Performance of a triple-GEM detector for high-rate particle triggering

G. Bencivenni[1], W. Bonivento[2,4], A.Cardini[2], C. Deplano[2], P. de Simone[1], G. Felici[1], D. Marras[2], F.Murtas[1], D.Pinci[2,3], M. Poli-Lener[1] and D. Raspino[2]

- 1 - Laboratori Nazionali di Frascati - INFN, Frascati , Italy
- 2 - Sezione INFN di Cagliari – Cagliari, Italy
- 3 - Università degli Studi di Cagliari, Cagliari, Italy
- 4 - Now at CERN, Geneva, Switzerland

OUTLINE

- Principle of Operation
- Triple-GEM Prototypes Construction and LHCb Requirements
- Optimizing Time Performances
- Detector Performances with CF_4 and iso-C_4H_{10} gas mixtures
- Aging & Rate capability
- Preliminary results on Discharges
- Conclusions

Principle of Operation

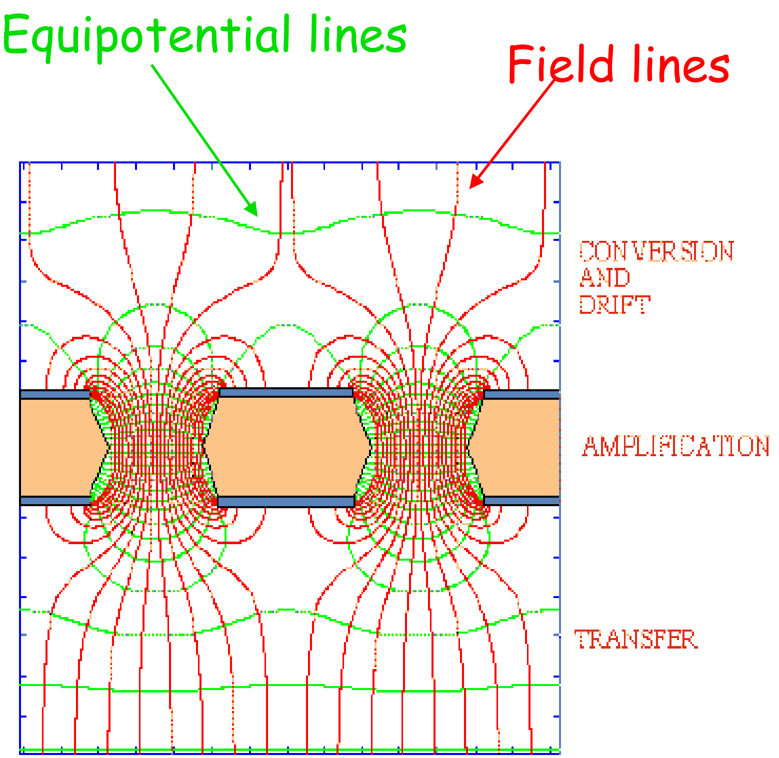
A Gas Electron Multiplier (GEM) is a thin (50 μm) **kapton** foil, copper clad on each side with a high density of holes acting as electron multiplication channels.

Holes are bi-conical with external diameter of 70μm, internal of 50 μm and pitch of 140 μm.

Voltages of 400-500 V are applied between the two copper sides, giving fields as high as ~100 kV/cm into the holes, resulting in a **gain of the order of 10^3 for mono-GEM detector.**

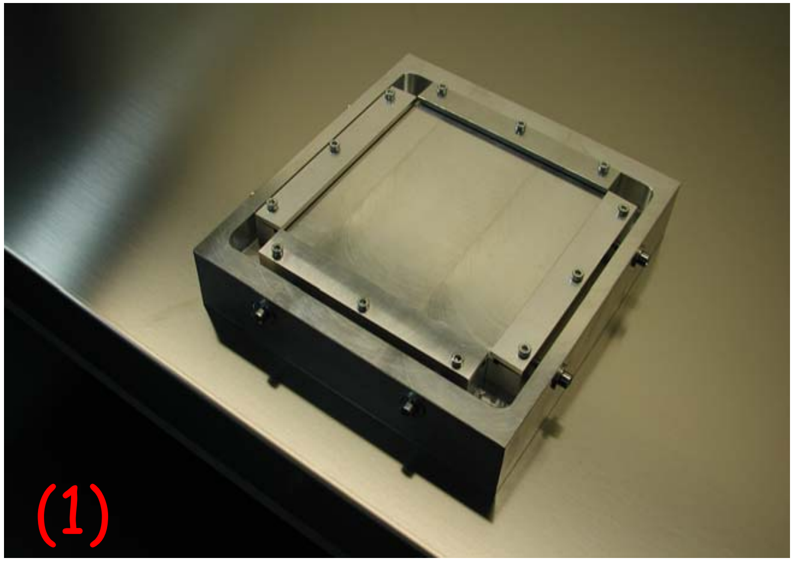
Larger gain, in safe condition, up to **10^4-10^5**, are usually achieved using **two or more GEM foils in cascade.**

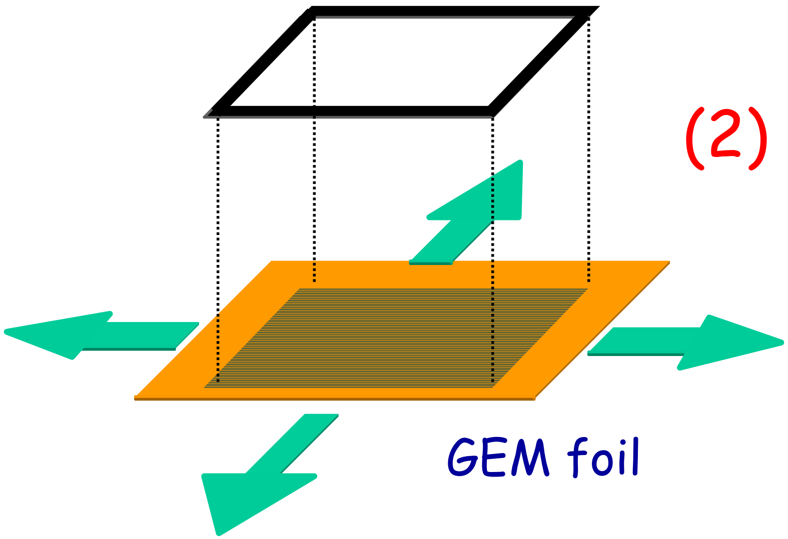
Signals are read out at the anode with pad/strip electrodes.



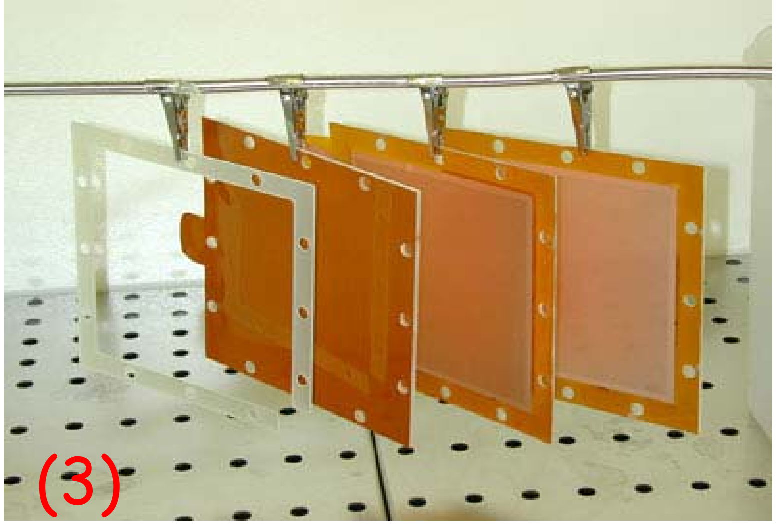
Maxwell 3D Simulation

Prototype Construction: GEM foil preparation

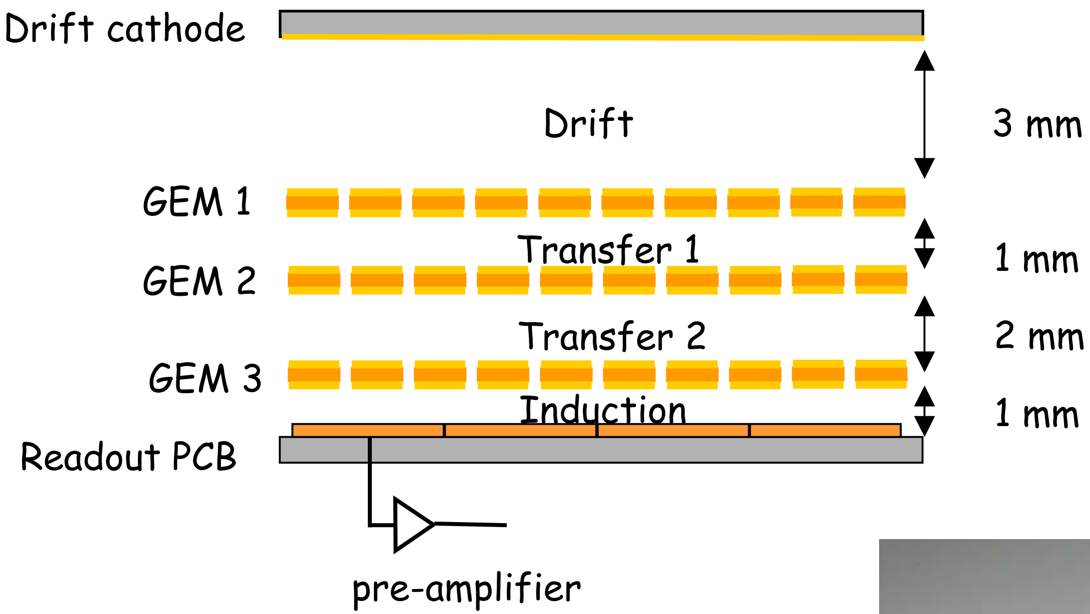




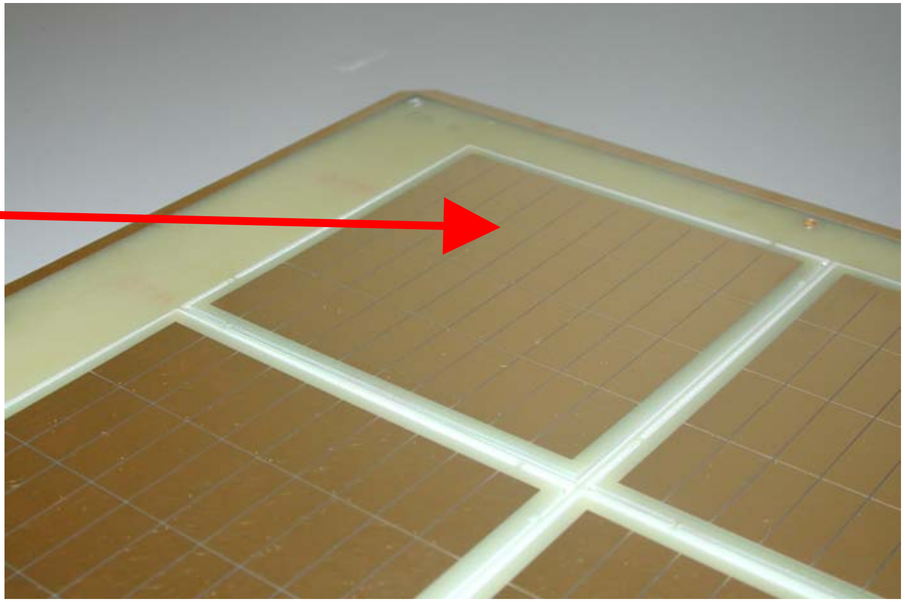
- A special tool is used to stretch the 100x100 mm^2 GEM foils (1)
- A 1mm-thick frame is then glued to the GEM with a fast polymerizing epoxy resin (2)
- After gluing, the GEM is removed from the stretching tool and the kapton foil exceeding the frame is removed (3)



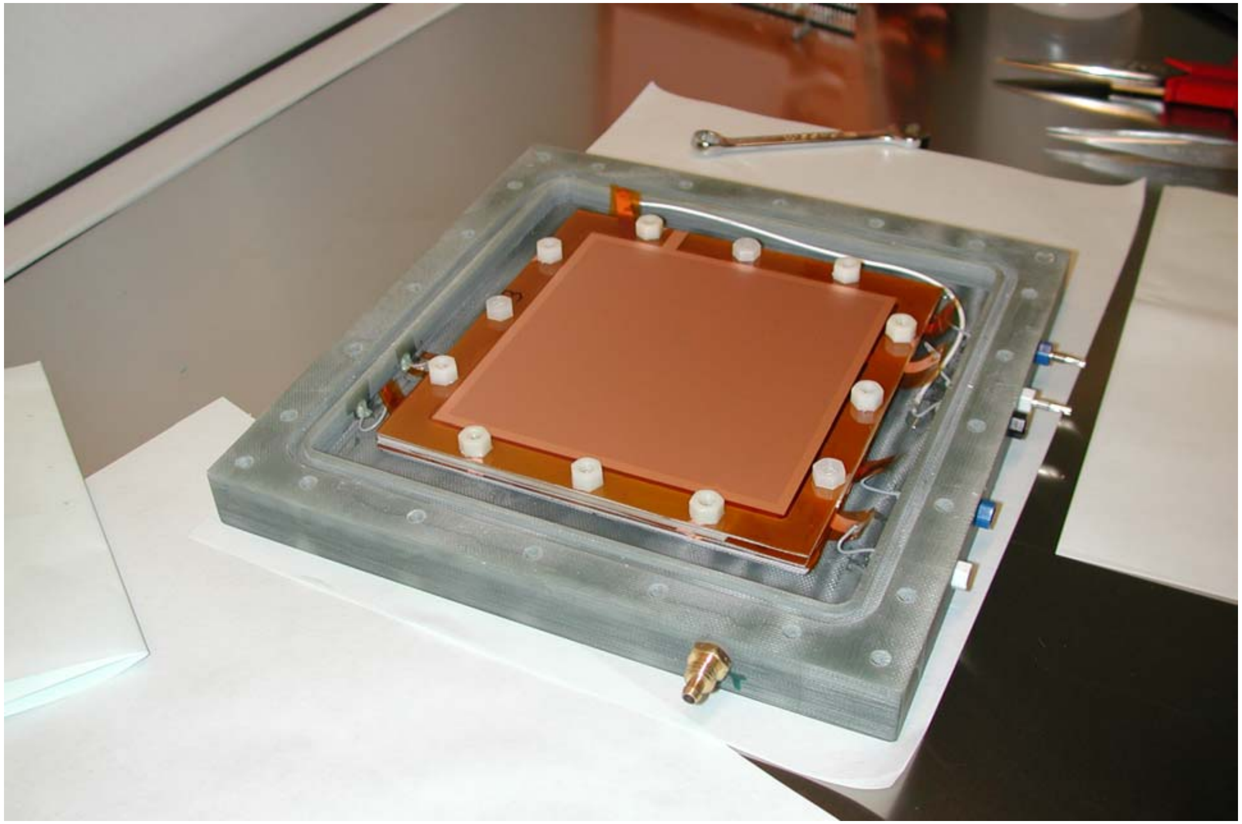
Prototype construction: detector geometry



Gold-plated PCB with 10x25 mm² pads (total active area 100x100 mm²) is used to readout the detector. Each pad is connected to a fast pre-amplifier.



Prototype construction: detector assembling



Detectors are assembled in a class 100 laminar flow bench. GEMs are stacked in a gas-tight G10 box above the pads. The cathode plane is positioned above the three GEMs. All electrodes are connected to small plugs used to supply HV to the GEMs

Prototype construction: f.e.e. & HV

Amplifier	Kloe/VTX	ASDQ (*)
Discriminator	external	on-chip
Input Impedance (Ω)	110	250
Peaking Time (ns)	6	8
Noise (e^- r.m.s.)	1350	2200
Sensitivity (mV/fC)	10	25
Baseline Restoration	yes	yes
Channel/Chip	6	8

(*) Not tested yet

Each GEM electrode is connected, through an R-C-R filter (for a total resistance of 2MΩ in series) to an individual HV channel

Detector Requirements

A triple-GEM detector is being proposed for the Central Region of the first Muon Station of the LHCb experiment at CERN, for which the requirements are:

- Rate Capability ~ up to about 0.5 MHz/cm^2
- Station Efficiency ~ 99% in a 25 ns time window **(*)**
- Cluster Size ~ 1.2 for a 10x25 mm^2 pad size
- Radiation Hardness ~ 6 C/cm^2 in 10 years (for $G \sim 10^4$)

(*) A station is made of two detectors "in OR", pad by pad. This improves time resolution and provides some redundancy.

Time Performances

- The time at which the charged particle crosses the GEM-based detector is measured with a single threshold leading edge voltage discriminator following a charge preamplifier/shaper.

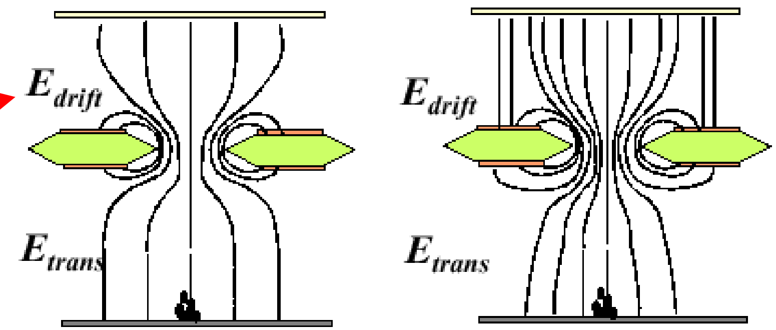
- Since the probability distribution of the distance x of the cluster closest to the first GEM is $P(x) = ne^{-nx}$ and $\sigma(x) = 1/n$, the intrinsic time spread of a GEM detector is: $\boldsymbol{\sigma(t) = 1/nv_{drift}}$, where **n** is the number of clusters per unit length and $\mathbf{v_{drift}}$ is the electron drift velocity in the ionization gap.

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

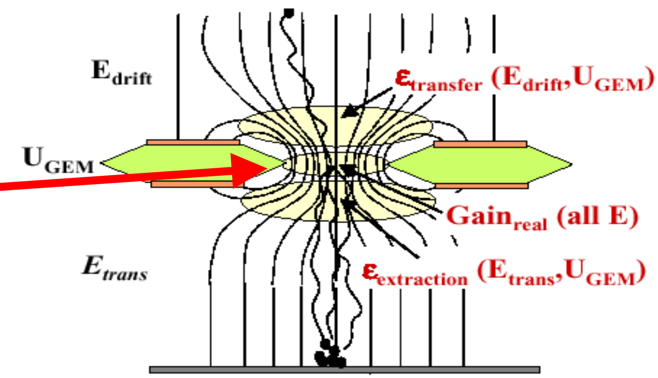
- In addition, **high efficiency for single cluster detection** is required. That is high **GEM transparency to electrons** (especially for the first GEM foil) is needed.

Time Performances: transparency

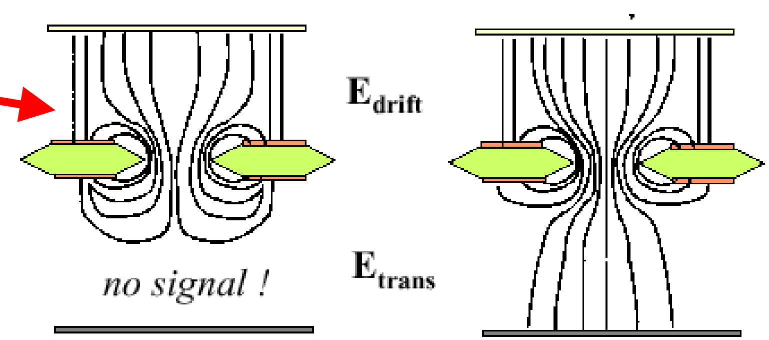
- The collection efficiency of primary electrons through the holes decreases with the increasing of the electric field above the GEM because of the defocusing of the field lines (some electrons could hit the GEM upper electrode);



- The electron multiplication into the holes, increases exponentially with the GEM voltage;



- The extraction efficiency of secondary electrons from the holes increases with the increasing of the electric field below the GEM.



By C.Richter (8th Elba Conference)

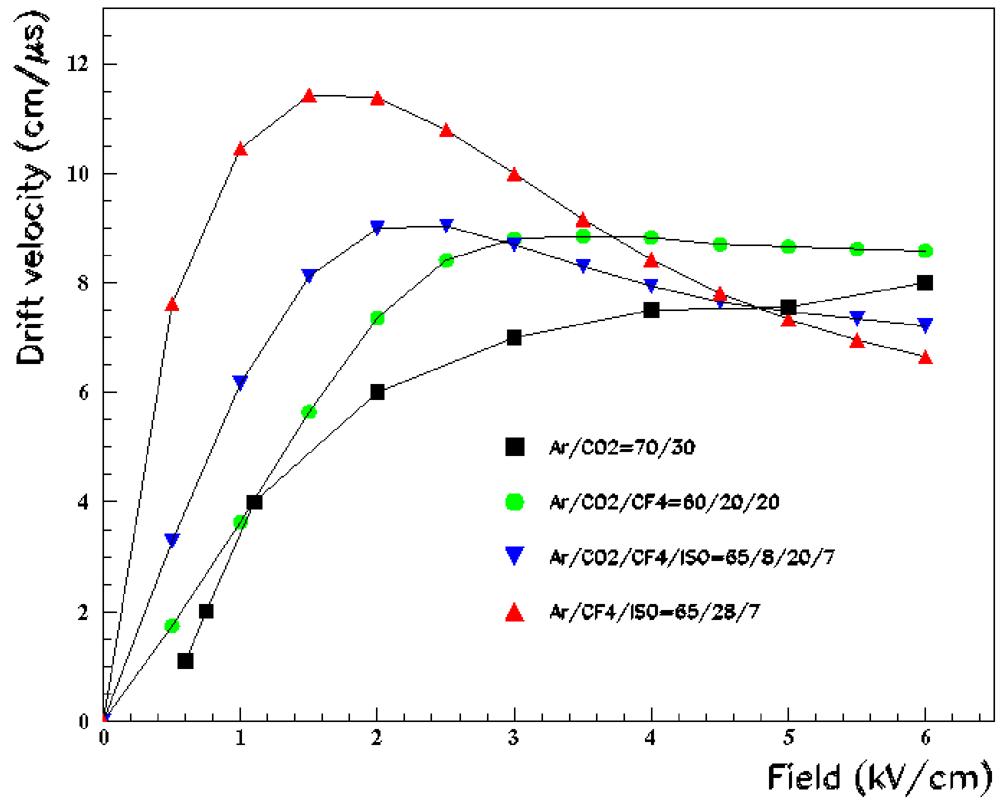
Time Performances: Drift velocity & Ionization

Ar/CO_2 (70/30):
- 7 cm/μs from @ 3 kV/cm
- 10 clusters in 3 mm

$Ar/CO_2/CF_4$ (60/20/20):
- 9 cm/μs from @ 3 kV/cm
- 15 clusters in 3 mm

$Ar/CO_2/CF_4/iso\text{-}C_4H_{10}$ (65/8/20/7):
- 9 cm/μs from @ 2.5 kV/cm
- 16 clusters in 3 mm

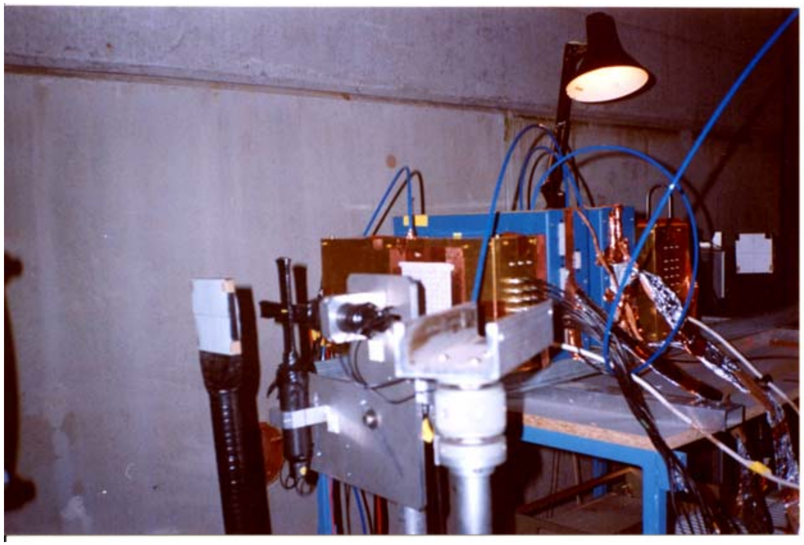
$Ar/CF_4/iso\text{-}C_4H_{10}$ (65/28/7):
- 11.5 cm/μs from @ 2 kV/cm
- 17 clusters in 3 mm



High drift velocity at low fields allows fast detector response while keeping high efficiency in electron collection at the first GEM (defocusing effect)

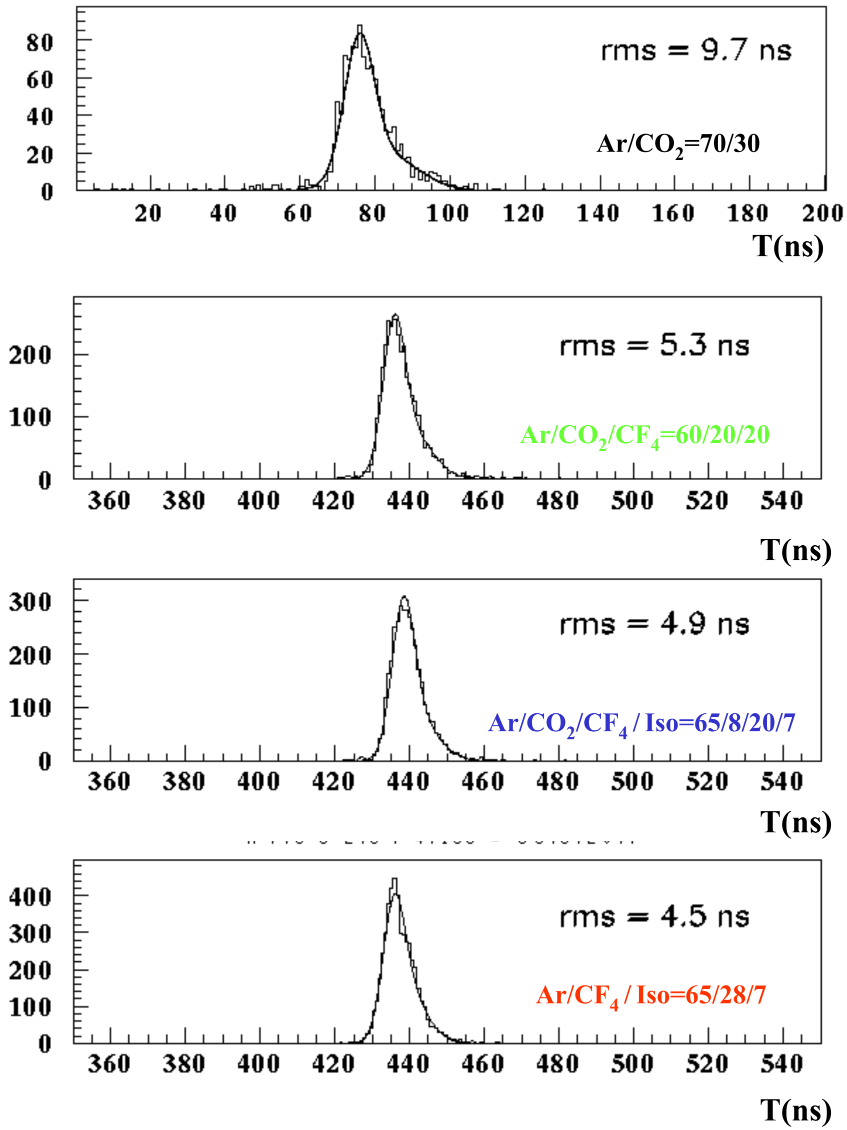
PSI - Test Beam

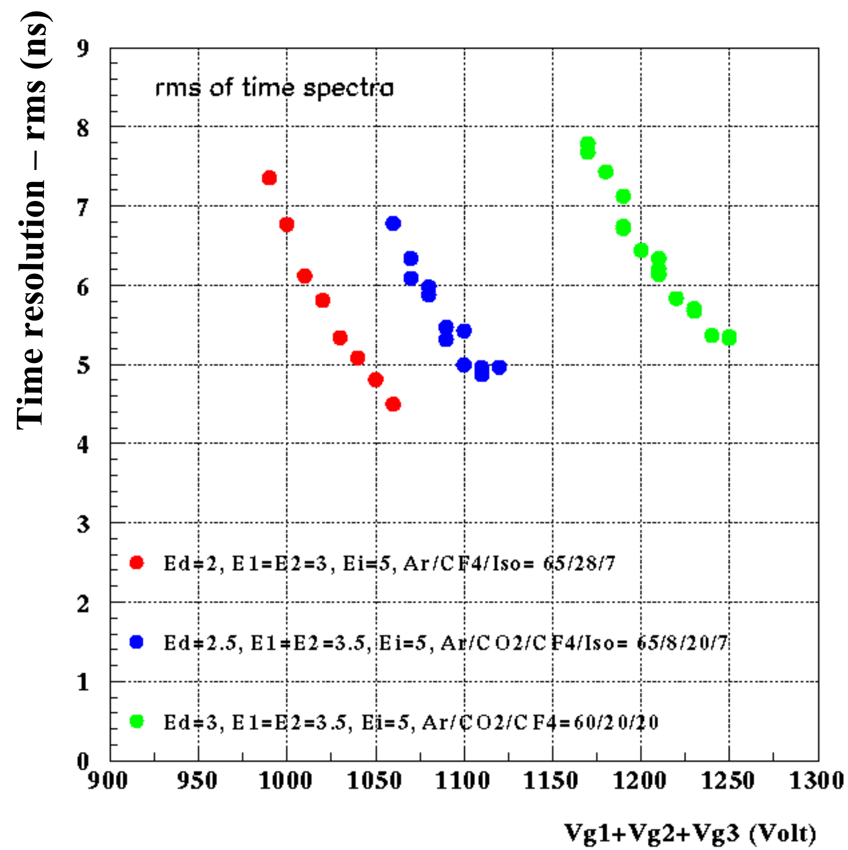
- The PSI πM1 beam is a (quasi) continuous high-intensity secondary beam (10^7 π^-/s or 10^8 π^+/s a 350 MeV/c for each mA of beam current in the primary beam).
  Pions arrive in 1 ns-wide bunches every 20 ns.
  Spot size on target (FWHM):
  15 mm horizontal, 10 mm vertical
  Pions at 350 MeV/c are at the minimum of ionization.



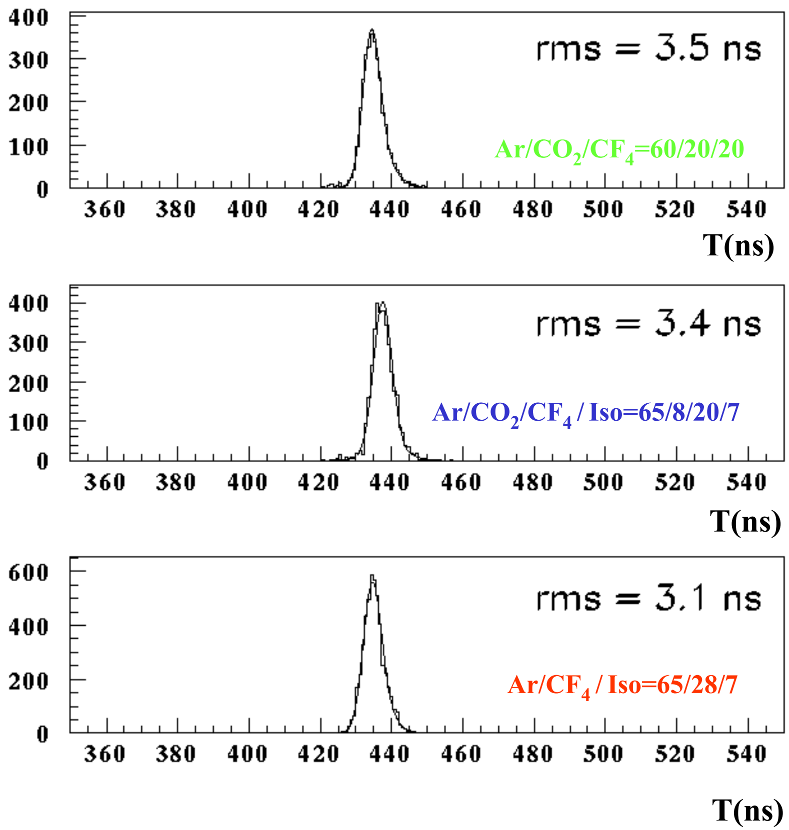
- Data were taken with two different beam setting:
  - LOW (~30 kHz on the detector active area)
  - HIGH intensity pions (~50 MHz on active area)
- LOW intensity: efficiency, time resolution measurement
- HIGH intensity: discharge probability measurement

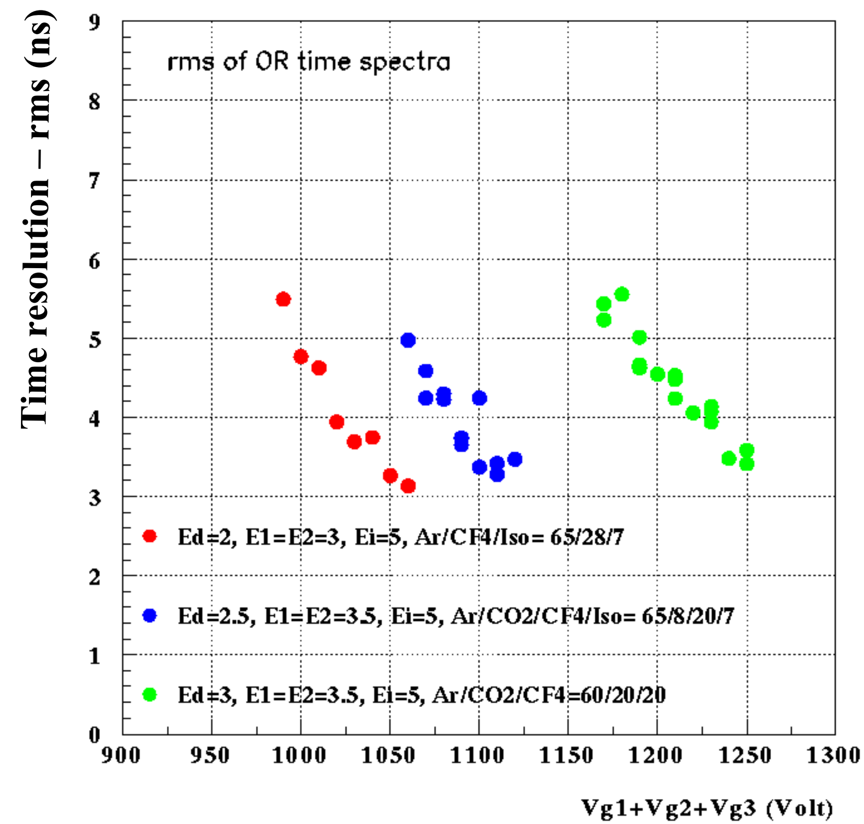
Time Resolution: single detector





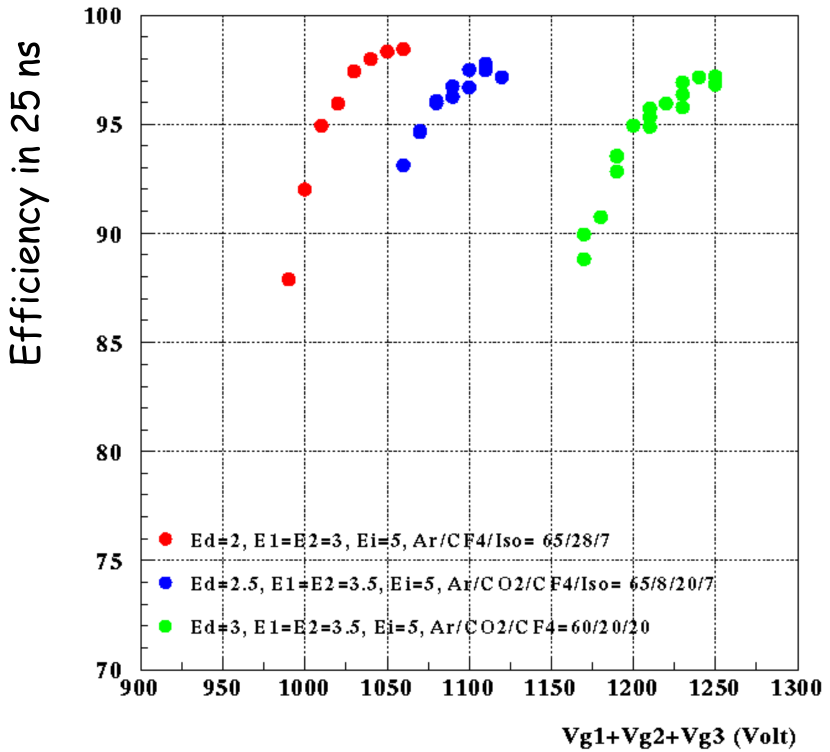
Time Resolution: two detectors in OR



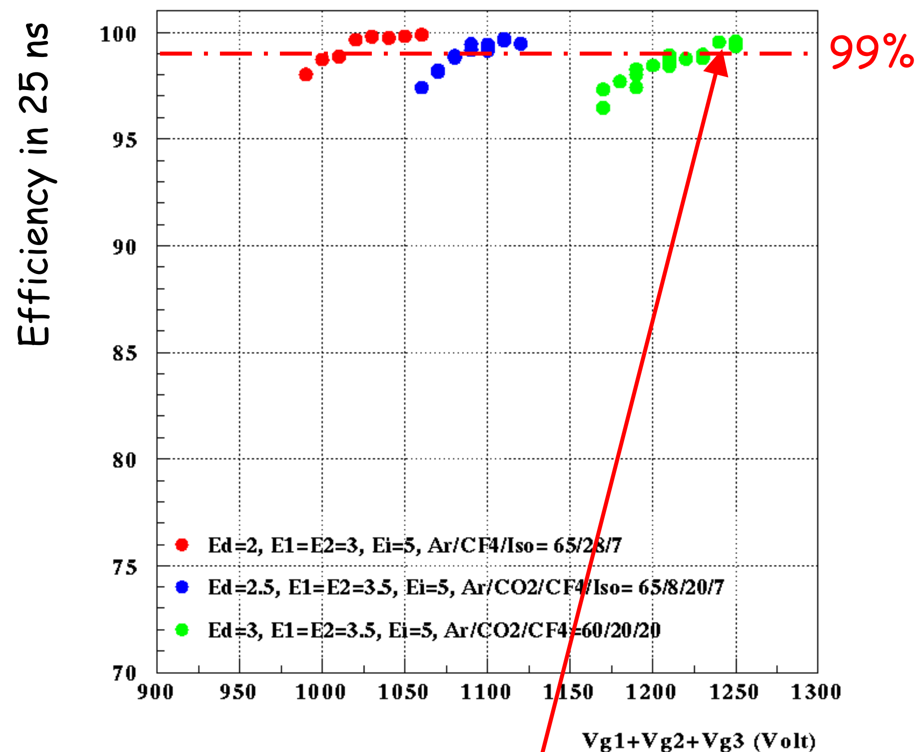


Efficiency in 25 ns time window

Single chamber



Two chambers in OR



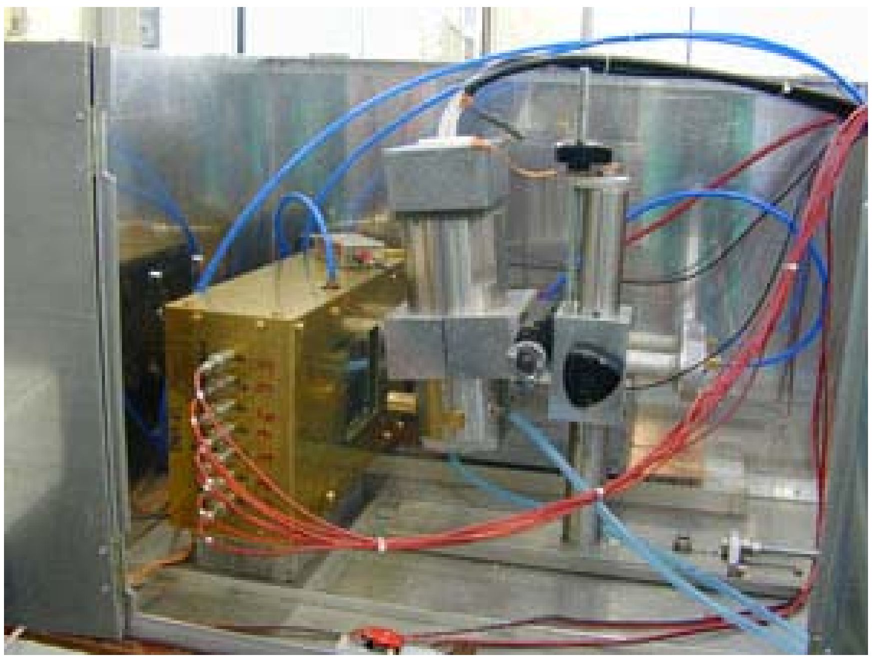
Working region

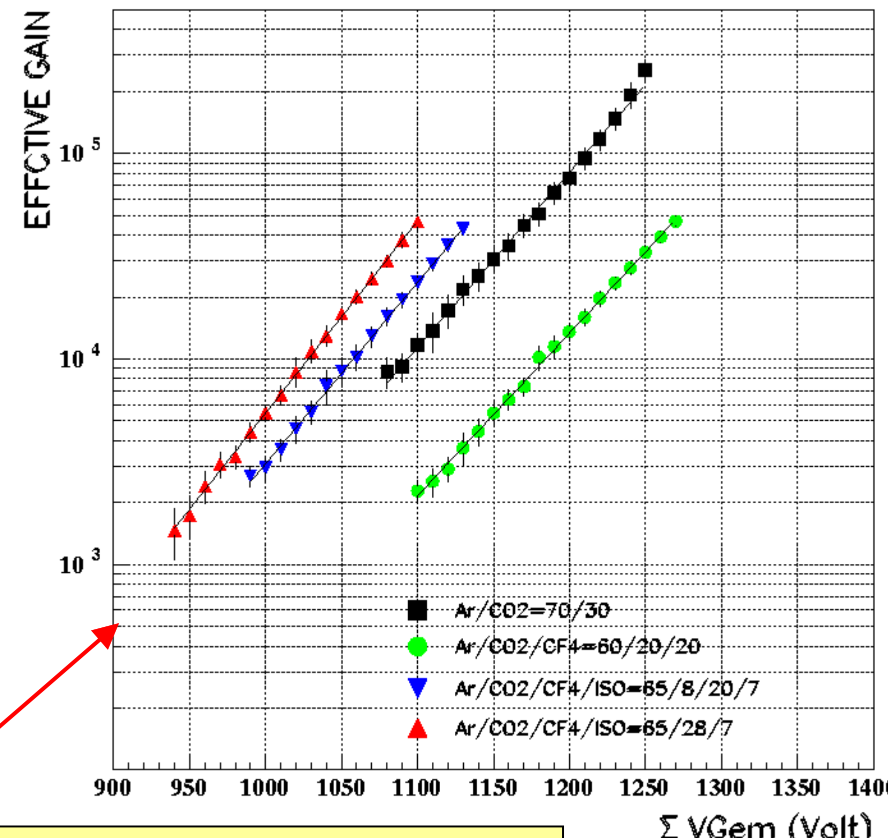
$Ar/CF_4/C_4H_{10}$ = 65/28/7 ε_{max} = 98.7 %
$Ar/CO_2/CF_4/C_4H_{10}$ = 65/8/20/7 ε_{max} = 97.8 %
$Ar/CO_2/CF_4$ = 60/20/20 ε_{max} = 97.2 %

To be compared with ε_{max} = 89.0 % measured with Ar/CO_2

GAIN MEASUREMENT

The effective GAIN " G_{eff}" of the detector has been estimated using a 5.9 keV X-ray tube, measuring the rate "R" and the current "i", induced on pads, by X-rays incident on the GEM detector.





$$G_{eff} = i / eNR$$

$$G_{eff} \propto e^{\alpha x(VG1+ VG2+ VG3)}$$

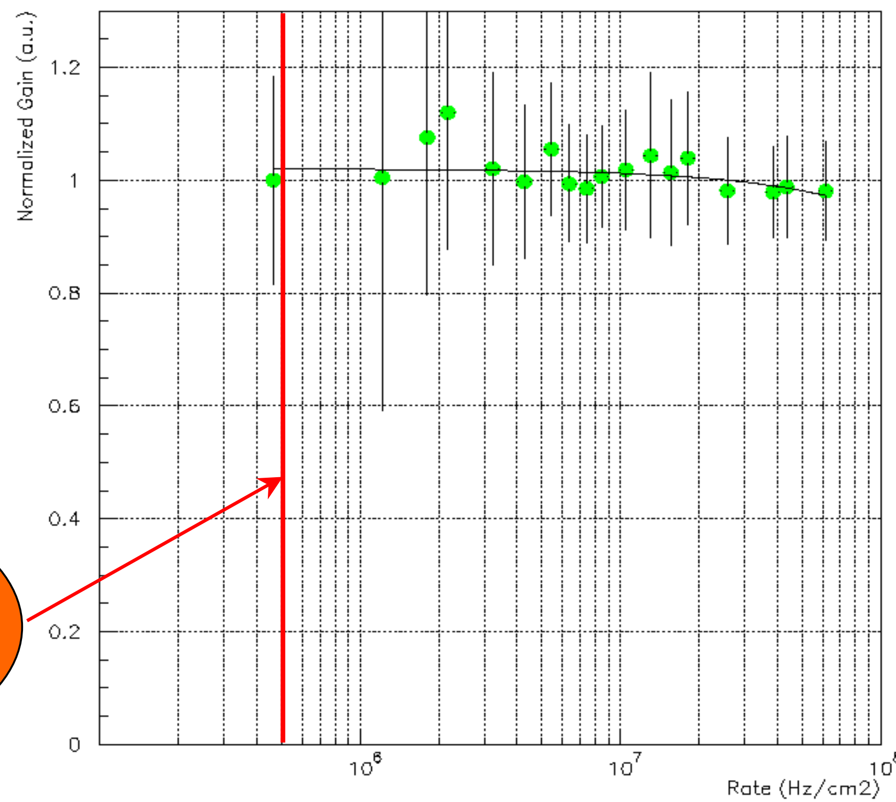
RATE CAPABILITY

The rate capability of the GEM detector (**at a Gain of ~ 10^4**) has been measured by means the X-ray tube up to **~ 60 MHz/cm^2**

Normalized Gain vs X-ray rate

The detector Gain remains stable up to very high X-ray fluxes

LHCb upper limit for R1,R2 of M1



AGING TEST

The aging test has been performed by irradiating with a high intensity (50 MHz/cm^2) 5.9 keV X-rays the detector operated with the

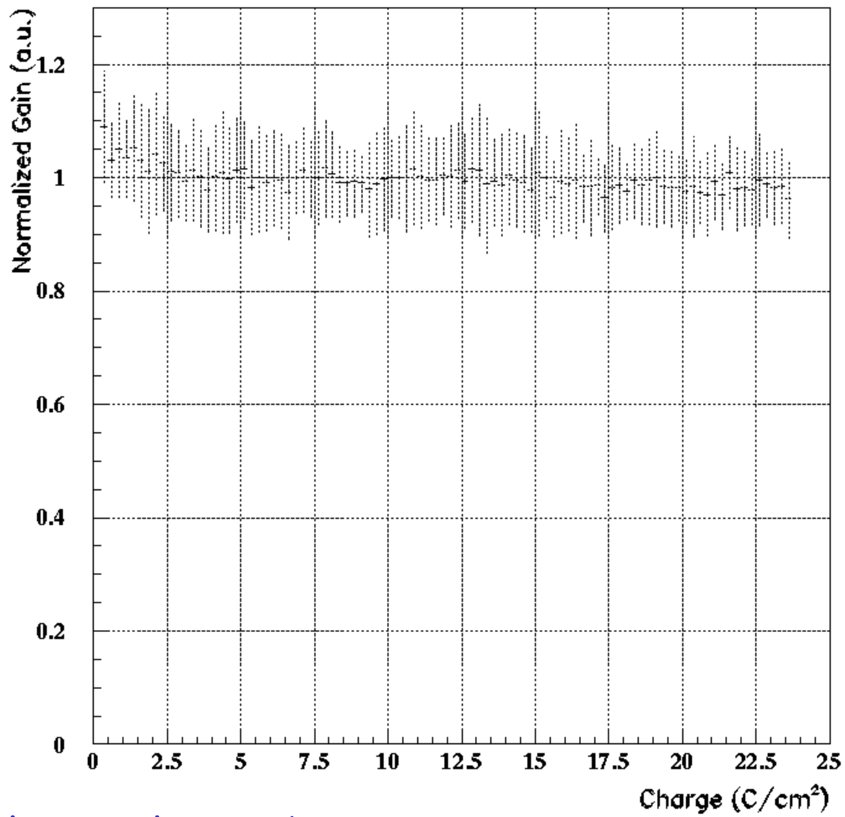
$Ar/CO_2/CF_4$ = 60/20/20 gas mixture @ G ~ 2×10^4 (ΣV_{GEM} = 1230 V)

A total charge of ~23 C/cm^2 has been integrated.

Taking into account 1 year (10^7 sec) at LHCb, the triple-GEM detector placed in R1,R2 of M1 will integrate a charge of Q_{LHCb} ~ 1.3 C/cm^2

We can conclude that the detector survives ~18 years with negligible changes (~5%) in its operation.

Variations of P,T have been corrected with a second, low irradiated, GEM chamber used as monitor.

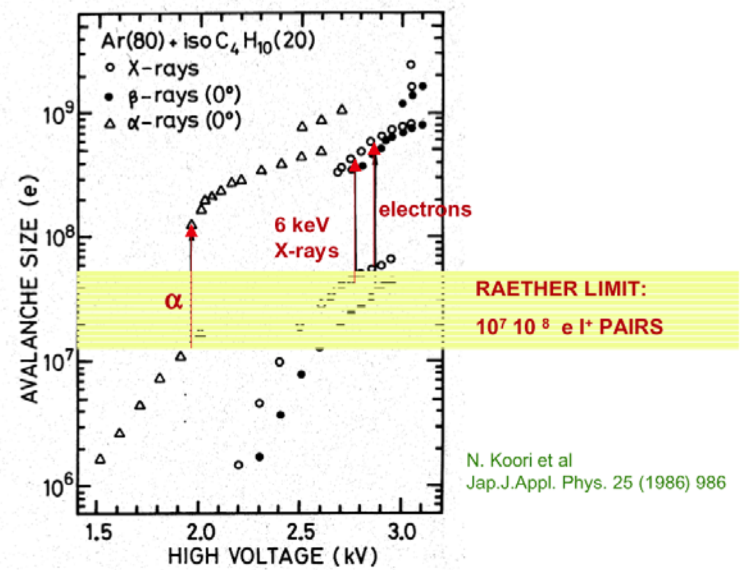


Gas was supplied with open flow system, using Polypropylene tubes.
The gas flow was 100cc/min, well above the limit for gas poisoning

AGING for isobutane gas mixtures will be done in the near future

DISCHARGE STUDIES (I)

- The occurrence of discharges in gas detectors is correlated with the transition from avalanche to streamer.
- The transition is voltage and ionization density dependent: in fact streamers more easily occur when a large number of electron-ion pairs is released by particles in the gas volume (highly ionizing particles).



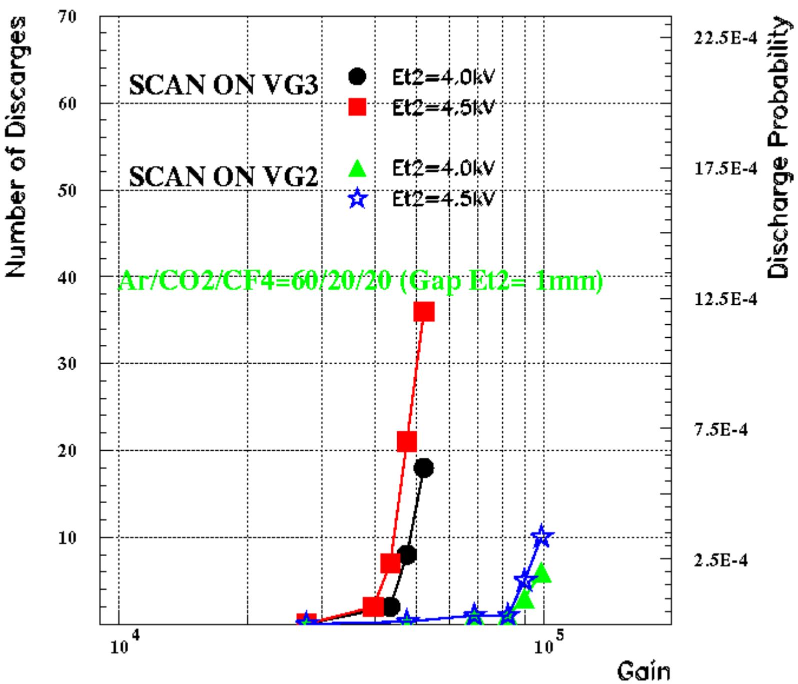
N. Koori et al
Jap.J.Appl. Phys. 25 (1986) 986

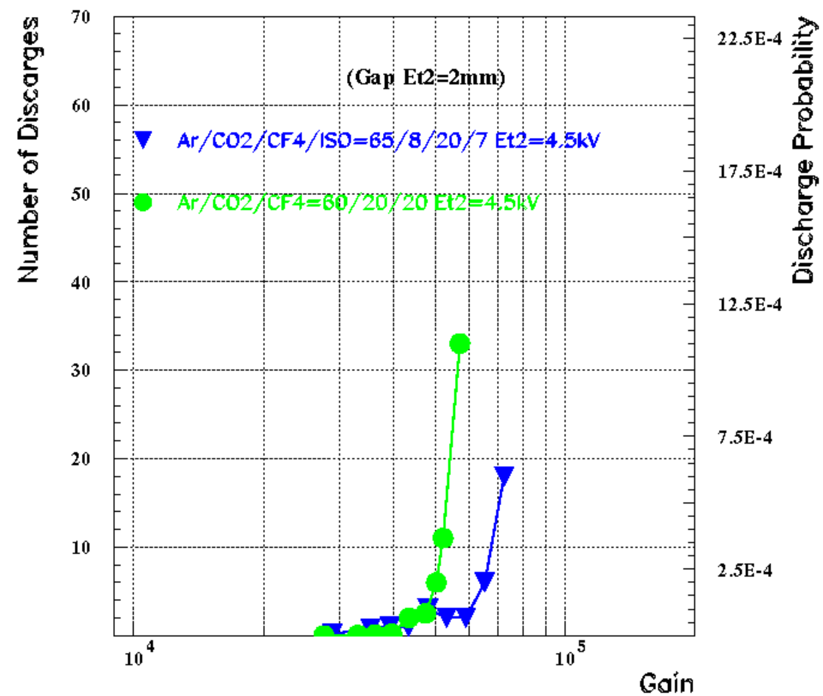
- In this case the total charge created by the multiplication processes could exceed the threshold value (Raether limit, 10^7-10^8 e-I$^+$ pairs) for the transition from avalanche to streamer.
- Due to the very small anode-cathode distance in GEM detectors (more generally in micro-pattern detectors) the transition from avalanche to streamer is most of the time followed by discharges.
- For triple-GEM detectors this means that the discharge probability is larger in the third GEM where the charge density is higher.

DISCHARGE STUDIES (II)

The dependence of the discharge probability on GEM voltages and gas mixtures has been studied by irradiating the detector with 5.6 MeV α-particles from an ^{241}Am source.

The statistical significance of the zero baseline corresponds to ≤ 1 discharge during a time of 12 hours, or a probability of less than ~2×10^{-7}.





Discharge probability is more sensitive to V_{G3} than the other GEM voltages.

$V_{G1} > V_{G2} > V_{G3}$

The use of a good quencher, like isobutane, allows to reduce the discharge probability and to reach higher gains.

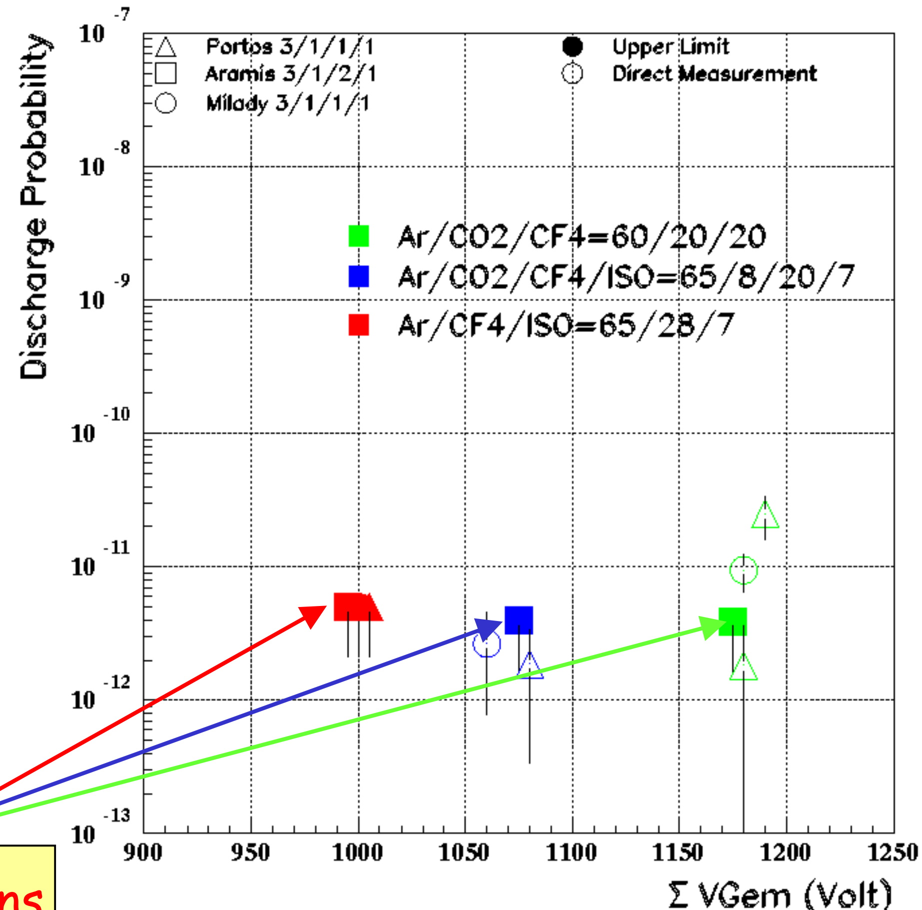
DISCHARGE STUDIES (III)

GEM detectors have been tested at PSI with a hadron beam of 50 MHz on the active area. Discharges have been counted by monitoring current spikes

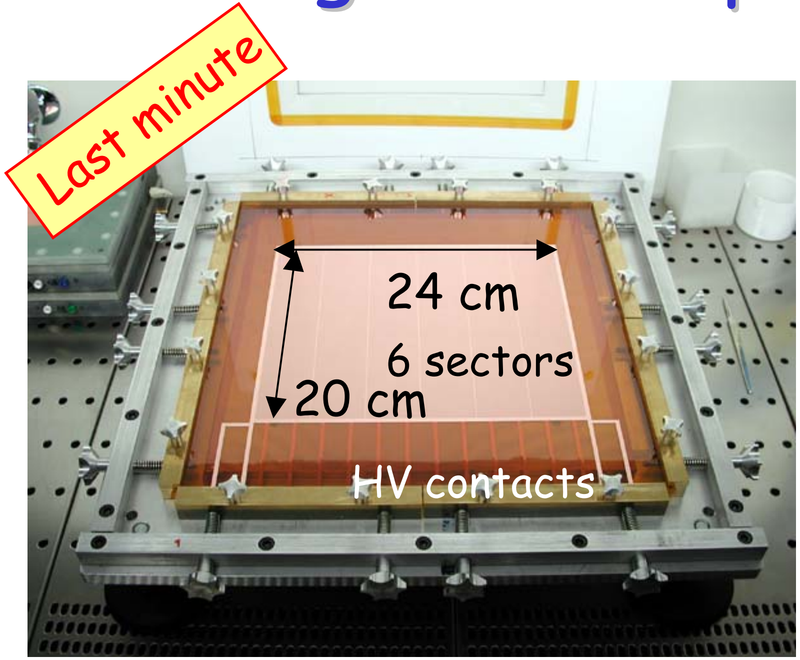
At the working points the discharge probability, at 95% C.L., is lower than $4x10^{-12} \div 2x10^{-11}$/ hadron, corresponding to 200 ÷ 1000 discharge/cm² in 10 years at LHCb (R1,R2 of M1)

During test beam exposures and α-particle tests the detector integrated, **WITHOUT DAMAGES**, about **220 discharges/cm²**, corresponding to **3÷10** LHCb years

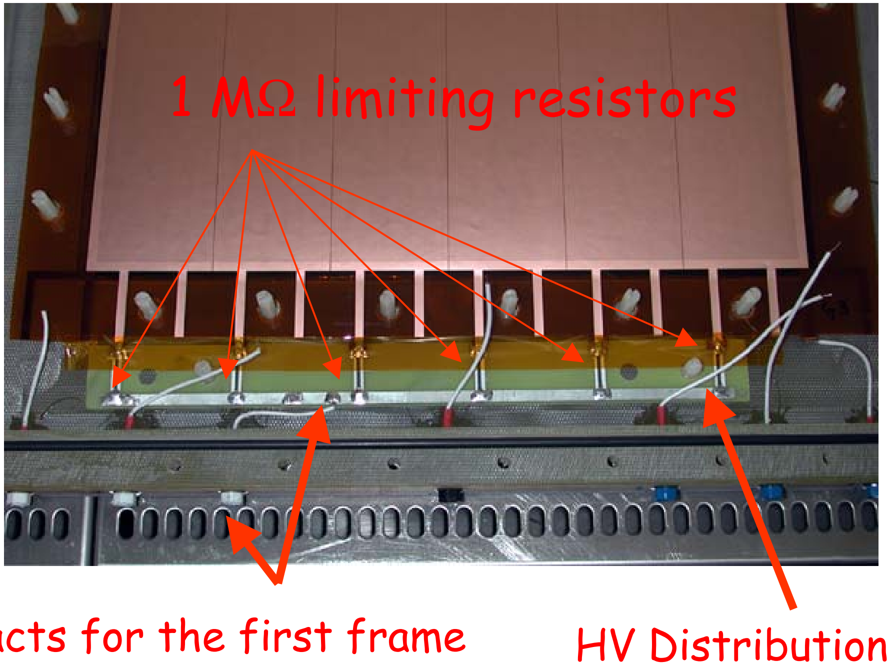
NO discharges in 6 hour runs



Large size triple-GEM: proto construction



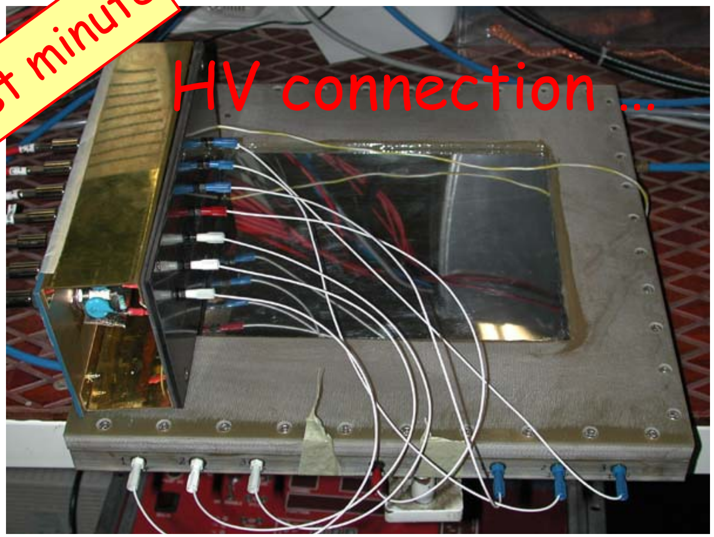
Since the stretching tool allows a very efficient foil tensioning, also for large size GEM, NO GRID SPACER is required to sustain the GEM

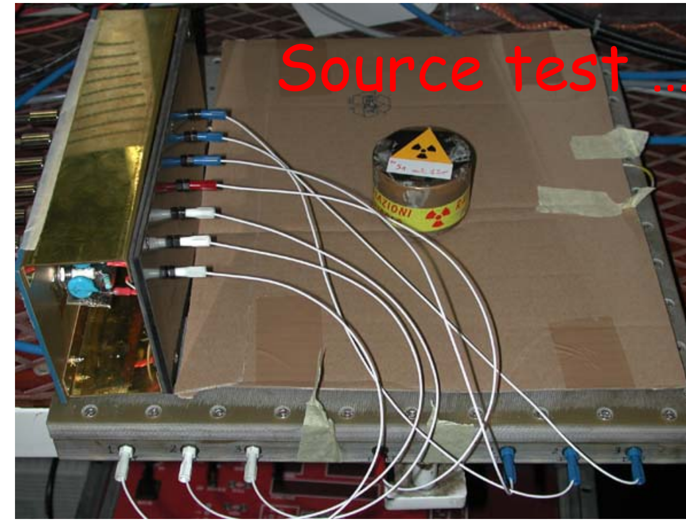


GEMs are stacked in a gas-tight G10 box above the pads.
The cathode plane is positioned above the three GEMs.
All electrodes are connected to small plugs used to supply HV to the GEMs

Large size triple-GEM: β-source test

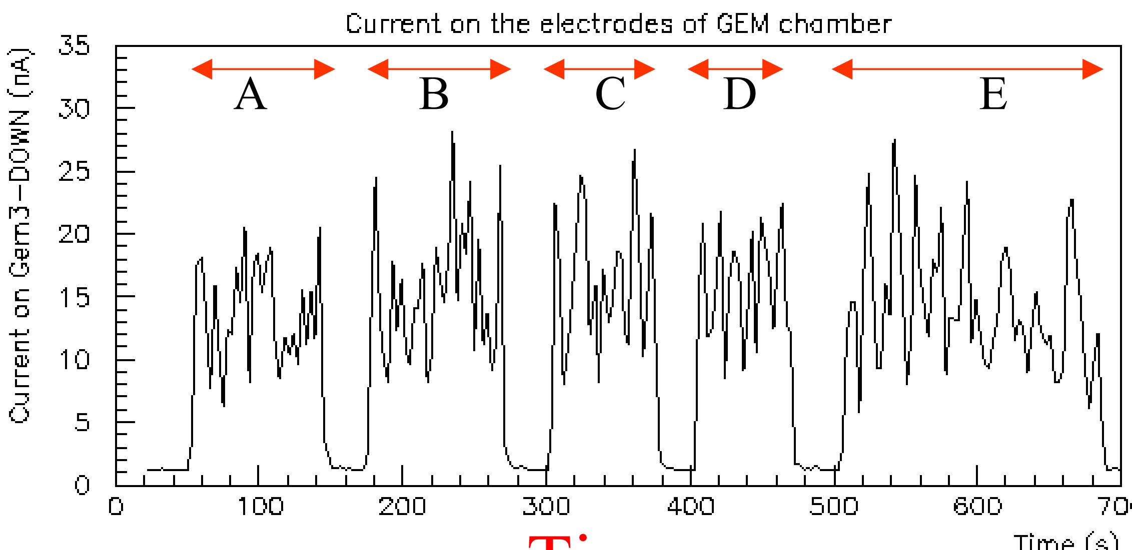
Last minute



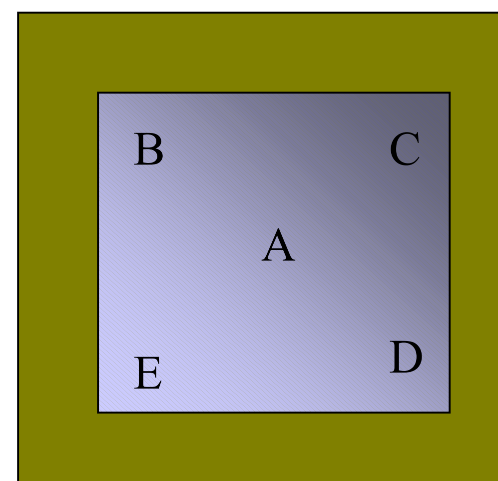


… in current mode

Current (nA)



Time



CONCLUSIONS

CF_4 and **isobutane** based gas mixtures allow to have a fast, stable and robust GEM detector, all the LHCb requirements are fulfilled:

- **Time performances** (large improvements with respect to the Ar/CO_2 gas mixture):
  - good, **5.3 ns r.m.s.**, for $Ar/CO_2/CF_4$ (60/20/20);
  - excellent, **4.5 ns r.m.s.**, for $Ar/CF_4/iso\text{-}C_4H_{10}$ (65/28/7);
  - good **efficiency in 25 ns** for isobutane/CF4 based gas mixtures.

- **Aging:** small effects observed after accumulating **23 C/cm^2** with $Ar/CO_2/CF_4$ (60/20/20) at an effective gain of **2×10^4** corresponding to **~18 years** at LHCb;

- **Rate Capability**: fine !!

- **Discharge probability:**
  - lower than **$4 \times 10^{-12} \div 2 \times 10^{-11}$/ hadron** with pions from the PSI πM1 beam;
  - with **α-particles** we studied the dependence on various parameters: voltages, electric fields and gas mixtures.
  - with α-particle the detector could withstand about **220** discharges/cm^2 **without damages**, corresponding to **3÷10** LHCb years.

- The first chamber of **20x24** cm^2 has been recently built and **works well** !!