduced transparency strongly suppresses photon and ion feedback





A. Buzulutskov et al, Nucl. Instrum. Methods A443(2000)164

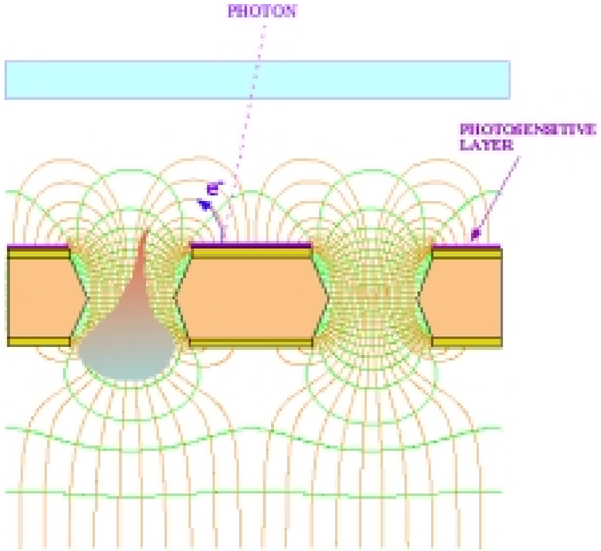
☞ Large area position-sensitive photomultipliers

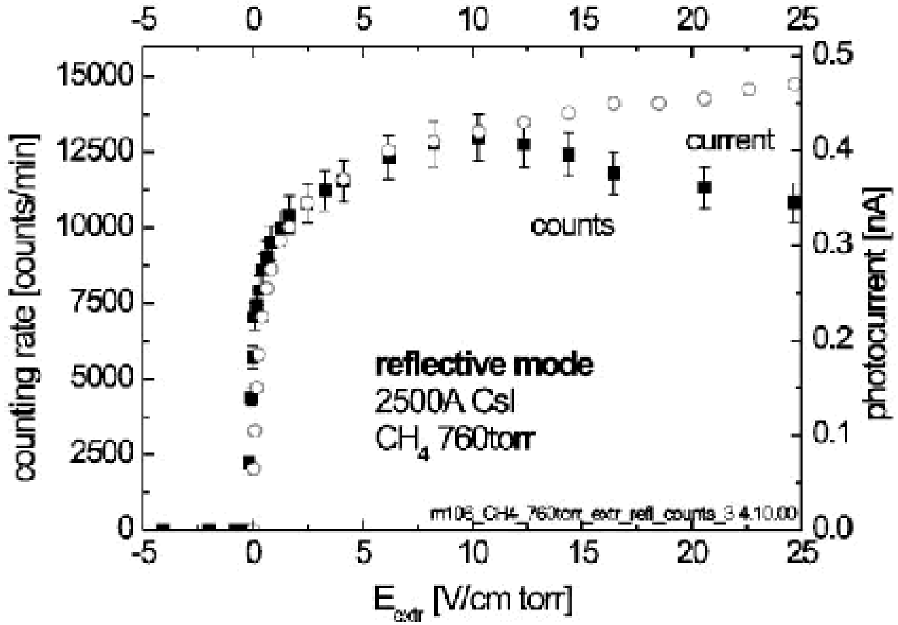
R. Chechik et al, Nucl. Instr. and Meth. A 419(1998)423

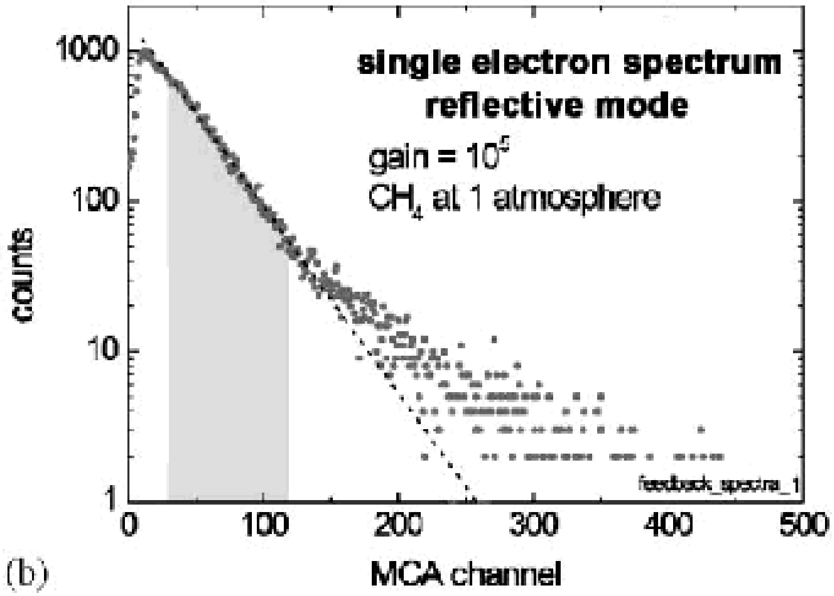
GEM: Reflective photocathode

CsI Photocathode deposited on GEM upper side:

- No photon feedback
- High Quantum Efficiency







(b)

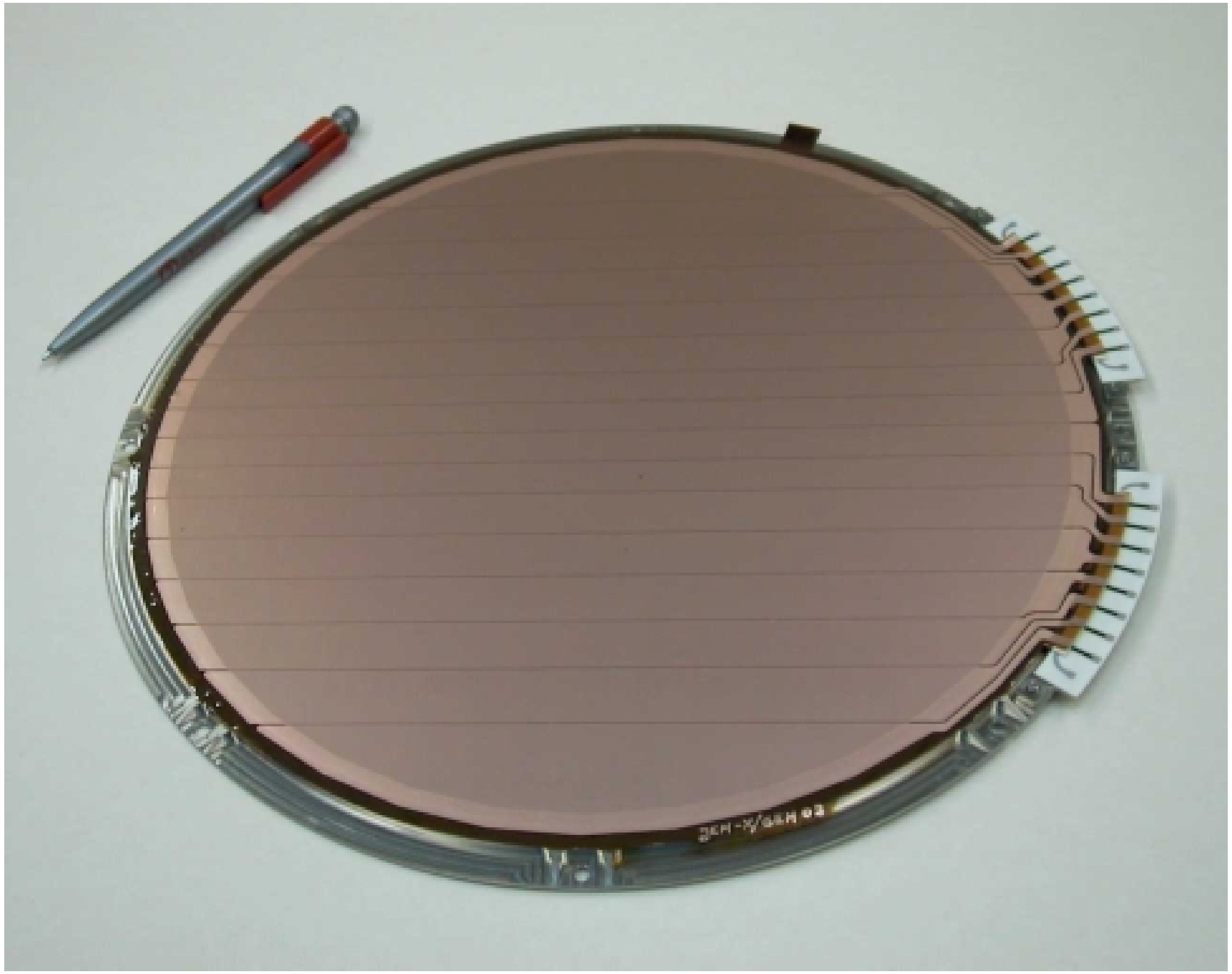
D. Mörmann et al,
Nucl. Instr. and Meth. A 471(2001)333

GEM Applications: X-ray imaging

JEM-X   Mission INTEGRAL of ESA

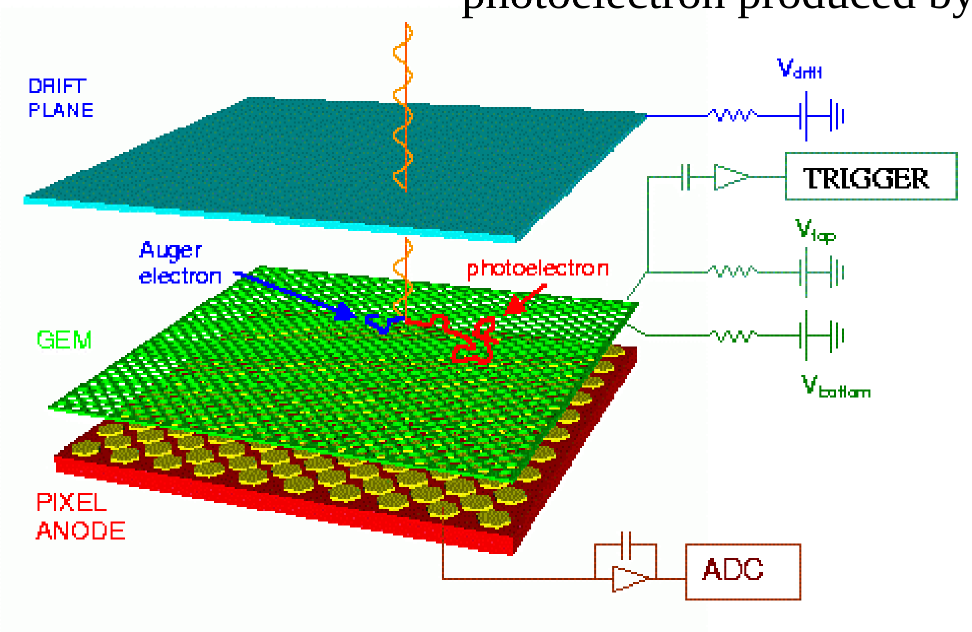
Prototype GEM amplifier (25 cm Ø):

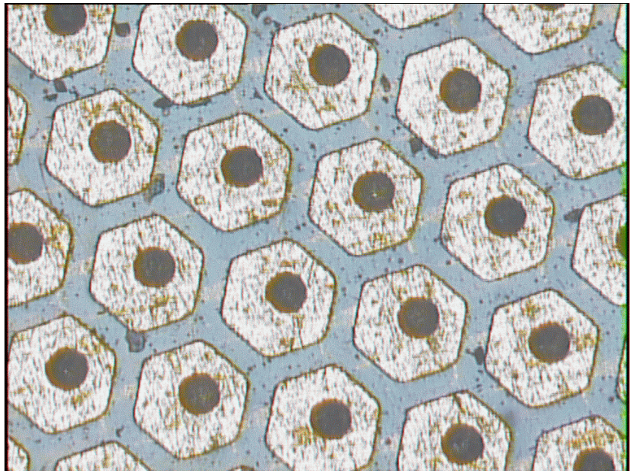
DSRI
Danish Space
Research Institute



X-ray polarimeter

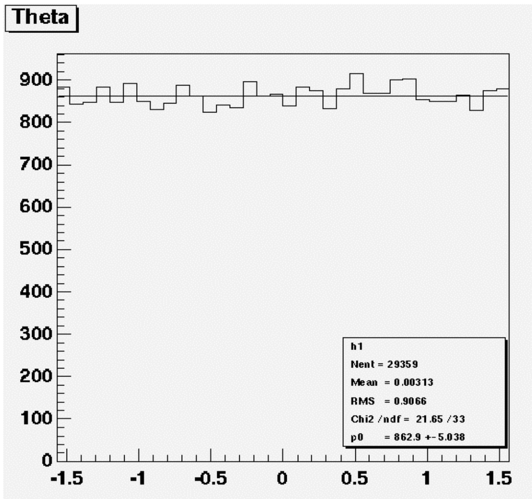
GEM chamber with pad readout to detect the direction of the photoelectron produced by X-rays



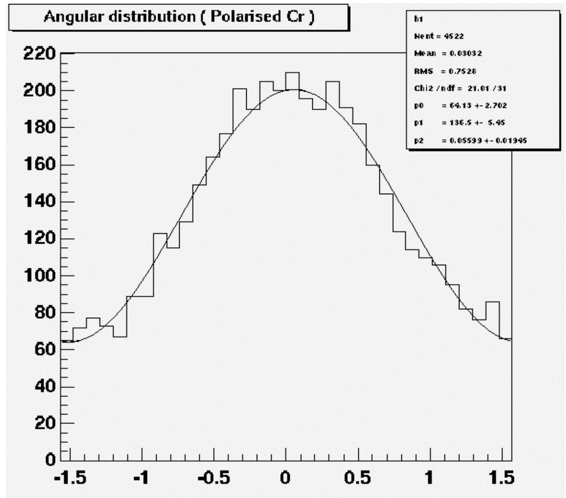


Charge asymmetry distributions for unpolarized and polarized 5.4 keV sources

5.9 KeV unpolarized source



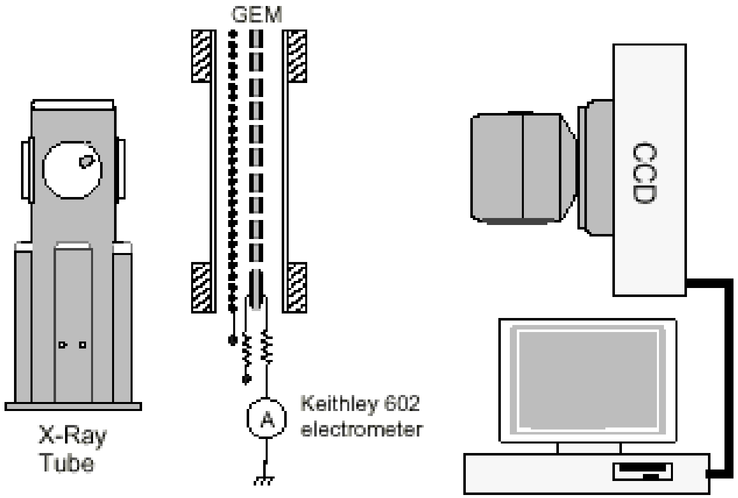
5.4 KeV polarized source



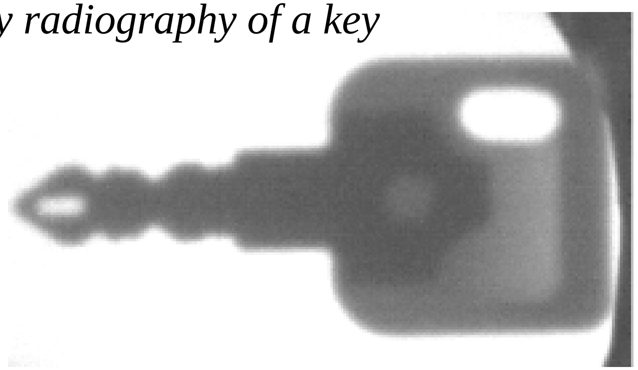
E. Costa et al, Nature 411(2001)662

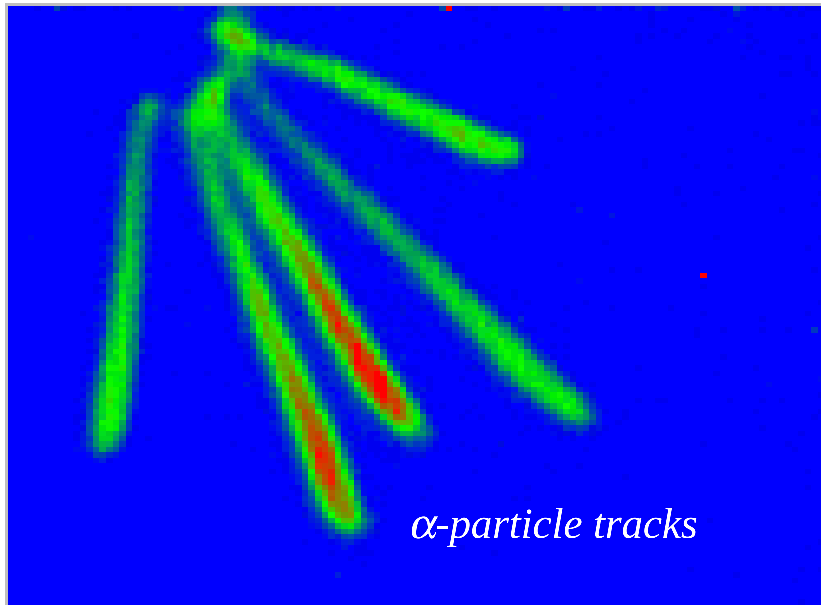
GEM optical imager

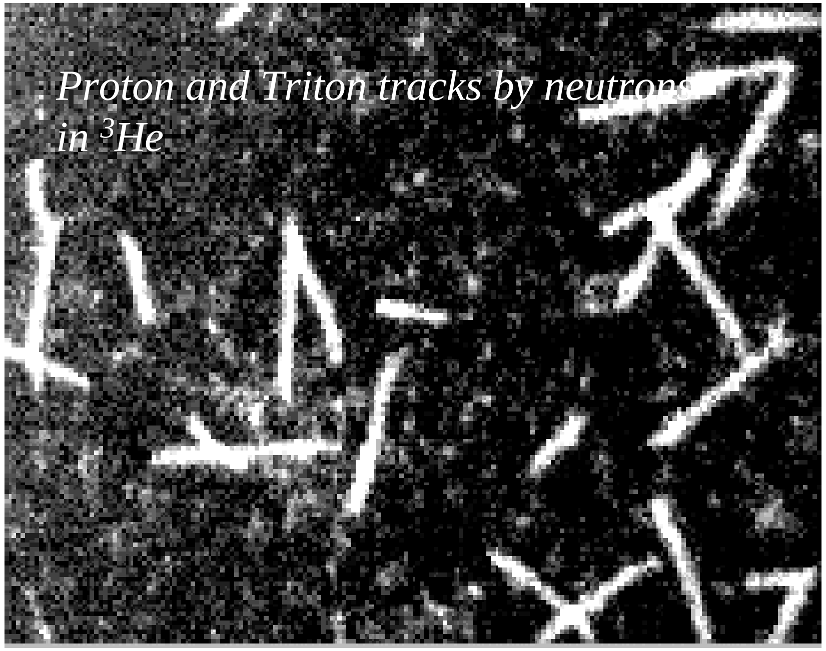
Scintillation light in a multiple GEM detector recorded by a CCD camera



X-ray radiography of a key





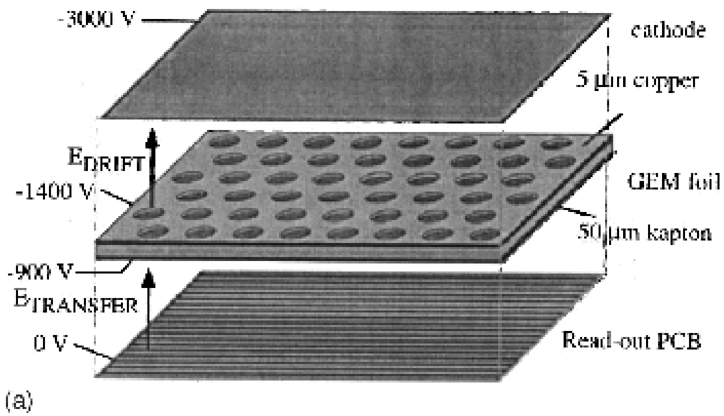


F.A.F. Fraga et al,
IEEE Nucl. Sci. Symp. NS-48 (2001)

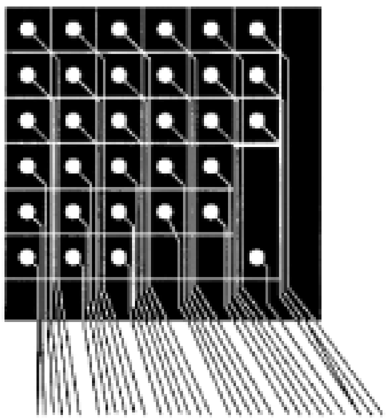
Ultrafast x-ray plasma diagnostics

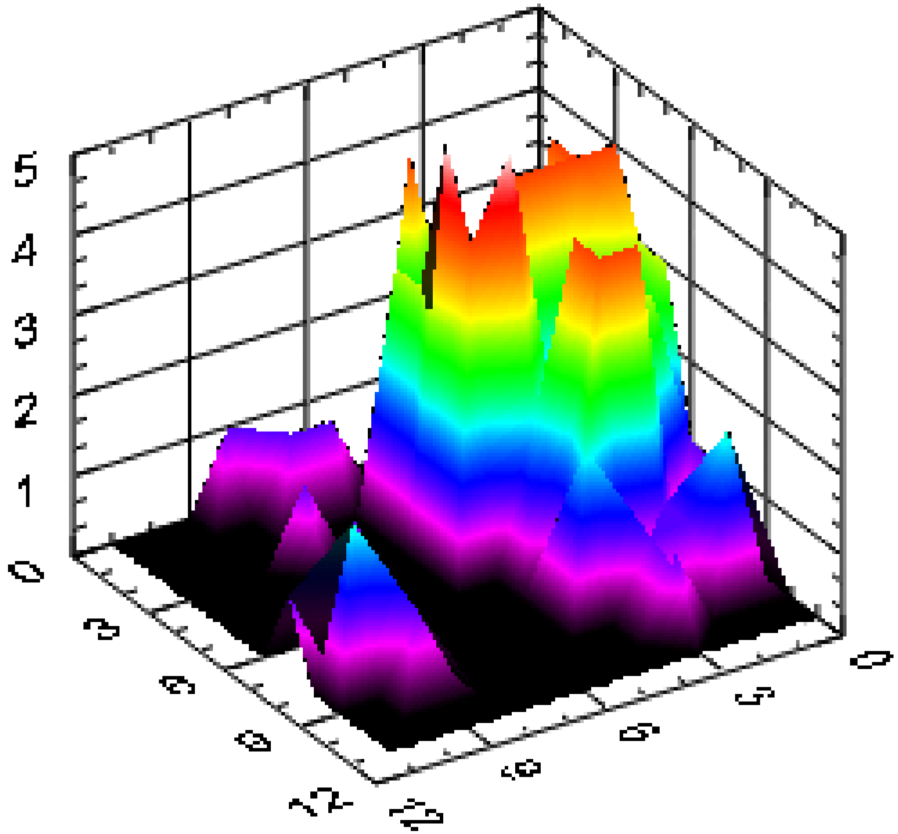
2-D mapping of soft X-ray activity of the plasma on a Tokamak fusion machine (EURATOM-ENEA Frascati, Italy)

Single GEM with fast pixel readout



Readout: 32 2 mm^2 pixels



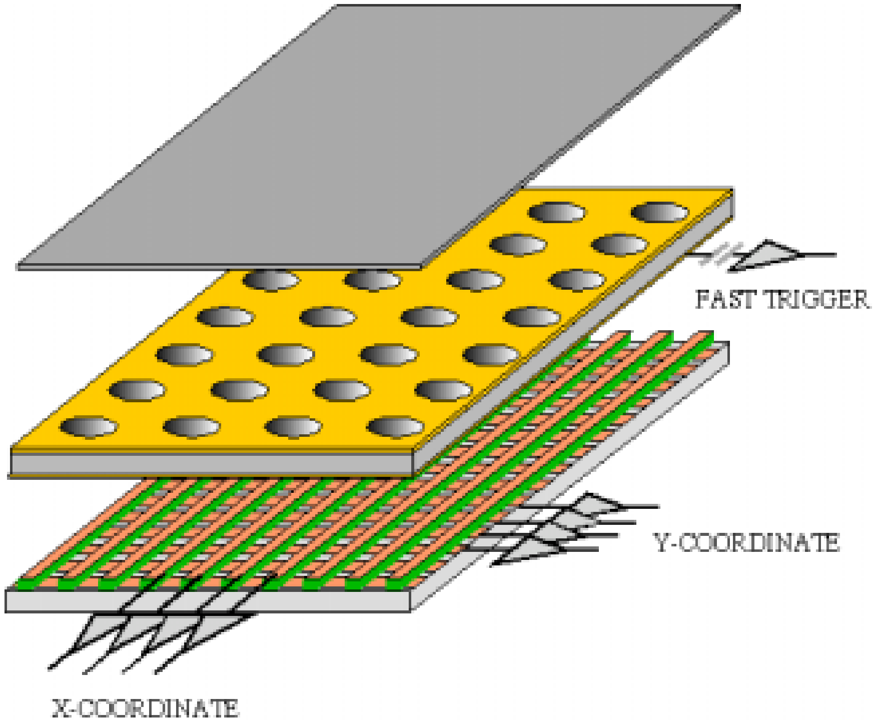


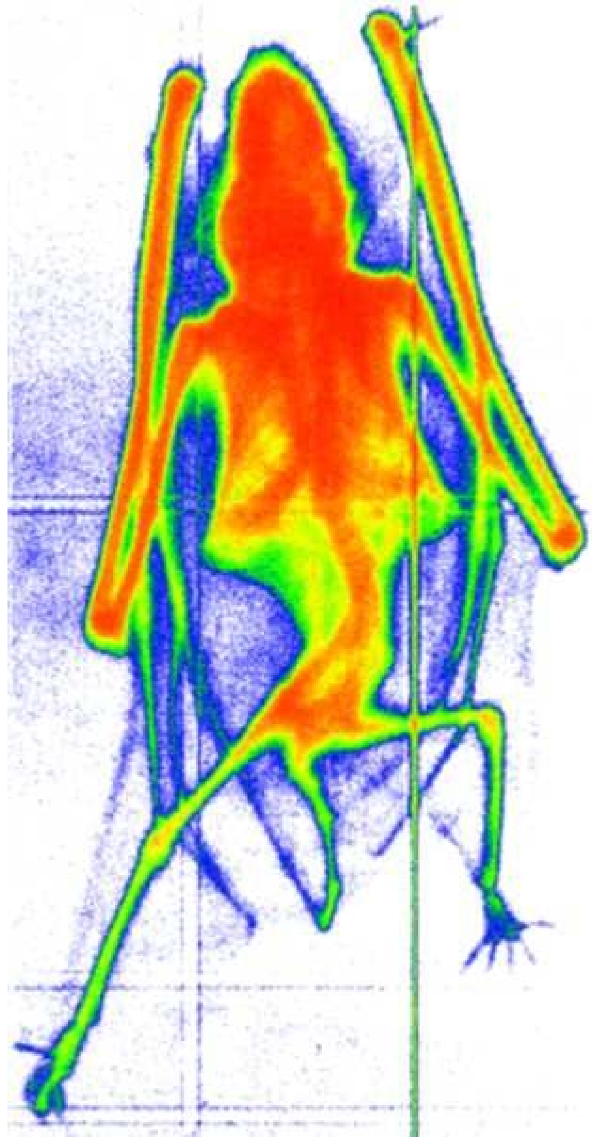
Counting rate vs position

D. Pacella et al, Rev. Scient. Instrum. 72 (2001) 1372

X-ray imaging

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:





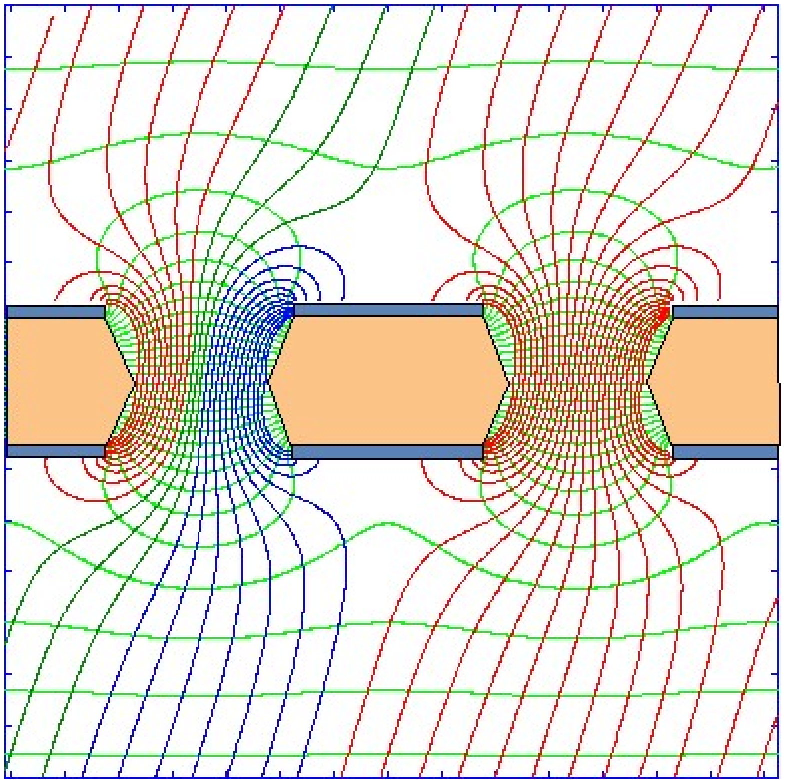
A. Bressan et al,
Nucl. Instr. and Meth. A 425(1999)254
F. Sauli,
Nucl. Instr. and Meth.A 461(2001)47

9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm^2)

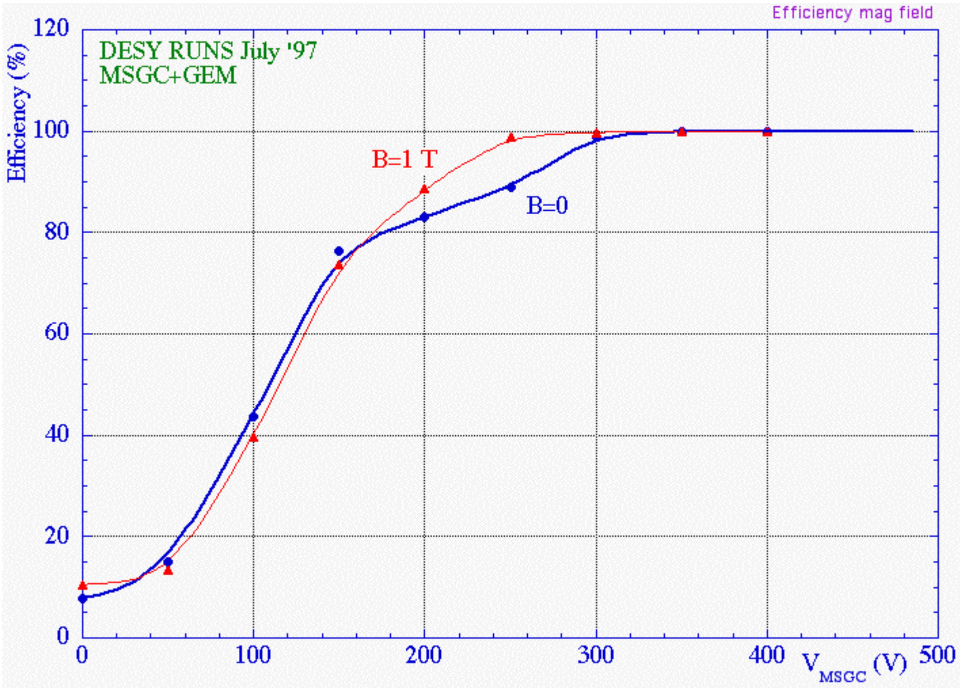
Operation in magnetic fields

Worst case: $\dot{E} \perp \dot{B}$

Computed electron drift lines:
Red: stopping on GEM
Green: through holes



Measured efficiency: even higher at B=1 T!

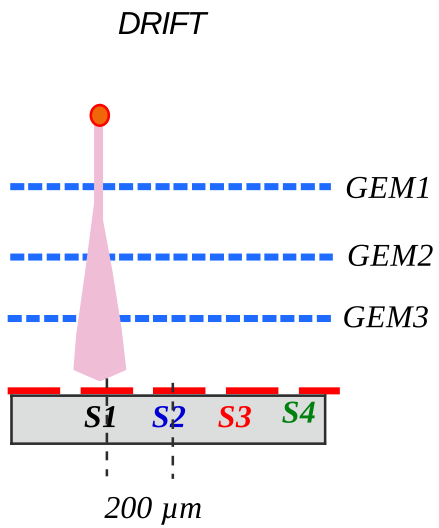


J. Benlloch et al, IEEE Trans. Nucl. Sci. NS-45 (1998) 234

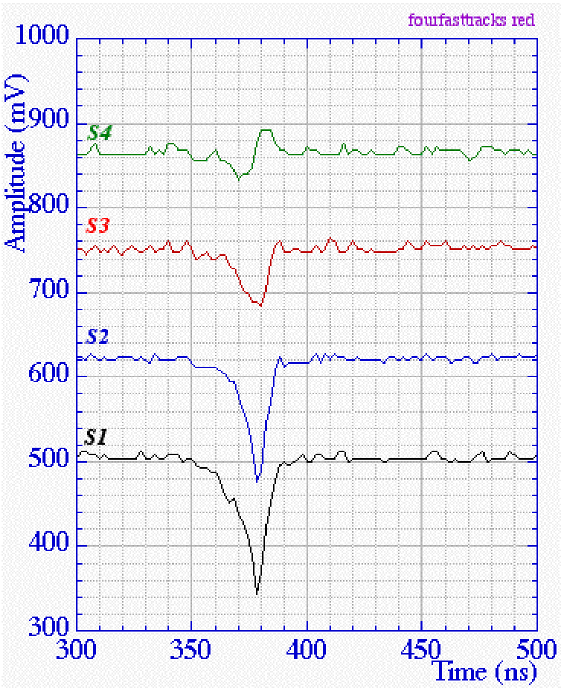
Demonstration of avalanche spread in the multiplication, filling the hole (also deduced from current sharing measurements)

GEM TPC

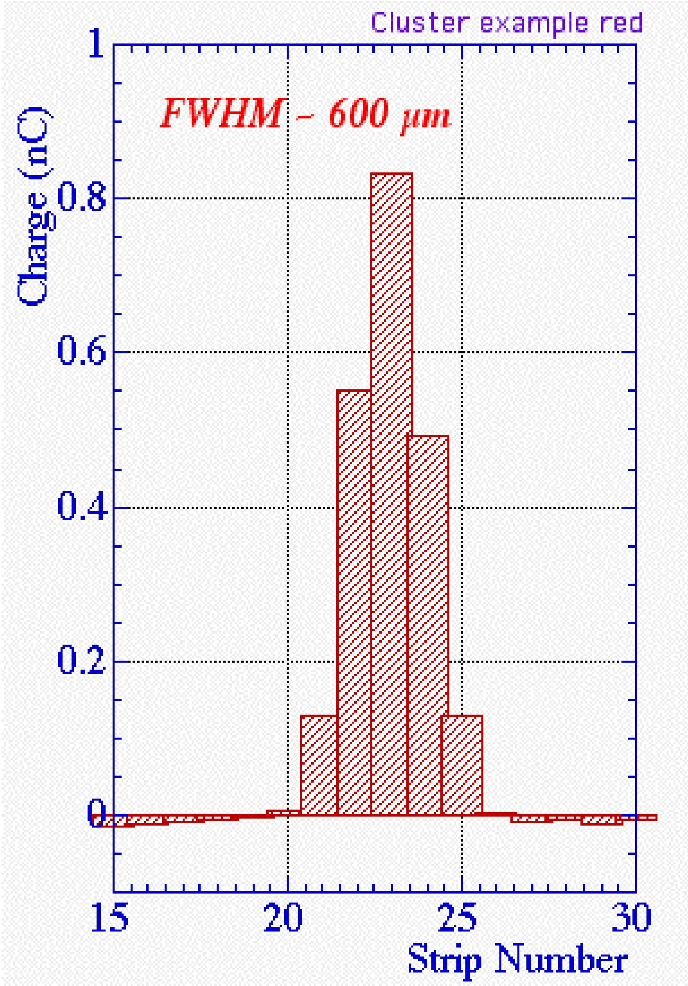
Improved multi-track resolution



Fast signals (no ion tail) $\Delta T \sim 20$ ns :



Narrow pad response function ($\Delta s \sim 1$ mm):

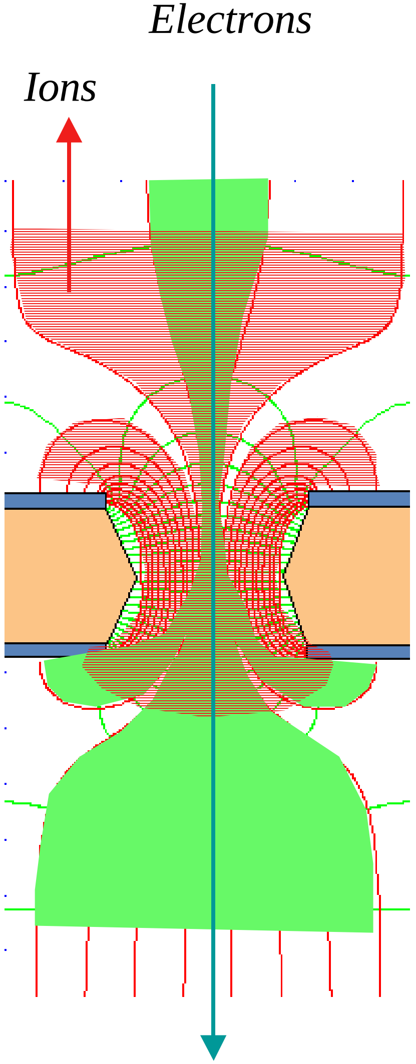


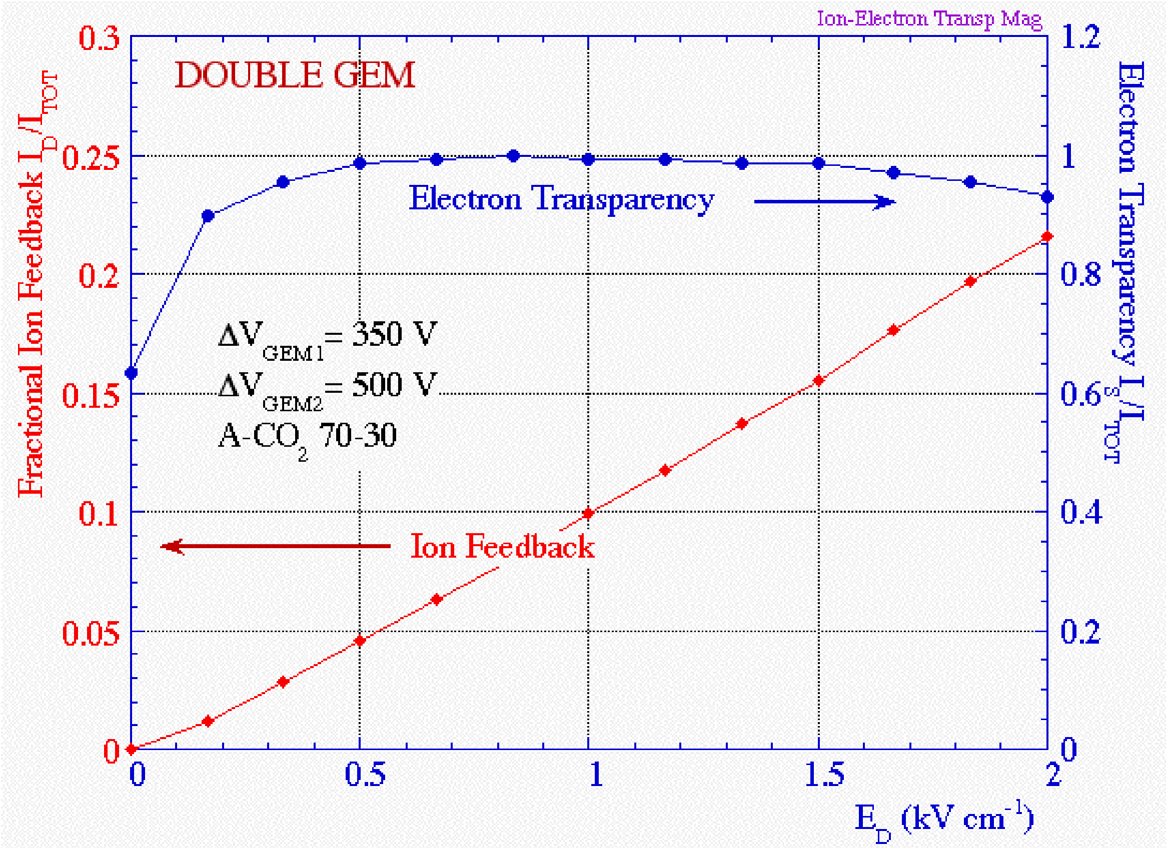
F Intrinsic multi-track resolution $\Delta V \sim 1\ mm^3$
(Standard MWPC TPC ~ 1 cm^3)

GEM TPC

Strong positive ion feedback suppression

Negligible $\dot{E} \times \dot{B}$ effects





S. Bachmann et al, Nucl. Instr. and Meth. A 438(1999)376

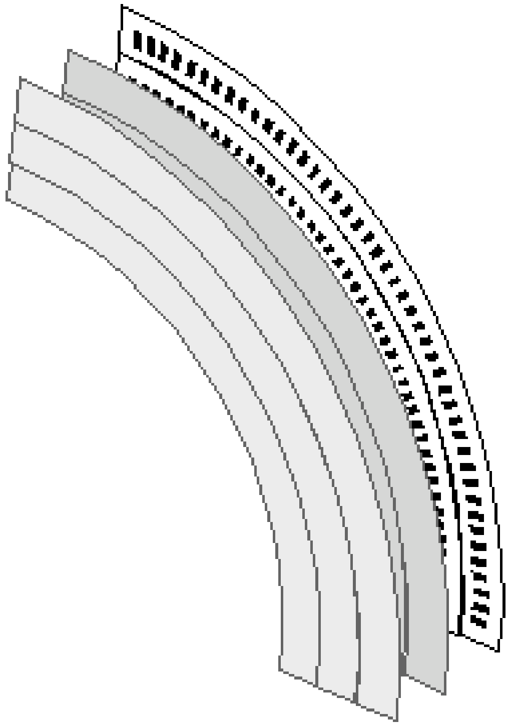
With a standard Double GEM, in normal operating conditions (E_{DRIFT}=200 V/cm), the Ion Feedback is ~ 1.5%

☞ Improve GEM geometry to reduce FB (---> 10^{-4}?)

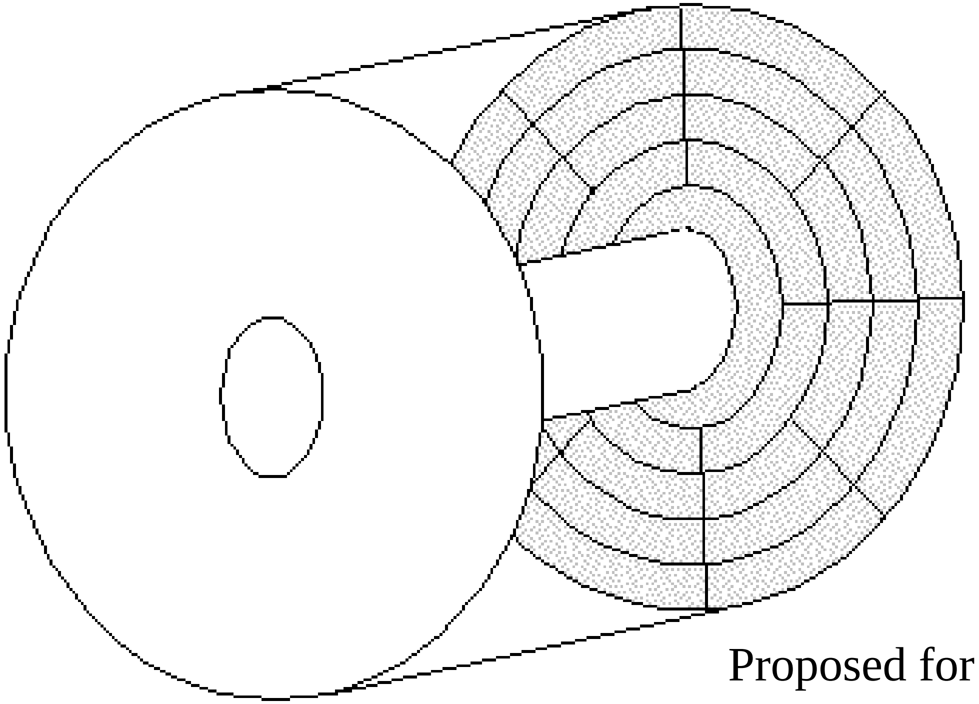
Gated operation easy!

GEM TPC

GEM sectors and readout board can have circular shape, with radial pad rows (no bias due to wire direction like in conventional MWPCs).
Gating (if needed) can be done at different times on radial sectors, modulating the in-depth sensitive volume.



F. Sauli, GEM readout of the TPC, CERN-TA1 Int, Note July 1999



Proposed for the central detector of TESLA (DESY Linear Collider)