High space resolution μ-RWELL for high rate applications

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OUTLINE

- Detector architecture & principle of operation
- The baseline layout: Pros & Cons
- High rate layouts: design & performance at PSI
- Space resolution studies
- Summary

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 mitigation)
- **simplified construction/assembly**
- **technology transfer to industry** (→ *mass production*)

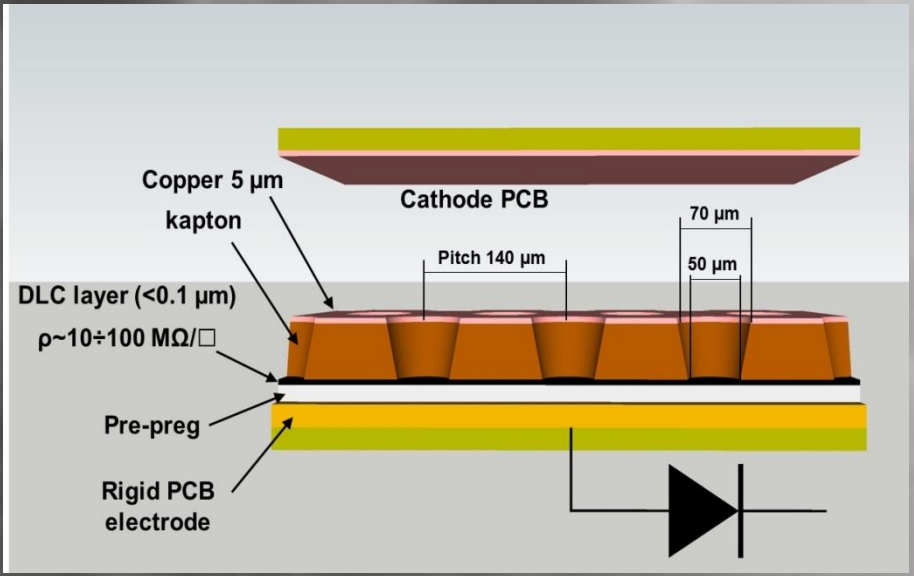
a MUST for large scale applications in fundamental research at the future colliders as well as for technology dissemination beyond HEP.

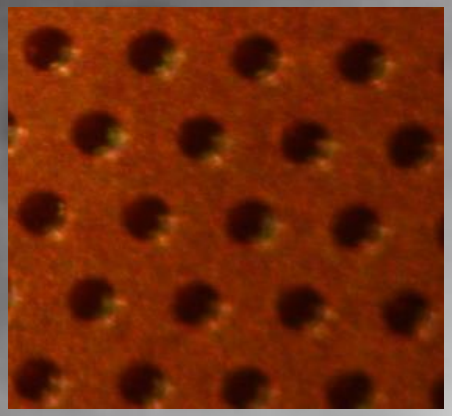
The μ-RWELL: the detector architecture

The μ-RWELL is composed of only two elements: the μ-RWELL_PCB and the cathode defining the gas gap.

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

1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression w/surface resistivity ~ 10÷100 MΩ/□ - different current evacuation schemes can be implemented
   i. LR << 1 MHz/cm^2 - SHiP, STCF, EIC, HIEPA
   ii. HR >>1 MHz/cm^2 - LHCb-Muon phase 2-upgrade & future colliders - CepC, Fcc-ee/hh
3. a standard readout PCB





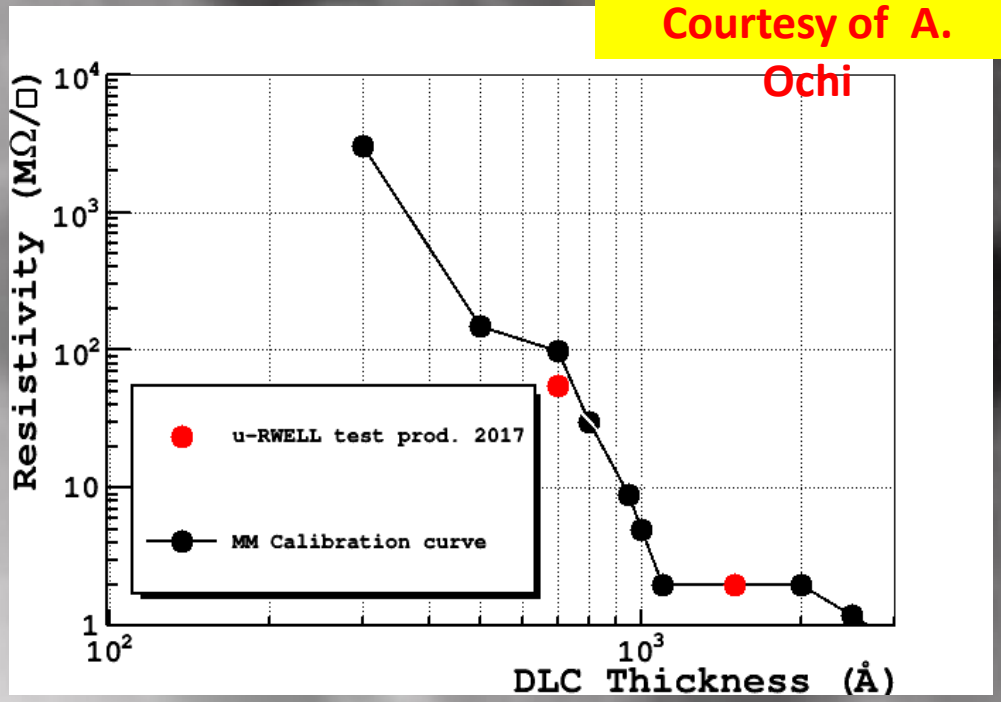
The μ-RWELL amplification stage

The resistive layer: DLC sputtering

The **Diamond Like Carbon (DLC) is sputtered** on one side of a **50 µm thick Apical® foil** using a pure graphite target, on **the other side** of the **foil the usual 5 µm thick Cu layer**, as for the base material used for GEM foil, is deposited.

The **resistivity, parametrized** as a function of the **DLC thickness**, can reach a uniformity on large foils, 1.2×0.6 m^2, at level of ± 30% .

Courtesy of A. Ochi

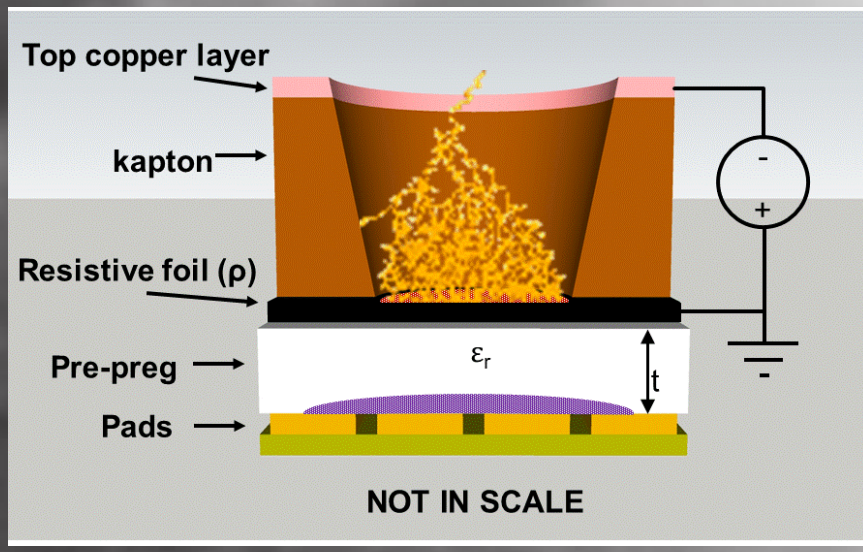


Very recent developments, at **USTC – Hefei (Zhou Yi, Lyu You poster 22-A)**, brought to the manufacturing **of DLC+Cu sputtered Apical® foils**, where an **additional layer of few microns of Cu above the DLC** coating has been deposited.

This positive result open the way towards **improved high rate µ-RWELL layouts** (*slides > # 14*).

Principle of operation

Applying a suitable voltage between the top Cu-layer and the DLC the "WELL" acts as a multiplication channel for the ionization produced in the drift gas gap.



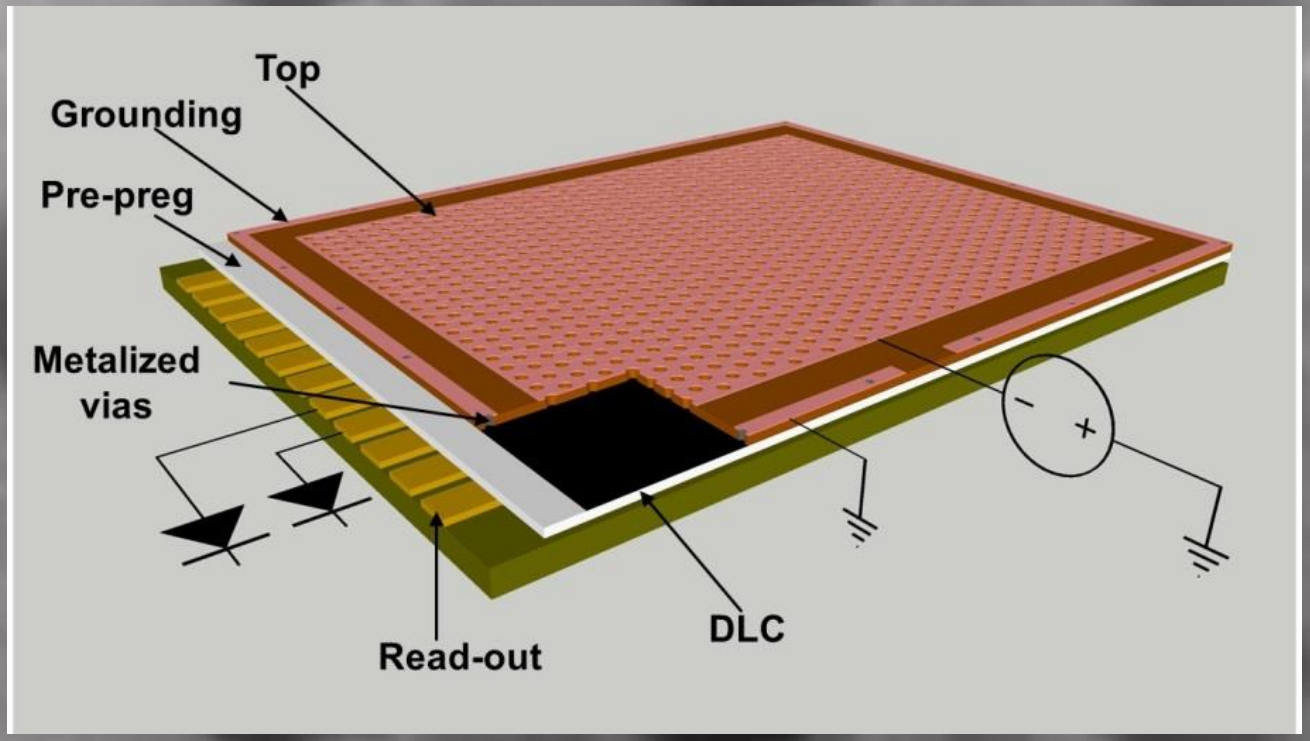
The charge induced on the resistive layer is spread with a *time constant*, $\tau \sim \rho \times C$ [*M.S. Dixit et al., NIMA 566 (2006) 281*]:

- 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

$$C = \varepsilon_0 \times \varepsilon_r \times \frac{S}{t}$$

- The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark, with a consequent reduction of the spark-amplitude
- As a drawback, the capability to stand high particle fluxes is reduced, but appropriate grounding schemes of the resistive layer solves this problem (*see High Rate layouts*)

The Low Rate Layout



Single Resistive Layer (SRL): a simple **2-D current evacuation** scheme based on a **single resistive layer** with a conductive **grounding all around the perimeter** of the active area.

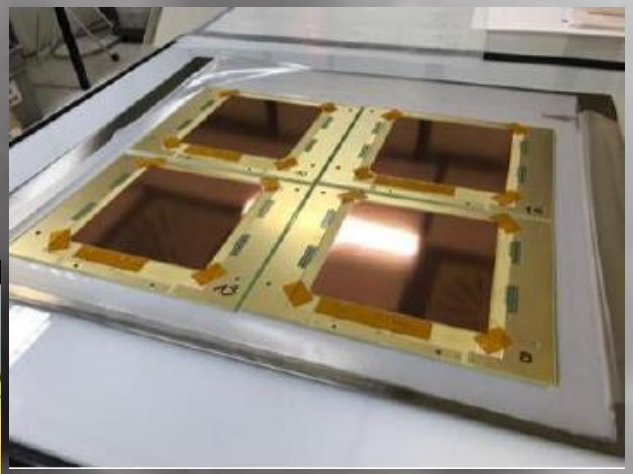
For **large area detectors** the **path of the current towards the ground connection** could be large and strongly dependent on the particle incident point giving rise to **detector response inhomogeneity → limited rate capability.**

Technology Transfer to Industry

The SRL being based on a **full Sequential Build Up (SBU) technology** allows an easy TT to industry operating in the field of multi-layer PCB.

Production Tests @ ELTOS (http://www.eltos.it)
small detectors:

- 10x10 cm^2 PCB – (PAD r/o)
- 10x10 cm^2 PCB – (strip r/o)



Production Tests @ ELTOS, large area detectors (w/CMS Muon group [*]):

- 1.2x0.5m^2 with strip r/o
- 1.9x1.2m^2 with strip r/o - (by splicing trapezoidal tiles with a dead zone <0.5 mm)

- The etching of the kapton is still done by Rui @ CERN
- Kapton etching test @TECHTRA (Poland) planned for the near future

[*] CMS-Muon group: ***L. Benussi, L. Borgonovi, P. Giacomelli, A. Ranieri, M. Ressegotti, I. Vai, V. Valentino***

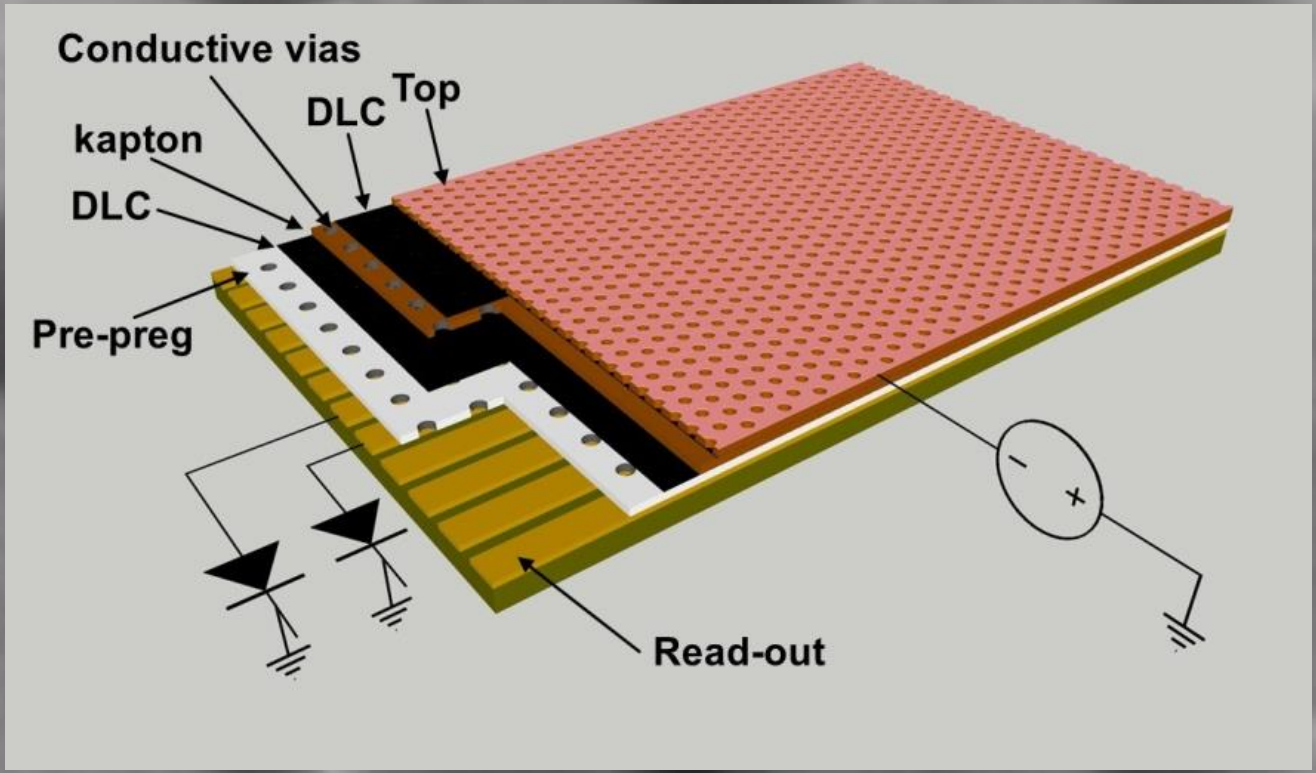
Towards high rate layouts

To overcome the **intrinsic limitation of the Single Resistive layout** with edge grounding **the solution** is to **reduce as much as possible the current path towards the ground connection** introducing a **high density "grounding network"** on the resistive stage of the detector.

Two layouts with a "dense" grounding network scheme have been designed and implemented:

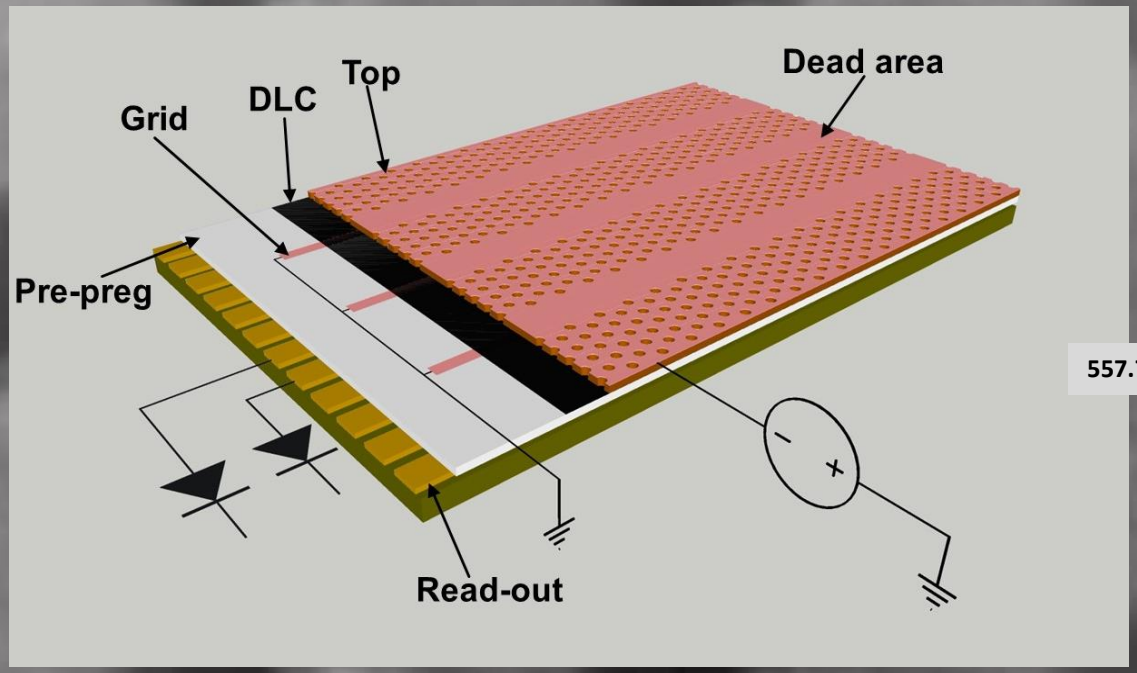
- the **Double Resistive layer** (**DRL**) with a sort of 3-D grounding scheme
- the **Single Resistive layout with a grounding grid** (**SG**) deposited on the resistive stage

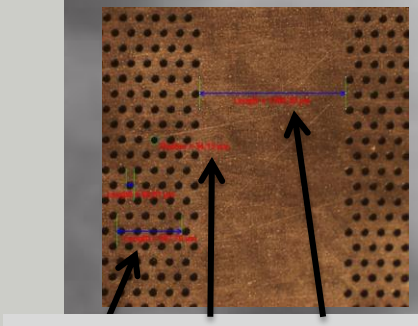
HR layouts: the double-resistive layer



Double Resistive Layer (DRL): 3-D current evacuation scheme based on **two stacked resistive layers** connected through a **matrix of conductive vias** and **grounded through a further matrix of vias to the underlying readout** electrodes. The **pitch of the vias** can be done with a density **less than 1/cm^2**. The TT to industry of such layout is not easy because the dense matrix of vias on kapton foils required not standard manufacturing procedures.

HR layouts: the Silver grid





The SG is a **simplified HR scheme** based on a **Single Resistive layer** with the implementation of a **2-D grounding** by means **conductive strip lines** realized on the DLC layer.
The **conductive grid/lines** can be screen-printed or better etched by photo-lithography (*using the DLC+Cu deposition technology developed at USTC – Hefei*).

The **conductive grid** can **induce instabilities due to discharges over the DLC surface**, thus requiring for the **introduction of a small dead zone** on the amplification stage (*dead_zone = 2×DOCA + line_width - with DOCA = distance of closest approach before discharge*)

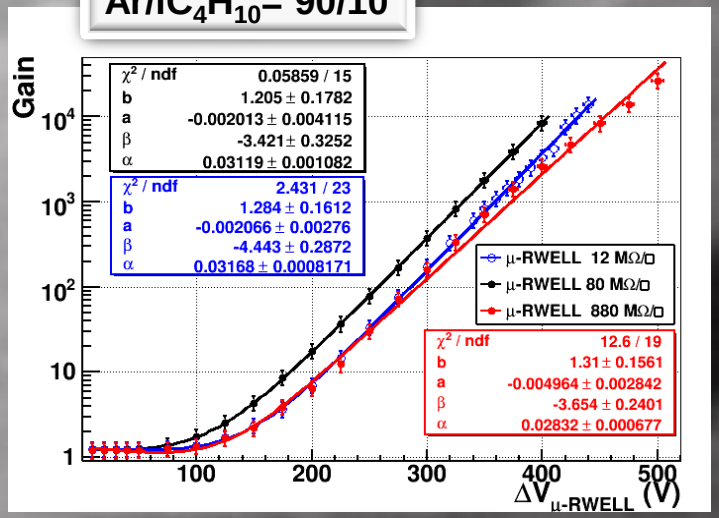
High rate layouts: relevant parameters

	SG1	SG2	SG2++	DRL	SRL
Grid-pitch (mm)	6	12	12	6	100
Dead zone (mm)	2	1.2	0.6	0	0
Geometric acceptance (%)	66	90	95	100	100
Conductive line width (mm)	0.3	0.3	0.1	-	-
DOCA	0.85	0.45	0.25	7	5.5
Ω_{eff} (MΩ)	134	209	200	270	1947
DLC resistivity (MΩ/□)	70	65	64	54	70

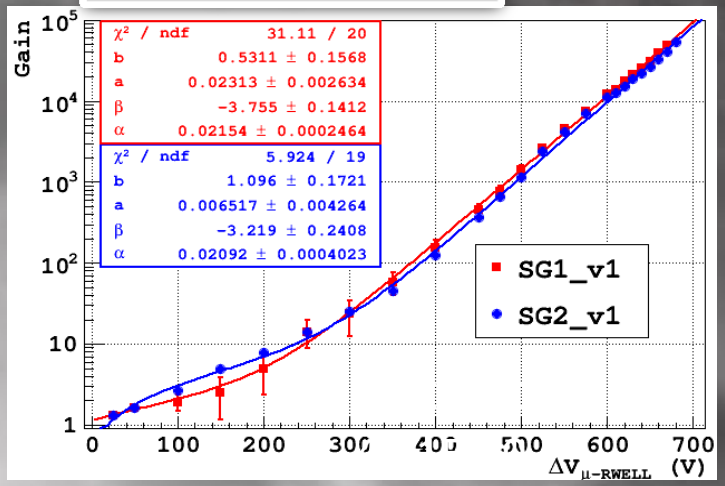
$\Omega \simeq \frac{\rho}{2} \times (pitch/2 + DOCA)/w$ → average resistance "seen" by a uniform particle flow irradiating the basic cell of the detector.
Ω summarizes the electrical and geometrical features of each current evacuation scheme.

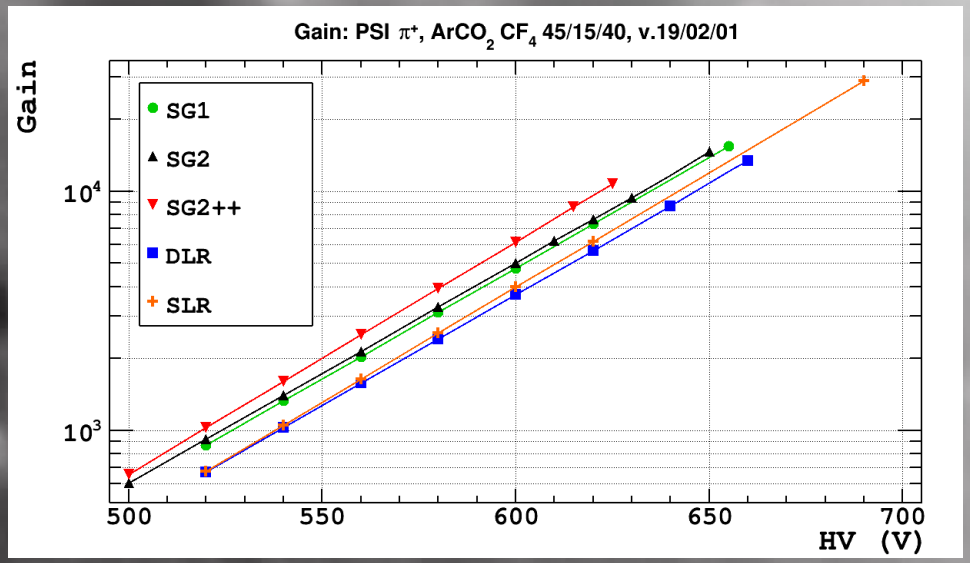
Detector Gain

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



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

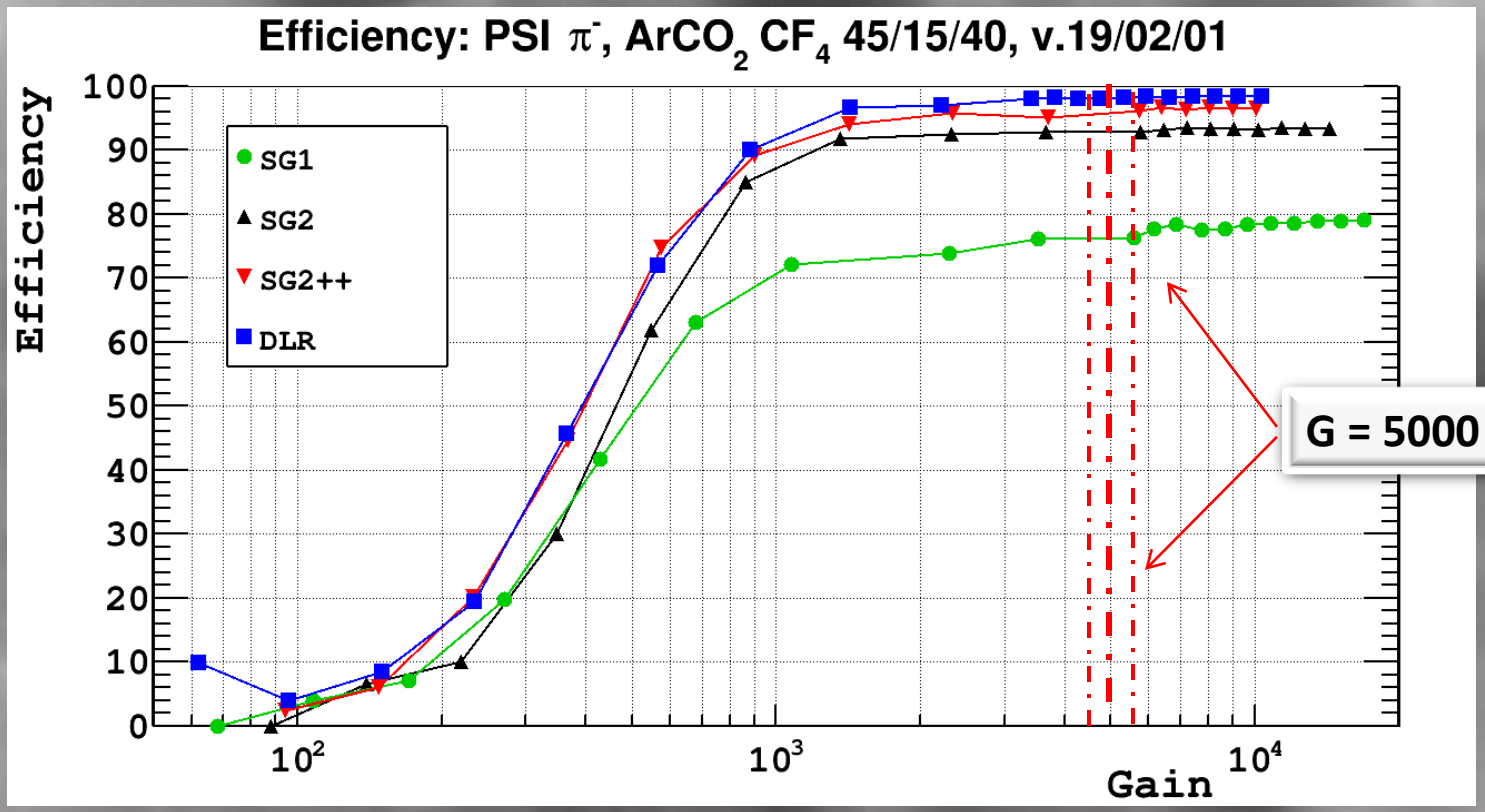




Gas gain of detectors as measured with a 270 MeV/c π^+ beam at PSI with particle fluxes ranging from ~320 kHz/cm^2 up to ~1.2 MHz/cm^2.

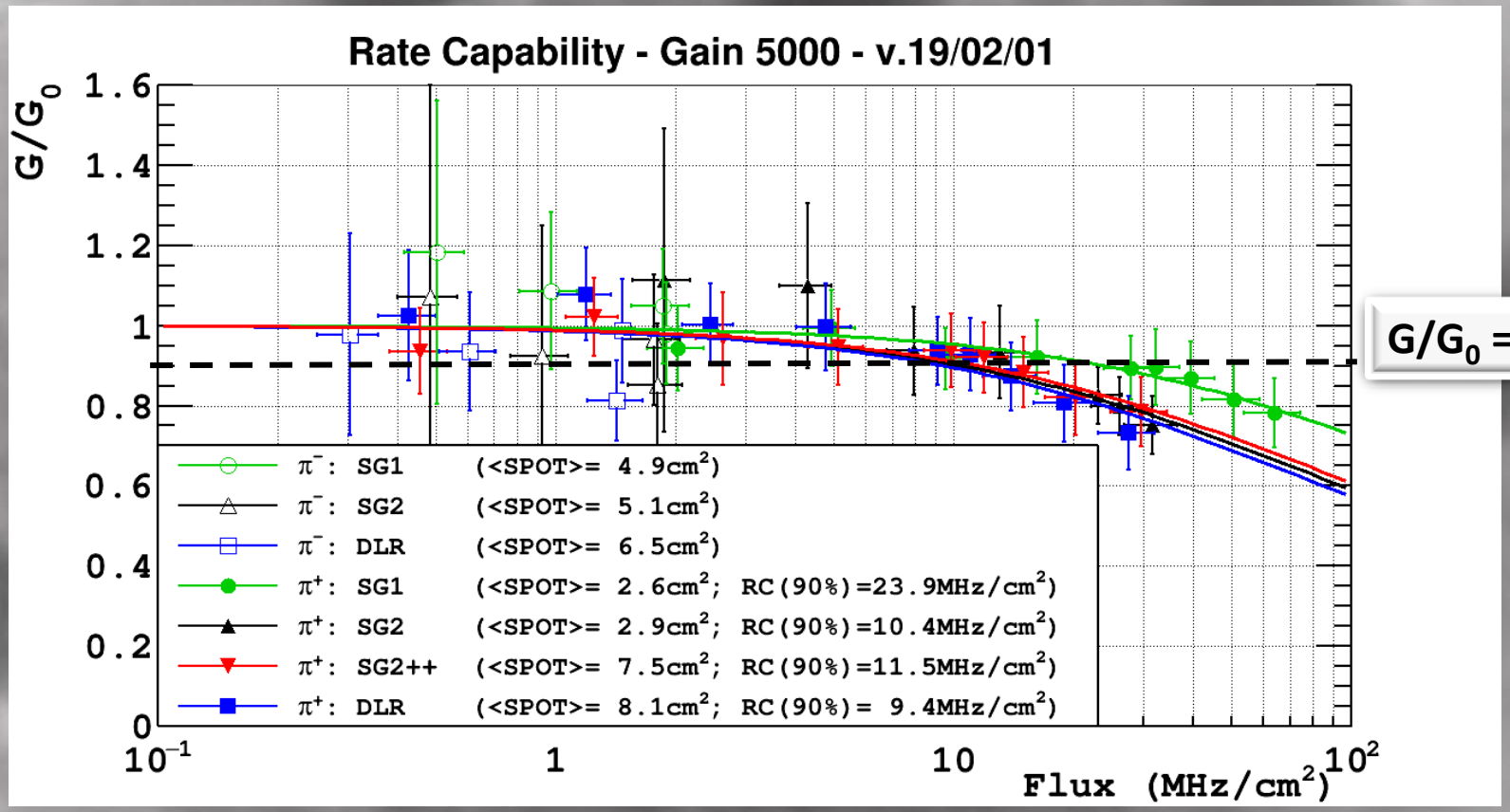
Gas gain measured with X-rays (5.9 keV), for several gas mixtures.

HR layouts performance: the efficiency



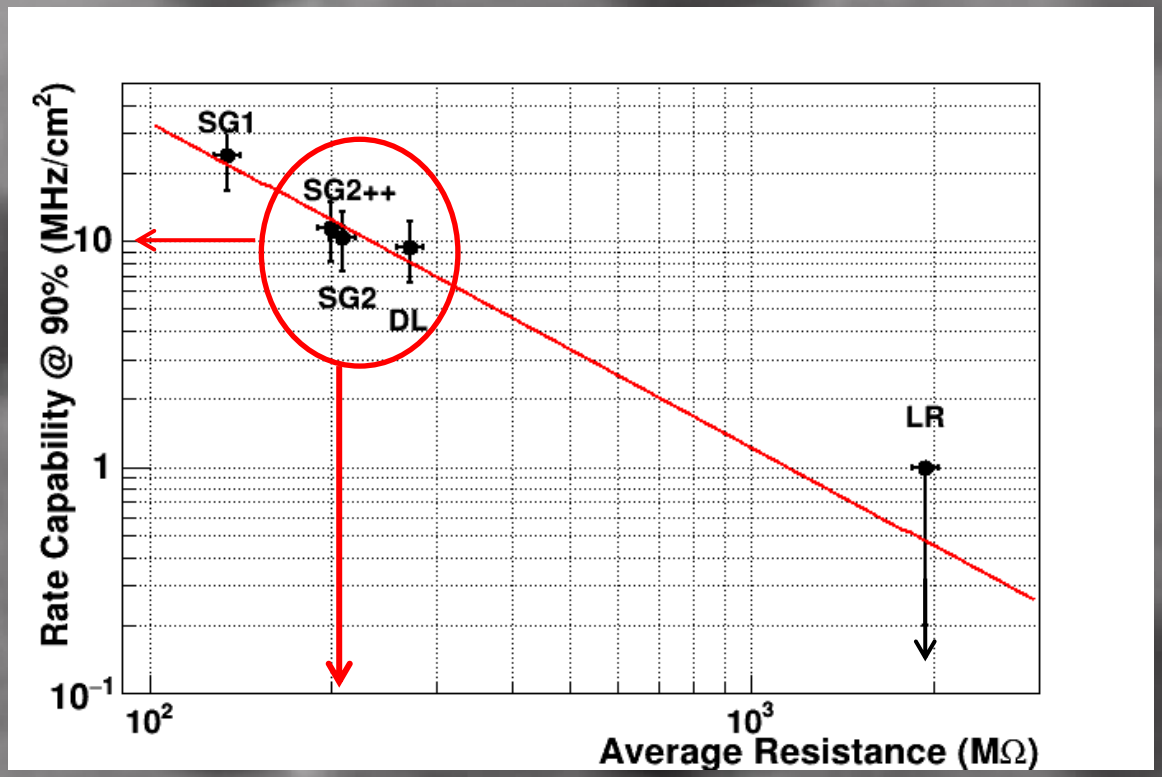
The DRL layout reaches full tracking efficiency , 98% (NO DEAD ZONE).
The SG1, SG2 and SG2++ show lower efficiency (76% - 93% - 97%) BUT higher than their geometrical acceptance (66% - 90% - 95% respectively), thanks to the efficient electron collection mechanism that reduce the effective dead zone.

Rate capability of HR Layouts



The normalized gain G/G_0 vs the particle flux, for a $G_0 \sim 5000$. Since the beam spots ($FWHM^2$) were larger than the basic cell of each layout the particle flux can be considered almost uniform over the detector basic cell. The gain drop is due to the Ohmic effect on the resistive layer.

Rate capability @ 90% vs $<\Omega_{eff}>$



Rate capability corresponding to a G/G_0 = 90% vs $<\Omega_{eff}>$: a gain drop of 10 % is largely acceptable since does not affect the detection efficiency (*as shown on slide #18*).

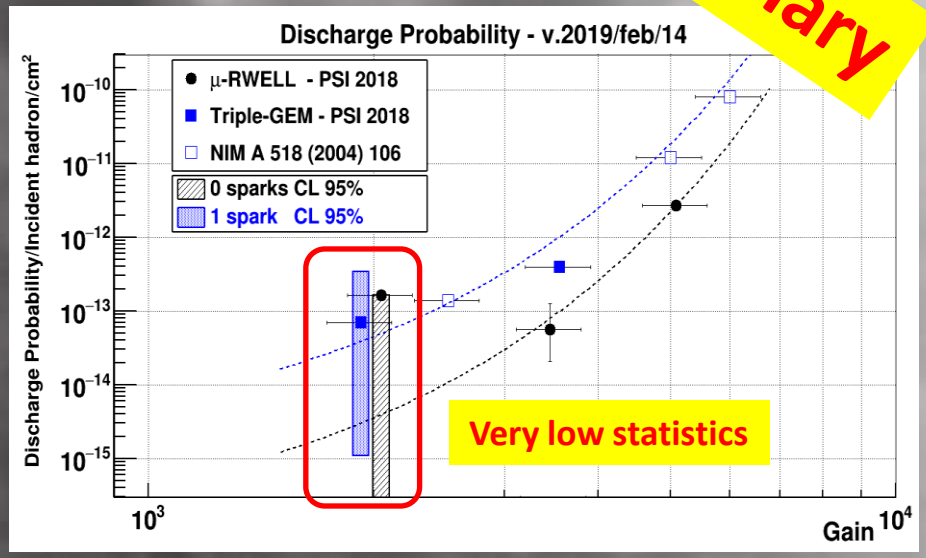
For the SRL, since the irradiation was not uniform, the measurement reported in this plot must be considered as an upper limit of its actual RC-90%.

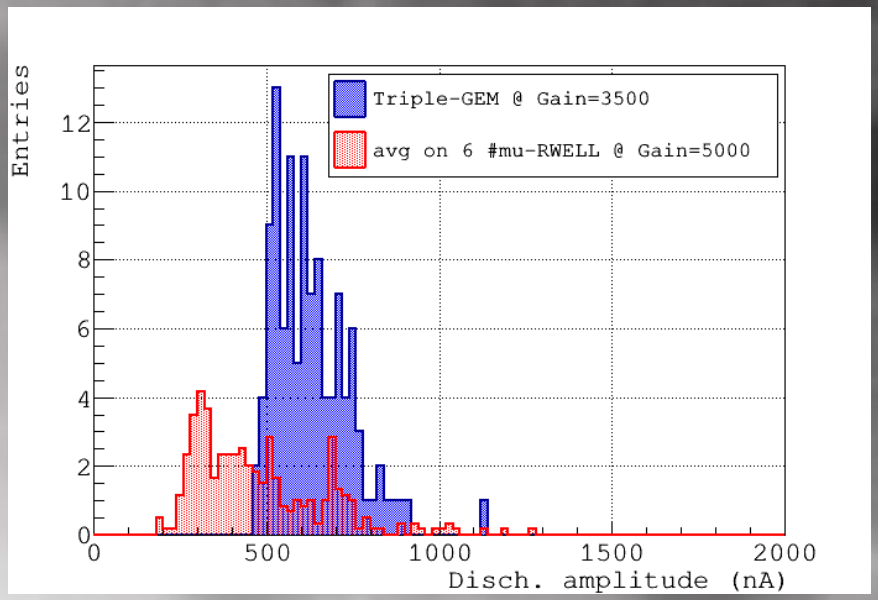
Discharge studies

preliminary

The μ-RWELL discharge probability measured at the PSI, and compared with the measurement done with GEM at the same time and in the 2004 (*same gas mixture - $Ar:CO_2:CF_4$ = 45:15:40*).

The measurement has been done in current mode, with an intense 270 MeV/c π^+ beam, with a proton contamination of the 3.5%.





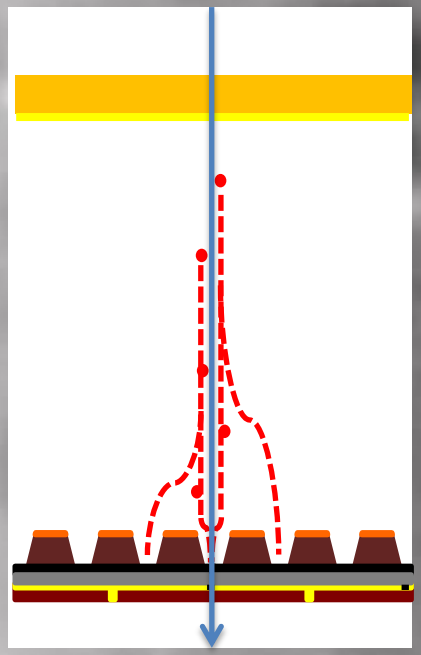
A "discharge" has been defined as the current spike exceeding the steady current level correlated to the particle flux (~90 MHz on a ~5 cm² beam spot size).

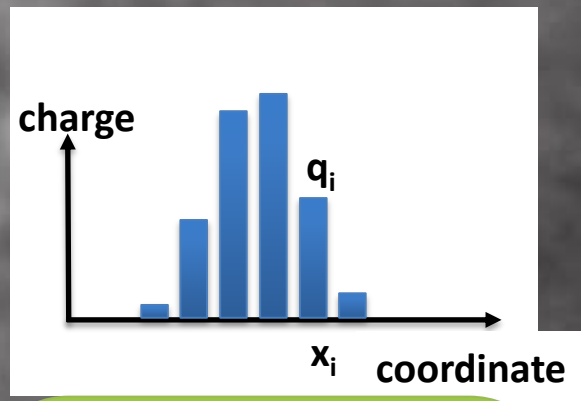
The discharge probability for μ-RWELL comes out to be slightly lower than the one measured for GEM.

While its discharge amplitude seems to be lower than the one measured for GEM.

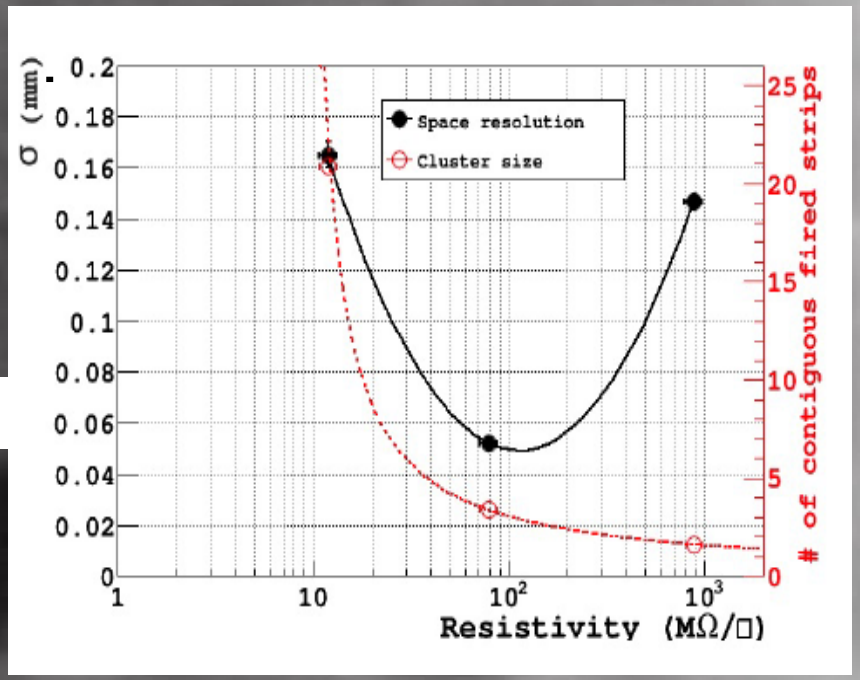
Space resolution studies: orthogonal tracks

The presence of **the resistive layer** affects also the **charge spread** on the readout strips and consequently the space resolution of the detector.
With the **charge centroid** analysis (for orthogonal tracks) the track position is determined as a weighted average of fired strips.





$$x_{hit} = \frac{\sum x_i * q_i}{Q_{TOT}}$$

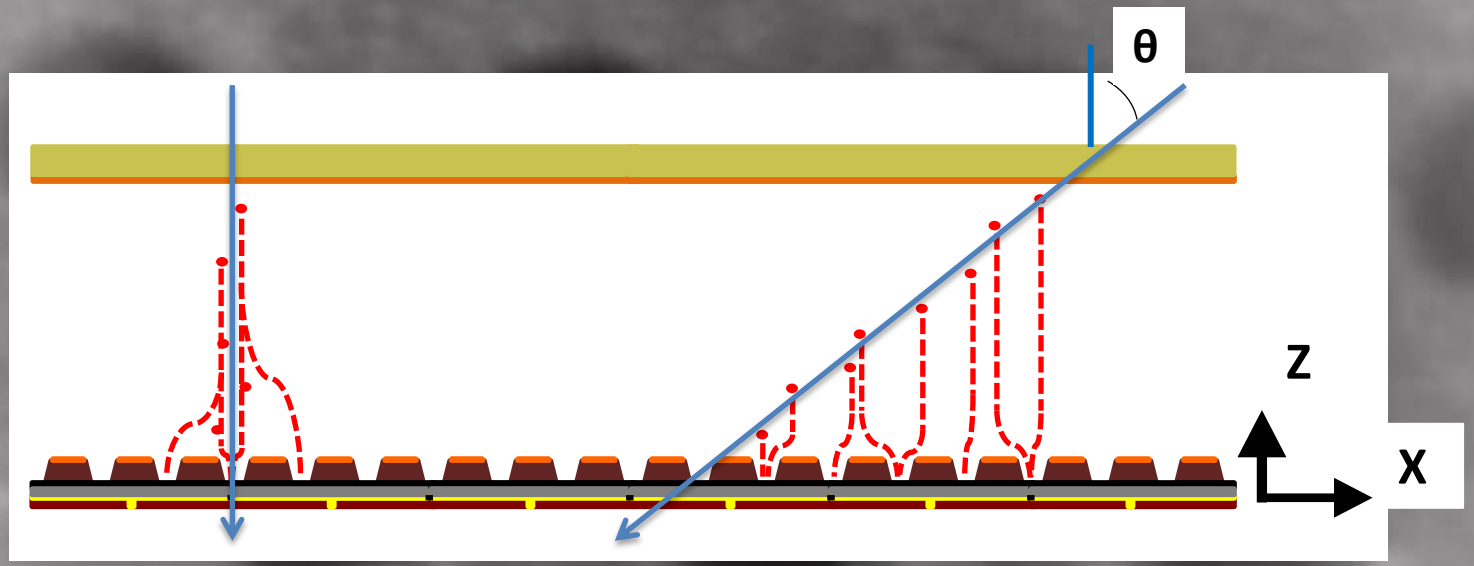


The space resolution exhibits a minimum around 70÷100 MΩ/□:

- 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-TPC mode

For inclined tracks and/or in presence of high B field, **the charge centroid method for MPGD gives a very broad spatial distribution** on the anode-strip plane.

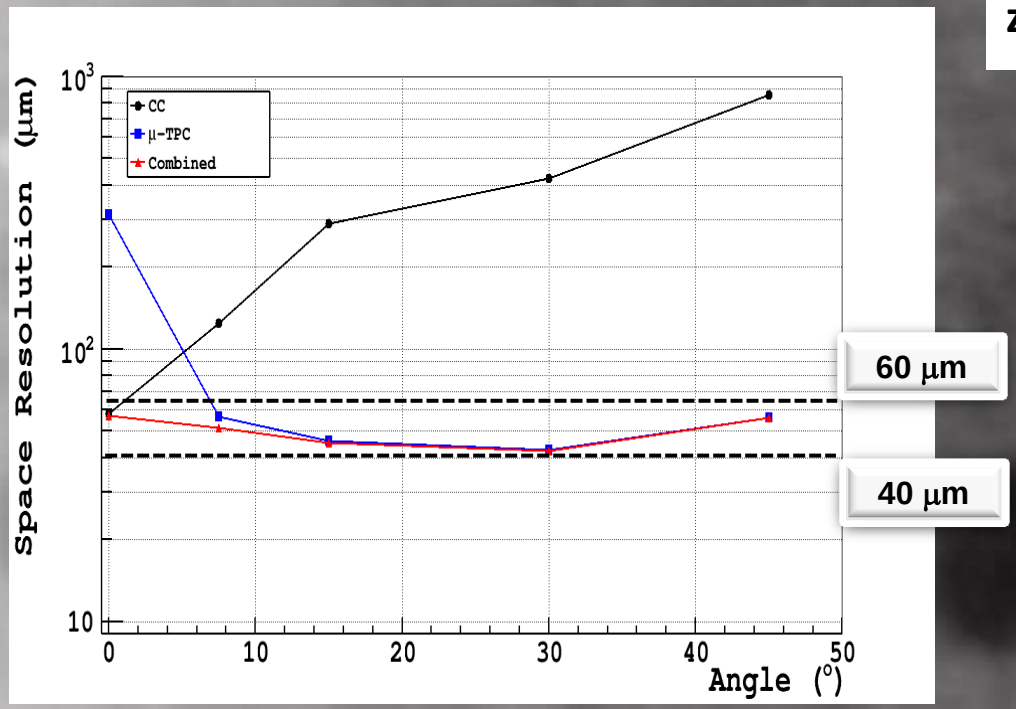


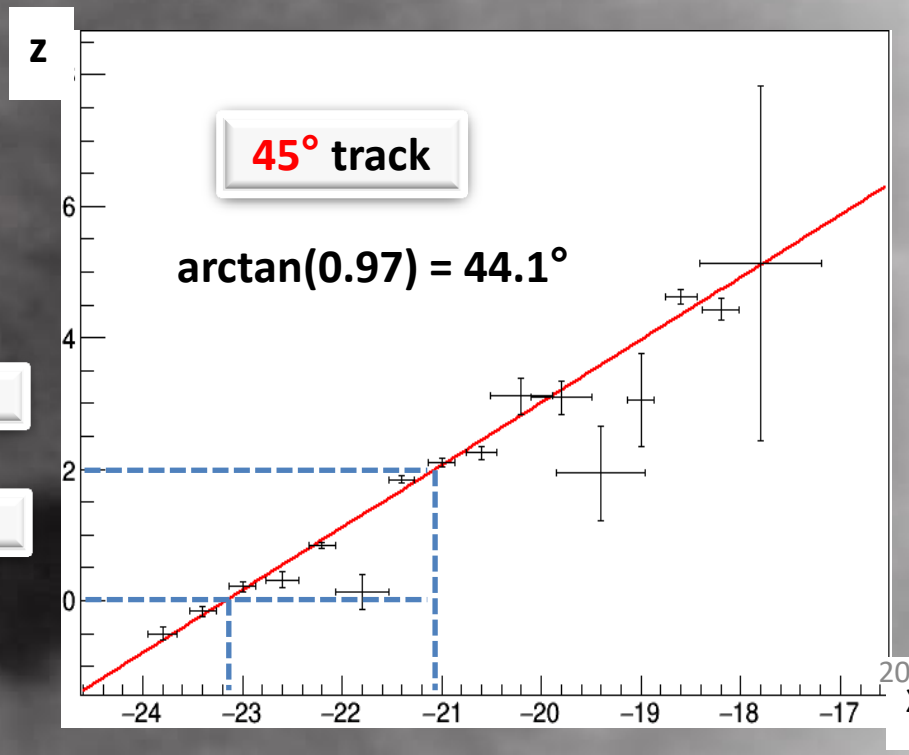
In the **u-TPC mode,** *introduced for MMs by T. Alexopoulos (NIM A 617 (2010) 161),* from **the knowledge** of the **drift time** and the **measurement of the arrival time** of electron clusters on the readout, **each ionization cluster is projected inside the conversion gap** and the track segment in the gas gap is reconstructed.

Space resolution vs inclined tracks: μ-TCP mode

Thanks to the collaboration with BESIII-CGEM, G. Cibinetto, R.Farinelli (Ferrara) & L.Lavezzi (To)

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





Combining the CC and the μ-TPC mode with E_d= 1 kV/cm a spatial resolution (40÷60 μm) almost flat over a wide range of incidence angles is obtained

Summary

The μ-RWELL is a single-amplification stage, spark-protected resistive MPGD based on a technology suitable for very large area planar tracking devices.

The detector has been characterized:

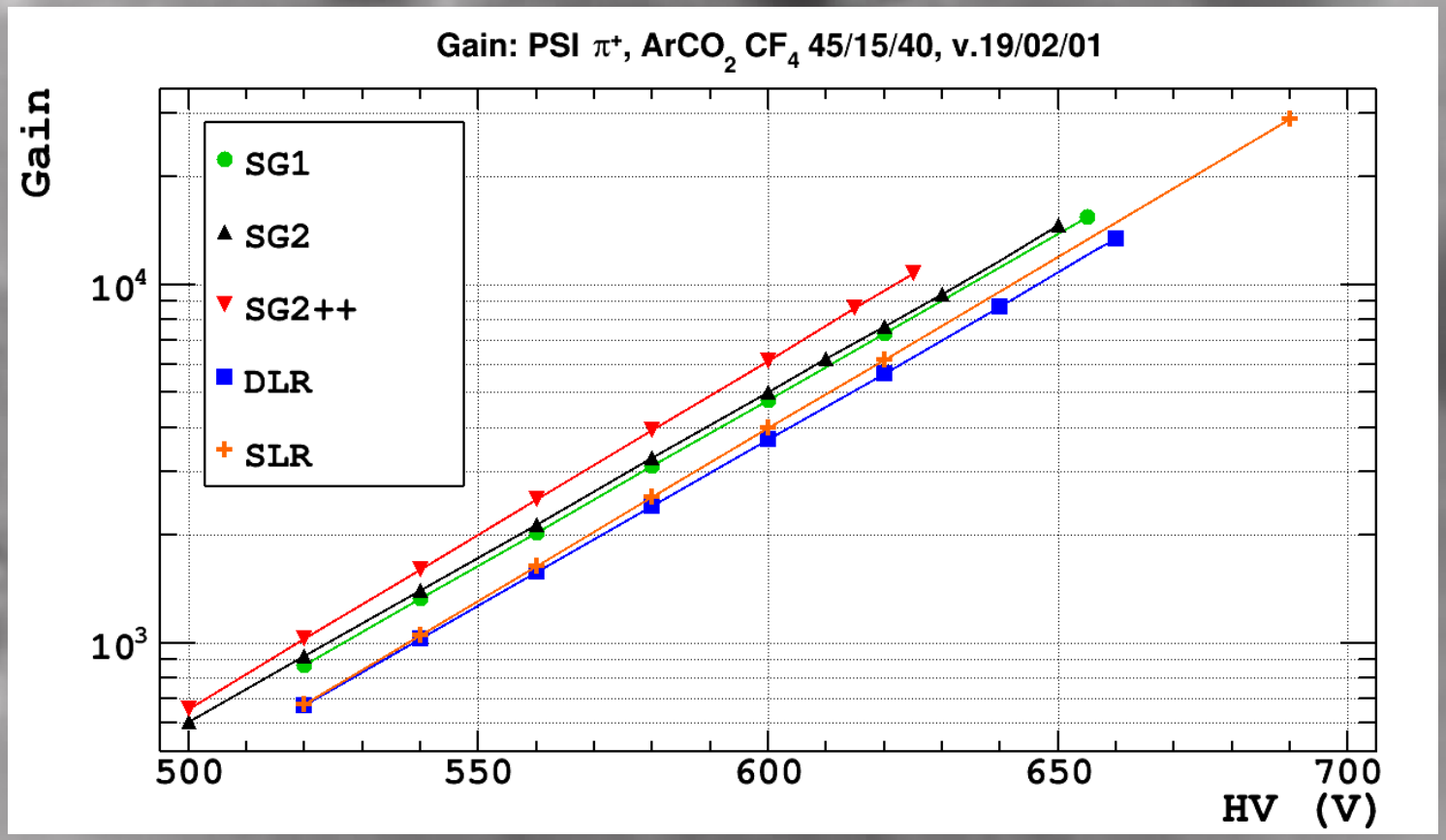
- gas gain ≥ 10^4
- rate capability ~ 10 MHz/cm^2 *(w/HR layouts)*
- space resolution < 60μm *(over a large incidence angle of the tracks)*
- time resolution ~ 5.7 ns

The detector is based on a **full-SBU technology (SRL, SG2++):**

- the SRL version is already partially built outside CERN at ELTOS (IT), while Kapton® etching test at TECHTRA (PL) is going to be started
- the high rate layout SG2++ is ready for TT to industry

Additional material

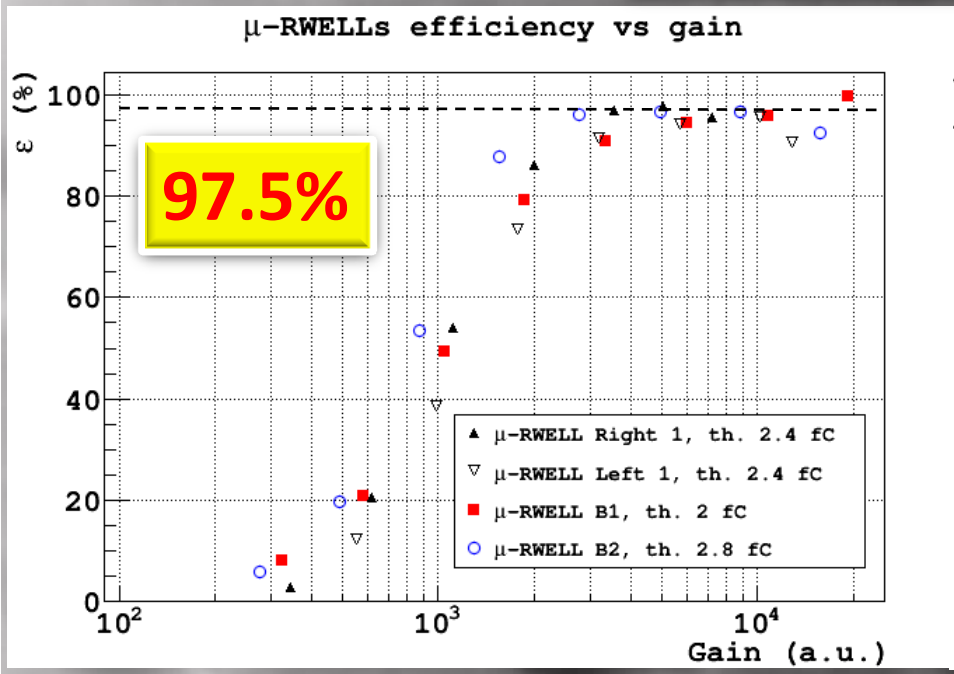
Maximum Gain under heavy irradiation

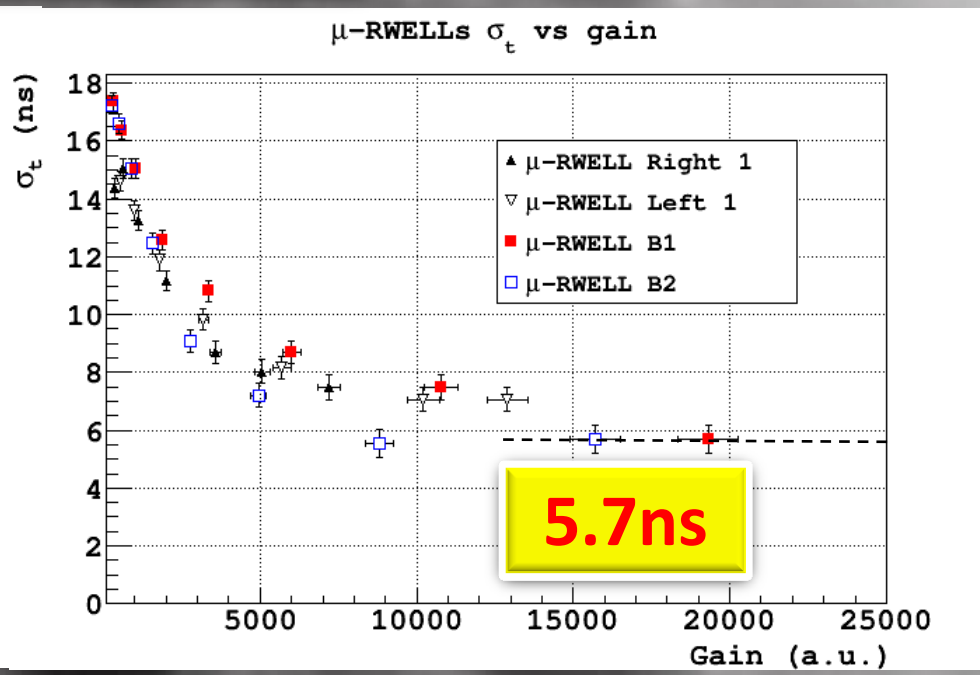


Gas gain of the detectors as measured with a 270 MeV/c π+ beam of the πM1 of the PSI with particle fluxes ranging from ~ 320 kHz/cm^2 up to ~ 1.2 MHz/cm^2.

Time Performance

Ar/CO2/CF4 = 45/15/40

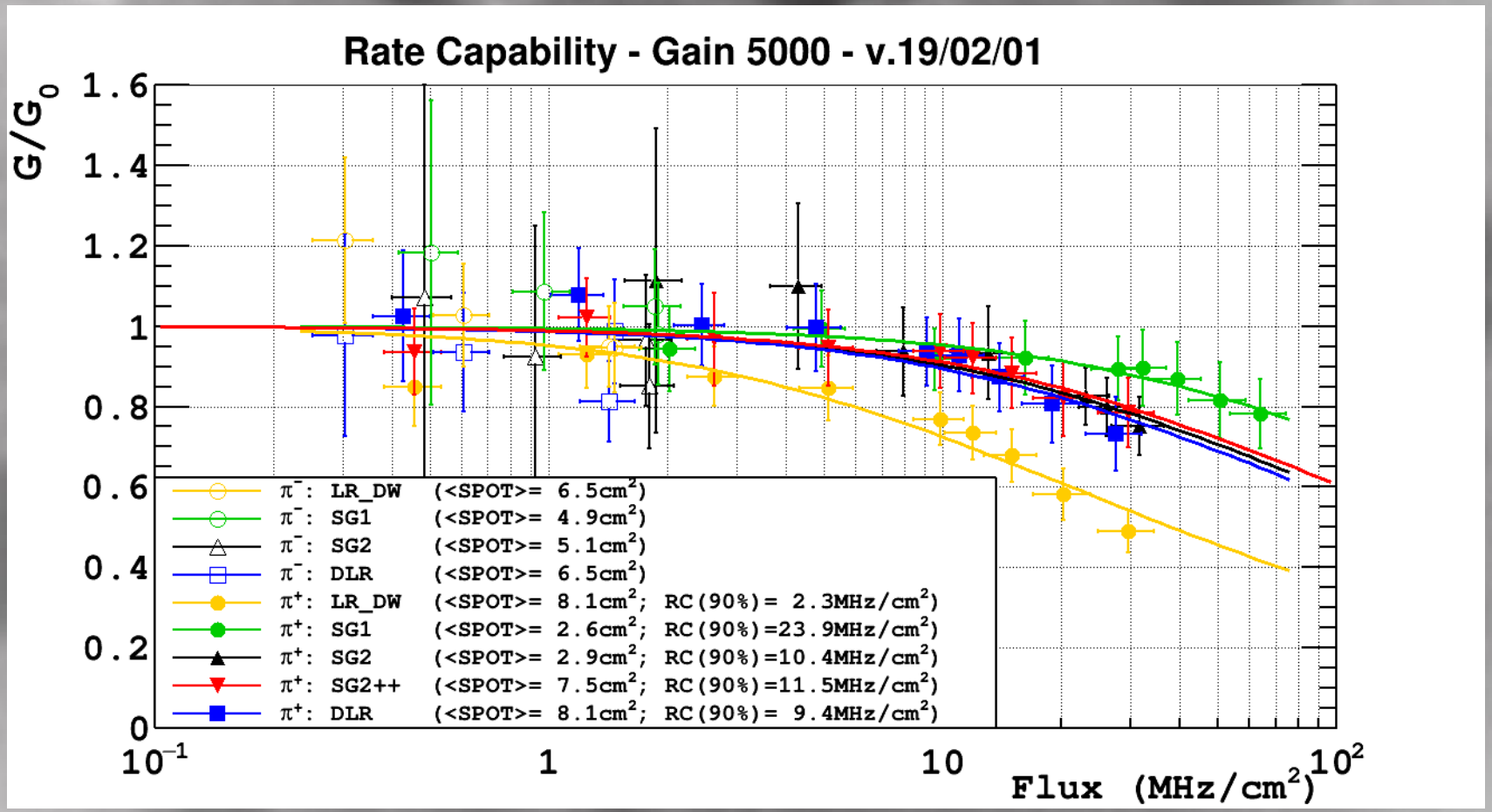


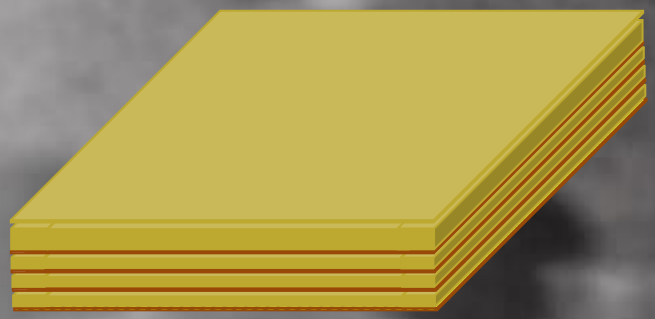


Different chambers with different dimensions and resistive schemes exhibit a very similar behavior although realized in different sites (large detector realized @ ELTOS).
The saturation at 5.7 ns is dominated by the FEE (measurement with VFAT2)

Collaboration with CMS-Muon group: L. Benussi, L. Borgonovi, P. Giacomelli, A. Ranieri, M. Ressegotti, I. Vai, V. Valentino.

Rate capability HR layouts vs SRL





GEM μ-RWELL MicroMegas

Main detector features

The μ-RWELL is a single-amplification stage, intrinsically spark protected MPGD characterized by:

Very simple design/assembly-procedure:

- *only two components*
- no critical & time consuming assembly steps:
  - *no gluing*
  - *no stretching* (→ *no stiff & large frames needed*)
  - *easy handling*
- *suitable for large area with* ***PCB splicing technique*** *w/small dead zone*

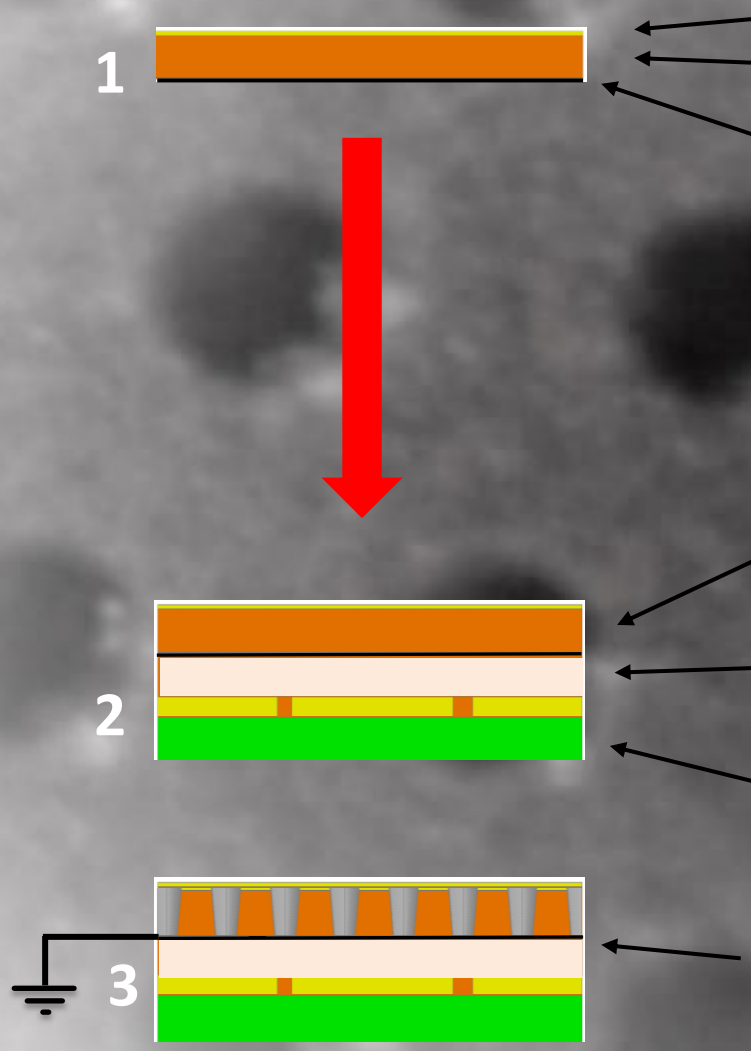
Cost effective & mass-production technology:

- based on full **Sequential Build Up (SBU) technology** thus allowing an easy TT to industry operating in the field of multi-layer PCB

Easy to operate:

- very simple voltage supply is required → only *2 independent HV channels* (*3-GEM detector → 7 HV floating/channels*)

The Low Rate Layout: manufacturing procedure



Copper layer 5 µm

Kapton layer 50 µm

DLC layer: 0.1-0.2 µm (10-100 MΩ/□)

DLC-coated kapton base material

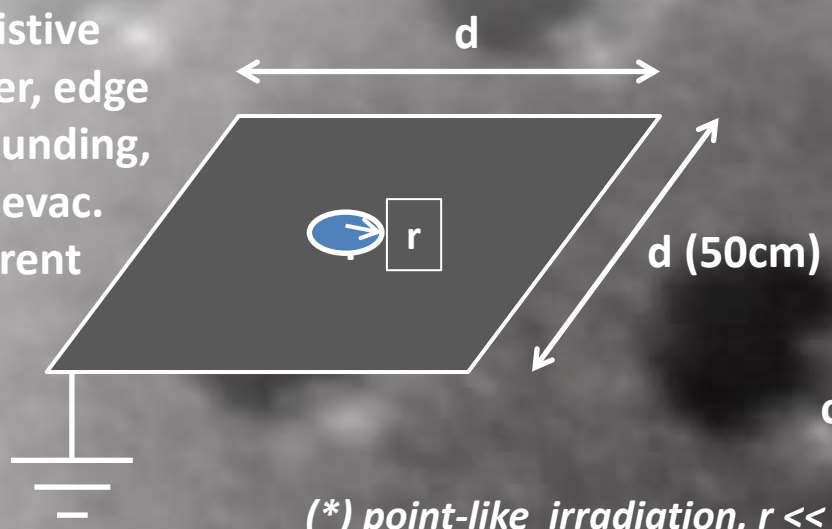
Insulating medium (50-100 µm)

PCB (1.6 mm)

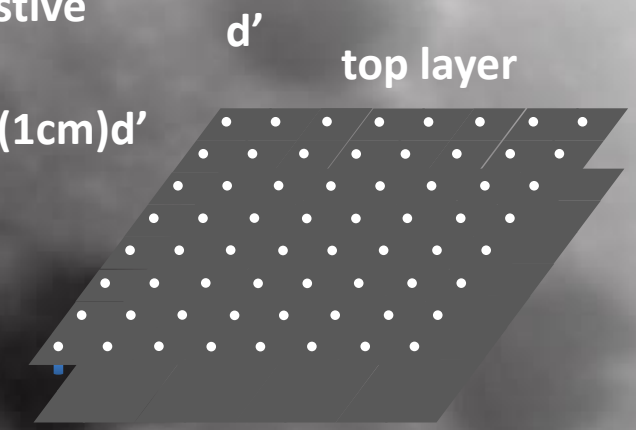
DLC-coated base material after copper and kapton chemical etching (WELL amplification stage)

Towards High Rate grounding schemes

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

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

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

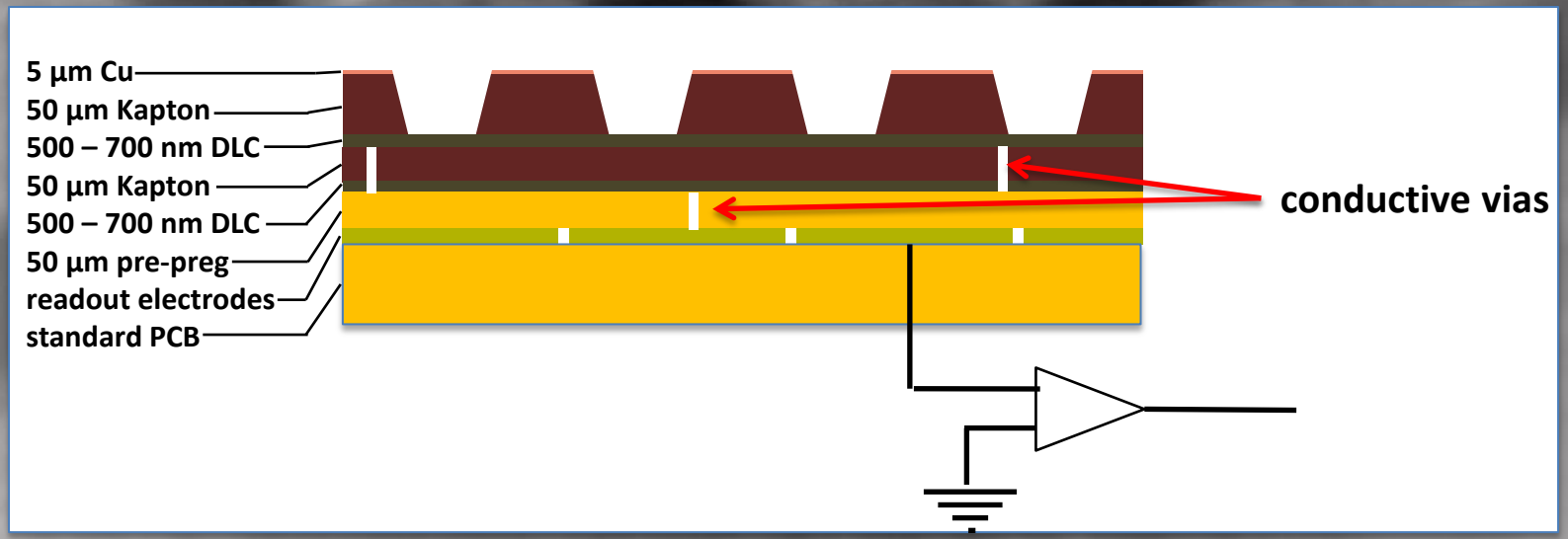
$$\text{If } \rho_s = \rho_s' \rightarrow \Omega/\Omega' \sim \rho_s/\rho'_s * d/3d' = 50/3 = 16.7$$

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

High rate layout: the double-resistive layer

The **idea is to reduce the path of the current on the DLC implementing** a **matrix of conductive vias** connecting **two stacked DLC layers.** A second **matrix of vias** connects the **second resistive layer to ground** through the readout electrodes (**3-D grounding scheme**)

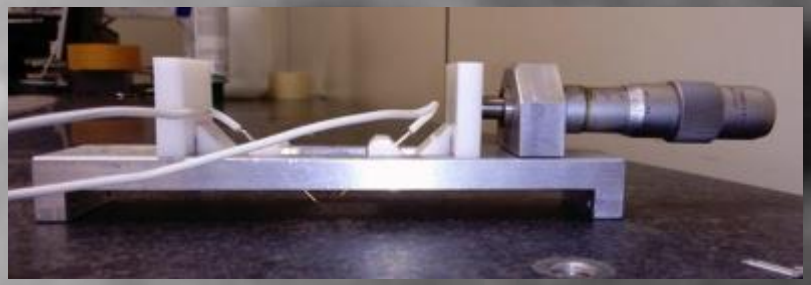
The **pitch of the vias is typically of the order 1/cm²** (or less).

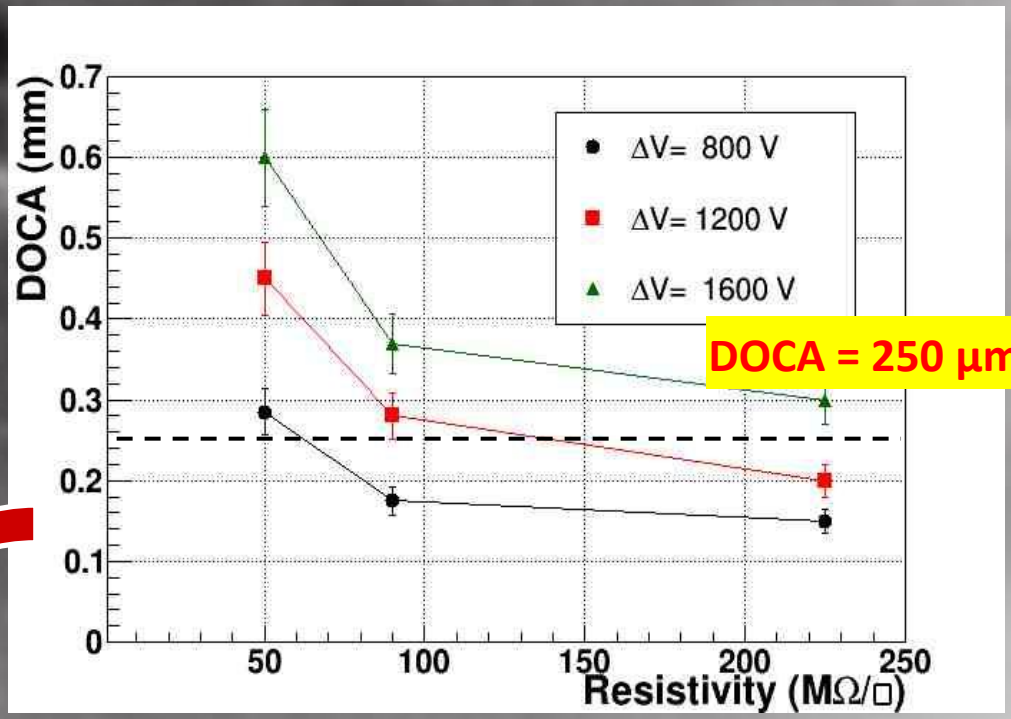


WARNING: *The **engineering/industrialization of the double-resistive** layer seems to be **difficult** due to the **manufacturing of the conductive vias on kapton foil***

Conductive Grid: optimization

In order to reduce the dead area, we studied the Distance Of Closest Approach *(DOCA) 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





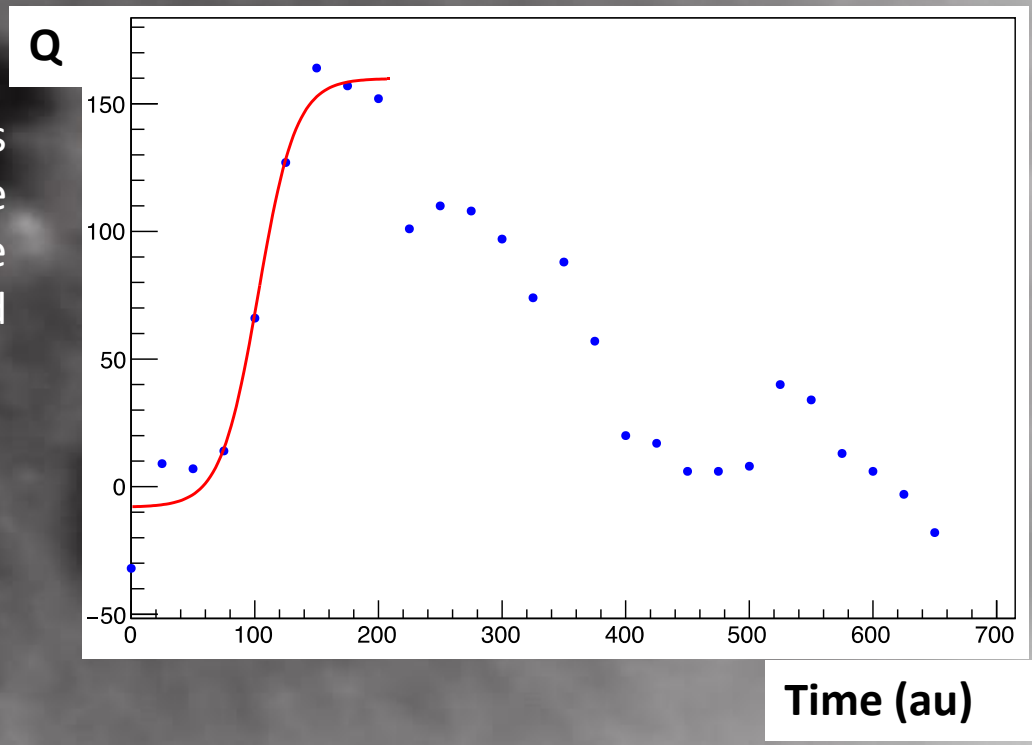
ρ > 60 MΩ/□ → DOCA < 250 µm

Improving space resolution: the μ-TCP mode

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 **arrival time** of the ionization clusters is obtained with a fit of the charge sampled every 25 ns (as seen by the 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



A fast time reference (t_0) must be provided to define the intercept of the track-segment on the z-axis inside the gas gap

Comparing different HR Layouts

Under the assumption of uniform irradiation, we can define an **average effective resistance (Ω_{eff})** to ground as follows:

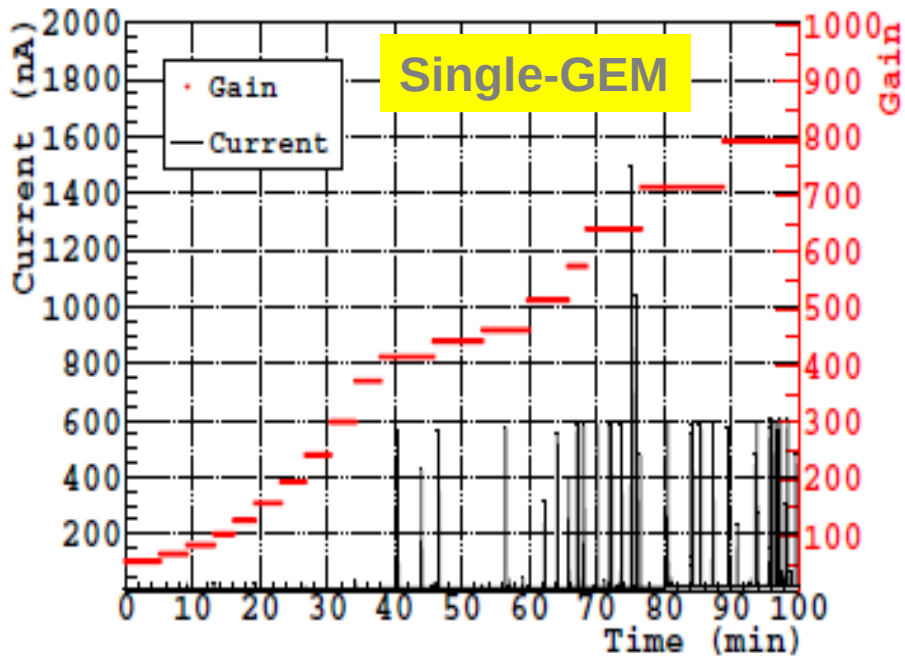
$$\Omega = \frac{1}{\int_{DOCA}^{pitch/2} \delta x} \times (\rho/w) \times \int_{DOCA}^{pitch/2} x\delta x$$

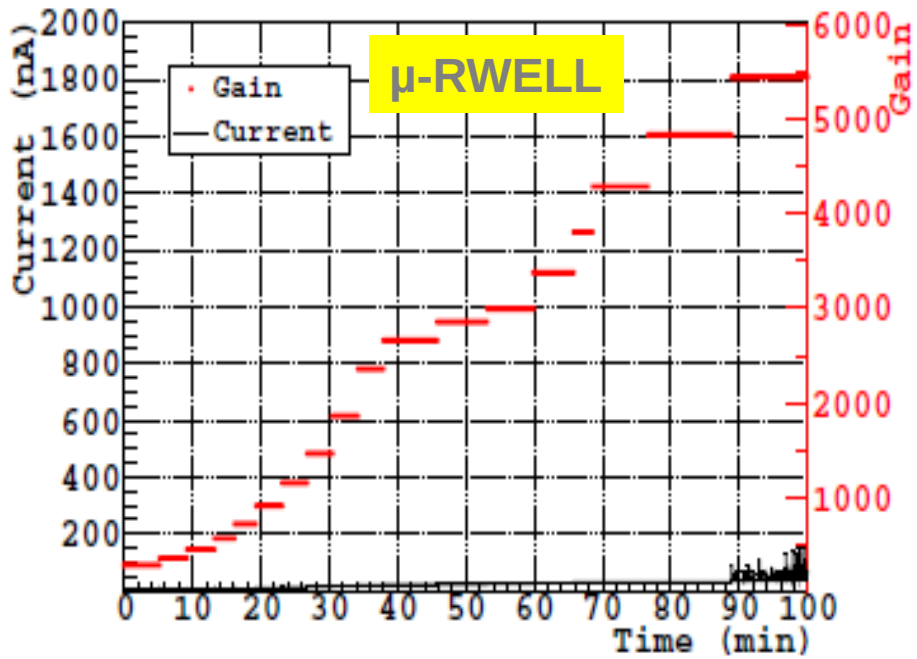
$$\Omega = \frac{\rho}{2} \times (pitch/2 + DOCA)/\mathrm{w}$$

Where:

- ***pitch/2*** is half of the distance between two grounding-grid lines
- ***ρ*** is the surface resistivity of the DLC layer
- ***DOCA*** is the distance between the last (or first) amplification hole and the center of the grounding-grid line
- ***w*** is the unitary transverse width of the resistive path of the current on the DLC

Preliminary study: μ-RWELL vs GEM

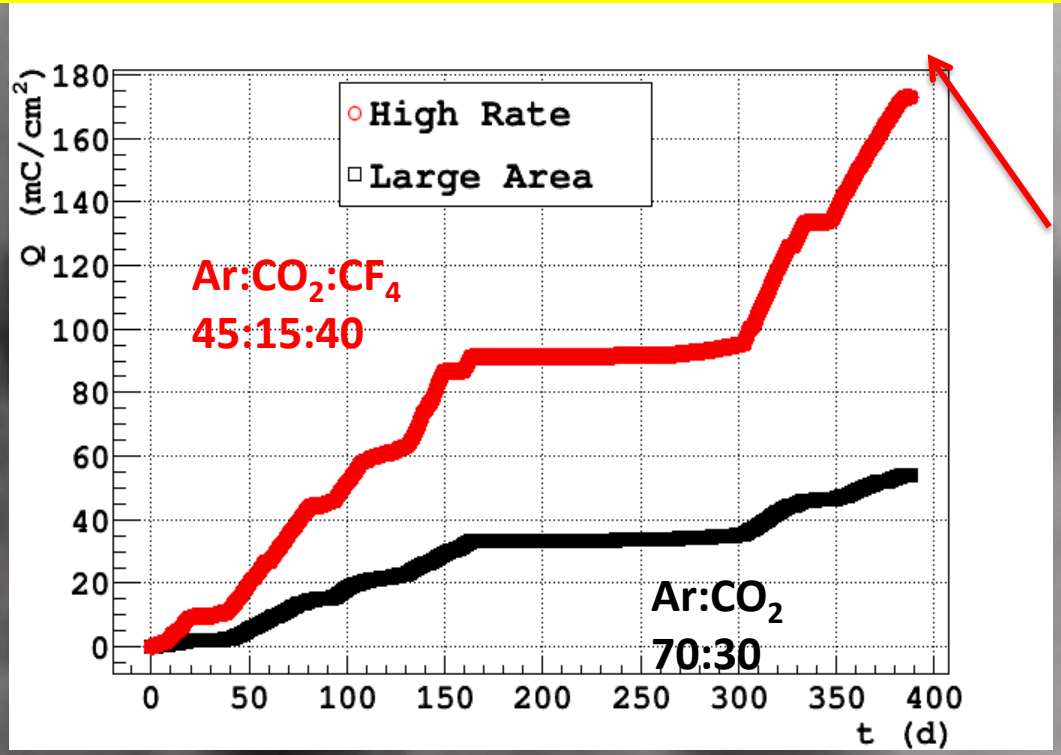




- discharges for μ-RWELL are of the order of few tens of nA (<20-300 nA @ high gain)
- for GEM discharges the order of 1μA are observed at high gas gain

Ageing test at GIF++ (I)

Collaboration with CMS – Bologna: *L. Borgonovi, P. Giacomelli*



m.i.p. equivalent rate ~200 kHz/cm²

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/cm² m.ip. equivalent) a charge of about 180 mC/cm² 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.

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	Not easy	YES-but not for mesh
Discharge protection	high	medium	high
Rate capability	Medium/high	Very high	Medium/high

(*) amplification stage resistively coupled with readout

Cylindrical μ-RWELL

KLOE – CGEM–IT

The Cylindrical MPGD concept, introduced the first time with GEMs (KLOE & BESIII), can be applied also to μ-RWELL (C-RWELL), with many advantages wrt CGEMs:

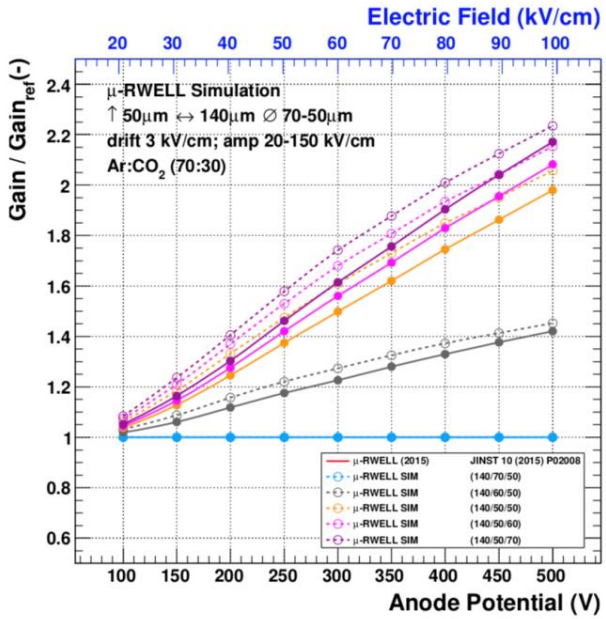
- lower material budget, down to 1-1,2% X_0 for n. 4 C-RWELL layers (tbc with 2% X_0 for KLOE2-CGEM)
- more simple construction/assembly and cheaper: less cylindrical electrodes (2 instead of 5), less toolings are required (2 molds instead of 5)
- the concepts of "openable detector", "floating-amplification", "reversed conical hole shape" (increasing the gain), can be easily implemented for the μ-RWELL making the C-RWELL more reliable & performing than CGEM (*great advantages for detector debug & fixing – when needed, while the spark suppression mechanism of the μ-RWELL make the operation of the detector more safe*)
- μ-RWELL operated in micro-TPC mode exhibits a spatial resolution down to 40-60 μm over a wide track incidence angular range (0-45°)

Increasing the Gain of a factor of 2 (I)

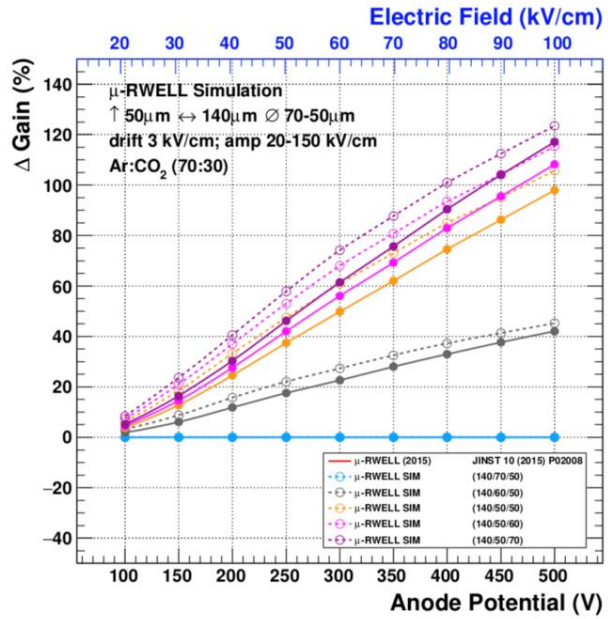
Courtesy of P. Verwilligen

Gain for different hole shapes

FTM (140/50/70) vs μ-RWELL (140/70/50)



(a) Ratio of $G_{\text{FTM}}/G_{\mu\text{-RWELL}}$



(b) $\Delta G = (G_{\text{FTM}} - G_{\mu\text{-RWELL}})/G_{\mu\text{-RWELL}}$

Figure: Gain ratio for different hole shapes (70/50 = μ-RWELL; 60/50; 50/50; 50/60; 50/70 = FTM) in Ar:CO_2 70:30 (left) and the percentual difference of the gain ΔG (%) (right).

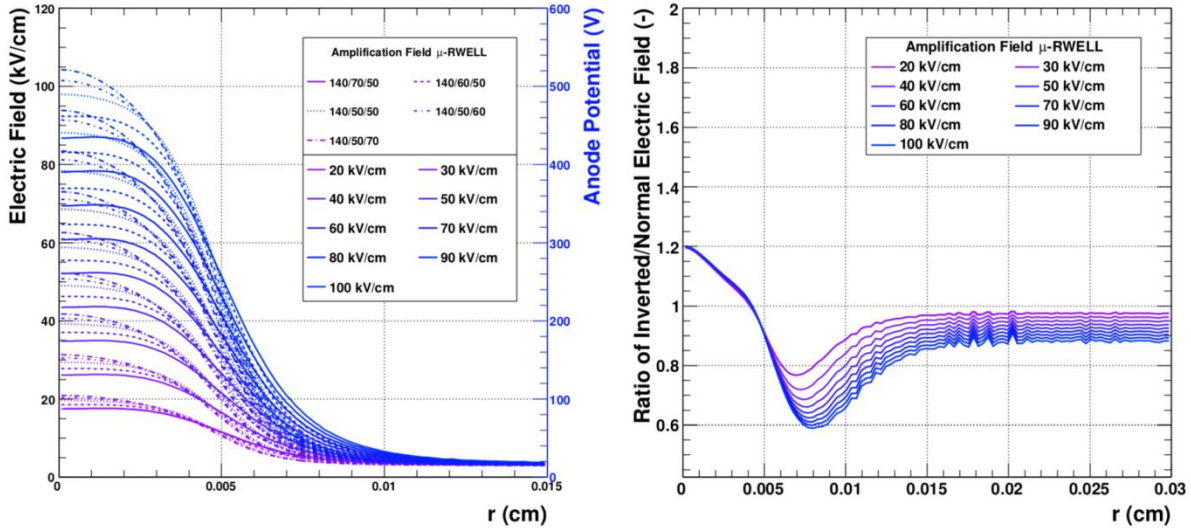
Simulation Studies for the fast timing mpgd (FTM)

(Dashed= no Penning, Full= Penning included)

Increasing the Gain of a factor of 2 (II)

Courtesy of P. Verwilligen

E field: hole shape μ-RWELL vs FTM

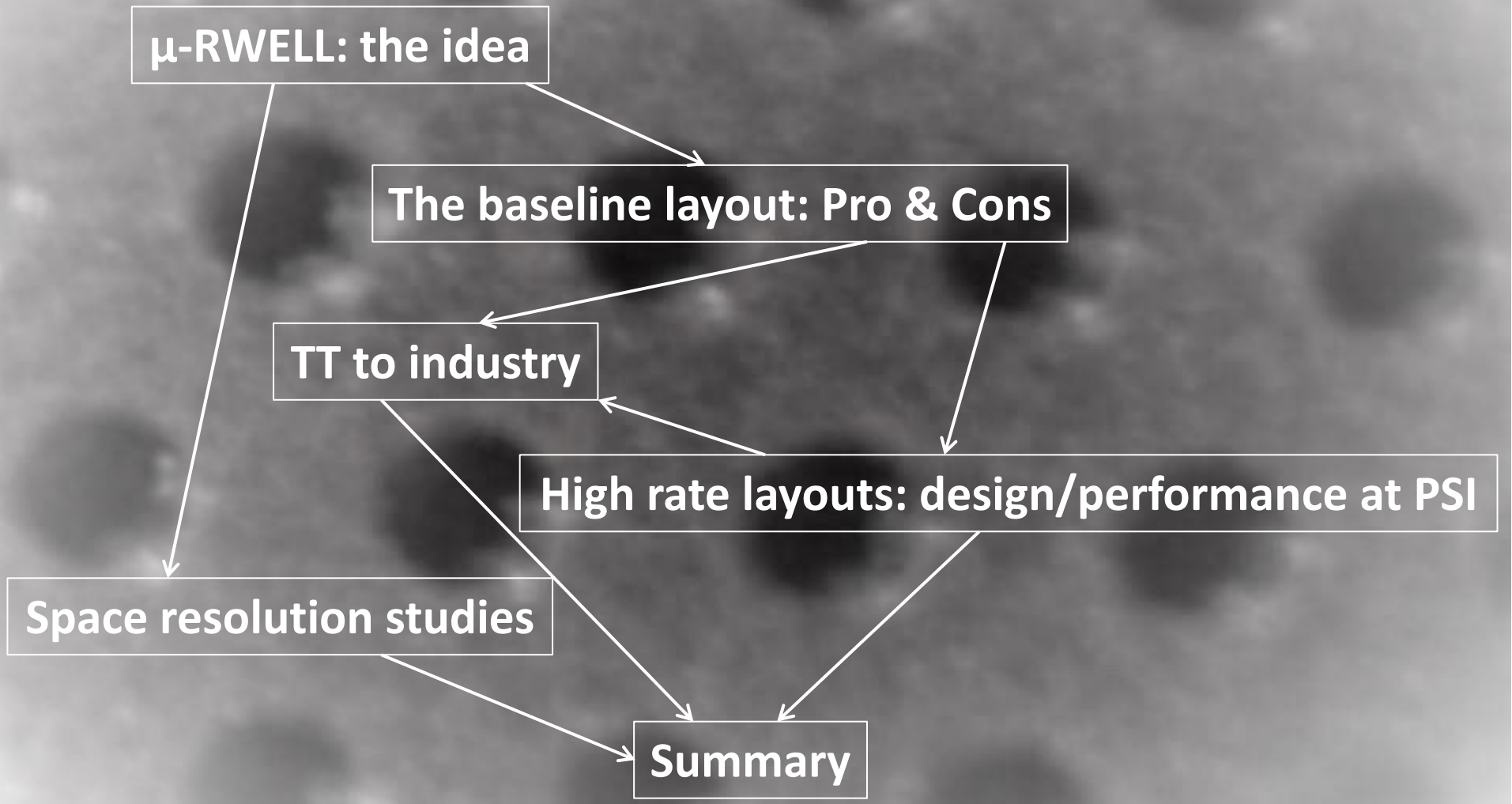


(a) Electric Field calculated for different well geometries

(b) Ratio Inverted / Normal geometry

Figure: Electric Field calculated for different well geometries, starting with the *Standard* geometry with a top diameter of 70 μm and bottom diameter of 50 μm, reducing first the top diameter to 50 μm with a step of 10 μm, then changing the bottom diameter to 70 μm, arriving at the *Inverted* geometry with 50 μm top diameter and 70 μm bottom diameter (left). Ratio of the *Inverted* and

R&D roadmap


μ-RWELL: the idea
The baseline layout: Pro & Cons
TT to industry
High rate layouts: design/performance at PSI
Space resolution studies
Summary

Why a new MPGD

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

stability under heavy irradiation → discharge containment

& simplify as much as possible the

construction/assembly → time consuming/complex operation