GEM detectors activity
at the
Laboratori Nazionali di Frascati
INFN

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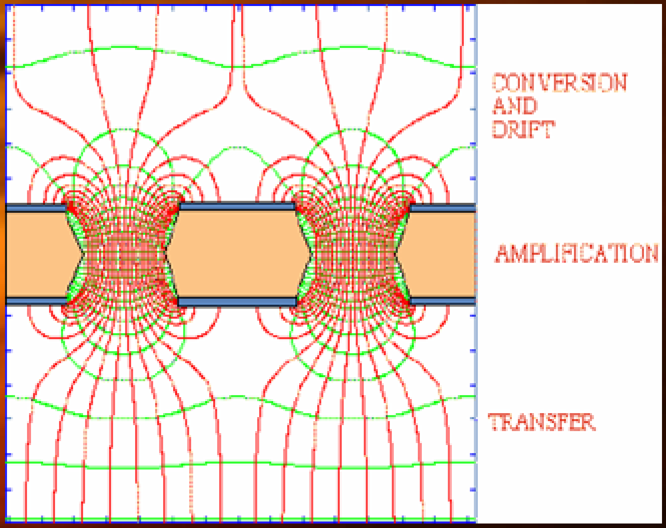
LNF-INFN

OUTLINE

- Introduction
- Planar GEM in LHCb
- Cylindrical GEM for Inner Trackers

INTRODUCTION

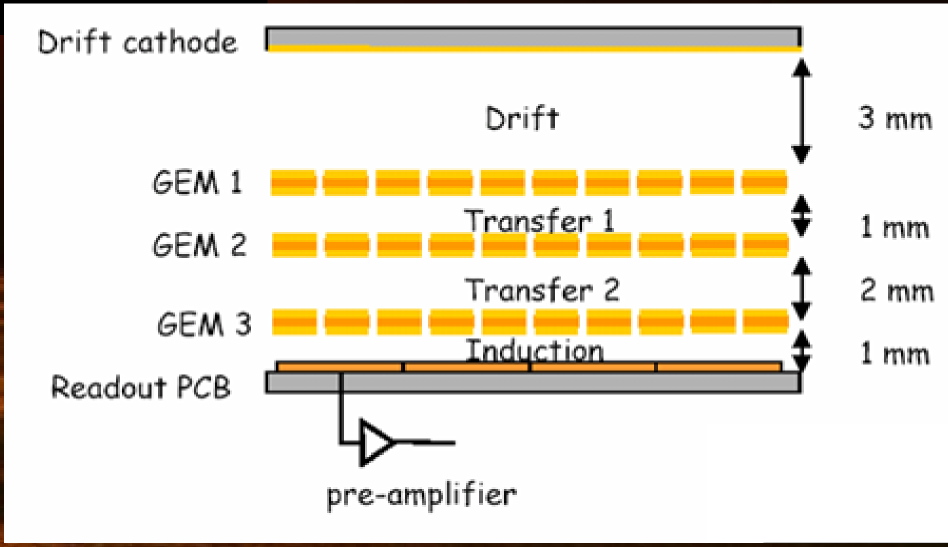
The GEM (Gas Electron Multiplier) **[F.Sauli,** NIM A386 (1997) 531] is a thin (50 μm) metal coated kapton foil, perforated by a high density of holes (70 μm diameter, pitch of 140 μm) → standard photo-lithographic technology.



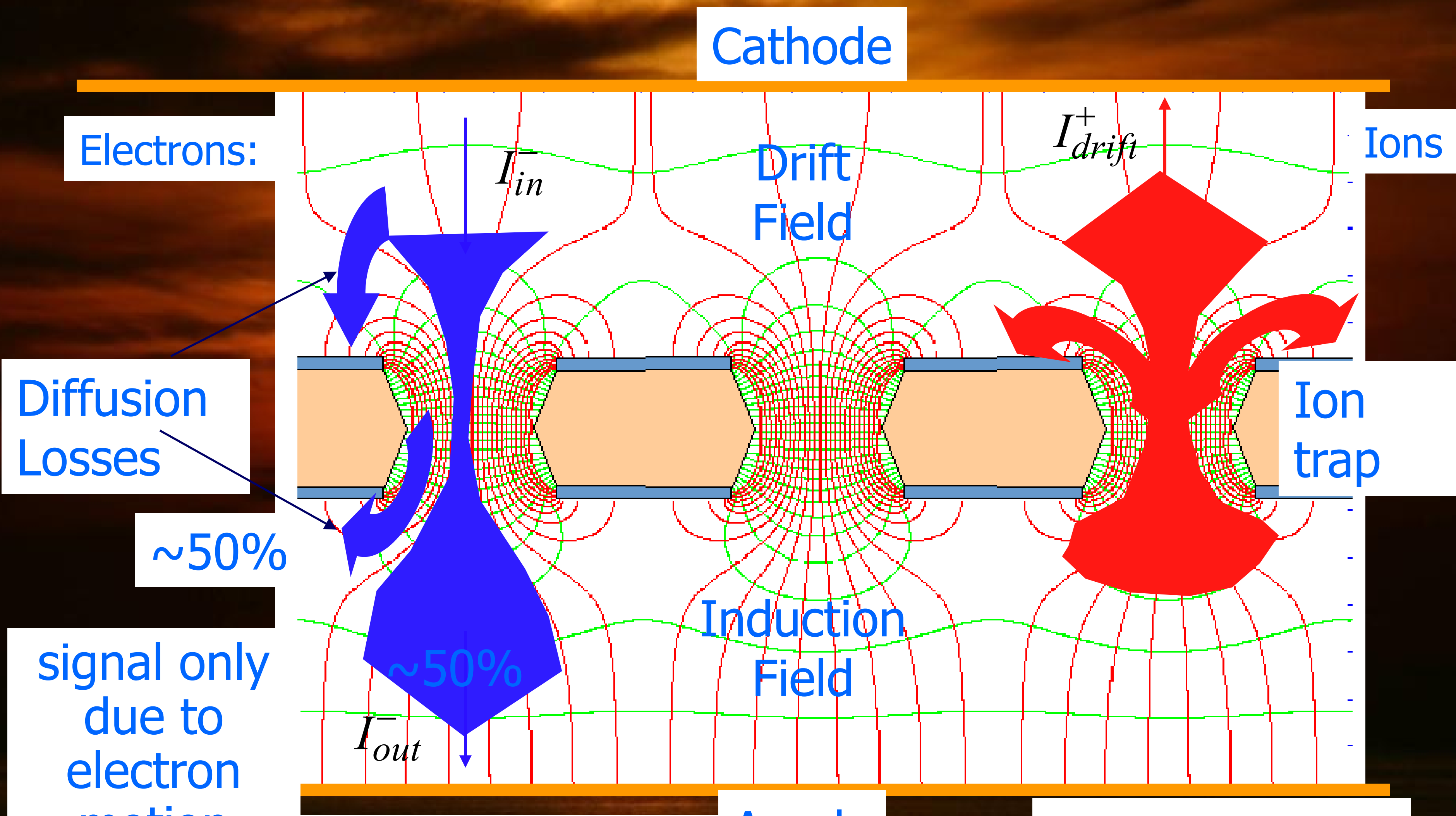
By applying 400-500 V between the two copper sides, an electric field as high as ~100 kV/cm is produced into the holes which act as multiplication channels for electrons produced in the gas by a ionizing particle.

Gains up to 1000 can be easily reached with a single GEM foil. Higher gains (and/or safer working conditions) are usually obtained by cascading two or three GEM foils.

A Triple-GEM detector is built by inserting three GEM foils between two planar electrodes, which act as the cathode and the anode.



Electron transparency (single-GEM)

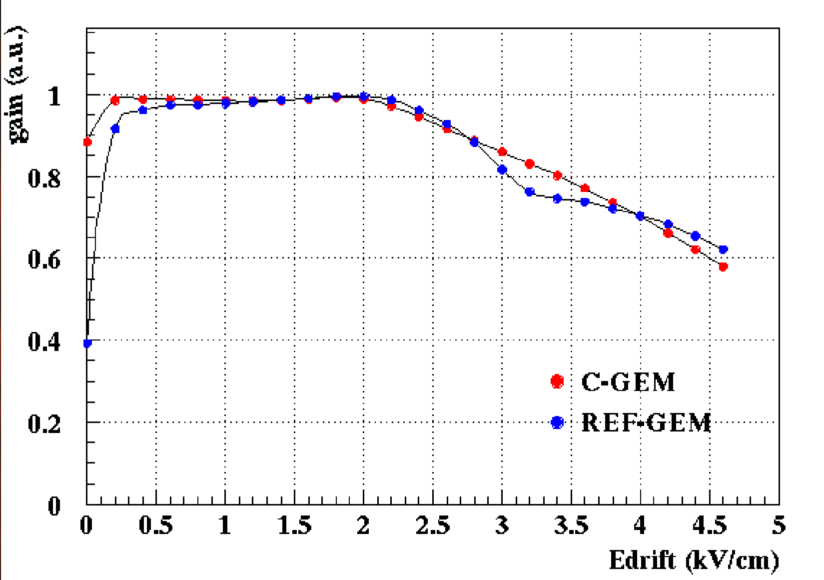


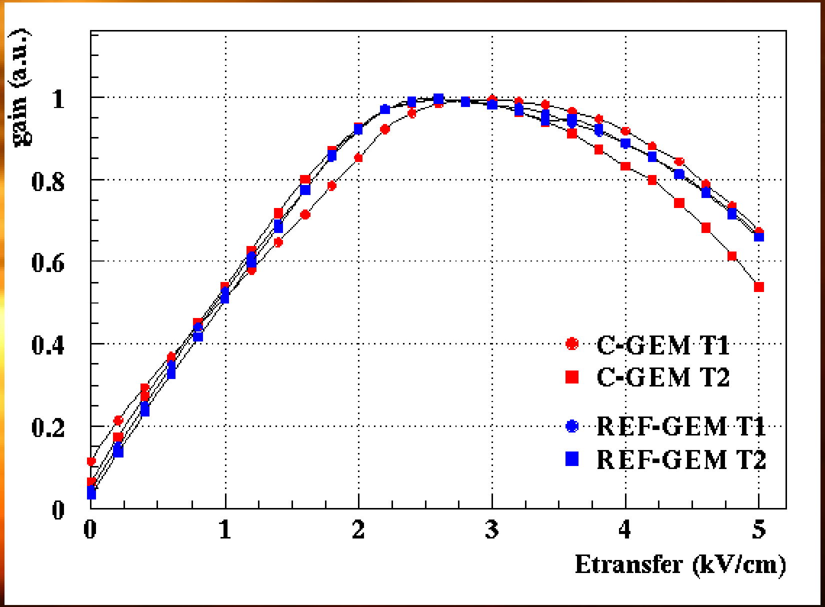
signal only due to electron motion

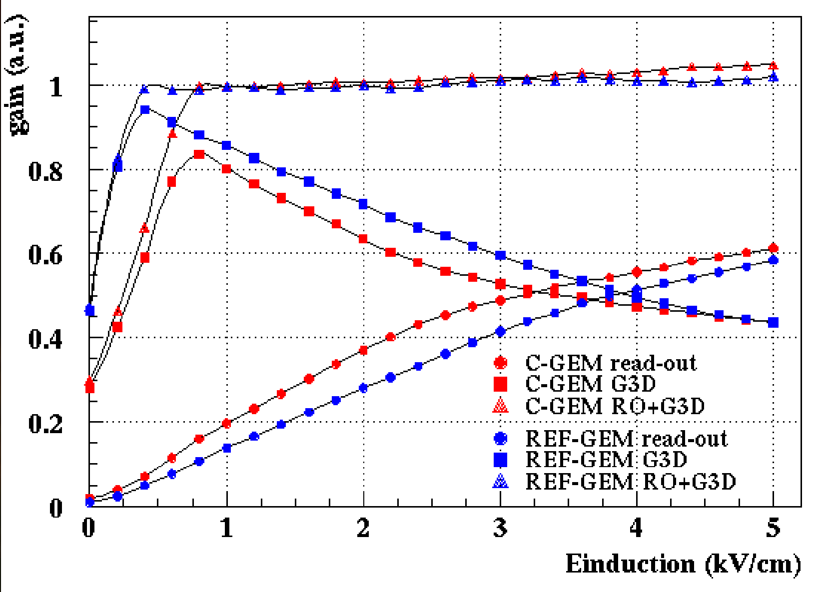
$I^-_{out} = I^-_{in} \cdot G \cdot T$
(gain x transparency)

Ion Feedback = I^+_{drift} / I^-_{out}

Electron transparency (triple-GEM)







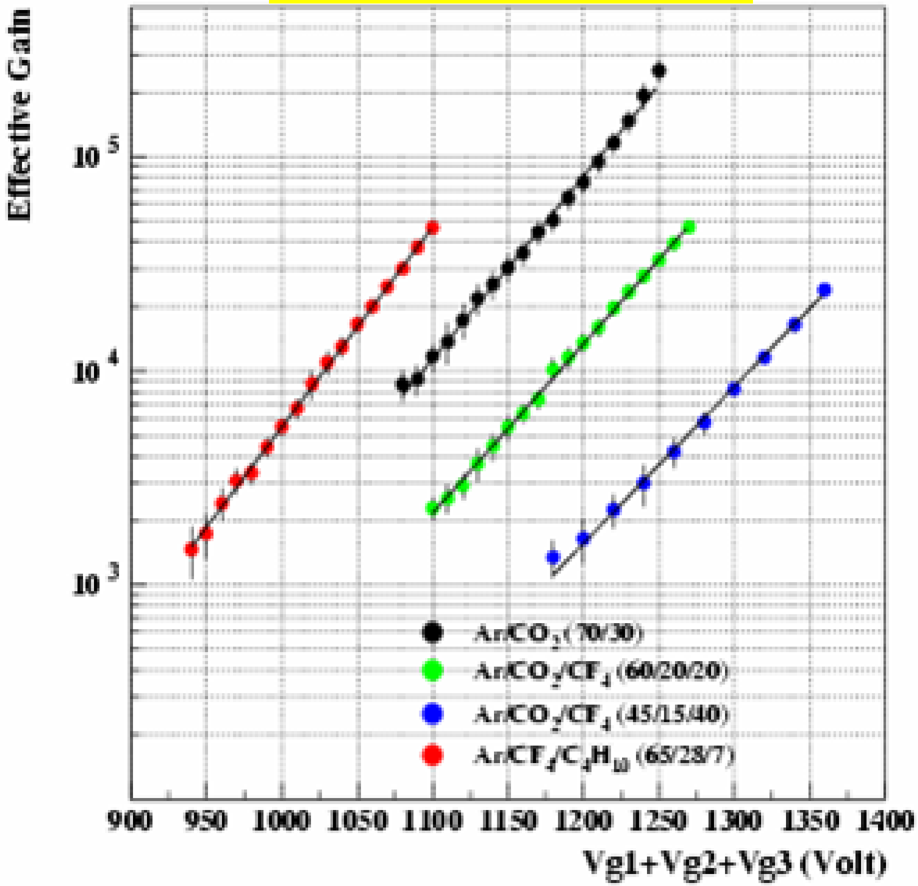
$Ar/CF_4/i\text{-}C_4H_{10}$ = 65/28/7

GEM polarization: 375/365/355 V

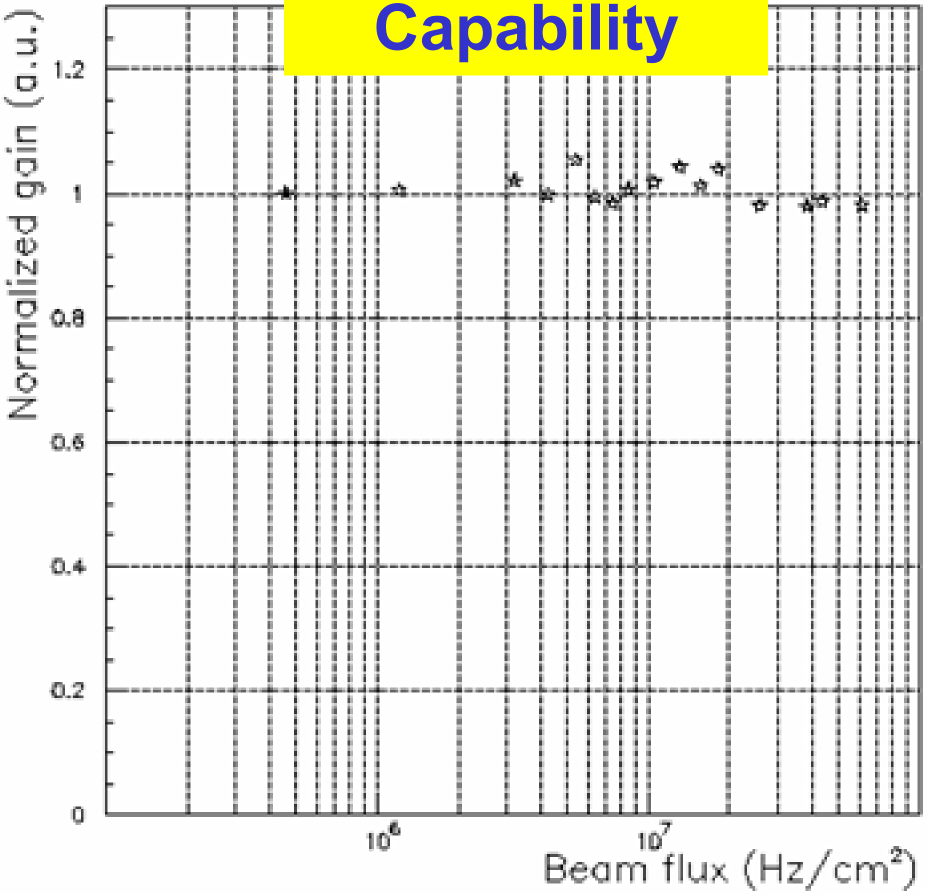
Gain ~ 20000

Triple-GEM operation

Gain



Rate Capability



GEM detector features

- **flexible geometry** → arbitrary detector shape: rectangular/square, annular, cylindrical …

- **ultra-light structure** → very low material budget: <0.5% X0/detector

- **gas multiplication separated from readout stage** → arbitrary readout pattern: pad, strips (XY, UV), mixed …

- **high rate capability:** >50 MHz/cm2

- **high safe gains:** > 10^4

- **high reliability:** discharge free, $P_d < 10^{-12}$ per incoming particle

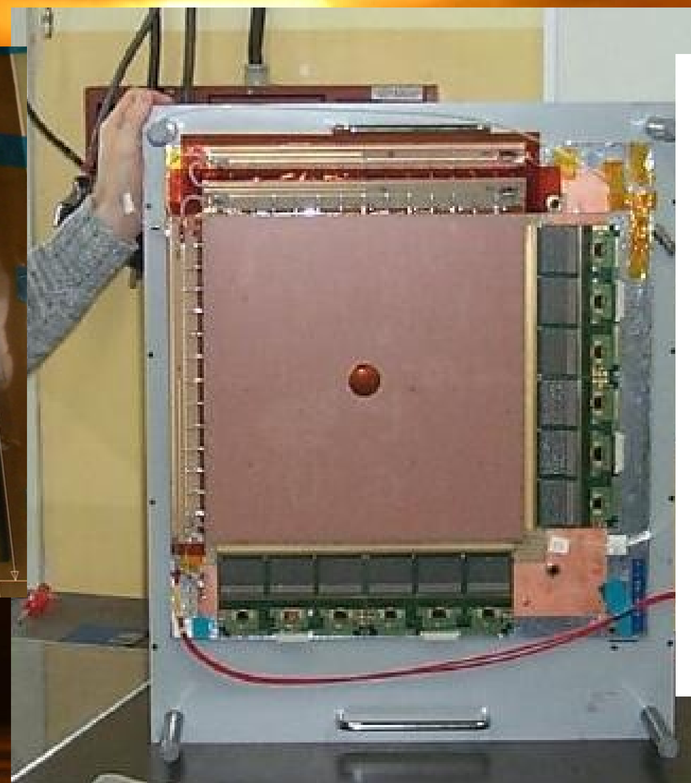
- **rad hard:** up to 2.2 C/cm^2 integrated over the whole active area without permanent damages (corresponding to 10 years of operation at LHCb1)

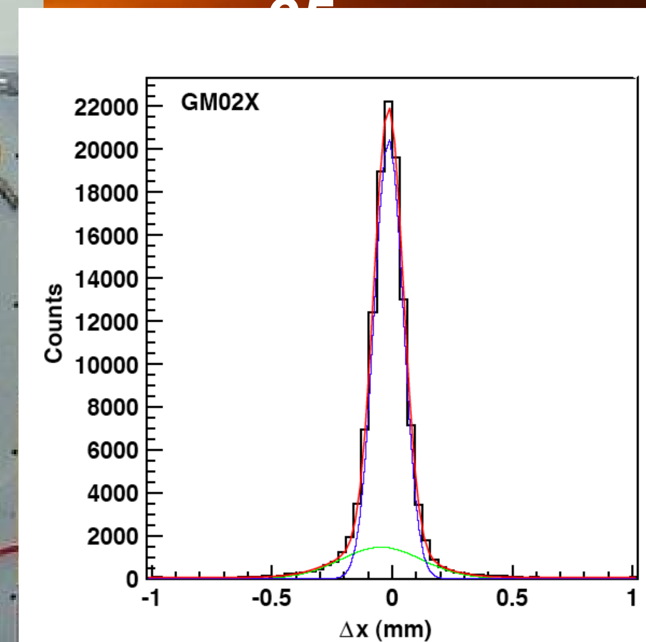
- **high spatial resolution:** down to 60μm (Compass)

- **good time resolution:** down to 3 ns (with CF_4)

GEM applications in HEP (I)

COMPASS: 22 triple-GEM chambers, 310x310 mm^2 active area; 2-D charge readout (XY strips with 400 μm pitch)



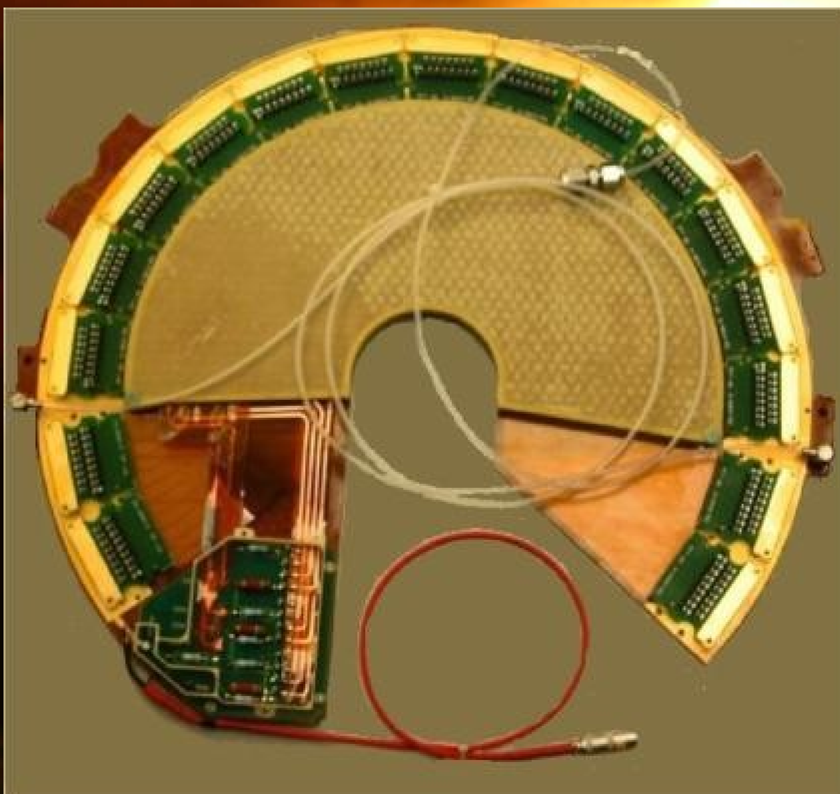


APV25 128 chs analog output

(C.Altunbas et al, Nucl.Instr.and Meth., A490(2002)177)

GEM applications in HEP (II)

TOTEM: 40 triple-GEM half-moon shaped, inner radius 40 mm, outer 150 mm; mixed readout → radial pad rows (3x3 ÷7x7 mm^2) and radial strips(400 μm pitch)



VFAT readout
128 chs chip with digital output

K. Kurvinen, 10 th Pisa Meeting on Advanced Detectors (Elba2006)

GEM in LHCb

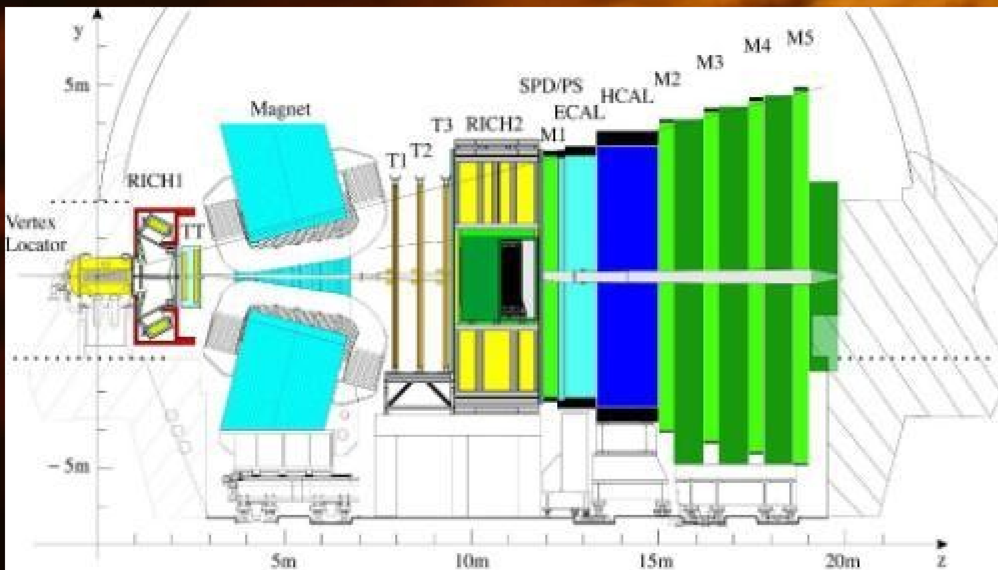
collaboration LNF-INFN and CA-INFN(*)

(*)CA-INFN: W. Bonivento, A. Cardini, D. Raspino, B. Saitta

The LHCb GEM detector in M1R1

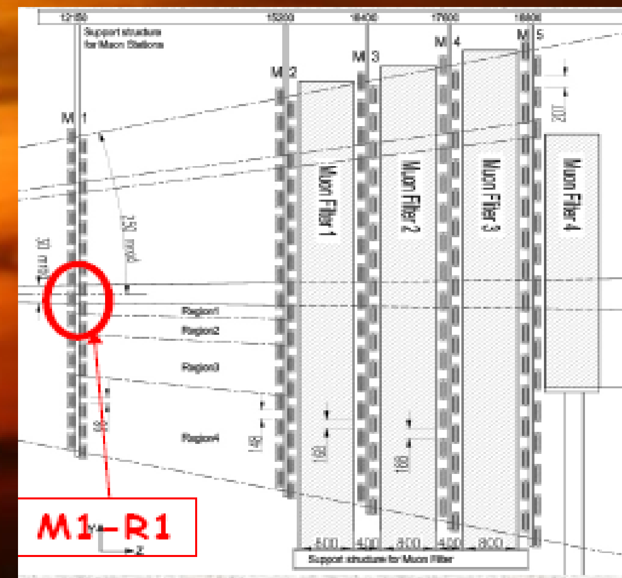
LHCb apparatus

CP in B-meson system | $B^0_d \rightarrow J/\Psi + K^0_S$ | $B^0_s \rightarrow \mu^+\mu^-$



$B^0_s \rightarrow J/\Psi + \phi$

Muon detector (5 stations):
L0 high p_T trigger + offline muon ID



All stations are equipped with small gap MWPCs with the exception of M1R1 station (area ~ 1 m^2), that it is instrumented with triple-GEM detectors.
About 20% of triggered muons will come from M1R1.
The M1R1 station is placed in front of the calorimeters and very close to the beam pipe, so that <u>low material budget</u>, <u>high rate capability</u> and <u>radiation tolerant</u> detectors are required.

The LHCb GEM detector in M1R1

M1R1 detector requirements:

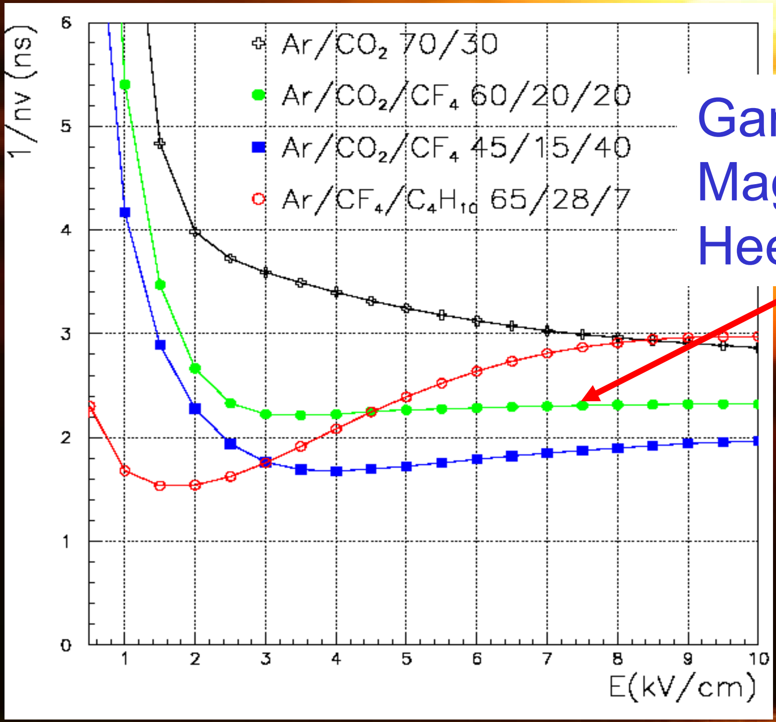
❑ Rate Capability	up to ~ 1 MHz/cm^2
❑ **Station efficiency**	**> 96% in a 20 ns time window (*)**
❑ Cluster Size	< 1.2 for a 10x25 mm^2 pad size
❑ **Radiation Hardness**	**1.8 C/cm^2 in 10 years (**)**
❑ Chamber active area	20x24 cm^2

(*) A station is made of two detectors “in OR”. This improves time resolution and provides some redundancy

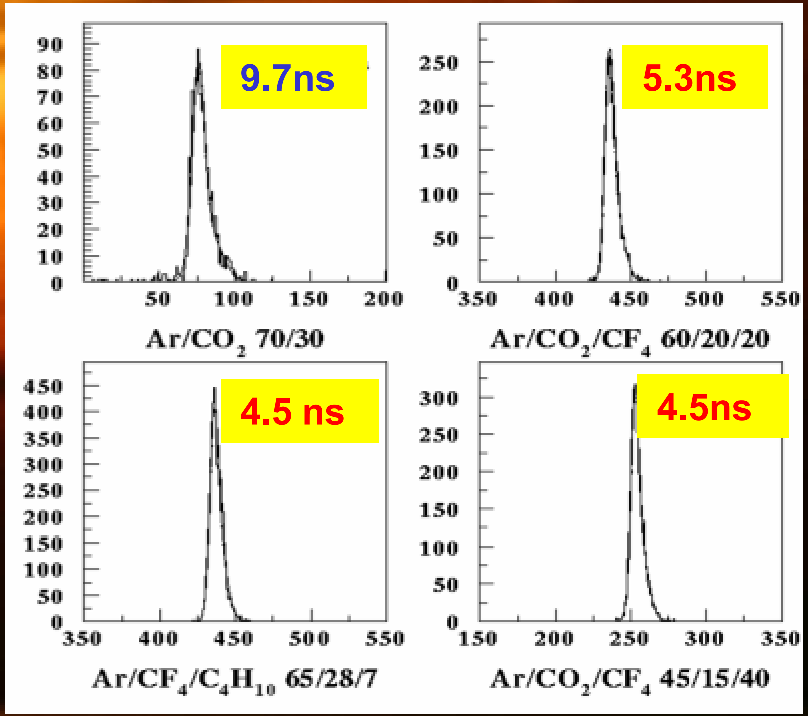
(**) Estimated with 50 e^-/particle at 184 kHz/cm^2 with a gain of ~ 6000

LHCb-GEM: R&D on fast gas mixtures

The intrinsic time spread : $\sigma(t) = 1/nv_{drift}$, where n is the number of primary clusters per unit length and v_{drift} is the electron drift velocity in the ionization gap.



Garfield: Magboltz + Heed simul.



To achieve a fast detector response, high yield and fast gas mixtures are then necessary

$Ar/CO_2/CF_4$ (45/15/40):

- 10.5 cm/μs @ 3.5 kV/cm
- 5.5 clusters/mm

fast & non flammable

Aging measurements: summary

- **Local Aging:**

performed with a high intensity 5.9 keV X-ray tube, irradiated area of about 1 mm2 (about 50 GEM holes). Integrated charge **4 C/cm^2 ⇔ 25 LHCb years**.

- **Large Area Aging:**

performed by means of the PSI πM1 positive hadron beam, with an intensity up to 300 MHz and an irradiated area of about 15 cm^2. Integrated charge **0.5 C/cm^2 ⇔ 3 LHCb years.**

- **Global Aging:**

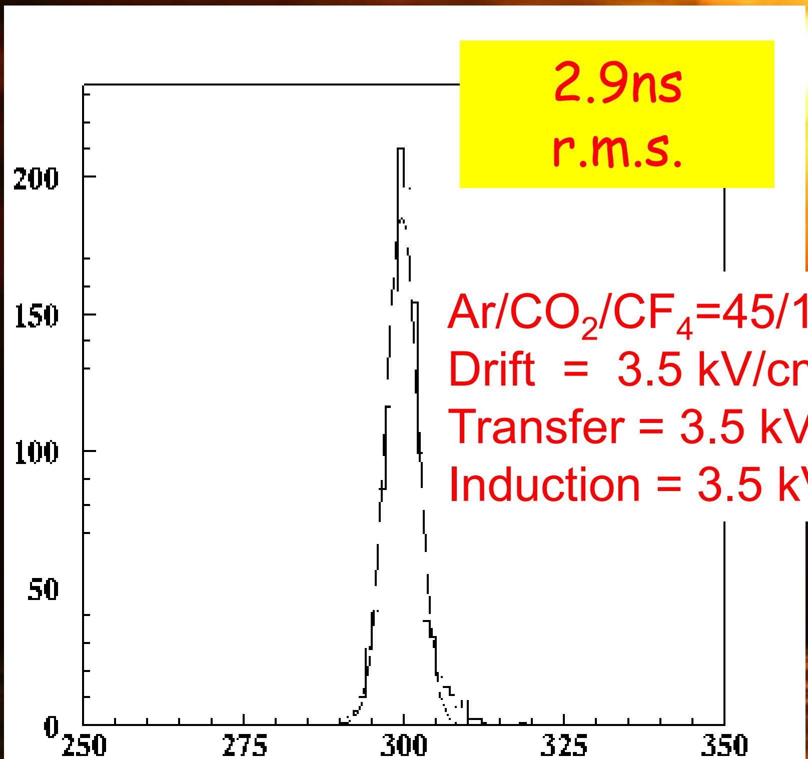
performed at Casaccia with a 25 kCi ^{60}Co source. Detectors were irradiated at 0.5 ÷ 16 Gray/h. Integrated charge up to **2.2 C/cm^2 ⇔ 12.5 LHCb years.**

Detailed information can be found at:

P. de Simone et al., “Studies of etching effects on triple-GEM detectors operated with CF4-based gas mixtures”,
IEEE Trans. Nucl. Sci. 52 (2005) 2872

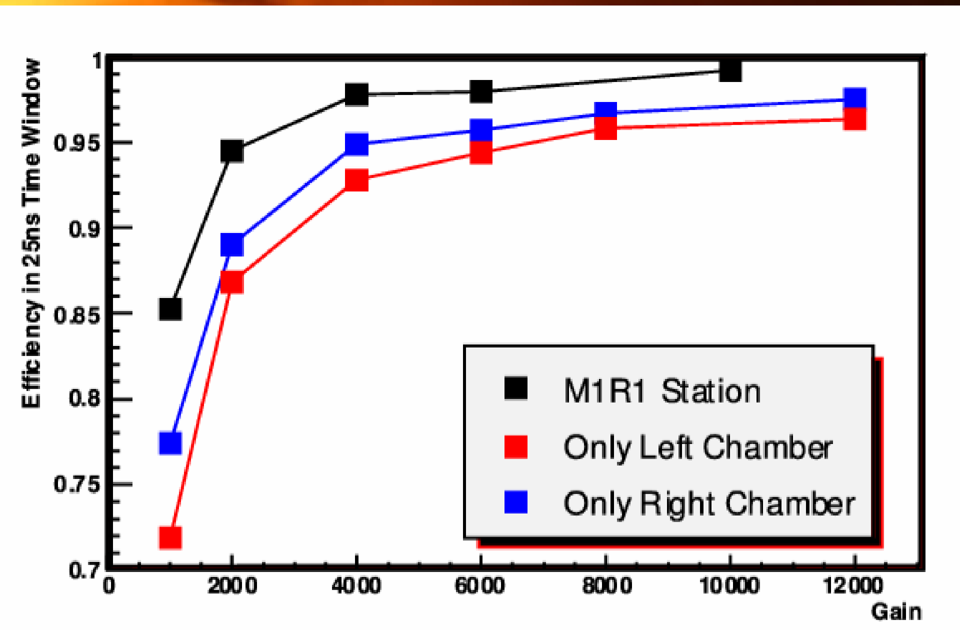
LHCb-GEM: detector performances

The performances of a full size detector, in almost final configuration, have been measured at the T11-PS CERN facility.



Time resolution of two chambers in OR

Efficiency measured on the last test beam



LHCb – GEM Construction

LHCb-GEM: detector construction

All the construction operations are performed in a class 1000 clean room.

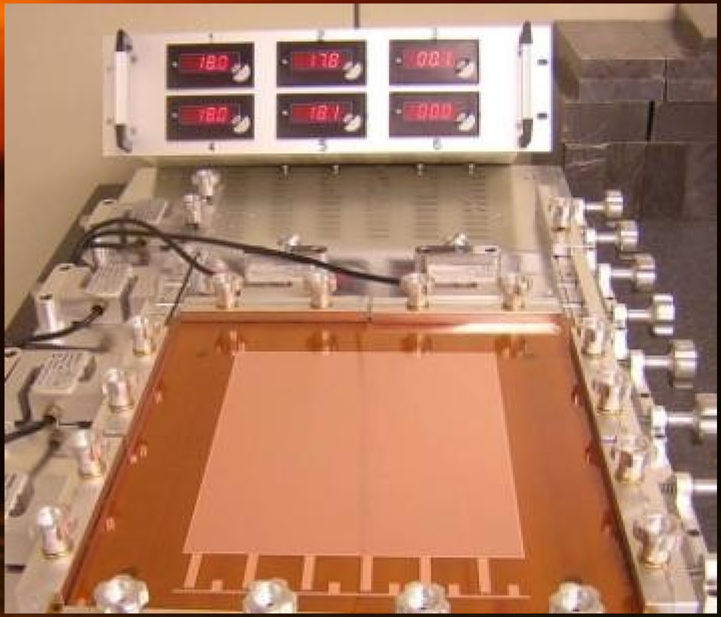
The detector is composed by three GEM foils glued on fiberglass (FR4) frames, then sandwiched between a cathode and anode PCBs, that are glued on a honeycomb structure panels.
A M1R1 detector is realized coupling two of such chambers.

A GEM foil stretching technique has been introduced: no spacer within the active area is required to maintain the gap

→ NO geometric dead area

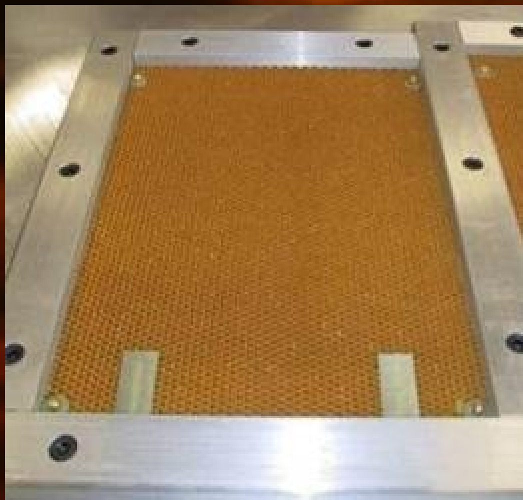
The mechanical tension (18kg/jaw → 20 MPa), applied to the edge of the foil, is monitored with gauge meters.

Kapton creep is negligible for this mechanical tension (see http: //www.dupont.com): **inside elastic limit.**



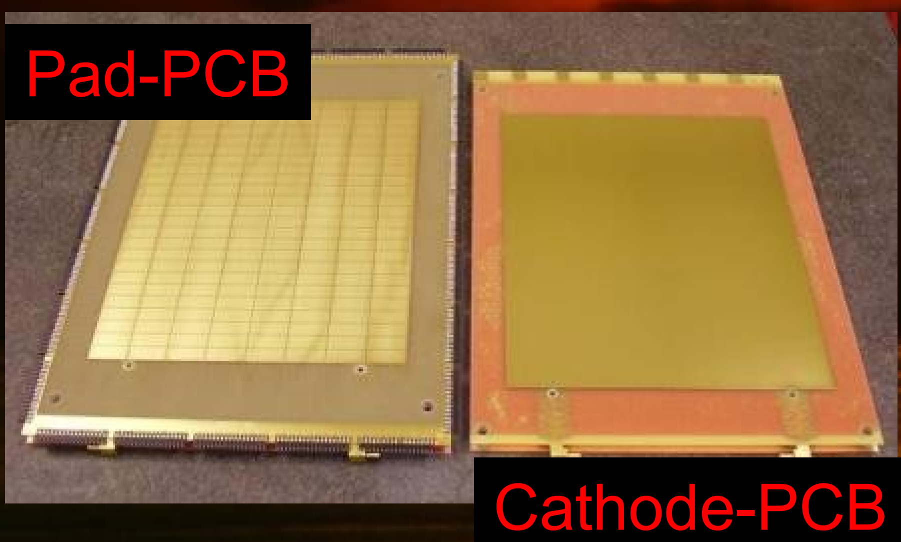
The GEM foil stretching device

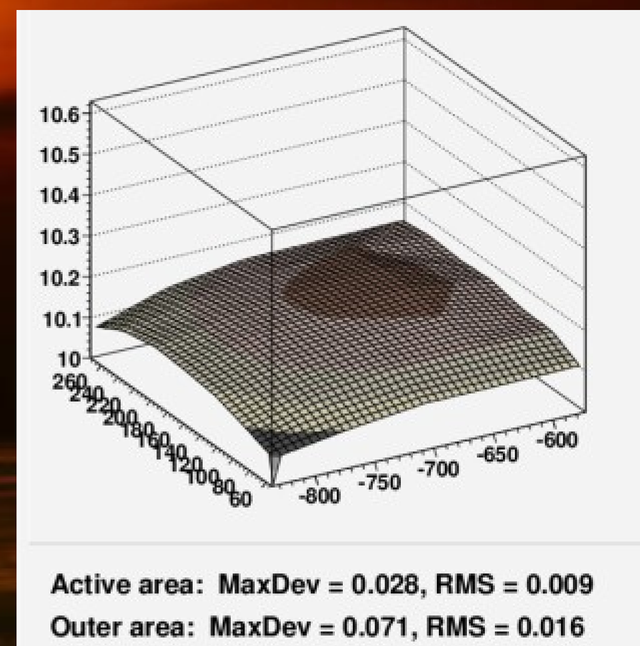
LHCb-GEM: detector construction



Honeycomb PCB panels:

The support panels of the GEM detector are realized coupling PCBs with FR4 copper clad back-planes with a 8mm thick honeycomb layer in between. Globally the panel has a material budget of the order few % of X_0 and a planarity ≤ 50μm (r.m.s.)





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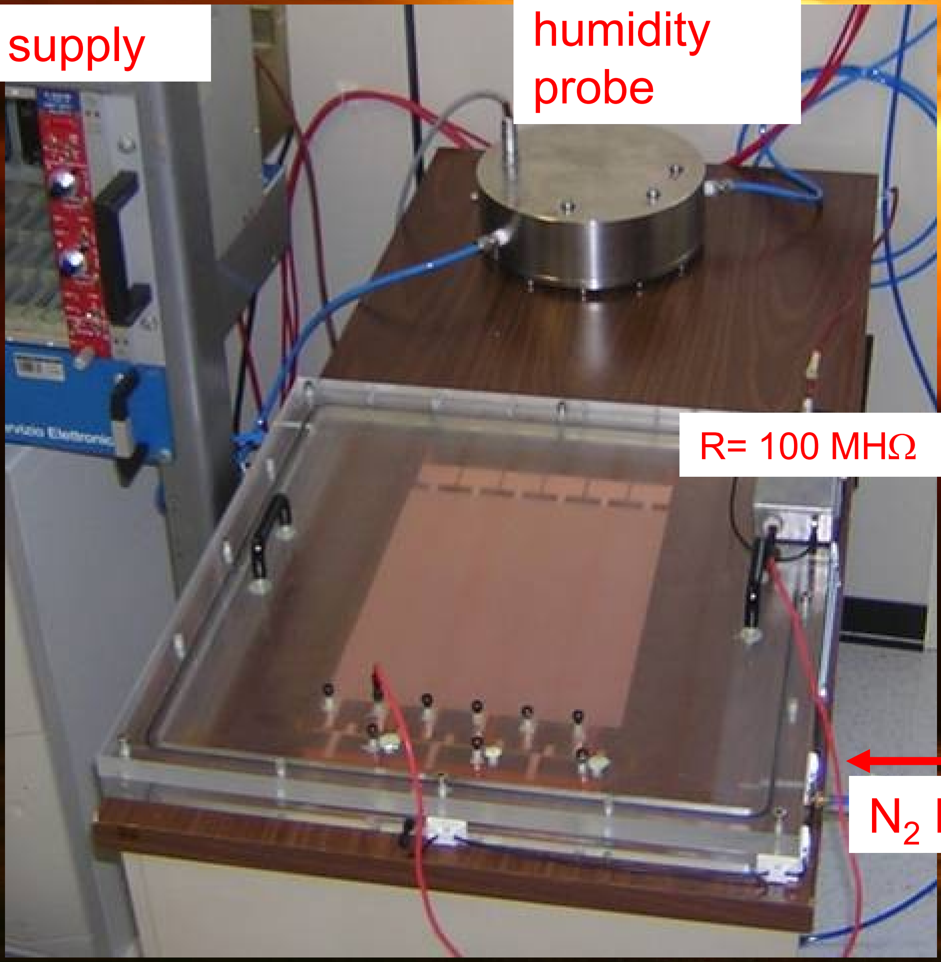
LHCb-GEM: detector construction

All GEM foils are tested before frame gluing in order to check their quality. The test, sector by sector, is performed in a gas tight box.



The gas box is flushed for about 1 hour with nitrogen in order to reduce the R.H. (<10%) before to start the test of the GEM foil

The voltage to each GEM sector is applied through a 100 MΩ limiting resistor in order to avoid GEM damages in case of discharges.

A GEM is OK if, for each sector, I < 1 nA @ 500 V

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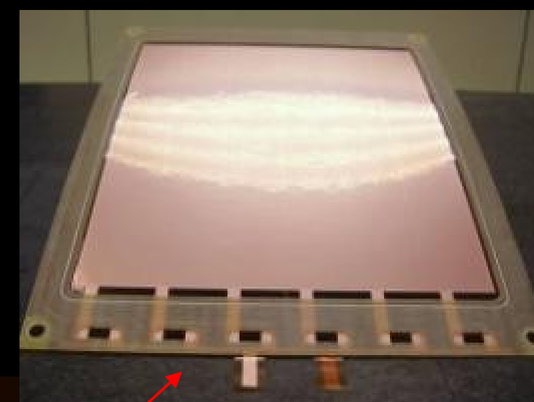
LHCb-GEM: detector construction-GEM framing

Before gluing, the frame is cleaned and checked for broken fibers

Araldite 2012 epoxy, 2 hours curing time, good handling properties & electrical behavior, aging tested , is applied with a rolling wheel tool on the frame. The frame is then coupled with stretched GEM foil



After epoxy polymerization the GEM foil is cut to size and 1 MΩ smd resistors are soldered on the HV bus of each of the six sectors.

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LHCb-GEM: detector construction - assembly (I)

For chamber assembly we use araldite AY103 + HD991 with good electrical behavior & well-known aging properties(*) and 24 h curing time.

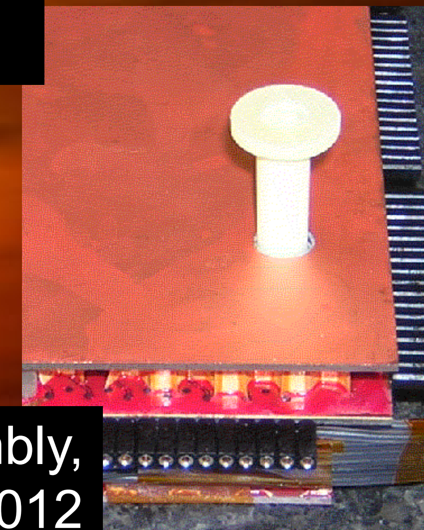
(*)C. Altunbas et al., CERN-[redacted]; CERN **PH-TA1-GS,** (http://detector-gas-systems.web.cern.ch)

The epoxy is applied with a rolling wheel tool on framed GEMs.

The 3mm, 1mm, 2mm framed GEMs, plus an additional bare 1mm frame, for the induction gap, are positioned on the cathode PCB panel.
The assembly operation is performed on a machined ALCOA reference plane, equipped with 4 reference pins. Over the whole structure a load of 80 kg is uniformly applied for 24h, as required for epoxy polymerization.

LHCb-GEM: detector construction - assembly (II)

Before the PCB pad panel gluing, HV connections of GEM foils are soldered on cathode PCB



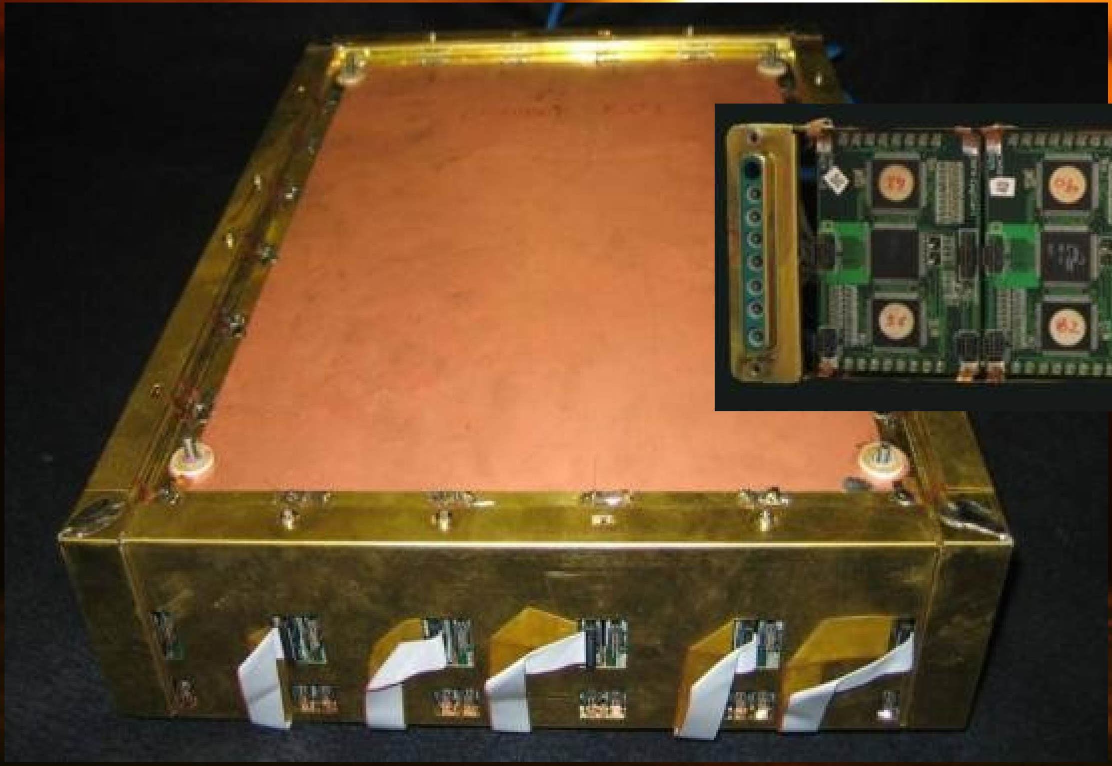
Inside the four reference holes, used for the chamber assembly, Stesalite bushings are inserted and glued with the Araldite 2012 epoxy. Bushings prevent gas leaks from the corners of the chamber and are used to hang-up the chamber on the muon wall

The gas leakage of the produced chambers is less than 5mbar per day
→ the humidity of the gas mixture is below 100ppm$_V$ with a flux of 80cc/min.

The gain uniformity, measured with a high intensity 6keV X-ray beam, is ~10%

LHCb-GEM: detector construction – assembly (III)

Two triple-GEM detectors are coupled, through the four pin holes, with cathodes faced one to each other. FEE boards are installed along the detector perimeter and closed with a Faraday cage.
The whole chamber, FEE and Faraday cage included, has a material budget of the order of 8% X_0.



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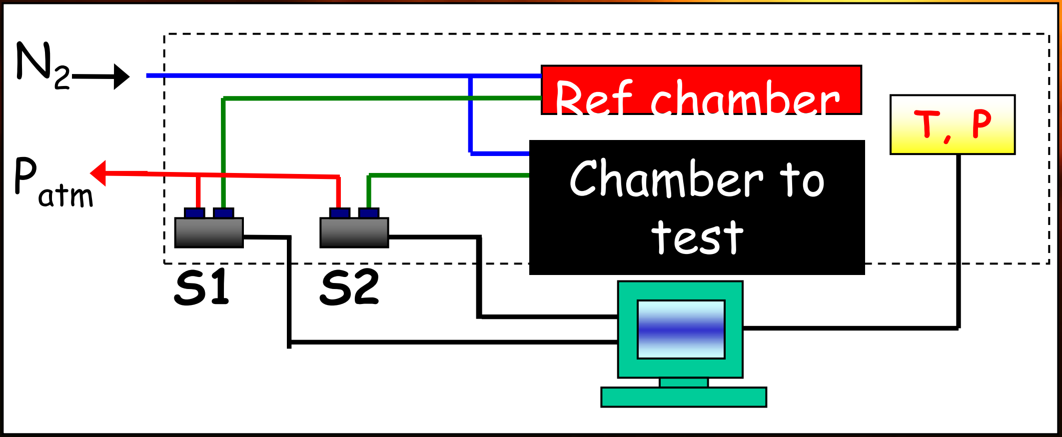
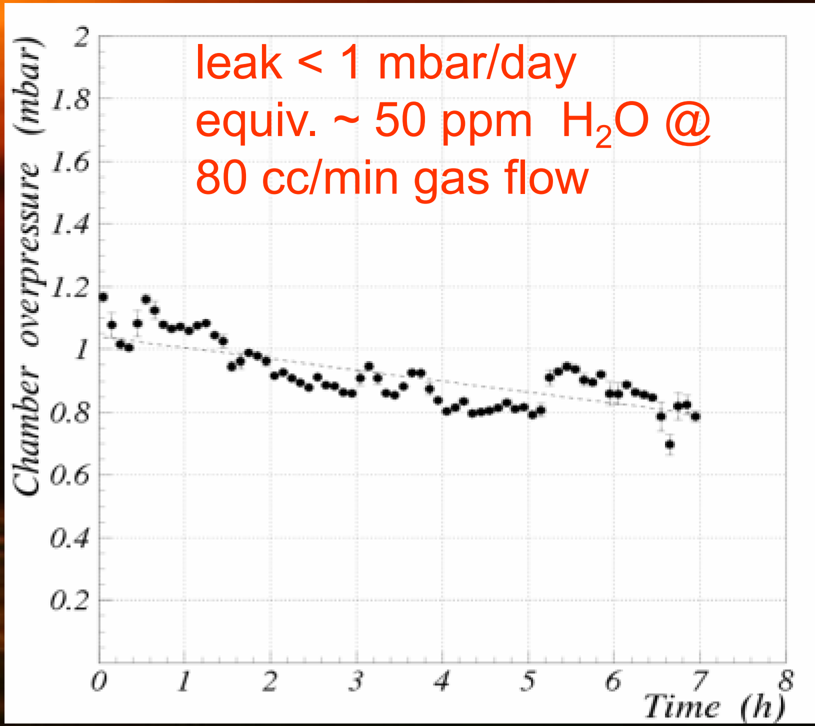
LHCb-GEM: detector quality test

Gas leak test

The gas leak rate measurement of a chamber is referred to a leak rate of a reference chamber (same volume, "no leak"), in order to take into account for atmospheric pressure and temperature variations. Both test and reference chambers are inflated in parallel, up to an overpressure of few mbar.



The difference between ΔP(S1) e ΔP(S2) measures the gas leak rate of the test chamber



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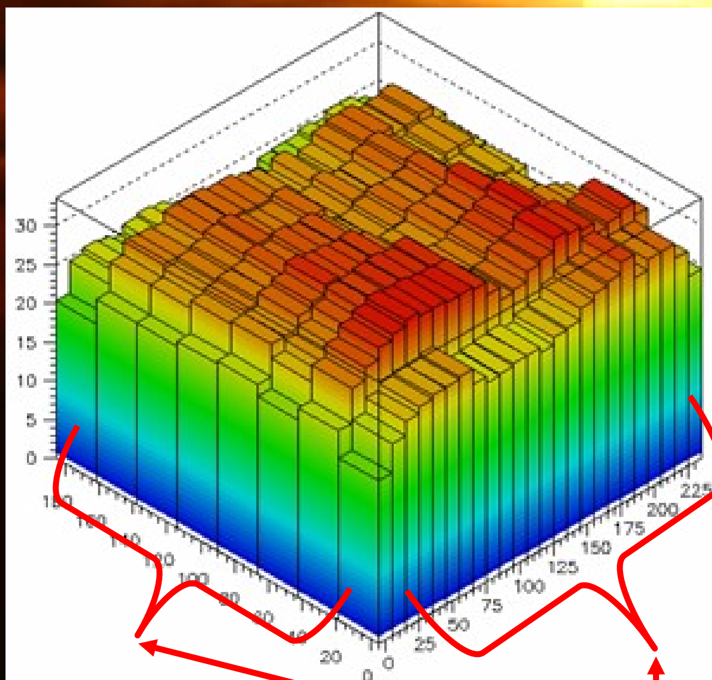
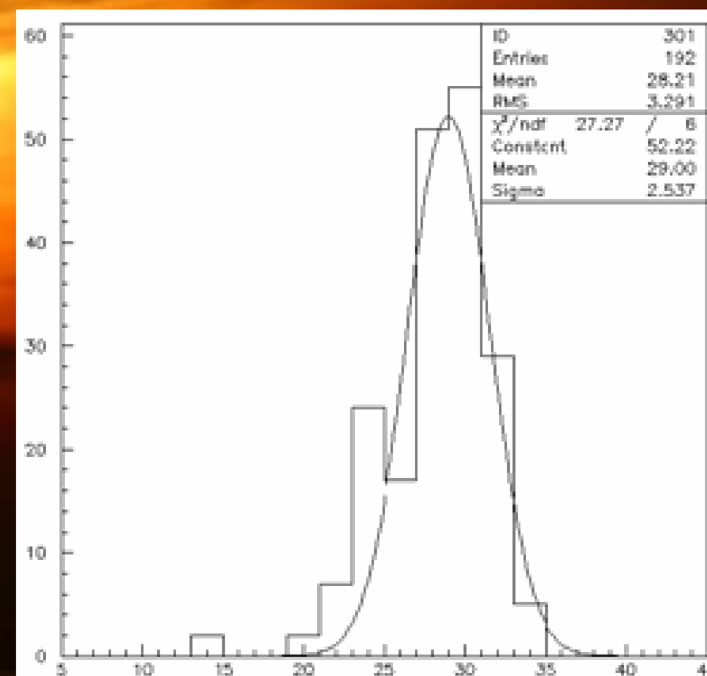
LHCb-GEM: detector quality test

X-ray tomography

The gain uniformity, pad by pad, is measured with a high intensity 6.0 keV X-ray tube, measuring the current drawn by the detector.





The drop on border pads is due to the large effective beam spot size . Gain uniformity ~ 10%

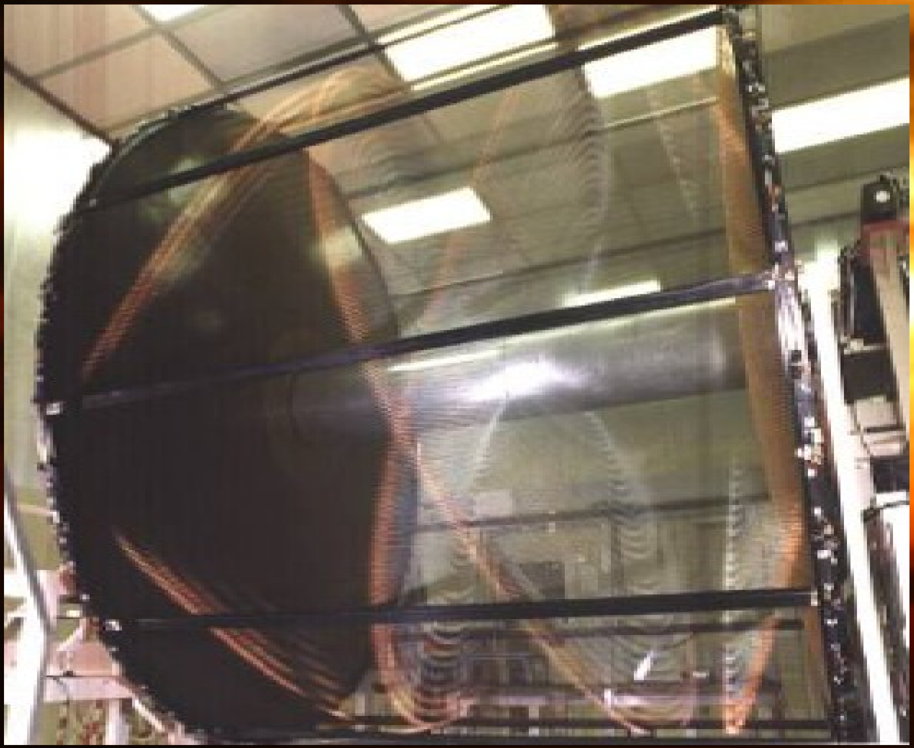
Cylindrical GEM Vertex R&D

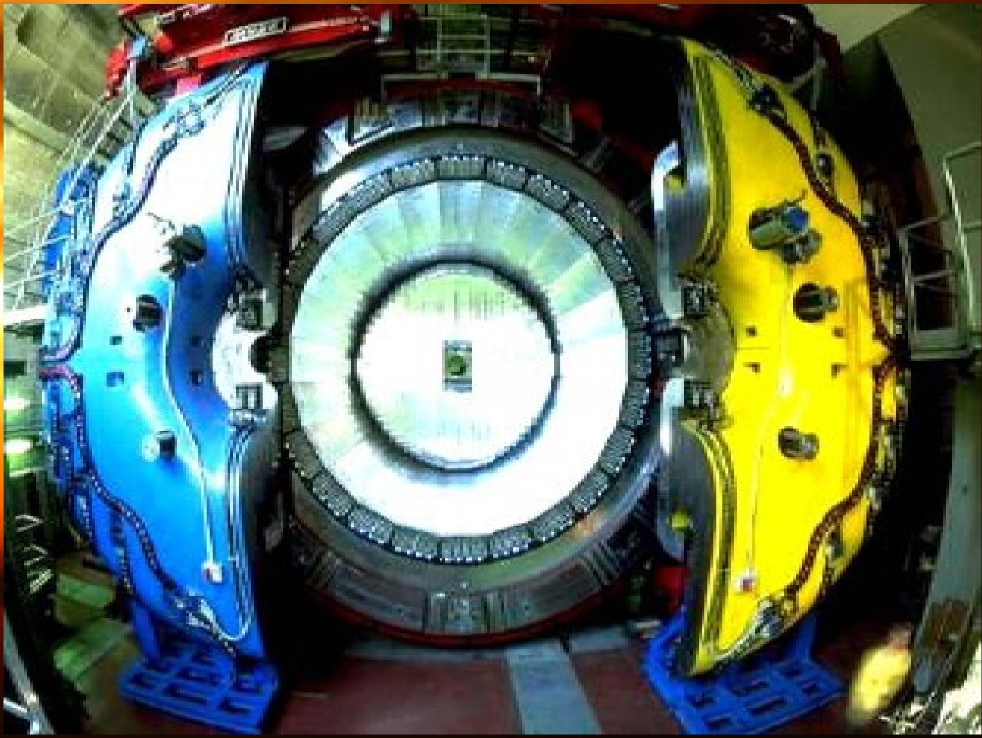
for KLOE-2

The Kloe experiment at DAΦNE Φ-factory

Multi-purpose detector for K_{long} physics

e^+e^- collider @ $\sqrt{s}$ = 1019.4 MeV





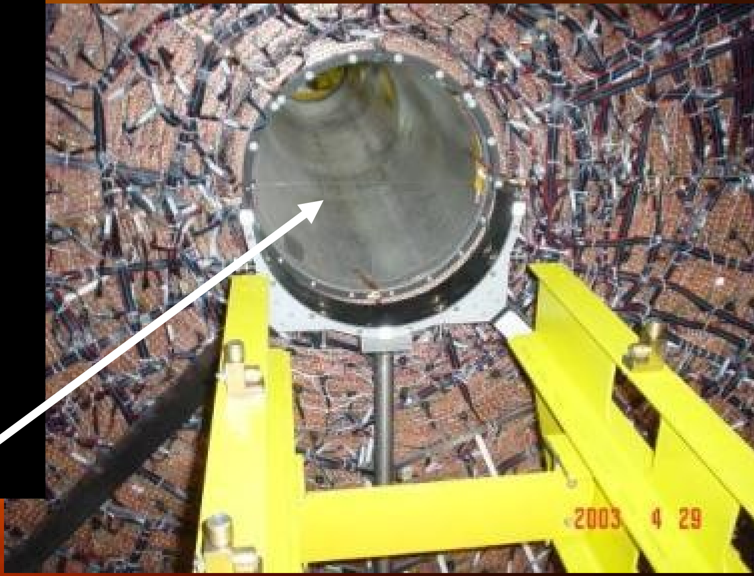
- ❑ Thin CF structure, Ø = 4m, L = 4m;
- ❑ 52140 stereo wires, 12540 W sense wires, Al field wires;
- ❑ He/i-C4H10=90/10 gas mixture;
- ❑ $\sigma(p_T)/p_T$ ~ 0.4% (in 0.5T of the SC coil)

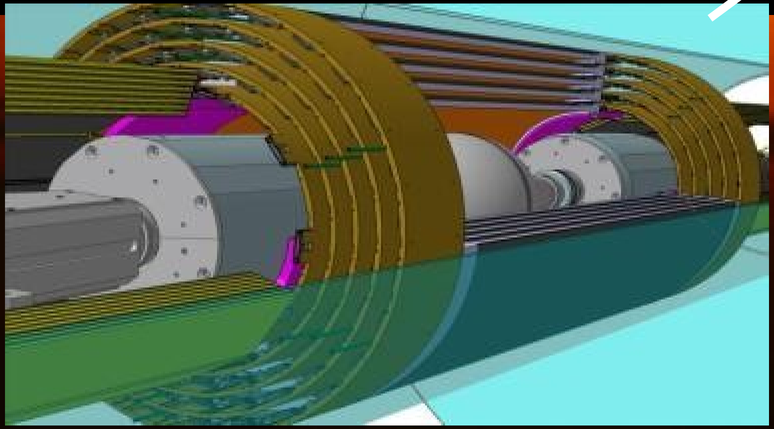
- ❑ Pb-scintillating fiber
- ❑ 24 barrel modules, 4m long * C-shaped End-caps for full hermeticity
- ❑ $\sigma_T = 54ps/\sqrt{E(GeV)}$
- ❑ $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$

KLOE upgrade: the Inner Tracker

Main detector requirements:

- $\sigma_{r\varphi} \times \sigma_z \sim 200 \times 500\mu m$ single layer spatial **resolution** for fine vertex reconstruction of **Ks, η decays and interferometry measurements**
- 4 tracking **layers with low material budget**:$1.5\% X_0$





The **IT will cover the space from the beam pipe to the inner wall** of the KLOE DC: **150 mm to 250 mm radius, with an active length of about 700 mm.**

The IT with CGEM technology

The **CGEM** is a ***low-mass***, ***fully cylindrical*** and ***dead-zone-free*** GEM based detector: **no support frames are required inside the active area**

The main steps of the R&D project:

1) Construction and complete characterization of a **full scale CGEM prototype**

2) Study the **XV strip** readout configuration and its operation in **magnetic field**

3) Construction and characterization of a **LARGE AREA GEM** realized with the new single-mask photolitografic technique (KLOE2 IT needs GEM foil as large as $450x700mm^2$)

Technical Design Report of the Inner Tracker for the KLOE-2 experiment [arXiv:1002.2572]

(1) CGEM: HOW to do that?

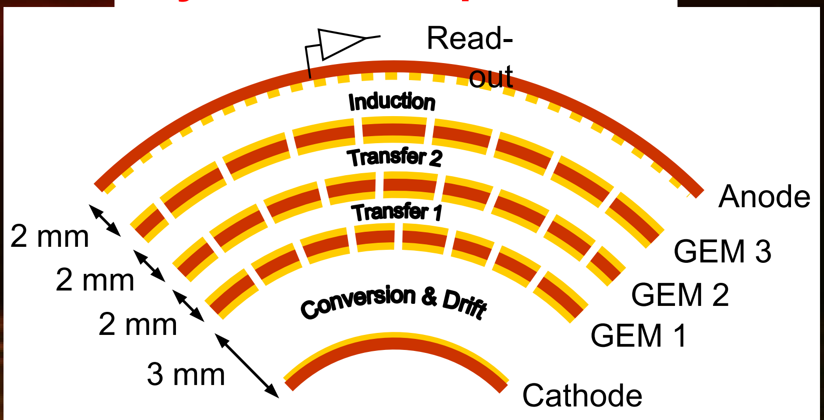
A cylindrical electrode is obtained exploiting:

- ❑ the **remarkable flexibility of polyimide** based GEM/anode/ /cathode foils
- ❑ the "**vacuum bag technique**"

rolling each polyimide foil on a machined PTFE cylindrical mould … the cylindrical electrode is obatined

❑ **C-GEM** is realized inserting one into the other the required **five cylindrical structures**: the cathode, the three GEMs and the readout anode.

Cylindrical Triple GEM



Proto0.1: Ø=300mm,L=350mm;1538 axial strips, 650 μm pitch

(1) CGEM building procedure

1. An epoxy glue is distributed along the edge of the GEM foil (<3 mm)

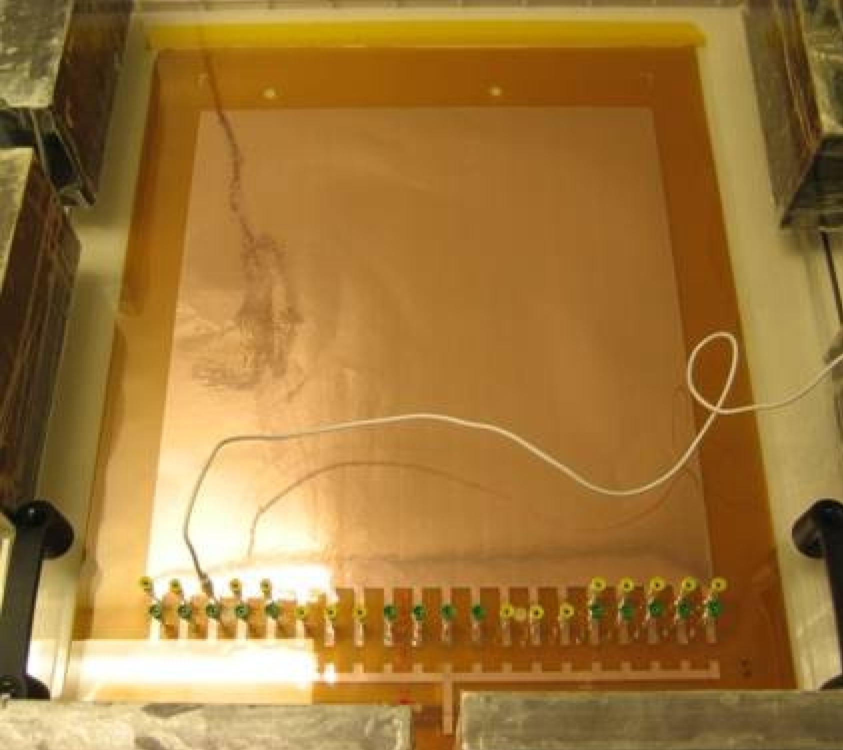
2. The GEM foil is rolled on an Aluminum mould covered with a 400 μm thick machined Teflon film for a non-stick, low-friction surface

3. The cylinder is enveloped in a vacuum bag. Vacuum is applied with a Venturi system, providing a uniform pressure of 1 kg/cm^2

4. A perfectly cylindrical GEM is obtained

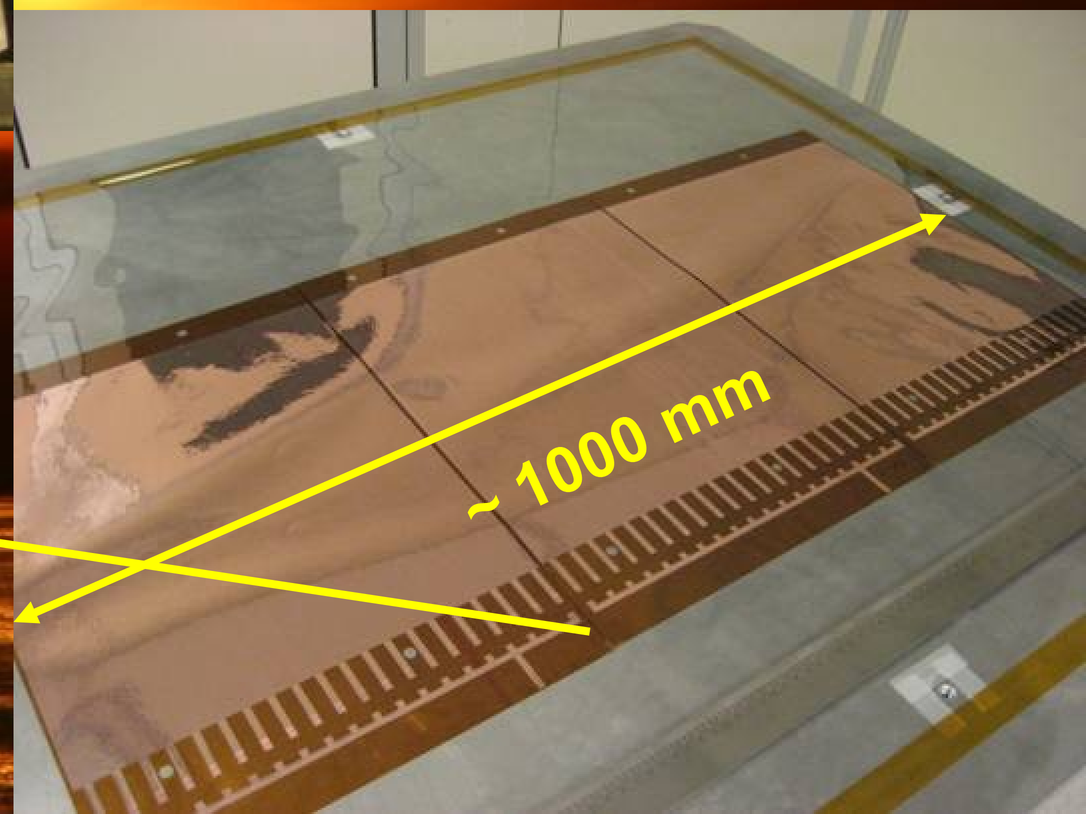
With the same procedure Anode and Cathode are obtained

(1) GEMs



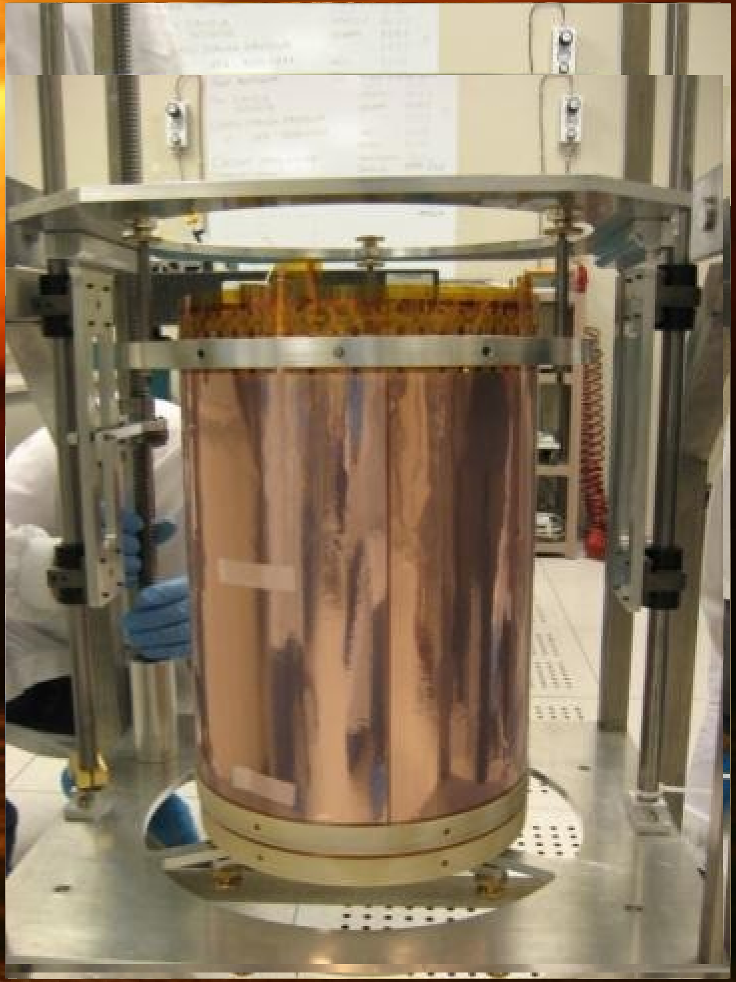
The GEM foil needed to build a cylindrical electrode is obtaind gluing three identical smaller GEM: “Planar Gluing”, always with with the *vacuum bag tecnhique*

<3 mm overlap region where no holes, so that no multplication is present. BUT THIS IS NOT A DEAD ZONE



(1) Vertical Insertion System

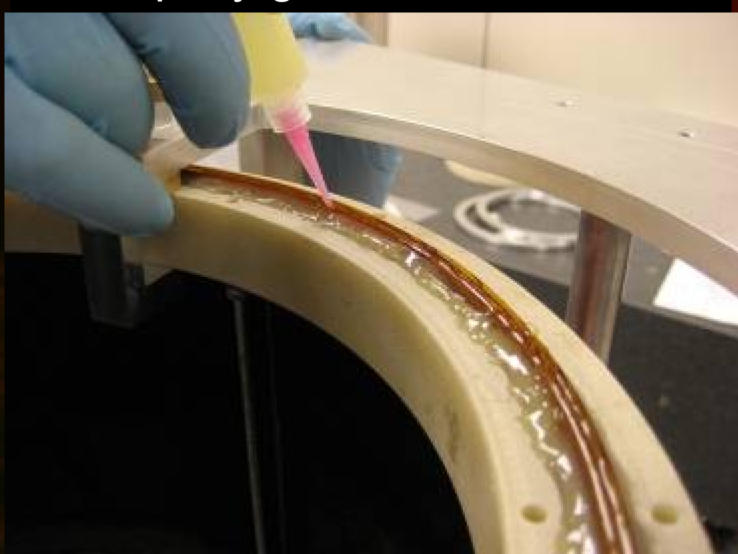
The Cathode is fixed on the bottom Al plate
The other electrodes are fixed on the top plate and are **pulled down slowly** with a precise linear bearing equipment



(1) Detector Sealing

glue is dispensed just before the full insertion of the electrode

detector is sealed on one side with epoxy glue



Once the detector is fully assembled the VIS can be rotated to allow the sealing of the other side…

(1) CGEM test at the CERN PS-T9

electronics rack

detectors

beam line: 10 GeV pion beam

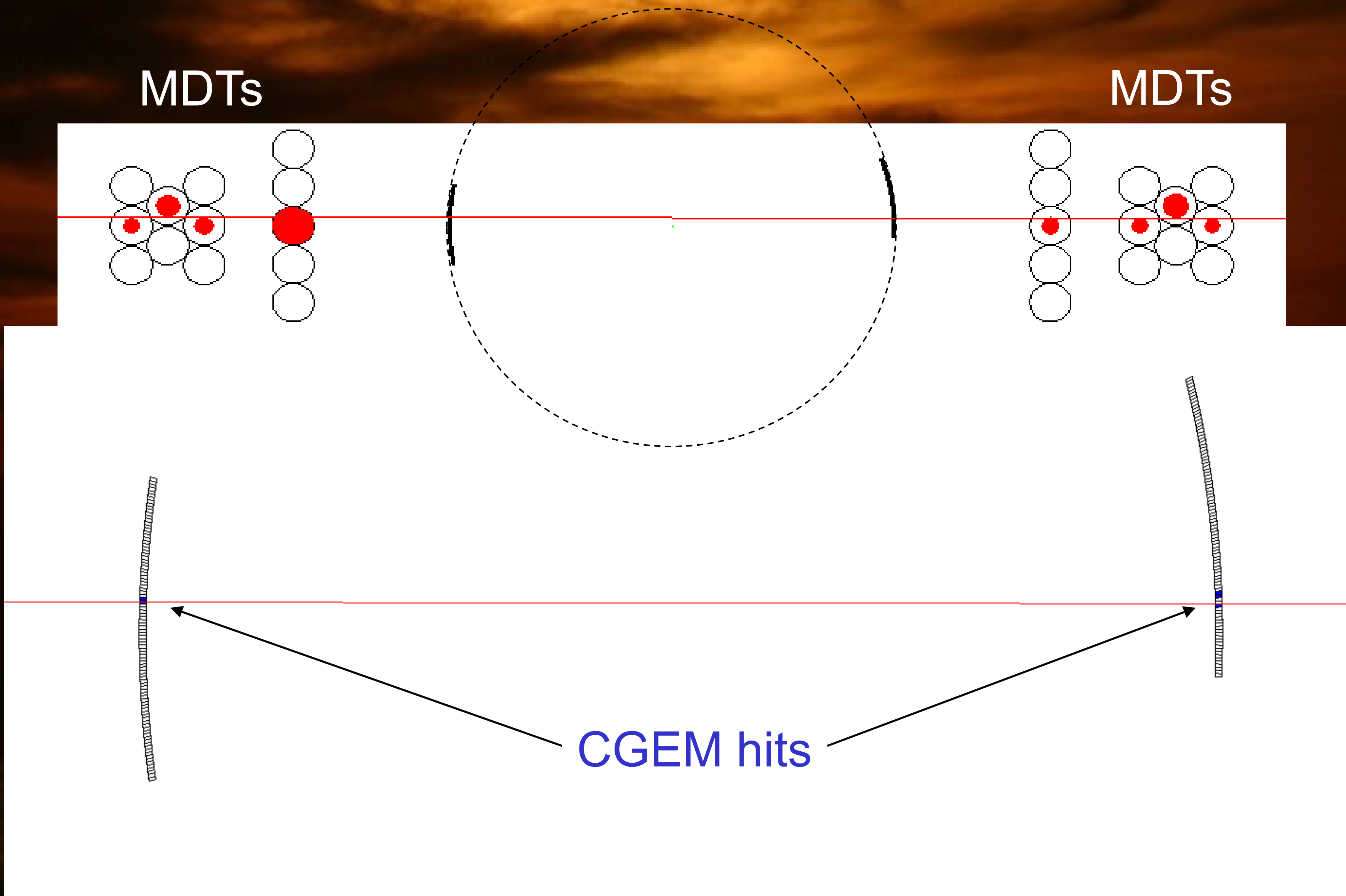
128 chs of GASTONE: 1 Mtrigg.

192 chs Carioca-GEM FEE, to study time chacteristics of the detector (too fast electronics with respect Ar/CO_2 detector operation … so some instability observed)

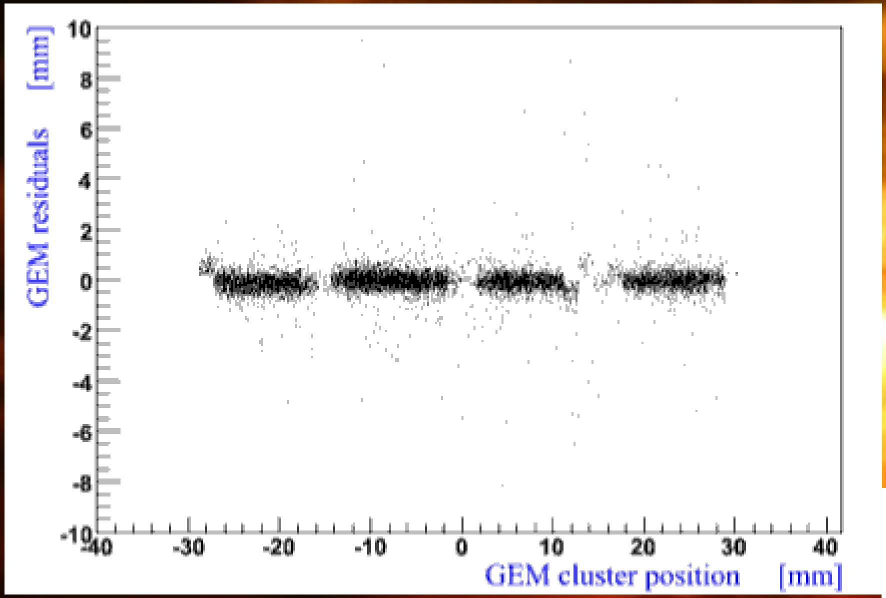
Detector operation conditions:

- ❑ Ar/CO_2 = 30/70
- ❑ V_{fields} = 1.5/2.5/2.5/4 kV/cm
- ❑ V_{GEM} = 390/380/370 V (ΣV_G = 1140V → G ~2÷3x10^4)

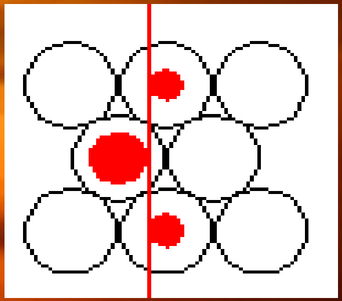
(1) CGEM event display

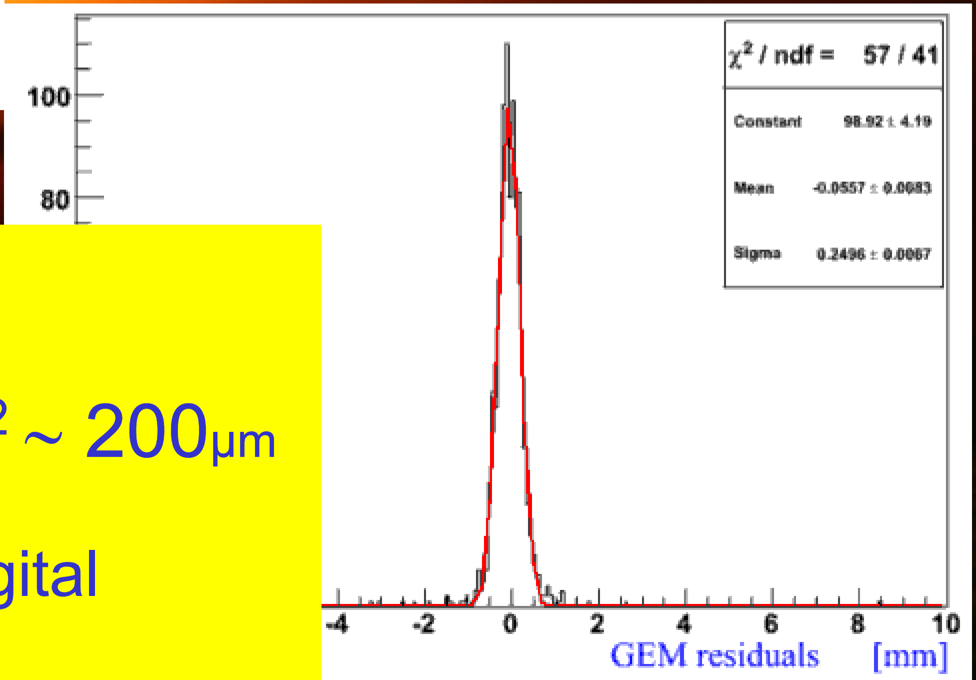


(1) CGEM prototype results



GEM residuals with respect to the track reconstructed by the external drift tubes



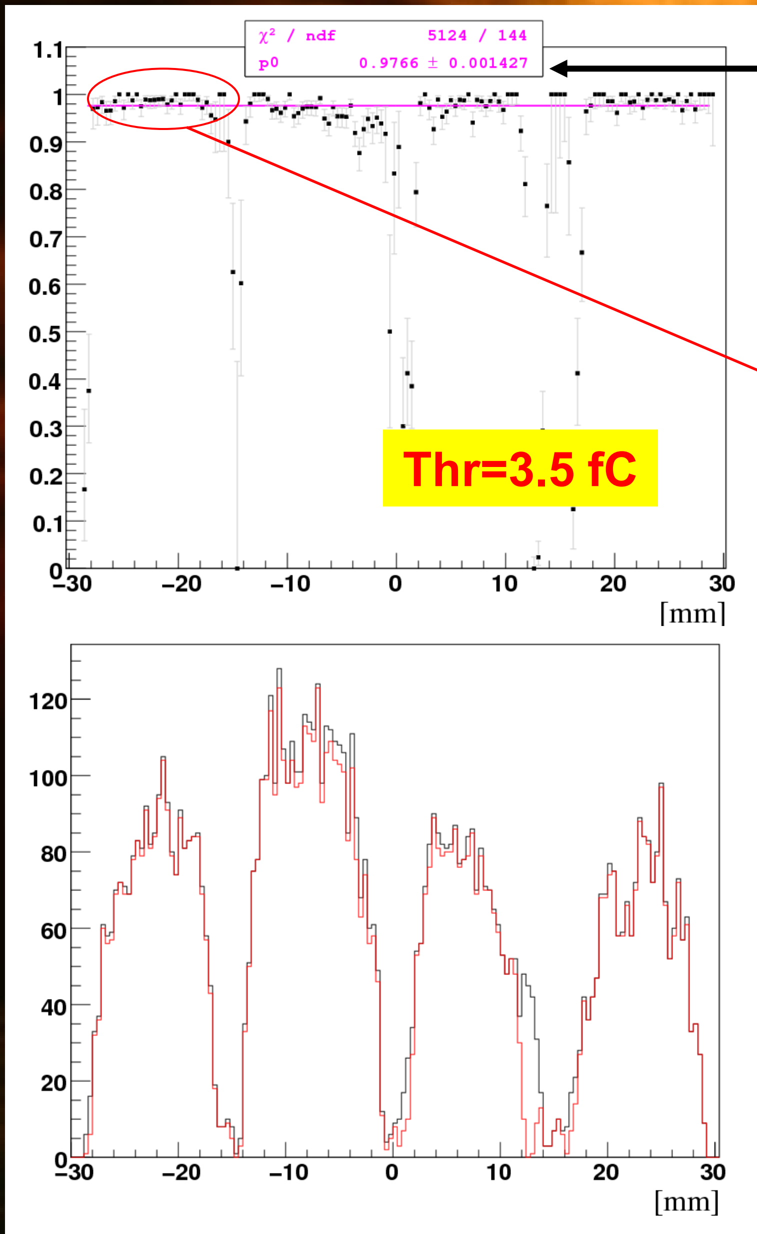


$\sigma(\text{global})^2 = \sigma(\text{GEM})^2 + \sigma(\text{tracker})^2$

$\sigma(\text{GEM}) = \sqrt{(250\,\mu\text{m})^2 - (140\,\mu\text{m})^2} \sim 200\,\mu\text{m}$

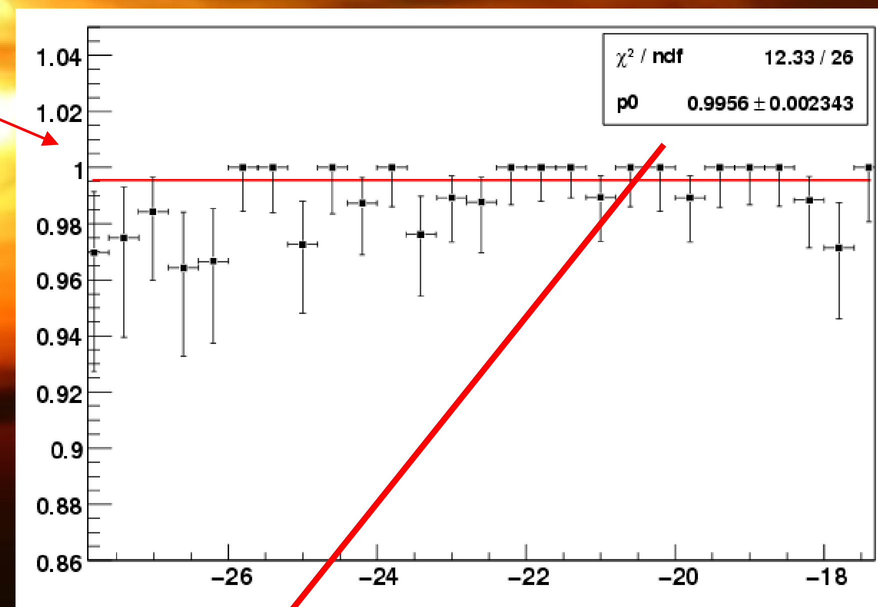
compatibile with <pitch>/√12 (digital readout)

(1) Efficiency in standard GEM zone



97.7% overall efficiency, including electronic dead channels

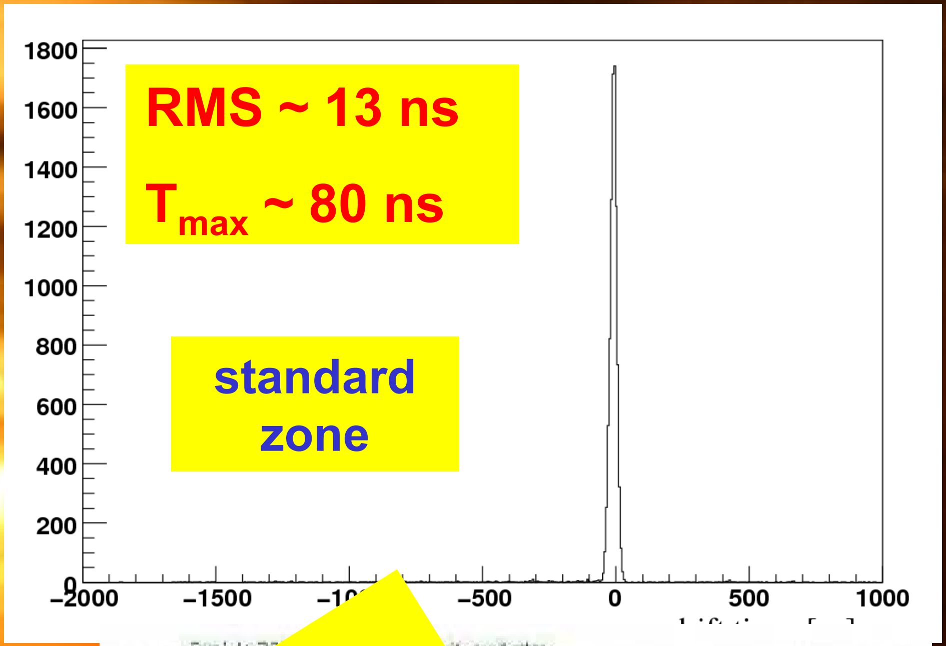
Without fee holes

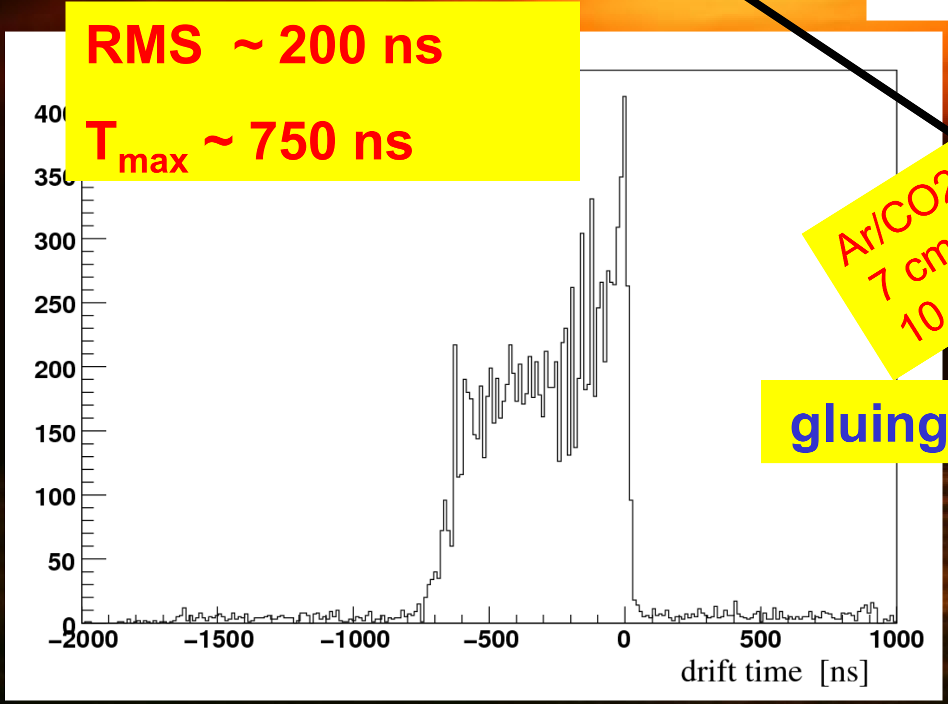


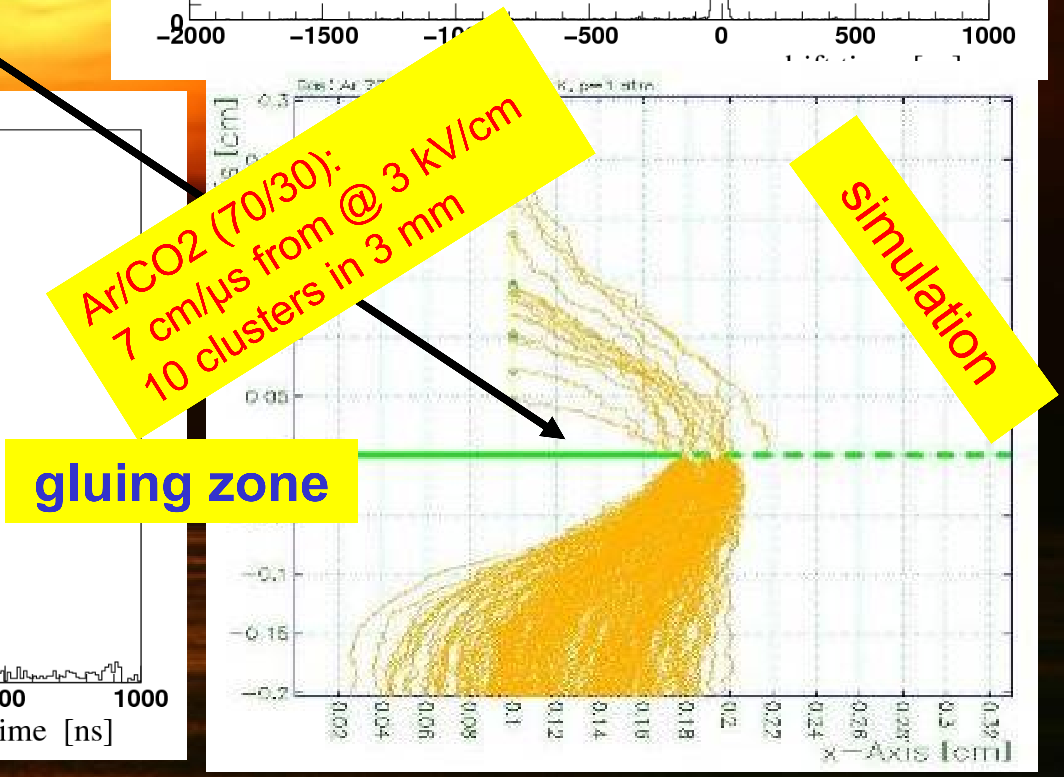
99.6% intrinsic efficiency

(1) CGEM time spectra

Time spectra with Ar/CO_2 = 30/70 gas mixture, obtained with CARIOCA-GEM.
Ionization electrons, generated above a gluing region by a track, drift along the distorted field lines and then are efficiently driven and focused in the multiplication holes of the GEM.



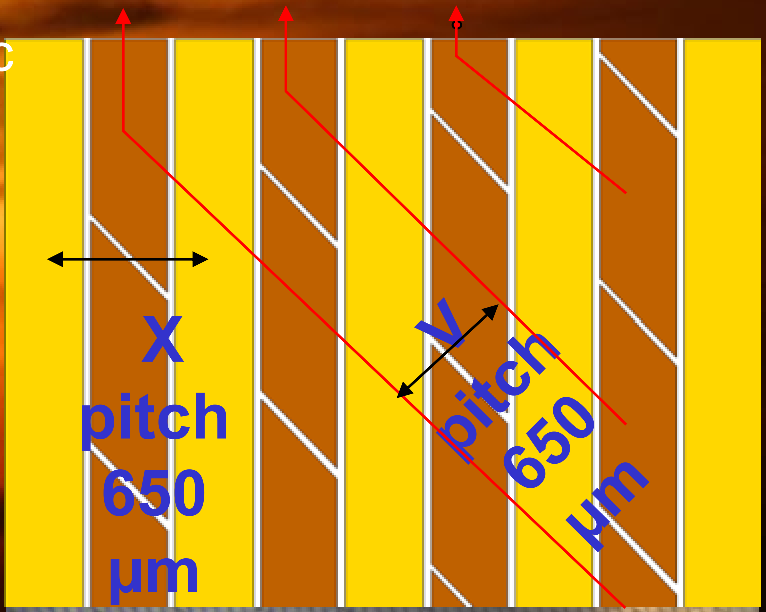




(2) XV readout and magnetic field

A 10x10 cm² Planar GEM w/650 μm pitch **XV strips** has been realized and tested in magnetic field:

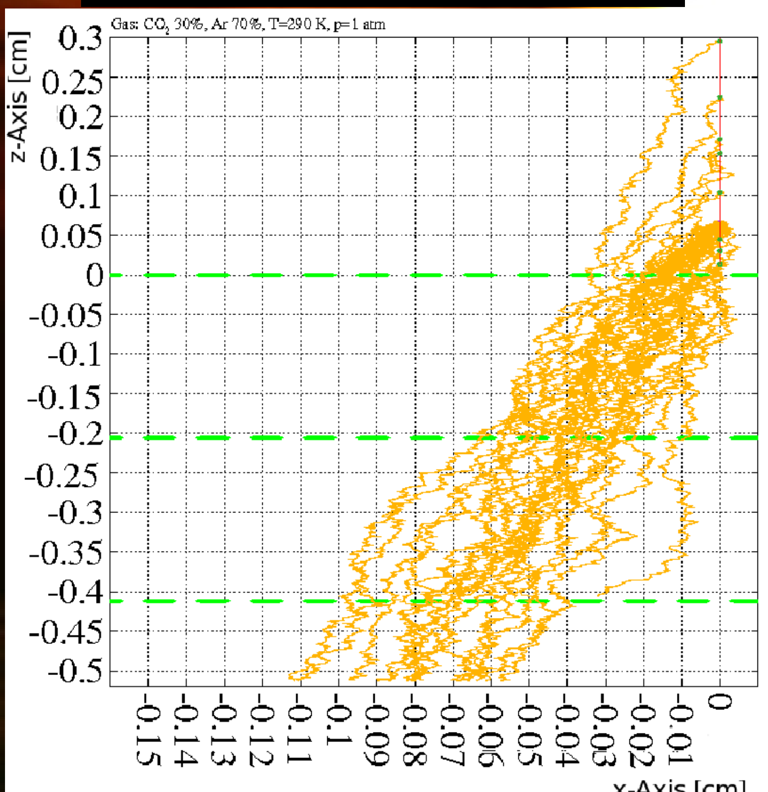
- ❑ X-view will provide r-φ coordinate in CGEM
- ❑ V-view made of pads connected by internal vias and with ~40°stereo angle
- ❑ XV crossing will provide z coordinate in CGEM
- ❑ readout w/GASTONE ASIC chip



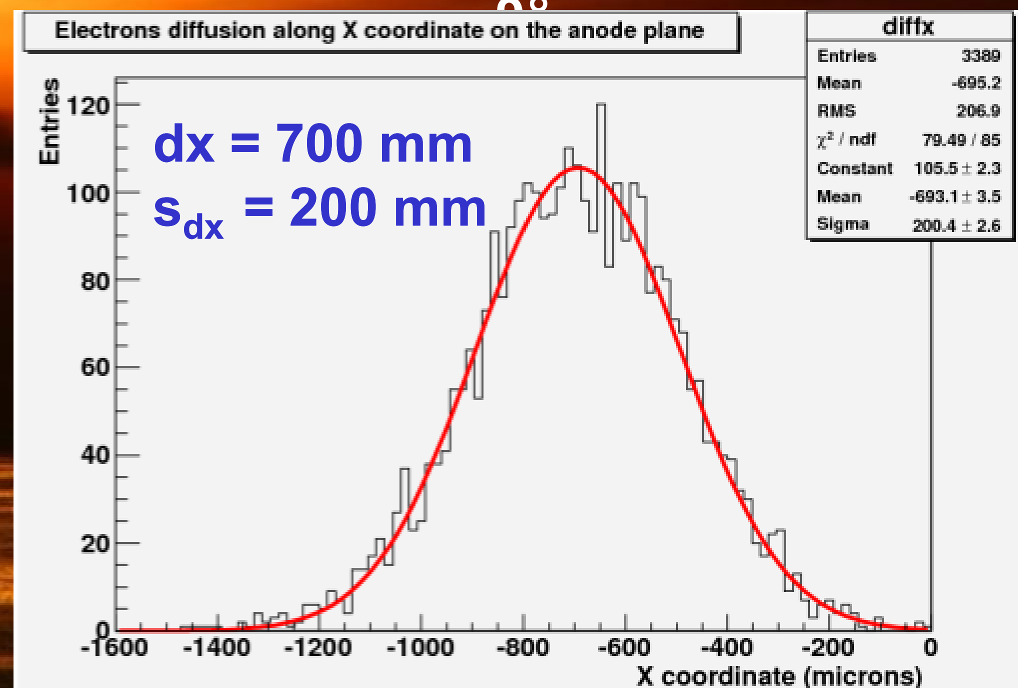
(2) XV readout and magnetic field

The effect of the magnetic field is *twofold*: a ***displacement*** (**dx**) and a ***spread*** of the charge over the readout plane (effect visible only on the "*bending plane*")

Garfield Simulation

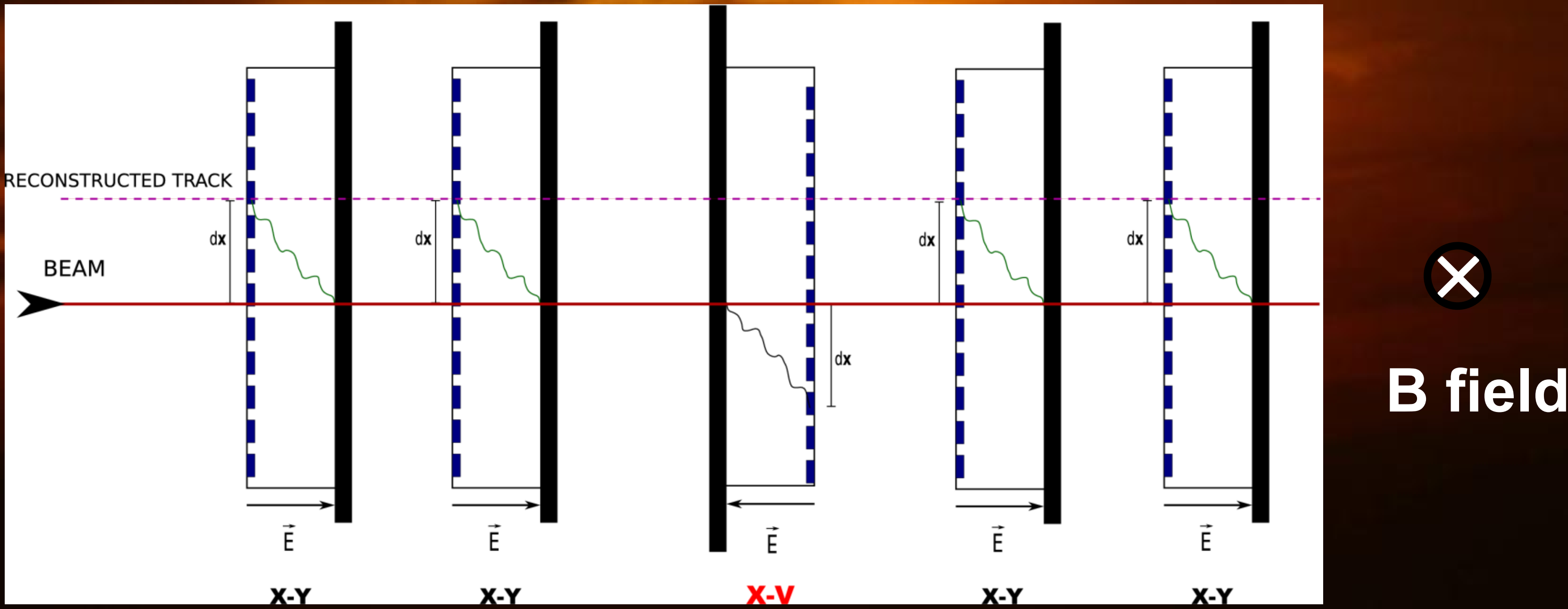


Ar/CO_2=70/30 and B=0.5 T
average Lorentz angle α_L = 8°-9°



(2) B-induced displacement

In our configuration the magnetic field effect is mainly present on the X-view

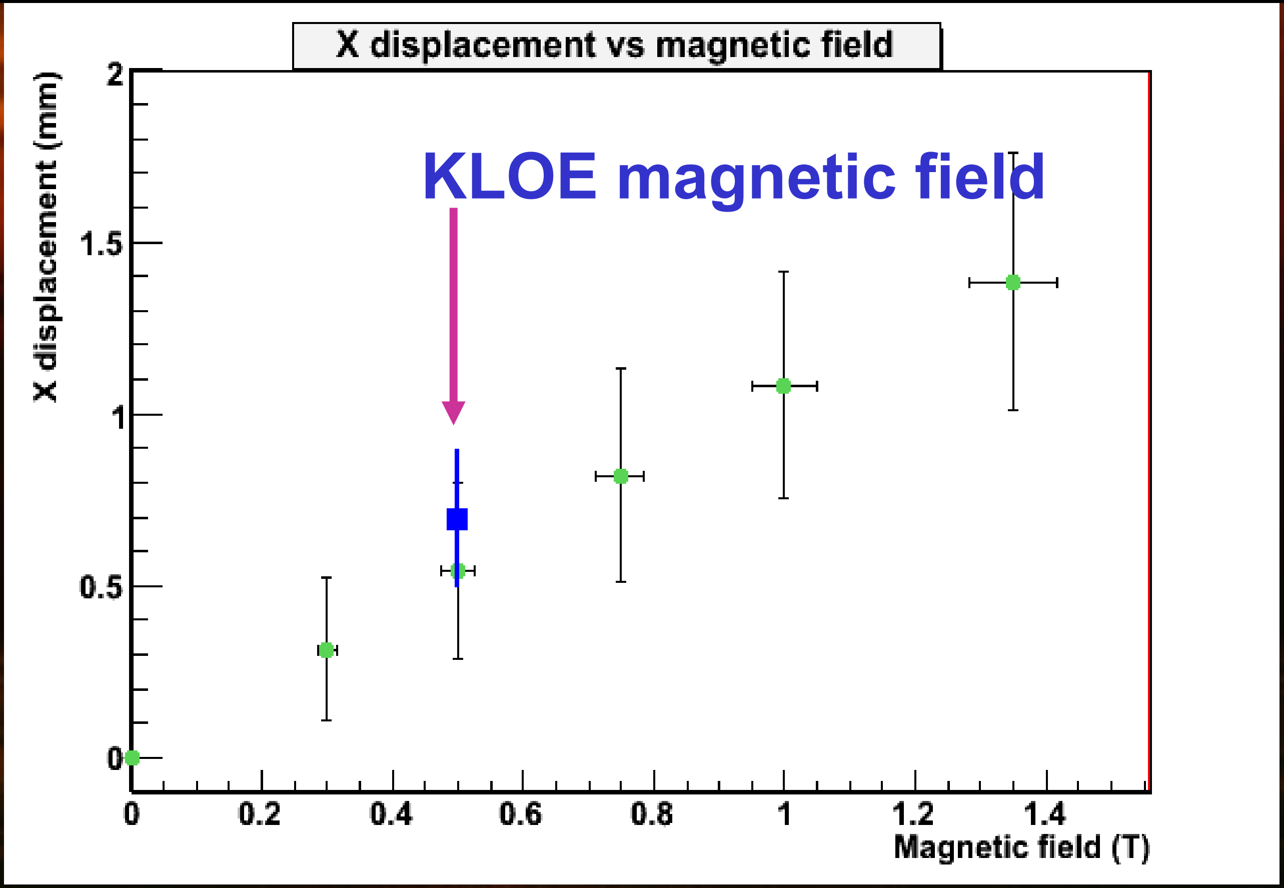


- Align the setup with B = 0
- Turn on B field
- Track reconstruction using the 4 X-Y GEMs (likewise oriented)
- Measure the displacement on the X-V GEM (reversed wrt the other GEMs)

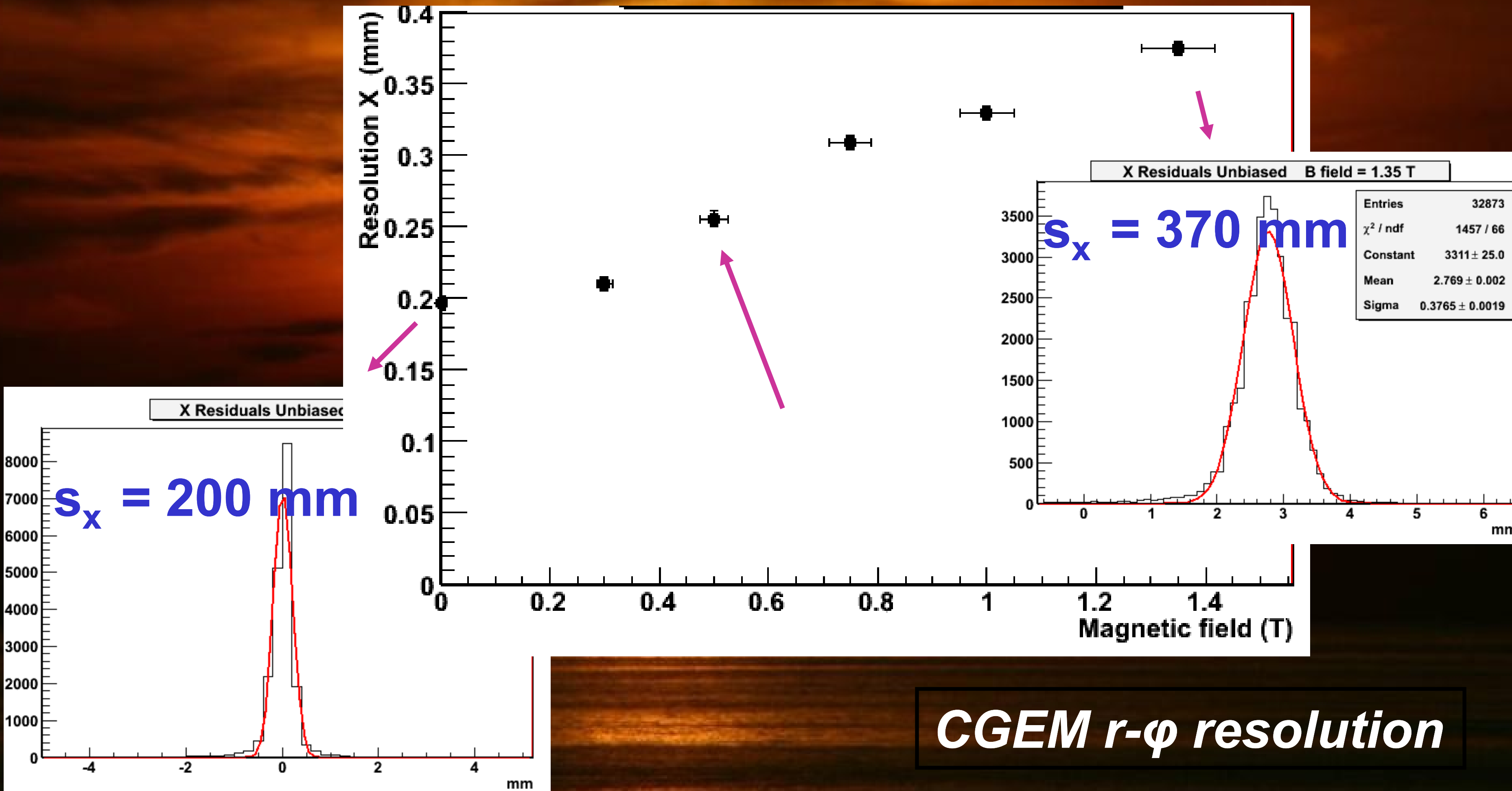
D = 2 × dx → $\tan(\theta_L) = \mathbf{D}/2r$ (r = effective detector thickness)

(2) B-induced displacement

Distribution of **dx = D (measured displacement)/2** as a function of B field
The blue point is the displacement value from GARFIELD simulation at B=0.5T



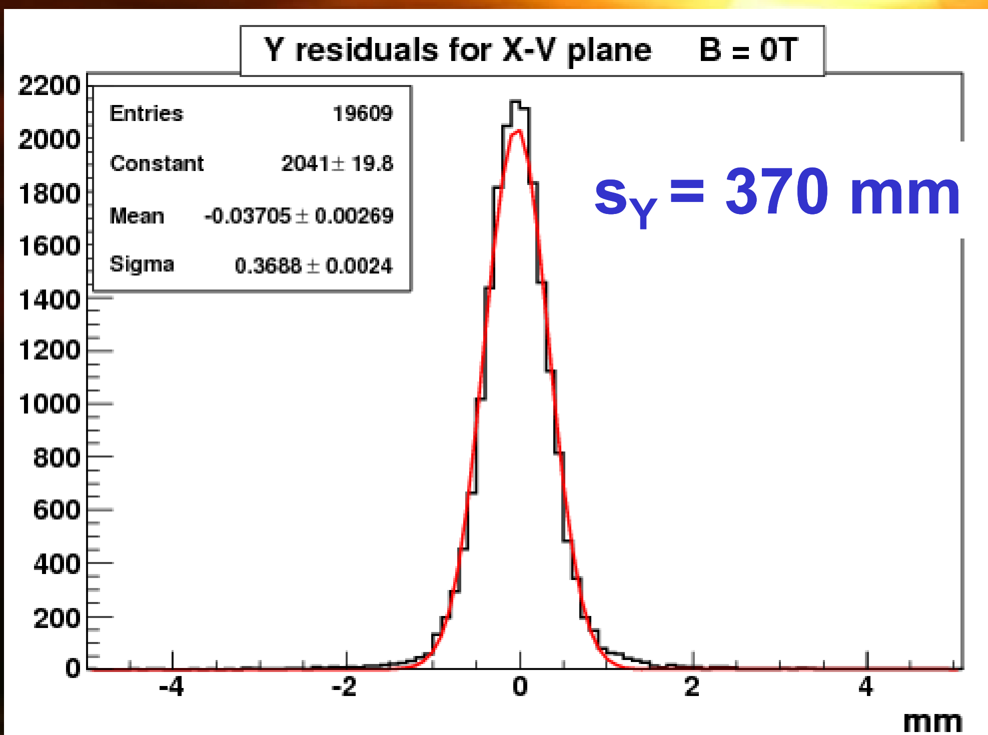
(2) Spatial resolution: X-view

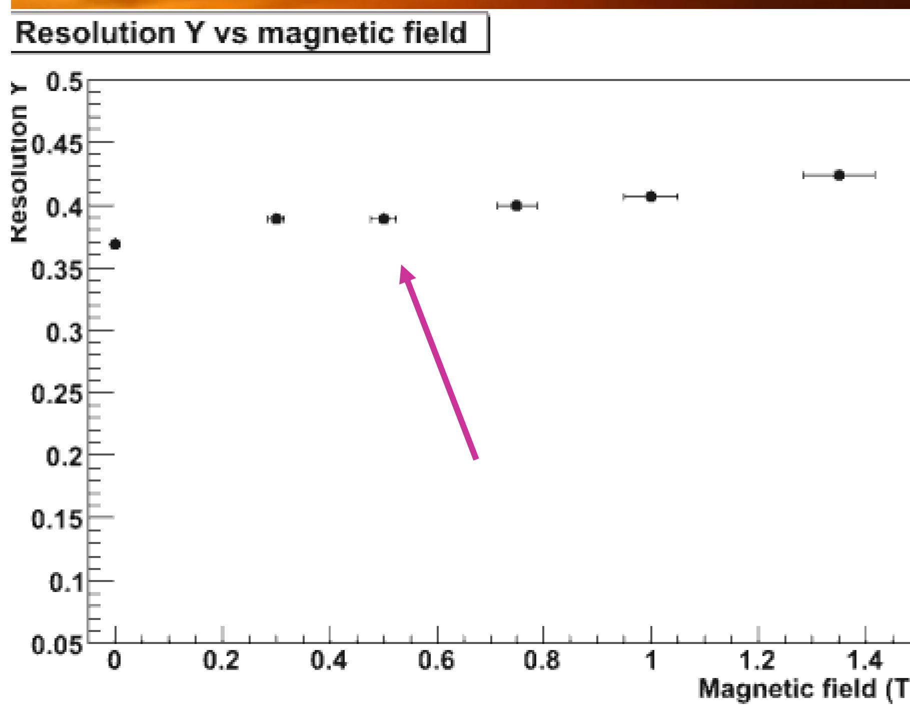


CGEM r-φ resolution

(2) Spatial resolution:Y coordinate

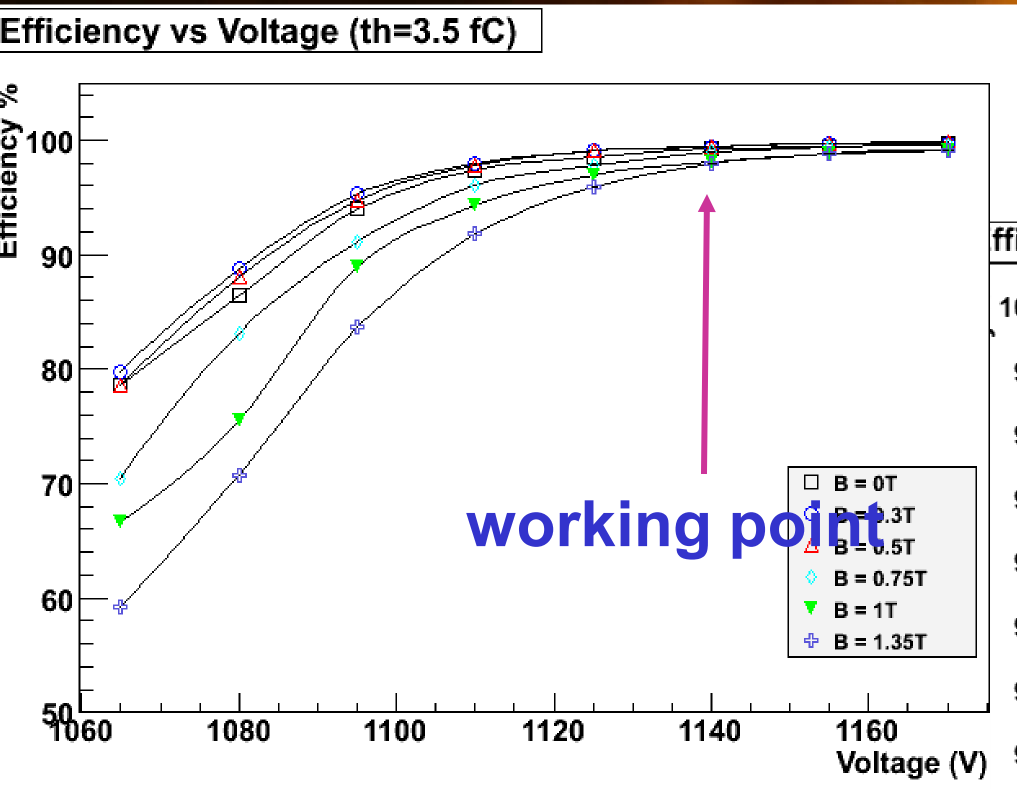
The Y coordinated is measured from the crossing of X and V views



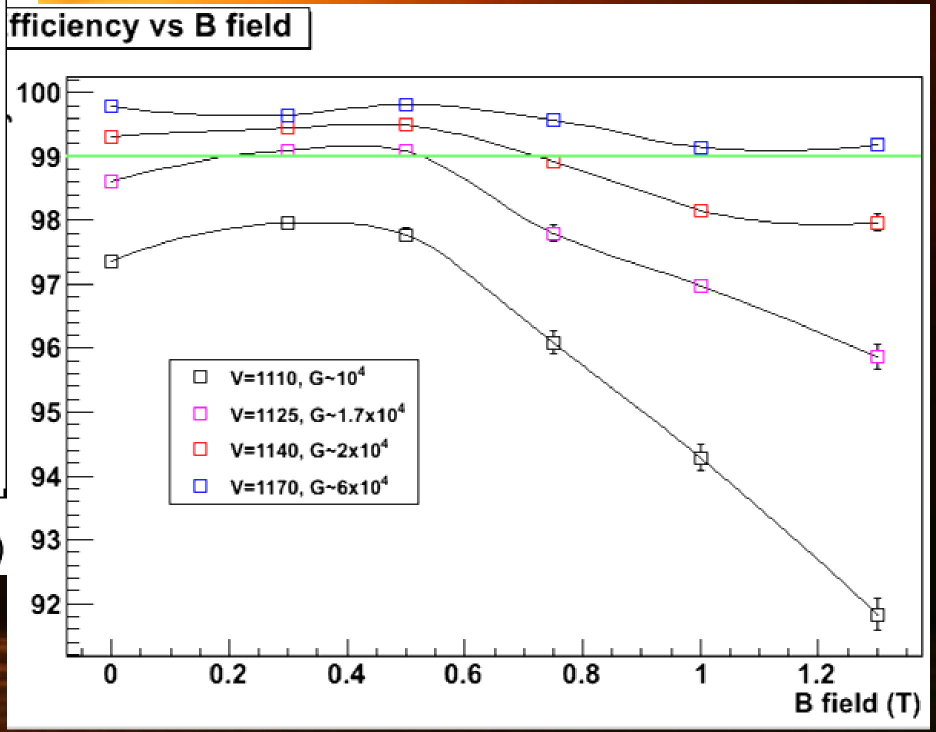


CGEM z resolution

(2) Efficiency vs B field and Gain

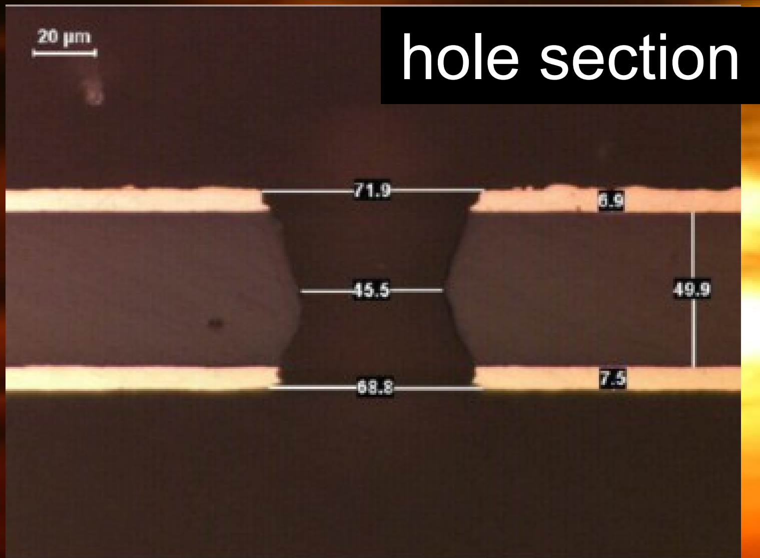


At working point, V_G = 1140 Volt, G~2x10^4, **efficiency drop is negligible for B < 0.5 T**



The **increase of the magnetic field,** increasing the spread of the charge over the readout strips (less charge is collected by each single pre-amp channel) results in an efficiency drop, thus **requiring for higher gain to efficiently operate the detector.**

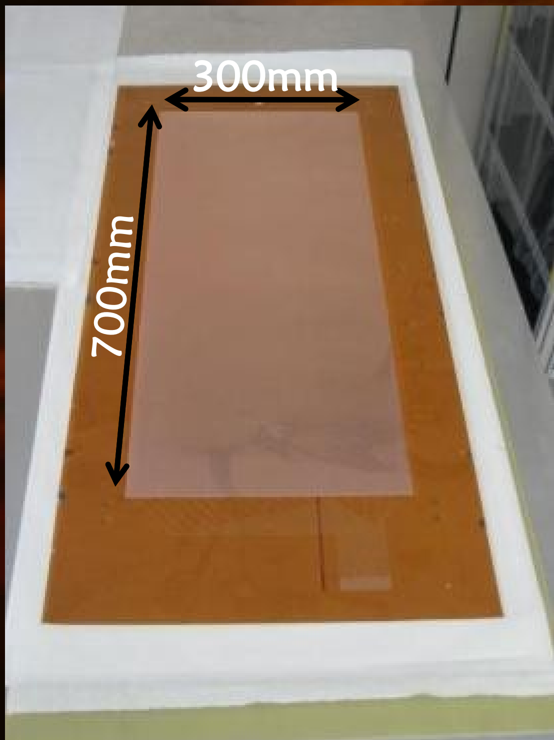
(3) Large area GEM R&D

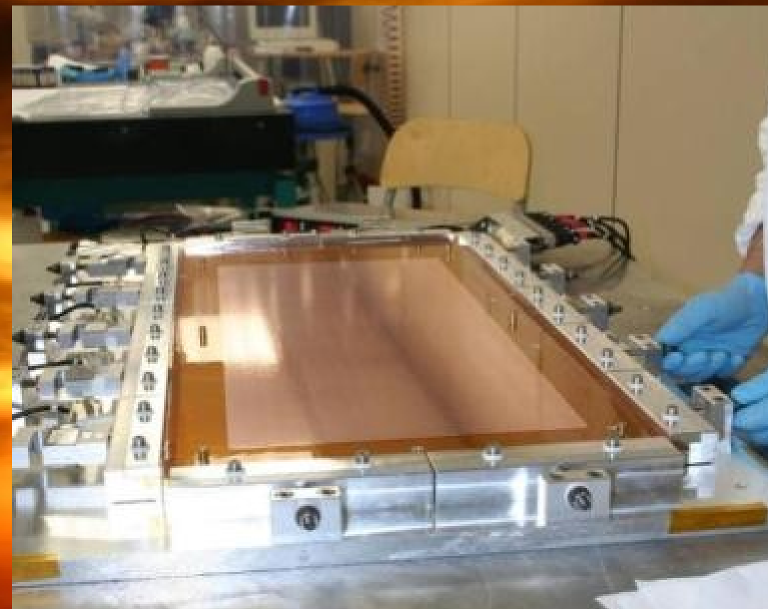


- GEM foils up to 350x700 mm^2 are needed for the IT (3 are spliced together for 1 electrode)
- After a change in the GEM manufacturing technique and >1 year R&D by CERN TS/DEM we received the first large GEM foils in April (2010)
- Two planar prototypes built with the final dimensions of IT foil for pre-production test

Very large GEM: 0.21 m^2

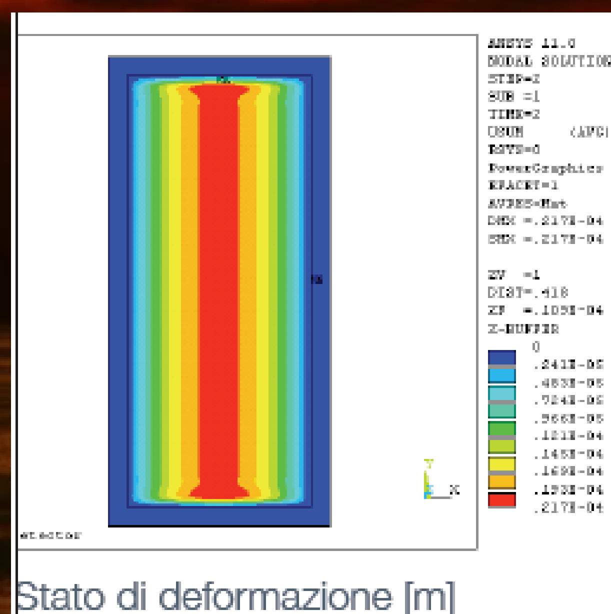
(3) Large planar prototype

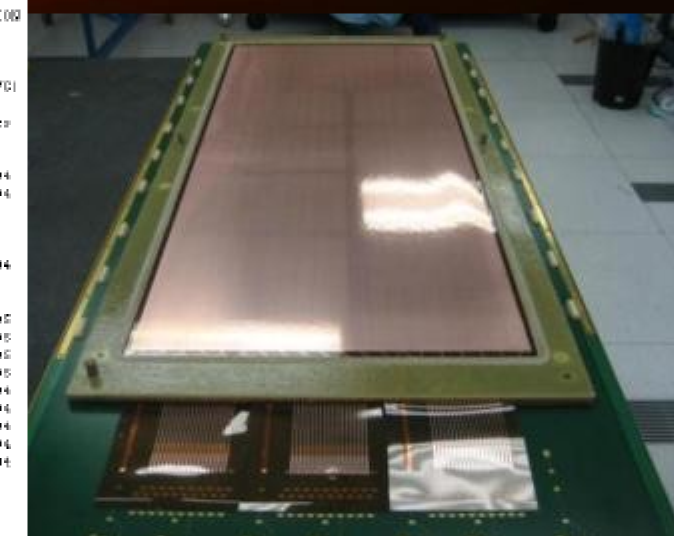




GEM are stretched on a custom-made machine with a tension of **~1kg/cm** measured by load-cells

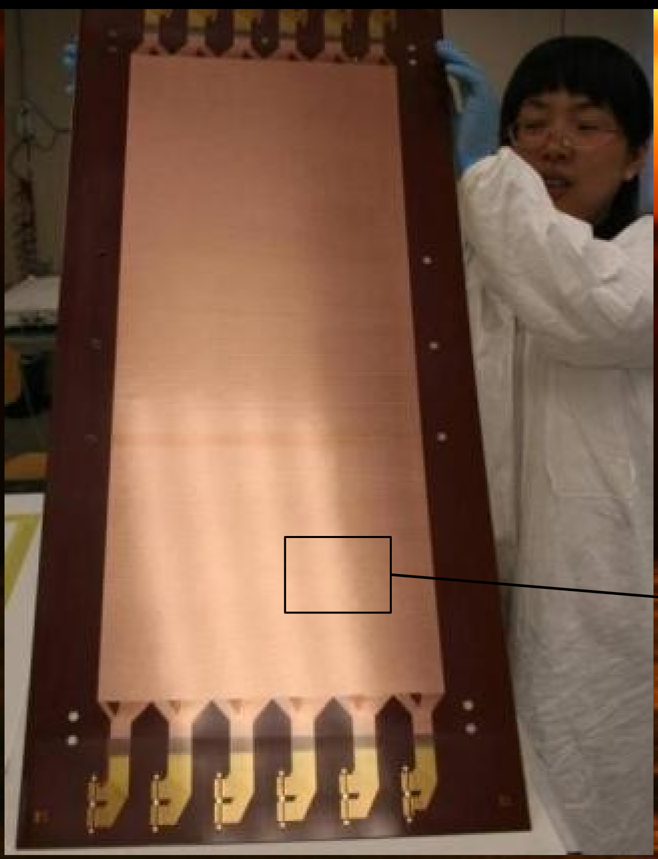
FR4 frame is glued on the GEM with a vacuum-bag.
The result is a planar foil (20 μm sag) with no need of frames inside the active area.



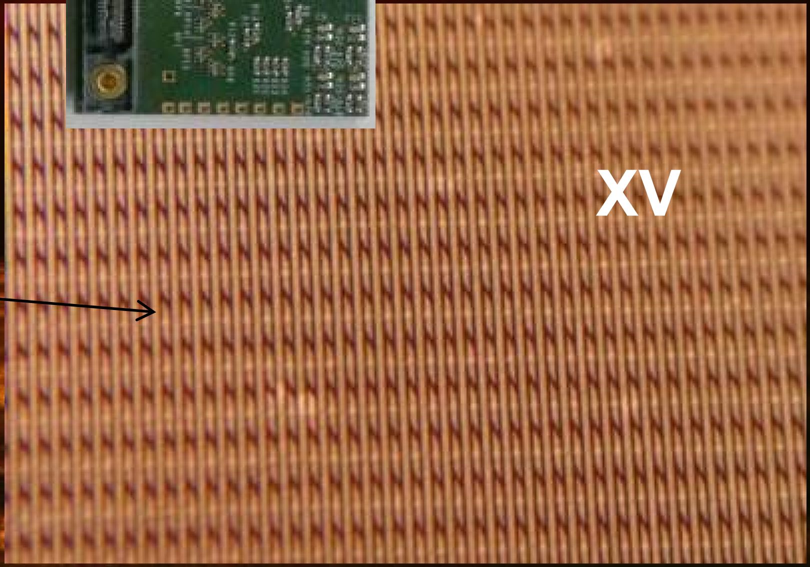


(3) XV readout

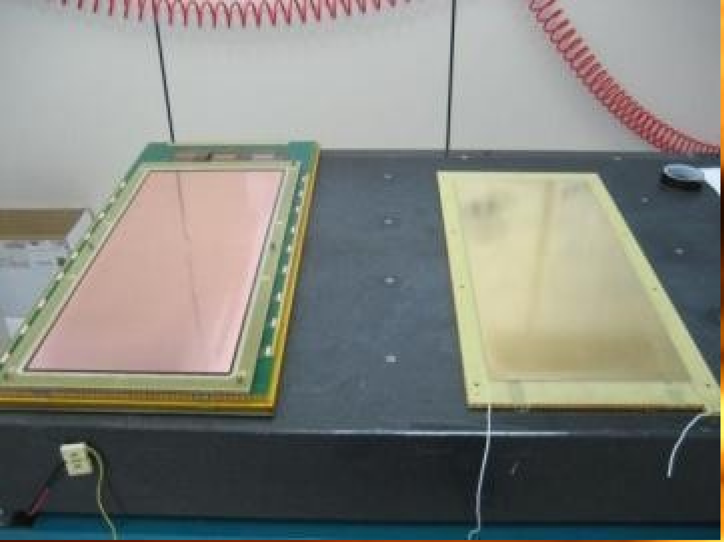
- The prototype has been assembled with the final KLOE-2 readout: XV strips with 650 μm pitch (~220k vias)
- It will be equipped with GASTONE-64 and tested CERN-T9 in october 2010



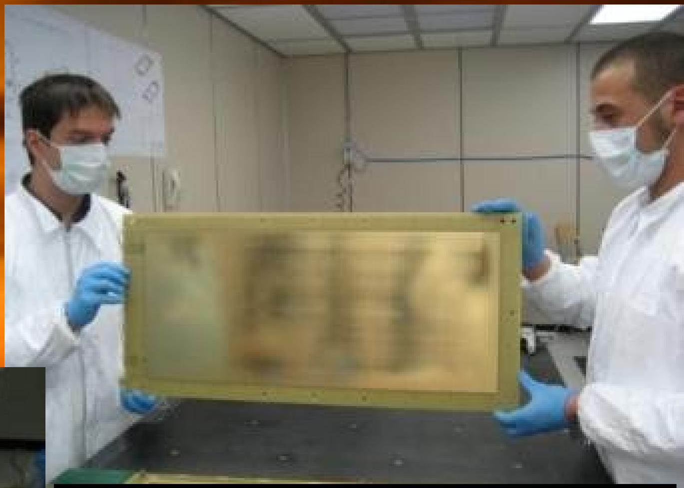
first GEM framed and placed on the readout

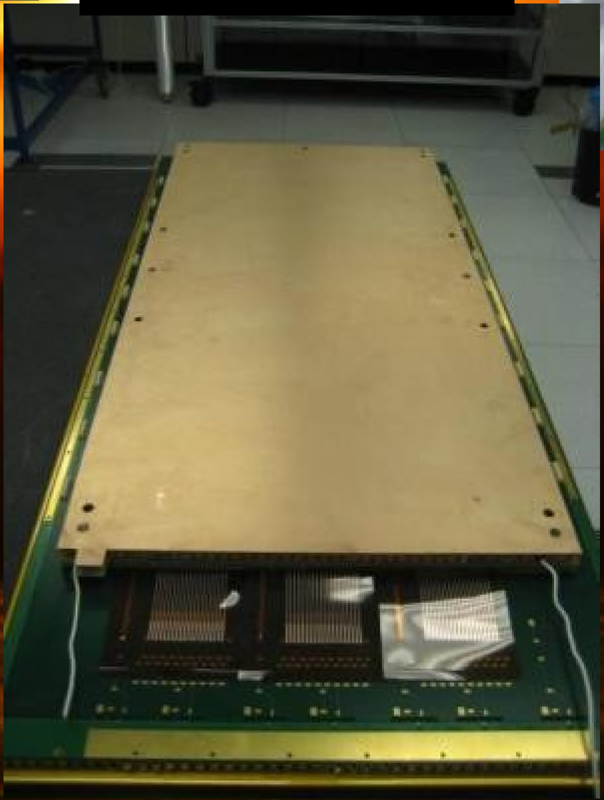


(3) Final assembly

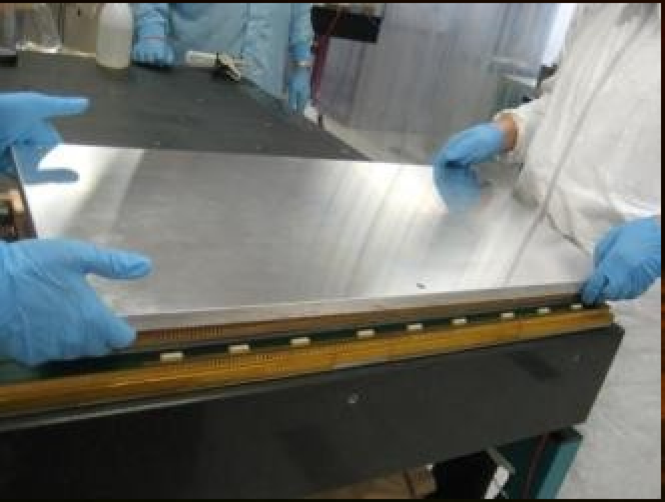


Closing the chamber



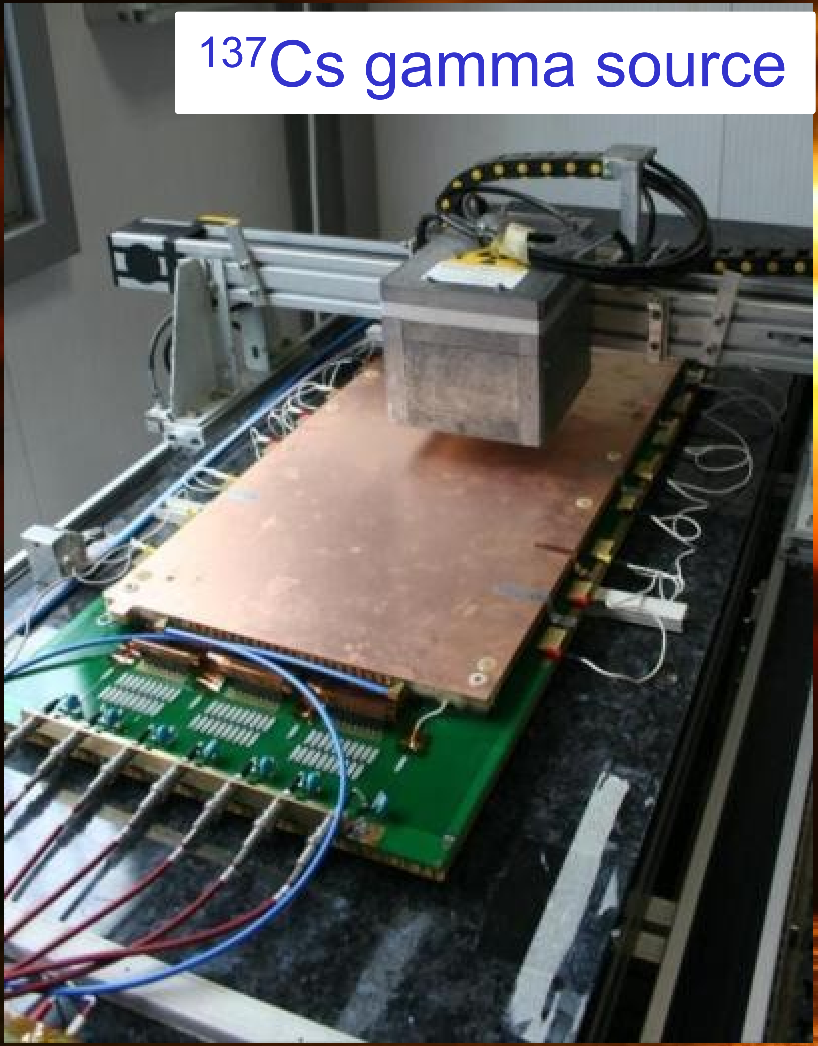


A heavy Al plate is placed to distribute the pressure



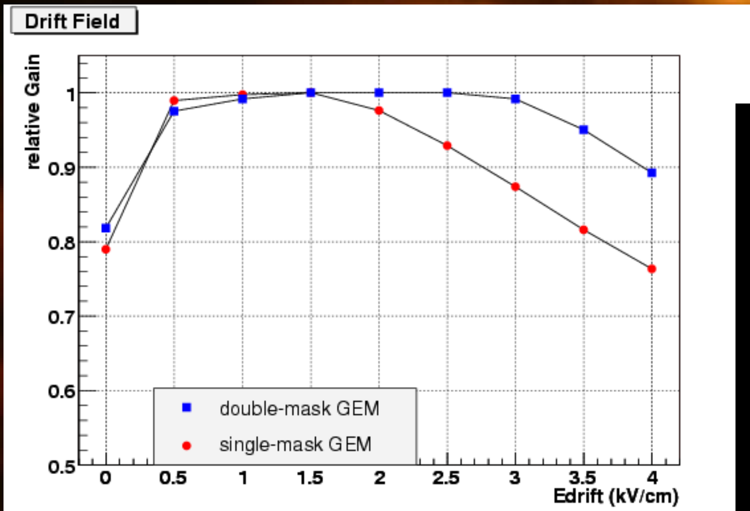
final gluing vacuum bag

(3) Preliminary tests

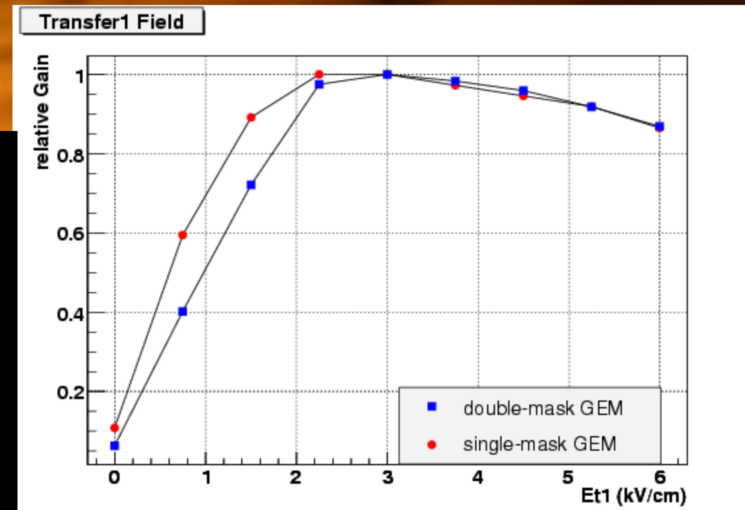


The detector has been flushed with **Ar/CO_2 (70/30)** and tested in current-mode with a **^{137}Cs source** (660 keV photons).
Cosmic ray test is starting soon.

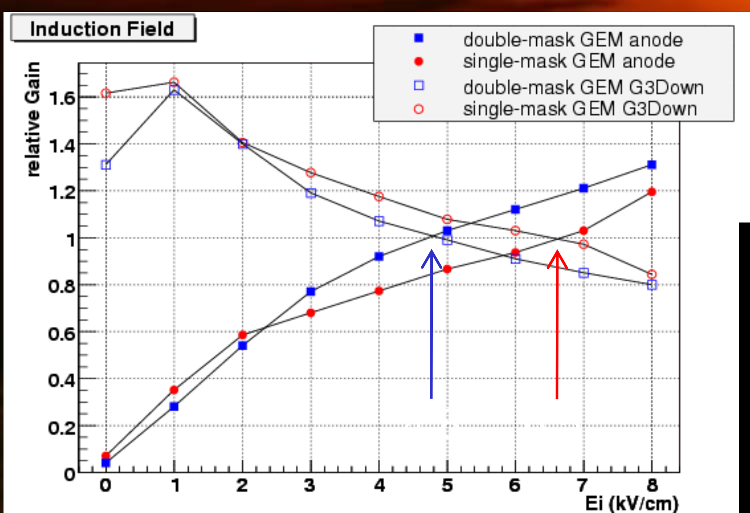
(3) Optimization of the fields



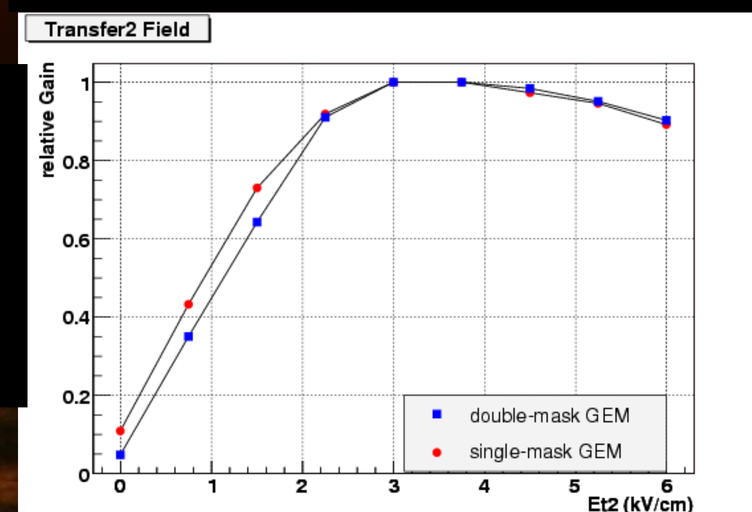
Only slight difference between the two GEM (due different hole shapes)



Final operating fields values:
1.0 – 3.0 – 3.5 – 6.5 kV/cm
(Drift – Transf1 – Transf2 – Induction)

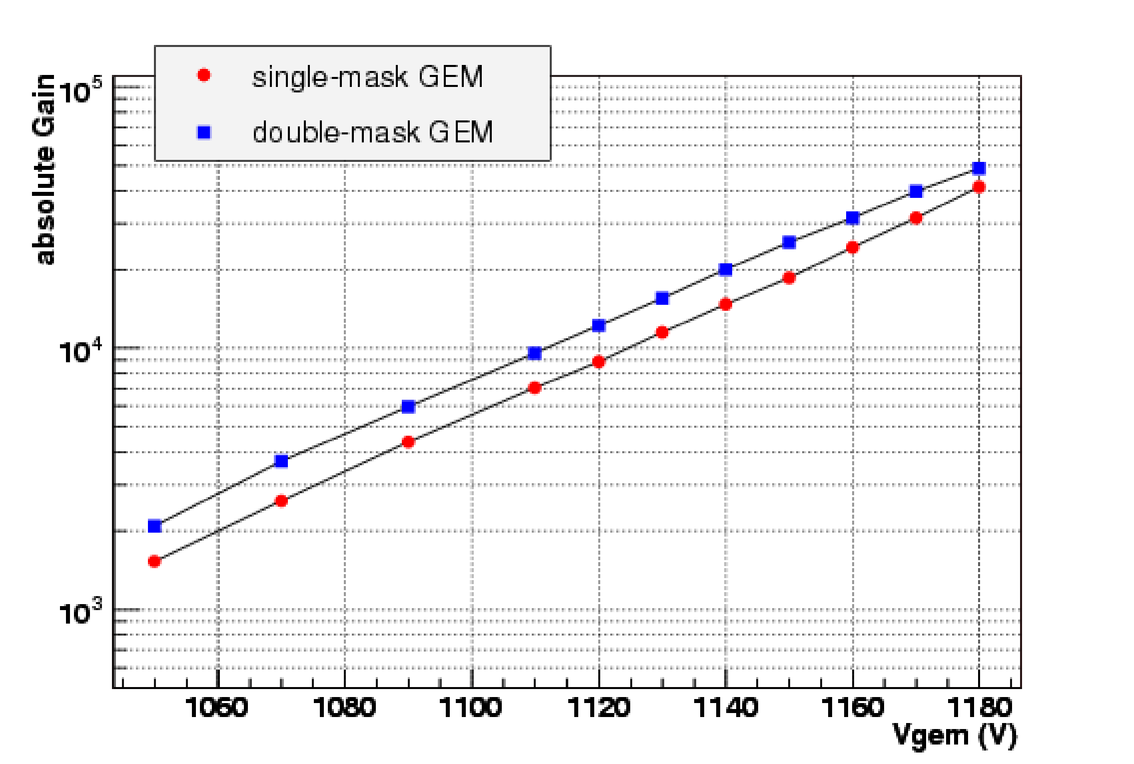


Equal charge sharing occurs at higher induction field in the single-mask



(3) Gain measurement

- ❑ The different shape of the hole affects the gain of the GEM
- ❑ Gain ~25% lower in single-mask GEM
- ❑ Only ~20 V increase in the operating voltage of a Triple-GEM to reach same gain
- ❑ NO discharge observed up to 40000 gain



Very stable operation

Conclusions

Among Micro-Pattern Gas Detectors, the GEM technology has demonstrated **great robustness**, **long-term stability of operation**, **remarkable flexibility** and capability to accomplish different tasks in **harsh environments**

- Planar **GEMs are installed and running in LHCb**

- **R&D** on a **innovative Cylindrical GEM** detector as **very low-mass inner tracker** for the KLOE experiment has been completed