Status of the μ-RWELL technology

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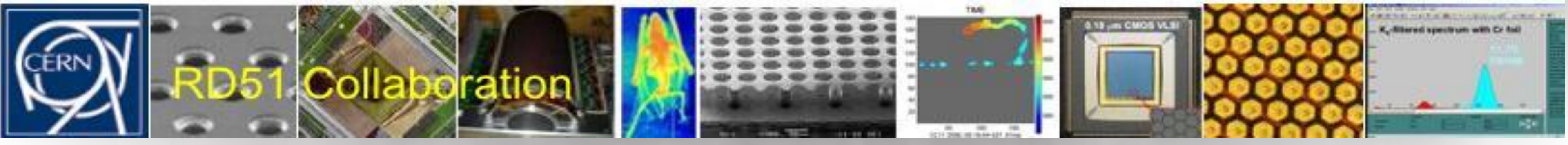


OUTLINE

- Introduction
- Detector architecture & principle of operation
- Low rate: the single resistive layer layout
    - performance & Technology Transfer to Industry
- High rate: layouts design & performance
- Improving space resolution
- Summary

The motivations for a new MPGD

The **R&D on μ-RWELL** aim for a **step-forward** in the MPGD world **in terms of**

- **stability under heavy irradiation (discharge suppression)**
- **simplified construction/assembly**
- **technology transfer to industry (mass production)**

a MUST for very large scale applications in fundamental research at the future colliders as well as for technology dissemination beyond HEP

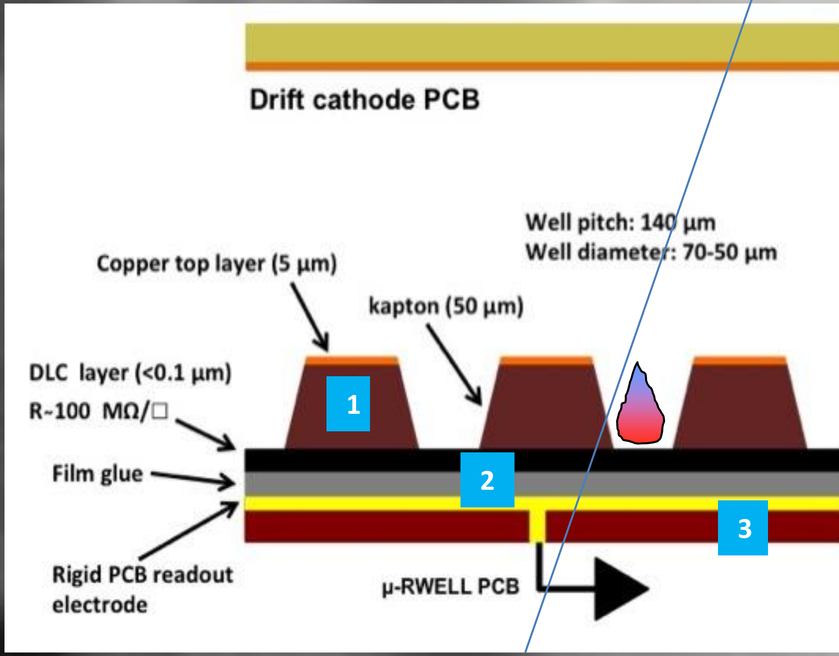
The original idea was conceived in 2009 @ LNF during the construction of the CGEM, to try to find a way to simplifying as much as possible the construction of the CGEM and its toolings. Only in the 2014 we really started a systematic study of this new technology in collaboration with CERN (Rui de Oliveira)

The µ-RWELL: the detector architecture

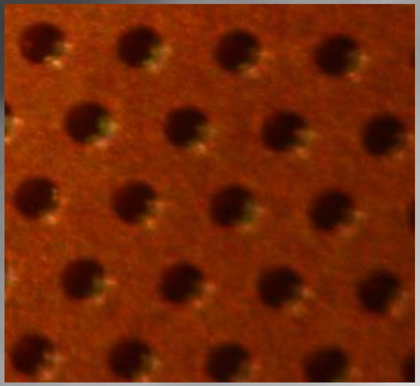
The µ-RWELL is composed of only two elements: the **µ-RWELL_PCB** and the **cathode**

The **µ-RWELL_PCB, the core of the detector,** is realized by **coupling:**

1. a **WELL patterned kapton foil** as **amplification stage**
2. a **resistive layer (*)** for discharge suppression & current evacuation:
   - i. **Single resistive layer (SRL) <100 kHz/cm²:** surface resistivity ~100 MΩ/□(SHiP, CepC, Novosisbirsk, EIC, HIEPA)
   - ii. **Double resistive layer (DRL) >1 MHz/cm²**: for LHCb-Muon upgrade & future colliders (CepC, Fcc-ee/hh)
3. a **standard readout PCB**



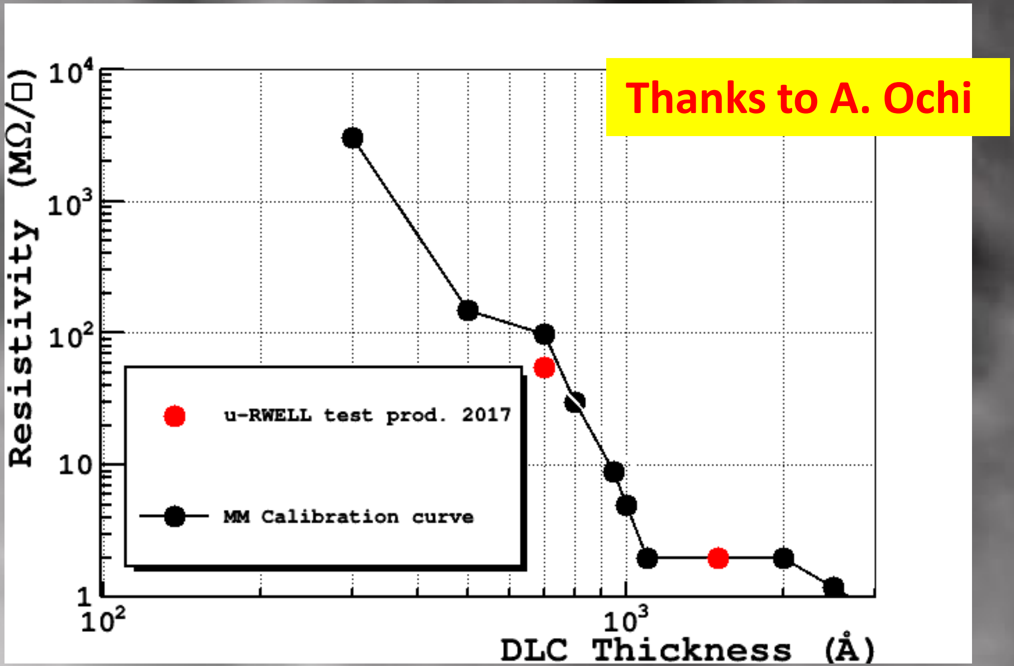
(*) DLC = Diamond Like Carbon
highly mechanical & chemical resistant



The resistive layer: DLC sputtering

The **kapton foil,** copper etched on one side, **is sputtered with DLC** (by **Be-Sputter Co., Ltd. in Japan)**. Simultaneous sputtering of 6 foils (1.2x0.6 m^2) per production batch is possible.

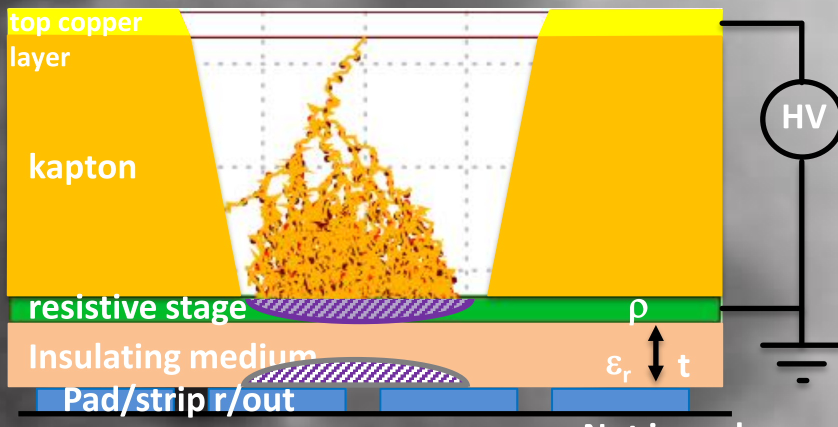
The **resistivity depends** on several manufacturing conditions, but can be parametrized as function of the **DLC thickness**. The resistivity uniformity is at level of 10-20%.



In parallel a profitable collaboration with Zhou Yi and Jianbei Liu from USTC – Hefei (PRC) for the manufacturing of improved DLC foils, has been recently started.

Principle of operation

Applying a suitable voltage between **top copper layer and DLC** the "**WELL**" **acts as multiplication channel for the ionization.**



The charge induced on the resistive foil is dispersed with a ***time constant, τ = ρC ,*** determined by:

- the **DLC surface resistivity, ρ**
- the **capacitance per unit area,** which depends on the **distance between the resistive foil and the pad/strip readout plane, t**
- the **dielectric constant** of the insulating medium, 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**
- 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 (see High Rate scheme)**

μ-RWELL vs GEM & MM

	μ-RWELL	GEM	MM
# electrodes/components	2	5	3
# amplification stage	1 (*)	3	1(*)
PCB splicing for large area	YES	NO	YES but not for mesh
Cleaning	easy	Very easy	YES-but not easy
Assembly	very easy	complex	simplest than GEM
Stretching	NO	YESx3	YES (mesh)
HV	2 chs - easy	7 floating chs	2 chs - easy
Technology Transfer → cost-effective mass production	easy	-	YES-but not for mesh
Discharge protection	high	medium	high
Rate capability	medium	Very high	medium

(*) amplification stage resistively coupled with readout

The Low Rate Layout

single resistive layer w/edge grounding

1


Copper layer 5 µm

Kapton layer 50 µm

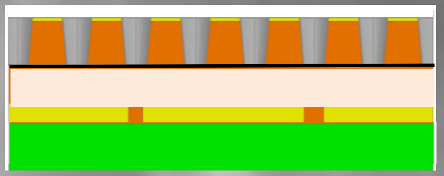
DLC layer: 0.1-0.2 µm (10-200 MΩ/□)

2


DLC-coated kapton base material

Insulating medium (50 µm)

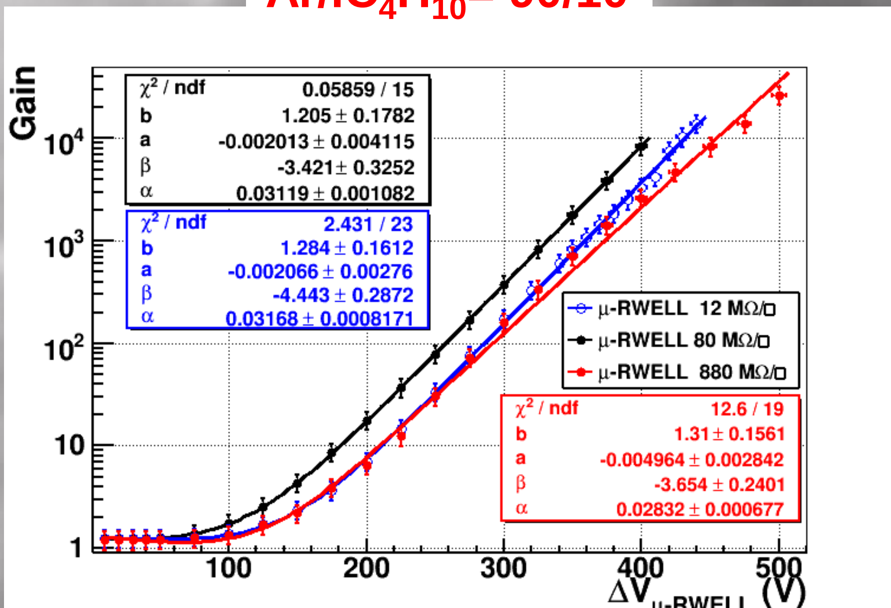
PCB (1.6 mm)

3


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

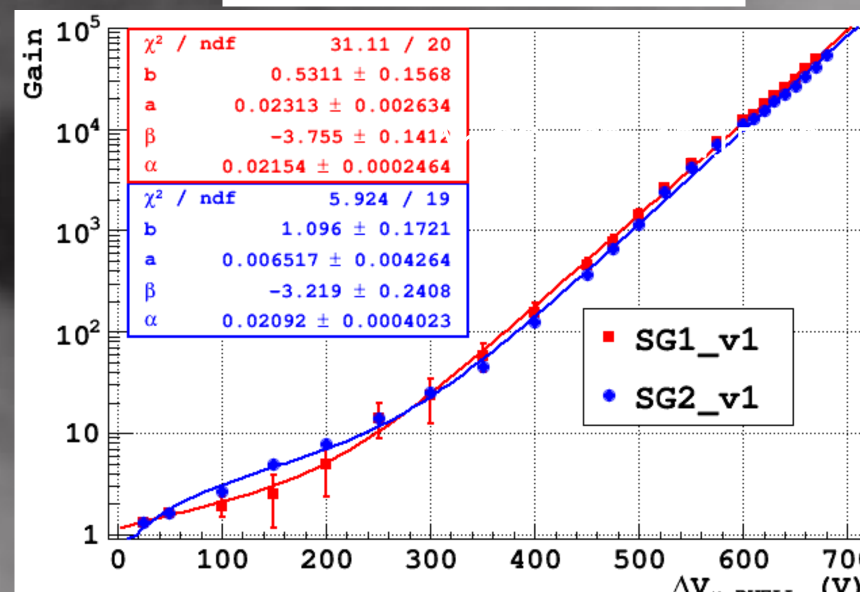
Detector Gain

Ar/iC$_4$H$_{10}$= 90/10



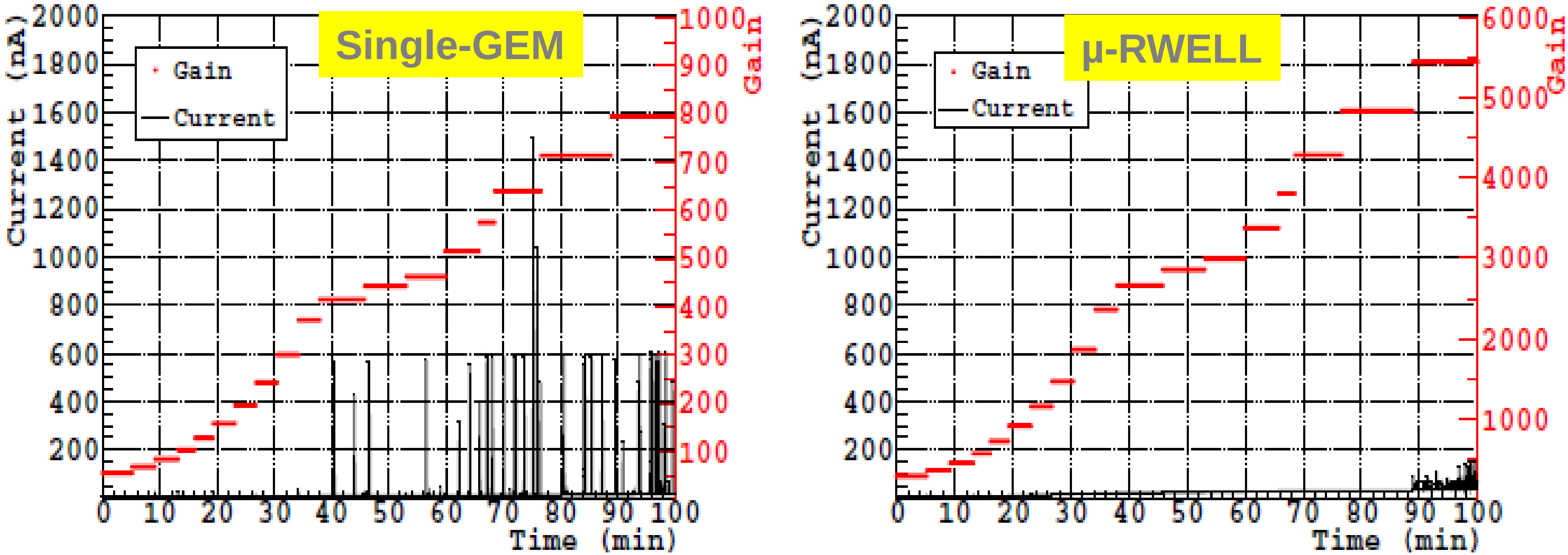
Single Resistive Layer prototypes with different resistivity have been tested with **X-Rays** (5.9 keV), with several gas mixtures, and characterized by measuring the **gas gain** in **current mode**.

Ar/CO$_2$/CF$_4$= 45/15/40



Recent prototypes achieved Gain ~10^5 in Ar/CO$_2$/CF$_4$= 45/15/40

Discharge study: µ-RWELL vs GEM

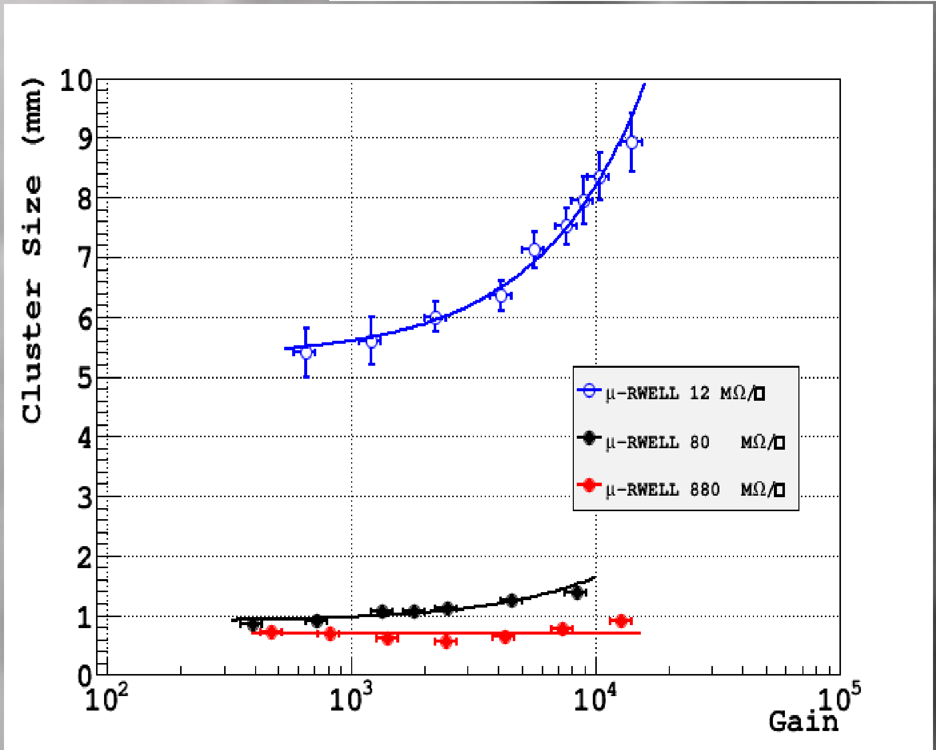


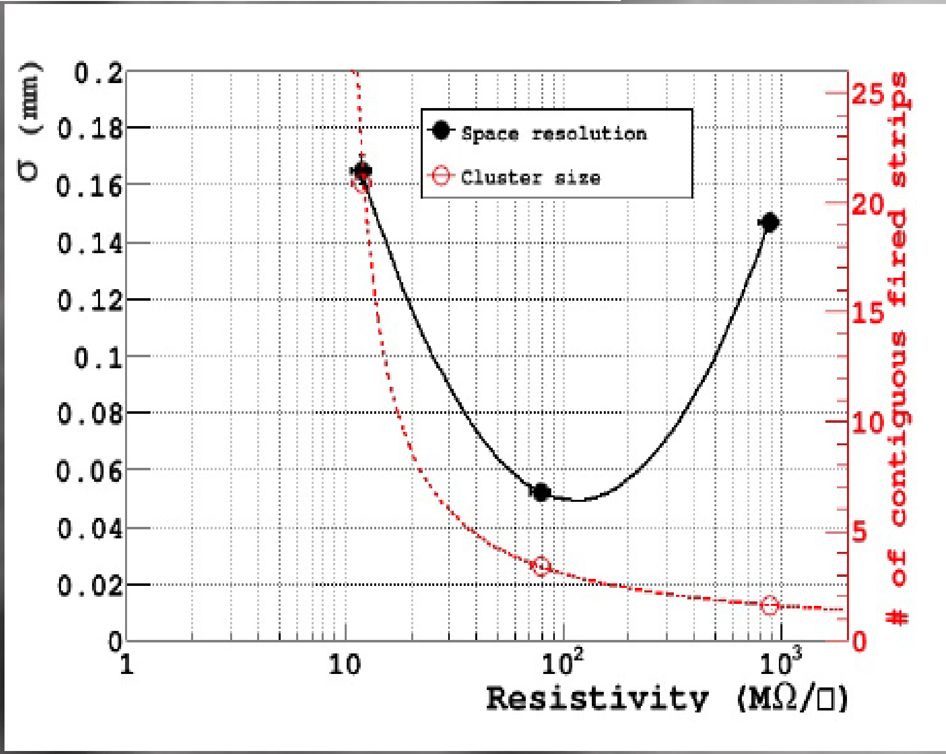
- discharges for µ-RWELL are of the order of few tens of nA (<100 nA @ high gain)
- for GEM discharges the order of 1µA are observed at high gas gain

Test campaign with alpha particles and low energy protons at PSI planned in the next months

Space resolution *vs* DLC resistivity

Charge Centroid analysis (orthogonal tracks)





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

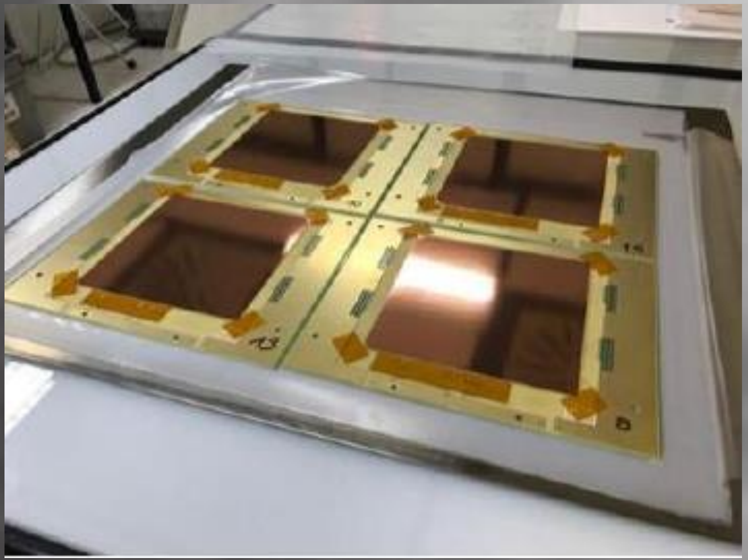
→ at **low resistivity** the **charge spread increases** and then **σ is worsening**

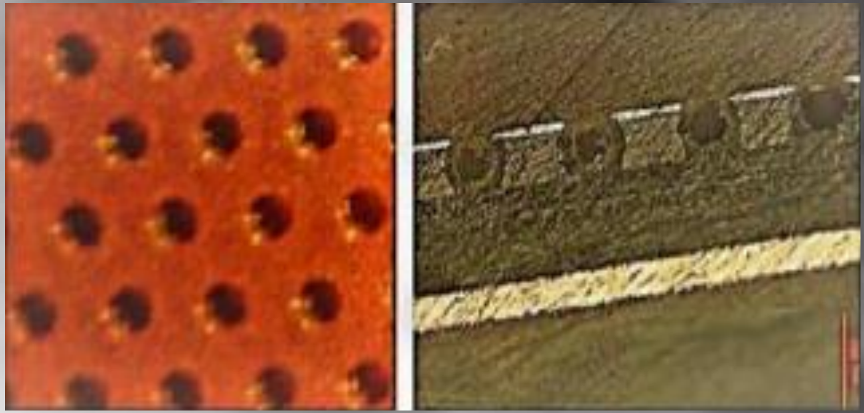
→ at **high resistivity** the **charge spread is too small (Cluster-size → 1 fired strip)** then the **Charge Centroid method** becomes **no more effective (σ → pitch/√12)**

Technology Transfer to Industry (I)

The **engineering and industrialization** of the μ-RWELL technology is one of the **main goal of the project**.
TT to industry can open the way towards **cost-effective mass production.**

Manufacturing process of the **<u>single resistive layer</u> has been extensively tested at the ELTOS SpA (http://www.eltos.it)**





Production Test @ ELTOS:
- **10x10 cm2 PCB – uRWELL (PAD r/o)**
- **10x10 cm2 PCB – uRWELL (strip r/o) coupled with kapton/DLC foils**

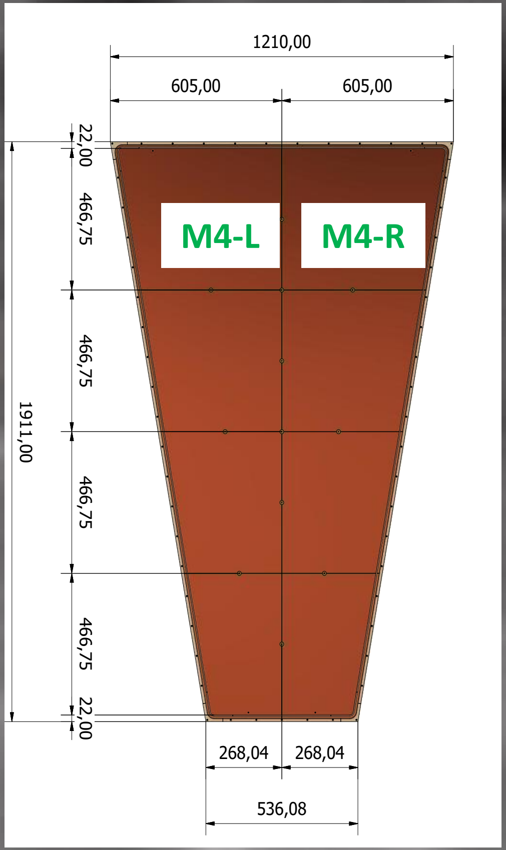
The etching of the kapton STILL done by Rui (CERN)

Technology Transfer to Industry (II)

In the framework of the **CMS-phase2 muon upgrade** different prototypes of **large size single-resisitive layer μ-RWELLs** have been **built at ELTOS**:

- **1.2x0.5m² μ-RWELL**
- **1.9x1.2m² μ-RWELL**

1.2x0.5m² (GE1/1) μ-RWELL

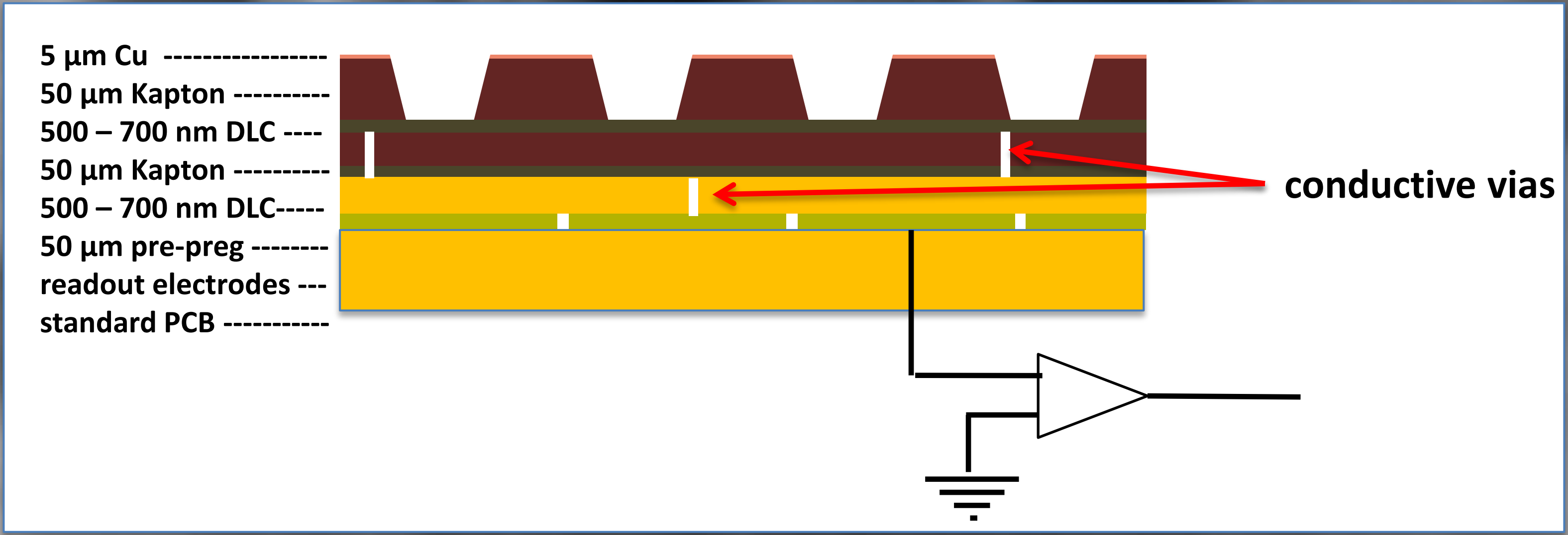


1.9x1.2m² (GE2/1) μ-RWELL

1st High rate layout: the double-resistive layer

The **idea is to reduce the path of the current on the DLC surface implementing** a **matrix of conductive vias** connecting **two stacked resistive layers.** A second **matrix of vias** connects the **second resistive layer to ground** through the readout electrodes.

The **pitch of the vias is typically of the order 1/cm²** (or less).

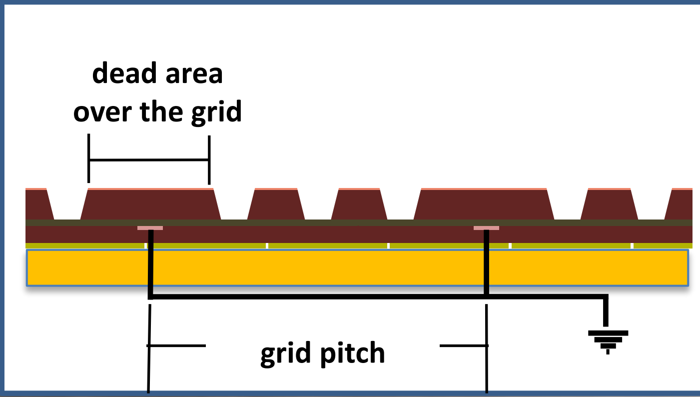


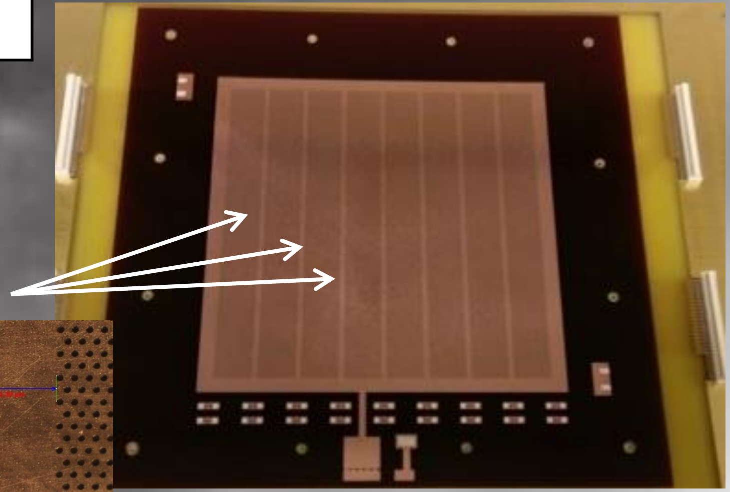
WARNING: The **engineering/industrialization of the double-resistive** layer is **difficult** due to the **manufacturing of the conductive vias on kapton foil.**

New ideas for the HR layout

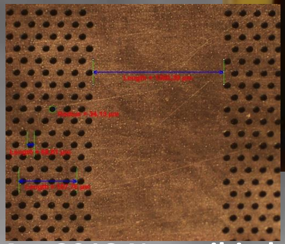
Two new simplified grounding schemes are now under study, both based on **Single Resistive Layout**: **silver grid & resistive grid (for the moment) screen printed on the DLC side.**

High Rate layout	Resistivity [MΩ/□]	Dead Area over grid	Grid Pitch	Geometrical acceptance [%]	Type
Silver Grid 1 (SG1)	60-70	2 mm	6 mm	66	conductive grid
Silver Grid 2 (SG2)	60-70	1,2 mm	12 mm	90	conductive grid
Resistive Grid (RG)	60-70	-	6 mm	Full	resistive grid

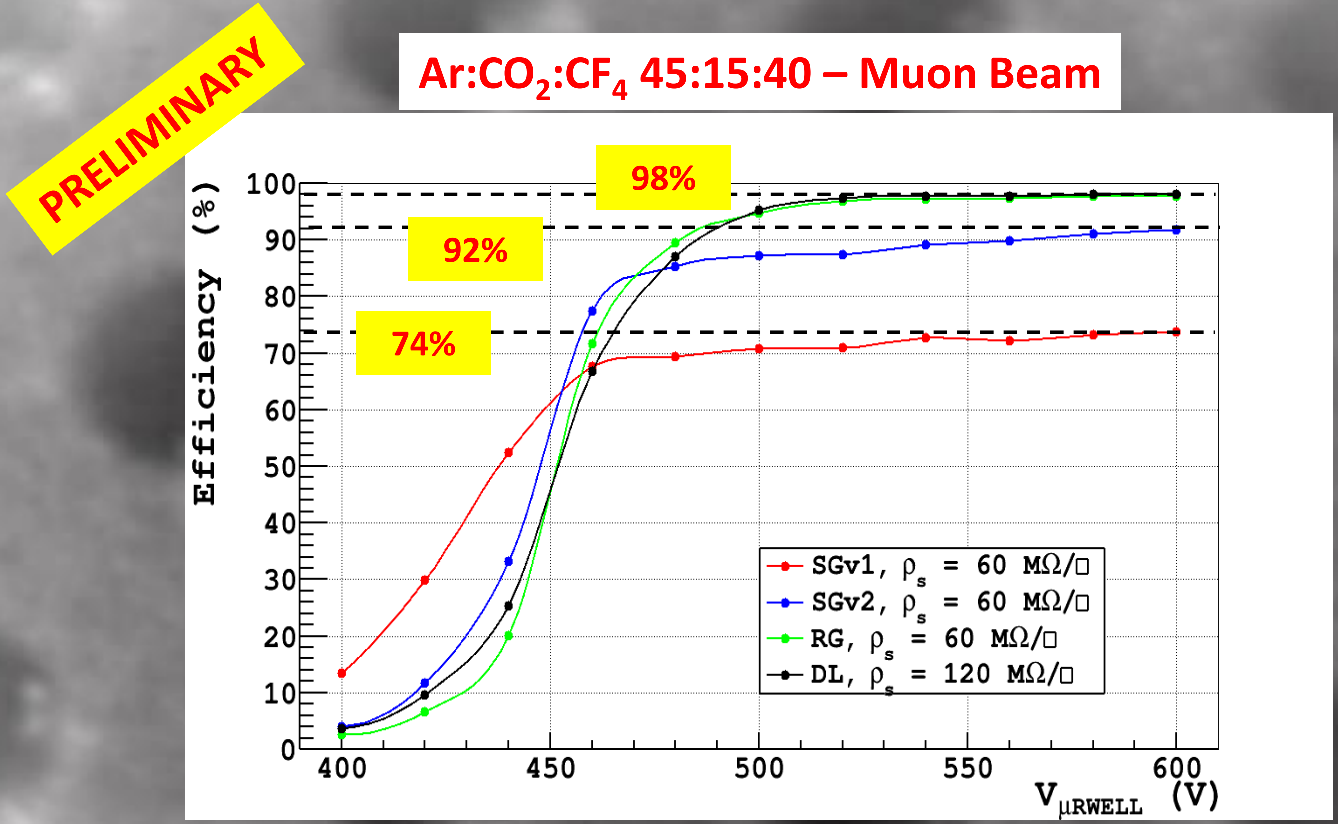




The **conductive grid** on the bottom of the amplification stage **can induce instabilities due to discharges over the DLC surface, thus requiring for the introduction of a dead zone on the amplification stage.**
This is not the case for the resistive grid layout.



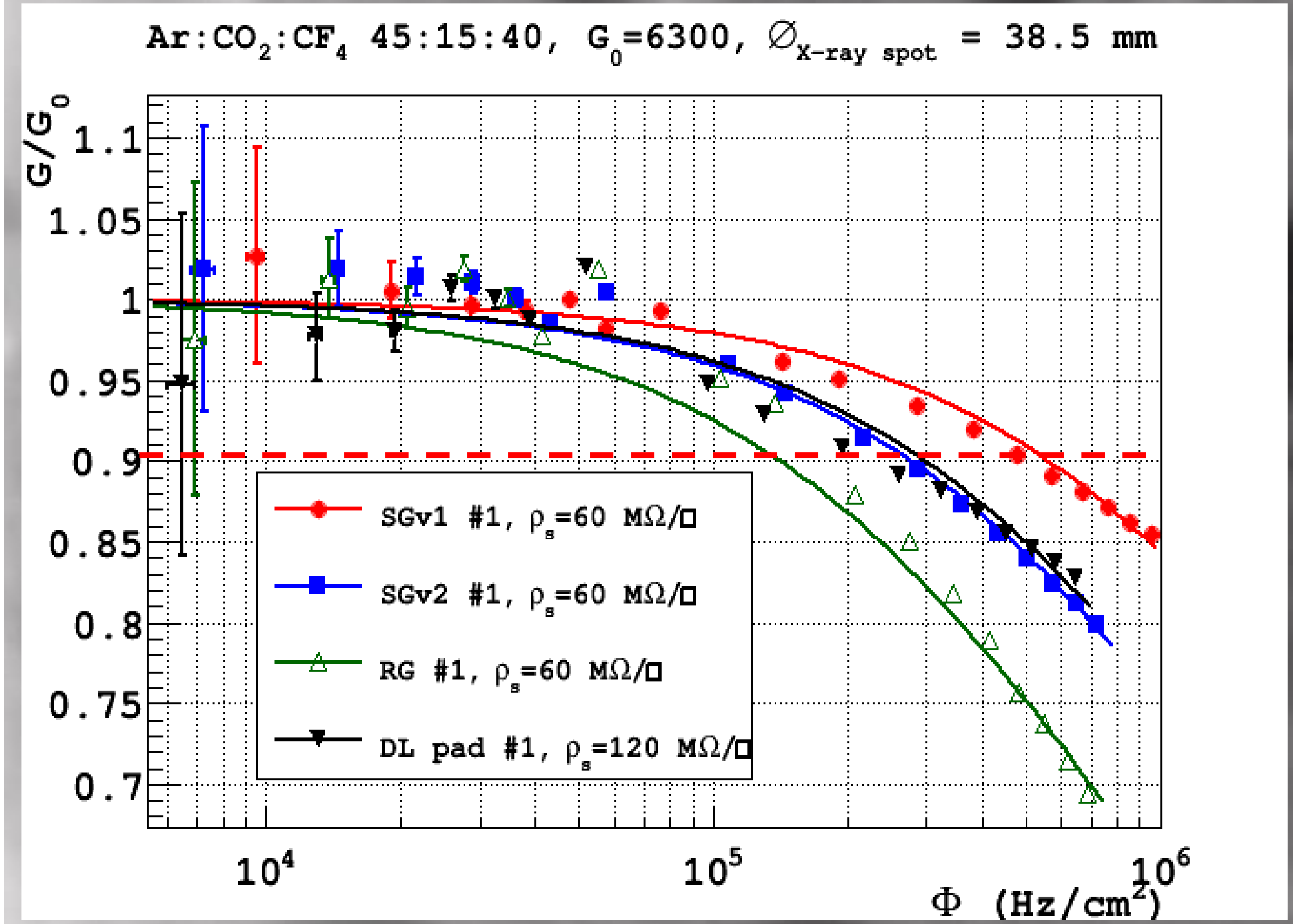
HR layouts performance: the efficiency



As expected **RG & DL prototypes** reach **full tracking efficiency – 98%** (NO DEAD ZONE in the amplification stage).

The **SG1 & SG2** show lower efficiency **(74% -92%) BUT higher than their geometrical acceptance (66% and 90%** respectively), thanks to the **efficient electron collection mechanism** that **reduce the effective dead zone.** **An optmized SG2 version ($SG2^{++}$ w/95% geometrical acceptance) is under production , with the goal to achieve an almost full efficiency (~97%).**

Rate measurement w/5.9 X-ray



The **gain drop** is due to the **Ohmic effect** on the resistive layer: **charges collected on the DLC drift** towards the **ground** facing an **effective resistance Ω**, depending on the **evacuation scheme geometry and DLC surface resistivity.** **Ω** is computed by the **parameter** p_0 coming from the **fit of the Gain curve.**

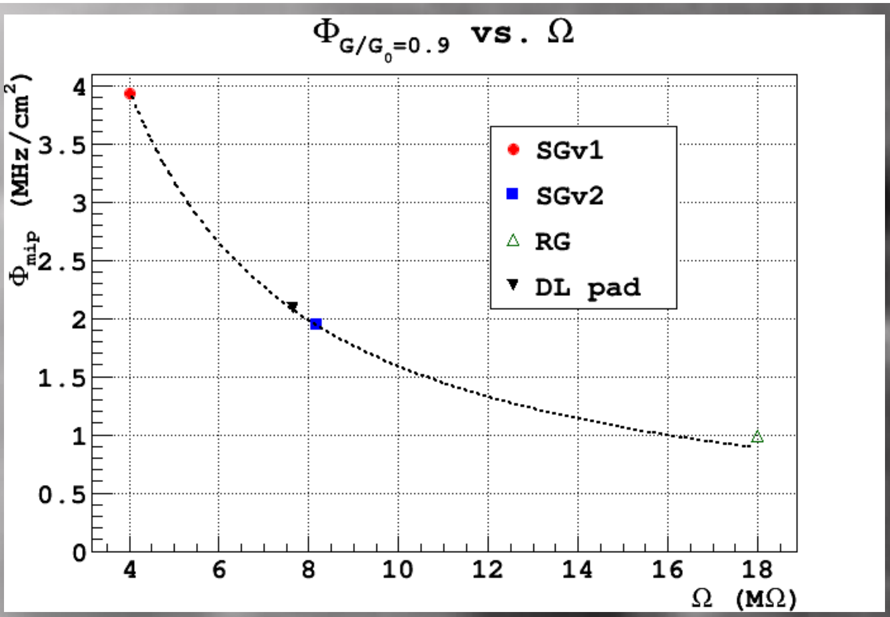
$$\frac{G}{G_0} = \frac{-1+\sqrt{1+4p_0\Phi}}{2p_0\Phi}$$

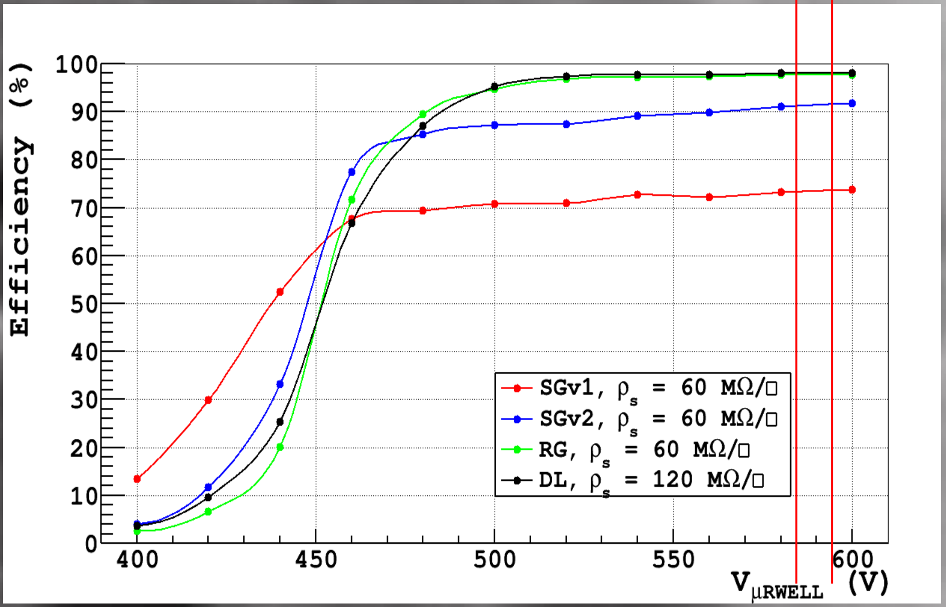
Rate Capability vs Ω (for m.i.p)

rate capability for m.i.p. accepting 10%gain drop

NO EFFICIENCY LOSS !!!

$G=0.9G_0$ $G_0=6300$

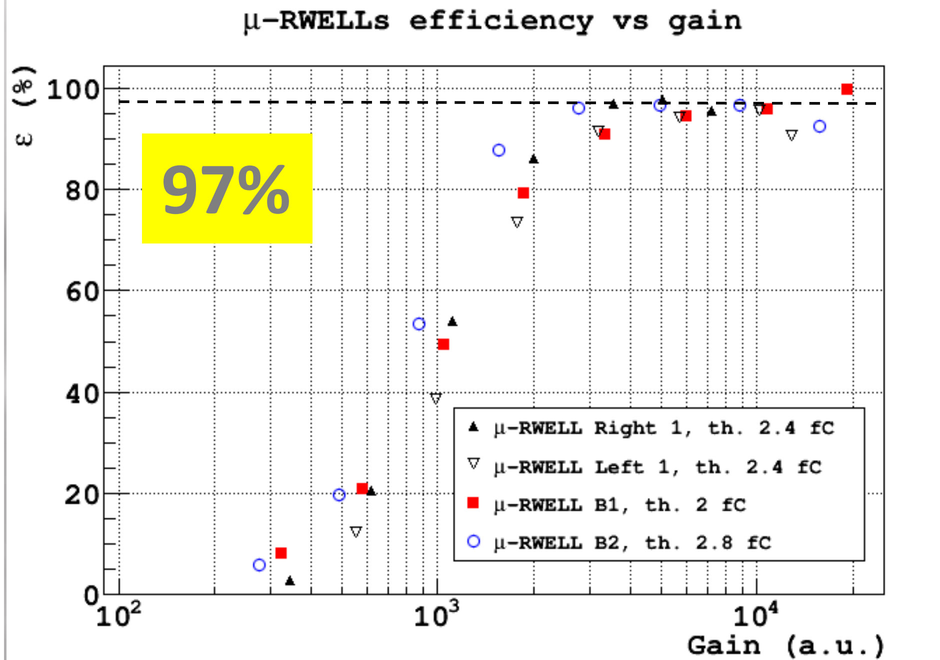


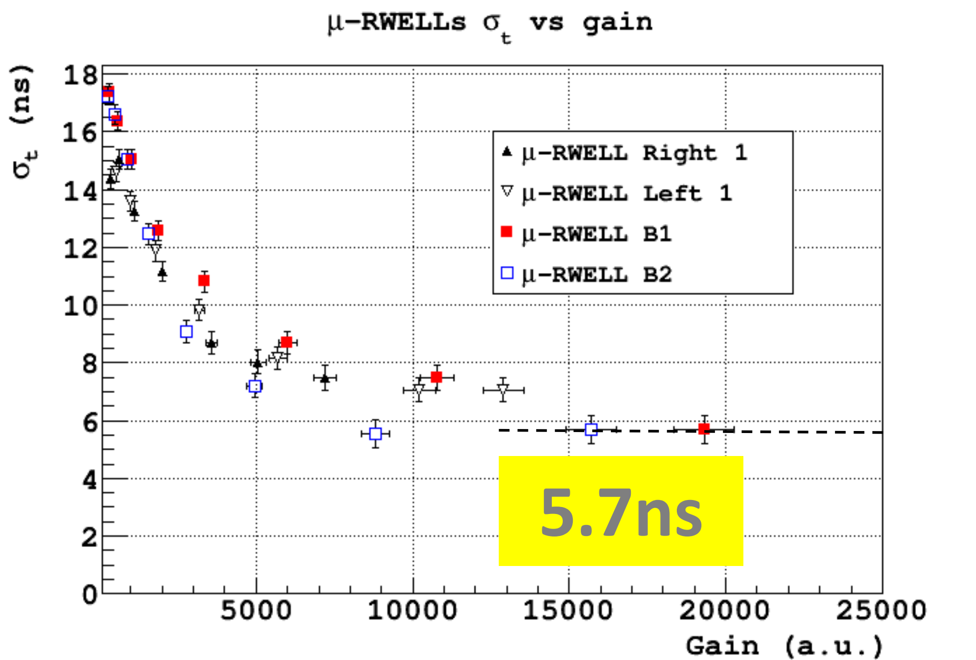


The **primary ionization of 5.9 keV X- ray is ~7 times larger than the one created by a m.i.p.**

It must be stressed that **10% gain drop (@ G_0=6300)** allows **still to operate the detector at full efficiency**.

Time Performance





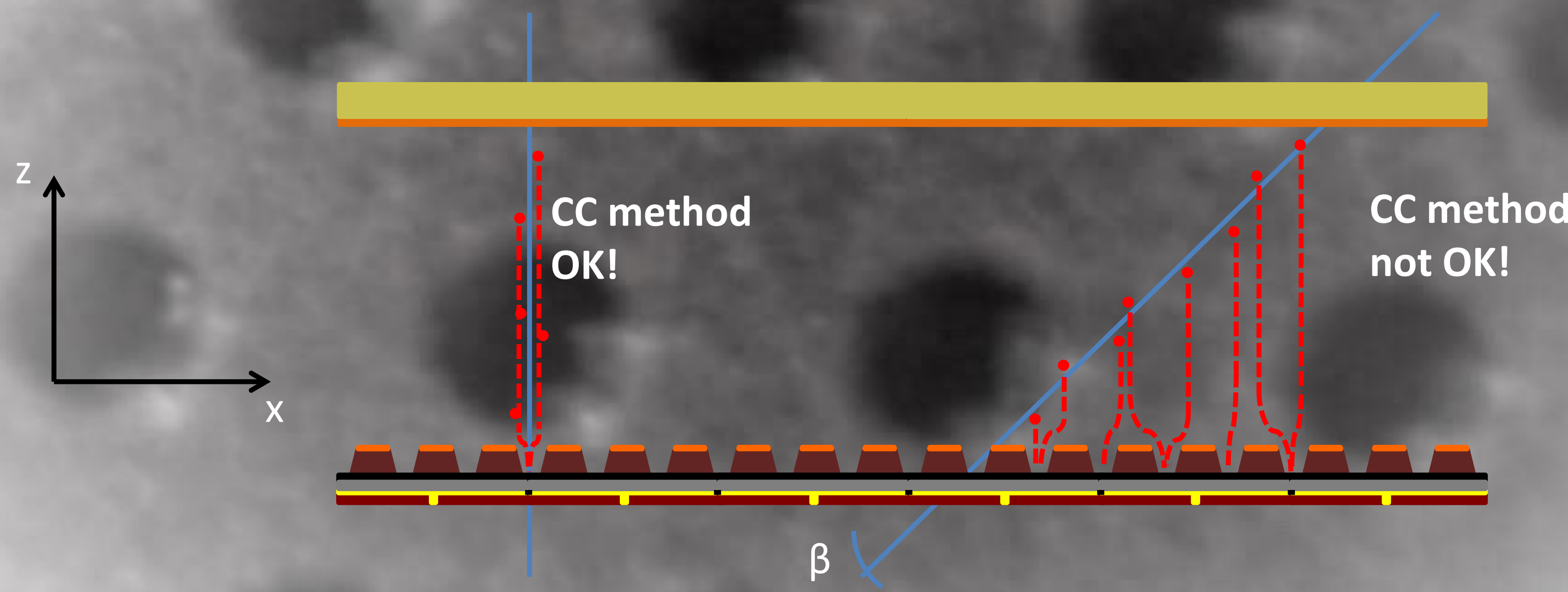
Different chambers with different dimensions and resistive schemes exhibit a <u>very similar behavior</u> although realized in different sites (large detector realized @ ELTOS)
The saturation at 5.7 ns is dominated by the fee (measurement done with VFAT2).

Past measurements done with GEM by LHCb group gave σ_t = 4.5 ns with VTX chip [1].
We wish to perform the same measurement with μ-RWELL in order to have a direct comparison with GEM. [1] G. Bencivenni et al, NIM A 494 (2002) 156

Improving space resolution: the µ-TCP mode

Thanks to the collaboration with the BESIII-CGEM group, see R. Farinelli 's talk

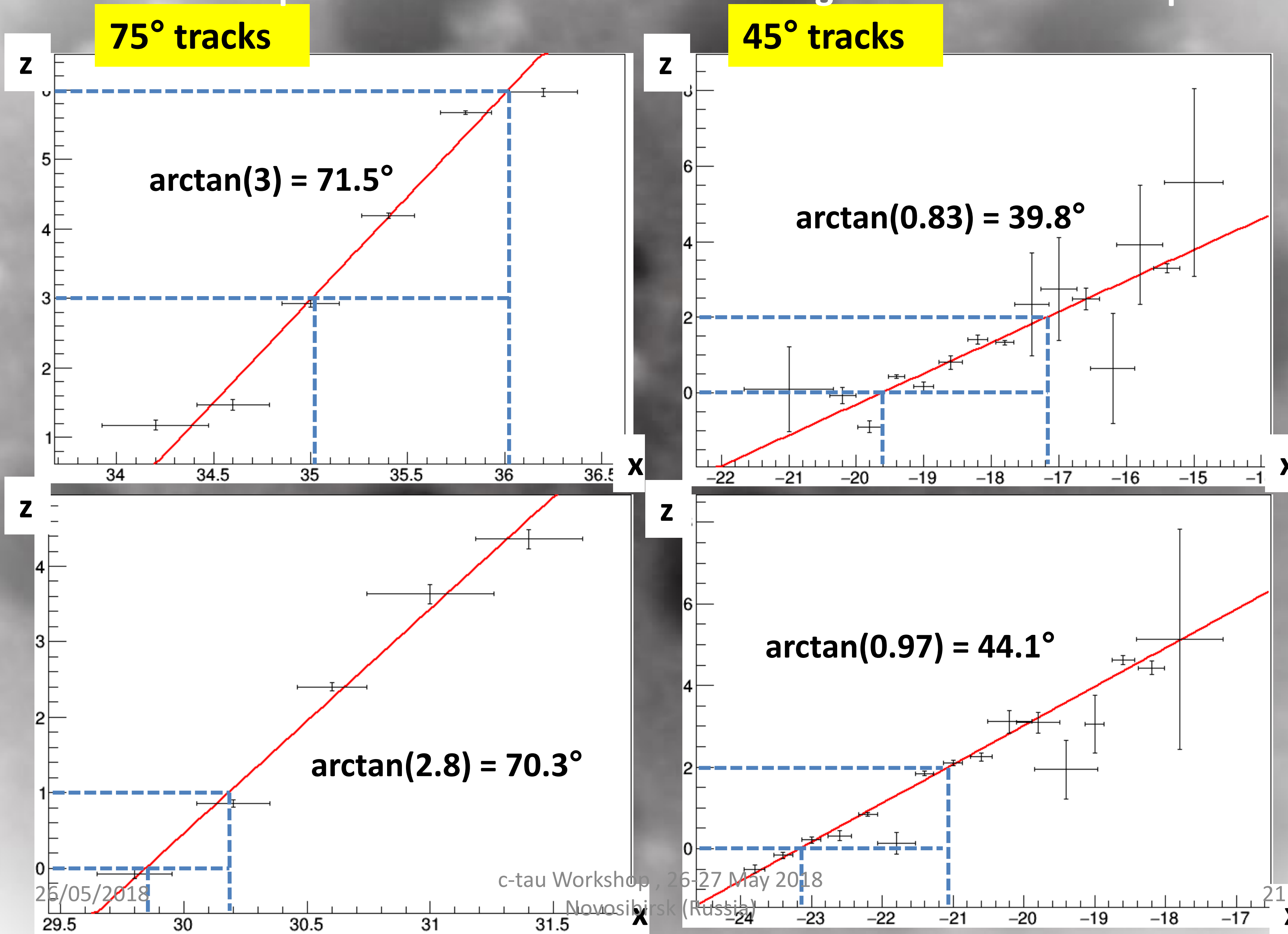
The use of an analogic front-end allows to associate a hit to a track using the charge centroid (CC) method. The space resolution associated to the hit with this algorithm is dependent on the track angle: minimum for orthogonal tracks and larger as the angle increases .



To improve the space resolution for non-orthogonal tracks the u-TPC algorithm combined with the CC method has been implemented

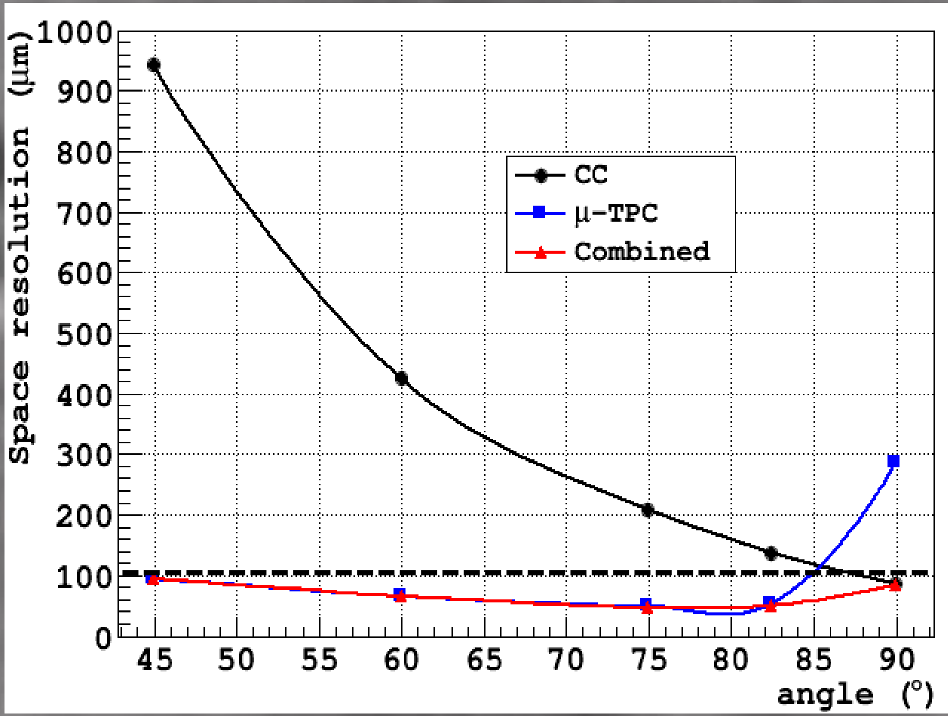
Example of µ-TPC reconstruction

Some examples where the tracks have an angle w.r.t. the readout plane



Improving space resolution: the μ-TCP mode

$Ar:CO_2:CF_4$ 45:15:40 - HV=600V, Ed=1kV/cm, Gain ~10^4, B=0 Tesla



100 μm

The **combination of the CC and the μ-TPC mode** with E_d= 1 kV/cm

The **combined spatial resolution** **is flattened over a wide range of incidence angles**.

Summary

The μ-RWELL is a break-through technology (*compact, simple to assemble and intrinsically spark-protected*) suitable for **large area planar muon devices** as well as **high space resolution very low material budget Cylindrical Inner Trackers:**

- **gas gain >> 10^4**
- **rate capability > 1 MHz/cm^2** *(w/HR layouts)*
- **space resolution < 100μm** *(over a large incidence angle of tracks)*
- **time resolution ~ 5.7 ns**

Status of the R&D/engineering:

- **Low rate (<100kHz/cm^2) :**
  - **small and large area prototypes built and extensively tested** *(R&D completed)*
  - **Technology Transfer to industry well advanced** *(→ cost effective mass production)*
- **High rate (>1 MHz/cm^2):**
  - **several layouts under study showing very promising performance**
  - **the engineering and the TT to industry will be started soon**

Thanks for the attention

SPARES SLIDES

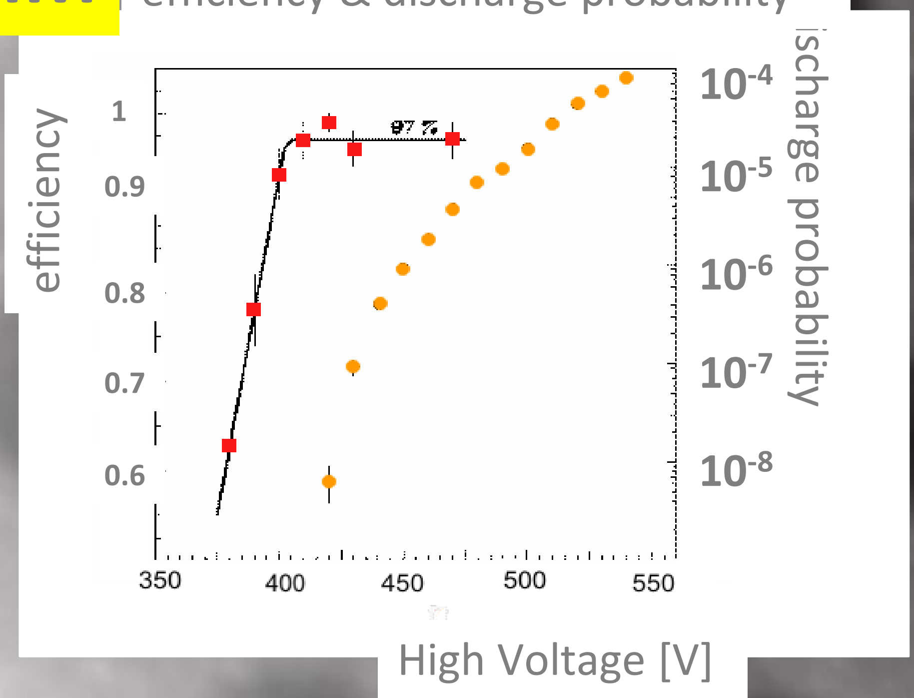
MPGDs: stability

The biggest"enemy"of MPGDs are the discharges.

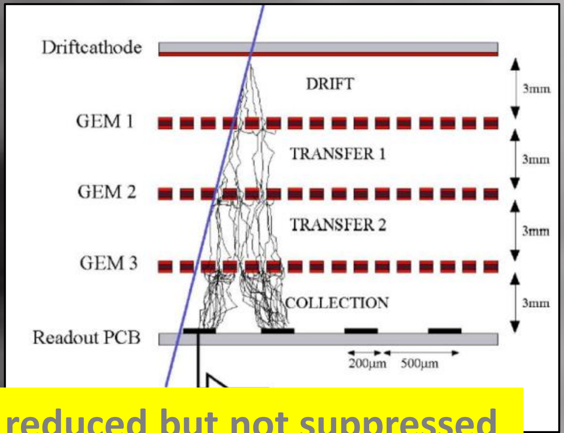
Due to the **fine structure and the typical micrometric distance of their electrodes**, MPGDs generally **suffer from spark occurrence that can eventually damage the detector and the related FEE.**

MM

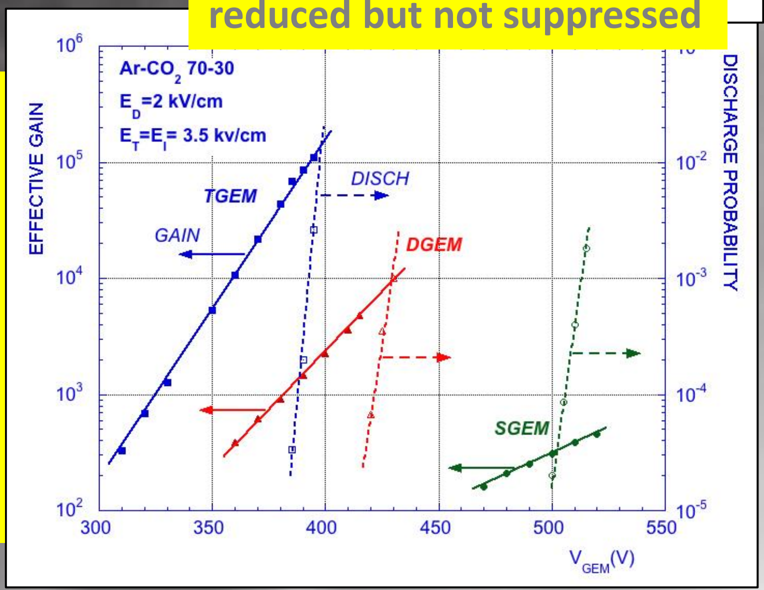
efficiency & discharge probability



GEM



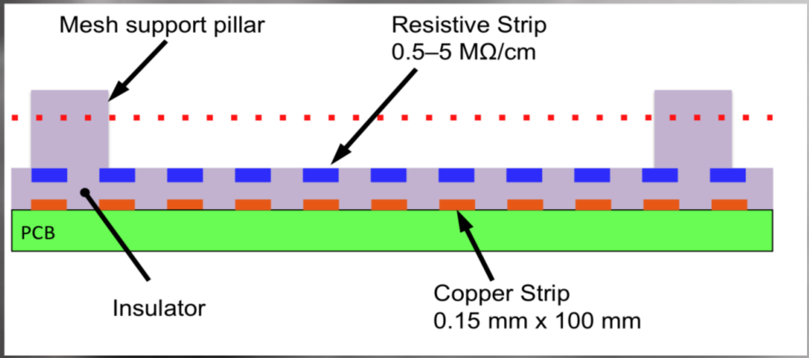
reduced but not suppressed



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

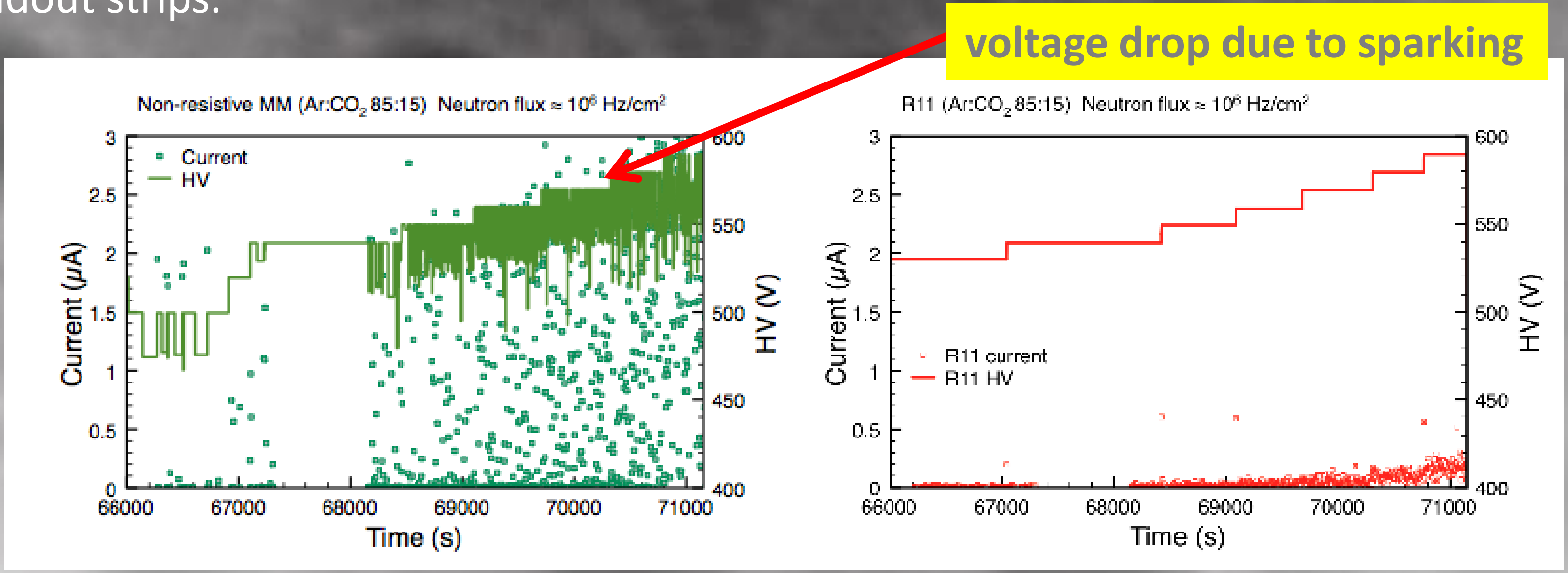
Technology improvements for MicroMegas

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. 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

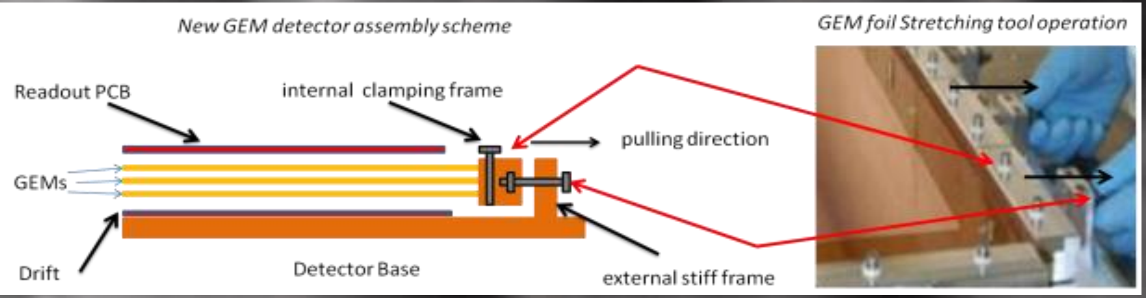
The resistive layer is realized as resistive strips capacitive coupled with the copper readout strips.



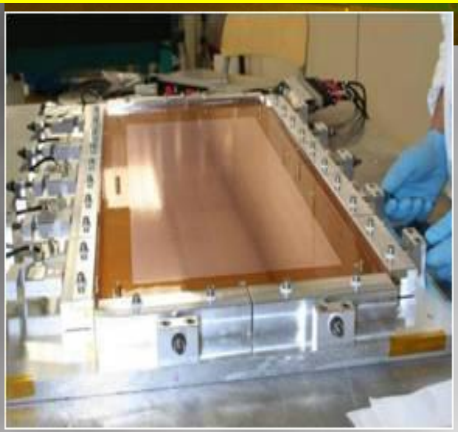
MPGDs: construction issues (I)

An **important limitation of such MPGDs** is correlated with the **complexity of their assembly procedure**, particularly evident in case of **large area devices.**

- The construction of a **GEM chamber requires time-consuming assembly steps such as the stretching** (with quite large mechanical tension to cope with – 1 kg/cm) and the **gluing** of the **GEM foil on frames**



NS2(CERN – R. de Oliveira): no gluing, but still stretching



- A **2 m long** detector requires a ~**200 kg mechanical tension** that must be sustained by **stiff mechanical structures (large frames, rigid panels** ...). While the max width of the raw material is about 60 cm.
- The **splicing/joining of smaller detectors** in order to realize large surfaces (as used for silicon detectors) is difficult **unless introducing not negligible dead zones .**

MPGDs: construction issues (II)

Similar considerations hold for MM:

- the **splicing/joining of smaller PCBs is possible**, opening the way towards the **large area detection covering**

- the **fine metallic mesh**, that defines the amplification gap, is a ***"floating component"***, because it is stretched on the cathode (@ 1 kg/cm) and electrostatically attracted toward the PCB ($P = \epsilon_0 \times (^{\Delta V}/_{d})^2$).

- this could be a **source of instability because a "not well defined" amplifying gap could generate gain non-uniformity.**
- In addition the **handling of large meshes is clearly "not trivial" (of course for large area)**

The µ-RWELL *vs* single-GEM

µ-RWELL is expected to exhibit a gas gain larger than a single-GEM

Single-GEM

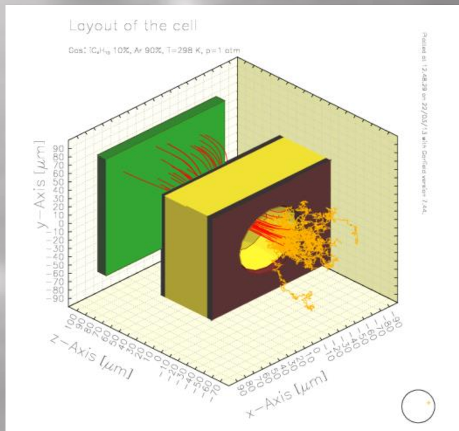
- **~50% of the electron charge** produced into the hole **contributes to the signal,** the rest of the electron charge is collected by the **bottom side of the GEM foil**
- the signal is **mainly due to the electron motion,** the **ion component is largely shielded by the GEM foil itself**

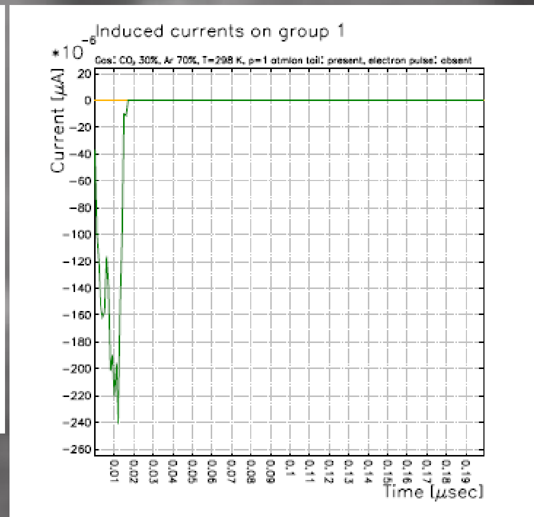
µ-RWELL

- **100% electron charge produced into the amplification channel is promptly collected on the resistive layer**
- the **ionic component, apart ballistic effects, contributes to the formation of the signal**
- further **increase of the gain achieved thanks to the resistive electrode which, quenching the discharges, allows to reach higher amplification field** inside the channel

The µ-RWELL vs GEM (*Garfield*)

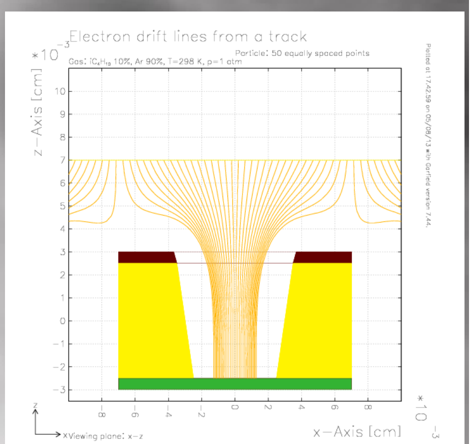
GEM – Ar:CO2 70:30 gas mixture

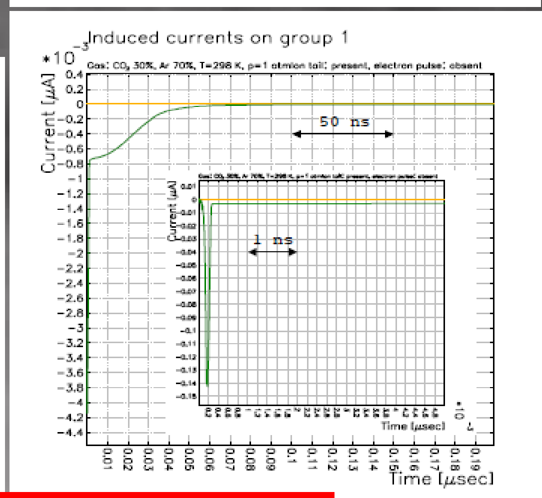




Signal from a single ionization electron in a GEM.

The **duration of the signal, about 20 ns**, depends on the **induction gap thickness, drift velocity and electric field in the gap.**





µ-RWELL – Ar:CO2 70:30 gas mixture

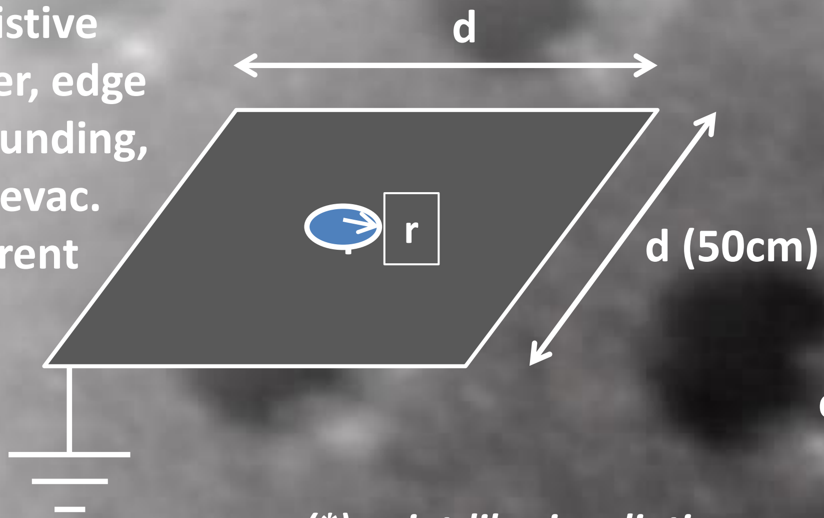
Signal from a single ionization electron in a µ-RWELL.

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** then **followed by a ~50 ns ion tail**.

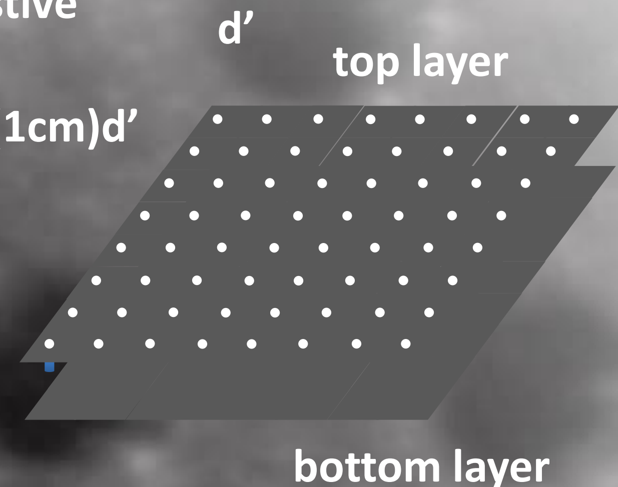
More similar to a MM !!!

Towards the High Rate

single resistive layer, edge grounding, 2D evac. current



double resistive layer, 3D grounding



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

$$\Omega \sim \rho_s \times d/2\pi r \qquad \Omega' \sim \rho_s' \times 3d'/2\pi r$$

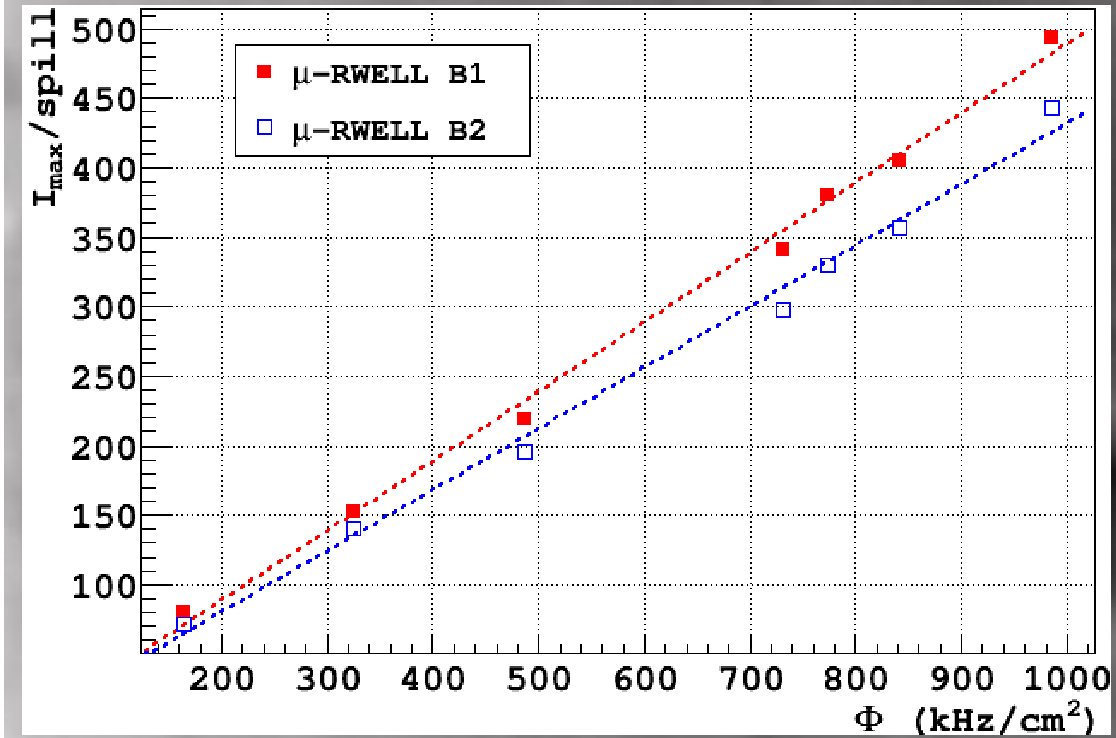
$$\Omega/\Omega' \sim (\rho_s / \rho_s') \times d/3d'$$

$$\text{If } \rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim \rho_s/\rho'_s * d/3d' = 50/3 = 16.7$$

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

Double-resistive layer: the performance

Rate capability as a function of the pion beam (H4-SpS CERN) intensity



Detectors operated at a gain of 10^4
Beam spot ~2 cm^2 (RMS)

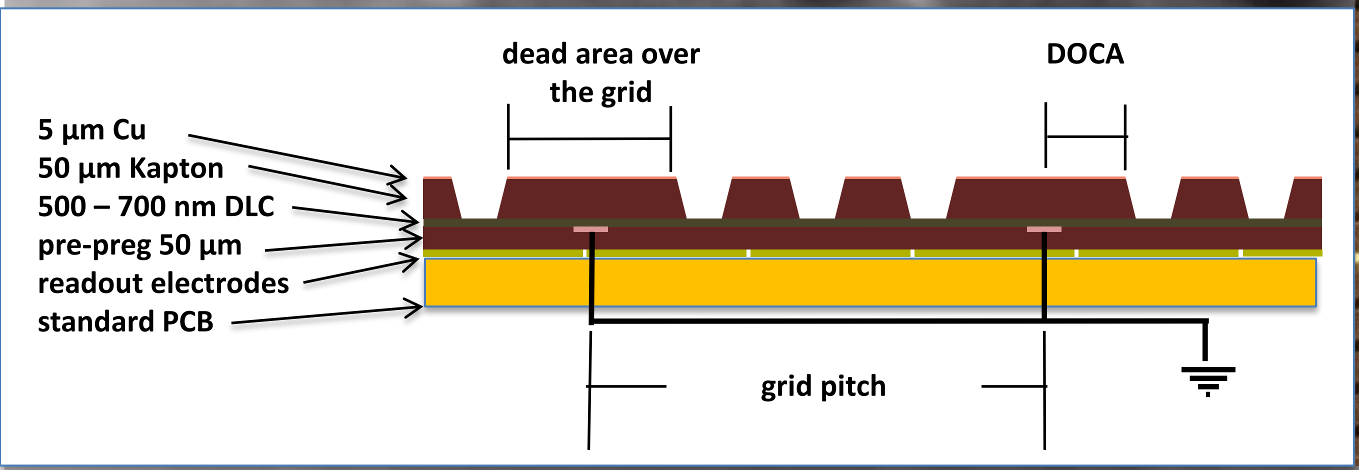
WARNING: The **engineering/industrialization of the double-resistive** layer is **difficult** due to the **manufacturing of the conductive vias**

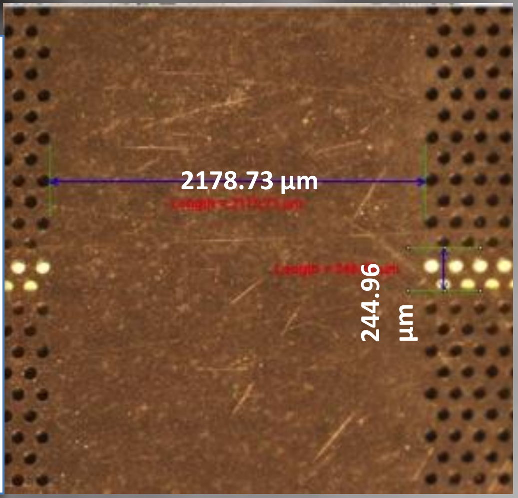
New ideas for the HR version

The aim is **to maintain a very short path for charges moving on the resistive layer,** while **simplifying the construction process.**
Two ideas are now under development: **silver grid and resistive grid**

1. Silver Grid (SG)

Thin **conductive strips are screen-printed** *(for the moment)* on the **bottom part of the DLC**



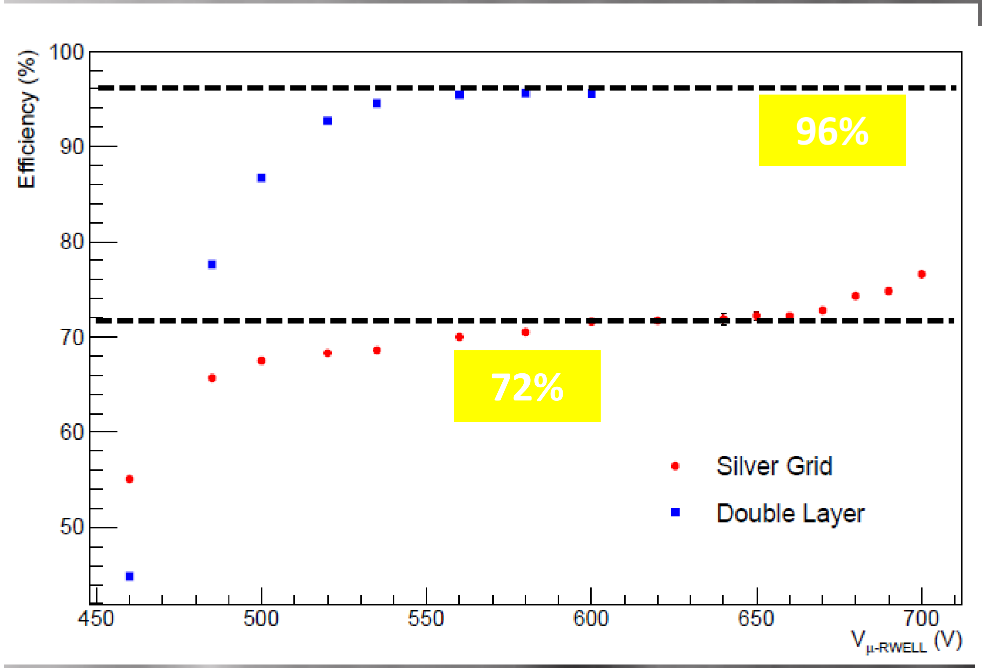


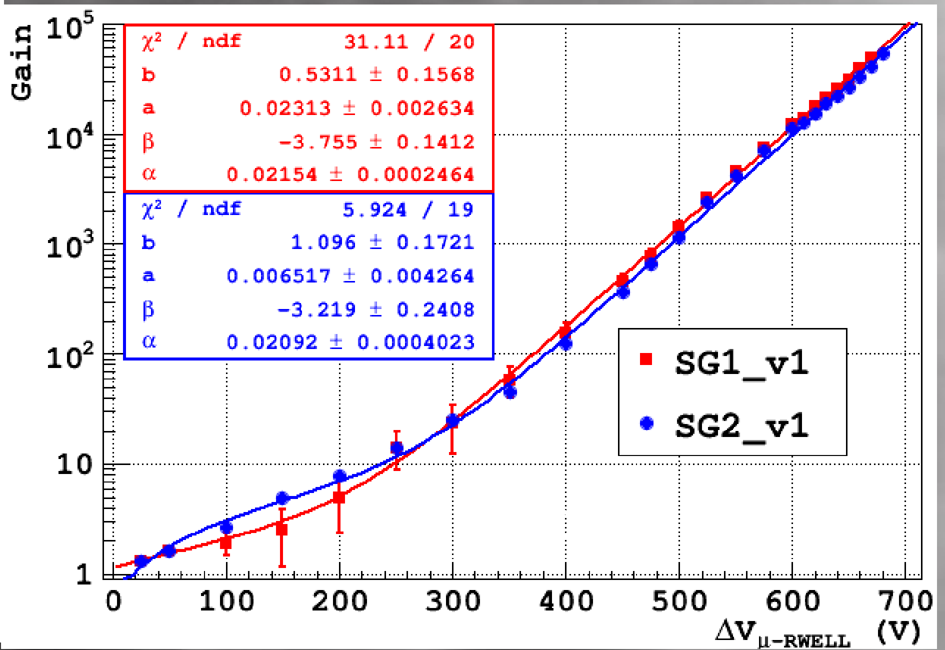
The **introduction of a conductive strip** on the bottom layer of the amplification stage **can induce instabilities due to discharges over the DLC surface**

→ **First SG** designed with **safe geometrical parameters: grid-pitch 6 mm**
dead area 2 mm

Silver Grid v1:
X-rays and test beam characterization

SG version of μ-RWELL vs Double Layer version

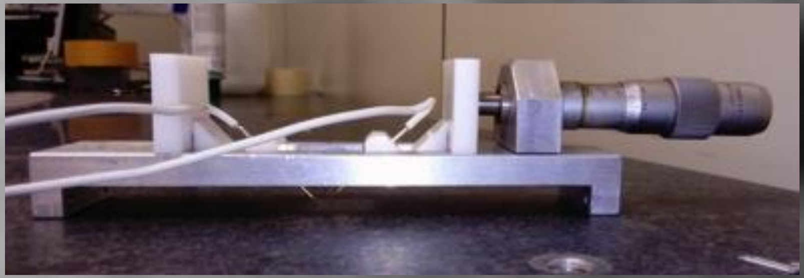


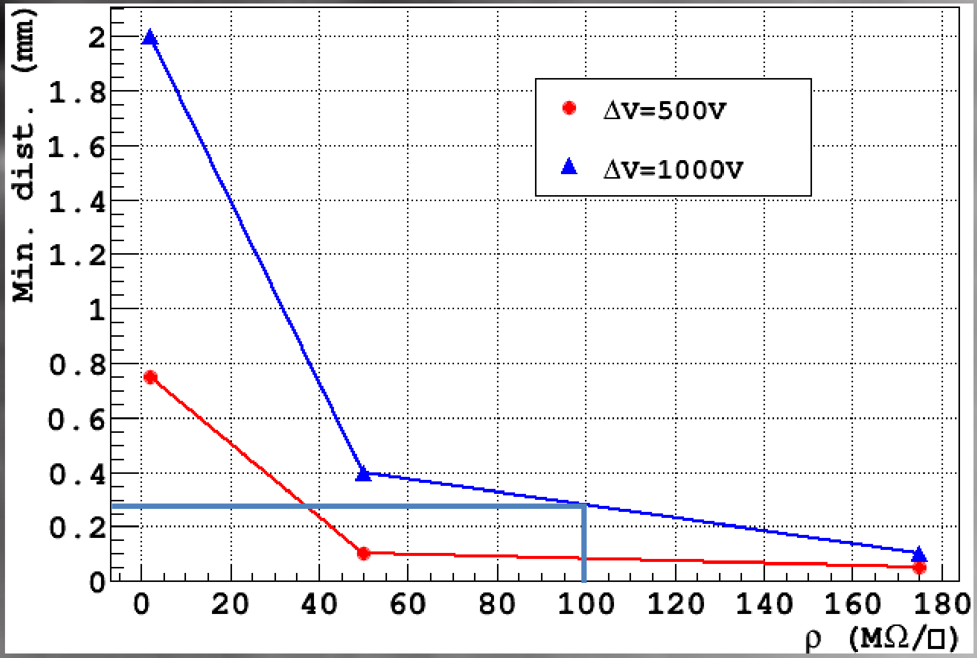


A **very high stability of the SG wrt the DL** has been observed: **the SG has been operated at gains largely exceeding the typical 10^4 (up to 10^5).** The **reason** of a so high stability is **under investigation**. The **lower efficiency is due to the geometrical dead zone**. A dedicated study of the **minimum distance between the conductive grid-strip and the amplifying well** has been done to increase the efficiency.

Silver Grid: optimization

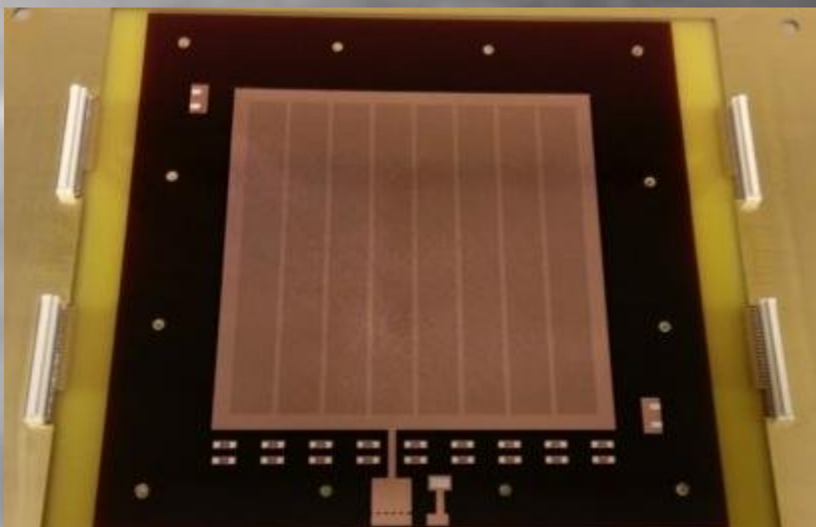
In order **to reduce the dead area,** we have studied the **Distance Of Closest Approach** (***without discharges***) between **two tips connected to an HV power supply**. We recorded the **minimum distance before a discharge on the DLC** occurred *vs* the **ΔV supplied** for foils with different surface resistivity.

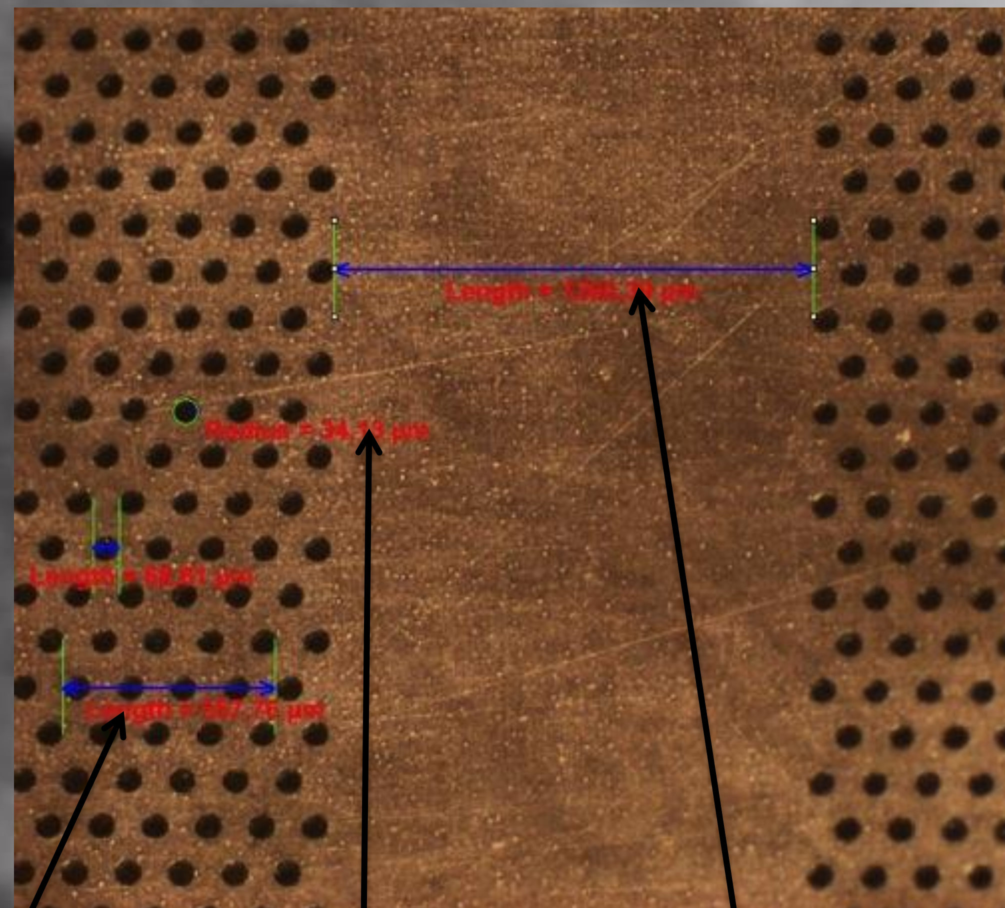




Silver Grid: 2nd generation

Two detectors have been equipped with 6 x 8 mm^2 pad-segmented readout



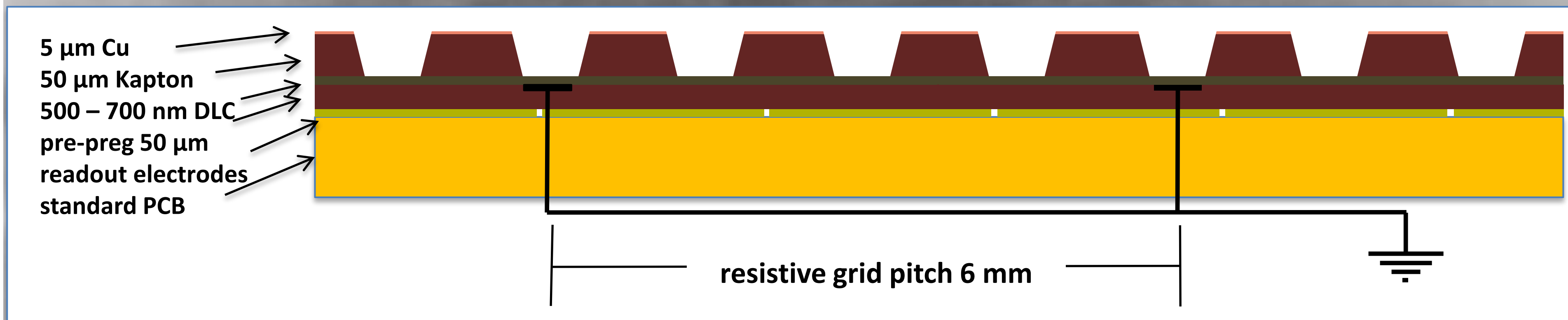


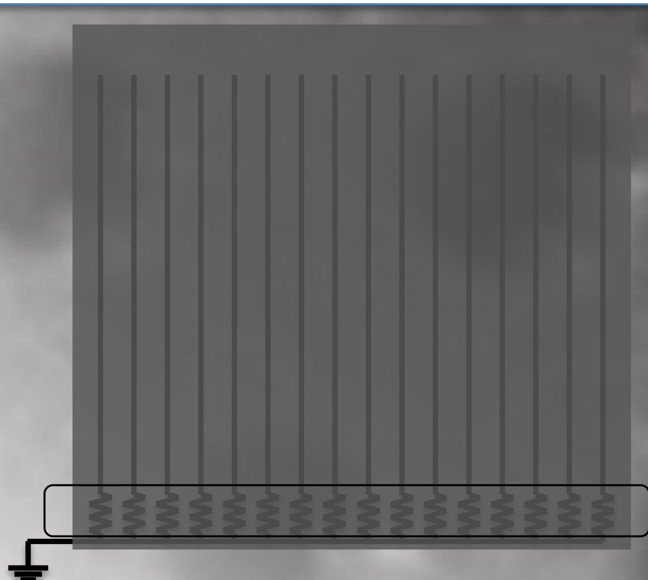
557.76 µm 34.13 µm 1260.39 µm

The grid lines are connected to the ground through the resistance provided by the DLC itself (~10 MΩ)

Resistive grid

Small resistive strips are screen-printed on the bottom side of DLC

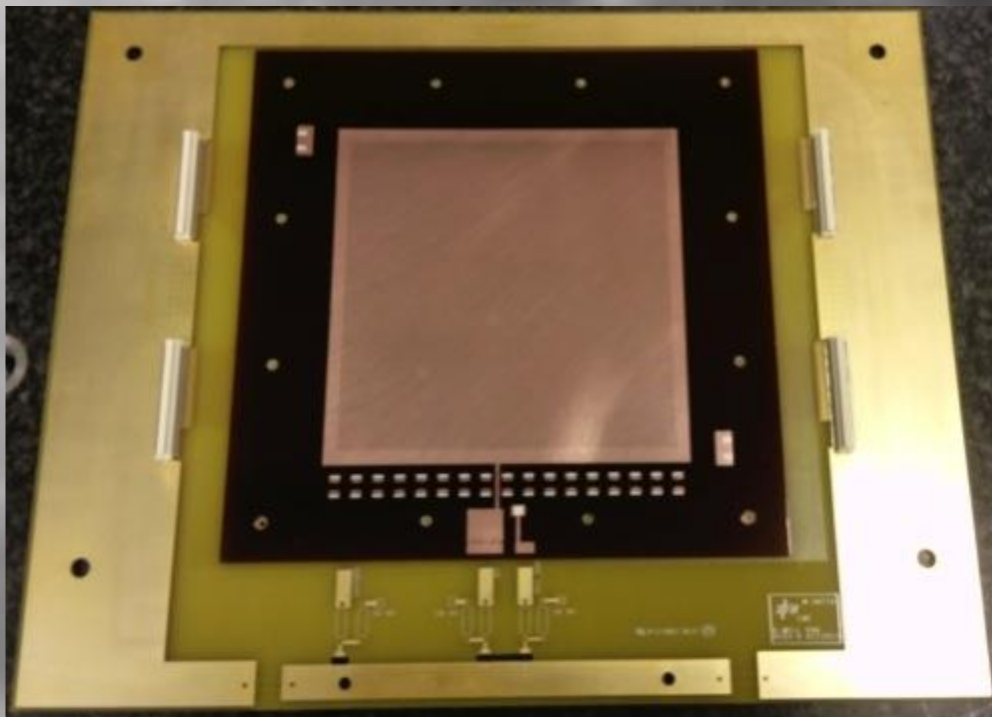


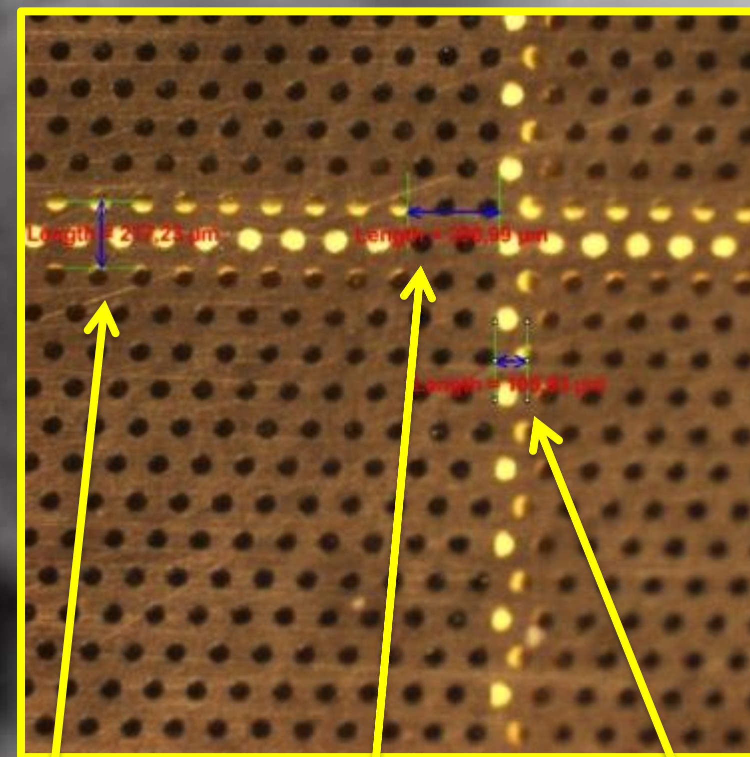


The **grid grounding** is **similar** to the one used for the **2nd generation SG**, as well as the **readout segmented in pads**.
The **grid pitch is 6 mm**.

Grounding through DLC

Resistive grid





No dead areas

Grounding resistance: 10 - 15 MΩ

Y distance of pads: 217.23 µm

Resistive strip width: 296.99 µm

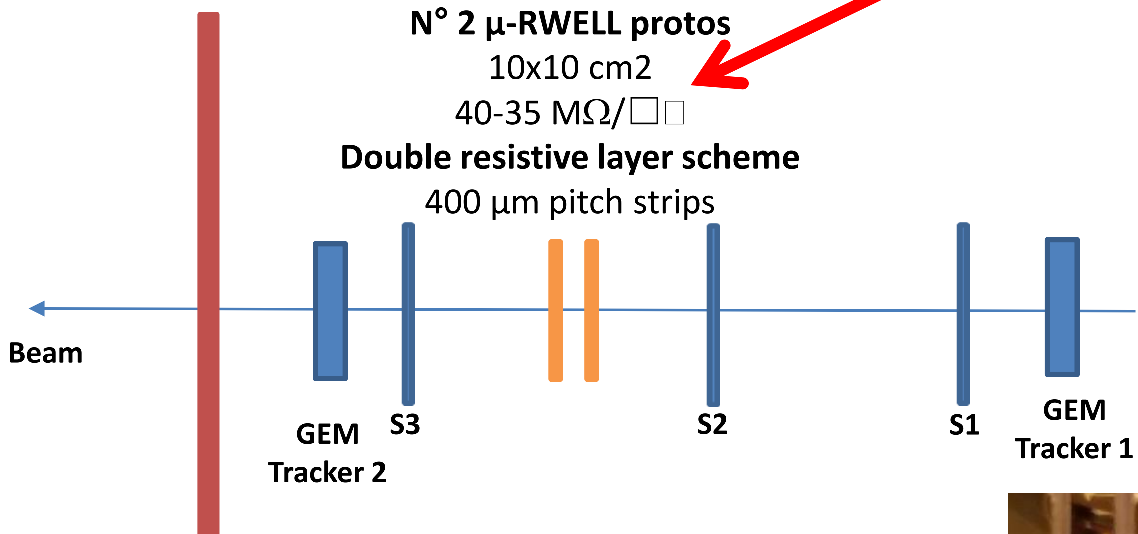
X distance of pads: 105.03 µm

Time performance

H8 Beam Area (18th Oct. – 9th Nov 2016)
Muon/Pion beam: 150 GeV/c

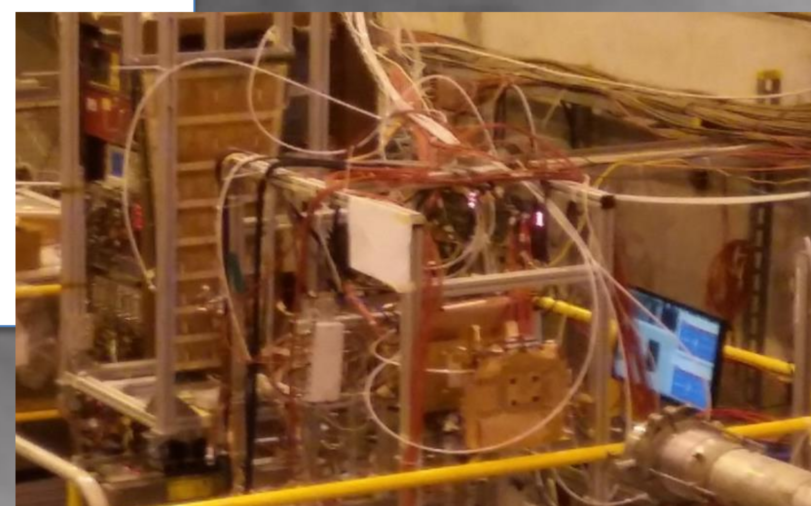
3 µ-RWELL prototypes:
- 40-35-70 MΩ /□
- VFAT (digital FEE)
- $Ar/CO_2/CF_4$ = 45/15/40

N° 2 µ-RWELL protos
10x10 cm2
40-35 MΩ/□
Double resistive layer scheme
400 µm pitch strips



Trigger=S1+S2+S3

N° 1 µ-RWELL proto
100x50 cm2
70 MΩ/□
Single resistive layer scheme
800 µm pitch strips



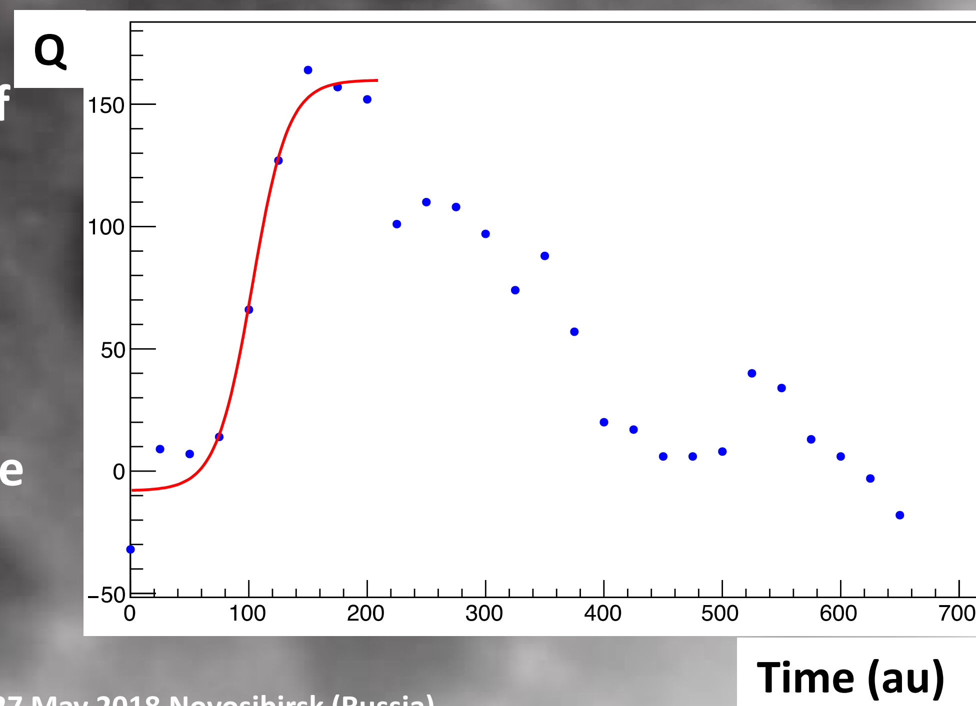
GOAL: time resolution measurement (never done before)

Improving space resolution: the µ-TCP mode

Introduced for **MicroMegas** by **T. Alexopoulos** et al. [NIM **A 617** (2010) 161] it suggests a way to overcome the **poor position reconstruction of the inclined tracks.**
Each **hit is projected inside the conversion gap**, where the ***x* position is given by each strip and the $z = v_d t$**
The drift velocity is provided by the Magboltz libraries.

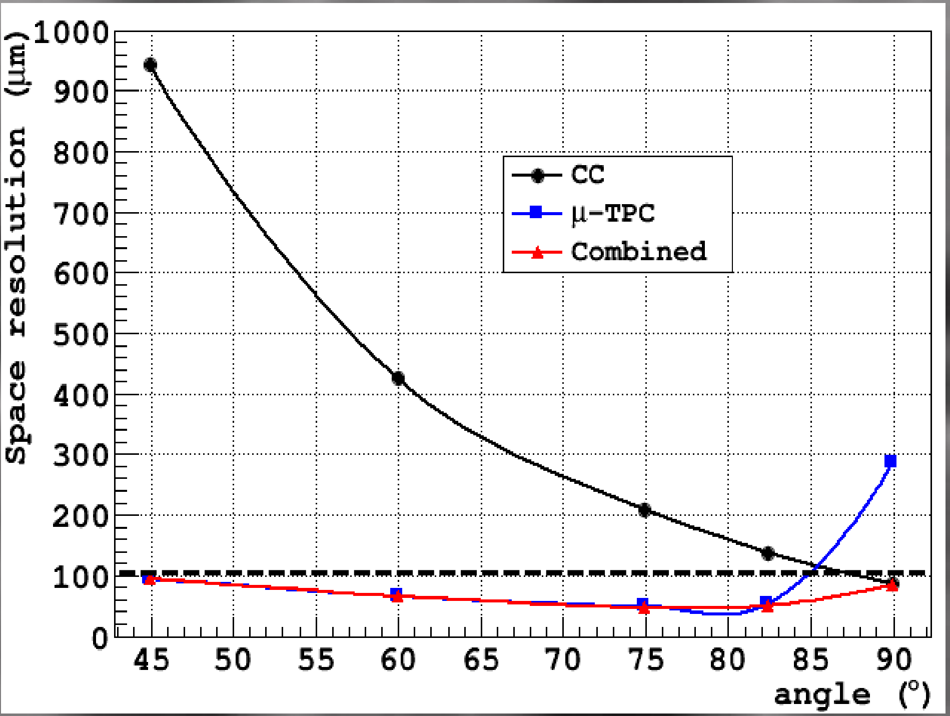
The **drift time is obtained with a fit of the charge sampled every 25 ns (APV25)** from each FEE channel associated to the strip.

For each event we obtain a set of projected hits that once fitted provide a track segment



Improving space resolution: the μ-TCP mode

$Ar:CO_2:CF_4$ 45:15:40 - HV=600, Ed=1kV/cm, Gain ~10^4



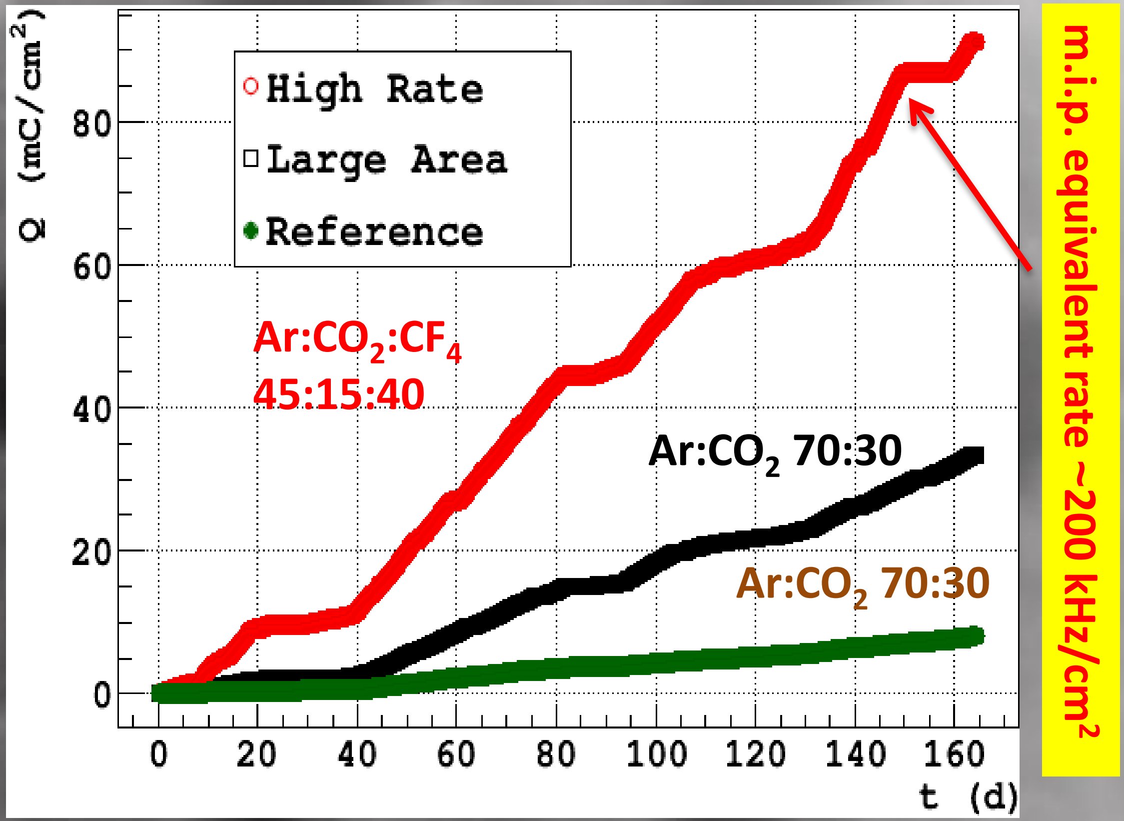
100 μm

The **combination of the CC and the μ-TPC mode** with E_d= 1 kV/cm
The **spatial resolution is flattened for a wide range of angles**.

$$x_{merge} = \frac{x_{cc} \cdot w_{cc} + x_{tpc} \cdot w_{tpc}}{w_{cc} + w_{tpc}}$$

$$w_{cc} \propto (clsize)^{-2} \quad w_{\mu-TPC} \propto (clsize)^2$$

Ageing test at GIF++ (CERN)



The ageing effects on DLC is under study at the GIF++ by irradiating different µ-RWELL prototypes operated at a gain of 4000 .

Up to now on the most irradiated detector (~200 kHz/cm² m.ip. equivalent) a charge of about 90 mC/cm² has been integrated (more intense irradiation facility should be considered in order to achieve more significant global irradiation)