Status of the R&D on μ-RWELL

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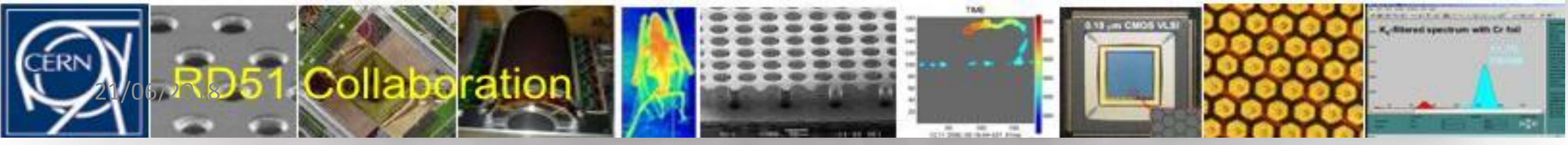


OUTLINE

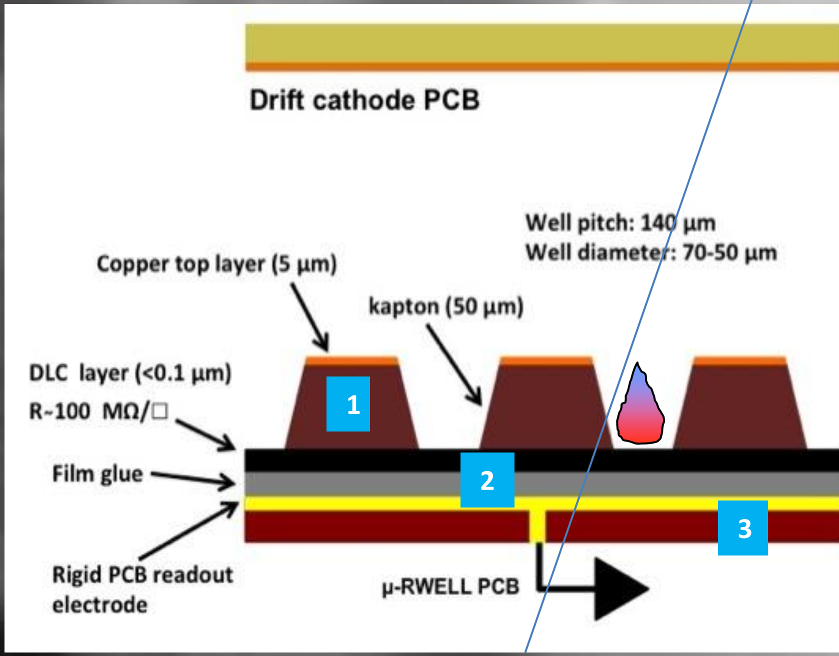
- ❑ Detector architecture
- ❑ Low rate layout: the single-resistive layer scheme
  - ❑ performance & Technology Transfer to industry
- ❑ High rate layouts: design & performance
- ❑ DLC aging: preliminary tests and future strategy
- ❑ Summary

The µ-RWELL: the detector architecture

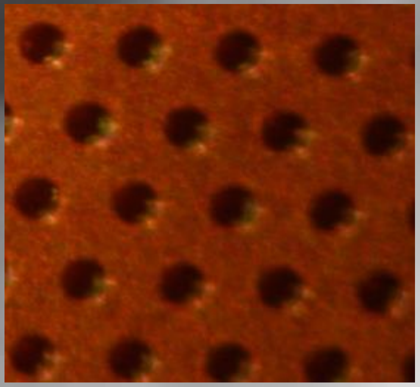
The µ-RWELL is composed of only two elements: the **µ-RWELL_PCB** and the **cathode**

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

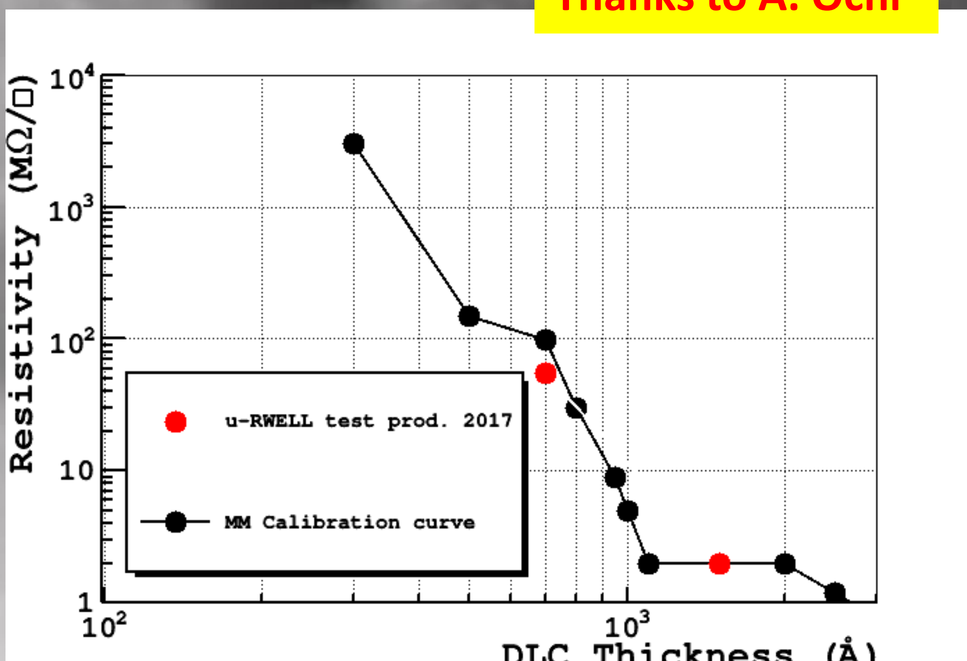


The resistive layer: DLC sputtering

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 20-30%.

Thanks to A. Ochi



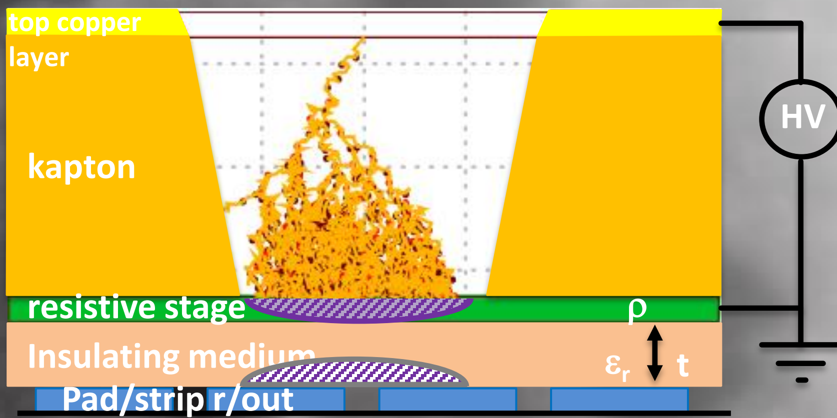
A profitable collaboration with Zhou Yi from USTC – Hefei (PRC) for the manufacturing of improved DLC foils, has been started.

A Common Project among Hefei, Kobe, CERN and LNF has been recently presented with three main objectives:

- **define manufacturing procedure**
- **define QC/QA procedures**
- **perform long term stability tests**

Principle of operation

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



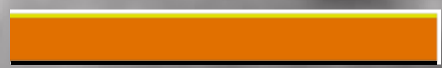
The charge induced on the resistive foil is dispersed with a *time constant, τ = ρC ,* determined by:

- 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)**

The Low Rate Layout

single resistive layer w/edge grounding

1 

Copper layer 5 µm

Kapton layer 50 µm

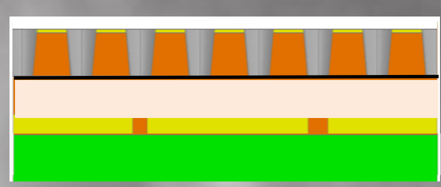
DLC layer: 0.1-0.2 µm (10-200 MΩ/☐)

2 

DLC-coated kapton base material

Insulating medium (50 µm)

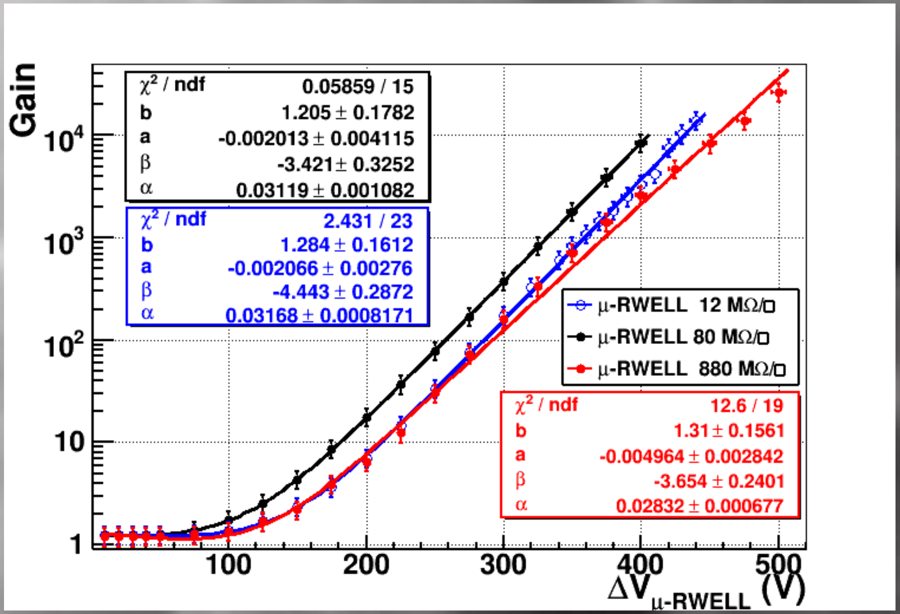
PCB (1.6 mm)

3 

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

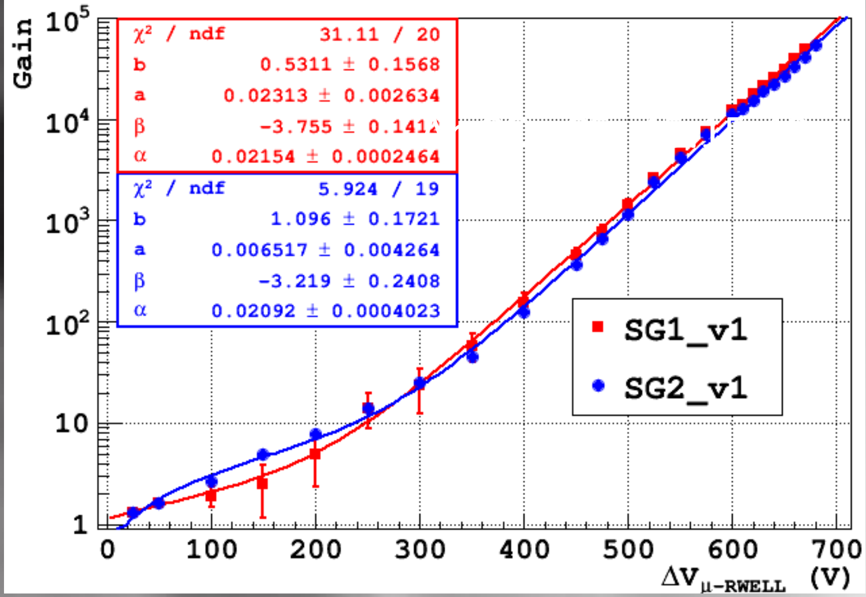
Detector Gain

Ar/iC_4H_{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**

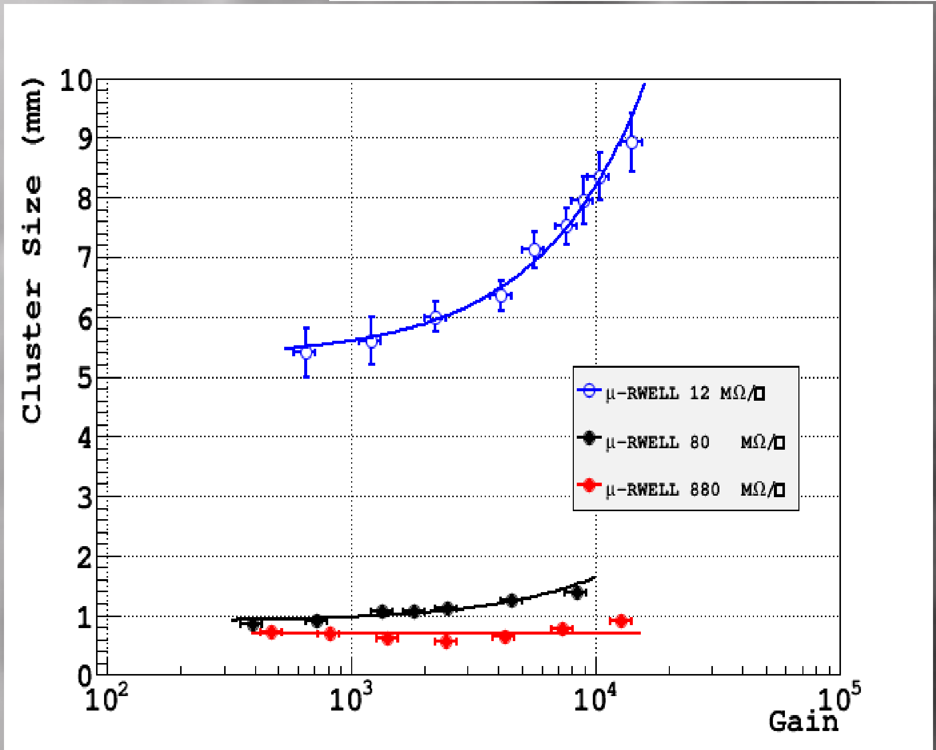
$Ar/CO_2/CF_4$= 45/15/40

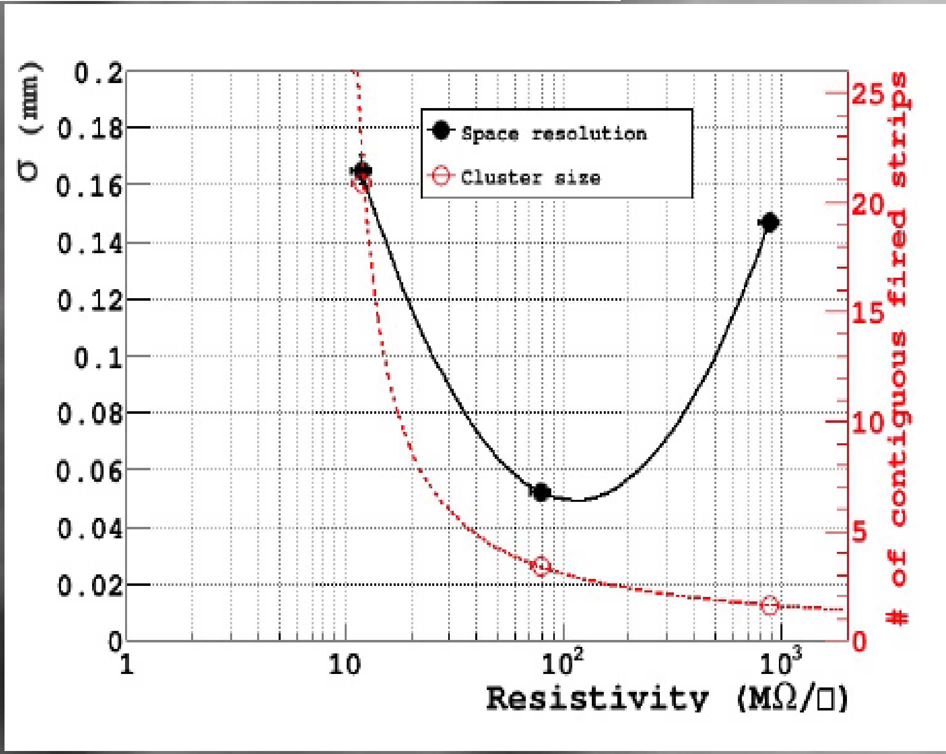


Recent prototypes showed Gain ~10^5 in $Ar/CO_2/CF_4$= 45/15/40

Space resolution *vs* DLC resistivity

Charge Centroid analysis (orthogonal tracks)





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

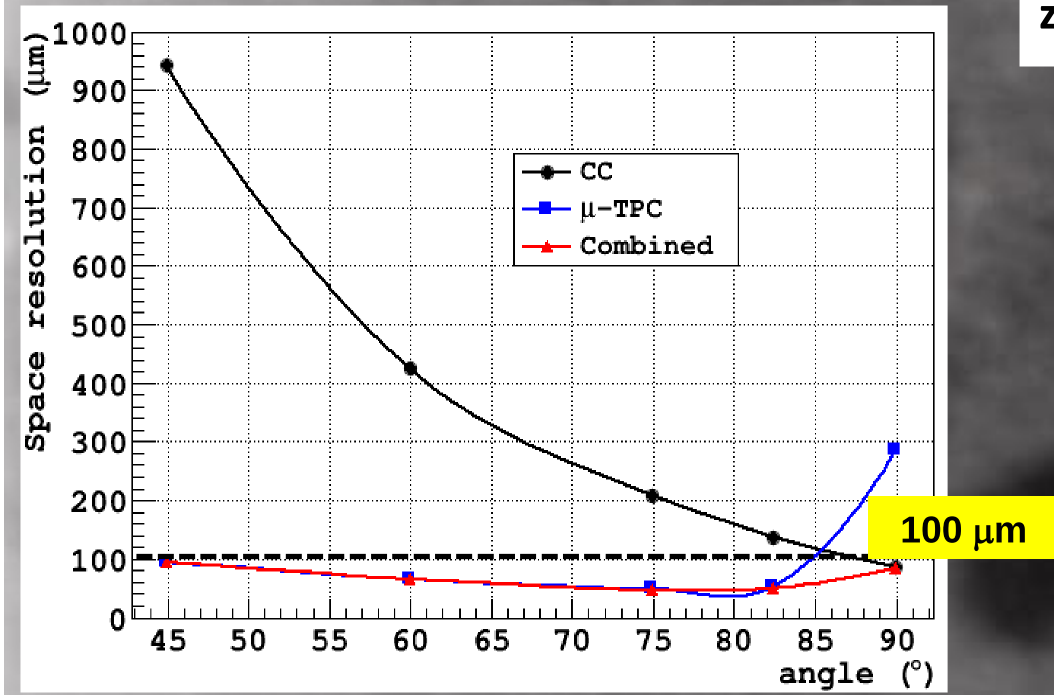
→ at **low resistivity** the **charge spread increases** and then **σ is worsening**

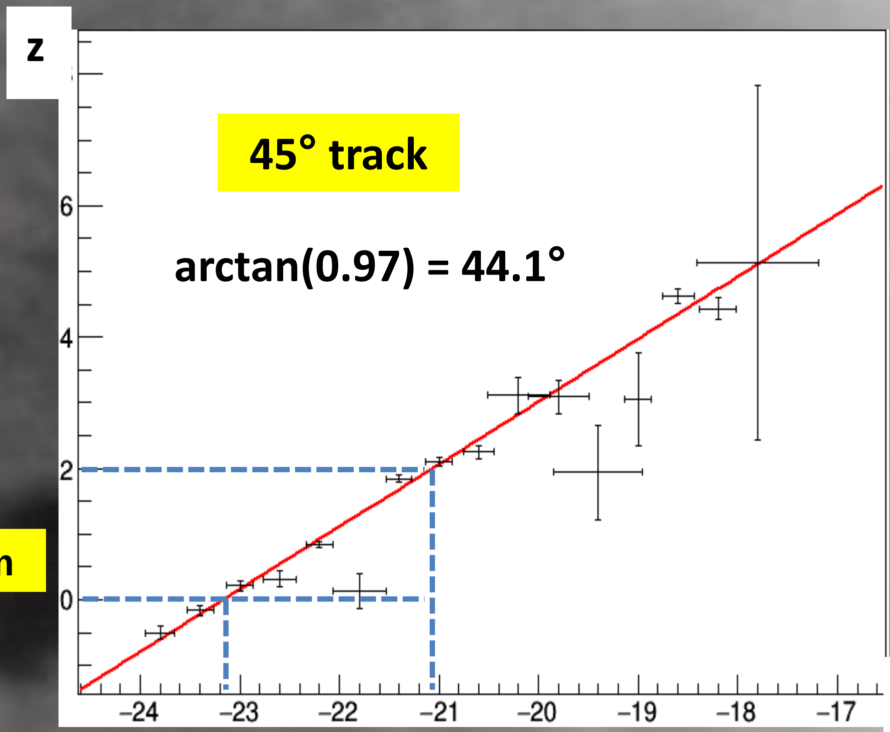
→ at **high resistivity** the **charge spread is too small (Cluster-size → 1 fired strip)** then the **Charge Centroid method** becomes **no more effective (σ → pitch/√12)**

Space resolution vs inclined tracks: µ-TCP mode

Thanks to the collaboration with BESIII-CGEM, R.Farinelli (INFN-Fe) & L.Lavezzi (INFN-To)

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





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

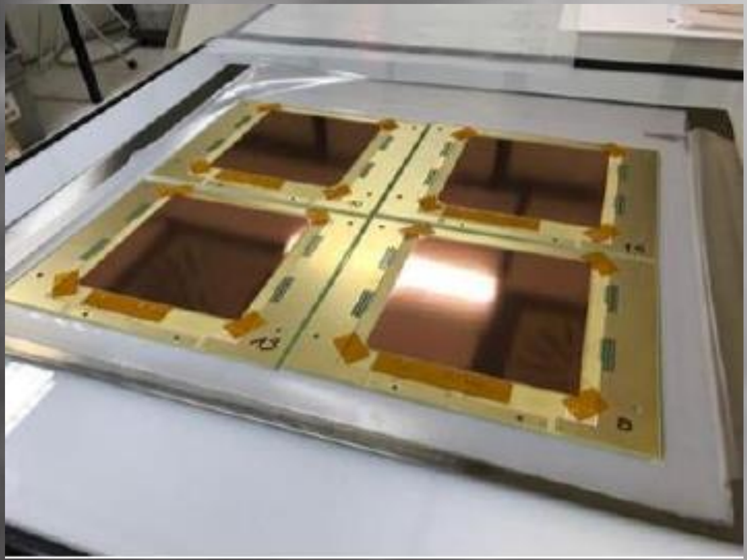
The **combined spatial resolution** **is flat over a wide range of incidence angles**.

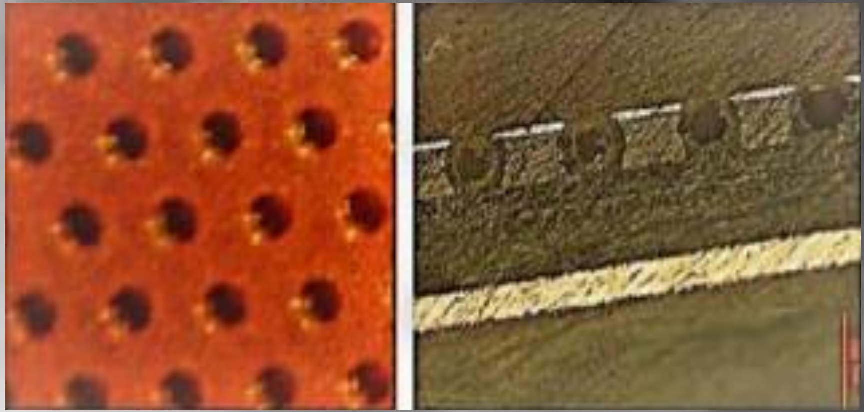
Single-resistive layout:
Technology Transfer to industry

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 **single resistive layer has been extensively tested at the ELTOS SpA (http://www.eltos.it)**





Production Tests @ ELTOS:
- **10x10 cm^2 PCB – uRWELL (PAD r/o)**
- **10x10 cm^2 PCB – uRWELL (strip r/o) coupled with kapton/DLC foils**

The etching of the kapton done by Rui (CERN)

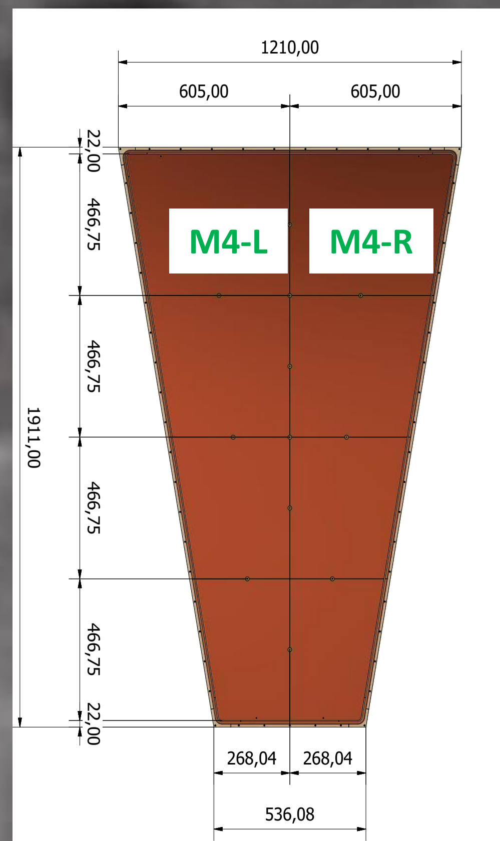
On the last tests done in Feb. 2018 the yield was 100%. More statistics needed.

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**:

- **$1.2 \times 0.5 m^2$ μ-RWELL**
- **$1.9 \times 1.2 m^2$ μ-RWELL**

$1.2 \times 0.5 m^2$ (GE1/1) μ-RWELL



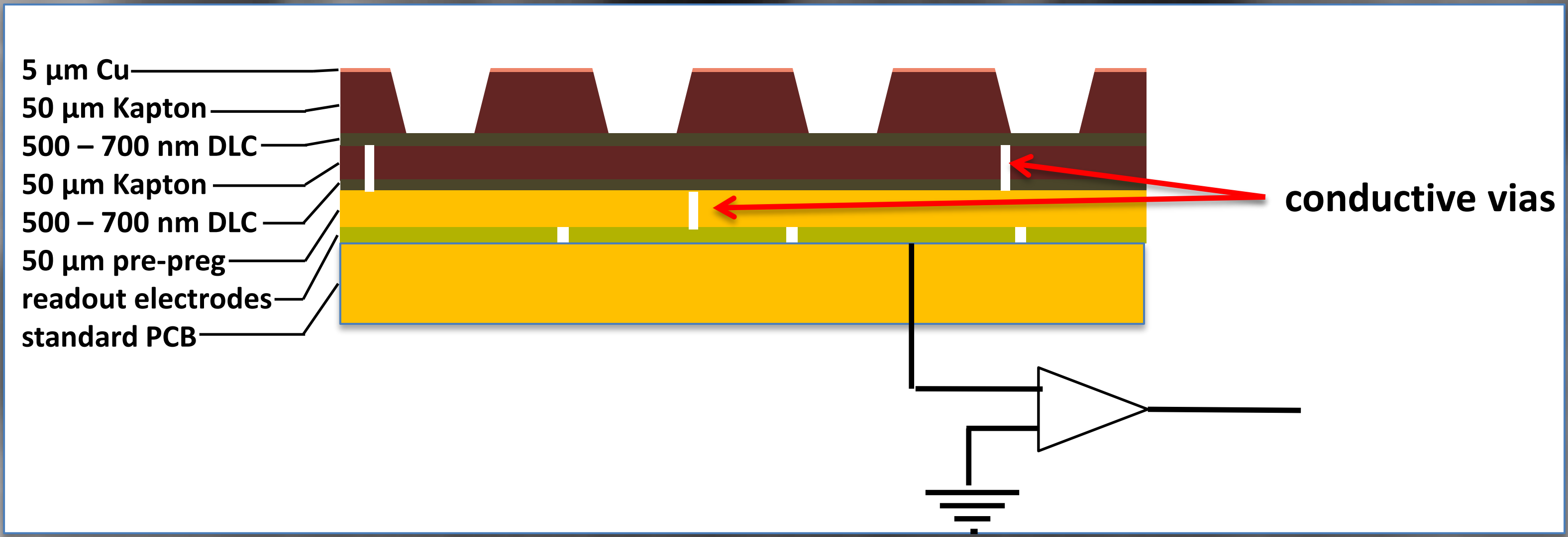
$1.9 \times 1.2 m^2$ (GE2/1) μ-RWELL

High rate layouts

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 (**3-D grounding scheme**)

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



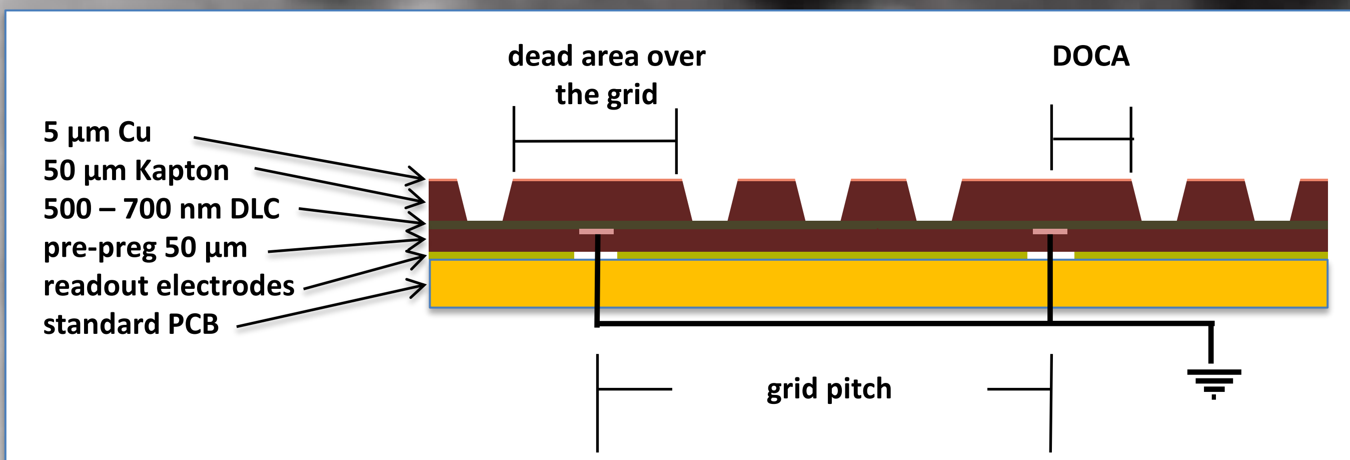
WARNING: The **engineering/industrialization of the double-resistive** layer is **difficult** due to the **manufacturing of the conductive vias on kapton foil.**

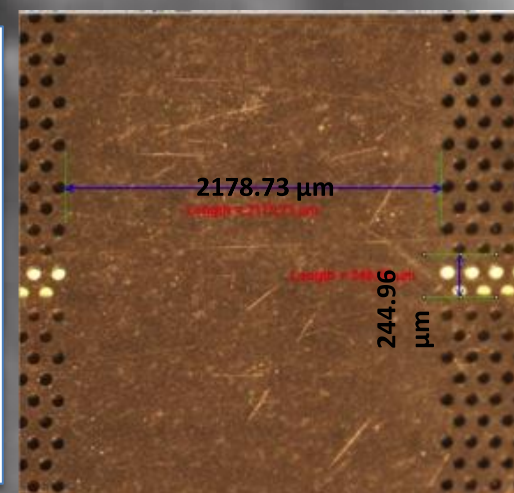
2 – High rate version based on single-resistive layout

The aim is **to maintain a very short path for charges moving on the resistive layer, while simplifying the construction process.**
Several ideas are under development, all based on a **surface grounding** through **continuous/dashed-conductive as well as resistive lines.**

1. Silver Grid: 1st generation - SG1

Relatively thin **conductive lines (250-300 µm wide) are screen-printed** onto **the DLC and surface-grounded at the edge of the active area (as LR version)**



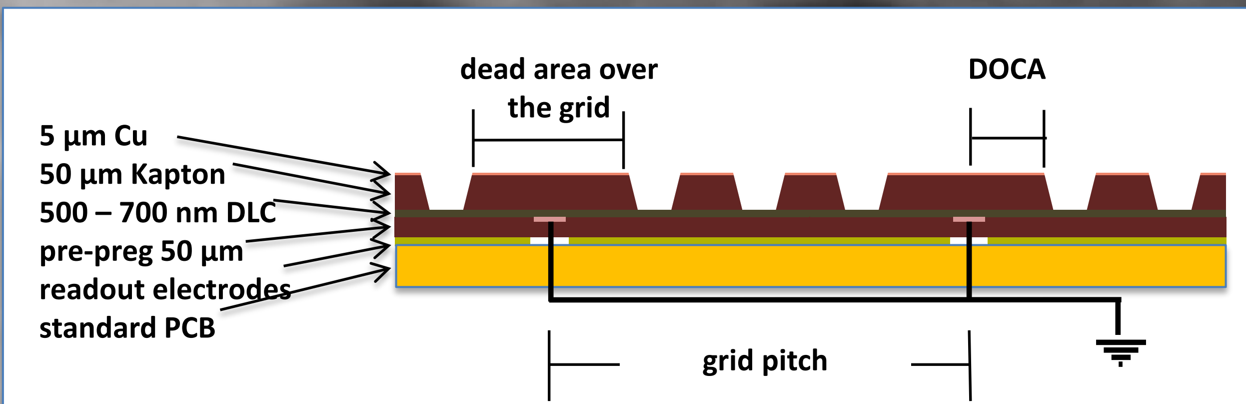


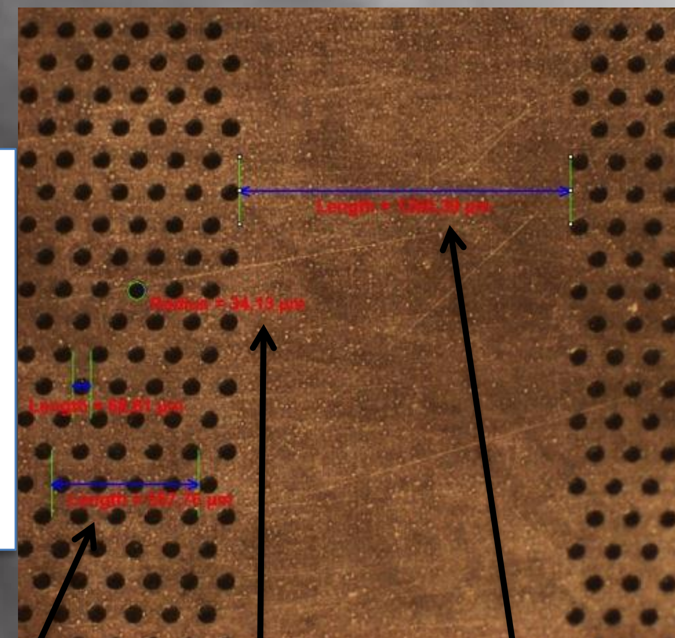
The **introduction of a conductive line** on the bottom layer of the amplification stage **can induce instabilities due to discharges over the DLC surface**

SG-1 designed with **safe geometrical parameters: grid-pitch 6 mm**
dead area 2 mm

Geometrical acceptance 66%

2. Silver Grid: 2nd generation – SG2





557.76 µm 34.13 µm 1260.39 µm

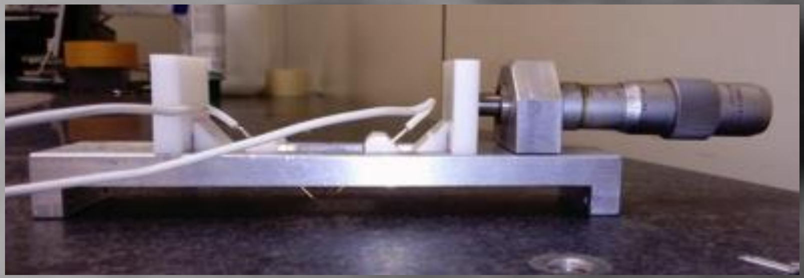
SG-2 designed with **following parameters:**

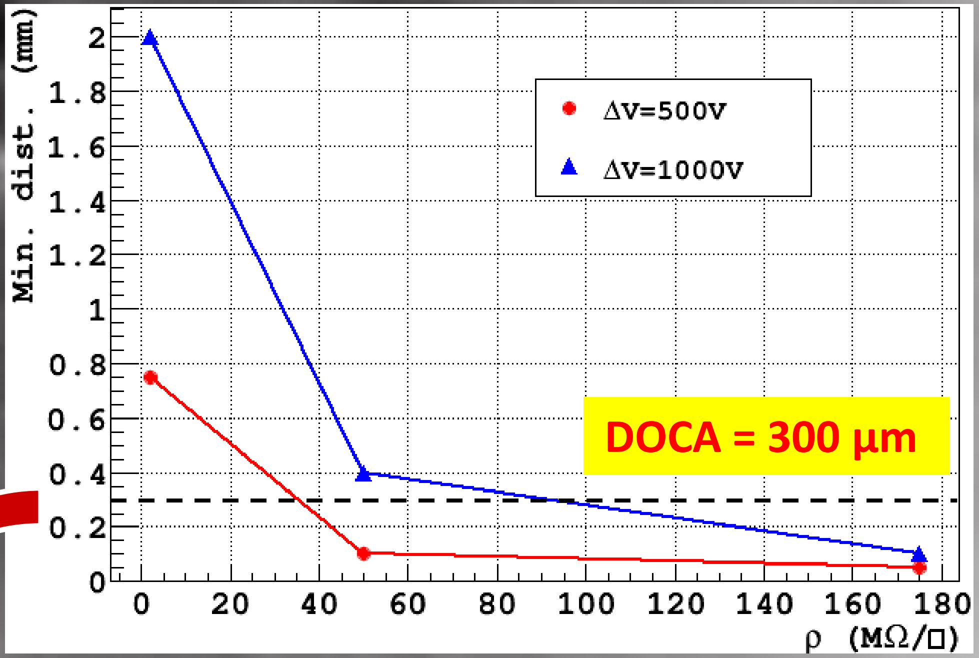
- **grid-pitch 12 mm**
- **dead area 1.2 mm**

➡ **Geometrical acceptance 90%**

Conductive Grid: optimization

In order **to reduce the dead area,** we 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.





ρ ~ 60-80 MΩ/□ → DOCA < 300 μm

Future SG2++ prototypes

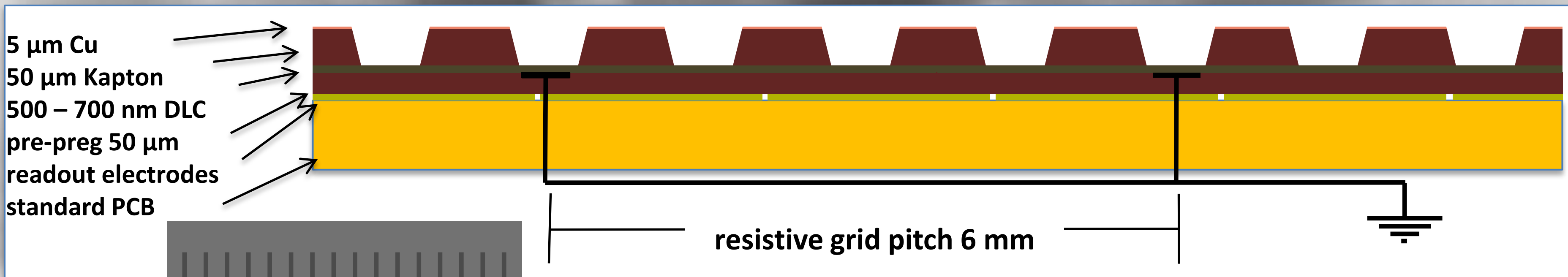
Next step

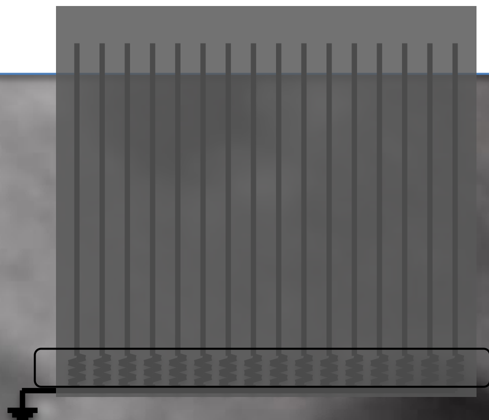
Following the **recipe for Silver Grid (SG1 & SG2)** layout based on the definition of the **grid-pitch, grid-width** we would like to **minimize as much as possible the dead zone** (for a given **DLC resistivity around 60-80 MΩ/□**)

HR Layout	Resistive layer	Grounding pitch (grid/vias)	Grounding type	Dead-zone	Grid width	DOCA
SG2++	single	12 mm	Conductive grid	0,3 + 0,3 mm	100 um	250 um

The very fine grid structure made possible thanks to the USTC DLC+Cu technology
We expect a geometric acceptance of the order of 95%

3 - Resistive Grid (RG)

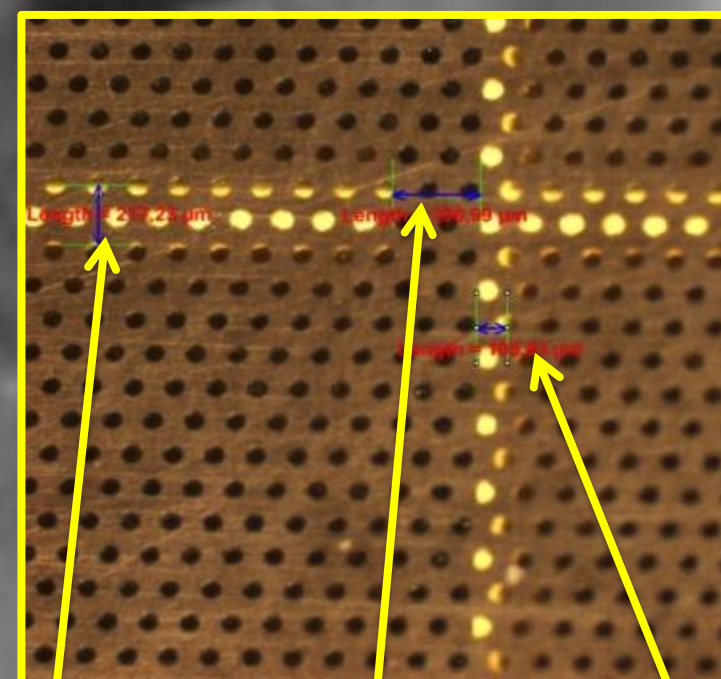




The resistive lines is done by screen printing and the grid (surface) grounding is performed via the resistive DLC. The geometrical parameters:

- grid pitch 6 mm
- No dead zone required

The main problem of such a layout are the poor precision of the lines and the very bad resistance uniformity among lines and along the lines → this scheme will be replaced with the new conductive-dashed scheme.



Y distance of pads: 217.23 µm

Resistive strip width: 296.99 µm

X distance of pads: 105.03 µm

4 – Conductive-Dashed Grid (DG)

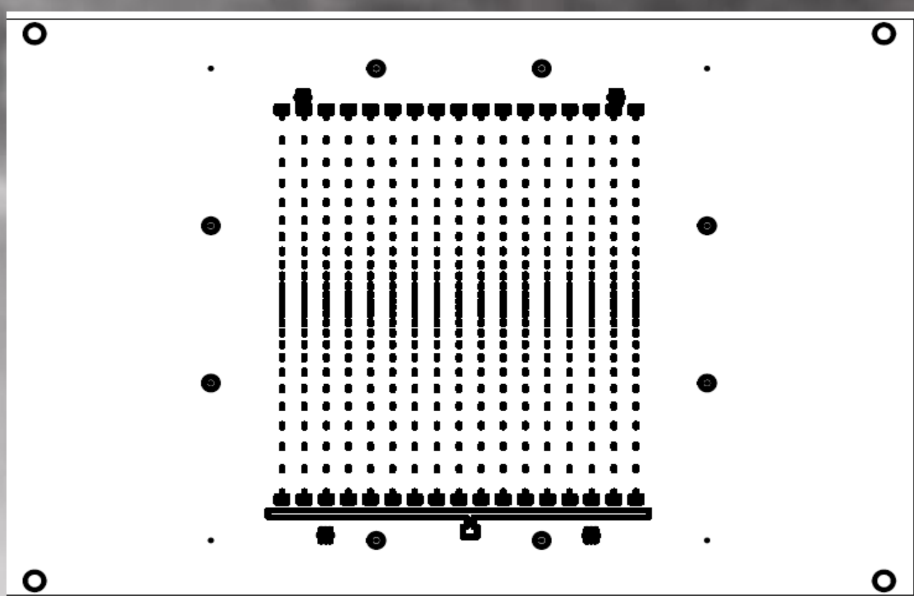
Next step

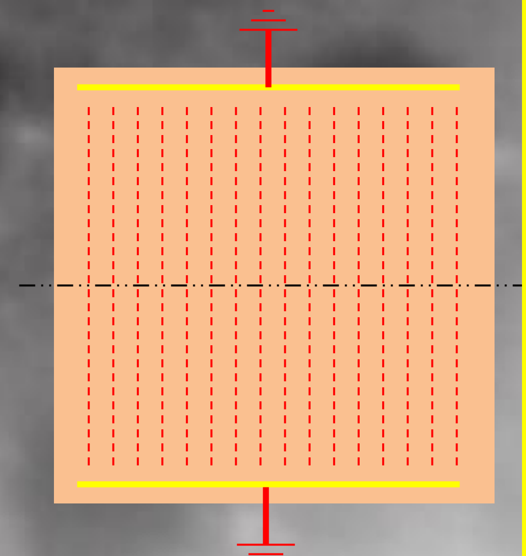
The idea is to **simulate resistive lines** with a suitable pattern of **conductive-dashed lines**.
The size of each element of the dashed is: 1 mm length and 0.1 mm width **(using USTC DLC+Cu technology)**
The **capacitance of the single element of the dashed-line should be kept very low**:

$$C = \varepsilon_0 \varepsilon_r \times \frac{w \times l}{t} \quad \rightarrow \quad C = 0,07\ pF\ (l = 1mm; w = 100\mu m; t = 50\mu m)$$

As a consequence the problem of **discharges on DLC surface should be kept under control.**

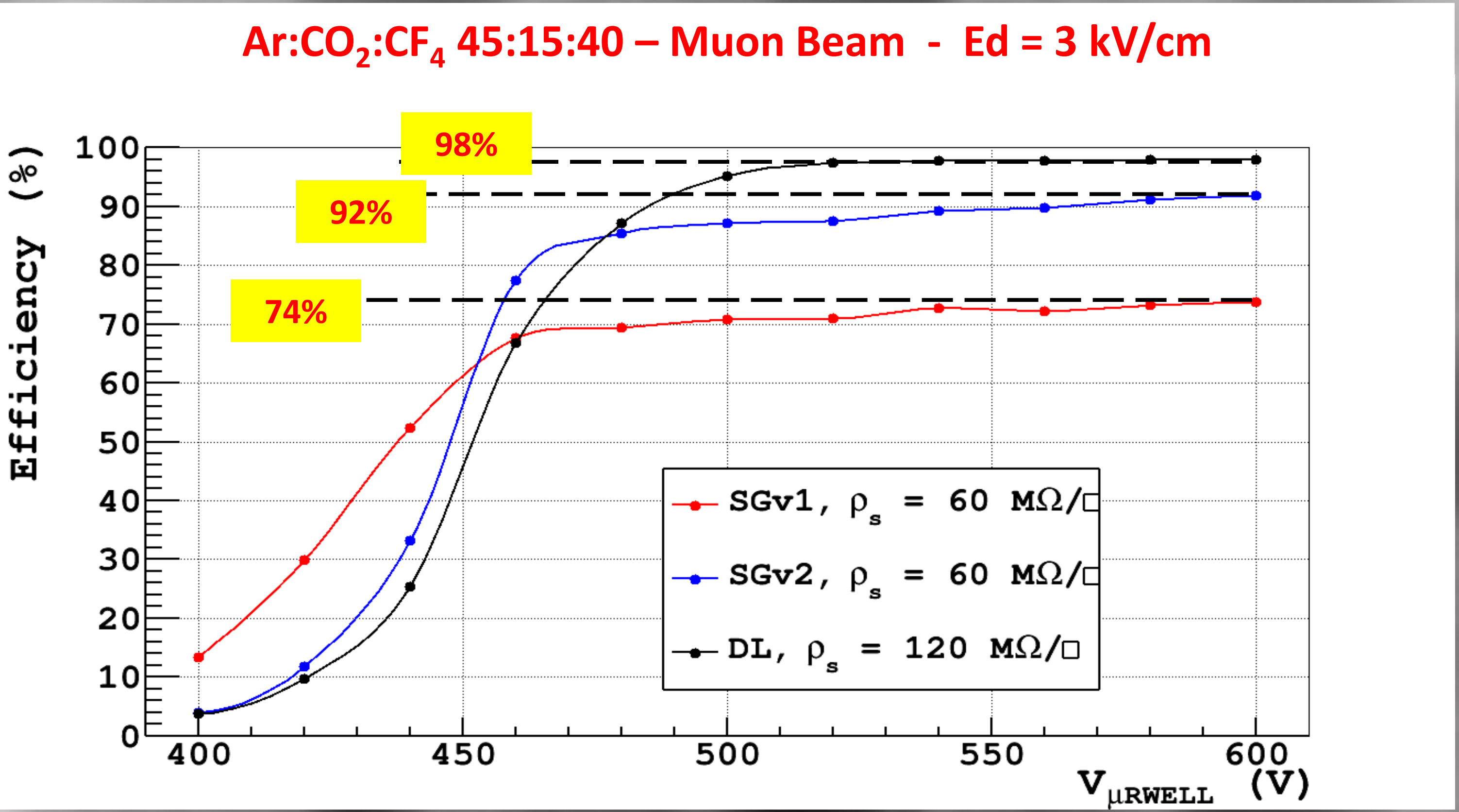
The **distance between dashes at the edges (close to ground connection)** is **ten times the one in the center**. In this way **the resistance at the center is negligible w.r.t the resistance at the edge** ensuring an acceptable uniformity (at level of 10%).





Design to be finalized
Construction foreseen this summer

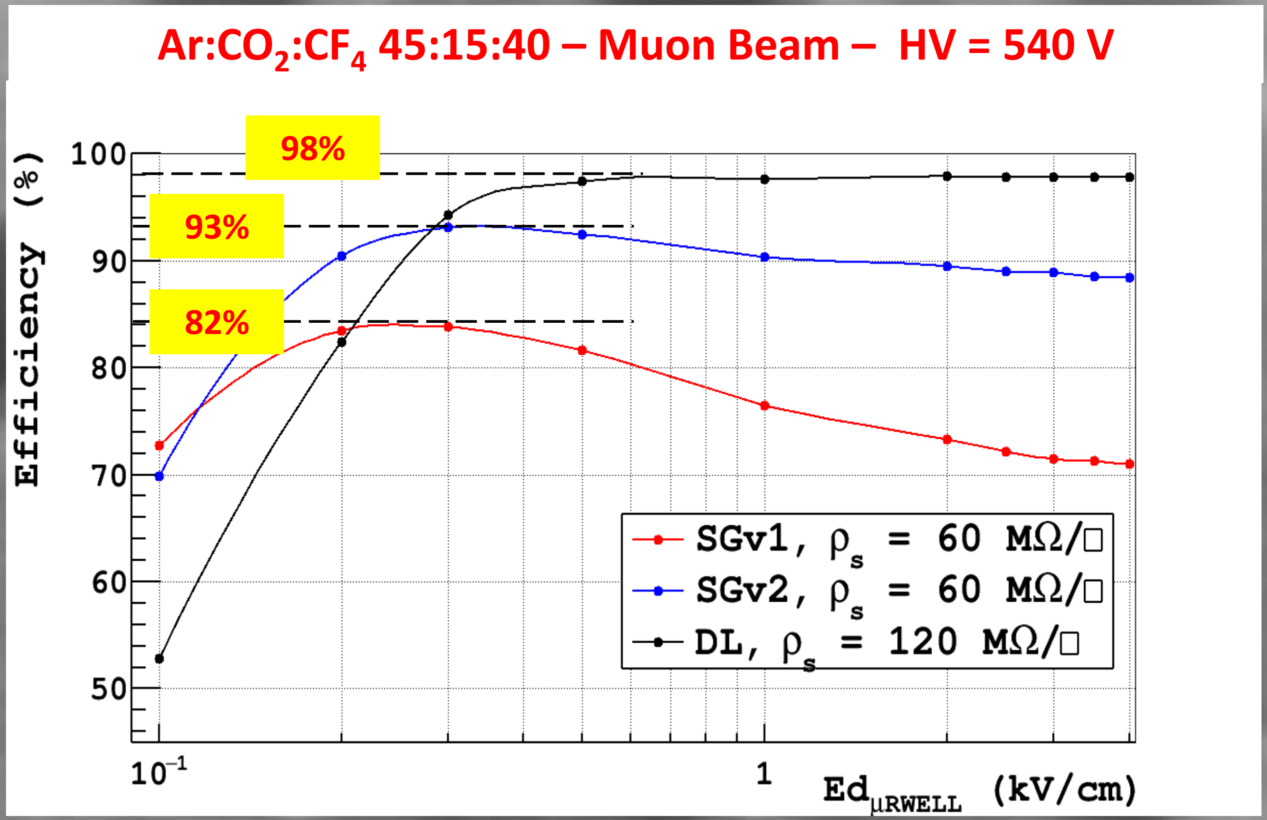
HR layouts performance: the efficiency (I)



As expected the **DL prototype** reaches **full tracking efficiency – 98%** (NO DEAD ZONE in the amplification stage).

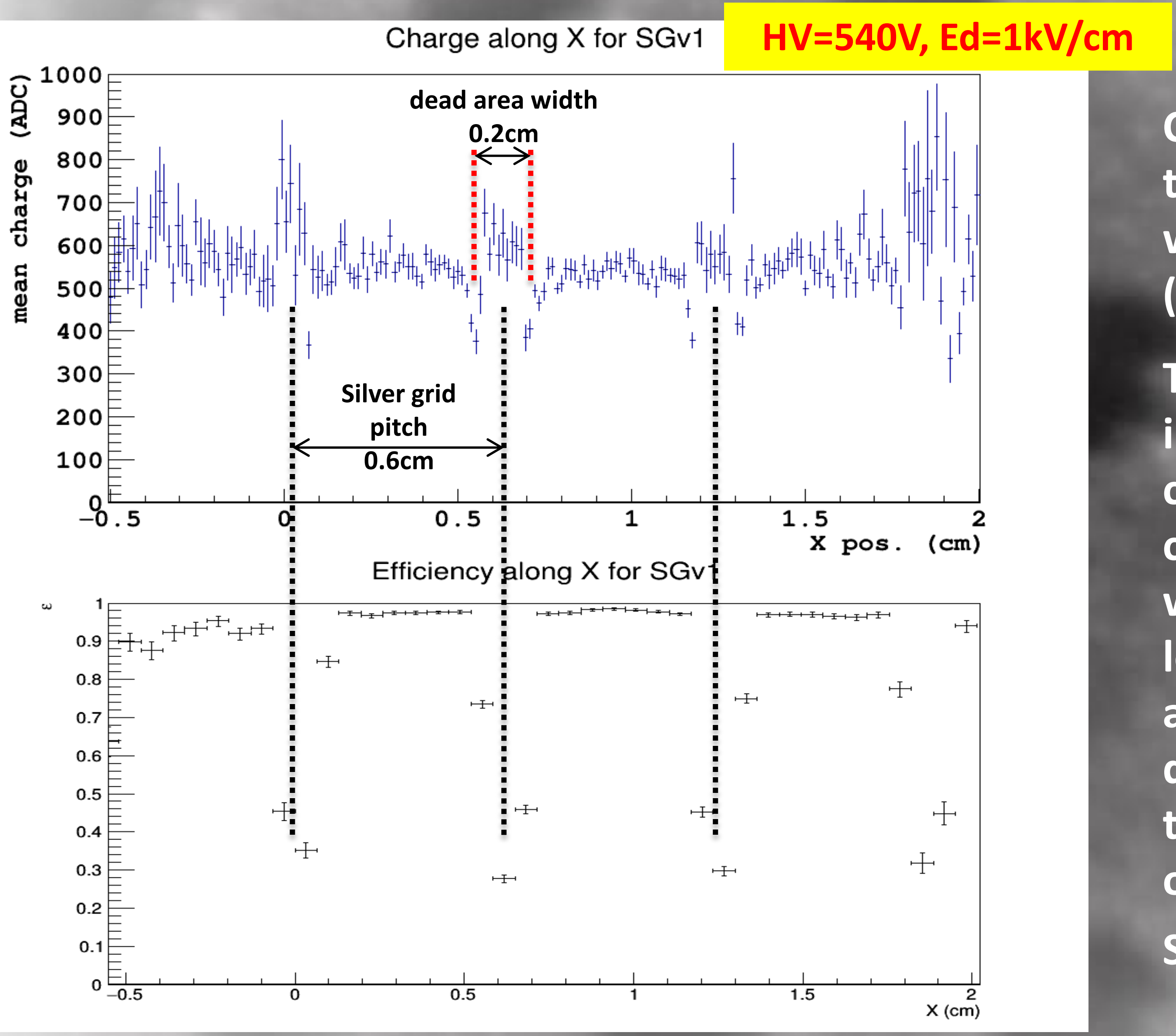
The **SG1 & SG2** show lower efficiency **(74% -92%) BUT higher than their geometrical acceptance** (**66% and 90%** respectively), thanks to the **efficient electron collection mechanism** that **reduce the effective dead zone.** **With the optmized SG2 version (SG2^{++} w/95% geometrical acceptance) we hope to achieve almost full efficiency (97-98%).**

HR layouts performance: the efficiency (II)



At low Ed (suitable for micro-TPC mode – see later on) the further rise of the efficiency of the SG prototypes could be explained with the <u>further increase of the electron collection efficiency close to the dead zone of the detectors</u>. While for the DL we observe the standard efficiency drop (generally due to e –I recombination …)

Charge & Efficiency profiles of SG1 (w/pions)

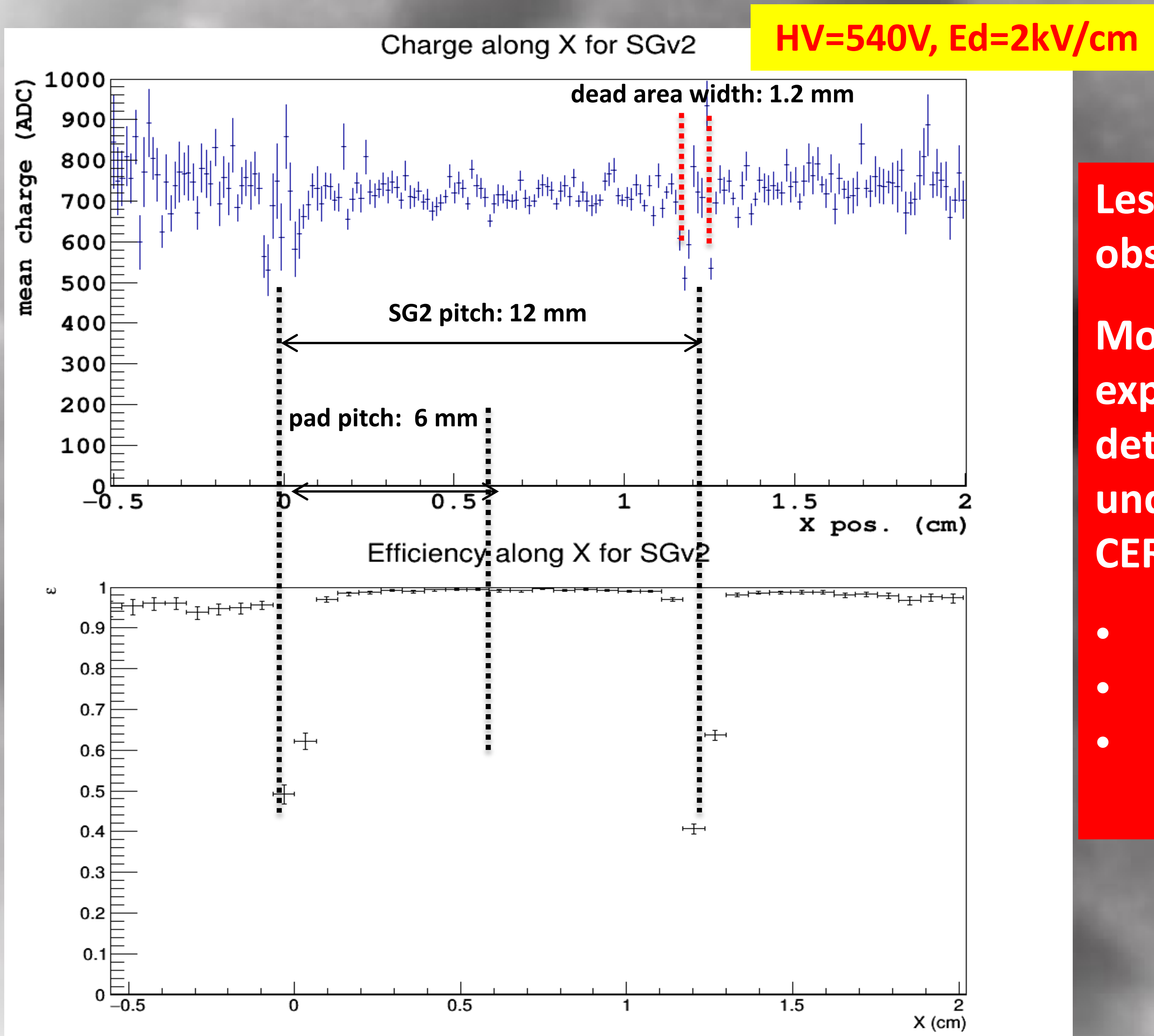


Close to dead zone the charge increases while the efficiency (obviously) decreases.

The systematic increase of the charge close to the dead zone could be correlated with edge effects locally increasing the amplification of the detector, extending the multiplication outside the wells.

Simulation needed !!!

Charge & Efficiency profiles of SG2 (with pions)

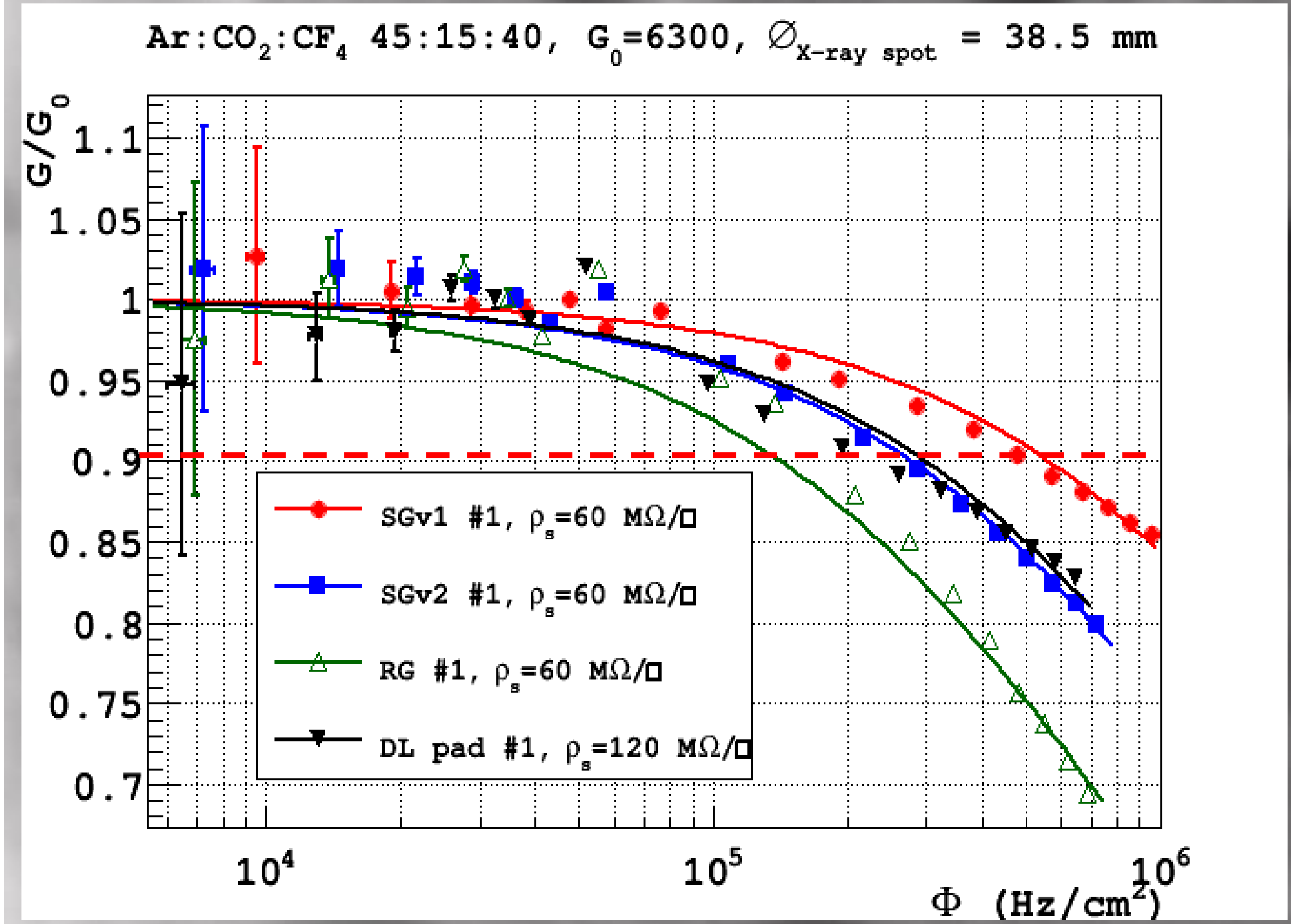


Less evident effects observed for the SG2

More uniform response expected with the new detector layout SG2++, under production at CERN (by Rui) for which:

- picth = 12 mm
- dead zone = 0,6 mm
- geometrical acceptance 95%

Gain drop measurement w/5.9 X-ray

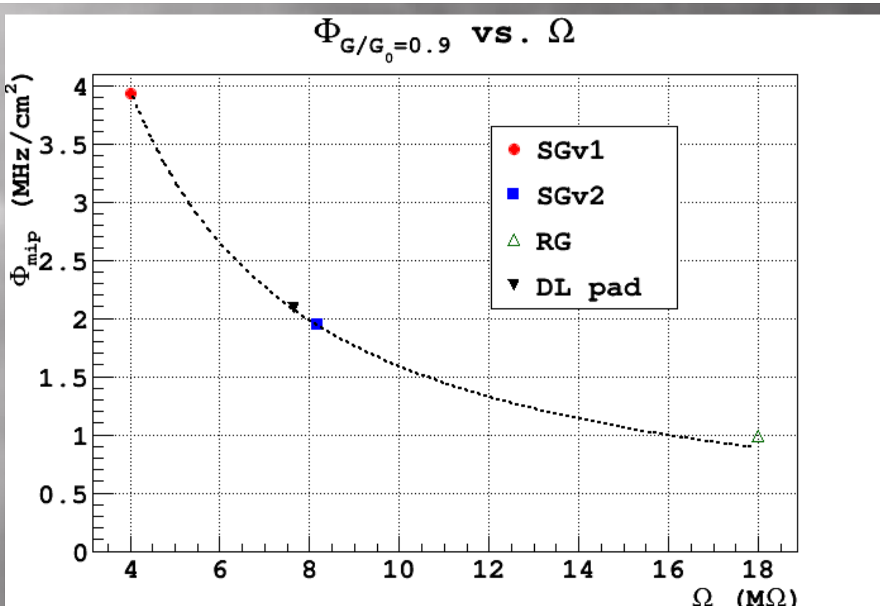


The **gain drop** is due to the **Ohmic effect** on the resistive layer: **charges collected on the DLC drift** towards the **ground** facing an **effective resistance Ω**, depending on the **evacuation scheme geometry and DLC surface resistivity.**
Ω is computed by the **parameter p_0** coming from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

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

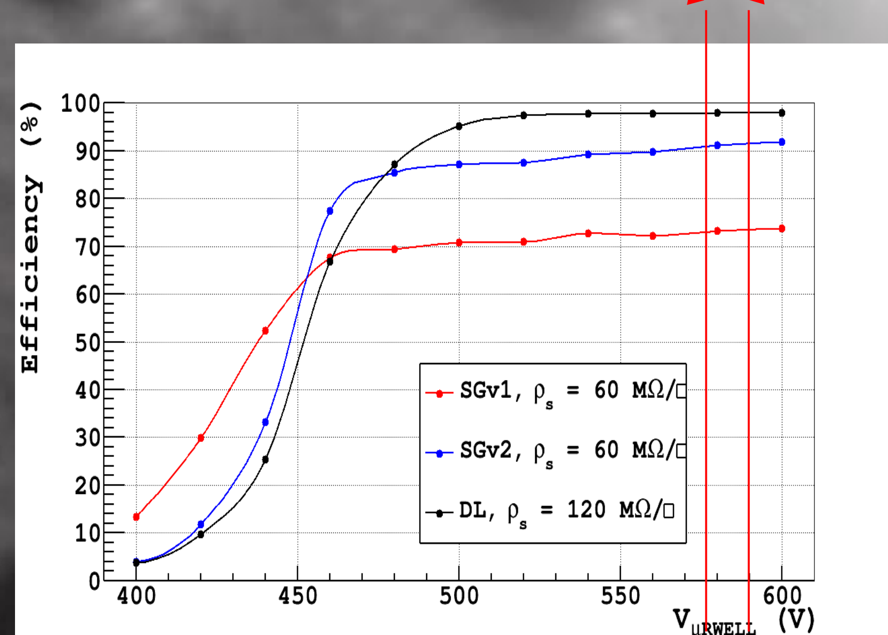
Rate Capability vs Ω (for m.i.p)

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



NO EFFICIENCY LOSS !!!

$G=0.9G_0$ $G_0=6300$



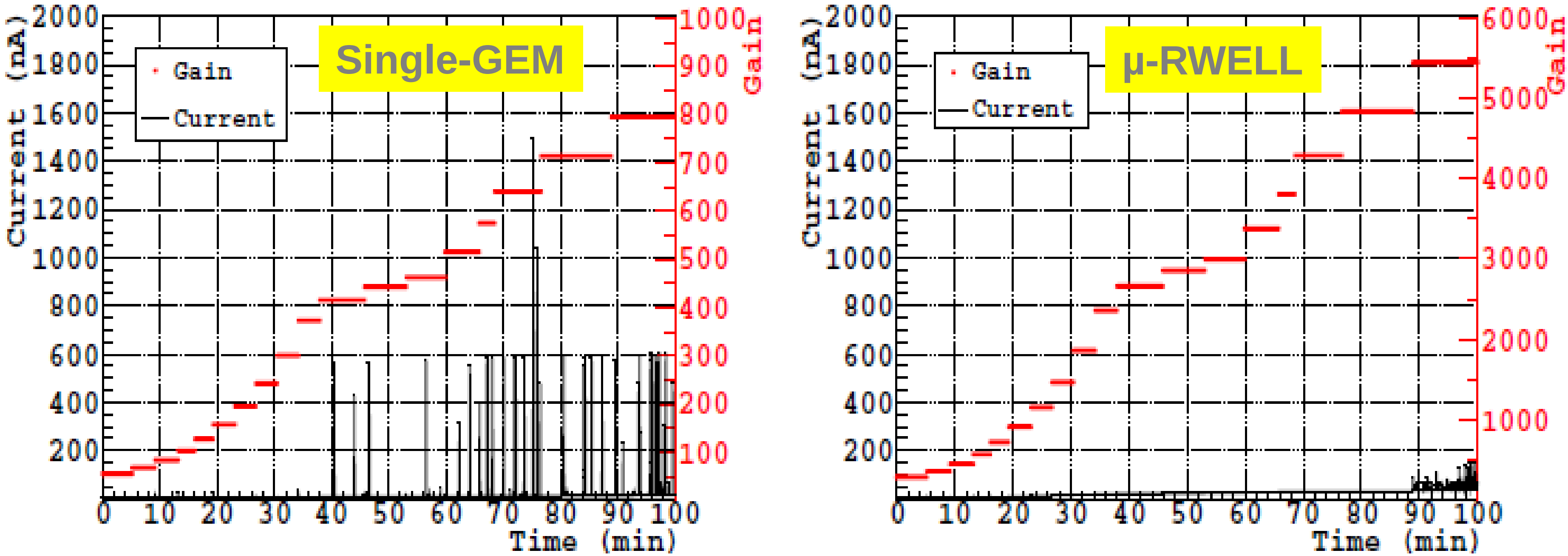
The **primary ionization of 5.9 keV X- ray is ~7 times larger than the one created by a m.i.p.**

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

DLC aging

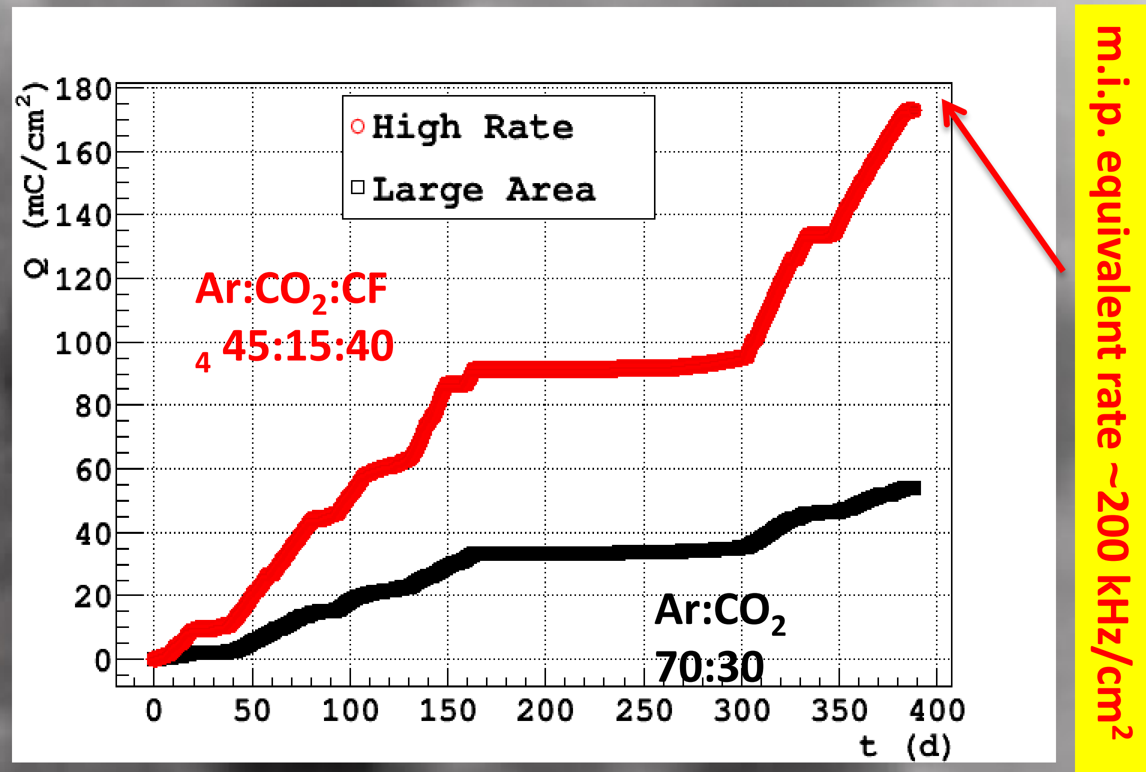
wrt to a GEM detector the only new component in the μ-RWELL is the DLC, so that we think that aging studies for μ-RWELL should mainly be focussed on DLC behaviour under irradiation and current drawing

Preliminary 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

Ageing test at GIF^{++} (I)



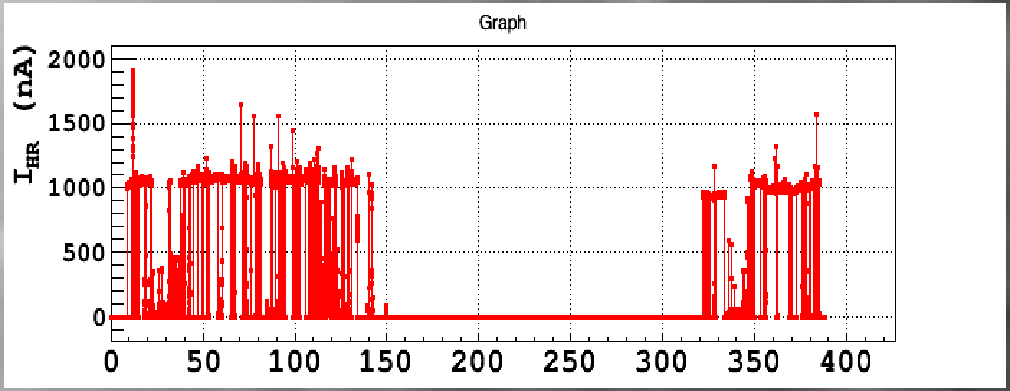
The ageing effects on DLC is under study at the GIF++ by irradiating different µ-RWELL prototypes operated at a gain of ~4000 .

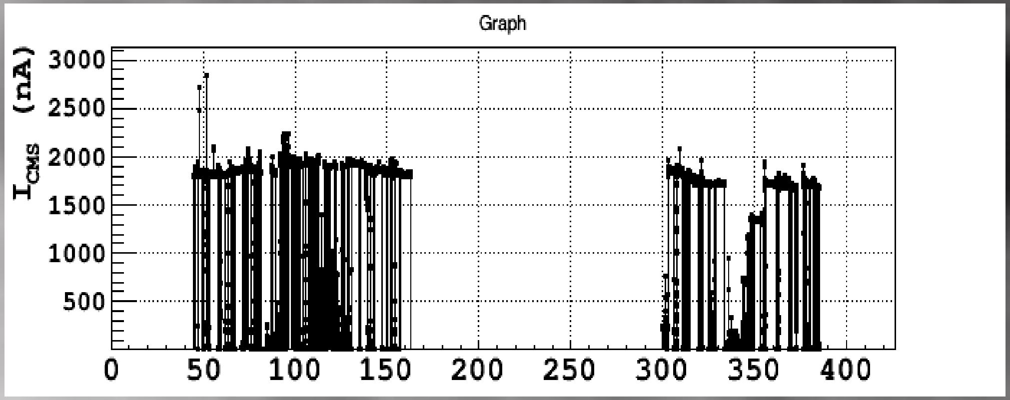
On the most irradiated detector (~200 kHz/cm^2 m.ip. equivalent) a charge of about 180 mC/cm^2 has been integrated (in about 240 days up-time of the source).

No effects have been observed till now. Detectors will be opened by the end of the 2018.

Ageing test at GIF^{++} (II)

Very Preliminary





HR:

- $Ar/CO_2/CF_4$= 45/15/40
- ρ_s ~ 12 MΩ/□
- 100 cm^2
- 200 kHz/cm^2 mip equivalent
- Up-time ~ $1{,}6x10^7$ sec
- N_{spark} ~ 32

P_{spark} ~ $1x10^{-13}$

LR:

- Ar/CO_2 = 90/10
- ρ_s ~ 70 MΩ/□
- 380 cm^2
- 130 kHz/cm^2 mip equivalent
- Up-time ~ $1{,}7x10^7$ sec
- N_{spark} ~ 19

P_{spark} ~ $2x10^{-14}$

sampling time 1 ms / acquisition rate every 2 seconds

Future DLC Aging/Discharge tests

A systematic **stress study of the DLC** as component of the micro-RWELL **is mandatory:**

In the framework of the RD51-CP (USTC, Kobe, CERN and LNF) we are planning:

- define a stable manufacturing process to deposit **DLC+Cu on APICAL foils, opening the way towards improved HR layouts**
- study possible surface resistivity of DLC changes during the detector manufacturing
- study the DLC stability under long-term irradiation

Long-term tests:

- check for **DLC aging effects** due to **current flow** inducing a **high current density, up to 10÷30 nA/cm^2 (@ GIF++ 10 nA/cm^2).**
- **aging test of DLC embedded on detectors** irradiated with different radiation sources: **localized 5.9 keV X-rays, gamma source (660 keV from ^{137}Cs), alpha particles (5.4 MeV from ^{241}Am) or thermal neutrons**

Every suggestion & help are welcome

Summary

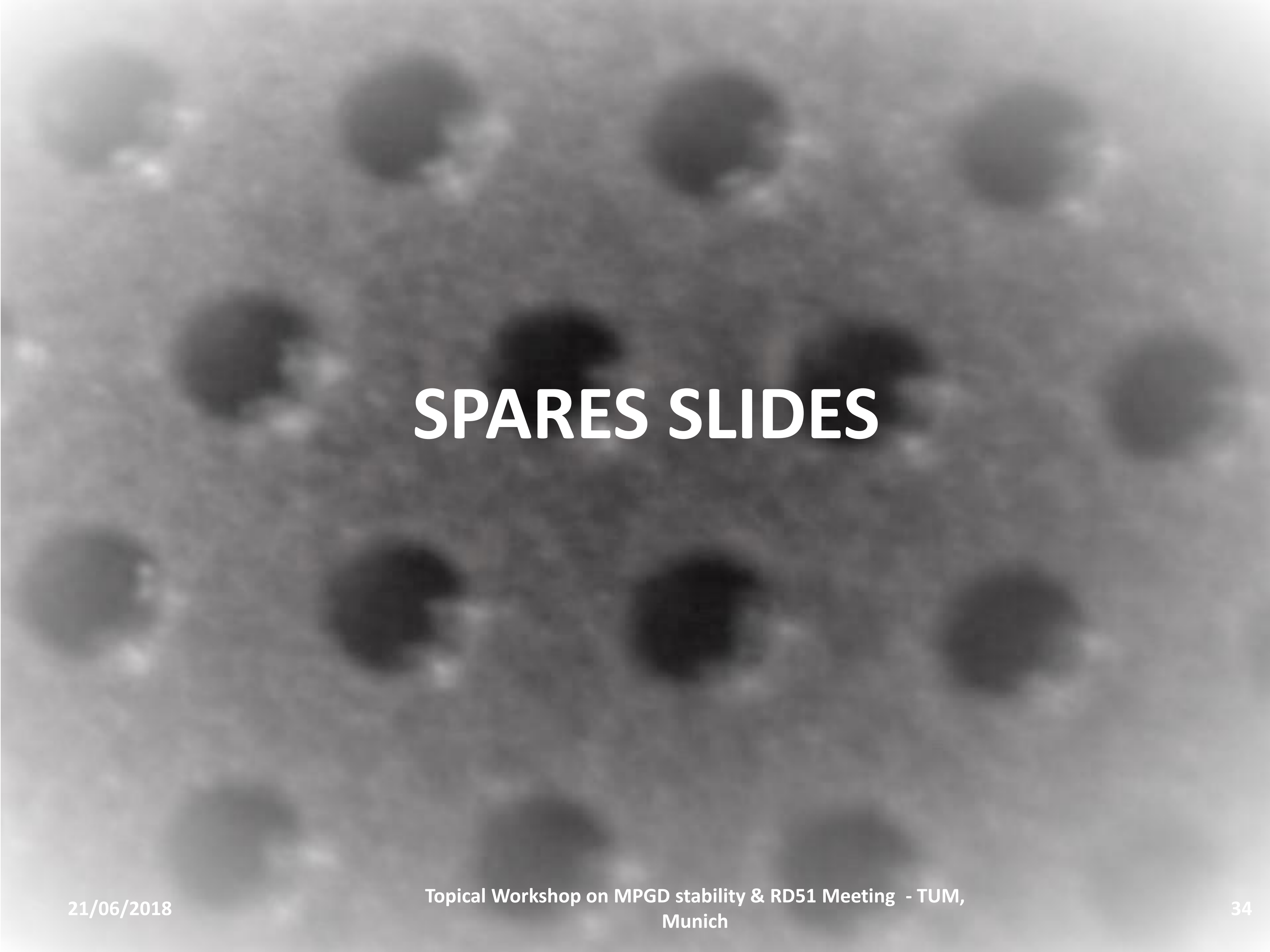
The µ-RWELL is a new technology suitable for **large area planar tracking devices** as well as **high space resolution Cylindrical Inner Trackers:**

- **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**

<u>**Status of the R&D/engineering:**</u>

- **Low rate (<100kHz/cm^2) :**
  - **small and large area prototypes built and extensively tested**
  - **Technology Transfer to industry (@ ELTOS) well advanced**
- **High rate (>1 MHz/cm^2):**
  - **several layouts under study showing very promising performance**
  - **the engineering and the TT to industry will be started in 2019**
- **R&D on DLC manufacturing processes, study of stability under irradiation and current flow strongly required by the *Resistive-Community***

Thanks for the attention



SPARES SLIDES

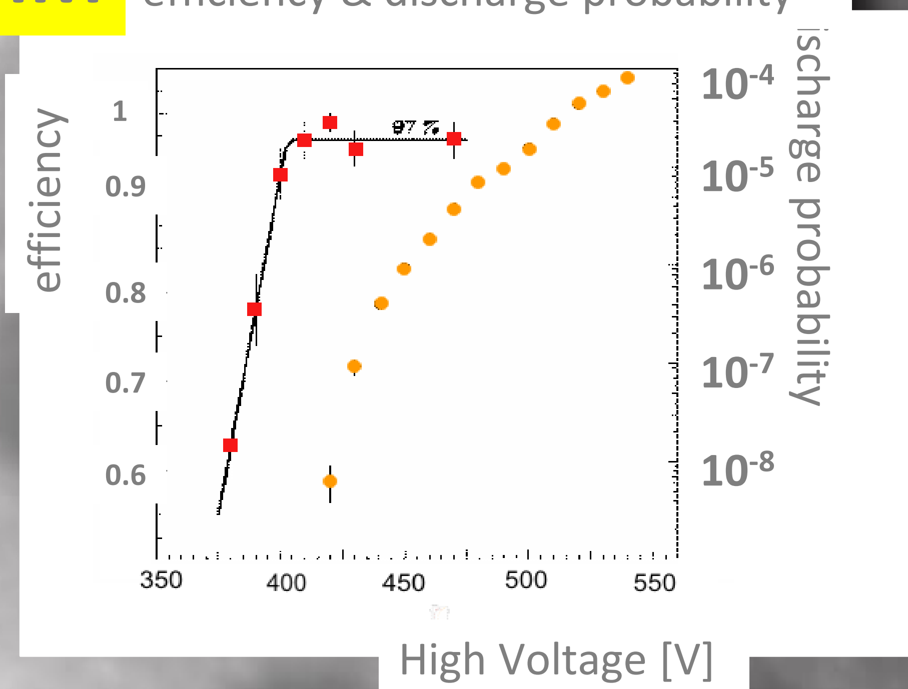
MPGDs: stability

The biggest"enemy"of MPGDs are the discharges.

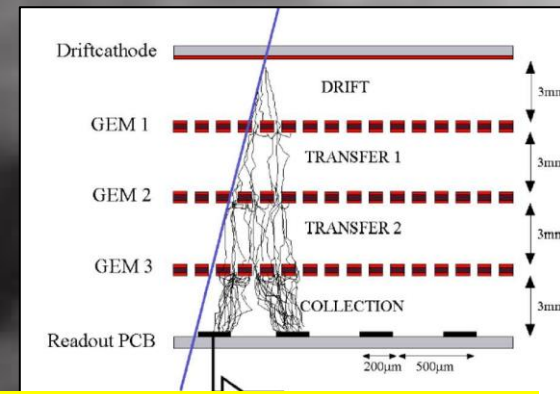
Due to the **fine structure and the typical micrometric distance of their electrodes**, MPGDs generally **suffer from spark occurrence that can eventually damage the detector and the related FEE.**

MM

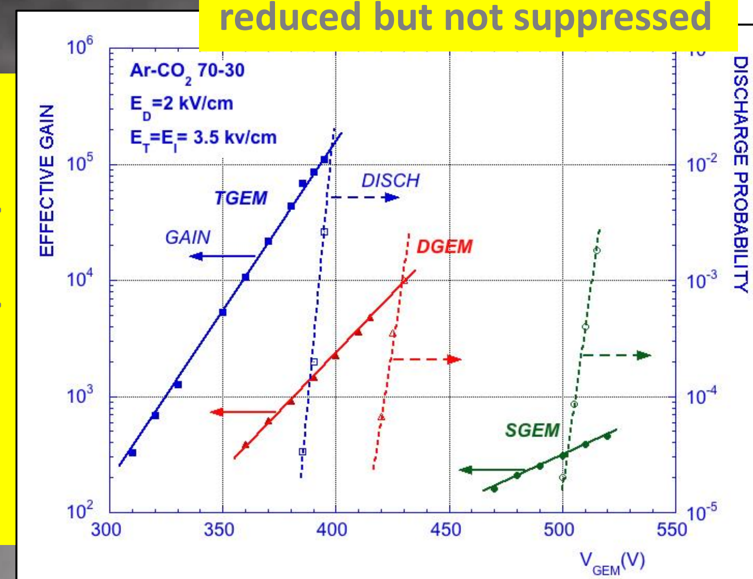
efficiency & discharge probability



GEM



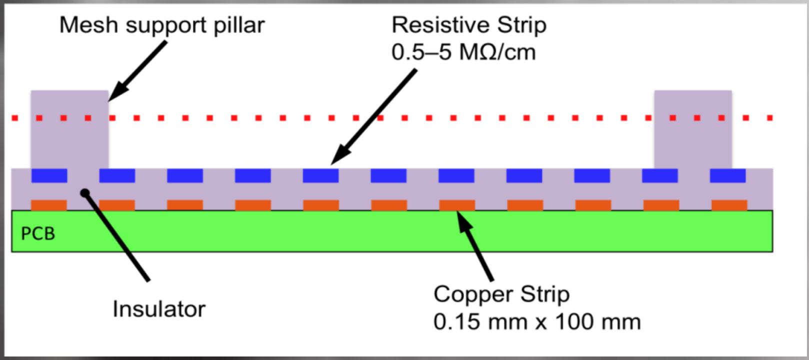
reduced but not suppressed



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

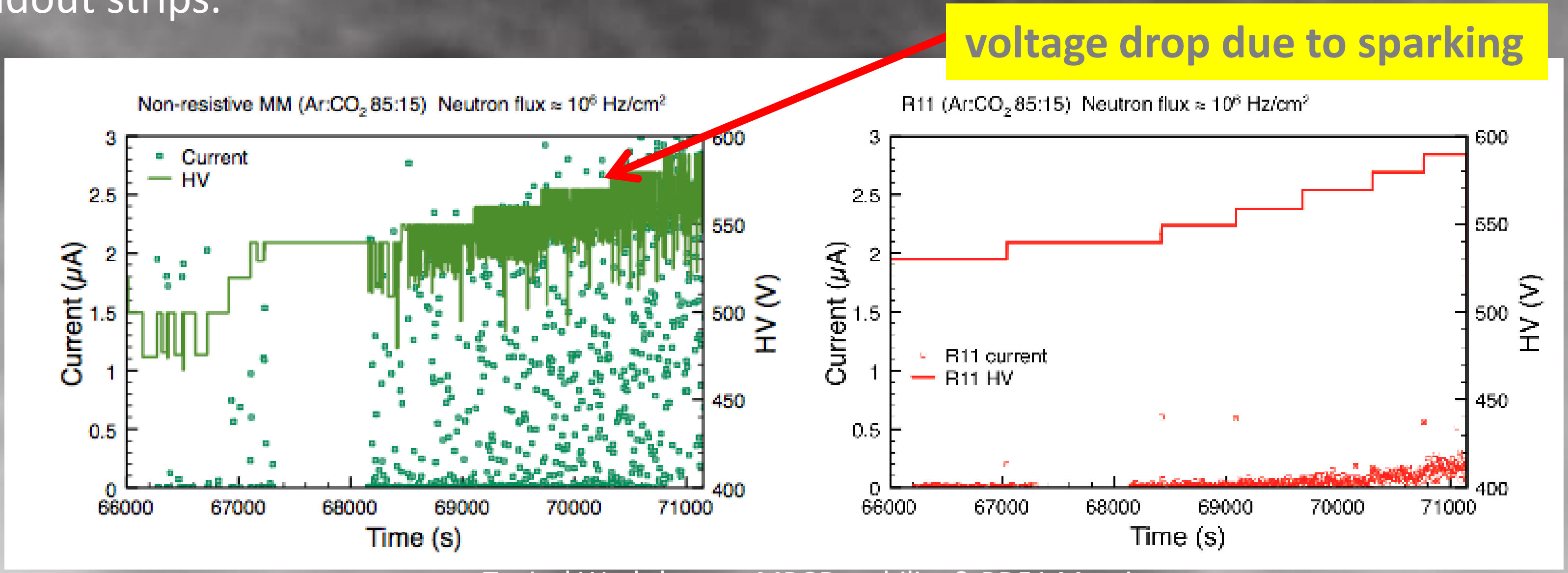
Technology improvements for MicroMegas

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.**



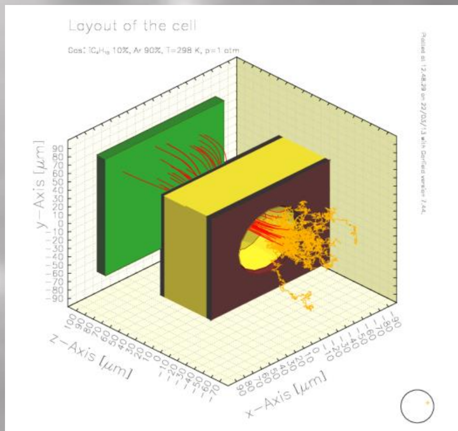
by R.de Oliveira TE MPE CERN Workshop

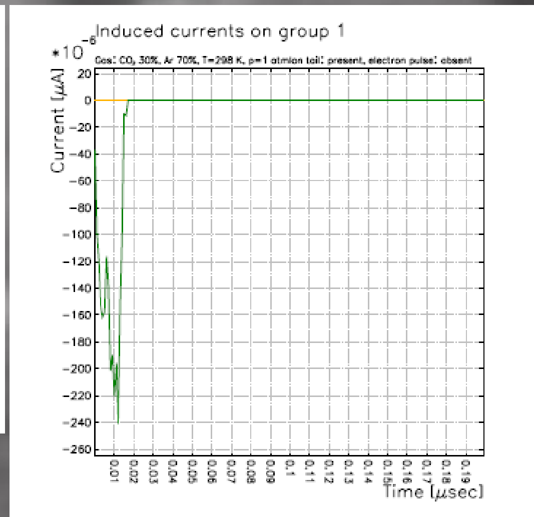
The resistive layer is realized as resistive strips capacitive coupled with the copper readout strips.



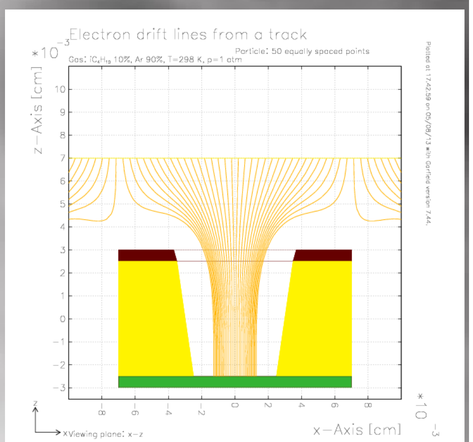
The μ-RWELL vs GEM (*Garfield*)

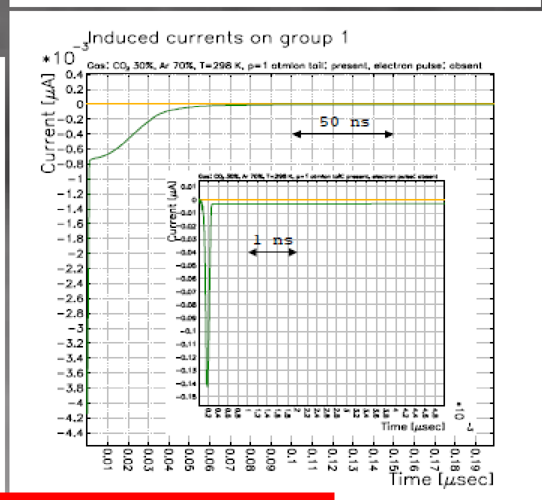
GEM – Ar:CO2 70:30 gas mixture





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.**



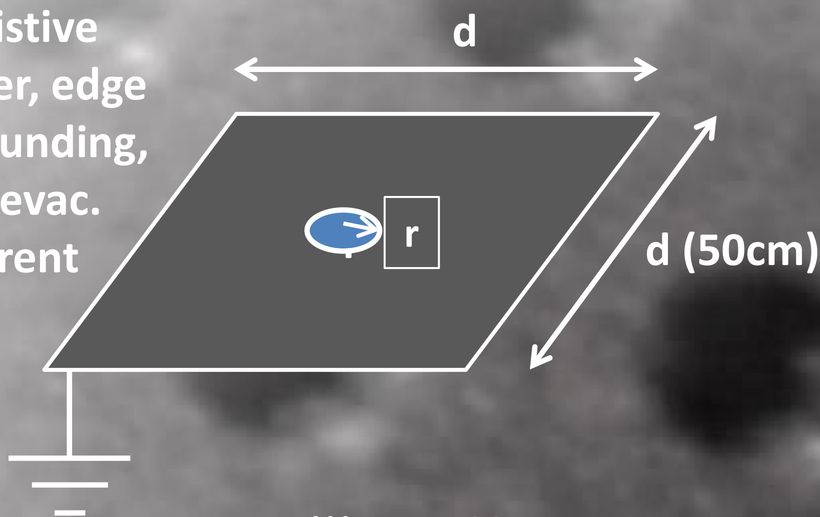


μ-RWELL – Ar:CO2 70:30 gas mixture

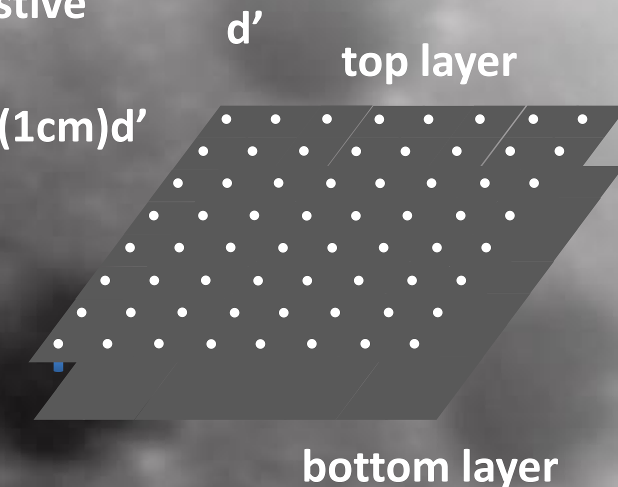
Signal from a single ionization electron in a μ-RWELL.
The absence of the induction gap is responsible for the **fast initial spike, about 200 ps**, induced by the **motion and fast collection of the electrons** then **followed by a ~50 ns ion tail**.
More similar to a MM !!!

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

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

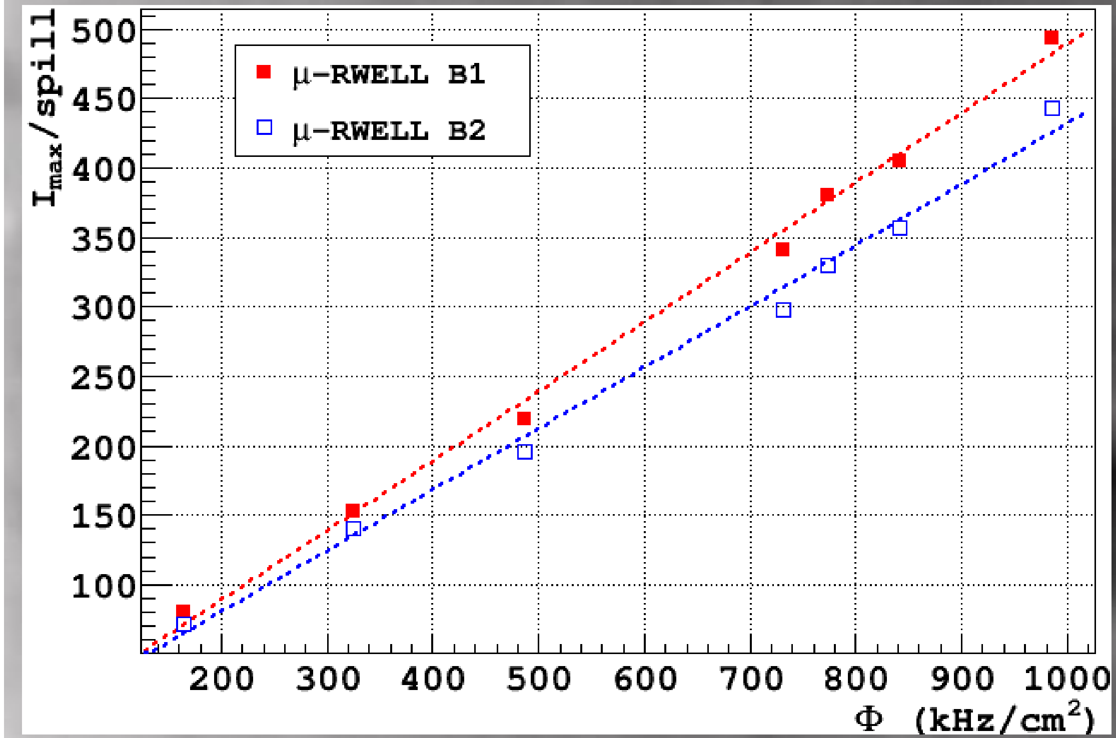
$$\Omega/\Omega' \sim (\rho_s / \rho_s') \times d/3d'$$

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

(*) 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

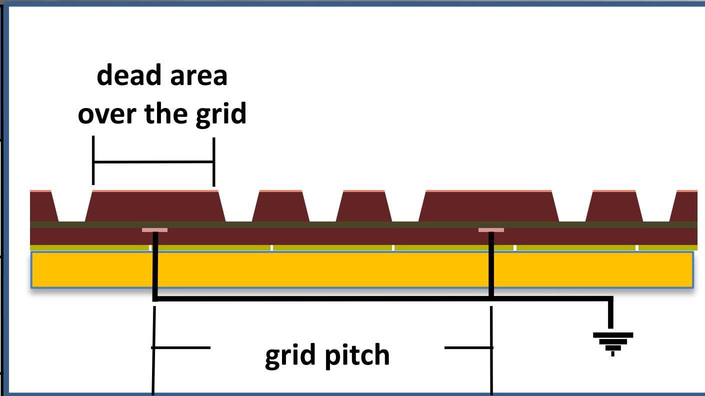
Beam spot ~2 cm^2 (RMS)

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

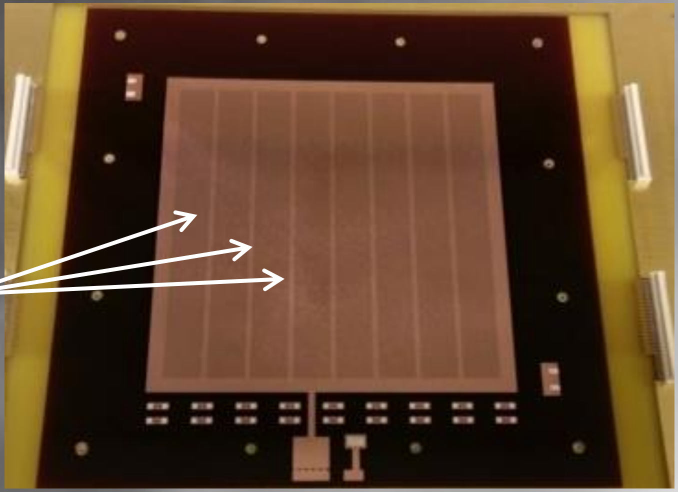
New ideas for the HR layout

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

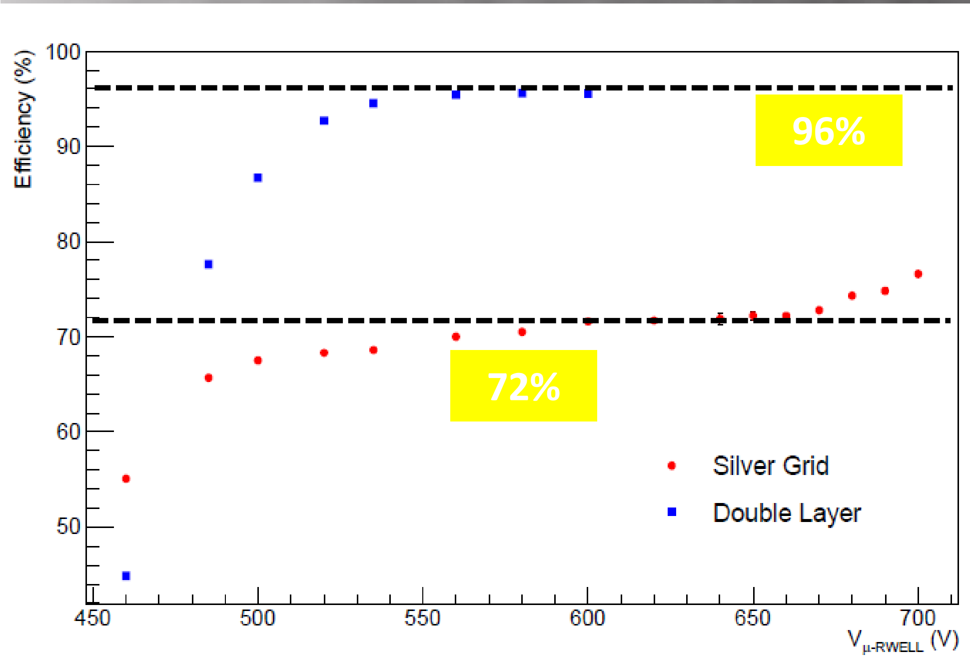


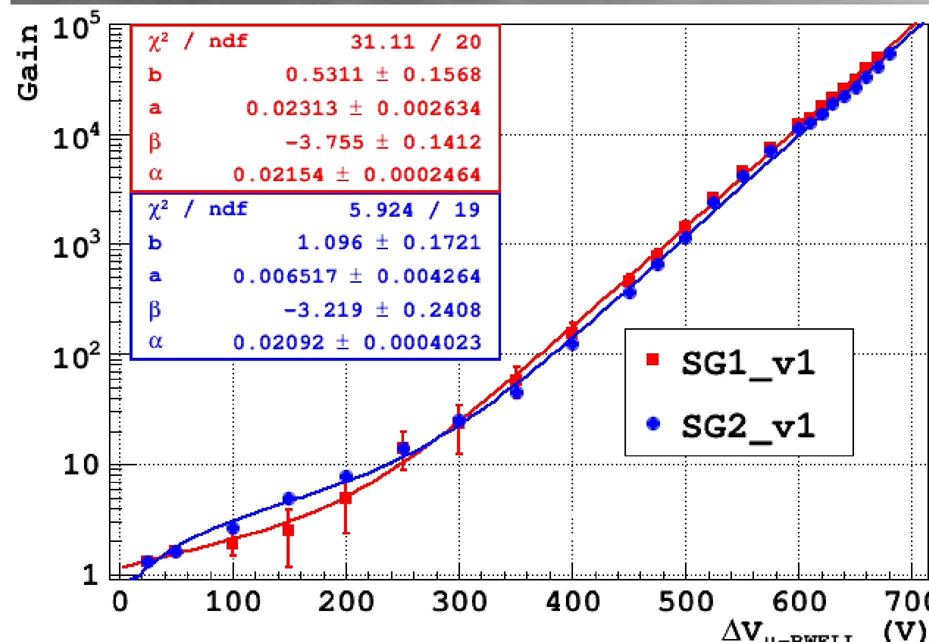
The **conductive grid** on the bottom of the amplification stage **can induce instabilities due to discharges over the DLC surface, thus requiring for the introduction of a dead zone on the amplification stage. This is not the case for the resistive grid layout.**



Silver Grid v1:
X-rays and test beam characterization

SG version of µ-RWELL vs Double Layer version





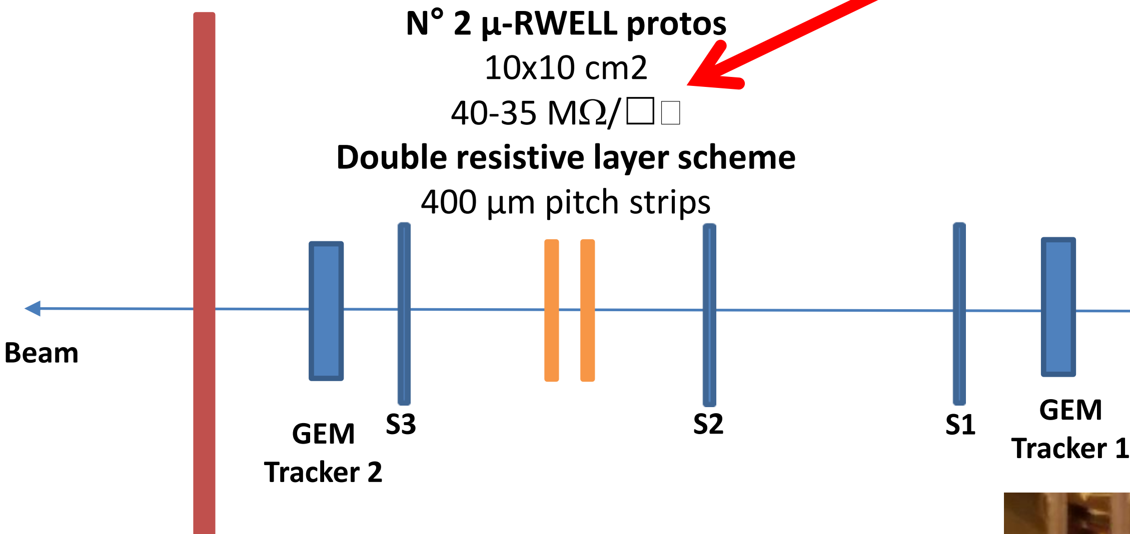
A **very high stability of the SG wrt the DL** has been observed: **the SG has been operated at gains largely exceeding the typical 10^4 (up to 10^5).** The **reason** of a so high stability is **under investigation**. The **lower efficiency is due to the geometrical dead zone**. A dedicated study of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

Time performance

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

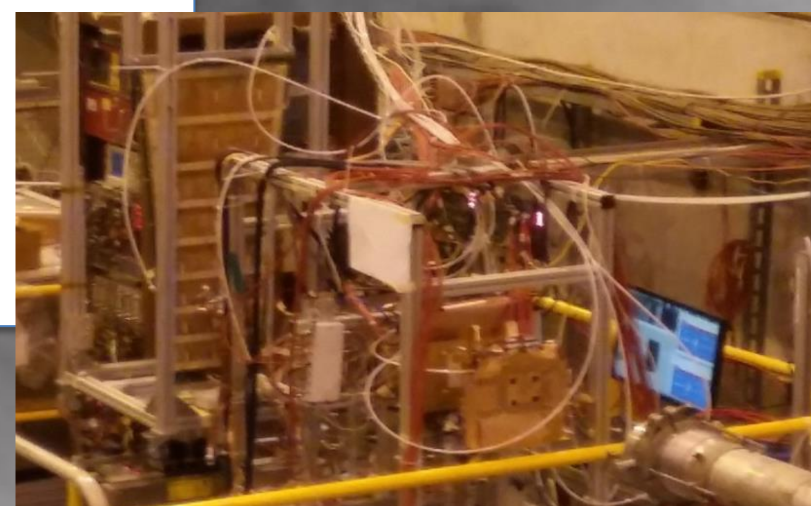
3 μ-RWELL prototypes:
- 40-35-70 MΩ /□
- VFAT (digital FEE)
- $Ar/CO_2/CF_4$ = 45/15/40

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



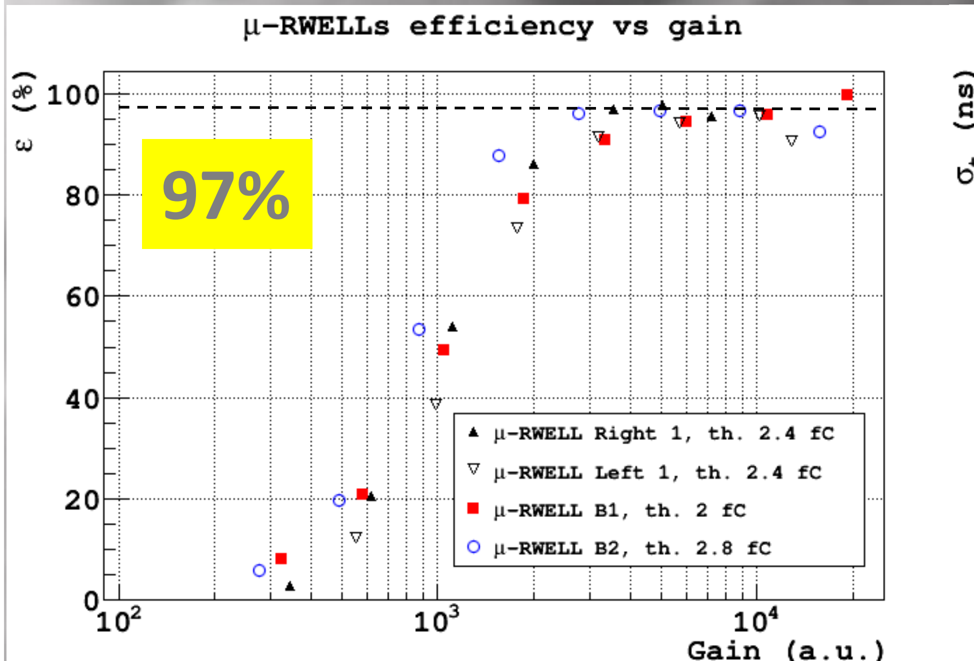
Trigger=S1+S2+S3

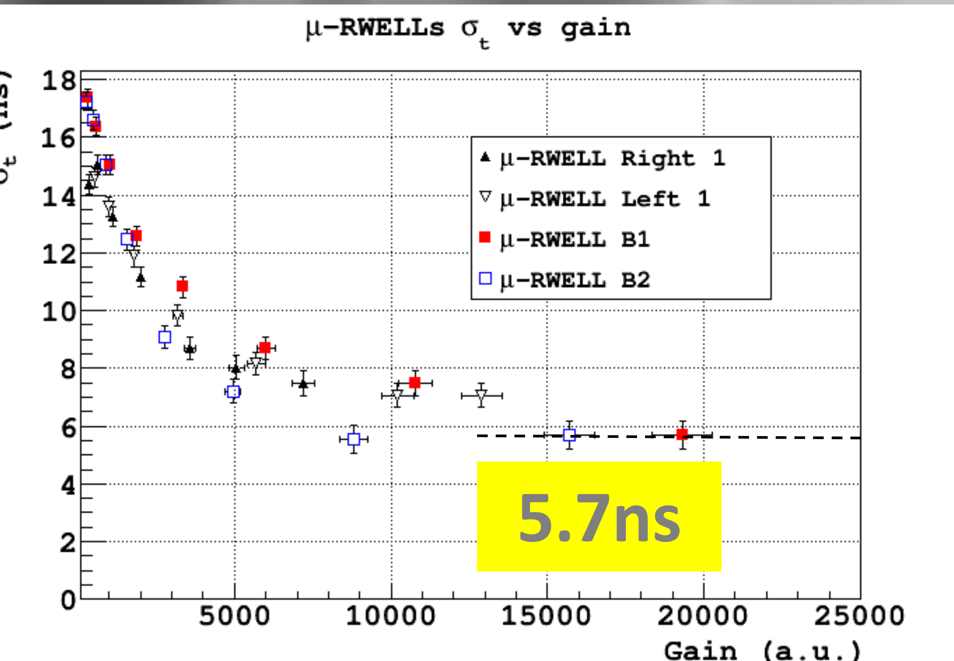
N° 1 μ-RWELL proto
100x50 cm2
70 MΩ/□
Single resistive layer scheme
800 μm pitch strips



GOAL: <u>time resolution measurement (never done before)</u>

Time Performance





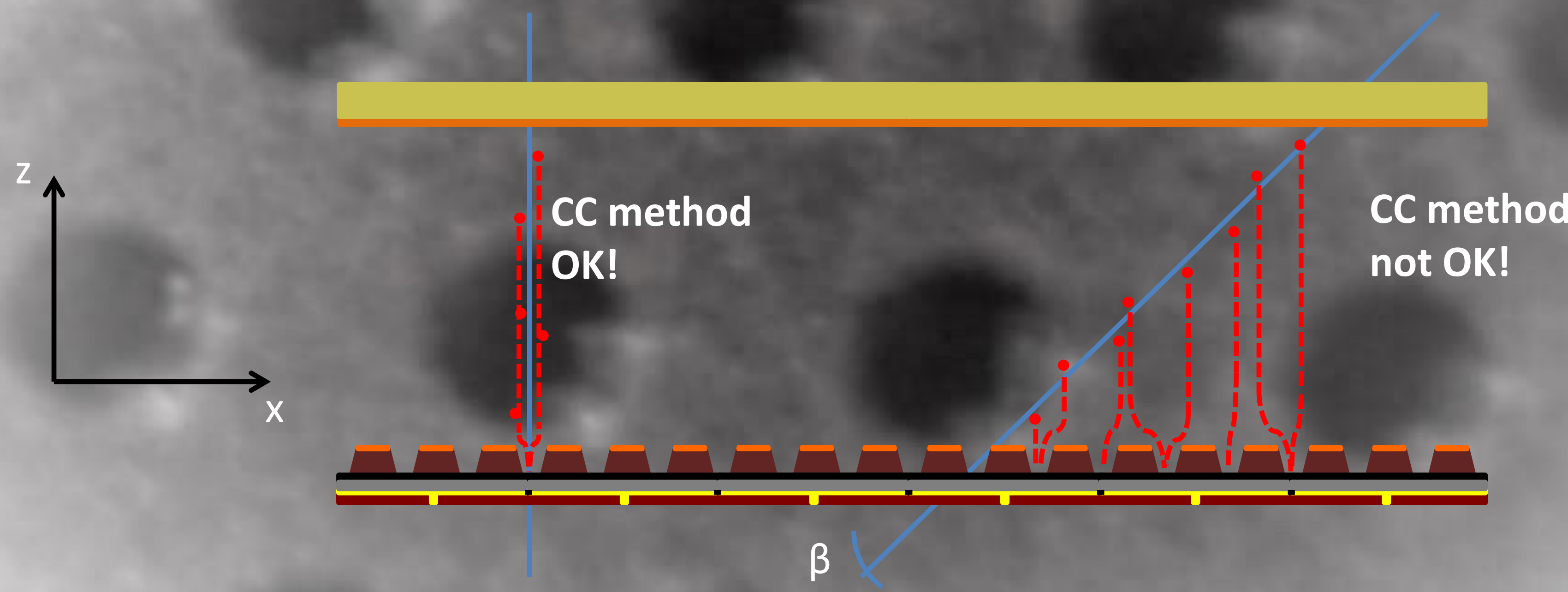
Different chambers with different dimensions and resistive schemes exhibit a very similar behavior although realized in different sites (large detector realized @ ELTOS)
The saturation at 5.7 ns is dominated by the fee (measurement done with VFAT2).

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 BESIII-CGEM, 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

Improving space resolution: the μ-TCP mode

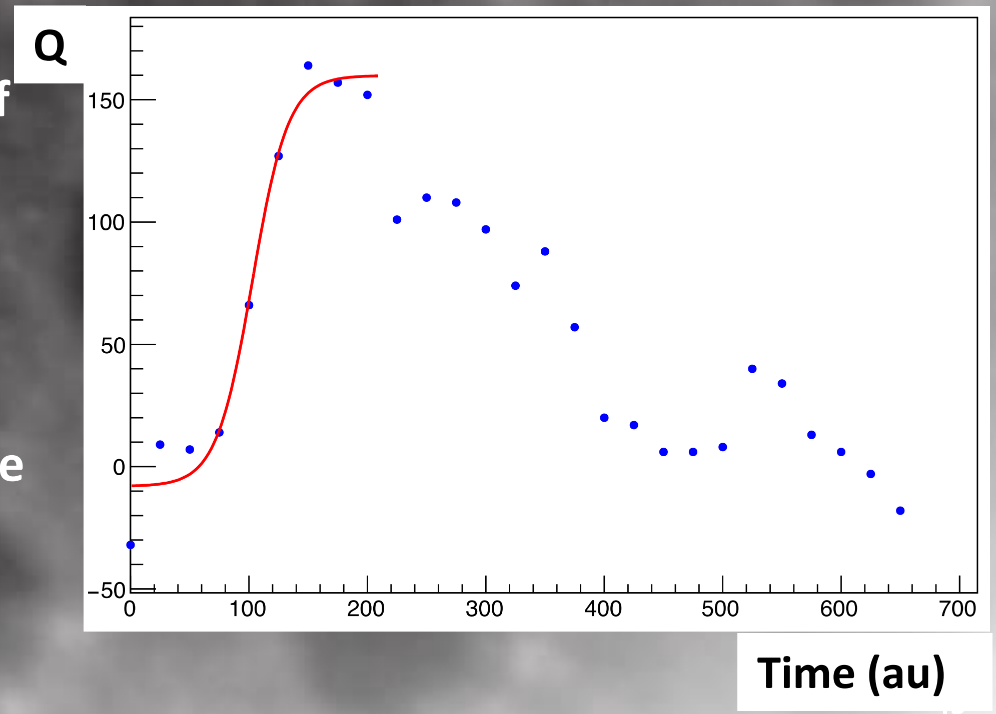
Introduced for **MicroMegas** by **T. Alexopoulos** et al. [NIM **A 617** (2010) 161] it suggests a way to overcome the **poor position reconstruction of the inclined tracks.**

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



Example of µ-TPC reconstruction

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