The µ-RWELL: from R&D to industrialization

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OUTLINE

- Why a new Micro Pattern Gas Detector
- The μ-RWELL
- Detector performance
- Towards the detector industrialization
- Summary

Why a new MPGD

The R&D on µ-RWELL is mainly motivated by the wish of improving the

stability under heavy irradiation

& simplify as much as possible

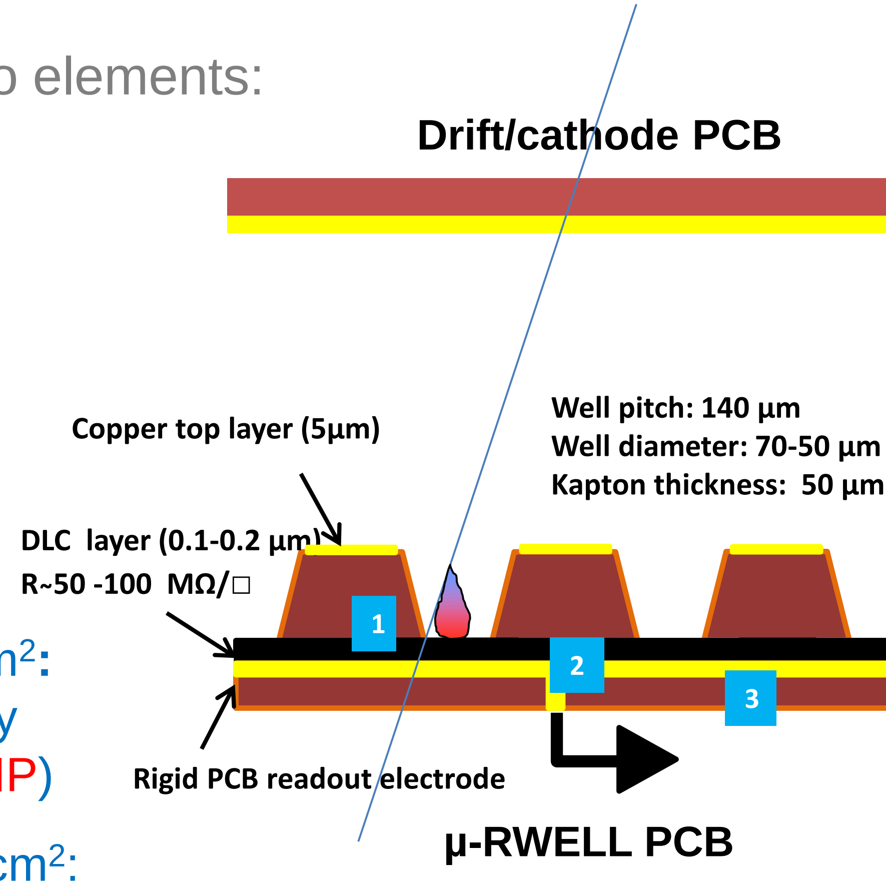
construction/assembly procedures

The μ-RWELL architecture

The μ-RWELL detector is composed by two elements: the **cathode** and the **μ-RWELL_PCB .**

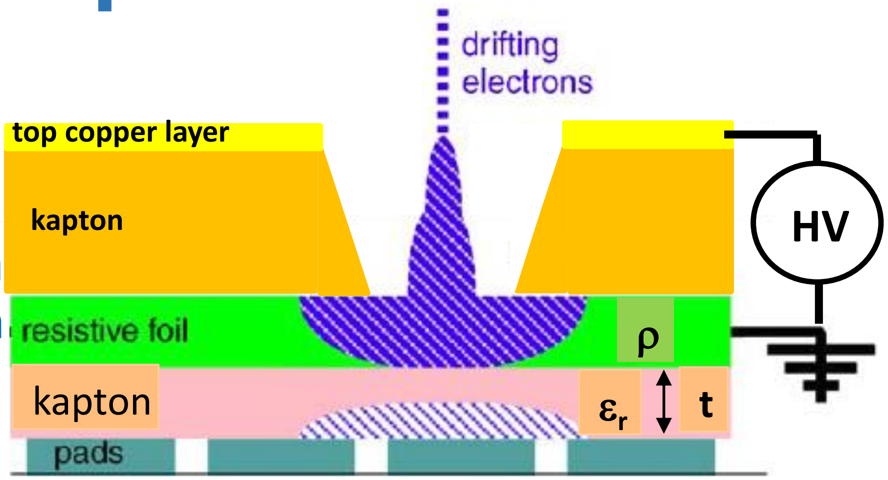
The **μ-RWELL_PCB** is realized by **coupling:**

1. **a "suitable WELL patterned kapton foil** as "amplification stage"
2. **a "resistive stage"** for the discharge suppression & current evacuation:
   i. **"Low particle rate" (LR)** << 100 kHz/cm^2**:** single resistive layer → surface resistivity ~100 MΩ/□ (CMS-phase2 upgrade - SHIP)
   ii. **"High particle rate" (HR)** >> 100 kHz/cm^2: more sophisticated resistive scheme must be implemented (MPDG_NEXT- LNF & LHCb-muon upgrade)
3. **a standard readout PCB**



G. Bencivenni et al., 2015_JINST_10_P02008

Principle of operation



A voltage 400-500 V between the top copper layer and the grounded resistive foil, generates an electric field of ~100 kV/cm into the **WELL which acts as multiplication channel**

The charge induced on the resistive foil is dispersed with a *time constant, RC,* determined by

- the ***surface resistivity,*** ρ
- the ***capacitance per unit area,*** which depends on the **distance between the resistive foil and the pad readout plane**, *t*
- the ***dielectric constant*** of the kapton, ε_r ***[M.S. Dixit et al., NIMA 566 (2006) 281]***

- **The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark** by a **local voltage drop** around the avalanche location.
- As a drawback, the **capability to stand high particle fluxes is reduced**, ***but an appropriate grounding of the resistive layer with a suitable pitch solves this problem (High Rate scheme)***

The two detector schemes (I)

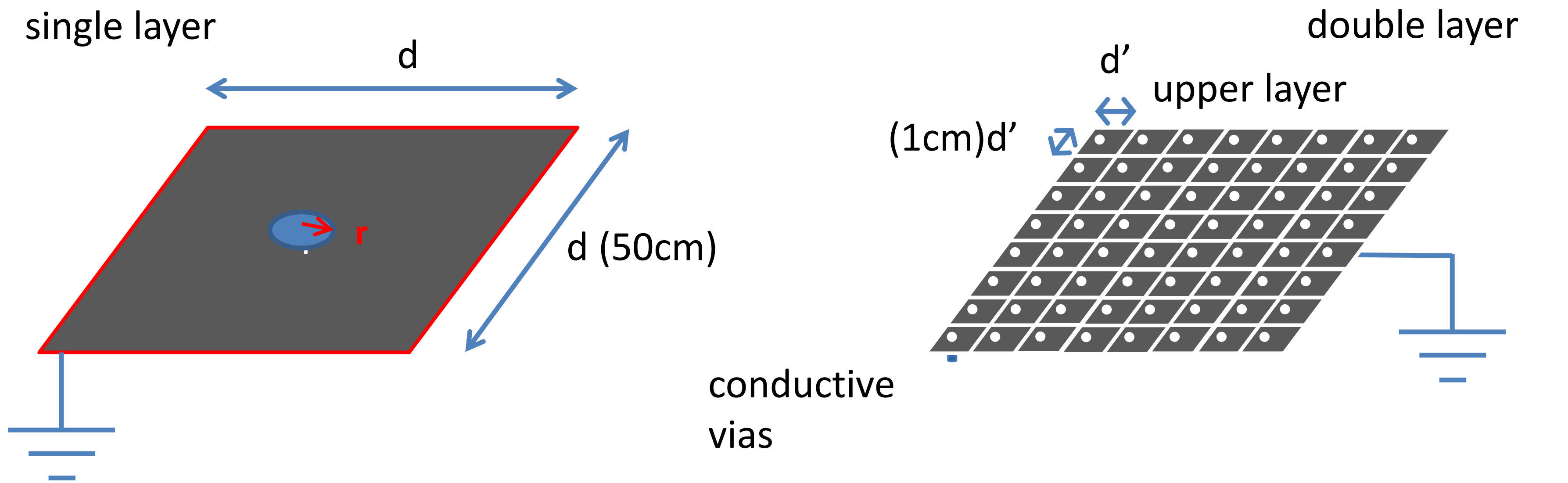
Low Rate scheme

- ❑ **single resistive layer** with **“*edge detector*”** grounding
- ❑ **“*2D*”** current evacuation
- ❑ **“*large current path to ground*”**
  - → **higher resistance to ground**
  - → **large Voltage drop spread**
  - → **large gain non-uniformity**
  - → **low rate ~10-20 kHz/cm^2**
- ❑ ***“easy” implementation: kapton foil + PCB coupling***
- ❑ ***R&D completed(*), engineering on-going***

High Rate scheme

- ❑ **double resistive layer** with ***“through vias”*** **grounding with a O(1cm^2) pitch**
- ❑ ***“3D”*** current evacuation
- ❑ ***“short current path to ground”***
  - → **lower resistance to ground**
  - → **small Voltage drop spread**
  - → **small gain non-uniformity**
  - → **high rate ≥ 1 MHz/cm^2**
- ❑ ***“more demanding” implementation: multi-layer flex w/through-vias + PCB coupling***
- ❑ ***R&D almost completed(*), engineering ready to be started***

(*) well shape/geometry still to be studied in details



inferior layer

(*) point-like irradiation, r<<d
Ω is the resistance seen by the current generated by a radiation incident in the center of the detector cell

$$\Omega \sim \rho_s \times d/2\pi r \qquad\qquad \Omega' \sim \rho_s' \times d'/\pi r$$

$$\Omega/\Omega' \sim (\rho_s/\rho_s') \times d/2d'$$

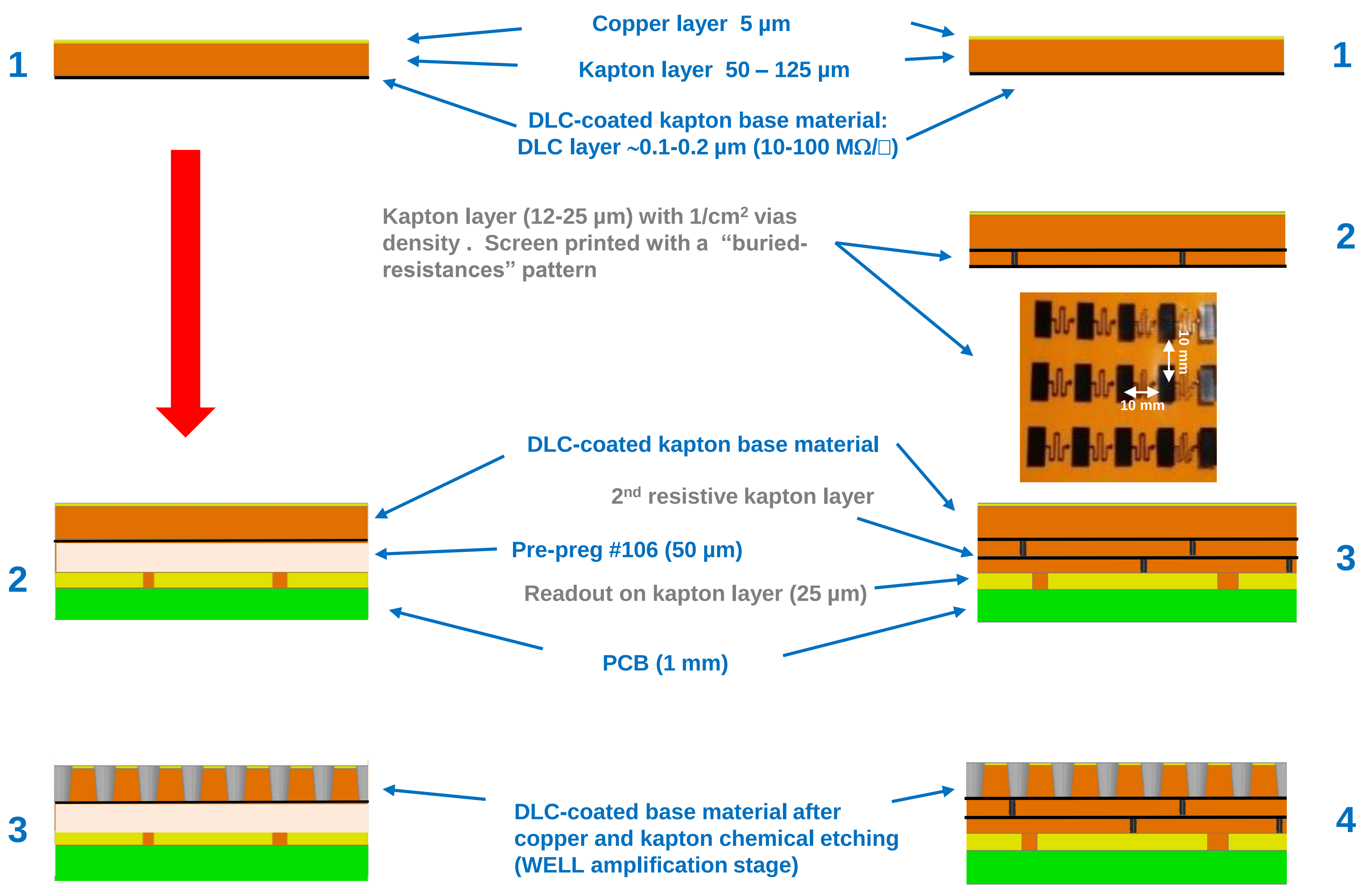
$$\text{If } \rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim d/2d' = 25$$

(*) Morello's model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)

The µ-RWELL_PCB manufacturing (V1.0)

LR scheme: single resistive layer

HR scheme: double resistive layers



The µ-RWELL_PCB for High Rate (V2.0)

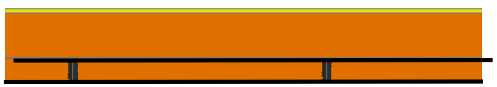
1

Copper layer 5 µm

Kapton layer 50 - 125 µm

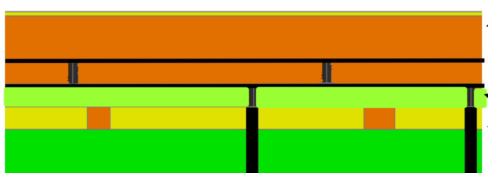
DLC-coated kapton base material: DLC layer ~ 0.1 – 0.2 µm (10 – 100 MΩ/□)

2



2^{nd} resistive kapton layer (25 – 50 µm) with $1/cm^2$ "*through vias*" density

3



DLC-coated kapton base material

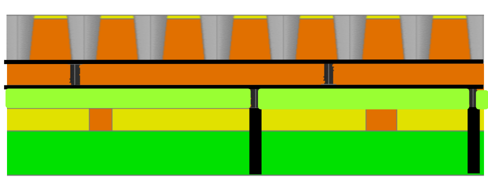
2^{nd} resistive kapton layer

solder resist (12 µm)

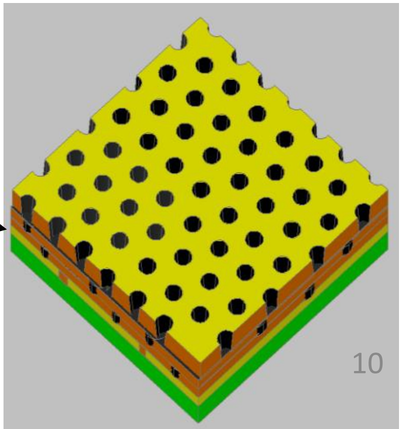
pad/strips readout on standard PCB (1 – 1,6 mm)

"through vias" for grounding

4



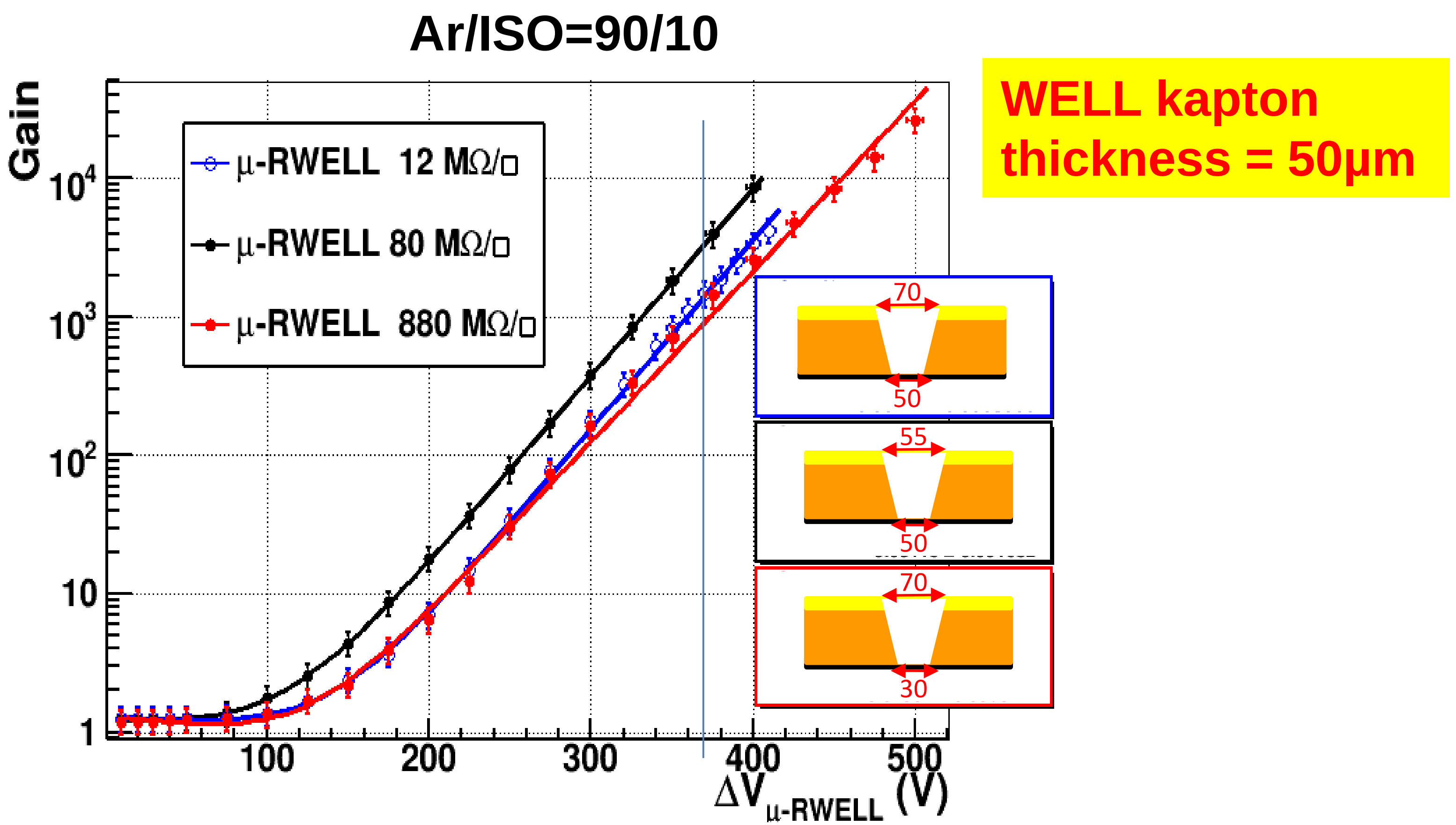
DLC-coated base material after copper and kapton chemical etching (the WELL amplification stage)



The μ-RWELL performance: Lab Tests

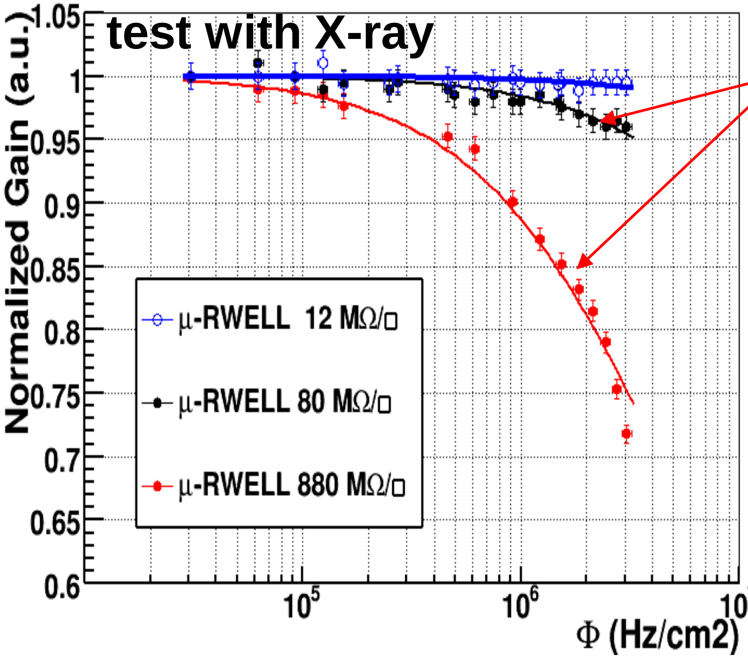
Detector Gain

prototypes with different resistivity (12-80-880 MΩ/□) have been tested with an **X-Ray** gun (5.9 keV), with **Ar/iC$_4$H$_{10}$= 90/10** gas mixture, and characterized by measuring the **gas gain** in **current mode**.



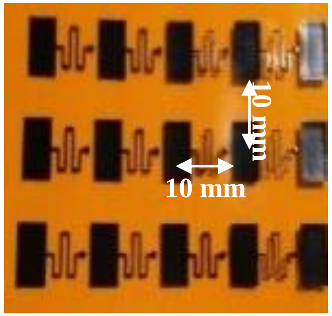
Rate capability vs layer resistivity

Ar/ISO =90/10, G = 1000



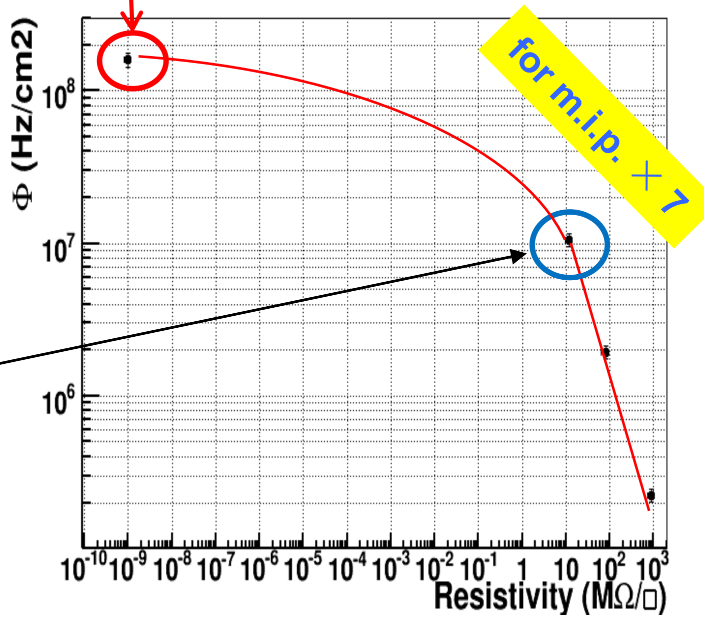
the **gain decrease** is correlated with the **voltage drop** due to the **resistive layer**

solution ➔ **grounding by “*through-vias with a suitable pitch*”**



GEM detector rate(*)

rate for a drop ΔG = -3%



a re-scaling with the right gain of 4000 would be required

with a **1×1 cm²** **grounding pitch** **μ-RWELL** & a resistivity of **≈10 MΩ/□**, a rate capability >> 1**MHz/cm²** can be achieved **fulfilling the LHCb requirement**

(*) Bellazini et al. NIMA 423 (1999) 125
Sauli et al., NIMA 419 (1998) 410

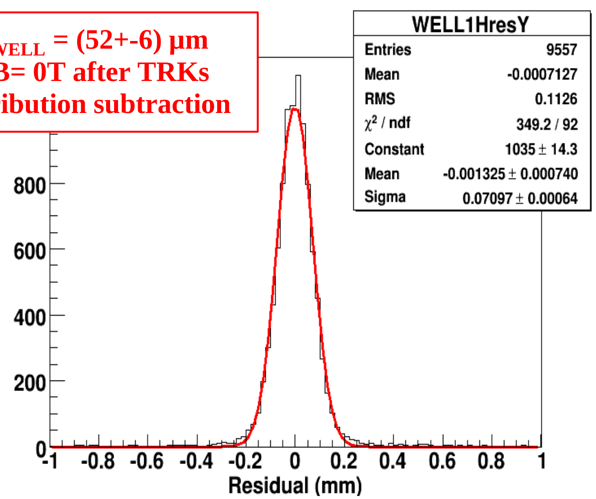
The μ-RWELL performance: Beam Tests

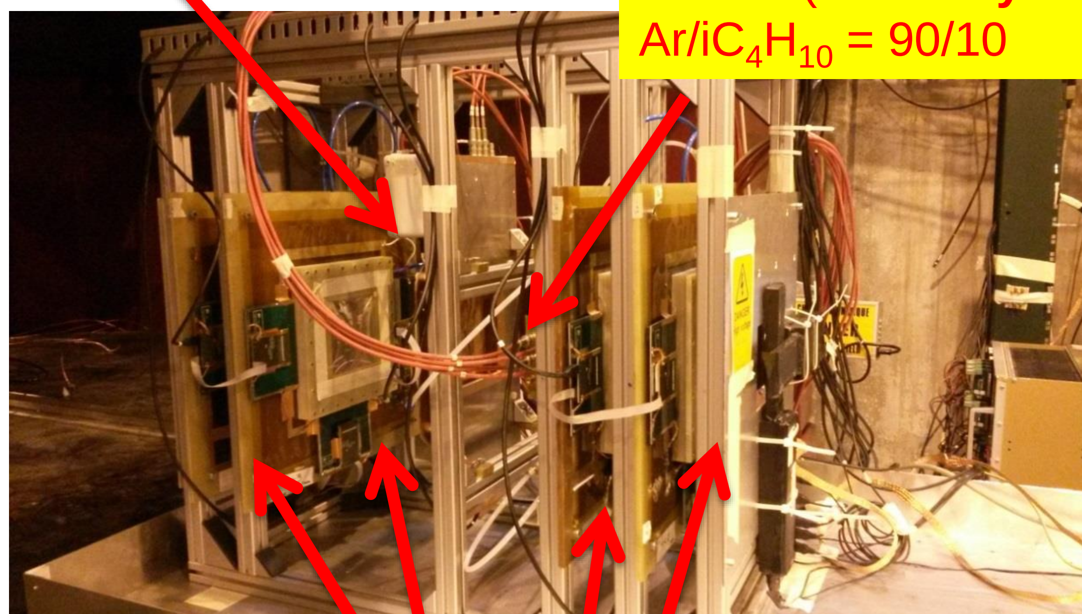
H4 Beam Area (RD51)
Muon beam momentum: 150 GeV/c
Goliath: B up to 1.4 T

μ-RWELL prototype
12-80-880 MΩ /□
400 μm pitch strips
APV25 (**CC analysis**)
Ar/iC$_4$H$_{10}$ = 90/10

BES III-GEM chambers

σ_{RWELL} = (52+-6) μm
@ B= 0T after TRKs
contribution subtraction



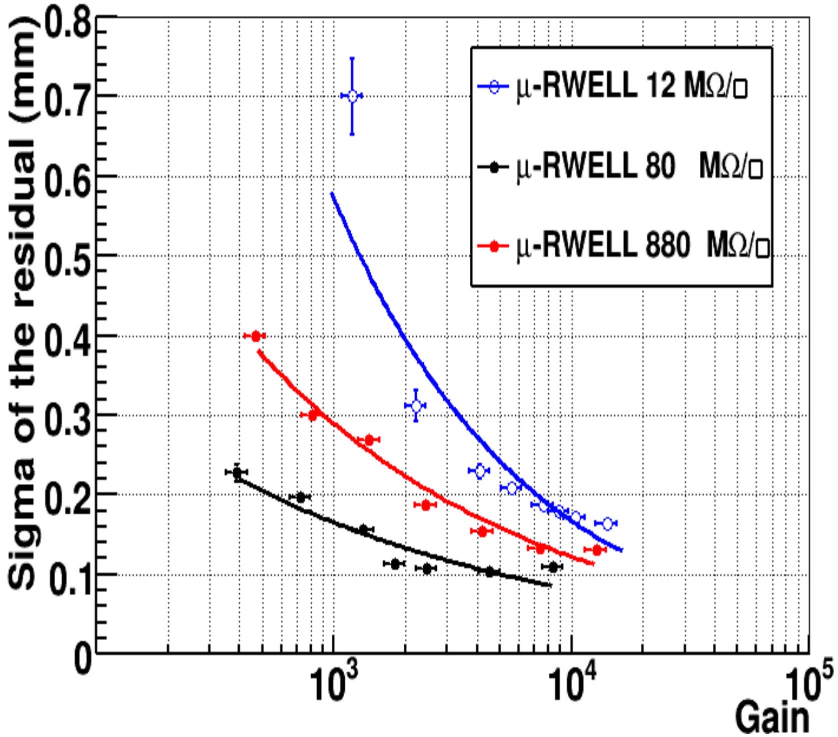


GEMs Trackers

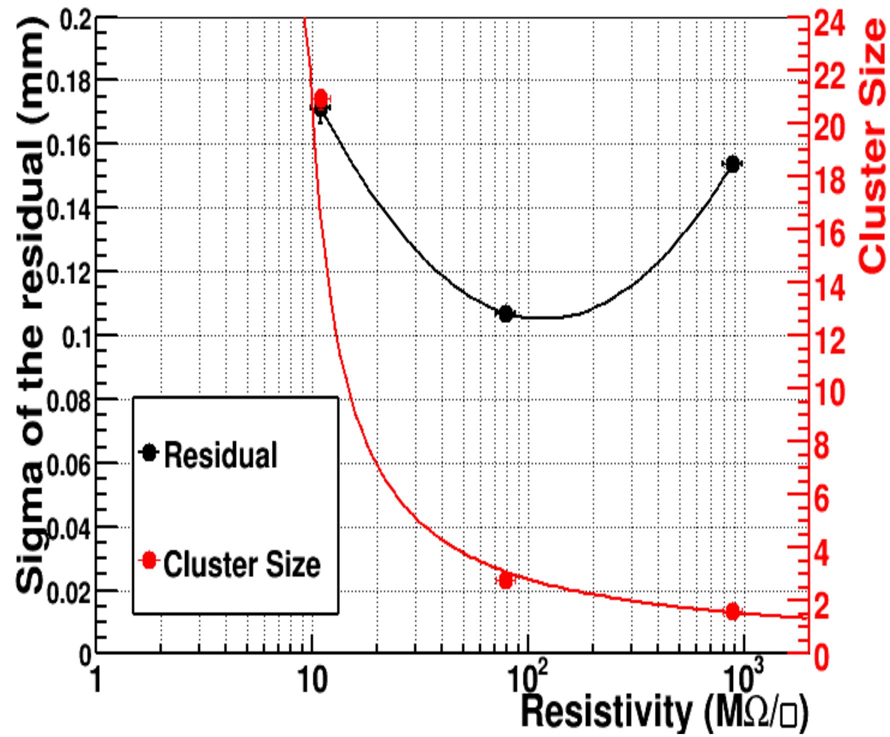
Space resolution: orthogonal tracks

CC analysis

Ar/ISO=90/10



Ar/ISO=90/10



The **space resolution** exhibits a **minimum around 100MΩ/□.**

At **low resistivity** the **charge spread increases** and then **σ is worsening.**

At **high resistivity** the **charge spread is too small (Cl_size → 1)** then the Charge Centroid method becomes no more effective **(σ → pitch/√12).**

Towards detector industrialization (LR scheme)

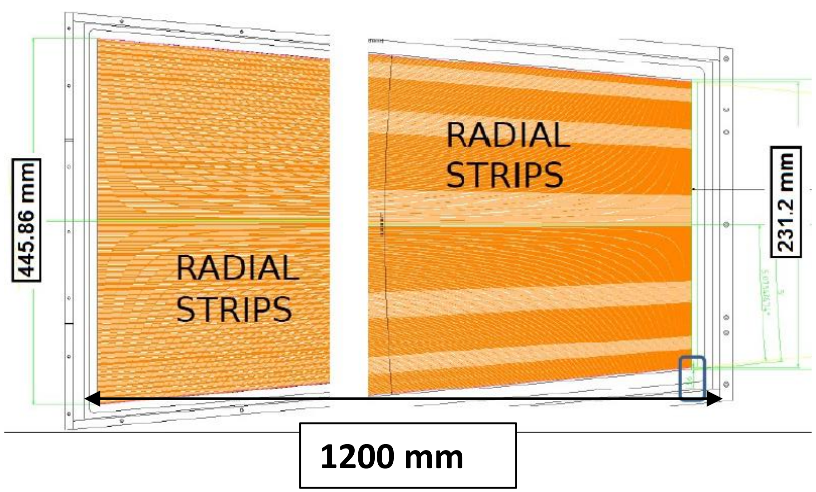
Towards detector industrialization (I)
LR scheme

In the framework of the **CMS-phase2 muon upgrade** we are developing **large size μ-RWELL**. The **R&D** is performed in strict collaboration with Italian industrial partners (**ELTOS & MDT**). The work will be performed in **two years** with following schedule:

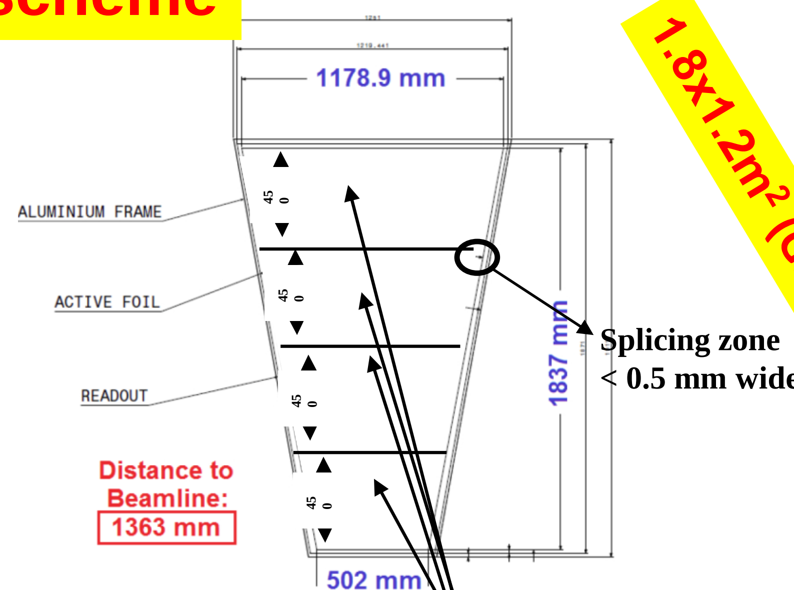
1. Construction & test of the first **$1.2x0.5m^2$ (GE1/1) μ-RWELL** **2016**
2. Mechanical study and mock-up of 1.8x1.2 m^2 (GE2/1) μ-RWELL **12/2016**
3. Construction & test of the first **$1.8x1.2m^2$ (GE2/1) μ-RWELL** **12/2017- 6/2018**

LR scheme

$1.2x0.5m^2$ (GE1/1) μ-RWELL



$1.8x1.2m^2$ (GE2/1) μ-RWELL



Four PCB μ-RWELL spliced with the same technique used for large ATLAS MM + only one cathode closing the detector

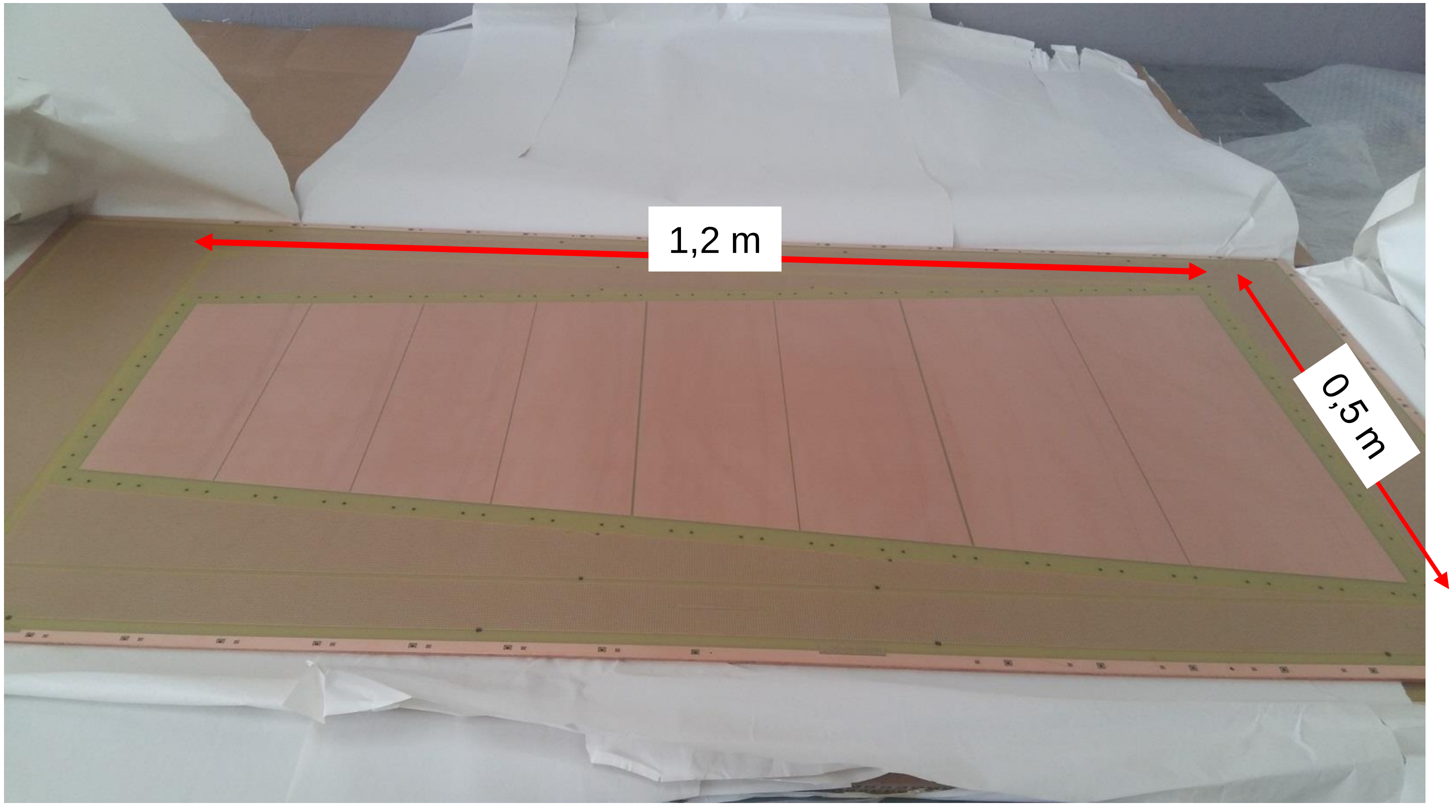
Towards detector industrialization (II) (LR scheme)

Principal actors: LNF(Gatta) – Be-Sputter Co Ltd (Ochi) – ELTOS – MDT – CERN (Rui)

- **G1/1 μ-RWELL design @ LNF (M.Gatta)**
- **GE1/1 – PCB-readout manufactured by ELTOS**
- **DLC sputtering on large Kapton foils (w/copper on one side) @ Be-Sputter Co., Ltd (Japan), supervised by A.Ochi**
- **gluing the DLCed foils on the readout -PCBs @ MDT**
- **etching of the kapton foils to produce the WELL-pattern @ CERN**

Readout-PCB production @ ELTOS

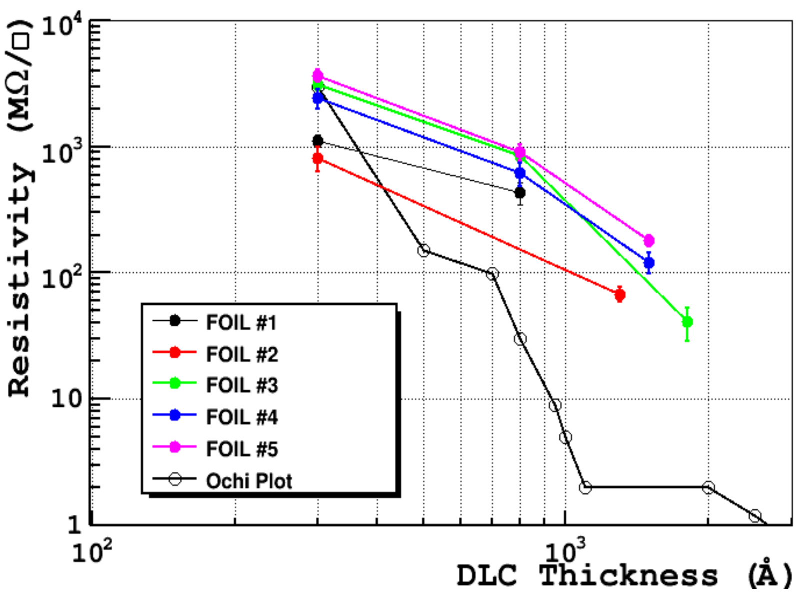
✓ GE1/1 – PCB-readouts manufatured at ELTOS



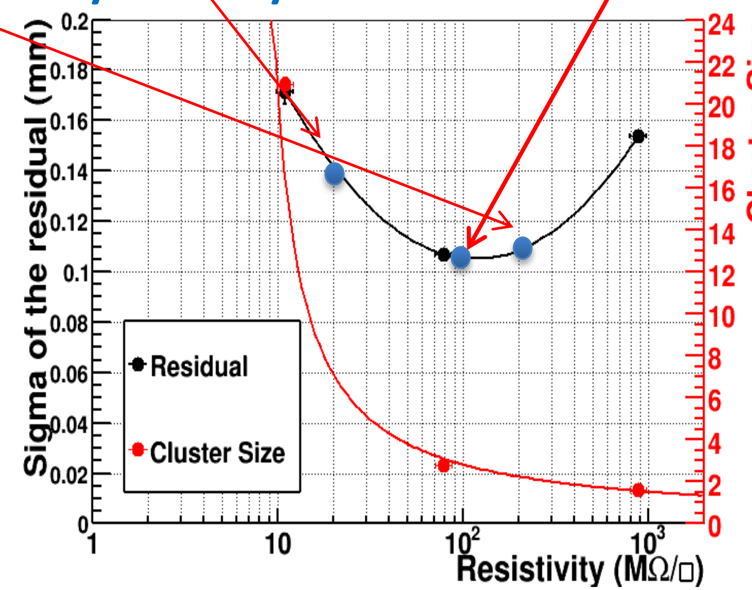
DLC sputtering on Kapton foils (supervised by A.Ochi)

✓ DLC sputtering on large Kapton foils (w/copper on one side) completed @ Be-Sputter Co., Ltd (Japan)

	Foil 1 (800A)	Foil 2 (1300A)	Foil 3 (1800A)	Foil 4 (1500A)	Foil 5 (1500A)
Average Surface Resistivity MΩ/□	433±90	68±9	41±12	122±22	180±17

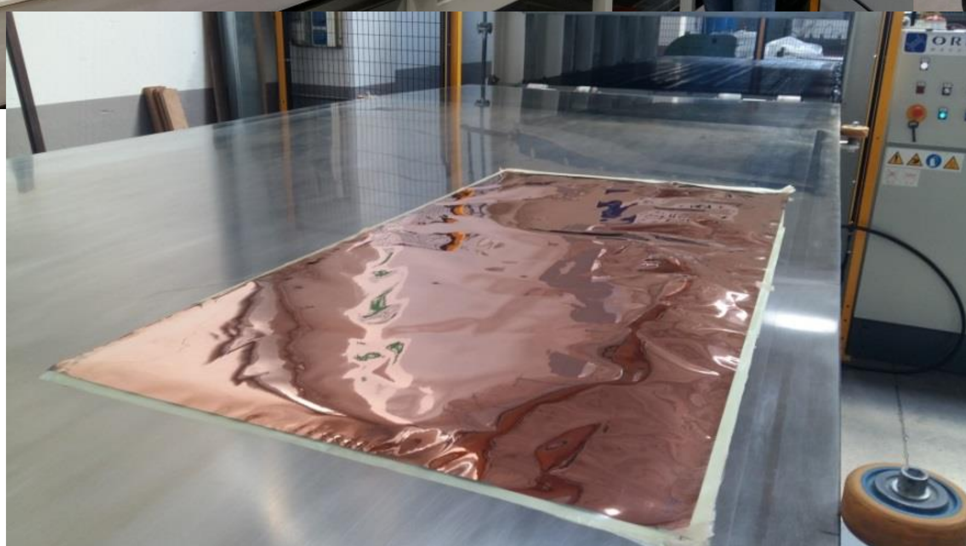


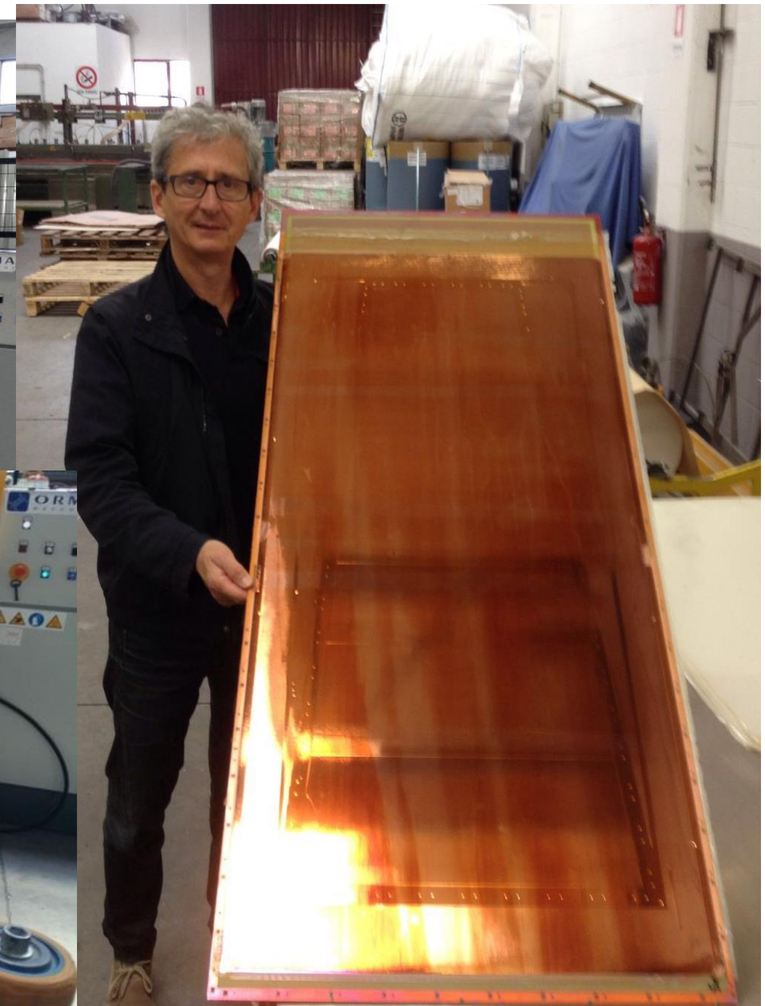
Ar/ISO=90/10



Coupling the DLCed Kapton with r/o-PCBs

✓ **gluing the DLCed foils on the readout -PCBs @ MDT**



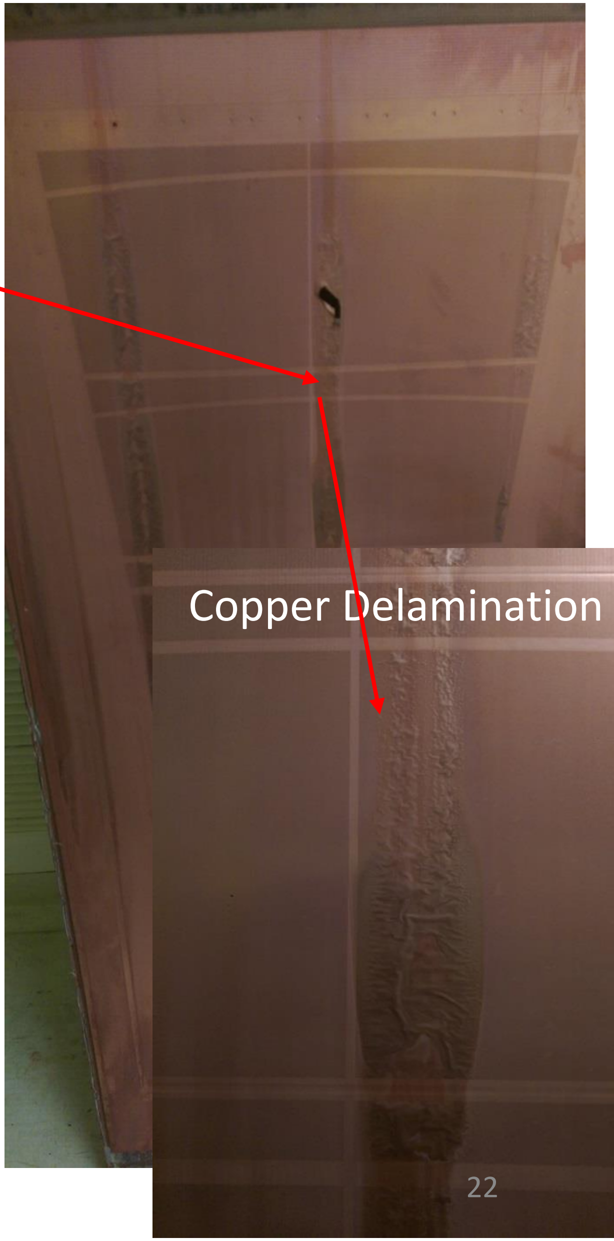


GE1-1 μ-RWELL etching @ CERN

The final copper/Kapton etching done @ CERN

- the ***etching on small DLC samples was perfect:*** after 10 minutes the holes were around 50 microns.
- the ***etching on the CMS μ-RWELL was not good***: during the kapton etching, the ***copper started to delaminate after 2 min,*** which means that copper adherence has been compromised:

→ the ELTOS, by mistake, has "scratched" the surface (in a "sanding-machine", just after the MDT pressing) and the copper adhesion on the kapton has been damaged.



Rui is trying to solve the problem as follows:

i. ***mechanically polishing one of the PCB in order to remove the kapton and the pre-preg down to the metal strips level (recovering one PCB)***
ii. ***etching a spare DLCed kapton foil (not damaged by ELTOS – glued on a pre-preg support last June)***
iii. ***gluing the DLCed kapton foil on the recovered PCB (@ LNF by vacuum bag tech.)***

Towards detector industrialization (III) (LR scheme)

The µ-RWELL manufacturing steps

Present	Future (?)
Detector design: LNF – Italy	Detector design: LNF – Italy
DLC sputtering: Be-Sputter – Japan	DLC sputtering: Be-Sputter – Japan
PCB manufacturing: ELTOS – Italy	**PCB manufacturing: ELTOS – Italy**
PCB – Kapton foil gluing: MDT – Italy	**PCB – Kapton gluing: ELTOS – Italy**
Cu/kapton etching: Rui's Work. – CERN	**Cu/kapton etching: ELTOS – Italy (?)**

ELTOS or another Company able to work on both rigid and flex …

Industrialization of the HR scheme

The ***HR scheme*** requires for a ***double kapton layer sandwich:***

- the **first** layer for the ***amplification stage*** and the ***first resistive layer***
- the **second** layer for the ***second resistive layer***

The ***two resistive layers*** must be connected one to each other by means a ***pattern of through-vias (1 cm^2 pitch).***

The ***second resistive layer*** is ***grounded*** through the readout electrodes by means ***conductive-vias (1 cm^2 pitch).***

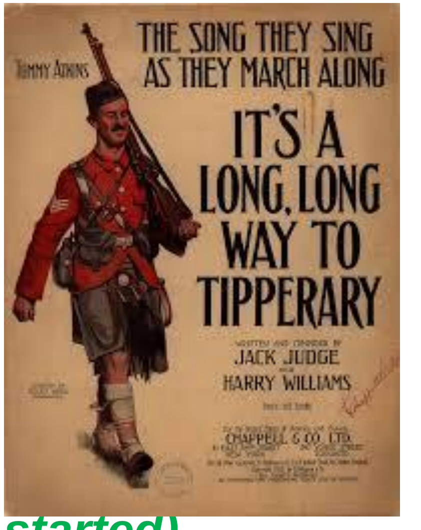
The other component is the ***readout board*****,** a standard PCB.

The ***industrialization*** of such a version of µ-RWELL clearly requires for a ***Company able to work on both flexible and rigid substrate (…)***

Summary & Outlook

The **μ-RWELL is a compact, simple to assemble & suitable for large area, MPGD:**

- ✓ **gas gain ~10^4**
- ✓ **intrinsically spark protected**
- ✓ **rate capability ~1 MHz/cm^2 for m.i.p (*with HR scheme*)**
- ✓ **space resolution < 60μm**

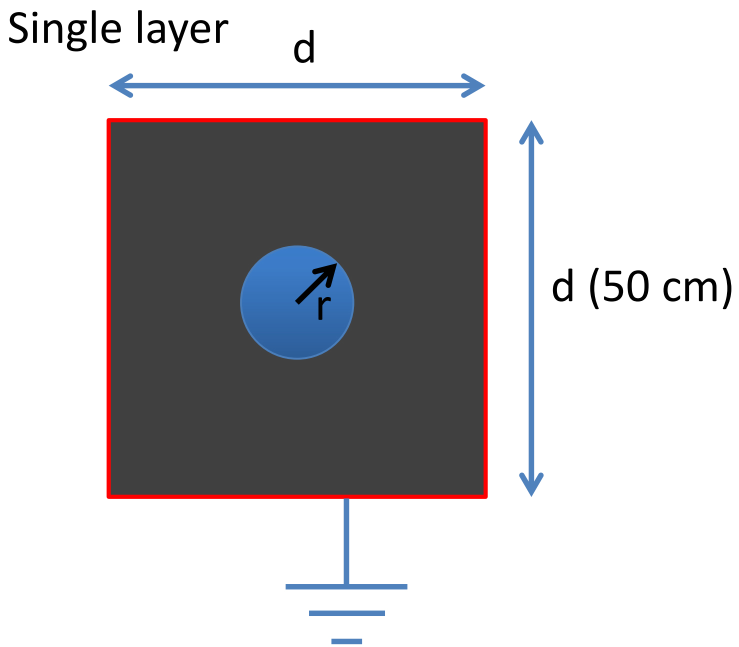


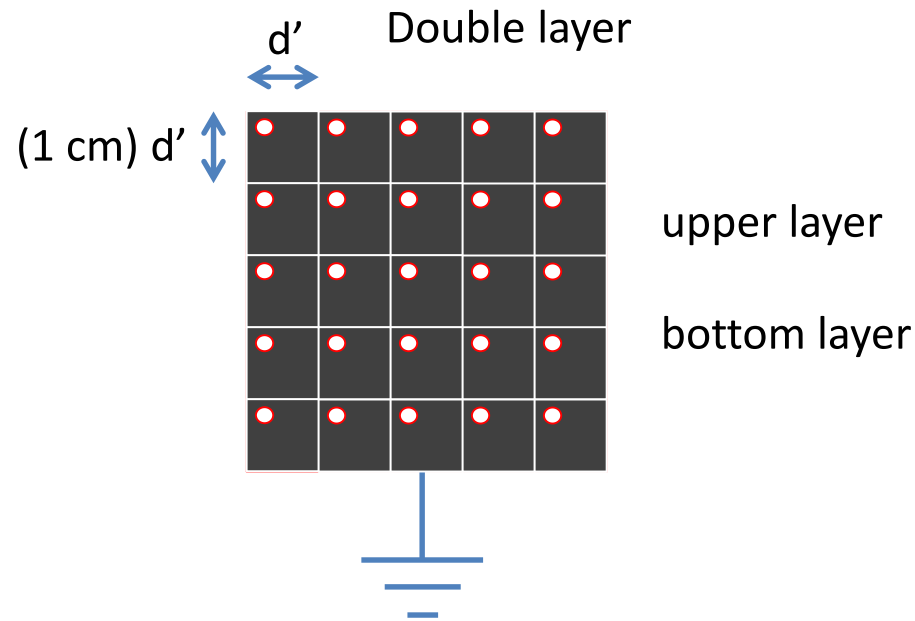
Lot of work/R&D still in progress:

- ***large area (CMS, SHIP) with LR scheme (industrialization started)***
- ***HR scheme (LHCb) with double resistive layer (looking for industrial partner …)***
- ***large gain w/125μm thick WELL amplification stage (work in progress w/Rui)***

SPARE SLIDES

The two detector schemes (II)





(*) point-like irradiation

$\Omega \sim \rho_s \text{ x } d/2\pi r$ $\qquad$ $\Omega' \sim \rho_s' \text{ x } d'/\pi r$

$$\Omega/\Omega' \sim (\rho_s/\rho_s') \text{ x } d/2d'$$

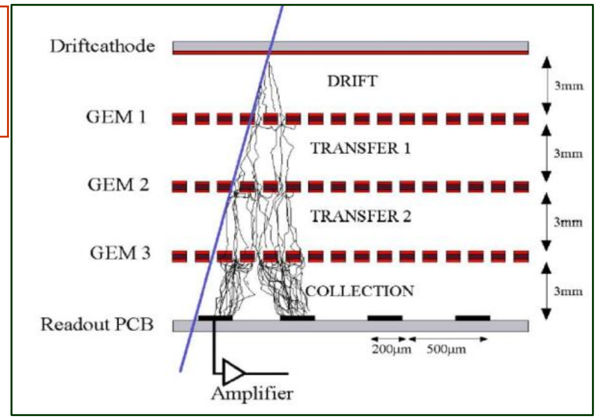
$$\text{If } \rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim d/2d' = 25$$

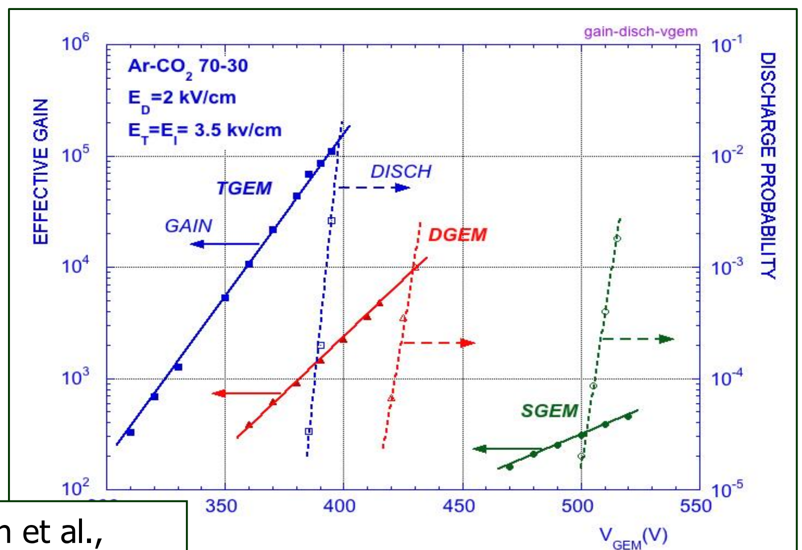
(*) Morello’s model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)

GEMs: stability

The biggest enemy of MPGDs are the discharges ➔ due to **the fine structure** and the **typical micrometric distance between their electrodes**, the occasional occurrence of **heavily ionizing particles** may trigger **local breakdowns** that can eventually damage the detector and/or the related readout electronics

GEM





with multiple structures the discharge probability is strongly reduced **but not completely suppressed**

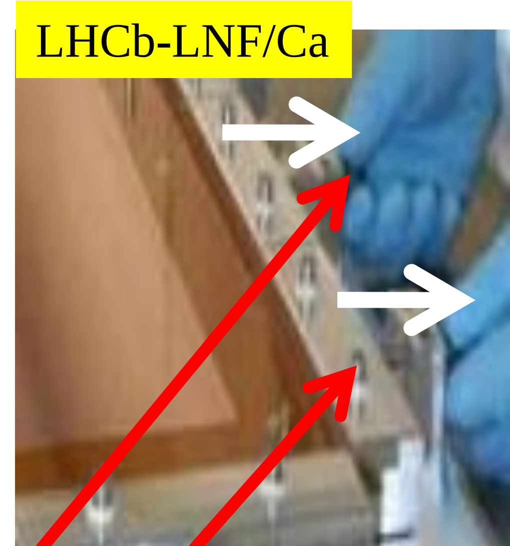
S. Bachmann et al., NIMA A479(2002) 294

GEM detector currently running @ HEP

Experiment	Instrumented area (m^2)	Gas Mixture	Gain	Flux (MHz/cm^2)	HV-type	# lost sector for shorts	% damaged area	Front-End Electronics
COMPASS	2	Ar/CO_2	4000	<1	HV passive divider	???		APV25
LHCb	0.6	$Ar/CO_2/CF_4$	8000	1	HV active divider	5 (All on GEM #1)	1%	CARIOCA-GEM
TOTEM	0.6	Ar/CO_2	8000	<1	HV passive divider	6	percent level	VFAT2
KLOE2	4	$Ar/i\text{-}C_4H_{10}$	12000	0,01	7 independent ch; then active divider	61 (8 GEM#1, 28 GEM#2, 25 GEM#3)	5%	GASTONE

A damaged GEM sector could required for the replacing of a whole a detector gap !!

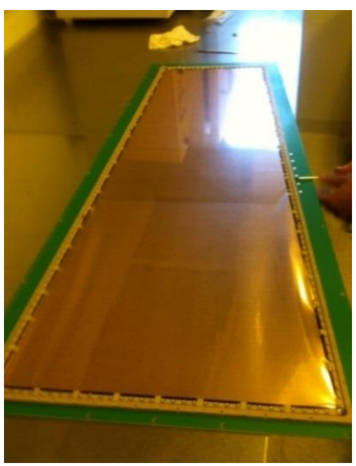
GEMs: the construction challenge



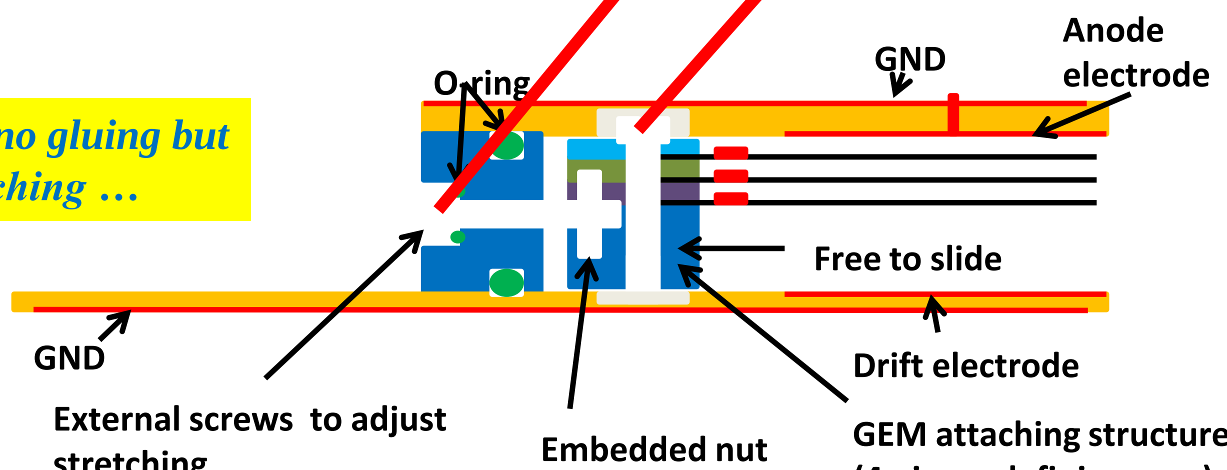
The construction of the GEM requires some assembly steps such as **the stretching of the 3 GEM foils,** with a quite **large mechanical tension** to cope with ➔ **~1 kg/cm**.

Improvements in the GEM construction process has been recently introduced by R. de Oliveira (NS2 detector assembly scheme): **no gluing, no soldering, no spacer in the active area ➔ re-opening of the detector if repairs needed became possible.**

But the GEM construction still remains a demanding & complex operation ➔ requiring delicate stretching with specialized man-power.



NS2(CERN): no gluing but still stretching …



The µ-RWELL: a GEM-MM mixed solution

The **µ-RWELL** has features in common either with **GEMs** or **MMs:**

- **MMs** are realized on **rigid** substrate
- **GEM** on **flex** substrate
- **µ-RWELL** exploits both technologies, **rigid and flexible (**but also **full-flex)**

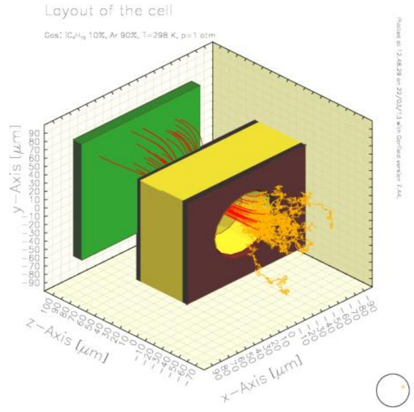
The **µ-RWELL** :

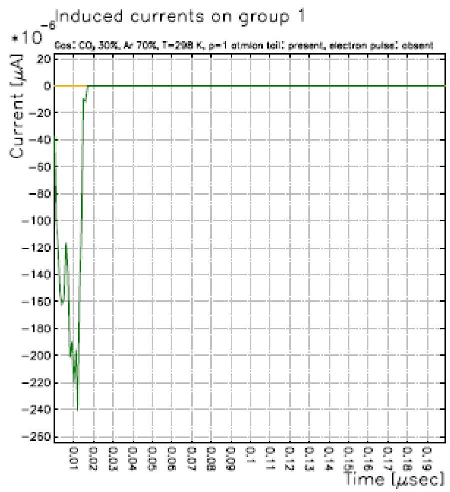
- inherits and improves the **GEM amplifying scheme** with the peculiarity of a "**well defined amplifying gap**", but ensuring **higher and more uniform gas gain,** with no transfer/induction gaps whose non-uniformity can affect the detector gain

- inherits the **MM resistive readout scheme** that allows a "**strong suppression**" of the amplitude of the **discharges.**

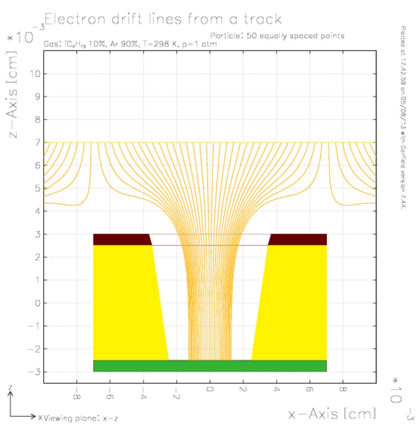
The μ-RWELL vs GEM (Garfield simulation)

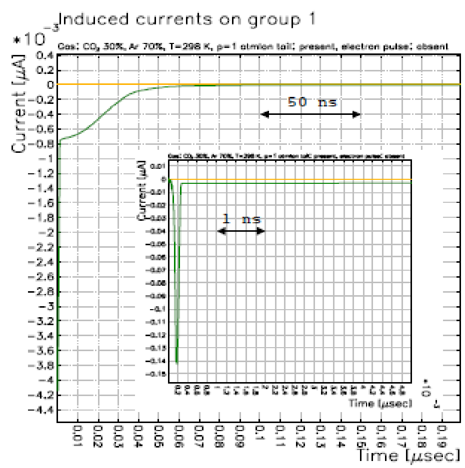
GEM – Ar:CO2 70:30 gas mixture





Signal from a single ionization electron in a GEM.
The duration of the signal, about 20 ns, depends on the induction gap thickness, drift velocity and electric field in the gap.





Signal from a single ionization electron in a μ-RWELL.
The absence of the induction gap is responsible for the fast initial spike, about 200 ps, induced by the motion and fast collection of the electrons and followed by a ~50 ns ion tail.

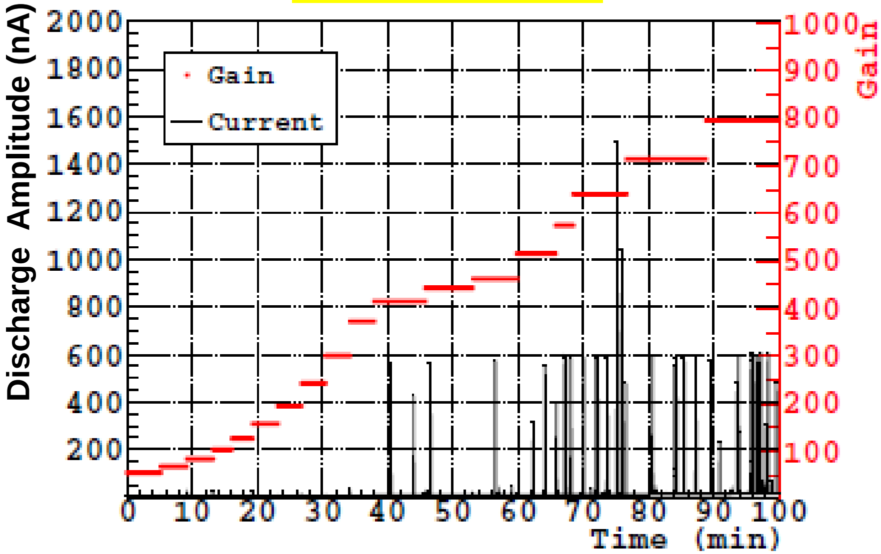
μ-RWELL – Ar:CO2 70:30 gas mixture

Discharges: µ-RWELL vs GEM

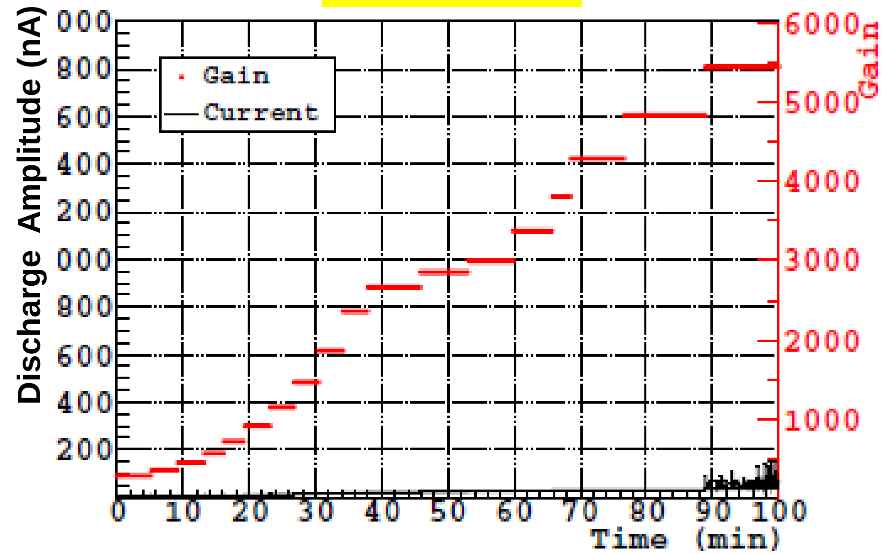
test with X-ray

Ar/CO_2 = 70/30

single-GEM



µ-RWELL



- the **µ-RWELL** detector reaches discharge amplitudes of **few tens of nA, <100 nA @ max gain**

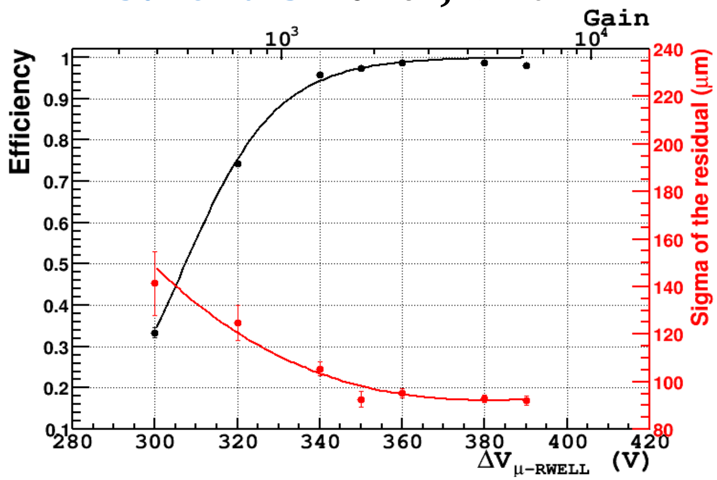
- the **single-GEM** detector reaches discharge amplitudes of **≈ 1µA**
  (of course the discharge rate is lower for a triple-GEM detector)

More quantitative studies must be performed

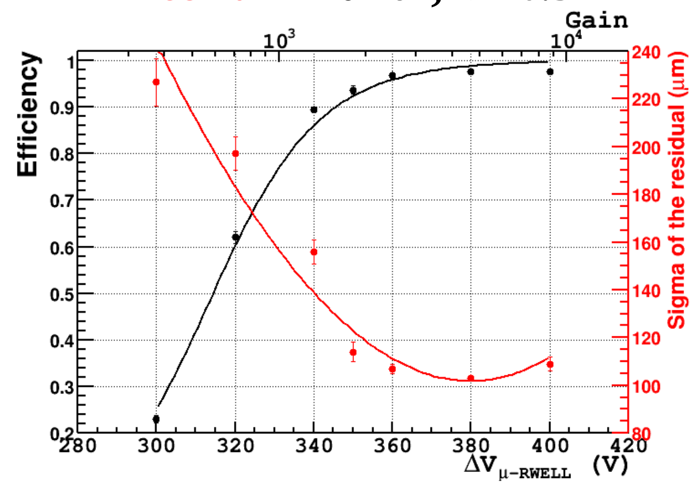
μ-RWELL: B≠0 with Ar/ISO=90/10

CC analysis

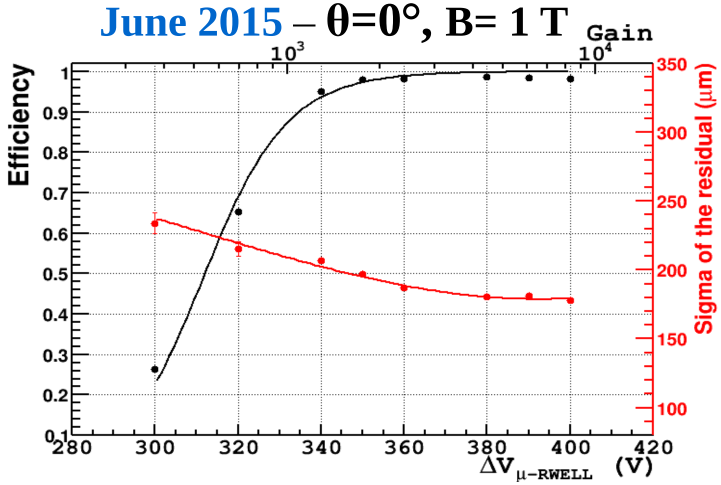
June 2015 – θ=0°, B= 0 T



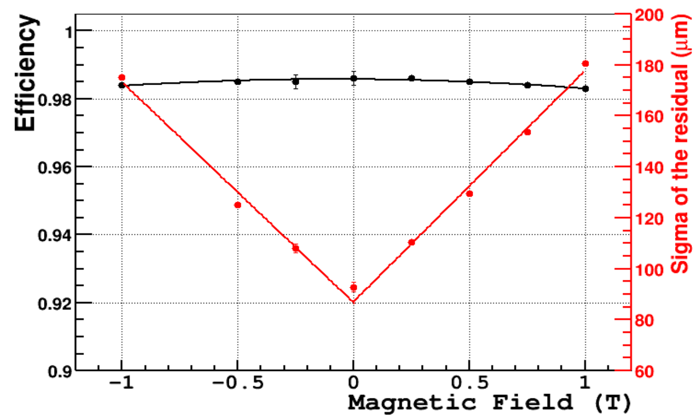
Dec 2014 – θ=0°, B= 0.5 T



June 2015 – θ=0°, B= 1 T



June 2015 - θ=0°

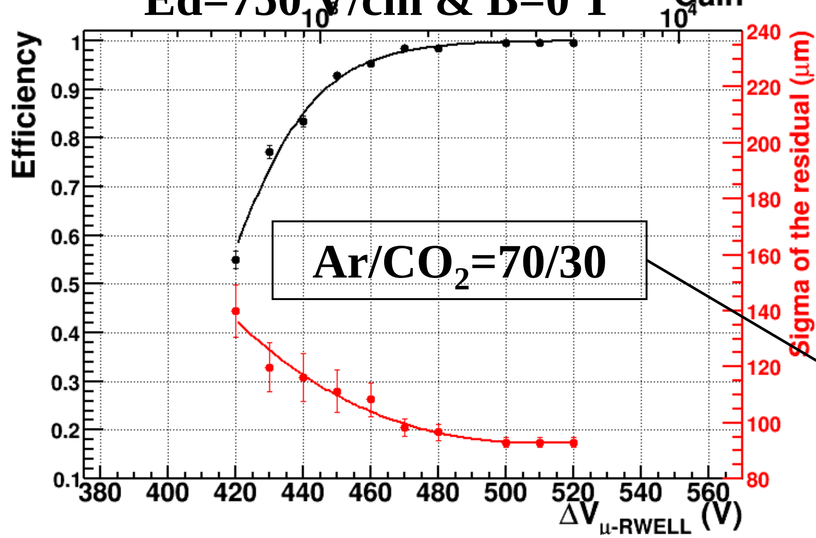


For **θ=0° and 0 < B < 1 T** → **σ < 180 μm** and **ε > 98%**

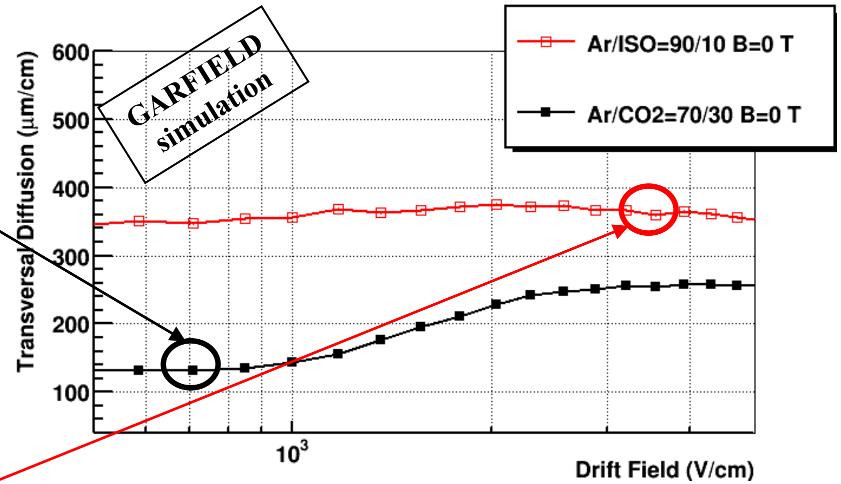
TB June 2015 B=0T & θ=0°
Efficiency & Residual vs gas mixture

σ-Residual w/out TRK subtraction

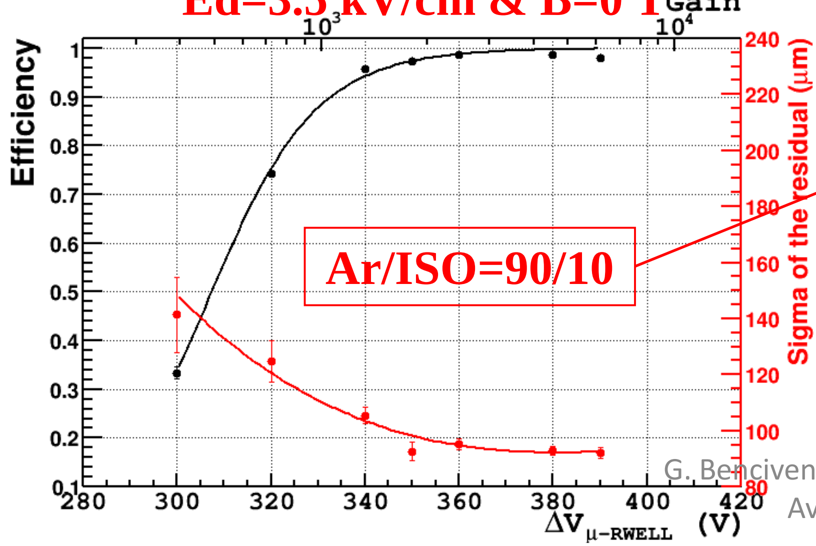
June 2015 – Ar/CO_2=70/30
Ed=750 V/cm & B=0 T



~60 µm on 4 mm gap



June 2015 – Ar/ISO=90/10
Ed=3.5 kV/cm & B=0 T



~ 140 µm on 4 mm gap

No large difference observed between Ar/CO_2 & Ar/ISO due to:

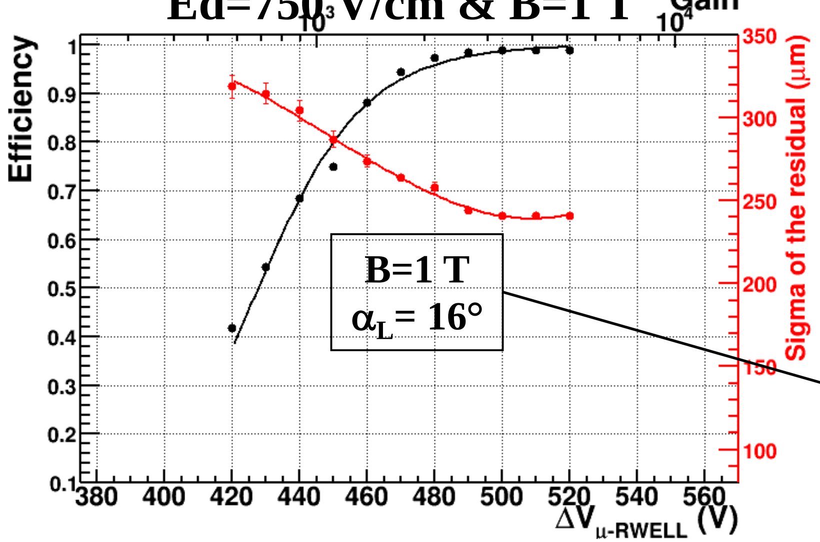
- µ-RWELL compactness
- relatively large strip pitch (400 µm)

TB June 2015, B=1T & θ=0°

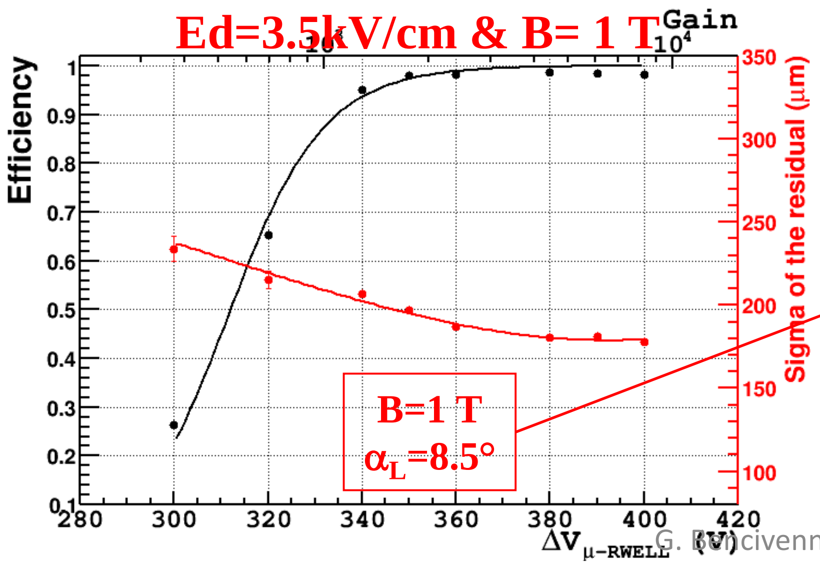
Efficiency & Residual vs gas mixture

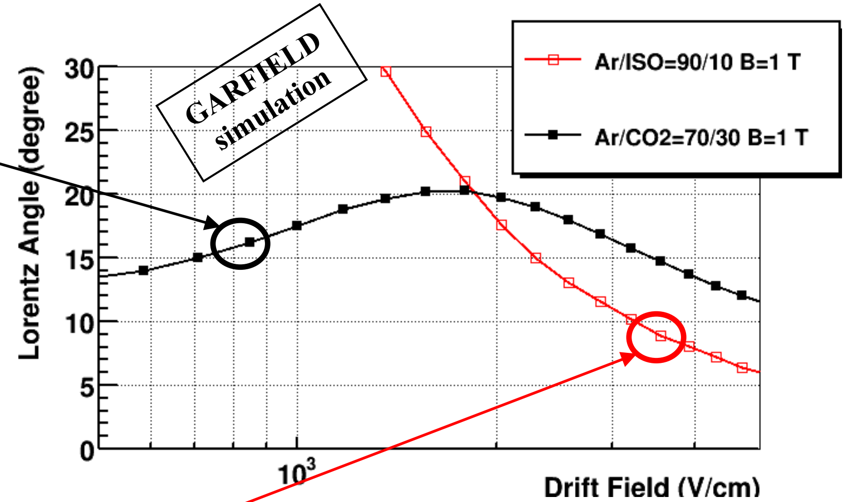
σ-Residual w/out TRK subtraction

Ar/CO_2=70/30
Ed=750 V/cm & B=1 T



Ar/ISO=90/10
Ed=3.5kV/cm & B= 1 T



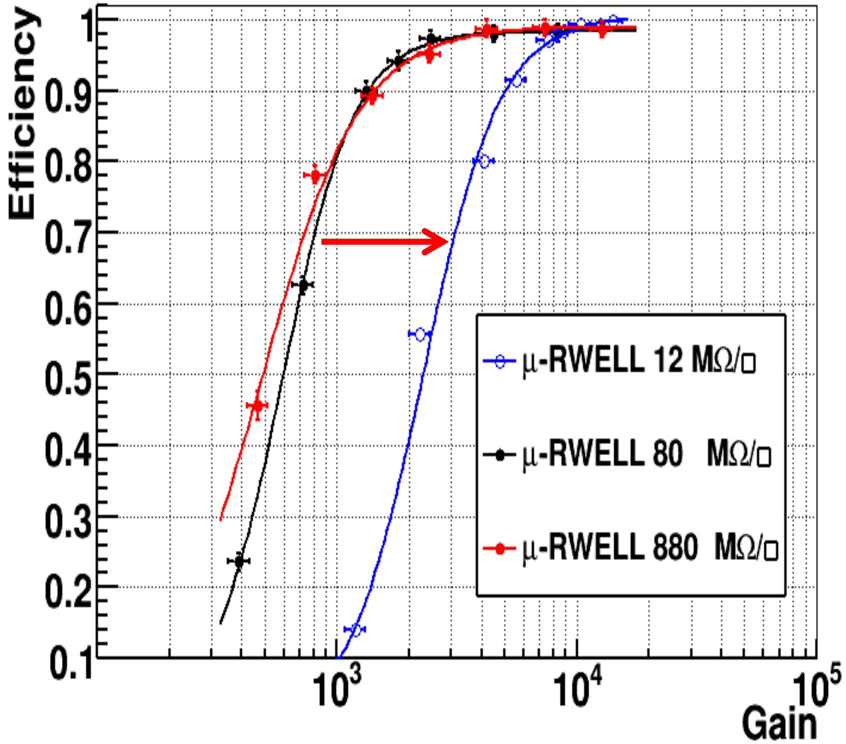


The difference on the residual is probably due to the diverse Lorentz angle

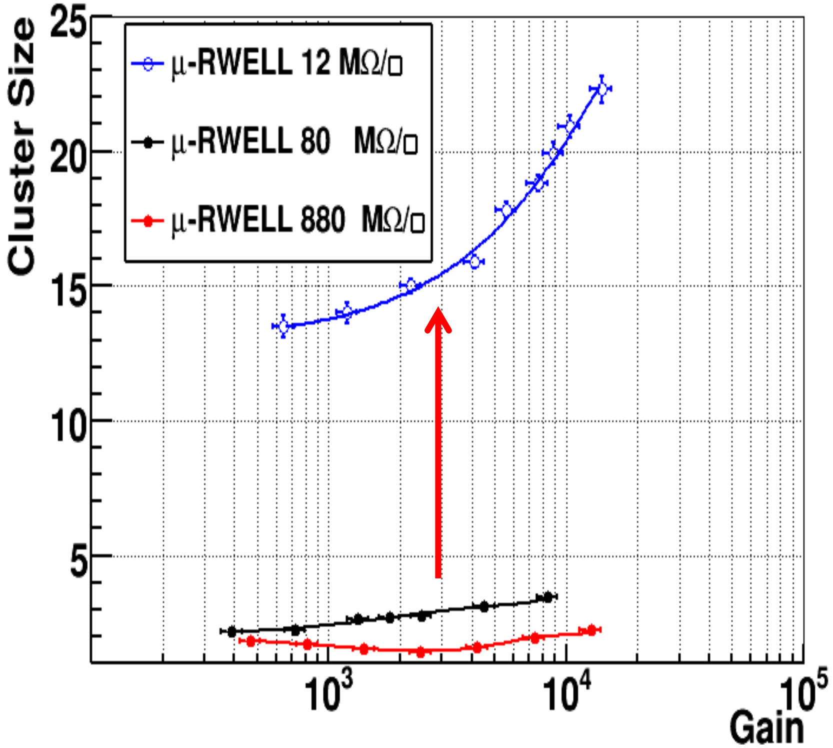
CC analysis

µ-RWELL: tracking efficiency

Ar/ISO=90/10



Ar/ISO=90/10

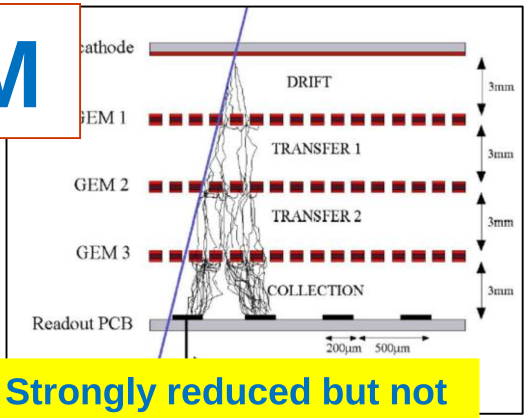


At **low resistivity the spread of the charge** (cluster size) on the readout strips **increases**, thus requiring a **higher gain** to reach the **full detector efficiency.**

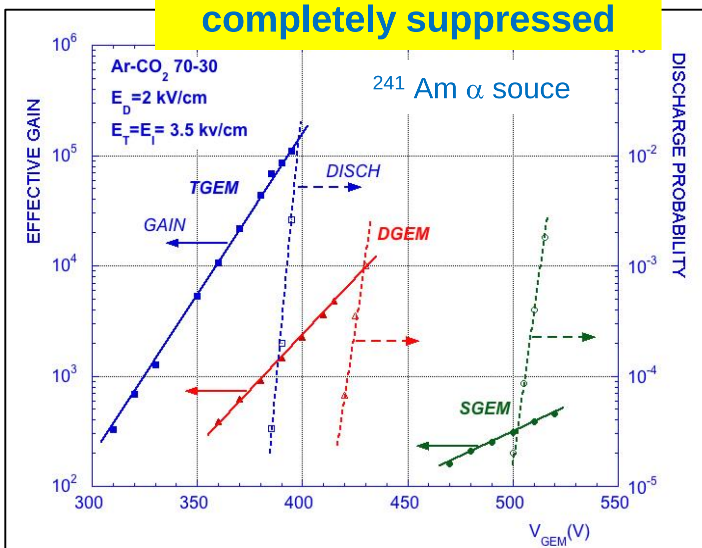
MPGDs: stability

The **biggest “enemy”** of MPGDs are the **discharges.**
Due to the **fine structure** and the **typical micrometric distance of their electrodes**, MPGDs generally suffer from **spark occurrence** that can be **harmful for the detector and the related FEE.**

GEM

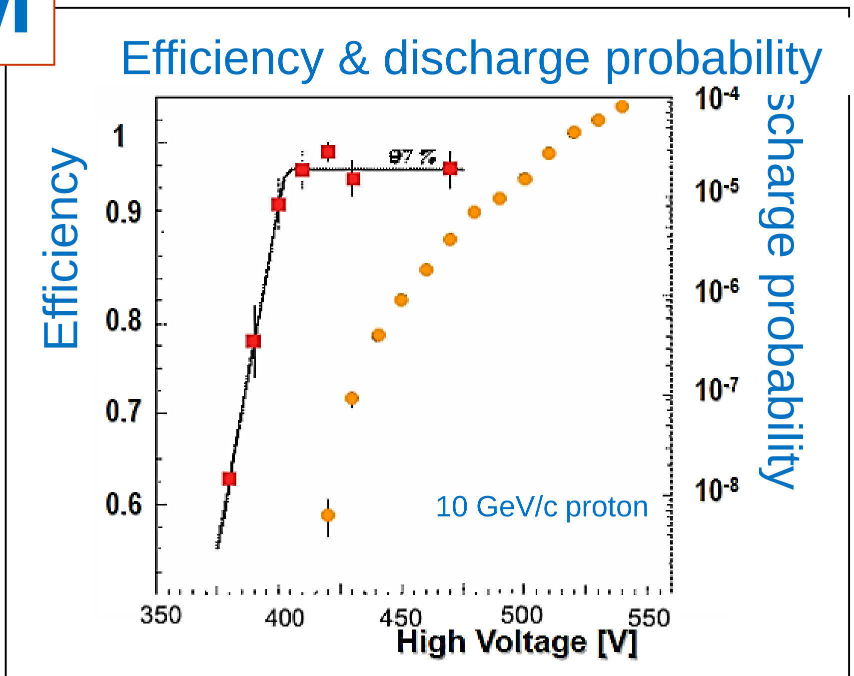


Strongly reduced but not completely suppressed



S. Bachmann et al.,
NIMA A479(2002) 294

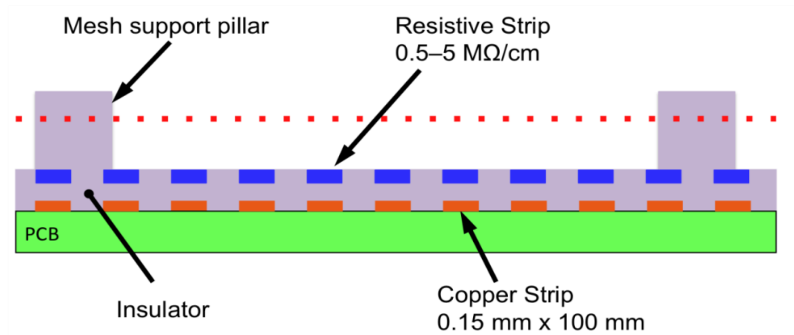
MM



A. Bay et al.,
NIMA 488 (2002) 162

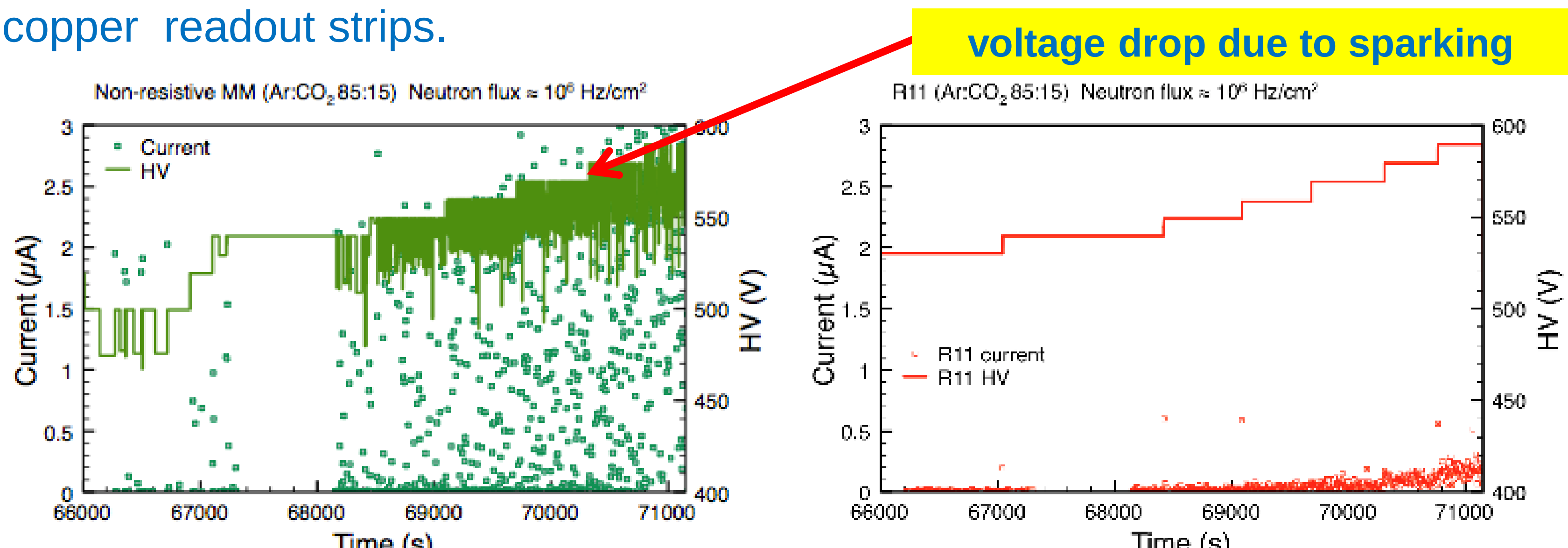
Technology improvement: resistive MPGD

For **MM**, the spark occurrence between the metallic mesh and the readout PCB has been overcome with the **implementation** of **a "resistive layer"** on top of the readout itself . The principle is the **same as the resistive electrode used in the RPCs: the transition from streamer to spark is strongly suppressed by a local voltage drop.**



by R.de Oliveira TE MPE CERN Workshop

The resistive layer is realized as resistive strips capacitive coupled with the copper readout strips.



MPGDs: the challenge of large area

A further **challenge for MPGDs** is the **large area:**

- the construction of a **GEM** requires some time-consuming (/complex) assembly steps such as:
  - the **stretching of the 3 GEM foils** (with quite **large mechanical tension** to cope with, ~1 kg/cm)
  - the **splicing of GEM foils** to realize large surfaces is a **demanding operation** introducing **not negligible dead zones (~3 mm)**. The width of the **raw material is limited to 50-60 cm**.

NS2(CERN): no gluing but still stretching …

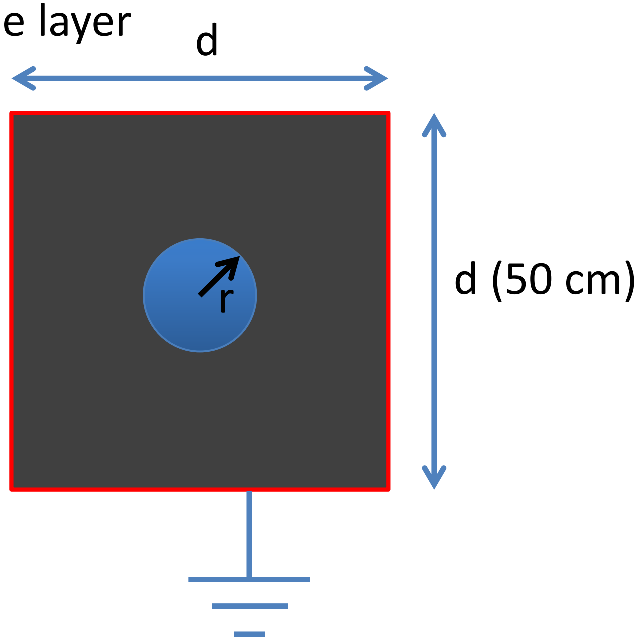
- similar considerations hold for **MM**:
  - ✓ the **splicing of smaller PCBs is possible**, opening the way towards the large area covering (**dead zone of the order 0.3 – 0.5 mm**).
  - The **fine metallic mesh**, defining the amplification gap, is a *“floating component”* stretched on the cathode (~1 kg/cm) and **electrostatically attracted toward the PCB**

→ **Possible source of gain non-uniformity**

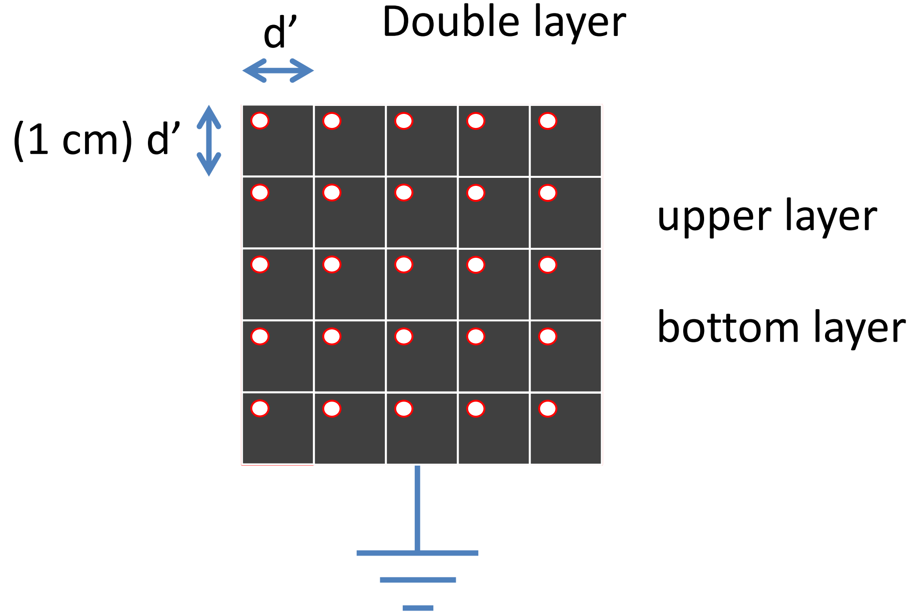
Handling of a stretched mesh

The two detector schemes (II)

Single layer



Double layer



$\Omega \sim \rho_s(d-r)/2\pi r$

$\Omega \sim \rho_s \times d/2\pi r$

since r<<d

$\Omega' \sim 2 \times \rho_s'(d'-r)/2\pi r$

$\Omega' \sim \rho_s' \times d'/\pi r$

$\Omega/\Omega' \sim (\rho_s/\rho_s') \times d/2d'$ (*)for point-like irradiation

If $\rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim d/2d' = 25$

Morello's model: appendix A-B (G. Bencivenni et al., 2015 JINST 10 P02008)