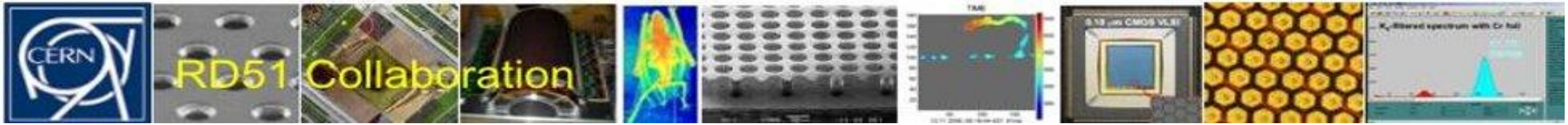

Highlights from Frascati's Detector Development Group activity

G. Bencivenni[1]
E. De Lucia[1], R. De Oliveira[2], G. Felici[1], M. Gatta[1],
M. Giovannetti[1], G. Morello[1], E. Paoletti[1], G. Papalino[1],
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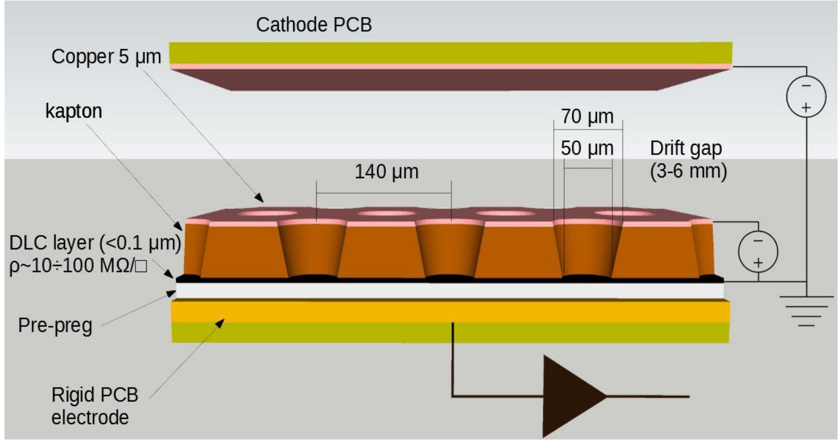
1 – Laboratori Nazionali di Frascati – INFN, Frascati (IT)
2 – CERN, Meyrin (CH)

Outline

- Introduction
- R&D on high-rate μ-RWELL
- R&D on tracking μ-RWELL
- R&D on the Hybrid GEM – RWELL layout (G-RWELL)
- Summary

The µ-RWELL

G. Bencivenni et al., The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD, 2015 JINST 10 P02008



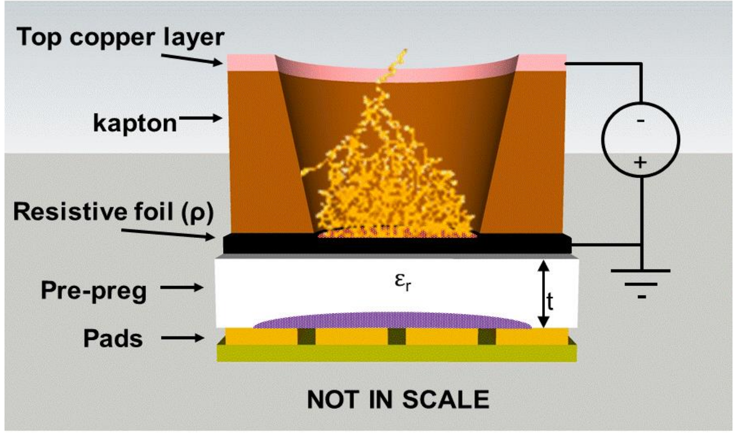
The **µ-RWELL** is a **resistive MPGD, with a GEM derived amplification stage,** composed of two elements:

- **Cathode**
- **µ-RWELL PCB:**

– a **WELL** patterned **kapton foil** (with **Cu-layer on top**) acting as **amplification stage**

– a **resisitive DLC film** with **ρ~50÷100 MΩ/□**

– a standard **readout PCB** with **pad/strip** segmentation



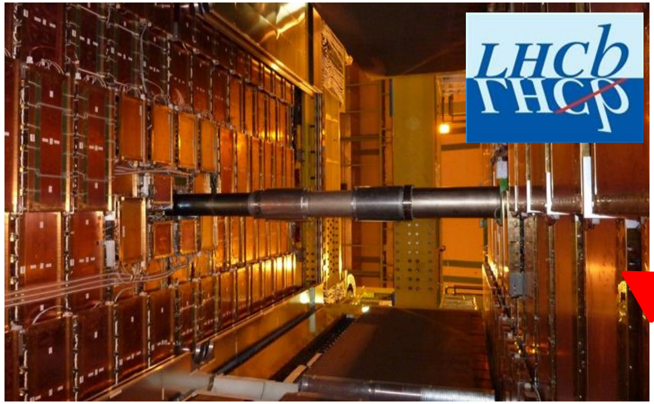
The **"WELL"** acts as a **multiplication channel** for the ionization produced in the drift gas gap.

The **resistive stage** plays a crucial role ensuring the **spark amplitude quenching,** which is **essential for stable operation.**

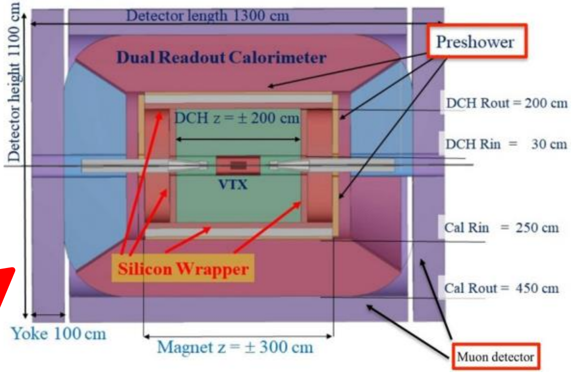
Drawback: the capability to **stand high particle fluxes** is **reduced but largely recovered** with appropriate **grounding schemes** of the **resistive layer.**

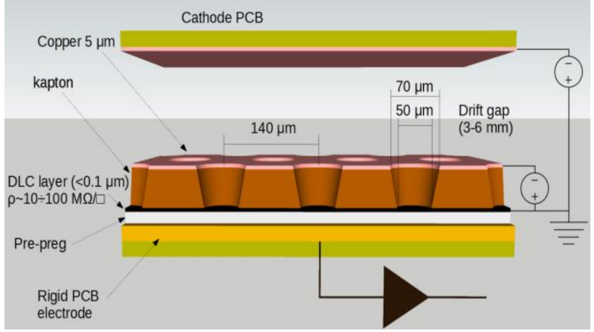
DDG – LNF R&D projects

LHCb



IDEA FCC-ee

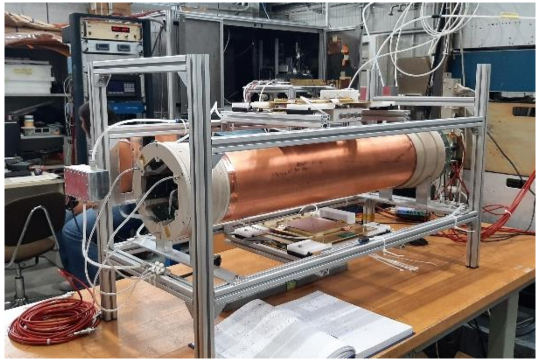




$$\mathrm{n}+{}^{10}_{5}\mathrm{B}\begin{cases}{}^{7}_{3}Li(1.02MeV)+\alpha(1.78MeV) & 6\% \\ {}^{7}_{3}Li(0.84MeV)+\alpha(1.47MeV)+\gamma(0.48MeV) & 94\%\end{cases}$$

uRANIA

EURIZON

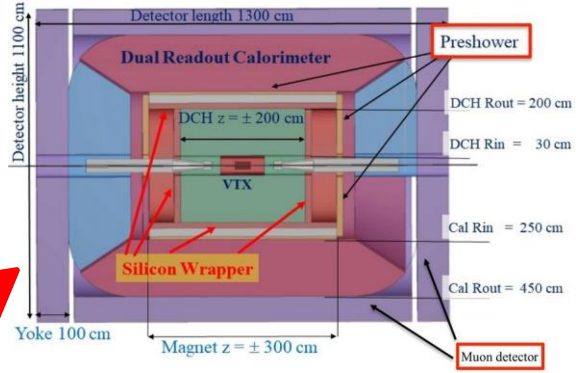


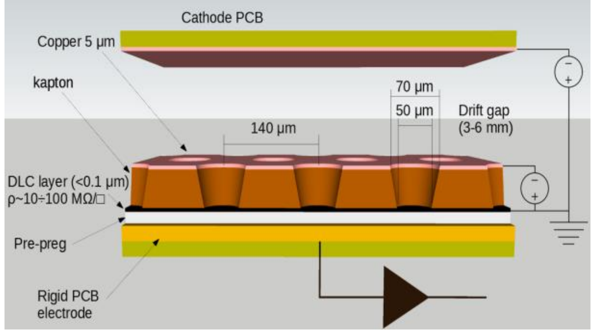
DDG – LNF R&D projects

LHCb

- rate up to **1 MHz/cm²**
- **576 detectors** w/**pad r/out > 9×9mm²**
- active area **30x25** to **74x31** cm²
- **90 m²** detectors
- **130 m²** DLC

IDEA
FCC-ee

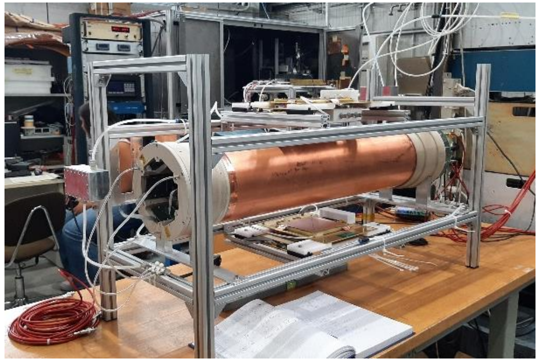




$$n+{}^{10}_{5}B \begin{cases} {}^{7}_{3}Li(1.02MeV)+\alpha(1.78MeV) & 6\% \\ {}^{7}_{3}Li(0.84MeV)+\alpha(1.47MeV)+\gamma(0.48MeV) & 94\% \end{cases}$$

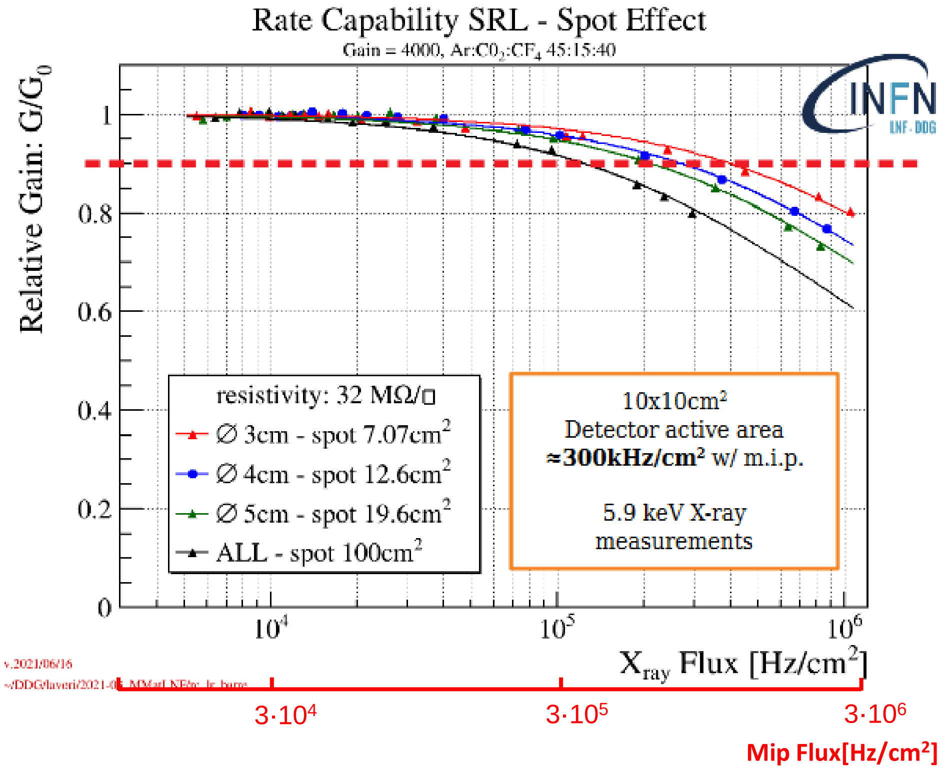
uRANIA

EURIZON

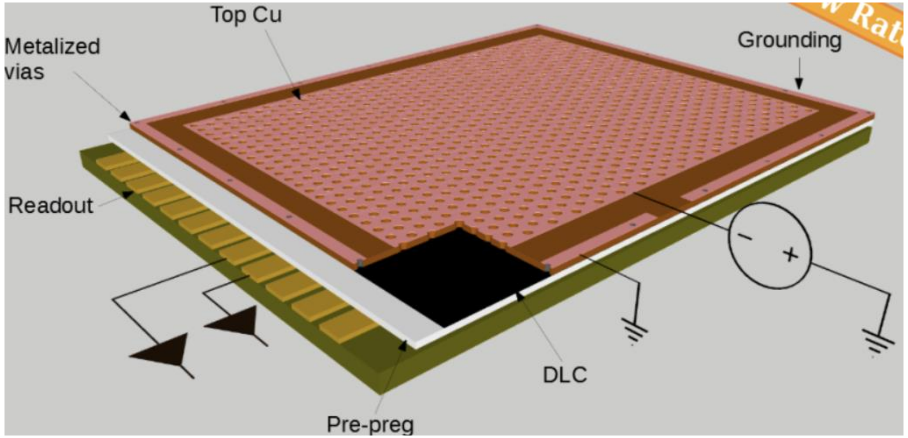


High-rate μ-RWELL for the LHCb experiment

The low-rate layout



Different primary ionization ⇒
Rate Cap.$_{m.i.p.}$ = 3×Rate Cap.$_{X\text{-}ray}$

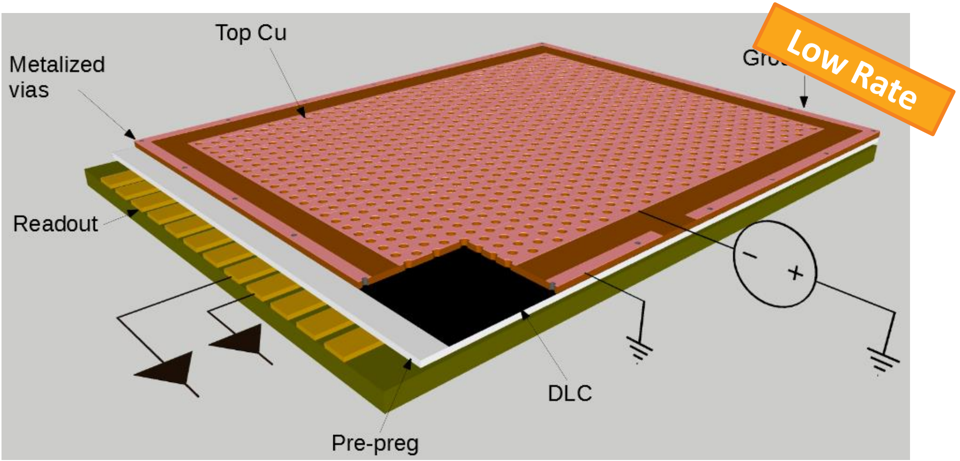


Single Resistive Layer (SRL)

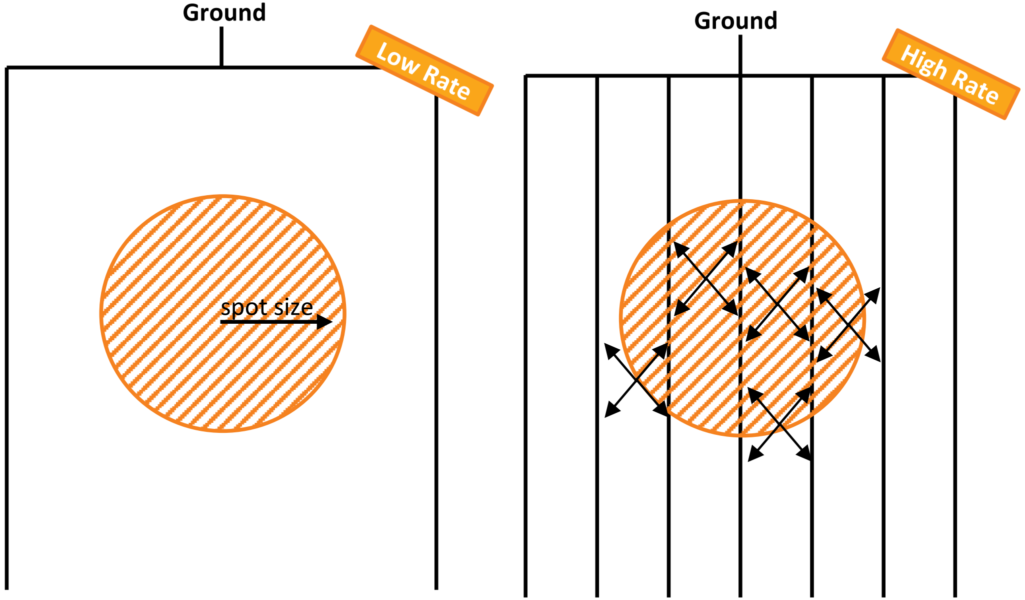
- **2-D current evacuation scheme based on a single resistive layer**
- DLC grounding around the perimeter of the active area
- **limitation for large area:** the path of the current towards ground connection depends on the particle incidence point → detector response inhomogeneity → **limited rate capability <100 kHz/cm²**

High-rate layouts: principle of operation

To overcome the **intrinsic rate limitations** of the **Single Resistive Layout,** it is necessary to introduce a **high-density grounding network** for the resistive stage (DLC).



Single Resistive Layout (SRL) with edge grounding



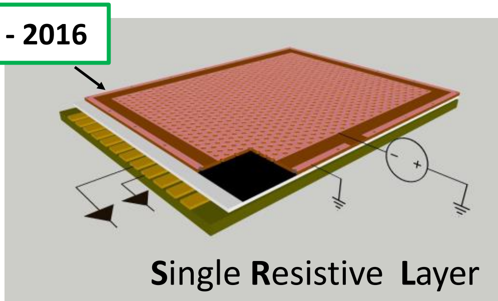
Segmenting the DLC with **conductive micro-strips/dots with a** typical **pitch of 1cm:** a sort of tiling of the active area using a set of smaller SRL.

High-rate layouts evolution

G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* 14 P05014

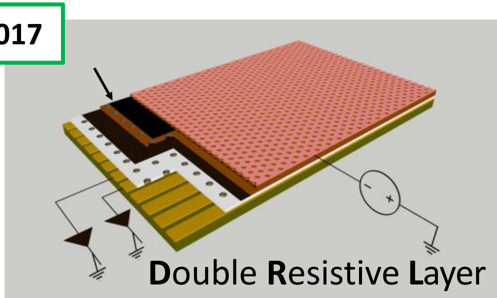
Extensive R&D has been performed to optimize the DLC grounding, enabling the detector to withstand up to 1MHz/cm^2

2014 - 2016


Single Resistive Layer

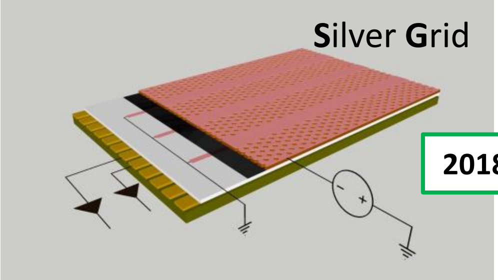
- **Single DLC layer with edge conductive line**
- **2-D current evacuation**
- rate capability **< 100 kHz/cm²**
- **Easy for industry**

2017


Double Resistive Layer

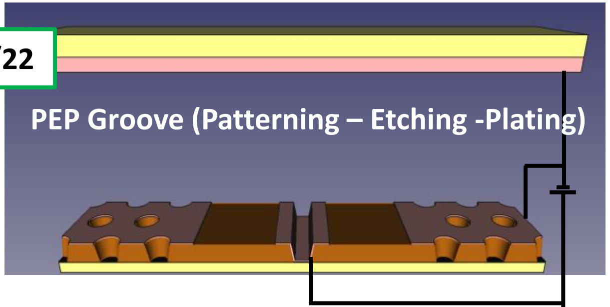
- **Two stacked resistive layers** with a **double matrix of conductive vias**
- **3-D current** evacuation
- Rate capability ~ **10MHz/cm²**
- **Complex manufacturing not easily engineered**

2018 - 2020


Silver Grid

- **Single DLC layer**
- **2-D current evacuation** through **conductive grid on the DLC layer**
- rate capability ~ **10MHz/cm²**
- **Easily engineered,** BUT **complex Cu+DLC sputtering/alignment**

2021/22


PEP Groove (Patterning – Etching -Plating)

- **Single DLC layer**
- **2-D current evacuation: conductive grid by etching** from the **top Cu, through** the **kapton foil down to the DLC**
- **No grid alignment issues, scalable to large size – large dead zone** (>15%)
- **Easily engineered, because based on SBU technology**

High-rate layouts: PEP-DOT

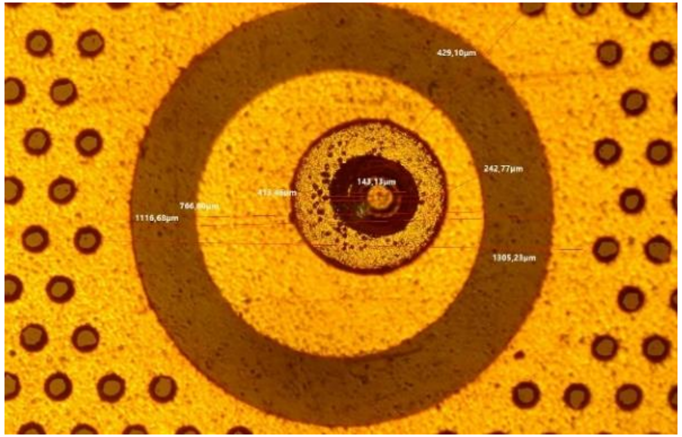
2023

PEP-DOT:

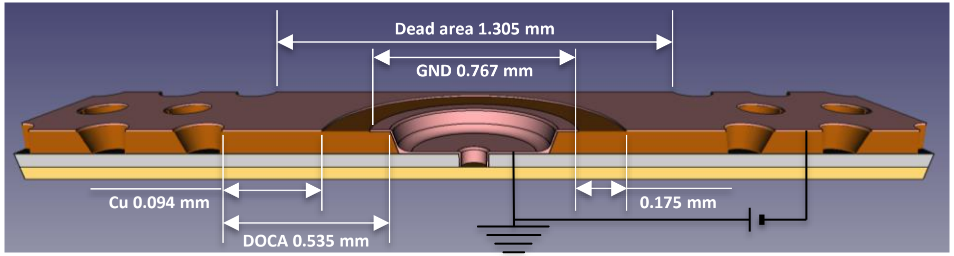
DLC grounding through conductive dots connecting the DLC with pad r/outs

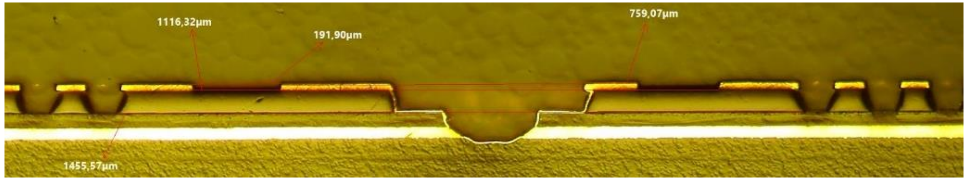
Pad R/O = 9×9mm^2
Grounding:
- Dot pitch = 9mm
- dot rim = 1.3mm

~ 97% geometric acceptance

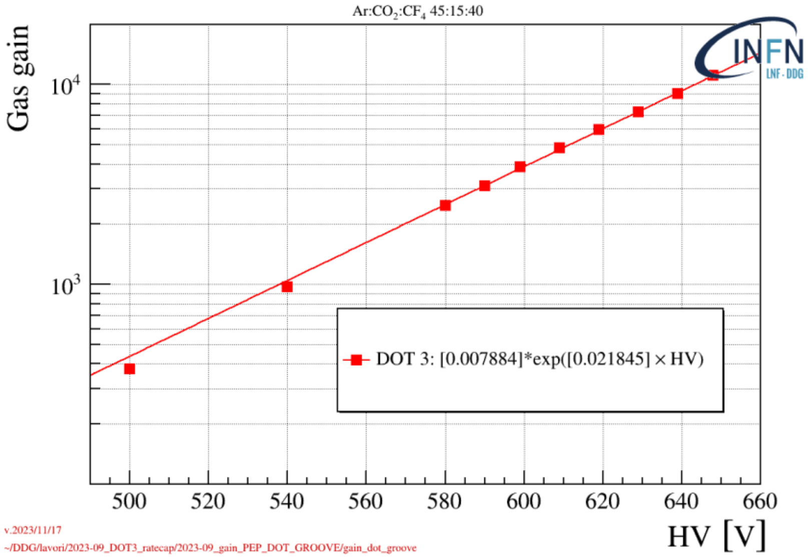


DOT = Cu plated blind vias

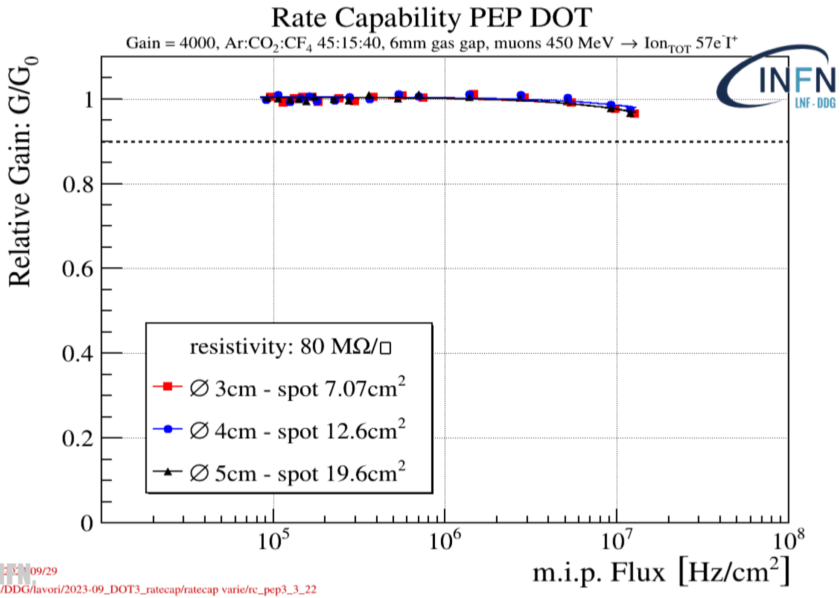




PEP - DOT gain & rate capability (X-ray characterization)



v.2023/11/17
~/DDG/lavori/2023-09_DOT3_ratecap/2023-09_gain_PEP_DOT_GROOVE/gain_dot_groove



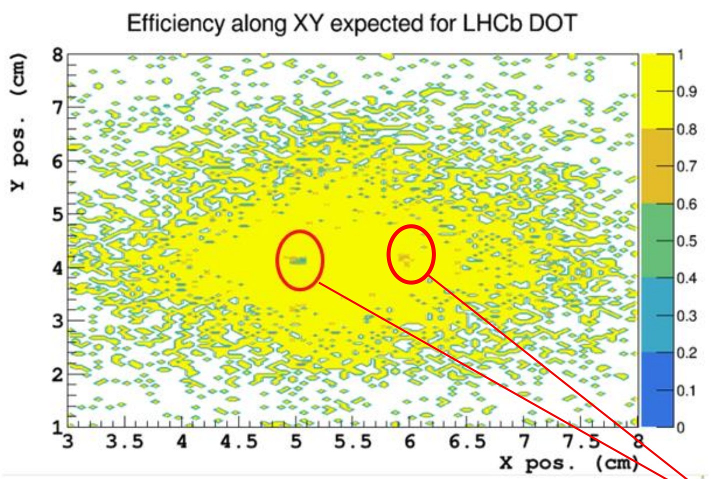
…09/29
~/DDG/lavori/2023-09_DOT3_ratecap/ratecap varie/rc_pep3_3_22

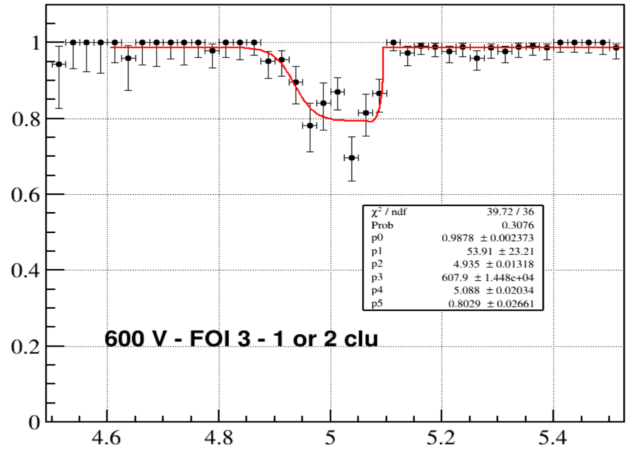
PEP – DOT performance:

- **gas gain** up to **10^4**
- **rate capability** (@ 90% gain drop) ~ **10 MHz/cm^2** , measured with **different irradiation spot size.**

PEP - DOT efficiency (TB-2023)

APV25 based Fee

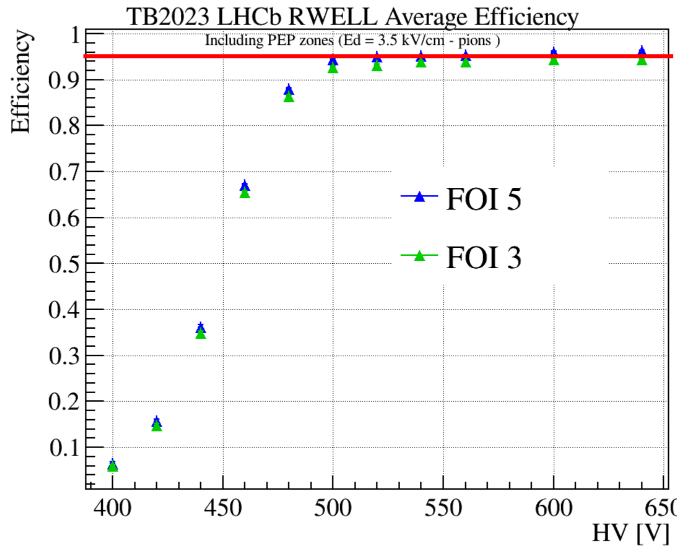




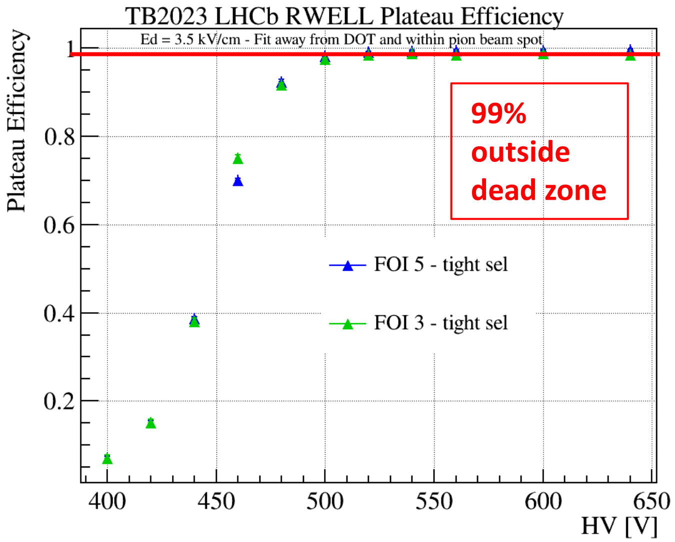
χ^2 / ndf	39.72 / 36
Prob	0.3076
p0	0.9878 ± 0.002373
p1	53.91 ± 23.21
p2	4.935 ± 0.01318
p3	607.9 ± 1.448e+04
p4	5.088 ± 0.02034
p5	0.8029 ± 0.02661

Small and localized efficiency drop around grounding dots

Efficiency with dead zone



96% including dead zone

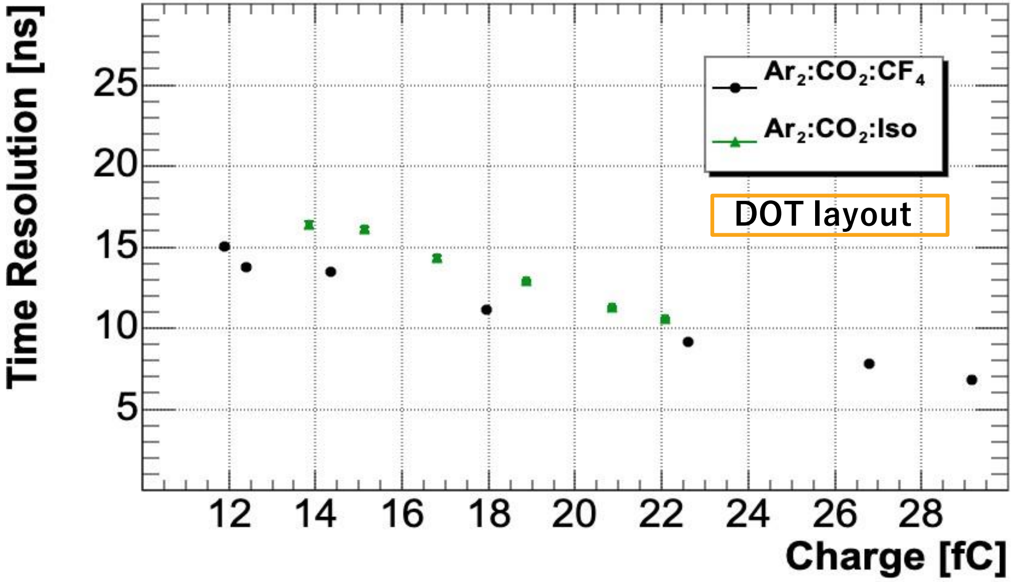


99% outside dead zone

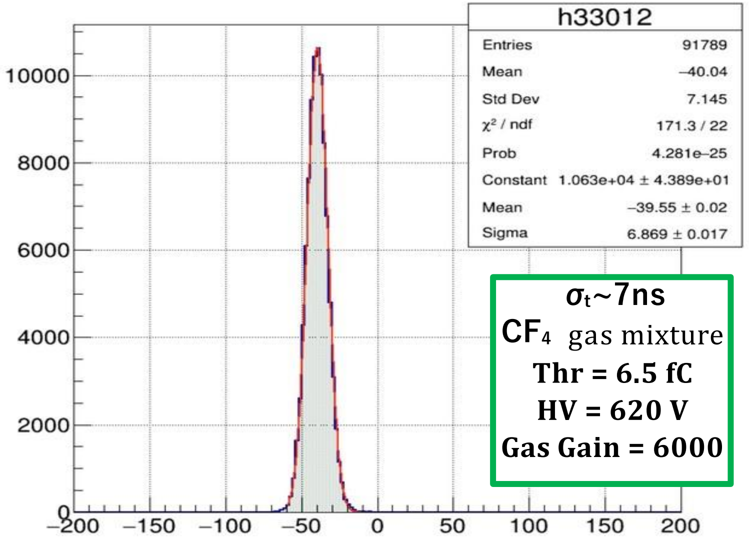
Efficiency w/out dead zone

PEP DOT – time performance (TB – 2023)

FATIC2 based Fee



DOT layout



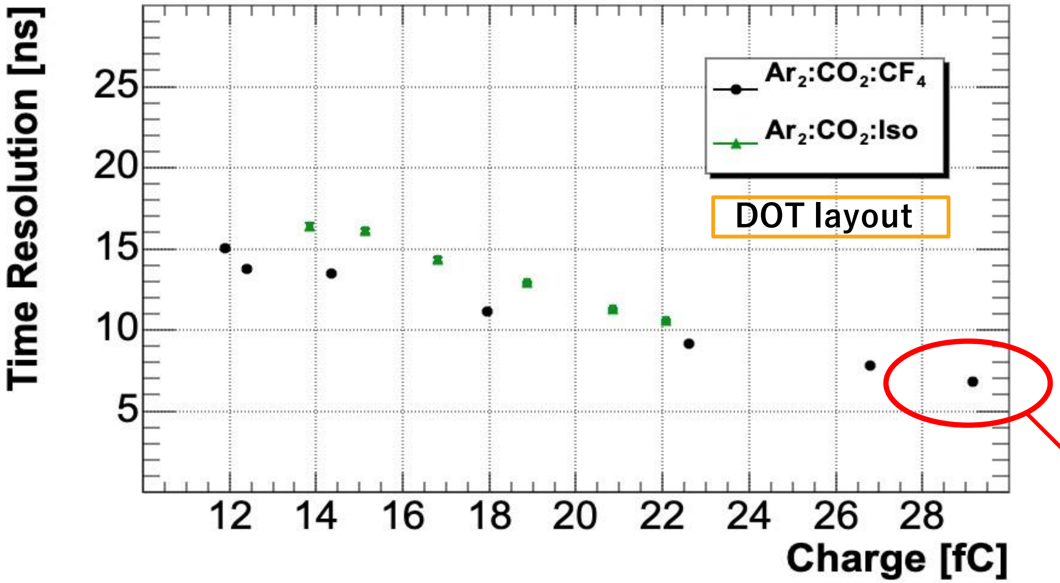
σ_t~7ns
CF_4 gas mixture
Thr = 6.5 fC
HV = 620 V
Gas Gain = 6000

TB-2023 at H8C with a **preliminary version of the FATIC chip** (developed by Bari Group) in the framework of the R&D for the **LHCb-Muon upgrade**.

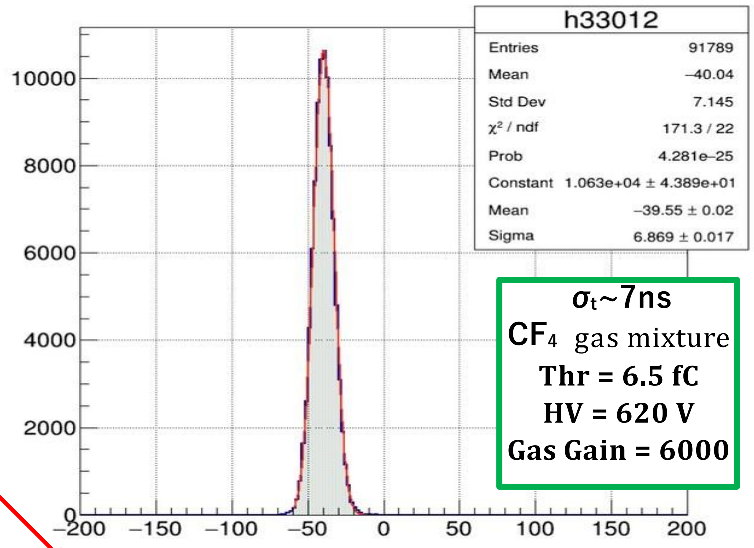
The goal is to achieve a time resolution ≤ 5 ns in safe operation mode.

PEP DOT – time performance (TB – 2023)

FATIC2 based Fee



DOT layout



σ_t~7ns
CF_4 gas mixture
Thr = 6.5 fC
HV = 620 V
Gas Gain = 6000

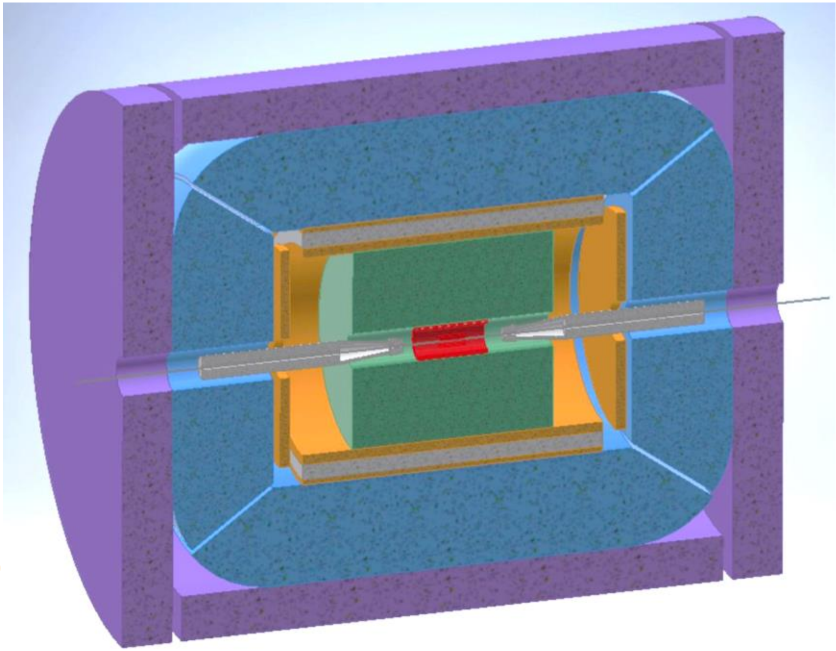
close to the max gain of the detector

TB-2023 at H8C with a **preliminary version of the FATIC chip** (developed by Bari Group) in the framework of the R&D for the **LHCb-Muon upgrade**.

The goal is to achieve a time resolution ≤ 5 ns in safe operation mode → further R&D needed on both detector & FEE

Tracking µ-RWELL for FCC-ee

IDEA: pre-shower and muon system



Pre-shower & Muon requirements:

Tiles: 50x50 cm^2 with X-Y readout

Efficiency ≥ 98%

Space resolution ≈ 100 µm (Pre-shower)

≈ 500 µm (Muon)

Instrumented Surface/FEE:

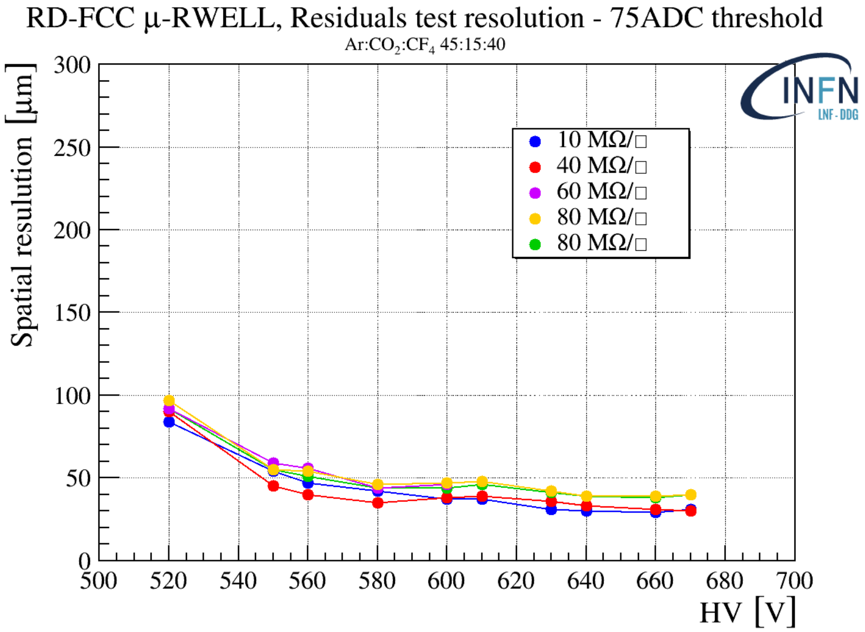
- pre-shower → 130 m^2, 520 det., 3×10^5 chs. (0.4 mm strip pitch)
- Muon → 1500 m^2, 1520 det., 5×10^6 ch. (1.2 mm strip pitch)

Mass production → Technology Transfer to Industry

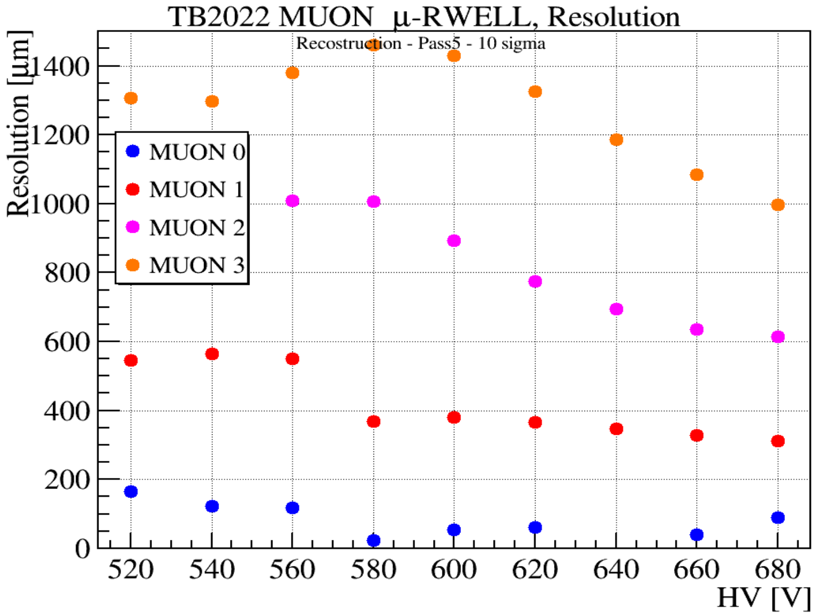
FEE Cost reduction → custom made ASIC

1-D Tracking

Resistivity scan



R/O pitch scan



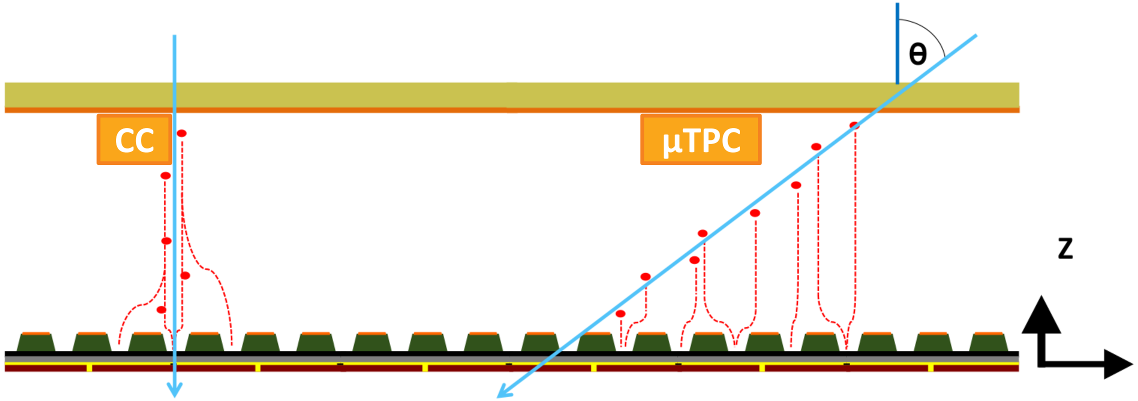
With a **0.4 mm strip pitch** and **0.15 mm strip width**, **no effects** were observed **within this resistivity range**. Additionally, **DLC resistivity uniformity is not a critical parameter** for spatial resolution.

Increasing the R/out pitch (0.8, 1.0, 1.2, 1.6 mm) results in a **reduction of the spatial resolution.**

1-D Tracking (inclined tracks)

For **inclined tracks** and/or in the presence of high B fields, the **charge centroid (CC)** gives **very poor results** due to the **very broad spatial resolution** on the anode-strip plane

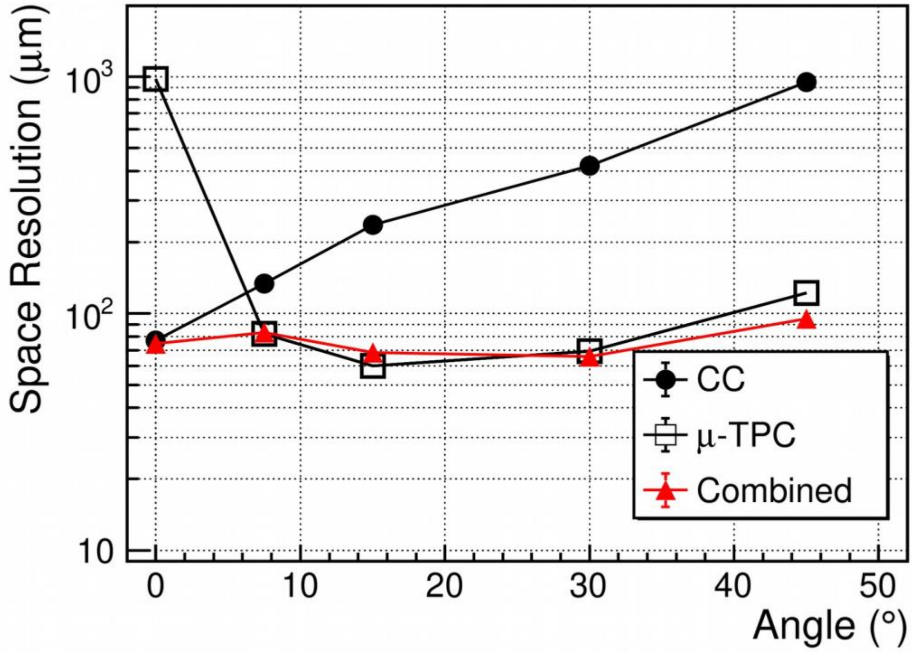
By **implementing the µTPC mode**[1] and using the knowledge of the **drift time of the electrons** (and the **drift velocity**), each **ionization cluster** is **projected inside the conversion gap**, and the **track segment in the gas gap** is reconstructed.



[1] introduced for ATLAS MMs by T. Alexopoulos

M. Giovannetti et al., *On the space resolution fo the µ-RWELL*, 2020 JINST 16 P08036

1D Strip R/O: 400um pitch, gain 4000, 80Ω/□



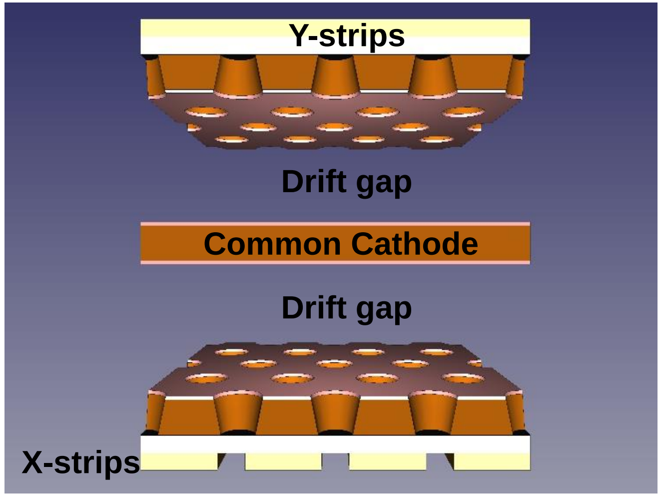
By combining the CC and µTPC reconstruction (through a wheighted average) **a resolution below 100 µm** could be reached over a wide incidence angle range.

2-D Tracking layouts

K.Gnanvo et al., NIM 1047 (2023) 167782

Precursor of the micro-Rgrooves introduced by Zhou Yi

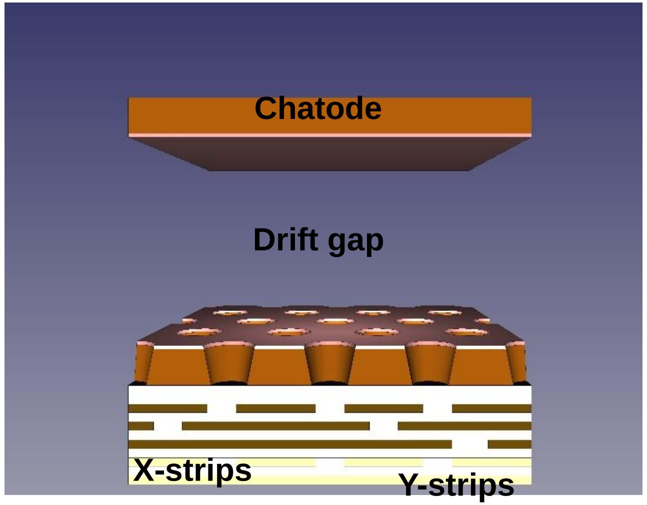
N.2 u-RWELLs 1D (2⊗1D)



The layout with **two separate detectors equipped with its own r/out** is operated at **lower gas gain,** with respect to the **single detector with 2D r/out (COMPASS like).**

Tested @ TB2022.

u-RWELL - Capacitive Sharing r/out

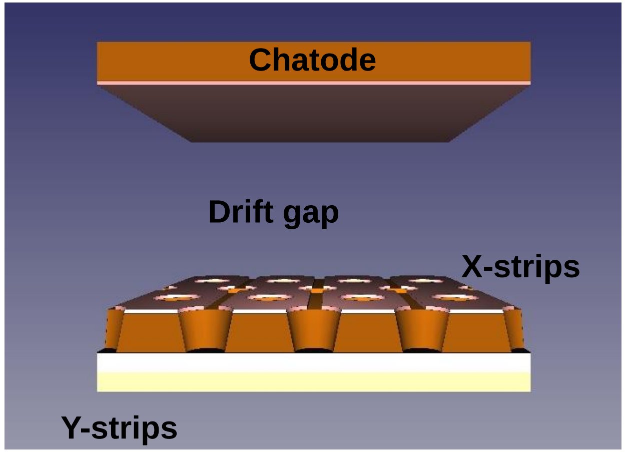


The **charge sharing performed through the capacitive coupling between a stack of layers** of pads and **the r/out board.**

Reduce the FEE channels, and the **total charge is divided between the X & Y r/out.**

Tested @ TB2023.

u-RWELL TOP r/out



The **TOP-readout layout** allows to work at **lower gas gain** wrt the «COMPASS» r/out (X-Y r/out decoupled).

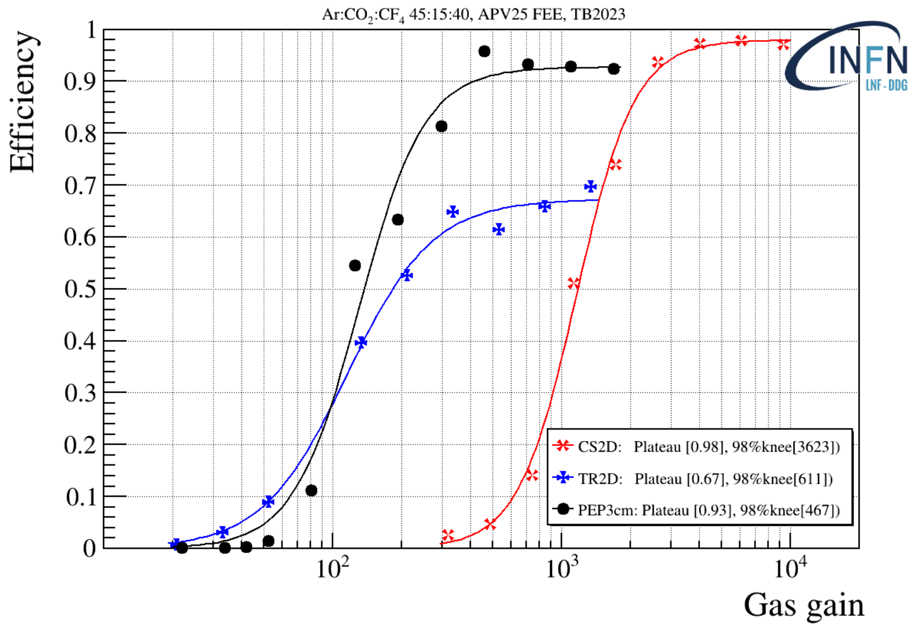
X-coordinate on the **TOP** of the amplification stage introduces **dead zone in the active area.**

Tested @ TB2023.

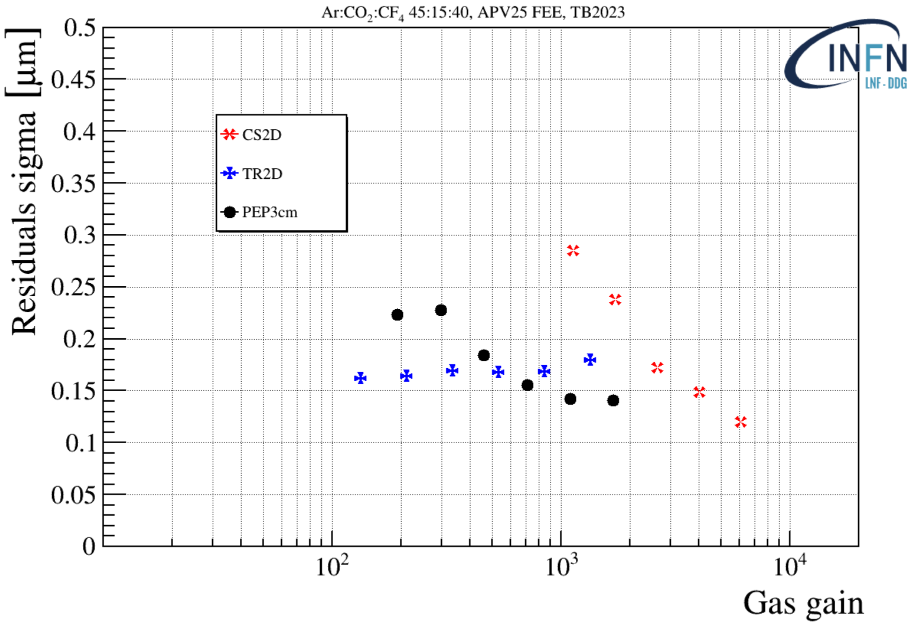
2-D Tracking layouts performance

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

2D layouts – 10x10 cm^2



2D layouts – 10x10 cm^2



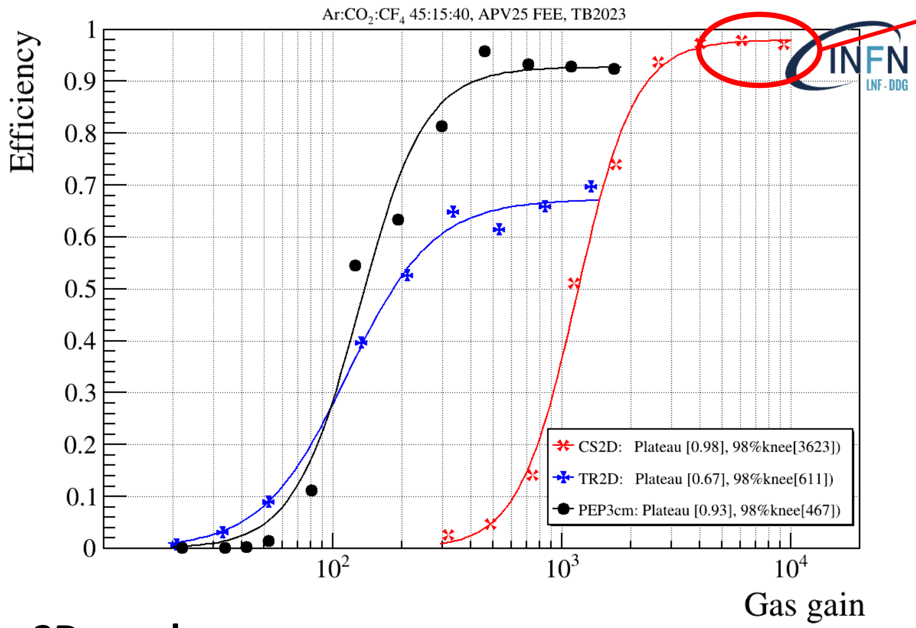
- **2x1D:** spatial resolution < 200um (pitch 0.8 mm), low voltage operating point ~520V, tracking efficiency ~95%
- **CS:** spatial resolution <200um (pitch 1.2 mm), high voltage operating point, ≥ 600V, tracking efficiency ~ 98%
- **Top r/out:** spatial resolution < 200um (pitch 0.8 mm), low voltage operating point ~520V, tracking efficiency ~70%

2-D Tracking layouts performance

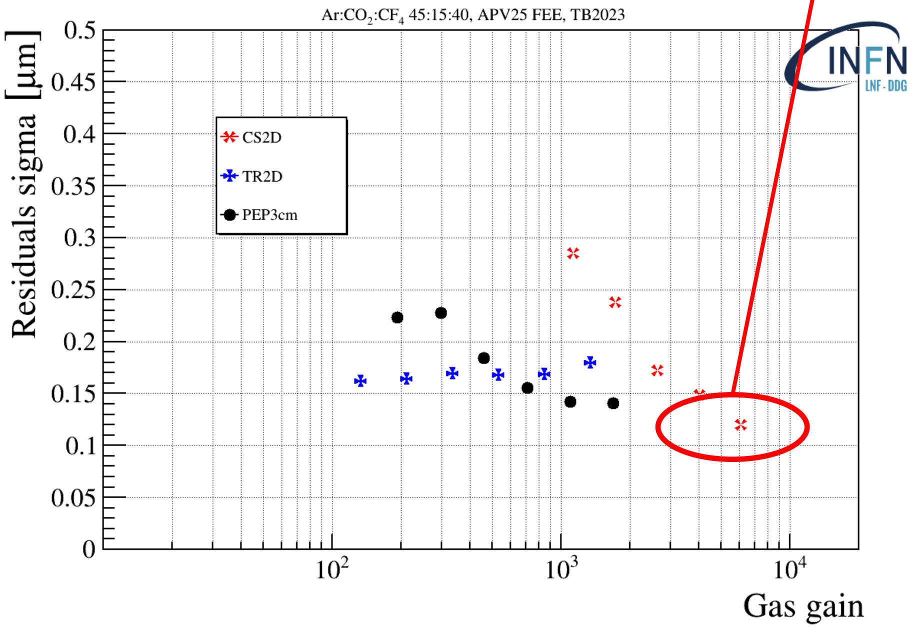
$Ar/CO_2/CF_4 = 45/15/40$

close to the max gain of the detector

2D layouts – 10x10 cm^2



2D layouts – 10x10 cm^2



The 2D puzzle:

2D tracking at high efficiency requires the detector to be operated at a **gain ≥ 10^4** (especially with inclined tracks),
While the typical **max-gain of a μ-RWELL is 1÷2×10^4**
It's NOT safe to operate a detector in a real experiment close to its max-gain → **further R&D needed on detector**

The σ_T and 2D puzzle

To address:

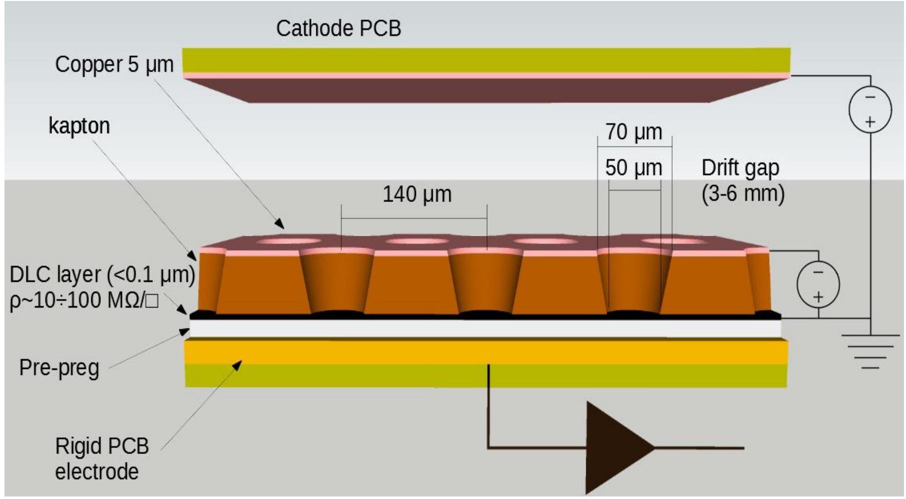
- the **stringent requirements of the LHCb** experiment's muon system upgrade, which demands **unprecedented time resolution (**$\sigma_T \leq 5$ **ns)** at **high operational stability**

- the **2D tracking for non-orthogonal particle tracks**

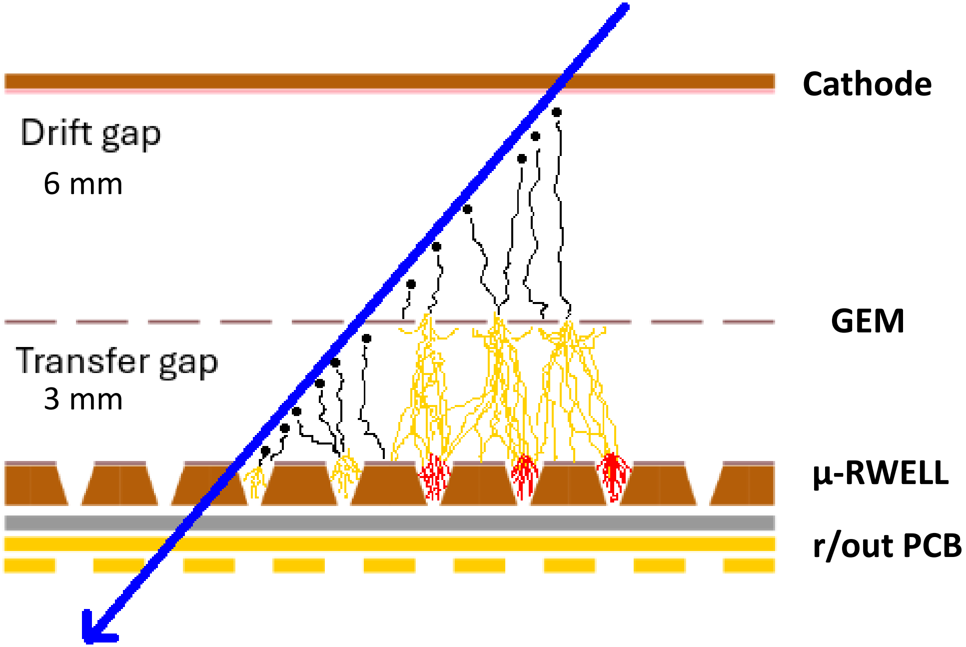
both **requiring gas gains larger than** 10^4

We explored **innovative detector layouts beyond the conventional μ-RWELL design**, based on a **hybrid technology**, in which a **GEM-based pre-amplification stage is combined with the classic μ-RWELL.**

The μ-RWELL vs Hybrid (G-RWELL)



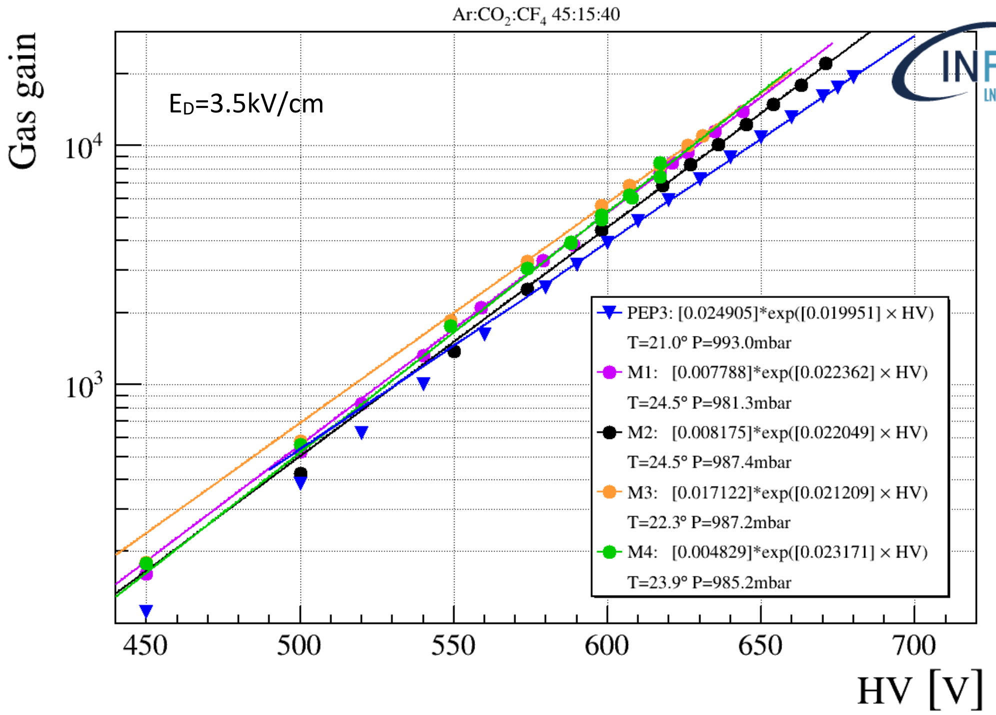
Classic μ-RWELL layout
Prototype tested: M2R1 - LHCb 250x300 mm^2



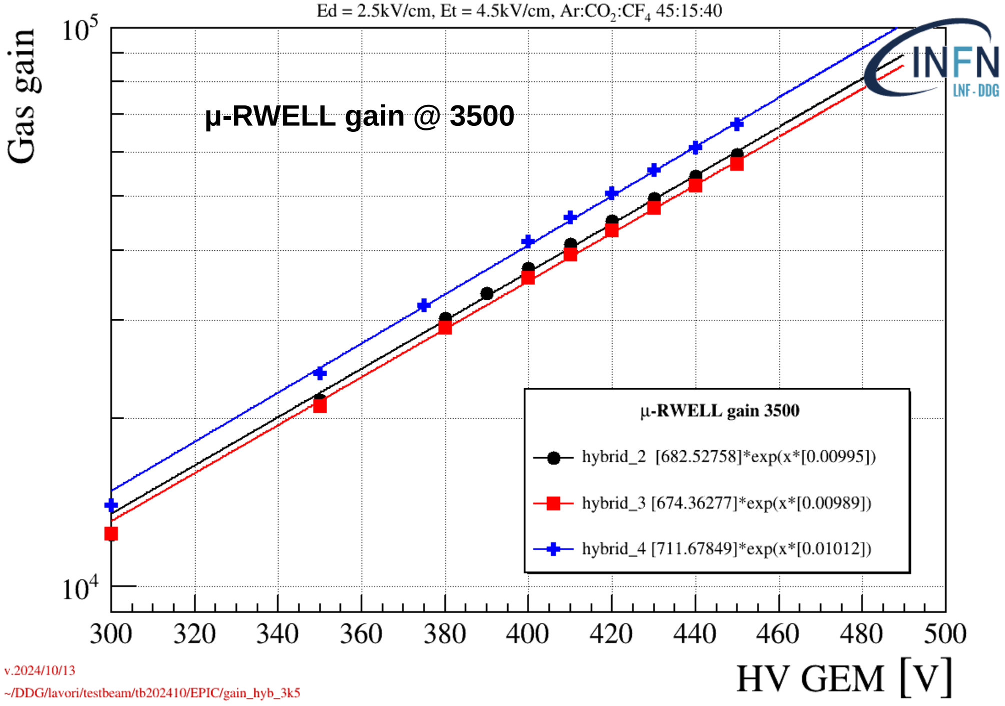
Hybrid layout → G-RWELL
Prototype tested: 100x100 mm^2

Gas gain measurement – w/ X-rays

M1-M4 (M2R1-LHCb) - uRWELL



HYBRID



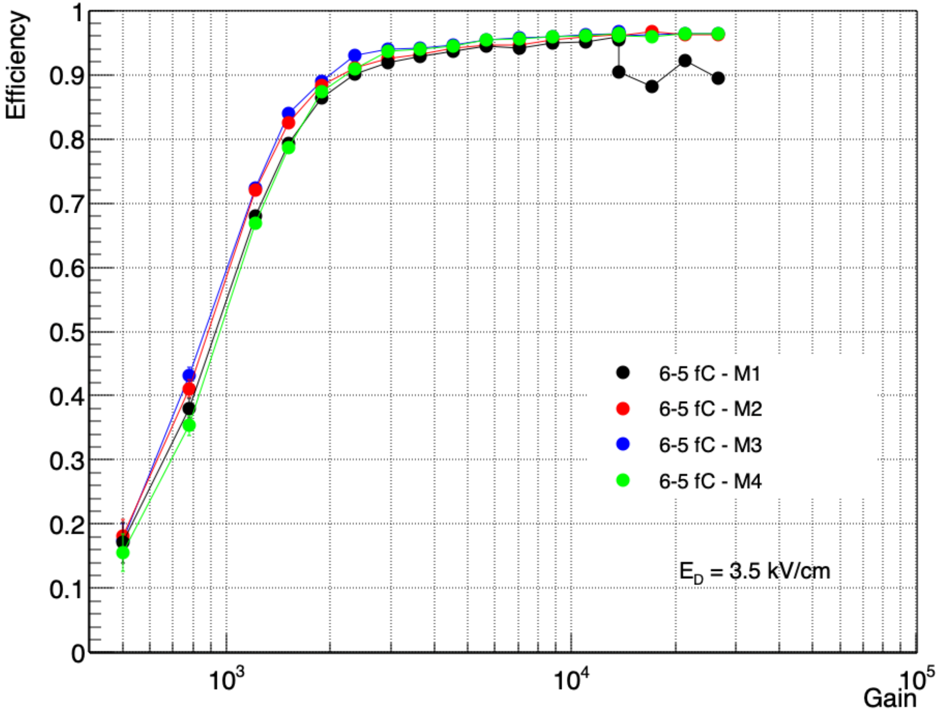
Classic uRWELL (M2R1-LHCb): max gain ≈2 x 10^4

G-RWELL: max gain >> 10^4

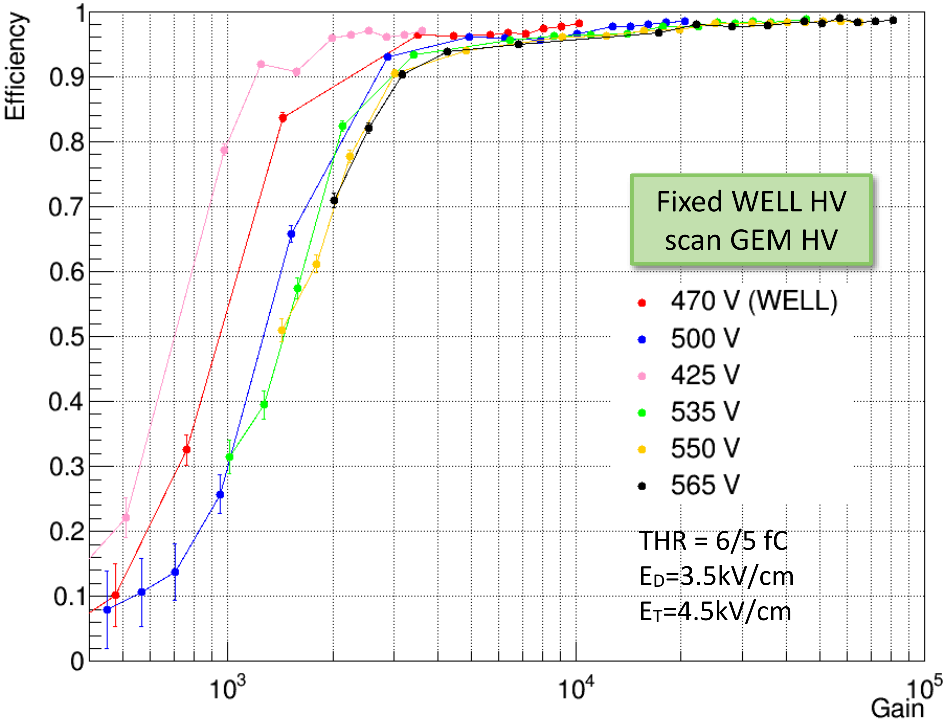
M2R1 μ-RWELL vs HYBRID – global efficiency

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

M1-M4 (M2R1-LHCb) - uRWELL



HYBRID



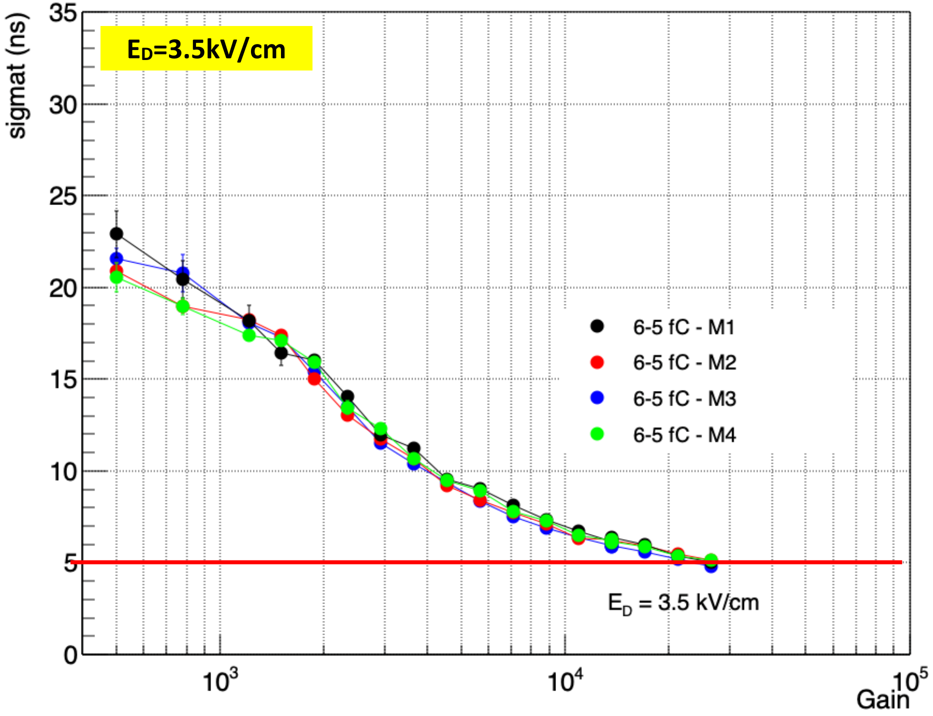
Fixed WELL HV
scan GEM HV

THR = 6/5 fC
E_D=3.5kV/cm
E_T=4.5kV/cm

A plateau >98% is reached for a gas gain above 6000.
The gain for **PINK (WELL@425V)** and **RED (WELL@470V)** is extrapolated, so the curves doesn't overlap likely for this reason.

M2R1 μ-RWELL vs HYBRID – time resolution

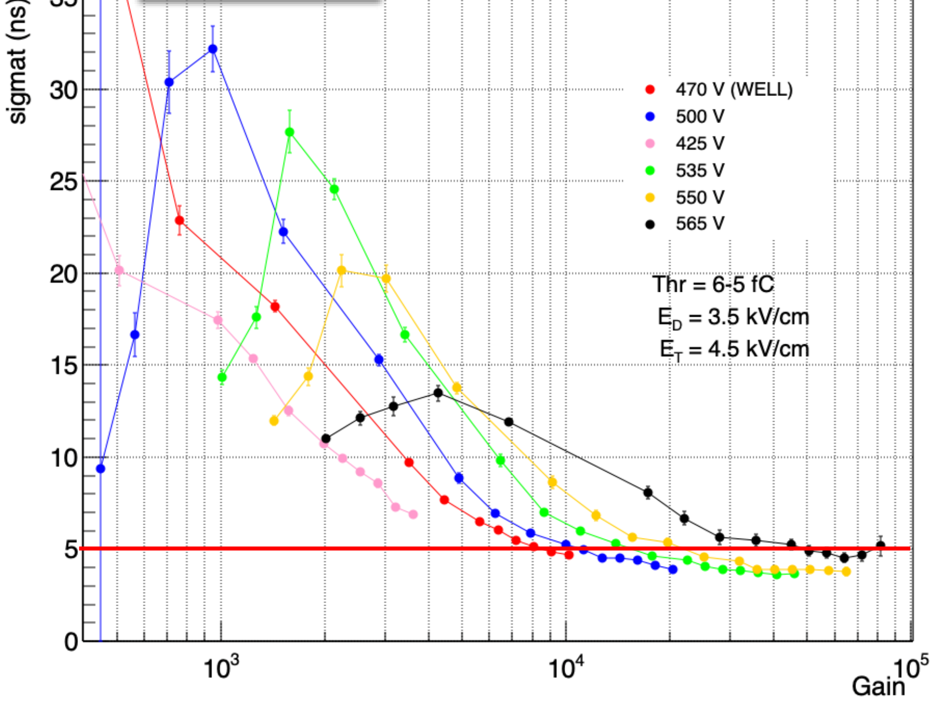
M1-M4 (M2R1-LHCb) - uRWELL



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

Fixed WELL HV
scan GEM HV

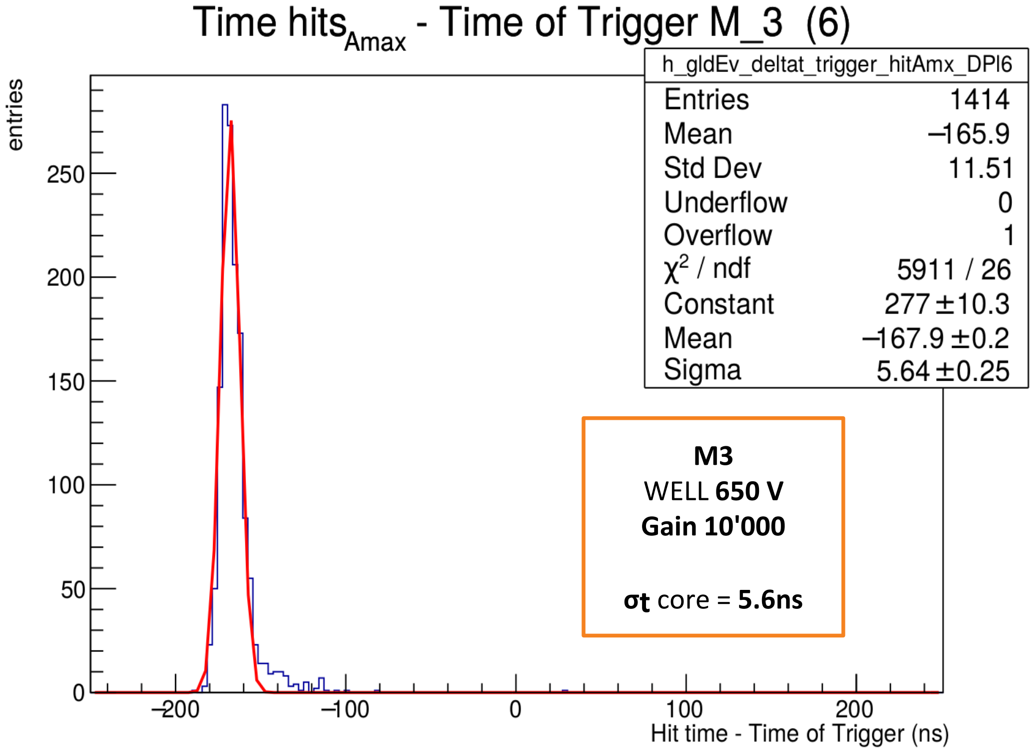
HYBRID



The HYBRID demonstrates better time performance than M2R1 at the same gain, thanks to higher efficiency on the first cluster. Differences among the families at varying HV_WELL values can be attributed to a well-known effect typical of multi-step amplification stage layouts, commonly referred to as the “Biwell effect”

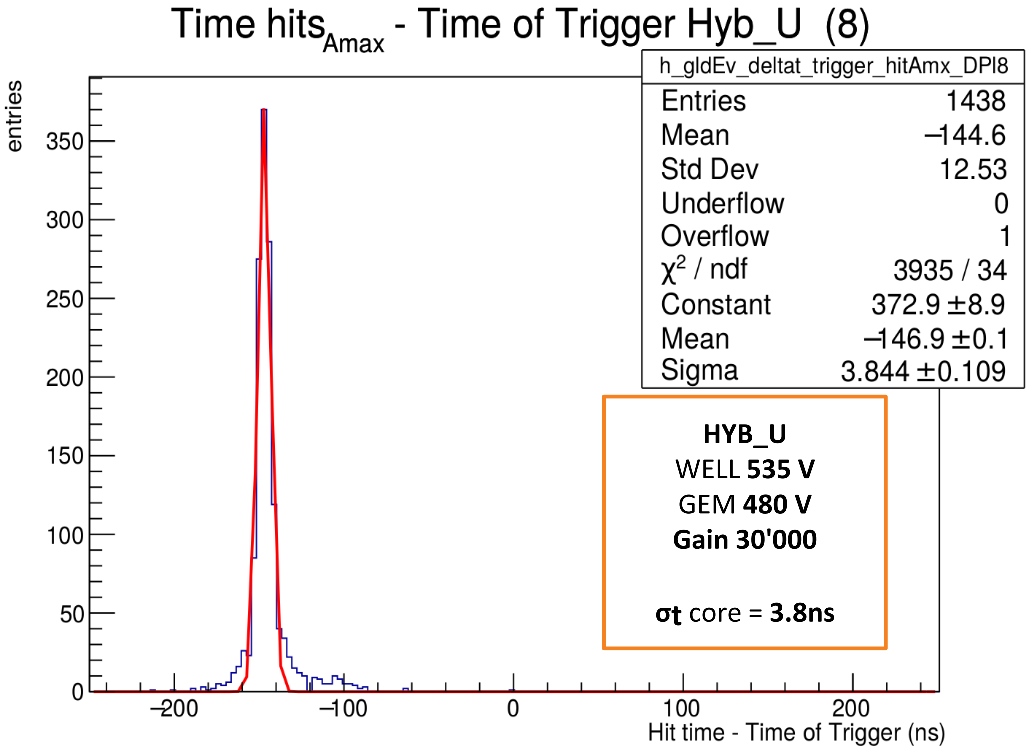
M2R1 µ-RWELL vs HYBRID – time resolution

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



M3
WELL **650 V**
Gain 10'000

σt core = **5.6ns**



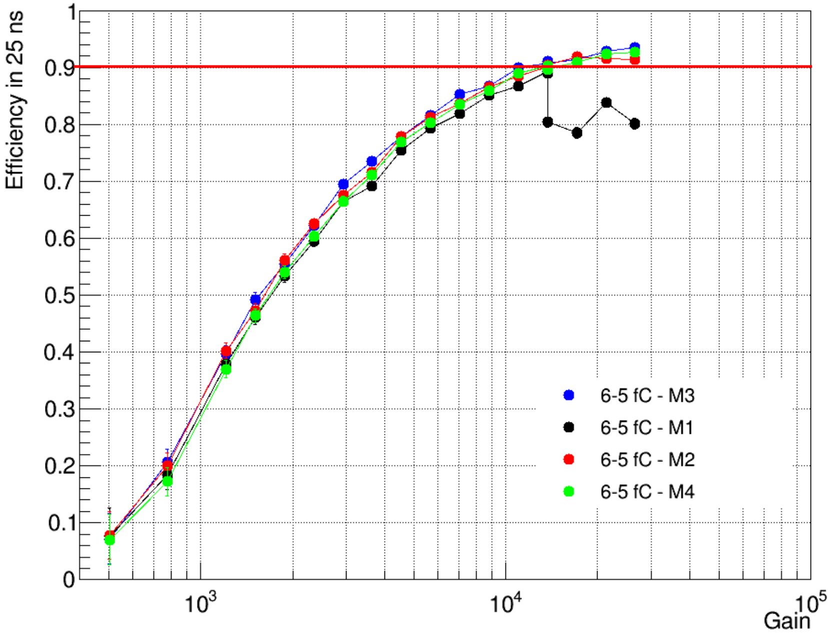
HYB_U
WELL **535 V**
GEM **480 V**
Gain 30'000

σt core = **3.8ns**

Time reference: one of the scintillator of the trigger (σ_t<1ns)
σ_t: gauss fit core of the Δ_t distribution

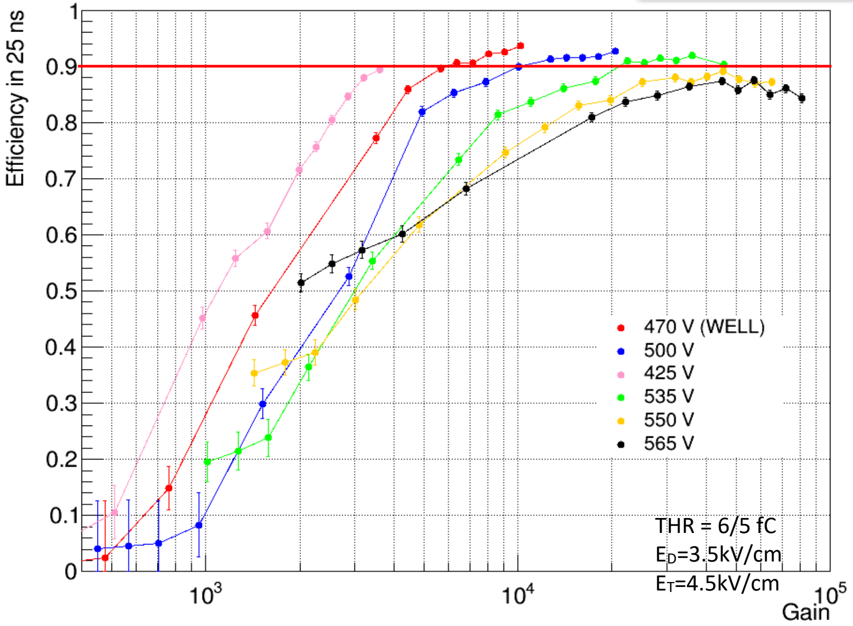
M2R1 μ-RWELL vs HYBRID – efficiency in 25ns

M3 - uRWELL



HYBRID

Fixed WELL HV
scan GEM HV



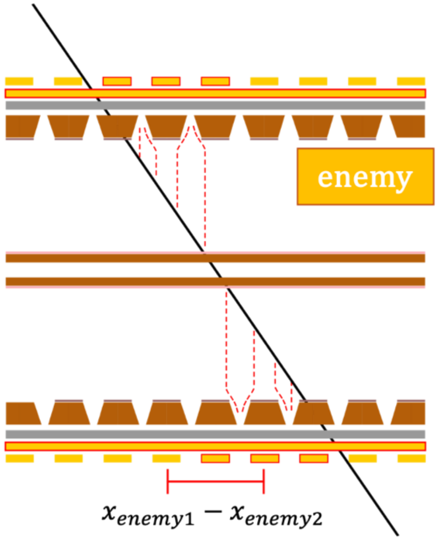
The best performance obtained for a **uRWELL gain around 10^4**, **close to the typical max gain of the detector**.

The best performance obtained for **HV-RWELL 500 – 535 V (gain = 500-1000)**, and **HV-GEM = 450 V (gain = 20)**
Further **improvement expected** with **transfer gap reduction (3 → 2mm)**

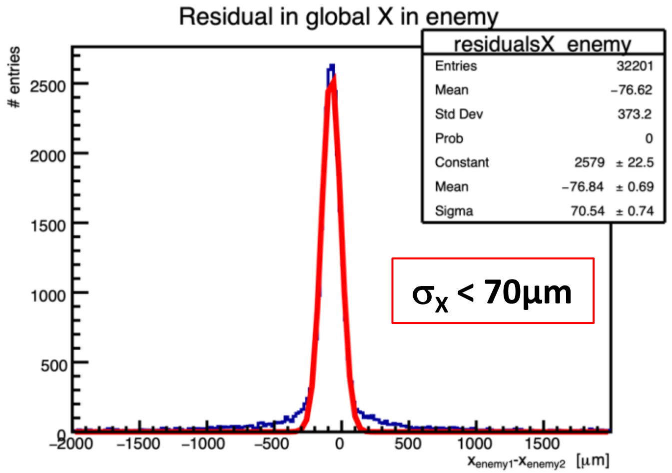
Effi(25ns) ≥ 0.9 per single gap allows to have **Effi(25ns) ≥ 0.98 per station** by using chambers with 4 gaps and requiring at least 2 fired gaps fired per chamber station

Tracking with Hybrid layout (ePIC - INFN Tor Vergata Group)

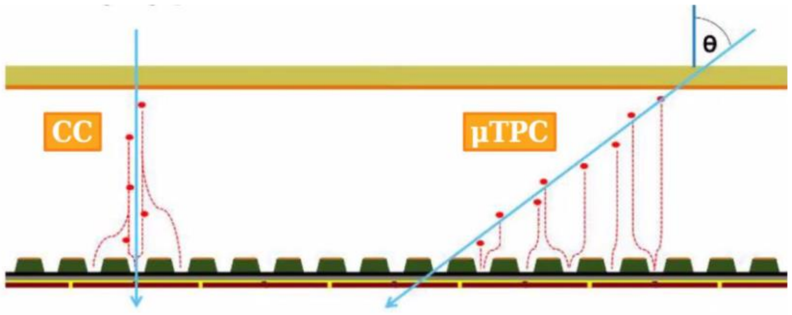
Very preliminary results – work in progress



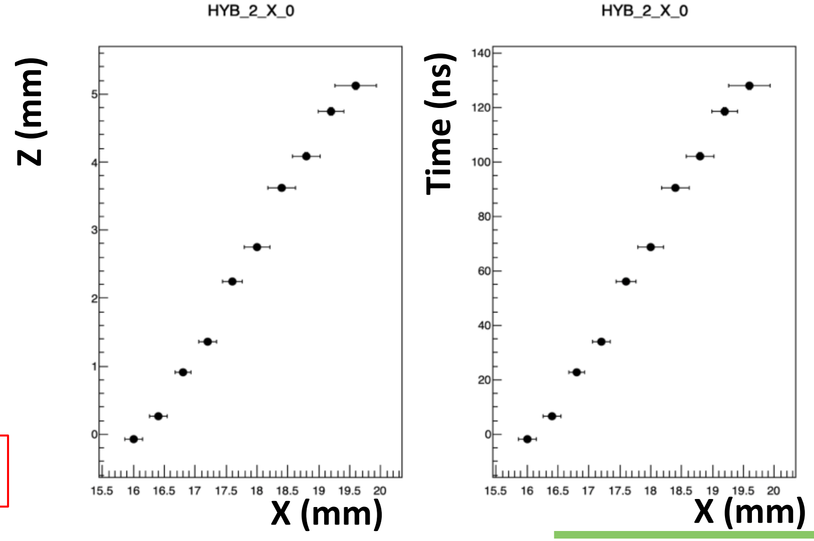
Residual of the distance between the reconstruct track centers inside the detector gaps (enemy mode).
90° track incidence



$\sigma_X < 70\mu m$



Reconstructed track inside the gap



Summary

The activity of the **DDG** at the **Laboratori Nazionali di Frascati** has been focused on the development of **MPGDs with and without resistive coupling:**

- planar and cylindrical **GEMs**
- planar and cylindrical **µ-RWELLs**

Including

- **Design of the detector layouts**
- **Preparation of some detector components** (DLC, cathode, frames …)
- **Technology Transfer** to Industry

More recently **very stringent requirements** in terms of **time** (LHCb) **and spatial resolution** (FCC_ee, ePIC, CLAS12 …) requiring **gas gains larger than 10^4** at **high operational stability**, pushed the R&D towards a **hybrid technology**, in which a **GEM-based pre-amplification stage** is combined with the **classic µ-RWELL.**

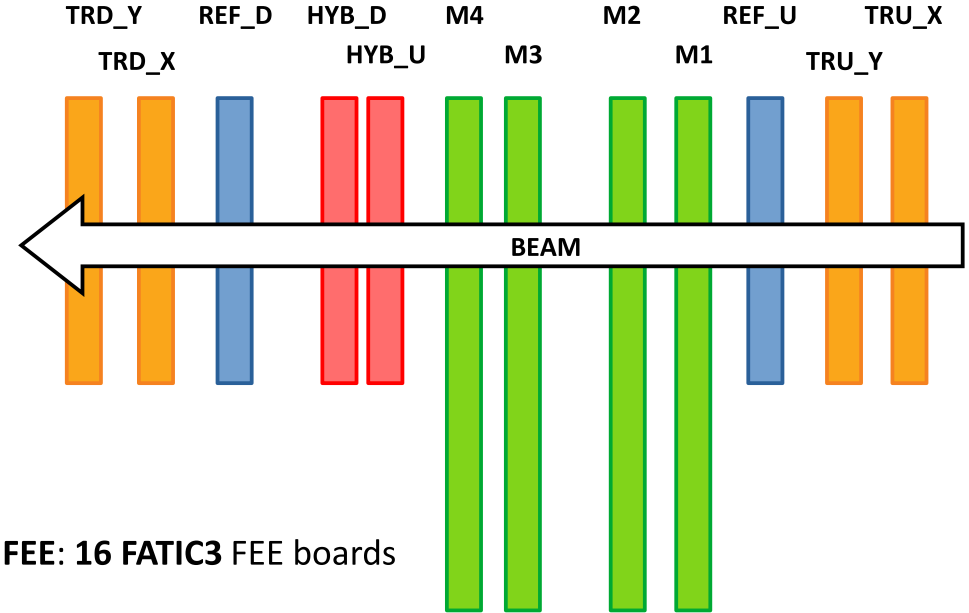
The G- RWELL shows very interesting performance:

- **very stable operation** at **gas gains >> 10^4** (approaching without instability 10^5)
- The **time performance** improved to as low as **3.8 ns** (a record for a single MPGD detector gap)
- Preliminary results of the **2D tracking features**, studied by the **ePIC- Tor Vergata group in the last joint TB**, show **very good spatial performance** (**$\sigma_X \sim 70\mu m$** for orthogonal track incidence … waiting for final analysis)

MANY THANKS

SPARE SLIDES

Test Beam setup



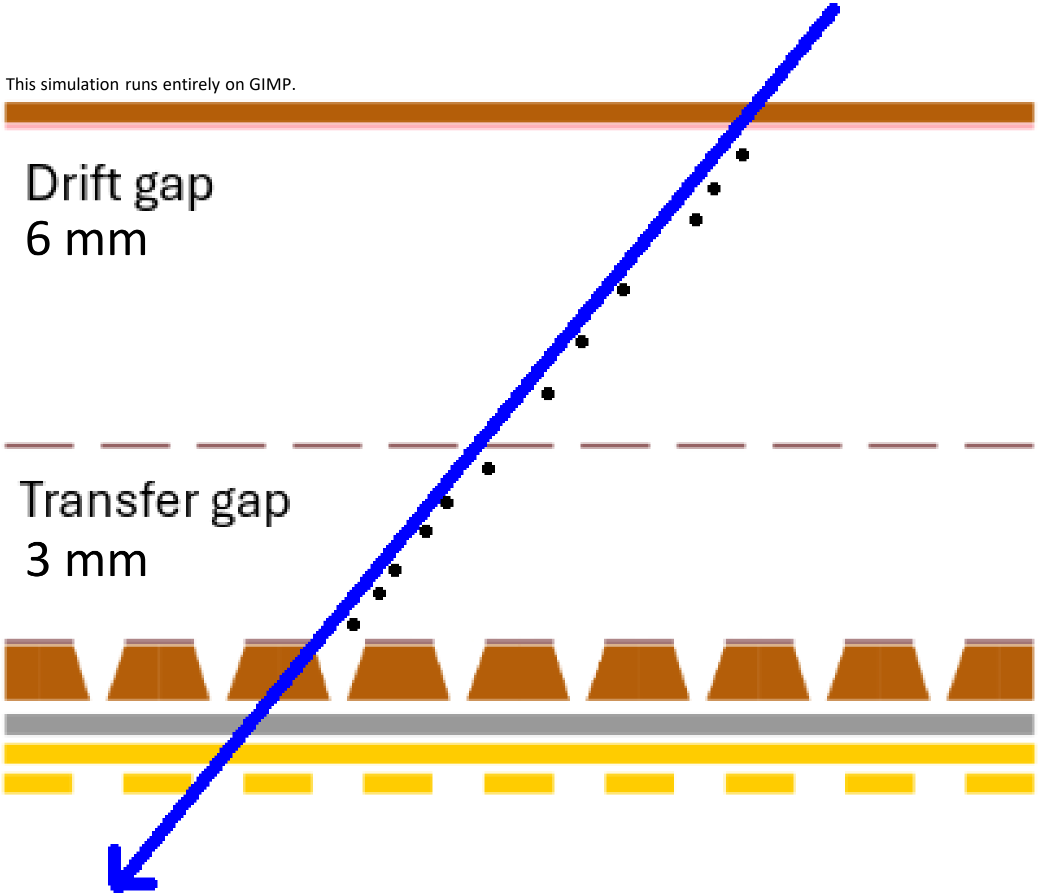
FEE: **16 FATIC3** FEE boards

Trackers: 10×10cm^2 - 1.2mm strip R/O (Capacitive Sharing)
Reference: 10×10cm^2 - 9×9mm^2 pad R/O
HYBRID: 10×10cm^2 - 9×9mm^2 pad R/O
M2R1: 30×25cm^2, instrumented 15×13cm^2 - 9×9mm^2 pad R/O
Gas MIXTURE: Ar/CO$_2$/CF$_4$ = 45/15/40

TB area: PS-T10 w/ 5 GeV muons

A special thanks to INFN LNF, Rome2, and Bari LHCb groups for the support during the beam test.

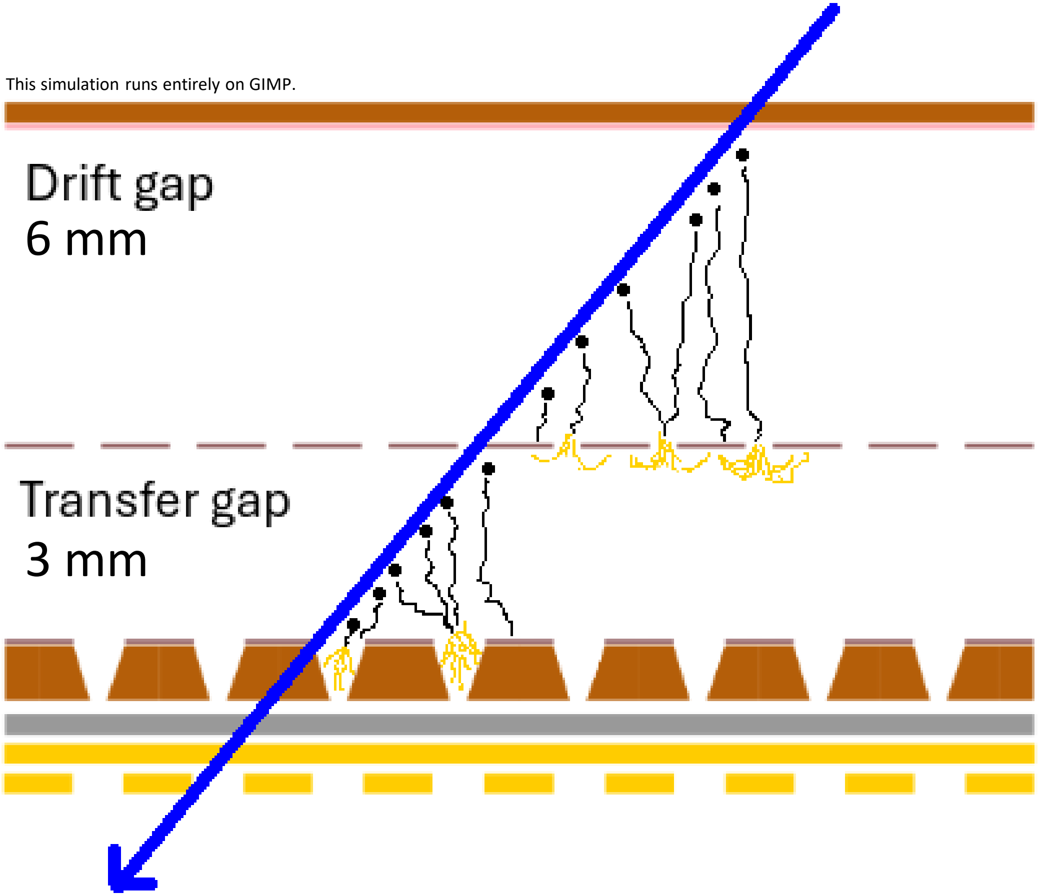
HYBRID – Biwell effect



Ionisation

The particle ionises in both the drift gap and the transfer gap

HYBRID – Biwell effect



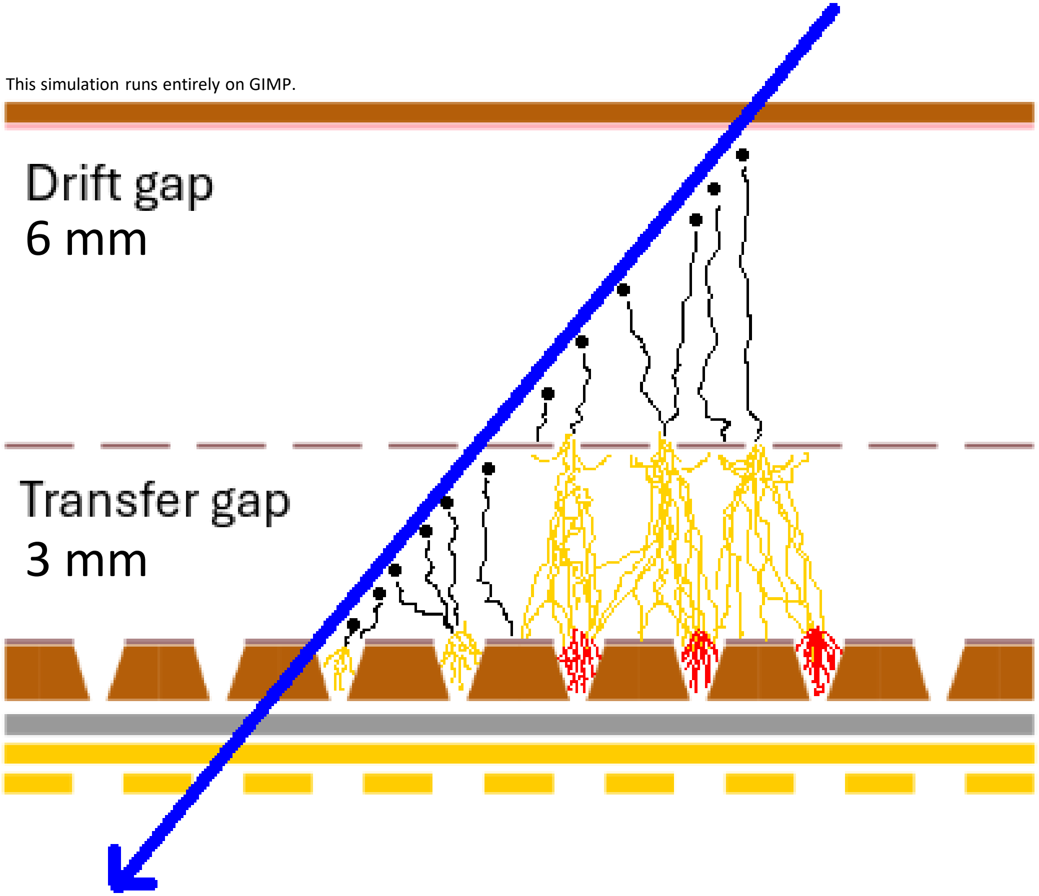
Ionisation

The particle ionises in both the drift gap and the transfer gap

GEM or RWELL

Electron from the drift gap
→ amplified from the **GEM** (gain **20**)
Electrons from the transfer gap
→ amplified by the **WELL** (gain **2000**)

HYBRID – Biwell effect



Ionisation

The particle ionises in both the drift gap and the transfer gap

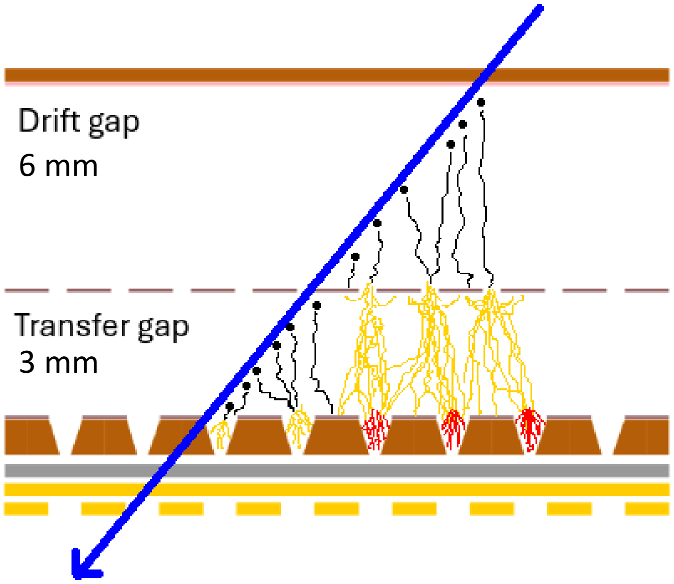
GEM or RWELL

Electron from the drift gap
→ amplified from the **GEM** (gain **20**)
Electrons from the transfer gap
→ amplified by the **WELL** (gain **2000**)

GEM + RWELL

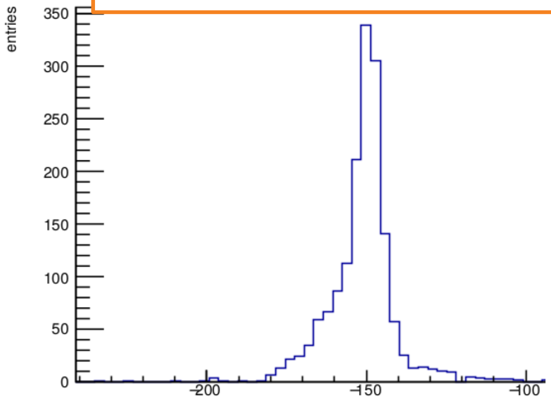
After a drift time in the “Transfer gap”, the electrons preamplified by the GEM reach the RWELL, and get amplified again.
→ **Total gas gain 40'000**

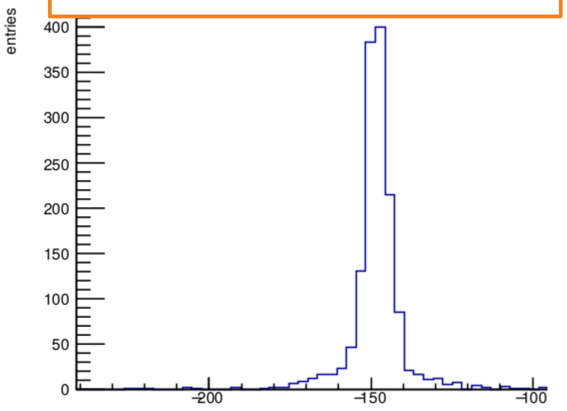
HYBRID – Biwell effect



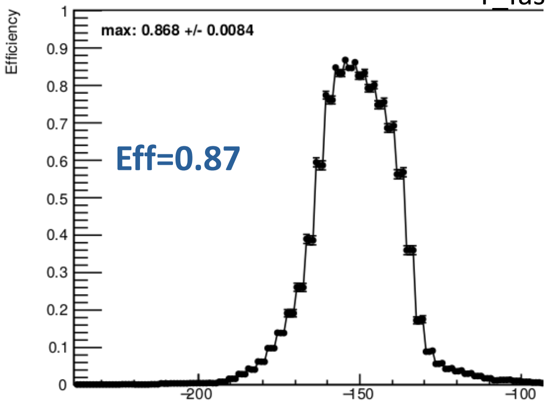
WELL **565** (gain **2000**)
GEM **460** (gain **25**)
Total Gain **50'000**
20241124_163532

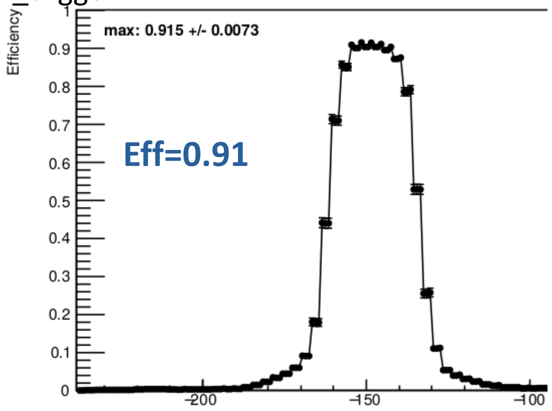
WELL **535** (gain **1000**)
GEM **510** (gain **50**)
Gain **50'000**
20241124_182541





Time window: 25ns
T_fastest_hit - T_trigger

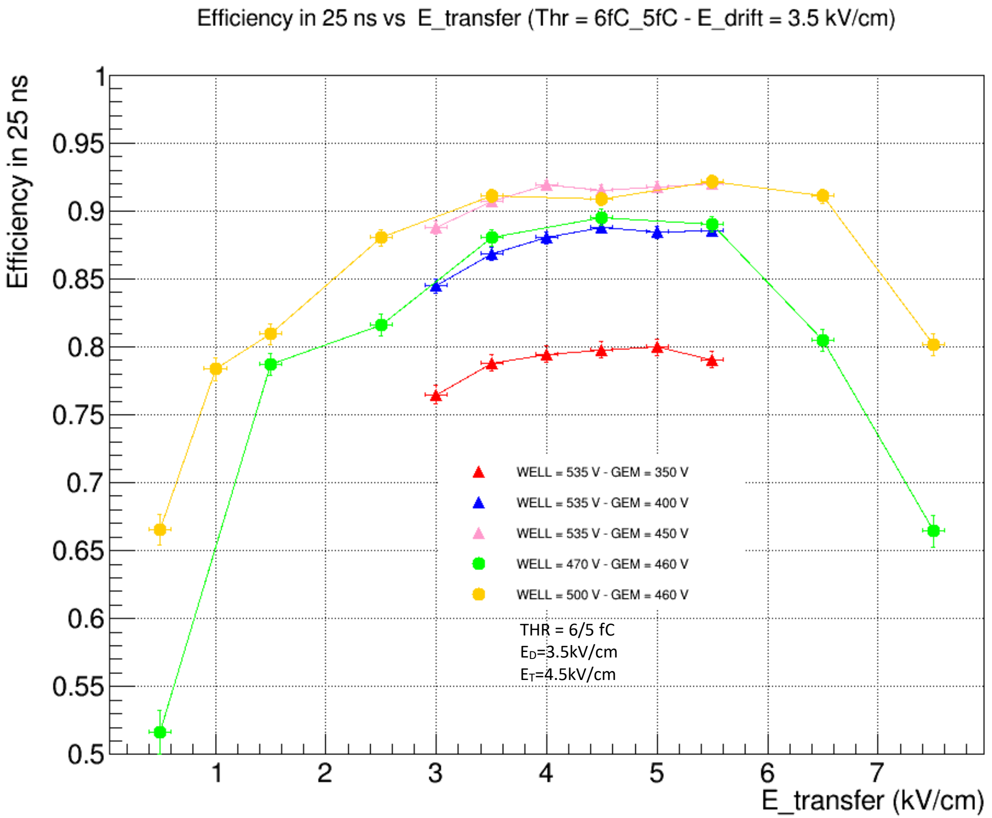


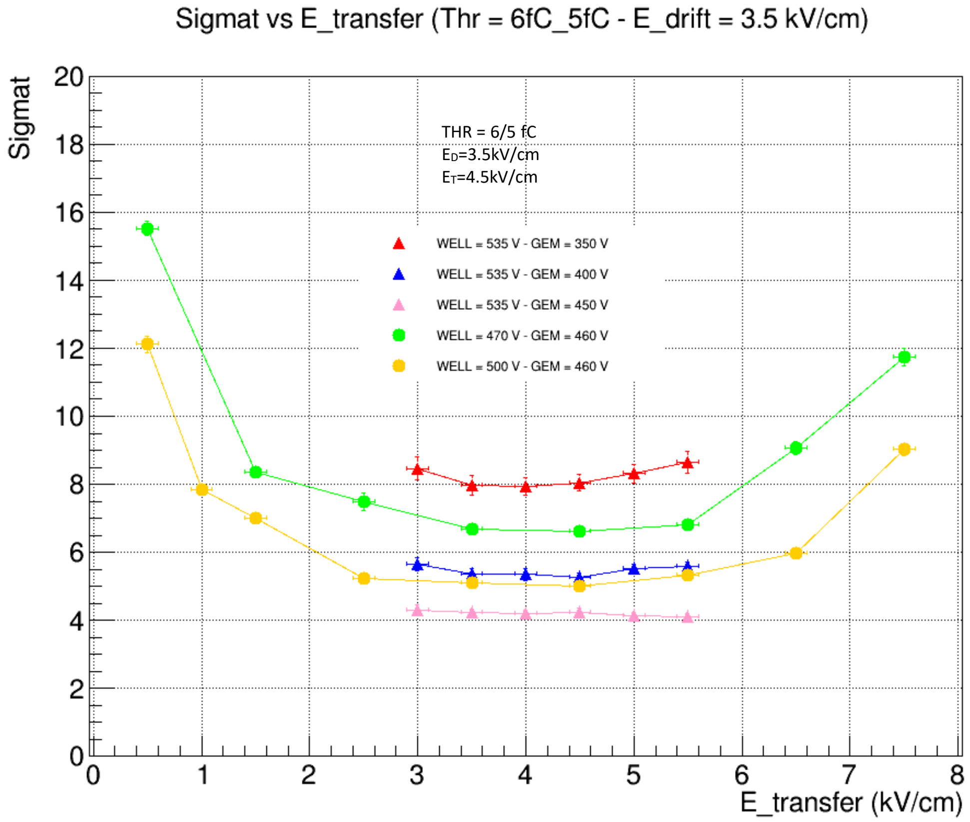


Transfer scan Hybrid

HYB_U

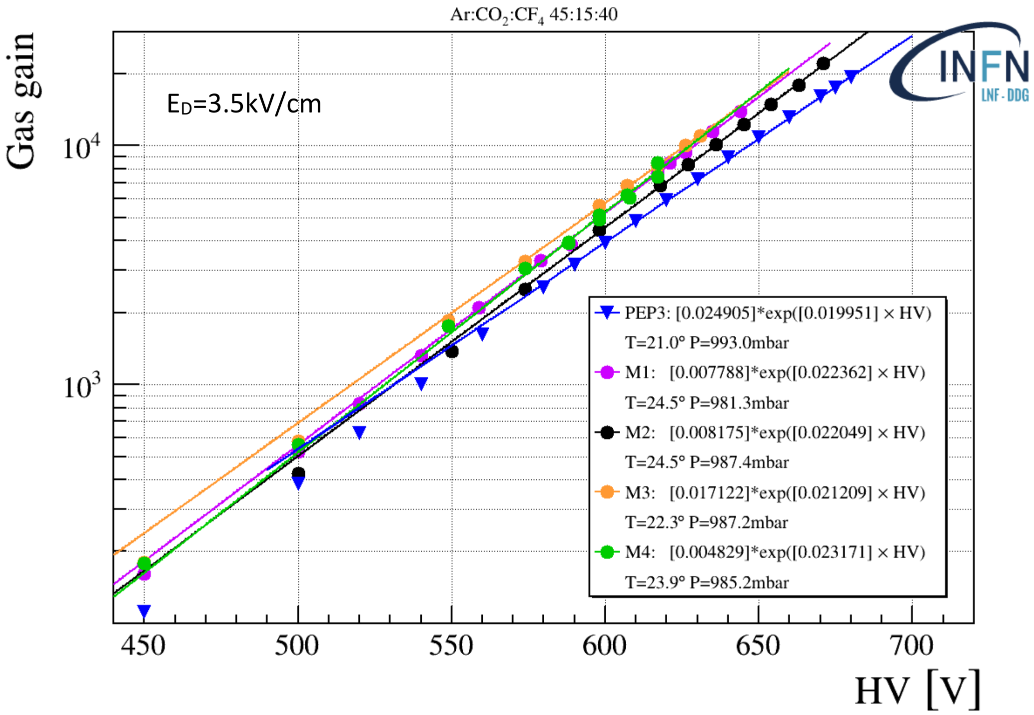
VERY PRELIMINARY: NOV'24



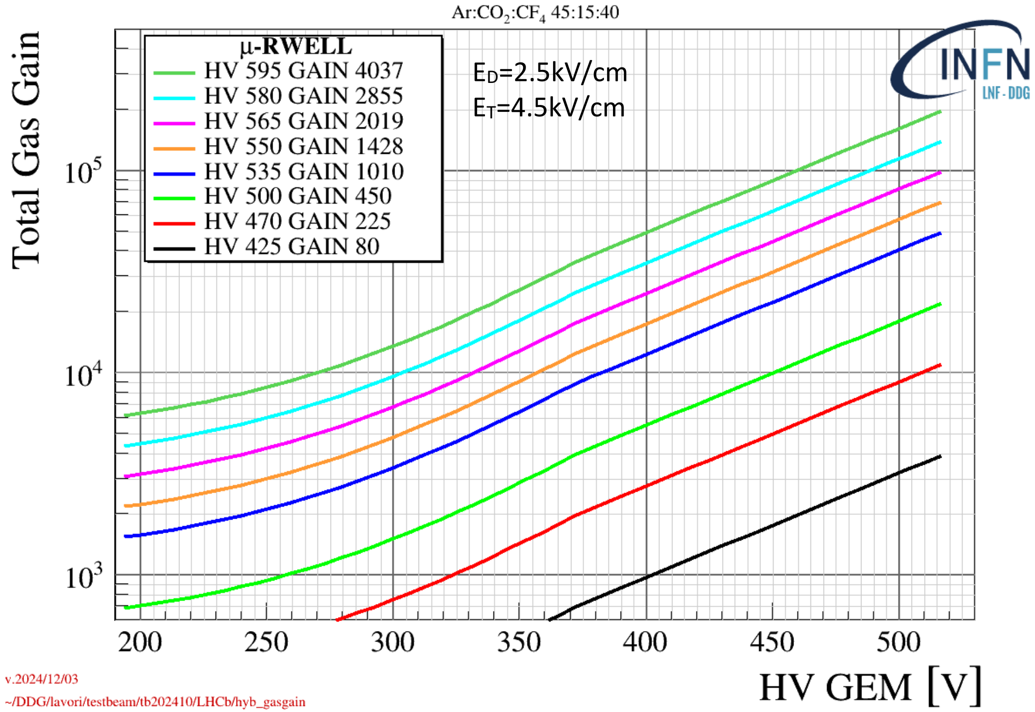


Gas gain measurement – w/ X-rays

M1 – M4 uRWELL



HYBRID



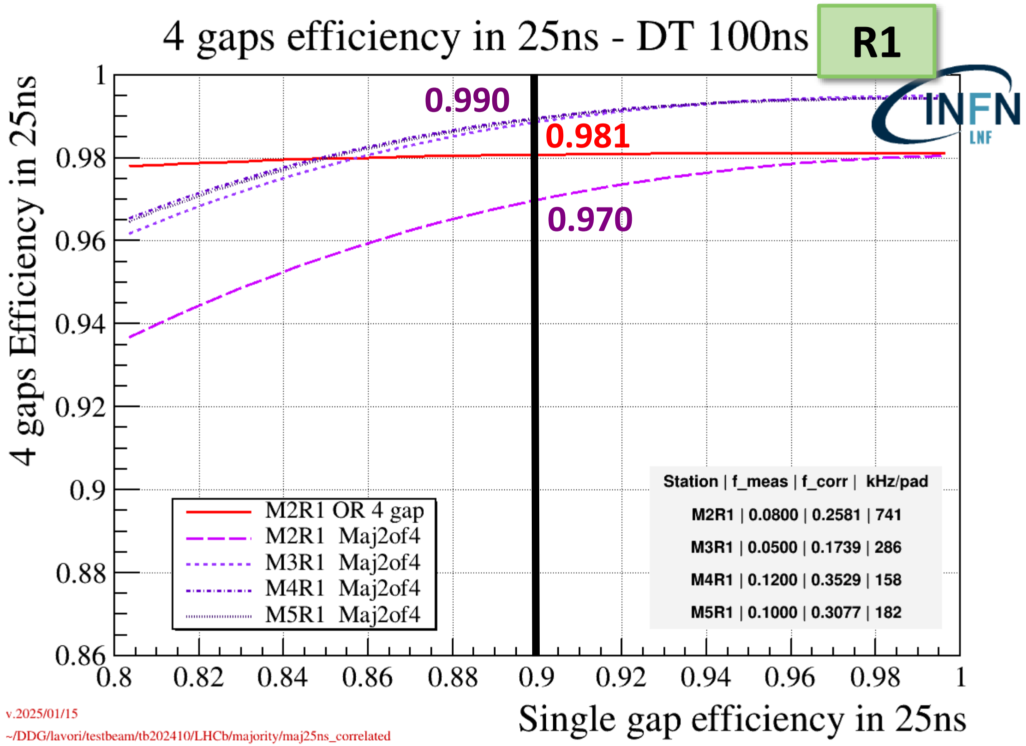
Classic uRWELL (M2R1-LHCb): max gain ≈2 x 10^4

G-RWELL: max gain >> 10^4

Majority

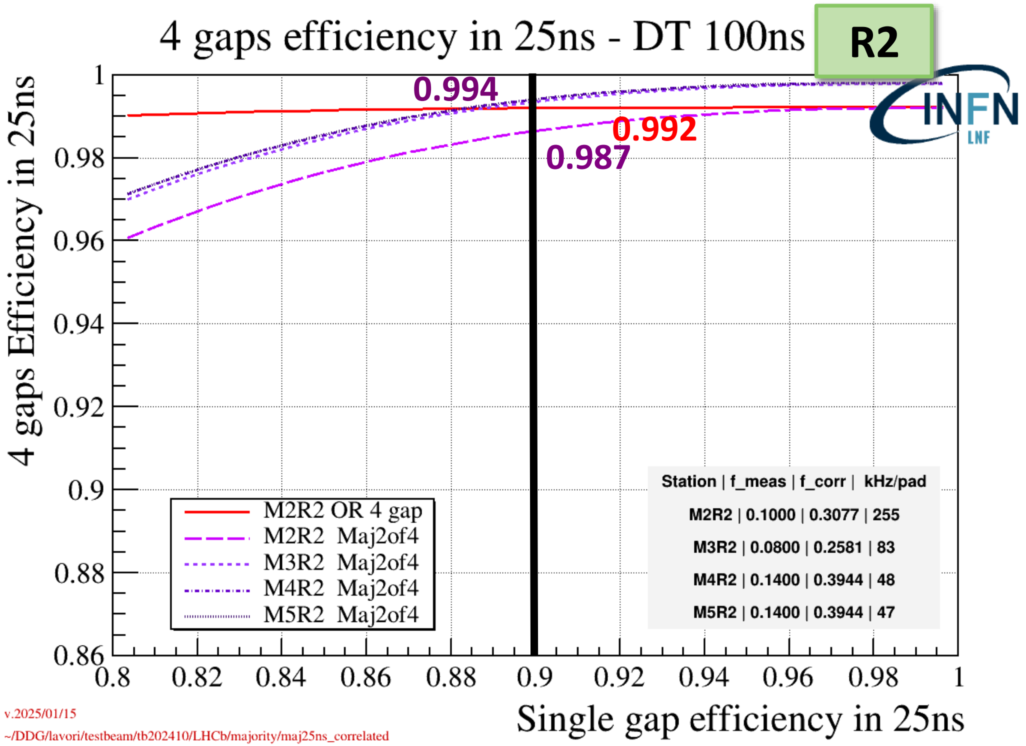
Majority – w/ Bkg

Analytic computation



Station	f_meas	f_corr	kHz/pad
M2R1	0.0800	0.2581	741
M3R1	0.0500	0.1739	286
M4R1	0.1200	0.3529	158
M5R1	0.1000	0.3077	182

v.2025/01/15
~/DDG/lavori/testbeam/tb202410/LHCb/majority/maj25ns_correlated



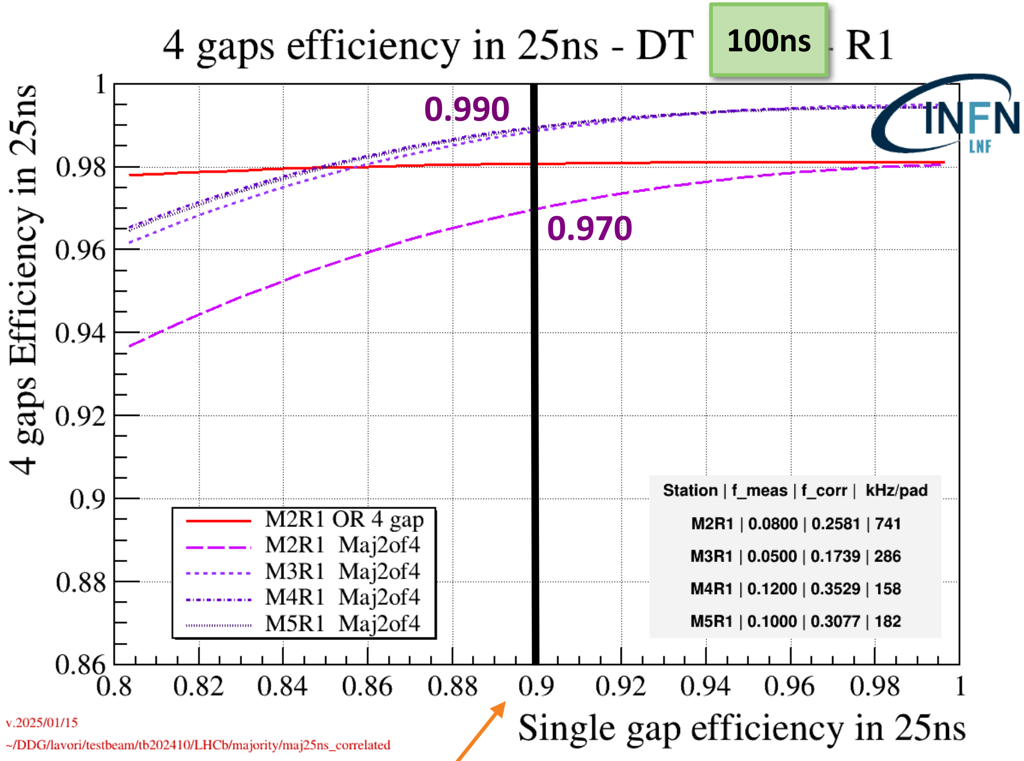
Station	f_meas	f_corr	kHz/pad
M2R2	0.1000	0.3077	255
M3R2	0.0800	0.2581	83
M4R2	0.1400	0.3944	48
M5R2	0.1400	0.3944	47

v.2025/01/15
~/DDG/lavori/testbeam/tb202410/LHCb/majority/maj25ns_correlated

LHCb case → f_meas & f_corr from "2023/03" → equations from "Palutan 2024/12"
Case "2 over 3" not present (I don't know the formula)

Majority – w/ Bkg – AND 4 stations – DT 100ns

Analytic computation



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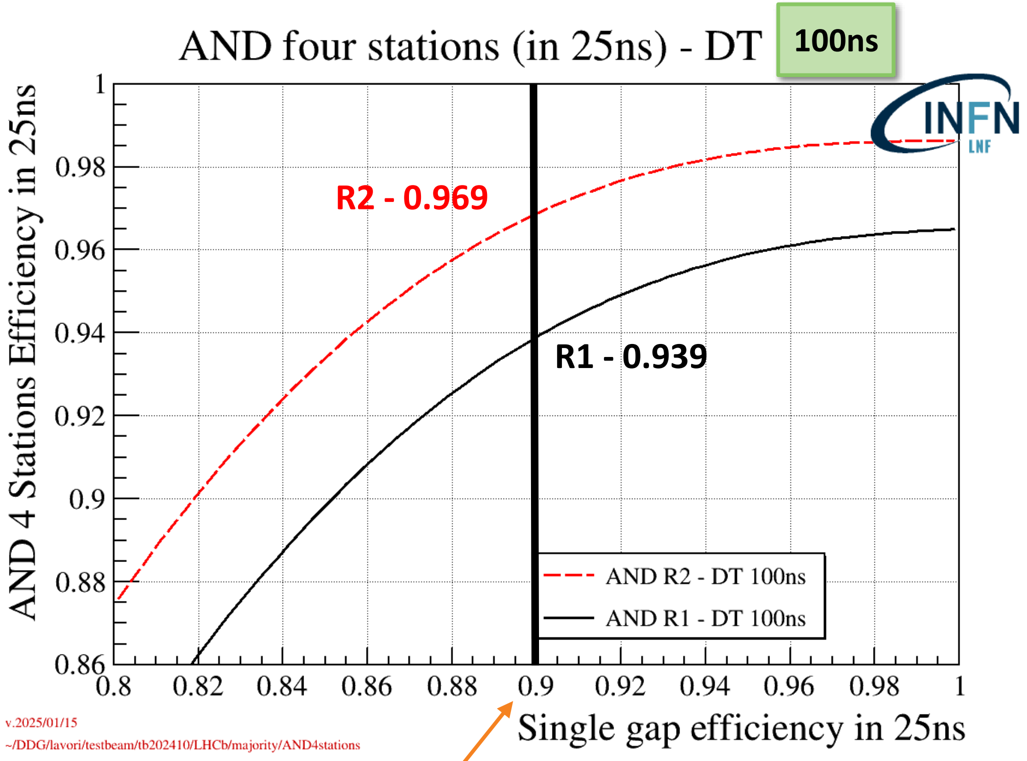
Beam test measured efficiency

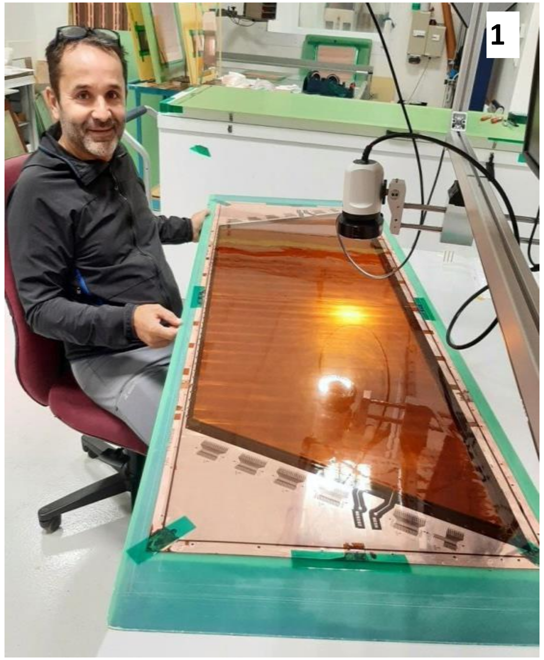


Beam test measured efficiency

Technology spread

In the last years there has been a significant spread of the technology among several research groups working on Nuclear and Sub-Nuclear experiments

1. **CLAS12 @ JLAB (USA):** the upgrade of the muon spectrometer
2. **EPIC @EIC (BNL - USA):** endcap tracker disks based on a hybrid GEM+μRWELL technology
3. **X17 @ n_TOF EAR2 (CERN)**:TPC with a μRWELL based amplification stage, for the detection of the X17 boson
4. **TACTIC @ YORK Univ. (UK):** radial TPC for detection of nuclear reactions with astrophysical significance
5. **Muon collider:** R&D for a digital hadron calorimeter
6. **CMD3 (RU):** GEM+ μRWELL disk for the upgrade of the tracking system
7. **UKRI (UK):** thermal neutron detection with pressurized ^{3}He-based gas mixtures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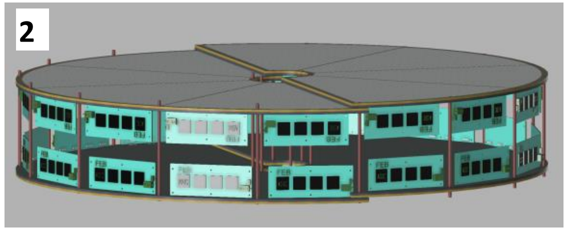
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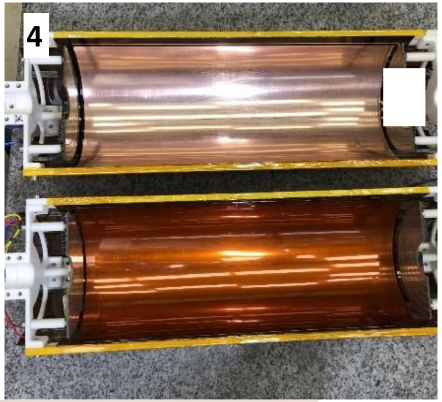
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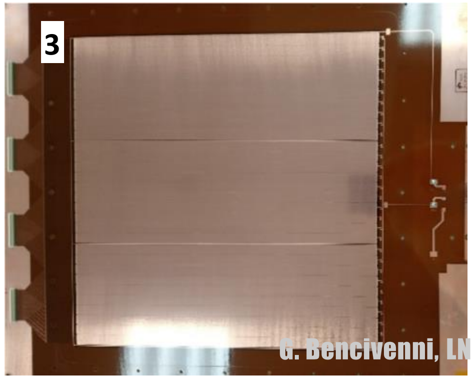
6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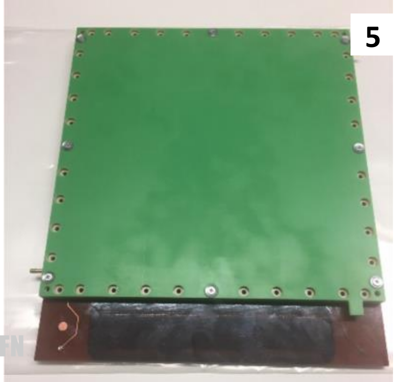
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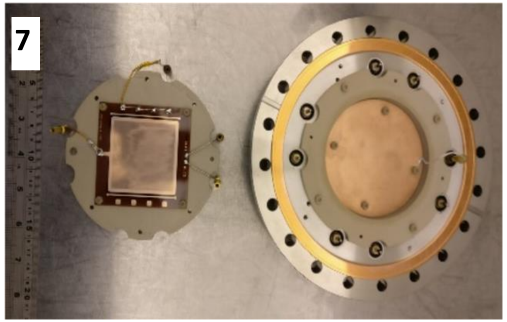
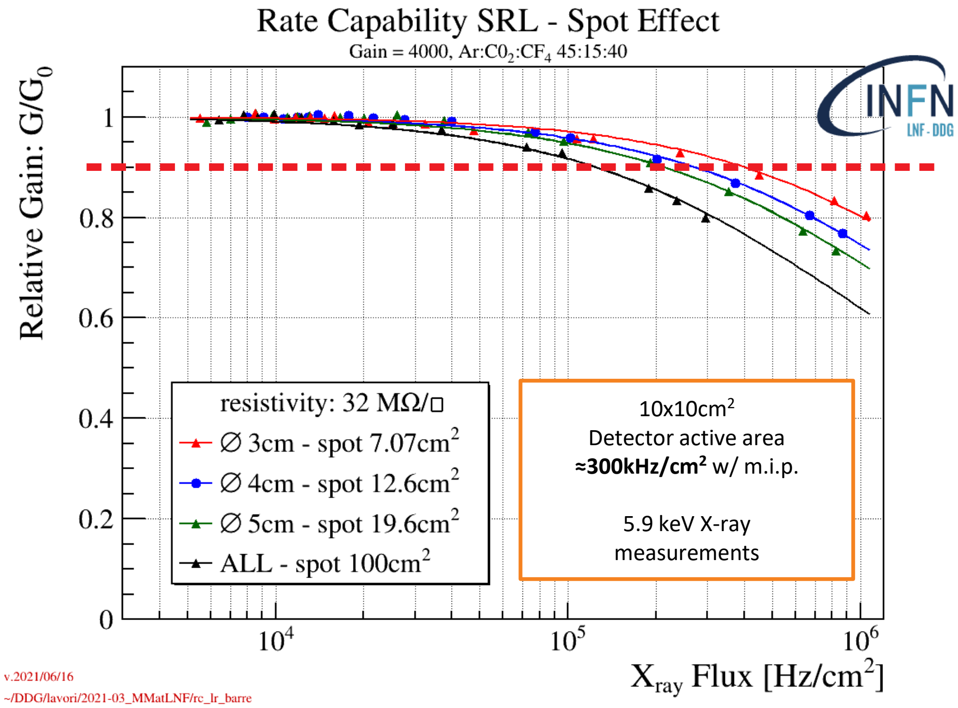

7

The SRL resistive model



10x10cm^2
Detector active area
≈300kHz/cm^2 w/ m.i.p.

5.9 keV X-ray
measurements

FLOW: DATA $\frac{G}{G_0} \to p_0$ → Extrapolation $\Omega \to \phi_{90\%}$

! **Different primary ionization ⇒ Rate Cap.$_{\text{m.i.p.}}$ = 3×Rate Cap.$_{\text{X-ray}}$**

Prediction

$$\Omega(r) = \rho_S \frac{d - \frac{r}{2}}{\pi \cdot r}$$

$$\phi_{90\%} = \frac{\Delta V_{drop\ 10\%}}{e \cdot N_0 \cdot G \cdot Spot \cdot \Omega}$$

← **ΔV$_{\text{drop 10\%}}$** from the gain measurement

$$\boldsymbol{\phi_{90\%} \approx \frac{1}{\rho_S \cdot r\,(d - r/2)}}$$

Validation

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

SPOT [cm^2]	p_0
12.6	1.4656E-6
19.5	2.0224E-6

$$\Omega(r) = \frac{p_0(r)}{\alpha \cdot e \cdot N_0 \cdot G \cdot \pi \cdot r^2}$$

G. Bencivenni et al., JINST 10 (2015) P02008

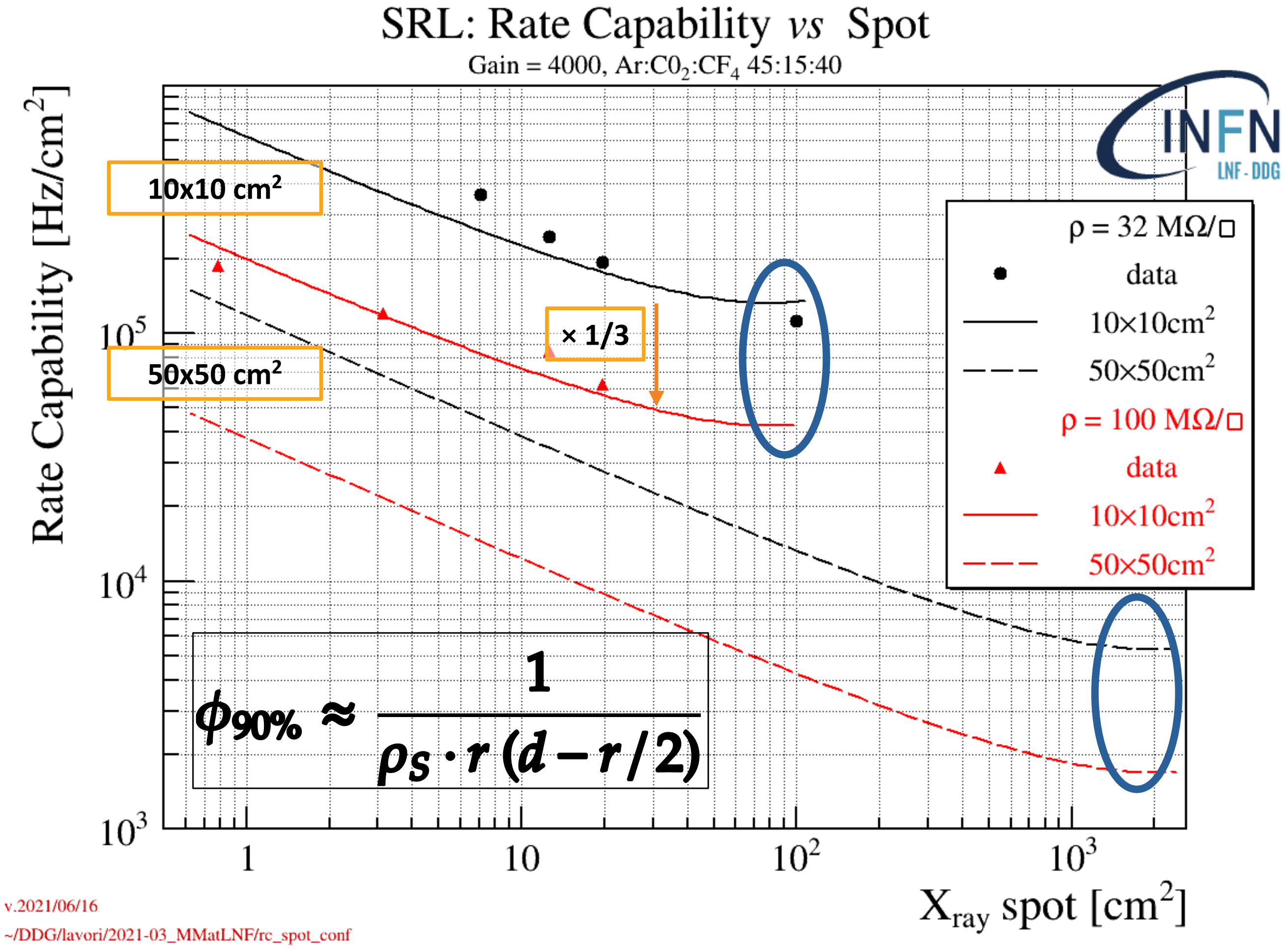
Rate capability vs spot-size & detector size

Comparison between a **model** of the **resistive stage** and **measurements of the rate capability for SRL.**

1. detectors with same size (d) but different resistivity exhibit **a rate capability scaling as the inverse of their resistivity**.

2. for the SRL, increasing the active area **from 10x10 cm² to 50x50 cm²** the rate capability should go **down few kHz/cm²**.

3. By using **a DLC ground sectoring every 10 cm, large (50x50cm²)** detectors could achieve **rate capability up to 100kHz/cm²** (with X-ray).



10x10 cm²

50x50 cm²

× 1/3

$$\phi_{90\%} \approx \frac{1}{\rho_S \cdot r\,(d - r/2)}$$

Different primary ionization ⇒ Rate Cap.$_{\text{m.i.p.}}$ = 3×Rate Cap.$_{\text{X-ray}}$

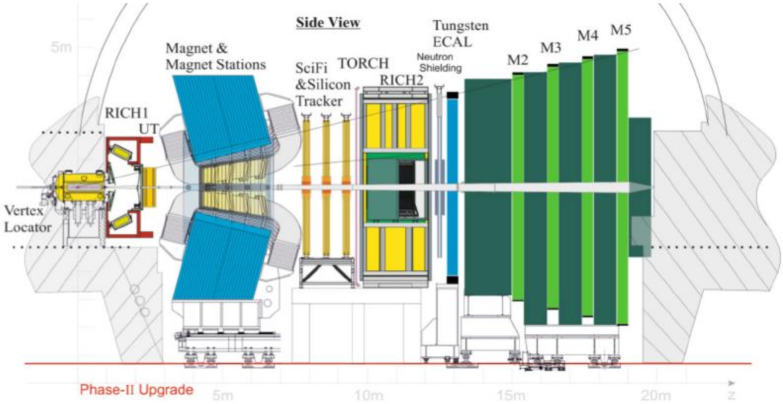
LHCb upgrade II (Run5 – Run6)

LHCb muon apparatus Run5 – Run6 detector requirements

- Rate up to **1 MHz/cm²** on detector single gap
- Rate up to **700 kHz** per electronic channel
- Efficiency quadrigap >=99% within a BX (25 ns)
- Stability up to **1C/cm²** accumulated charge in 10y at M2R1, G=4000

Detector size & quantity (4 gaps/chamber - redundancy)

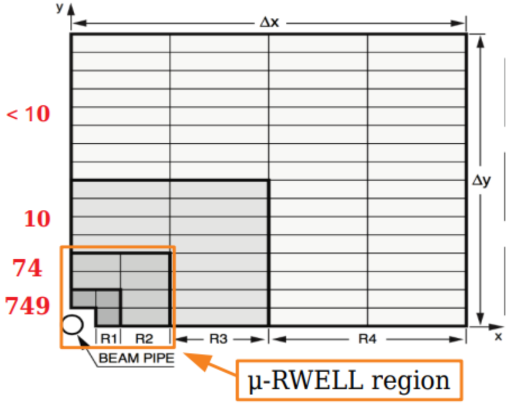
- **R1÷R2: 576 detectors, size 30x25 to 74x31 cm², 90 m² detector (130 m² DLC)**



Rates (kHz/cm²)	M2	M3	M4	M5
R1	749	431	158	134
R2	74	54	23	15
R3	10	6	4	3
R4	8	2	2	2

Area (m²)	M2	M3	M4	M5
R1	0.9	1.0	1.2	1.4
R2	3.6	4.2	4.9	5.5
R3	14.4	16.8	19.3	22.2
R4	57.6	67.4	77.4	88.7

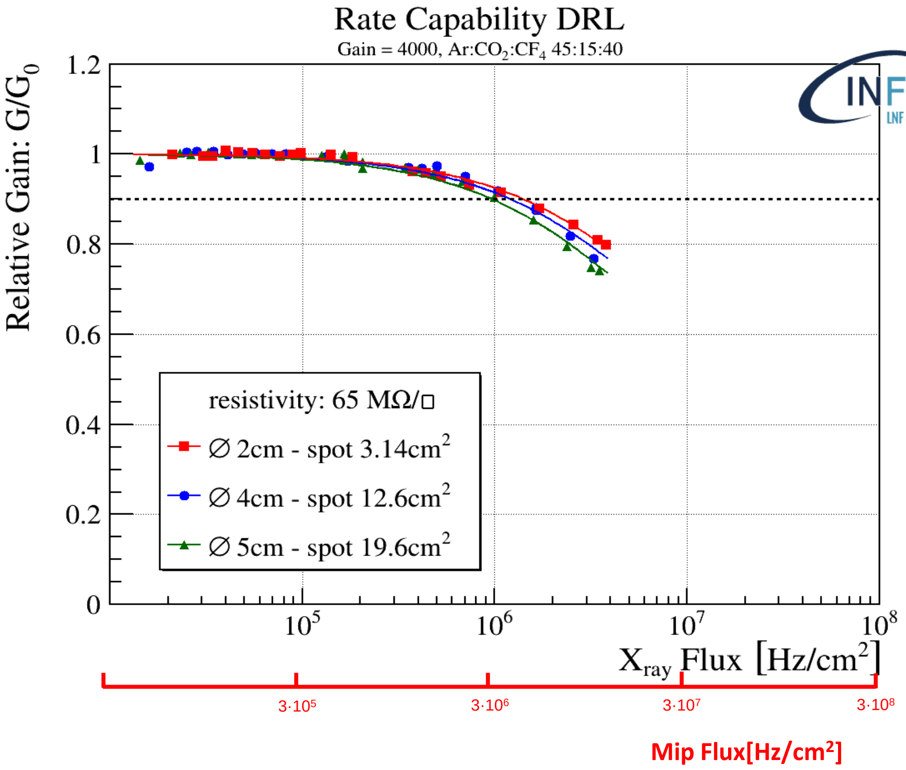
M2 station - max rate (kHz/cm²)

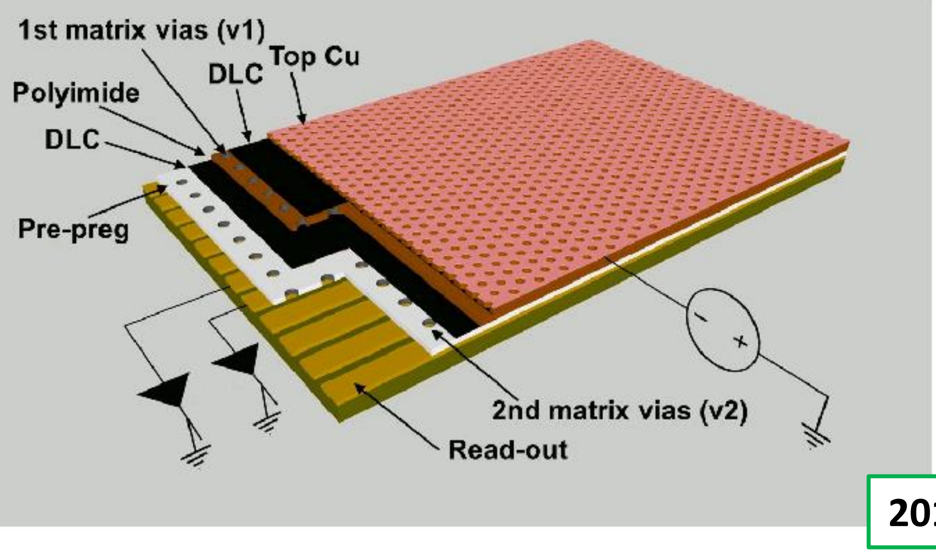


µ-RWELL region

High-rate layouts: DRL

G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* 14 P05014





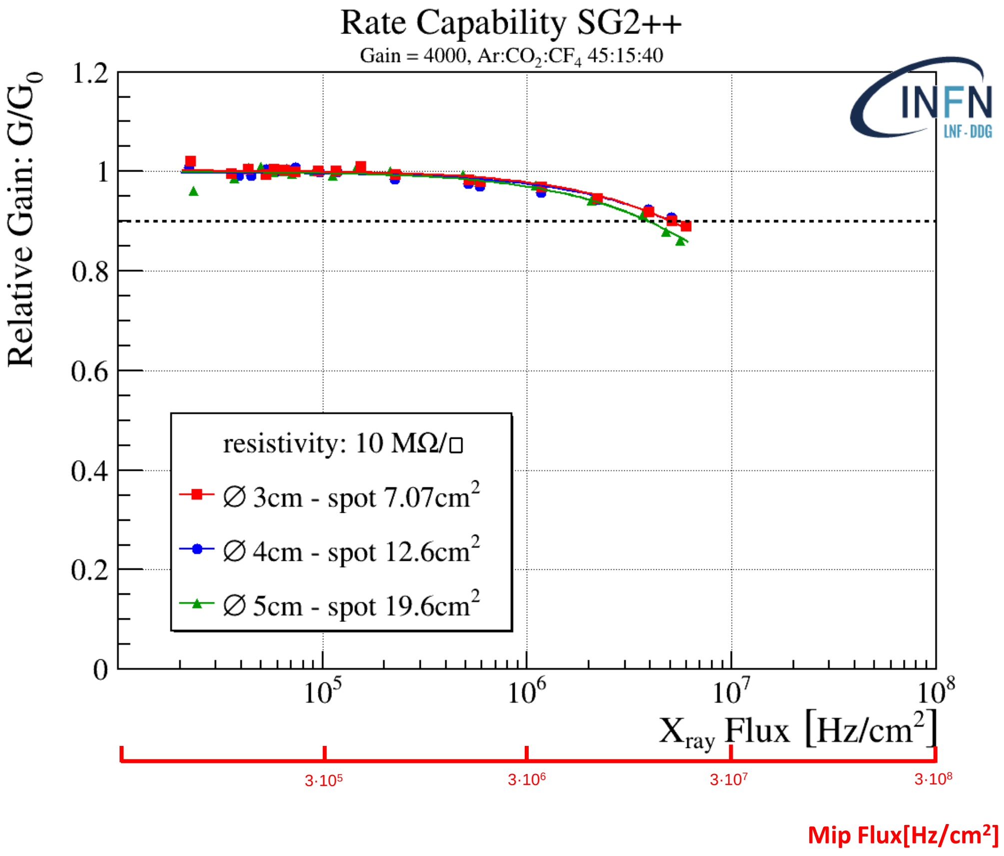
2017

Double Resistive Layer

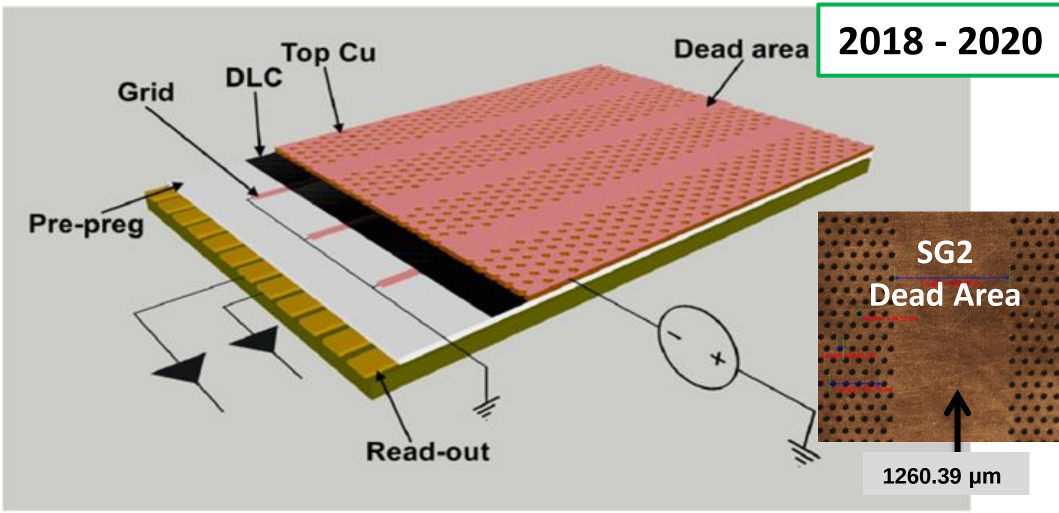
- **Two stacked resistive layers** with a **double matrix of conductive vias**
- **3-D current** evacuation
- Rate capability **> 10MHz/cm²**
- **Complex manufacturing not easily engineered**

High-rate layouts: SG

G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* 14 P05014



2018 - 2020



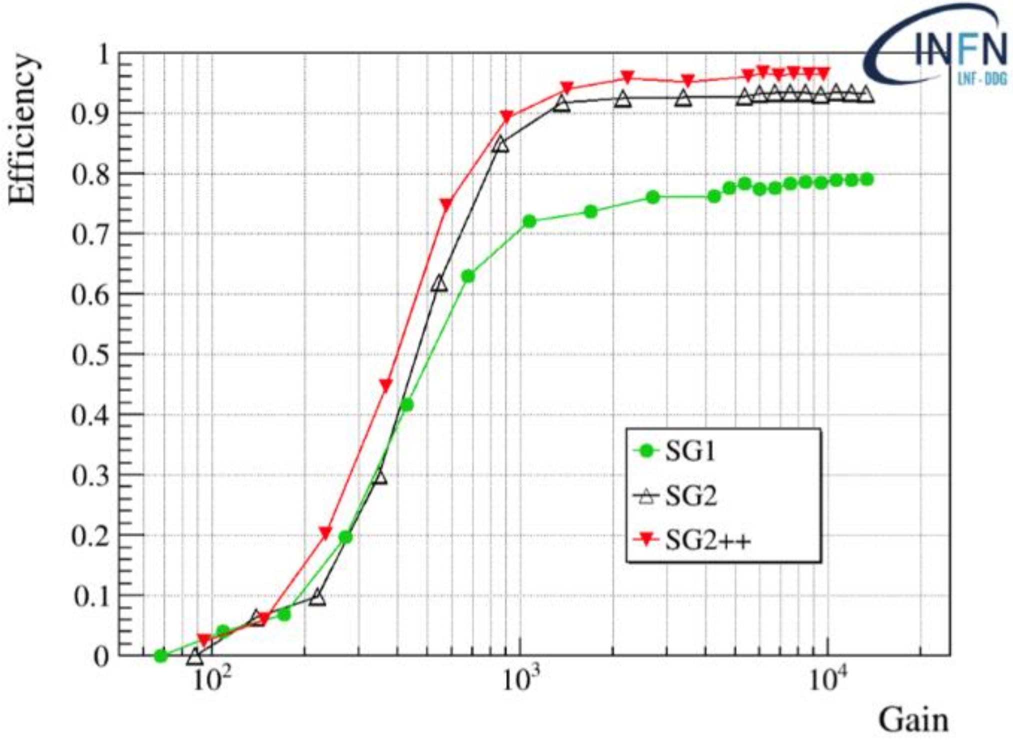
The Silver Grid layout

- **Single DLC layer**
- **2-D current evacuation** through **conductive grid on the DLC layer**
- rate capability **> 10MHz/cm²**
- **Easily engineered,** BUT **complex Cu+DLC sputtering/alignment**

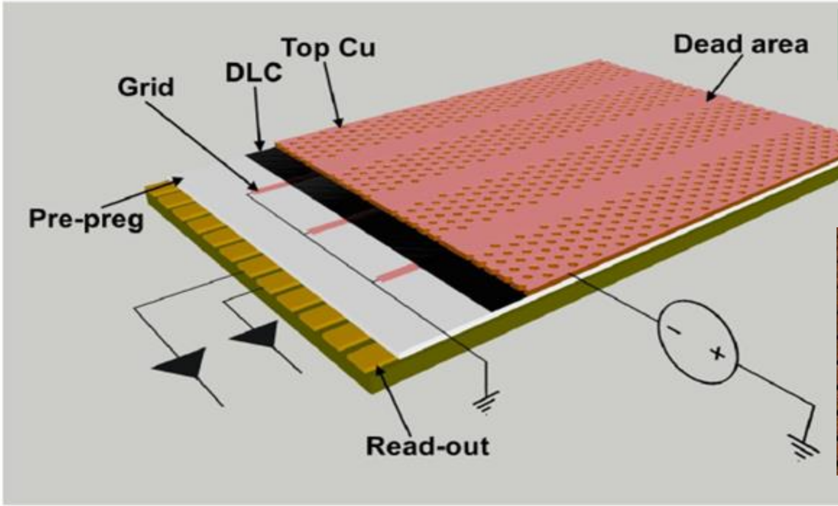
High-rate layouts: SG

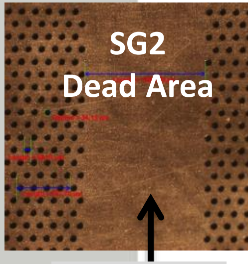
G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* 14 P05014

2018 - 2020



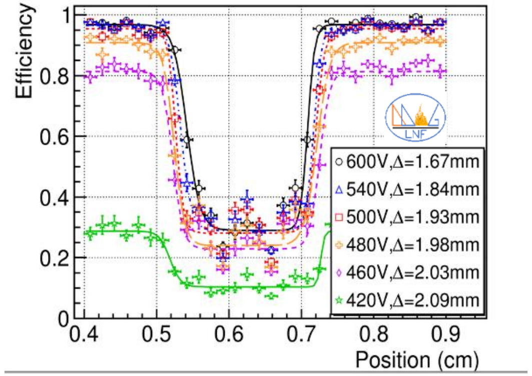
Dead zone of 2 mm (SG1), 1.2 mm (SG2) and 0.6 mm (SG2++)





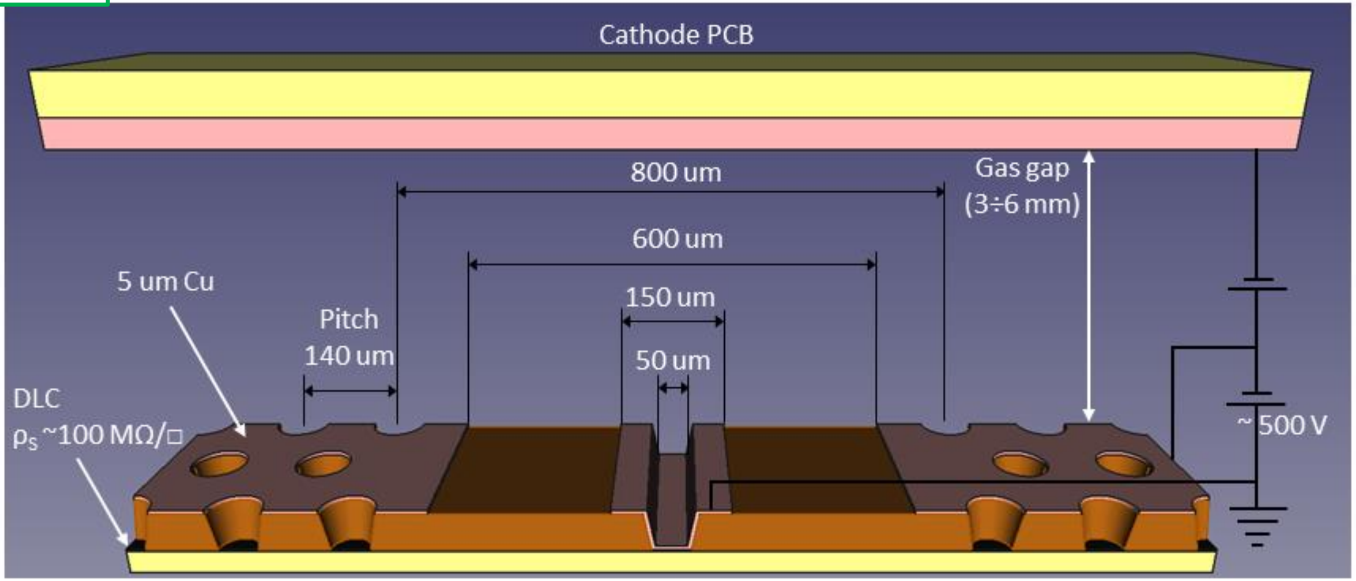
1260.39 μm

Effect of SG1 dead zone



High-rate layouts: PEP groove

2021/22



PEP (Patterning – Etching – Plating)

- Single DLC layer
- 2-D current evacuation: conductive grid by etching from the top Cu, through the kapton foil down to the DLC
- No grid alignment issues, scalable to large size – large dead zone (>15%)
- Easily engineered, because based on SBU technology

High-rate layouts: PEP layouts comparison

2022

PEP-Groove:

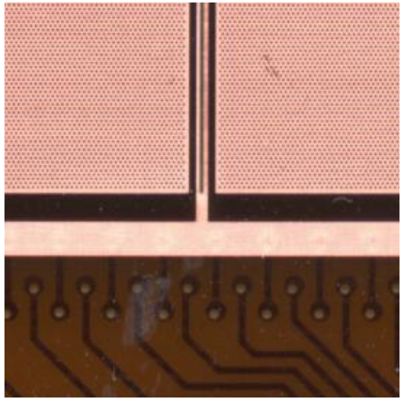
DLC grounding through conductive groove to ground line

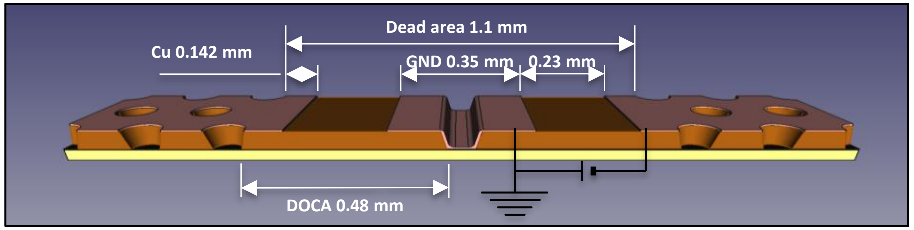
Pad R/O = 9×9mm^2

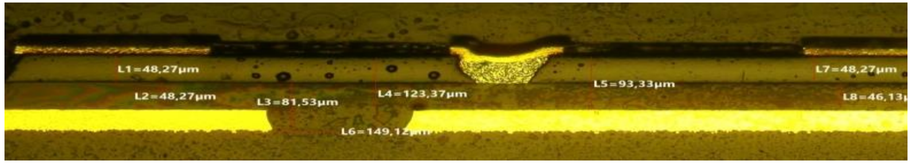
Grounding:

- Groove pitch = 9mm
- width = 1.1mm

→ 84% geometric acceptance







2023

PEP-DOT:

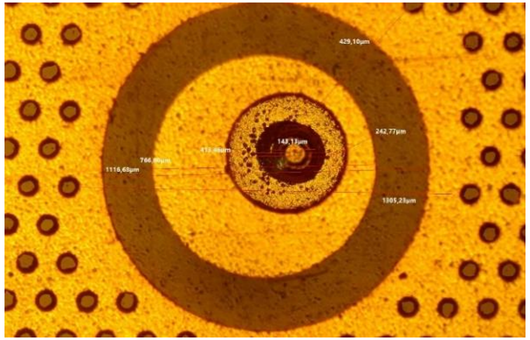
DLC grounding through conductive dots connecting the DLC with pad r/outs

Pad R/O = 9×9mm^2

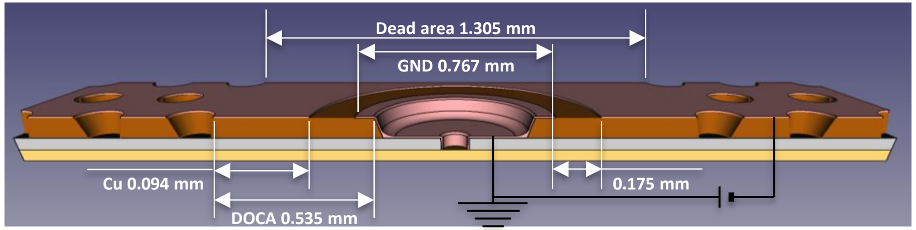
Grounding:

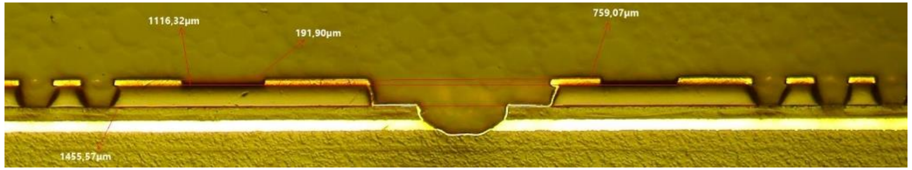
- Dot pitch = 9mm
- dot rim = 1.3mm

→ 97% geometric acceptance



DOT ≈ plated blind vias

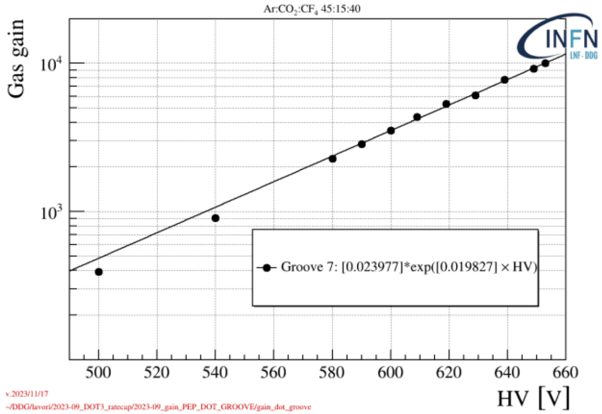


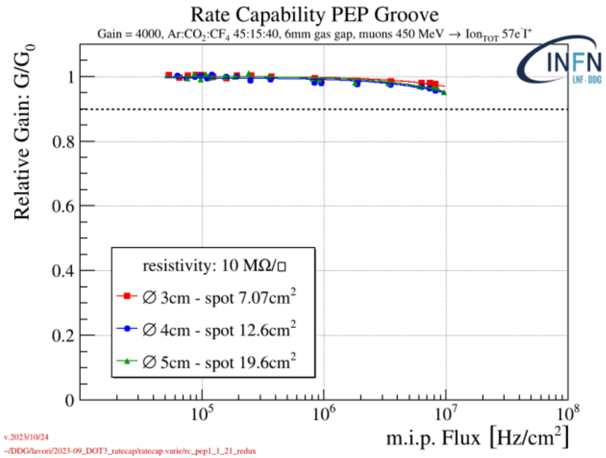


Groove vs DOT (X-ray characterization)

2022

PEP-Groove layout



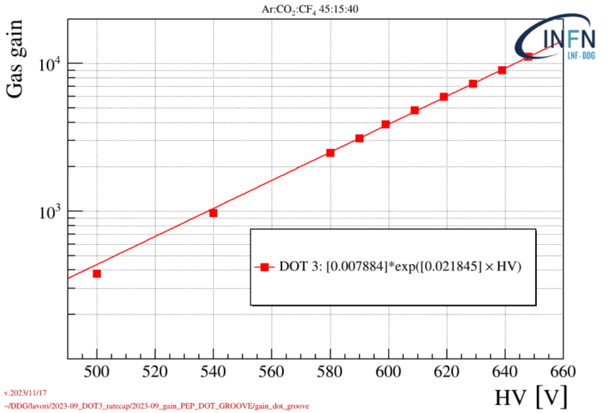


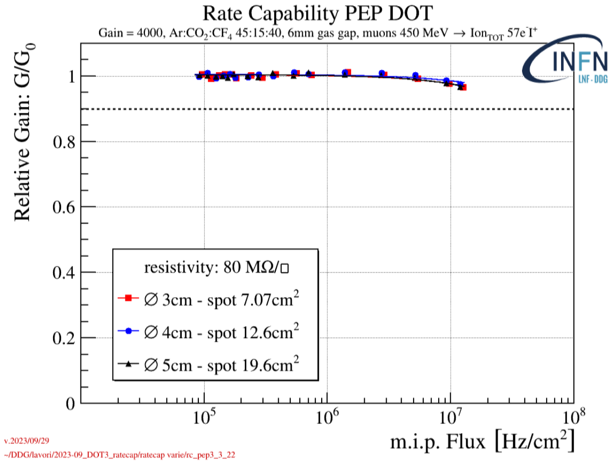
Both layouts exhibit **satisfactory performance:**

- **gas gain** up to **10^4**
- **rate capability** (@ 90% gain drop) ~ **10 MHz/cm²** , measured with **different irradiation spot size.**

2023

PEP-DOT layout

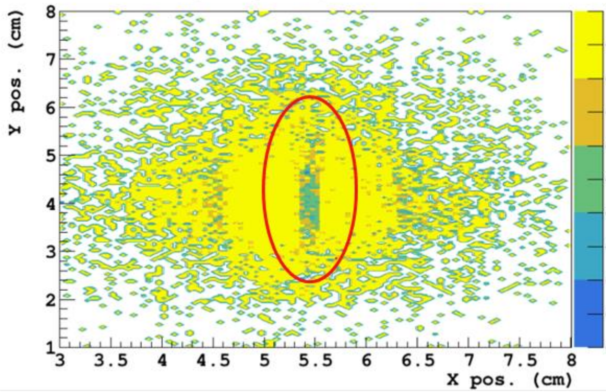


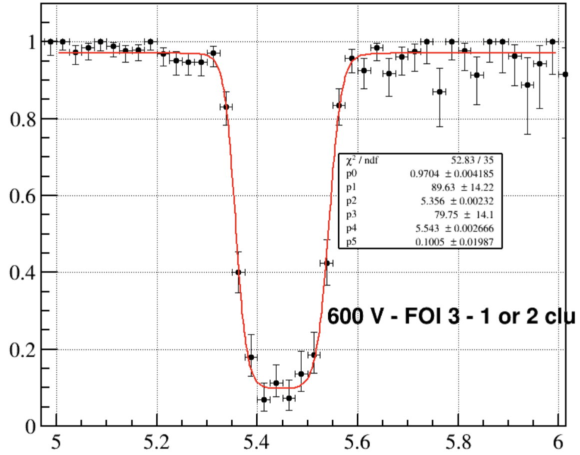


Groove vs DOT (TB-2023)

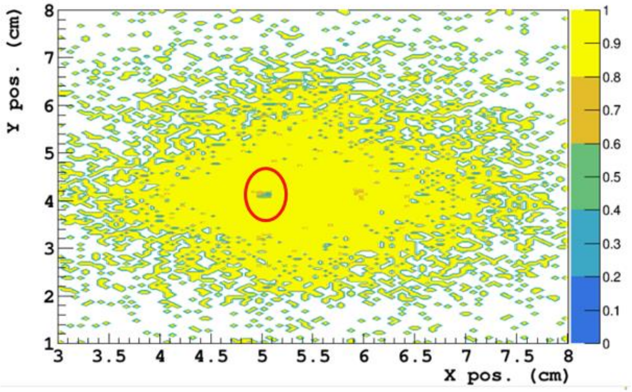
APV25 based Fee

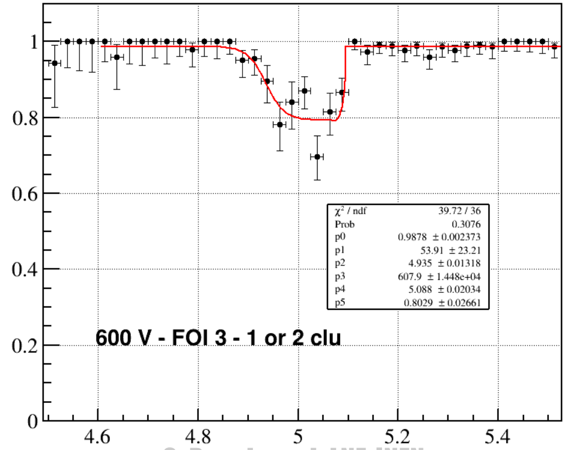
PEP-Groove layout

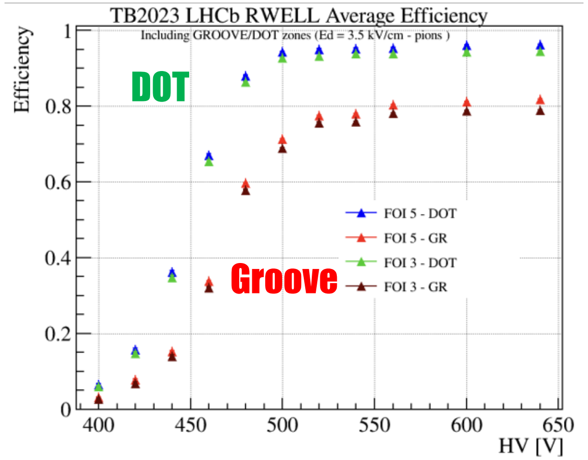

Efficiency along XY expected for LHCb GR

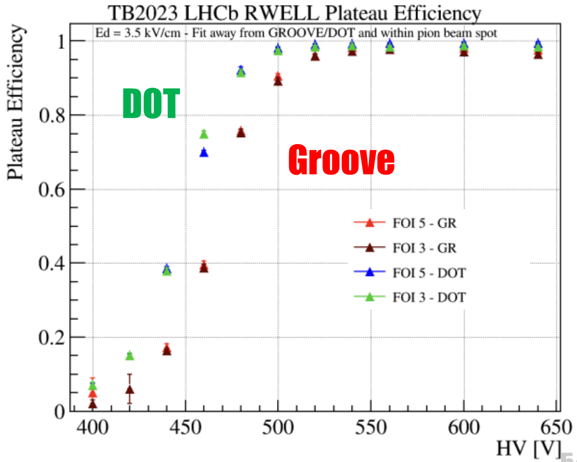


PEP-Dot layout


Efficiency along XY expected for LHCb DOT

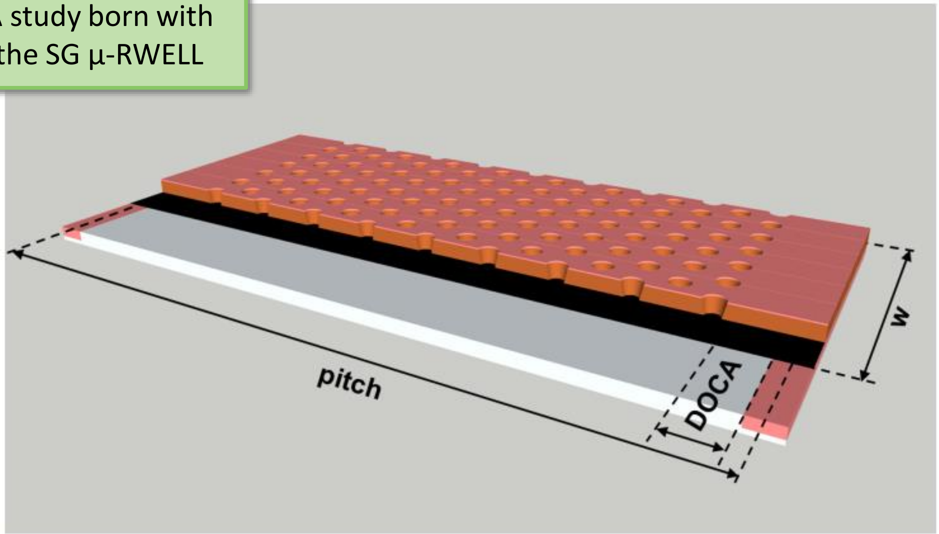



TB2023 LHCb RWELL Average Efficiency
Including GROOVE/DOT zones (Ed = 3.5 kV/cm - pions)


TB2023 LHCb RWELL Plateau Efficiency
Ed = 3.5 kV/cm - Fit away from GROOVE/DOT and within pion beam spot

The DOCA

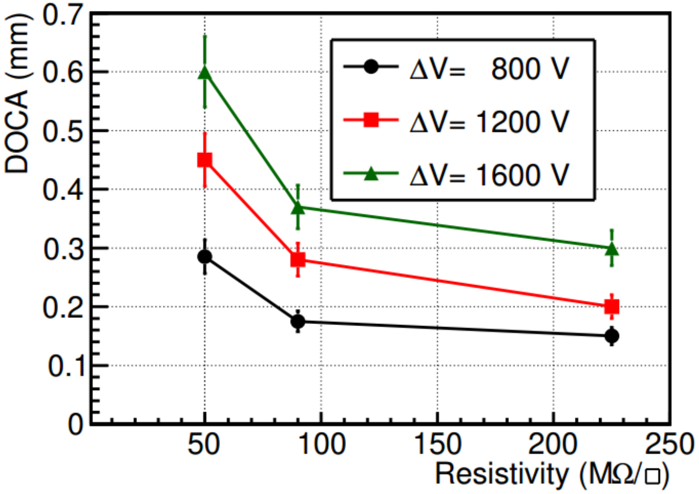
A study born with the SG μ-RWELL



Cross-section of a μ-RWELL with a conductive line on the DLC (High-Rate scheme).

The concept of **DOCA** (Distance-Of-Closest-Approach) before discharge is fundamental for the **stability** of the detector.

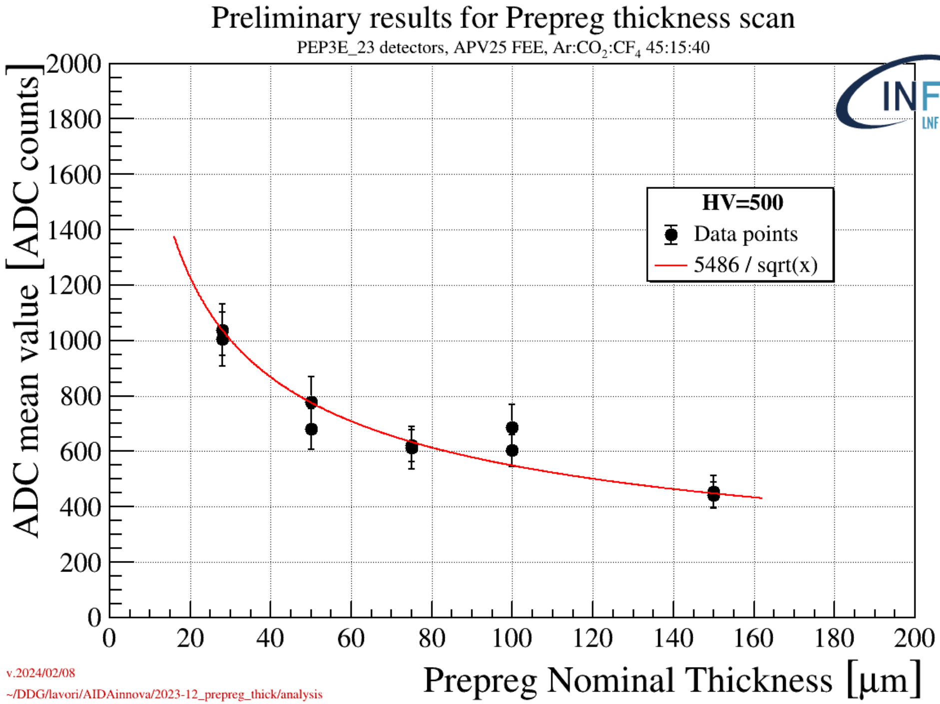
The **DOCA** is defined as the **distance between** the edges of the **conductive lines** and its **closest amplification hole**.

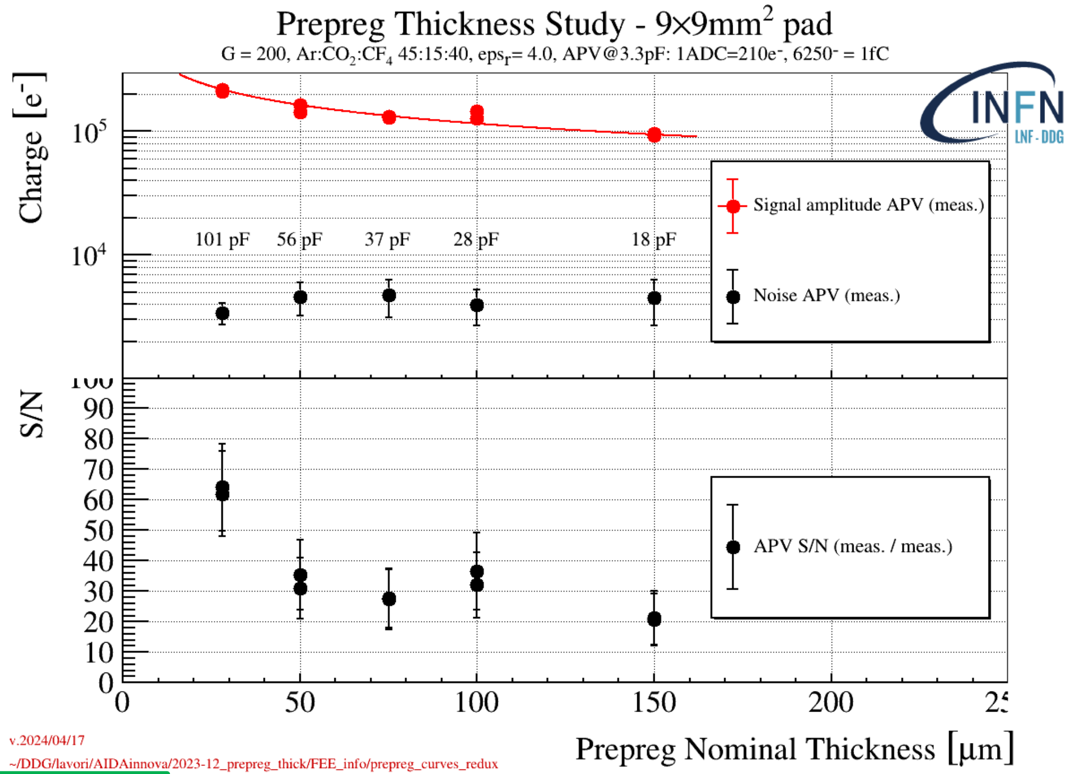


The **DOCA (before discharge)** as a function of the DLC **resistivity**, for different **voltages**.

The study has been performed with a custom tool, with two thin conductive movable tips.

Prepreg thickness optimization





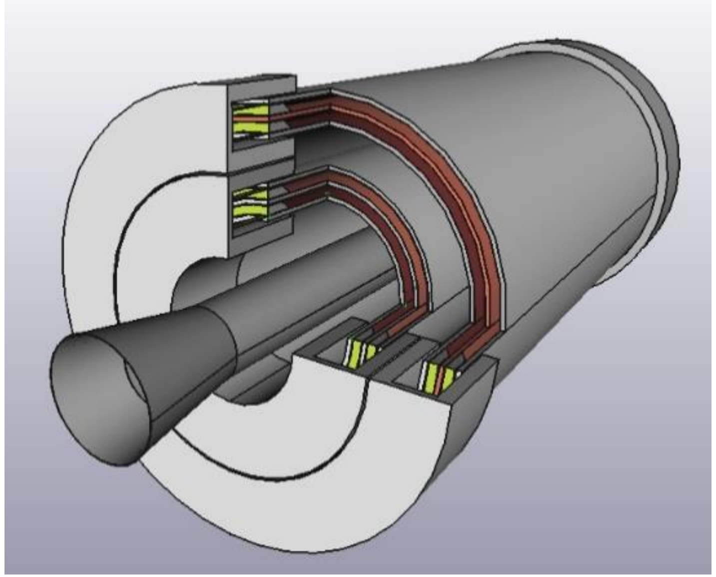
28μm thick prepreg maximize both the **amplitude of the signa**l induced on the pad readout, and **S/N ratio** (measurement done with APV25)

Low X0 cylindrical μ-RWELL

eurizon
European network
for developing new horizons for RIs

Exploiting the **flexible characteristic of the amplification stage** of the μ-RWELL, as well as the readout (to which it is coupled through the resistive DLC stage), we developed **a low-mass modular Inner Tracker for low-energy positron-electron colliders (SCTF) → Cylindrical μ-RWELL (C-RWELL).**

- **N.2 small gap B2B C+layers → 1.72% X_0**
- 2 × 1 cm gas gap/B2B device
- 4 cm global sampling gas

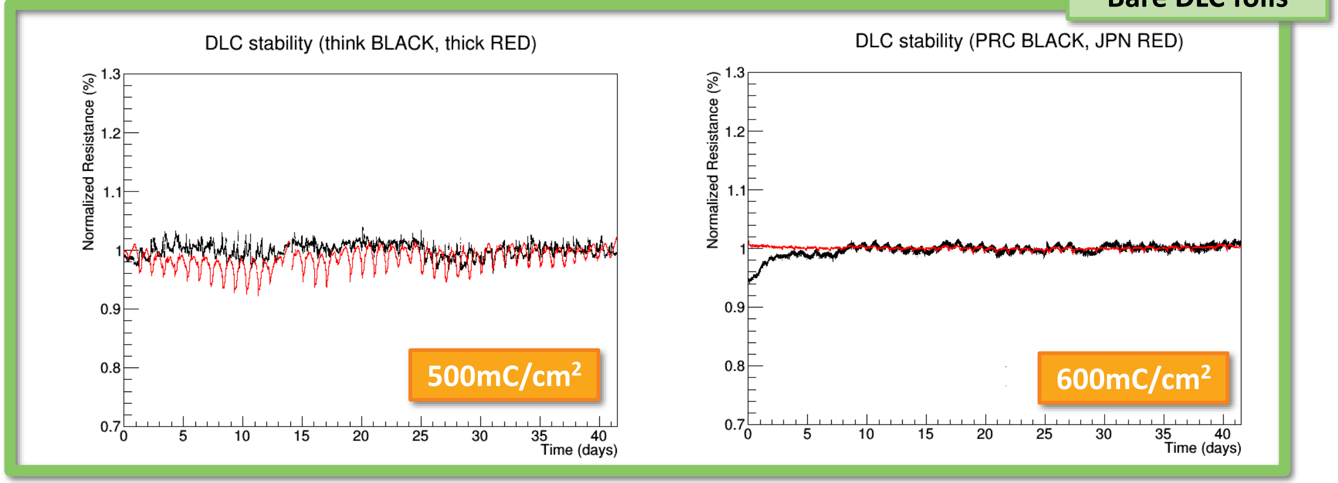


micro-TPC readout mode allowing **space resolution** of O(**100 μm)** for **inclined tracks** (on the radial view)

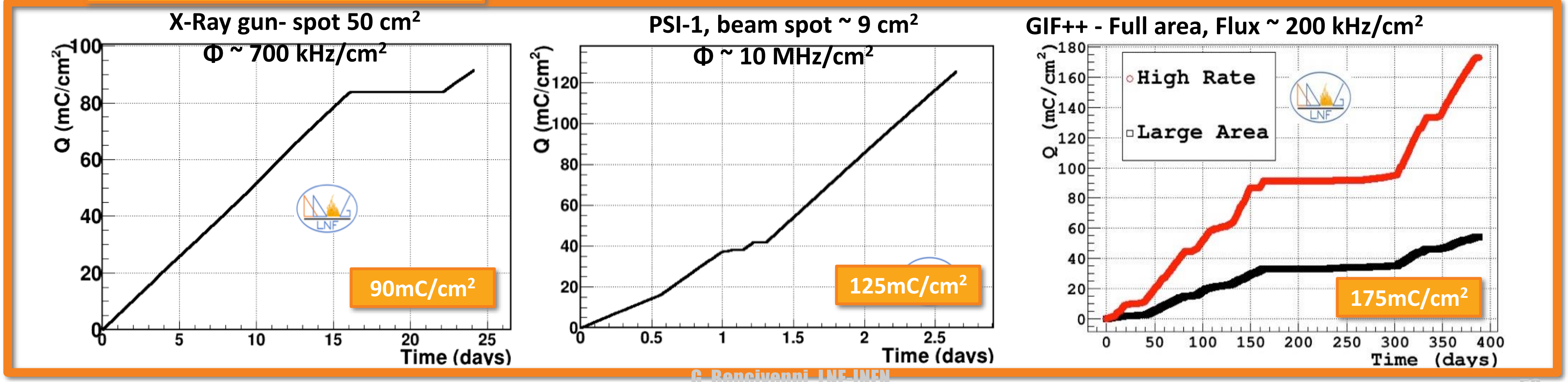
Irradiation test of DLC and μ-RWELL

- **DLC foils**: monitoring of the resistivity of two foils under x-ray irradiation.
- **μ-RWELL detectors**: prototypes irradiated with different radiation.

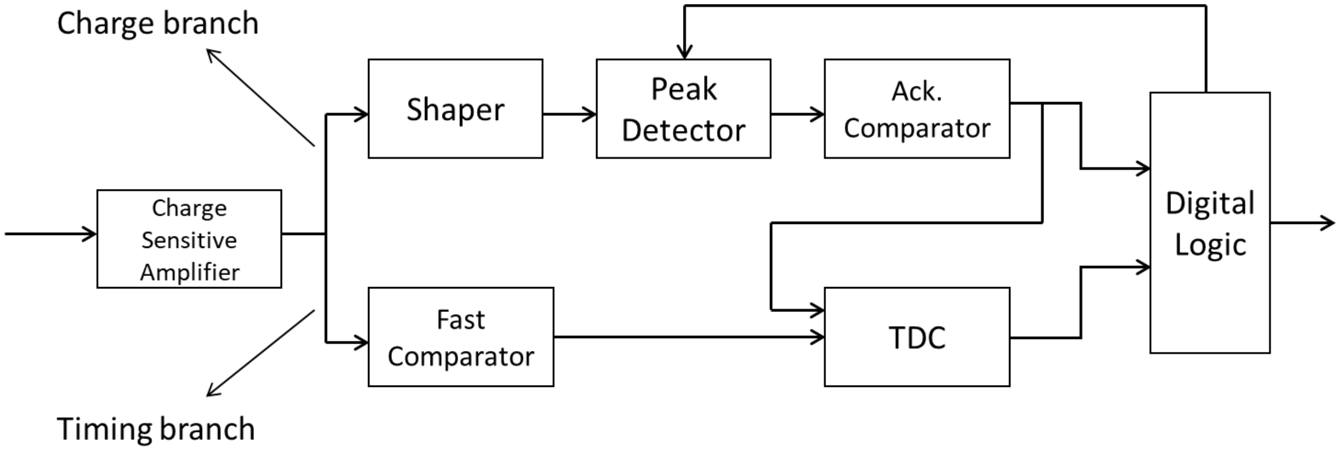
Bare DLC foils



μ-RWELL DETECTORS



FATIC2 block diagram



Preamplifier features:

- CSA operation mode
- Input signal polarity: positive & negative
- Recovery time: adjustable

CSA mode:

- Programmable Gain: 10 mV/fC ÷ 50 mV/fC
- Peaking time: 25 ns, 50 ns, 75 ns, 100 ns

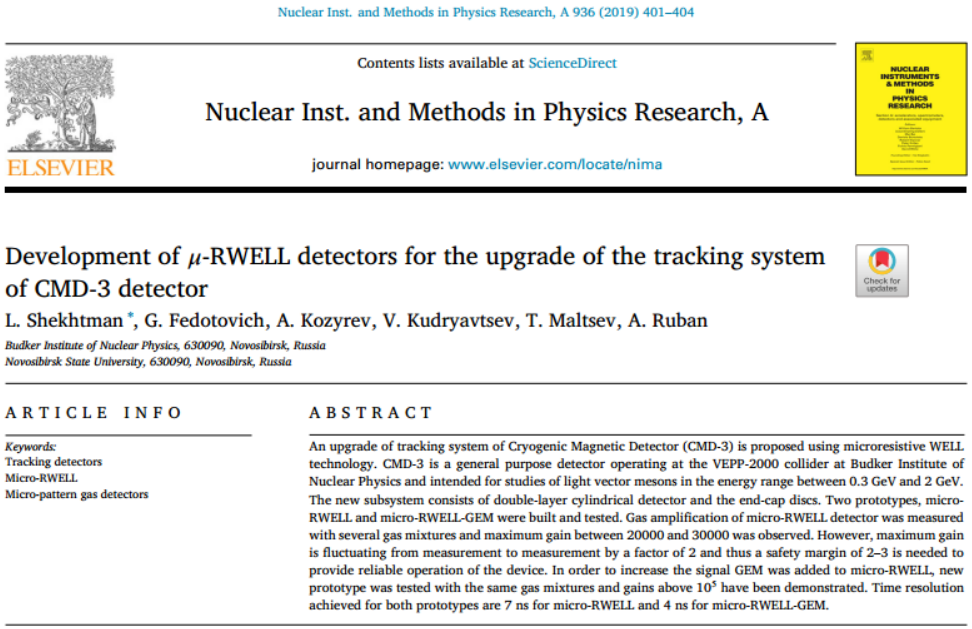
Timing branch:

- ✓ Measures the arrival time of the input signal
- ✓ Time jitter: 400 ps @ 1 fC & 15 pF (Fast Timing MPGD)

Charge branch:

- ✓ Acknowledgment of the input signal
- ✓ Charge measurement: dynamic range > 50 fC, programmable charge resolution

μ-RWELL + GEM



Nuclear Inst. and Methods in Physics Research, A 936 (2019) 401–404

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Development of *μ*-RWELL detectors for the upgrade of the tracking system of CMD-3 detector

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ARTICLE INFO

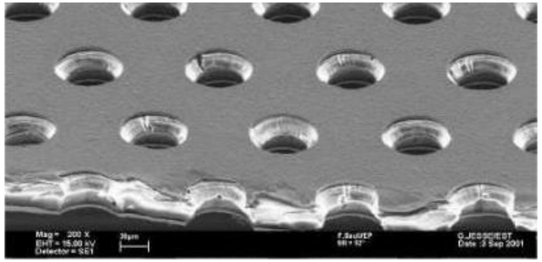
Keywords:
Tracking detectors
Micro-RWELL
Micro-pattern gas detectors

ABSTRACT

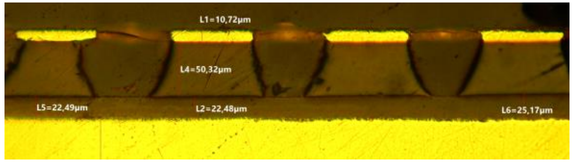
An upgrade of tracking system of Cryogenic Magnetic Detector (CMD-3) is proposed using microresistive WELL technology. CMD-3 is a general purpose detector operating at the VEPP-2000 collider at Budker Institute of Nuclear Physics and intended for studies of light vector mesons in the energy range between 0.3 GeV and 2 GeV. The new subsystem consists of double-layer cylindrical detector and the end-cap discs. Two prototypes, micro-RWELL and micro-RWELL-GEM were built and tested. Gas amplification of micro-RWELL detector was measured with several gas mixtures and maximum gain between 20000 and 30000 was observed. However, maximum gain is fluctuating from measurement to measurement by a factor of 2 and thus a safety margin of 2–3 is needed to provide reliable operation of the device. In order to increase the signal GEM was added to micro-RWELL, new prototype was tested with the same gas mixtures and gains above 10^5 have been demonstrated. Time resolution achieved for both prototypes are 7 ns for micro-RWELL and 4 ns for micro-RWELL-GEM.

L. Shekhtman, Nuclear Inst. and Methods in Physics Research, A 936 (2019) 401–404

Drift Gap: Shekhtman **3mm** – LNF+Roma2 **6mm**



Transfer Gap: Shekhtman **3mm** – LNF+Roma2 **3mm**

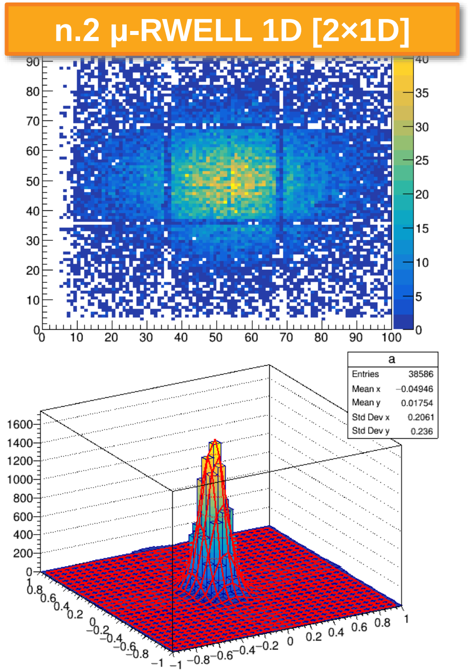


Developed for **CMD3 upgrade disks** (4 sectors 50×50cm^2)

The GEM **must be** stretched: sizes larger than 50×50cm^2 could be critical (depending on the gas gaps size).

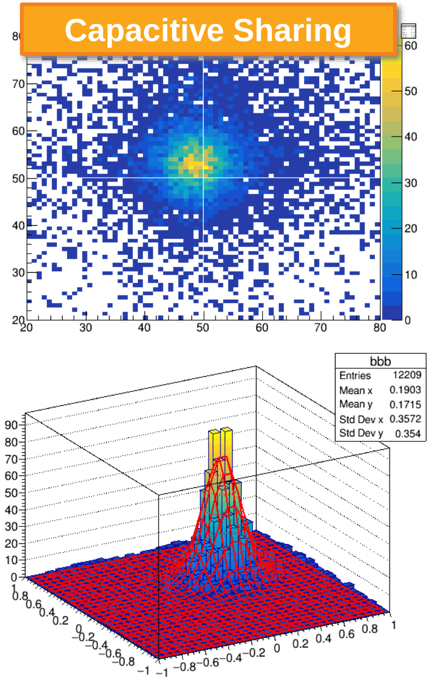
2-D Tracking layouts performance

n.2 μ-RWELL 1D [2×1D]



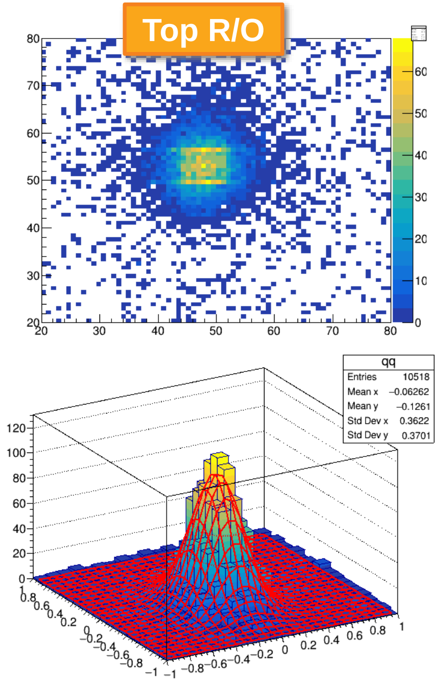
Fit Gauss-2D
sigmaX = 85μm
sigmaY = 121μm

Capacitive Sharing



Fit Gauss-2D
sigmaX = 142 μm
sigmaY = 147 μm

Top R/O



Fit Gauss-2D
sigmaX = 173 μm
sigmaY = 250 μm

2D - PROFILE

2D - RESIDUAL

μ-RWELL + GEM: gas gain

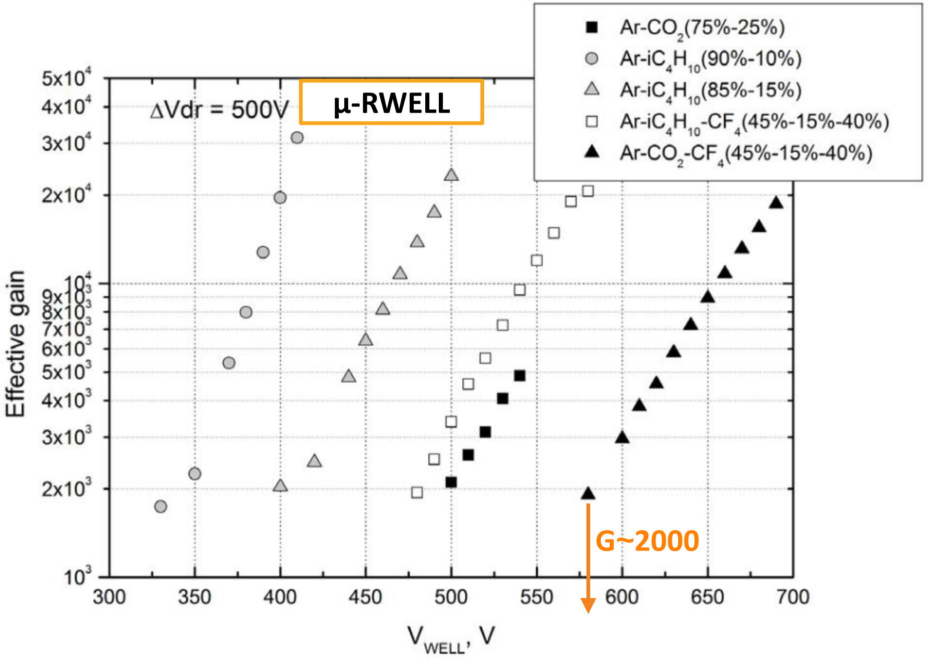


Fig. 4. Gain as a function of voltage on the top electrode of μ-RWELL for different gas mixtures. Voltage across the drift gap is 500 V.

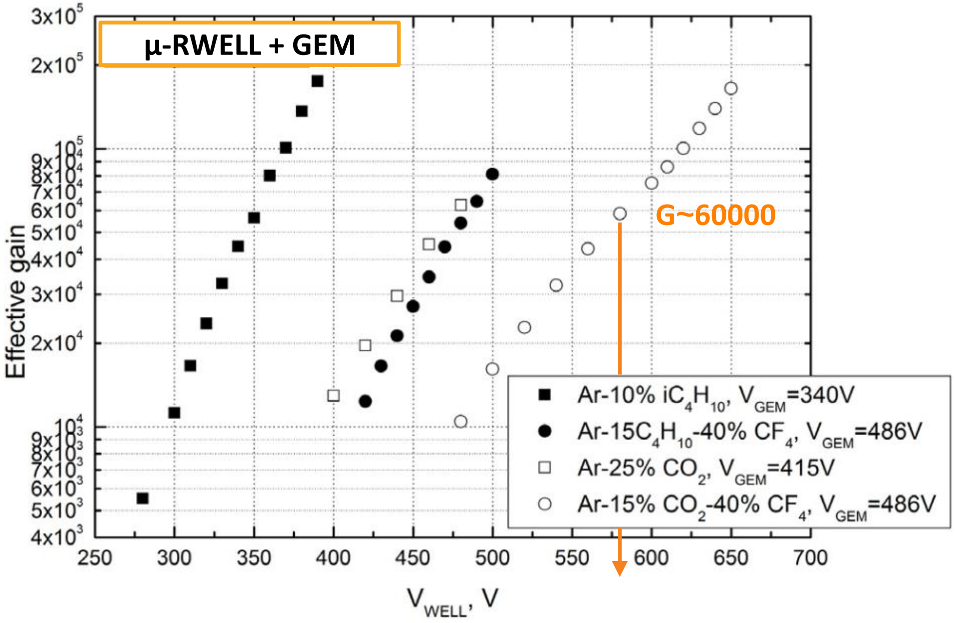


Fig. 5. Gain as a function of voltage on the top electrode of μ-RWELL for GEM voltages providing additional gain of 50–100 and for different gas mixtures. Voltage across the drift gap is 500 V.

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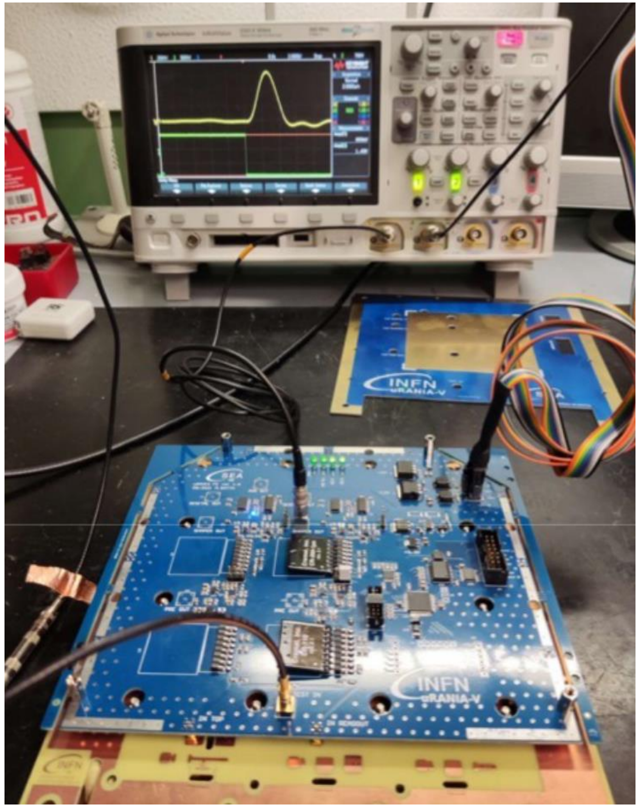
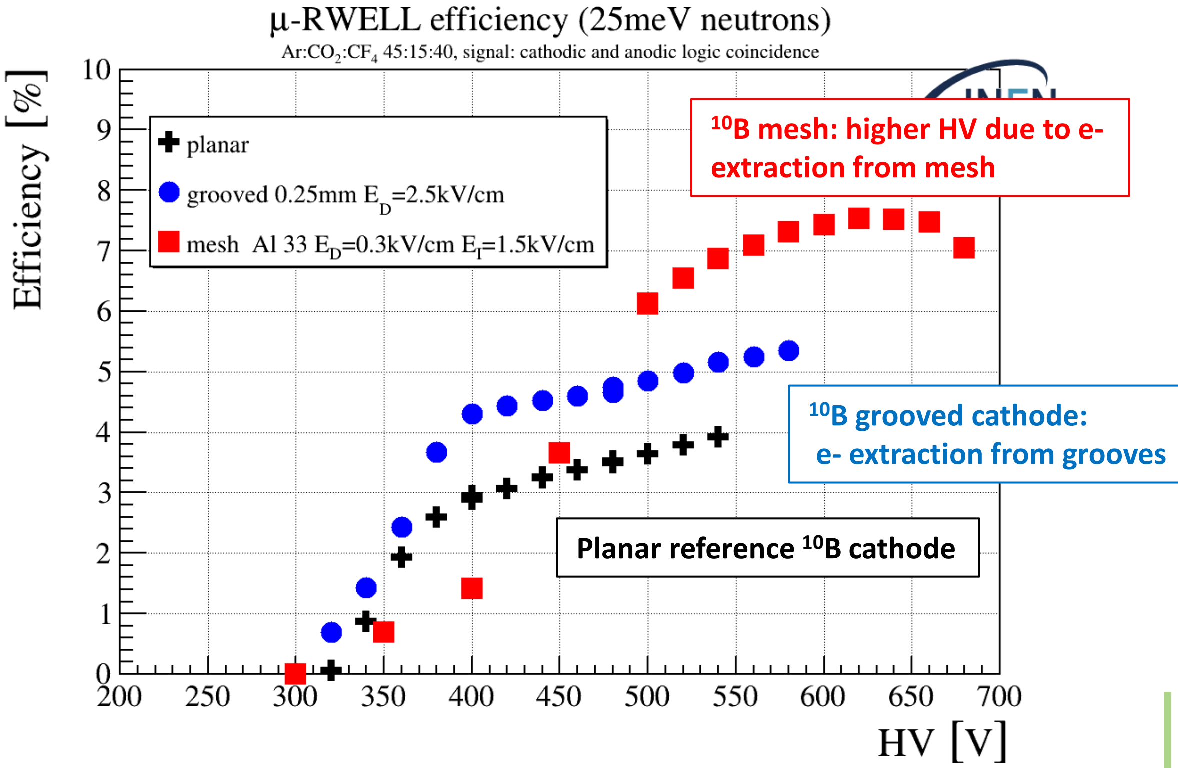
The μ-RWELL as neutron detector



Custom FEE by LNF electronic pool based on CR-200 & CR-110



^{10}B mesh: higher HV due to e- extraction from mesh

^{10}B grooved cathode: e- extraction from grooves

Planar reference ^{10}B cathode

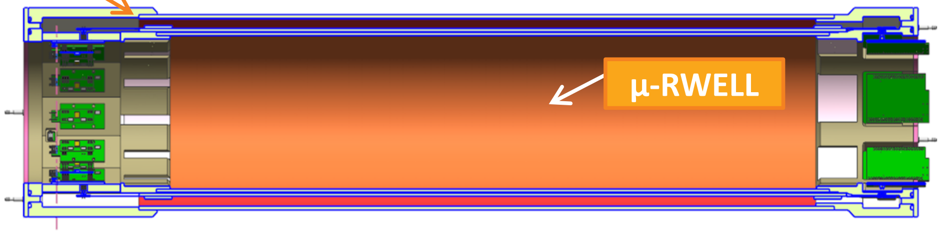
Efficiency (@25meV) ≅ 2 × Efficiency (HOTNES)

Cylindrical-RWELL for low-momentum experiments

Low X_0 Cylindrical µ-RWELL

By exploiting the **flexible characteristic of the amplification stage** of the µ-RWELL, as well as the readout, we developed **a low-mass (0.6% X_0) modular Inner Tracker** for **low-energy positron-electron colliders**, exploiting the innovative **Cylindrical µ-RWELL (C-RWELL) technology.**

- From standard **micro-RWELL technology on rigid PCB supports** we developed a **full flexible detector tile**
- **Three of such flexible detector tiles** have been **glued** on **composite/foam roof-tiles**, then mounted on the **anode cylindrical support**
- **A full cylindrical-cathode will close (externally) the detector**



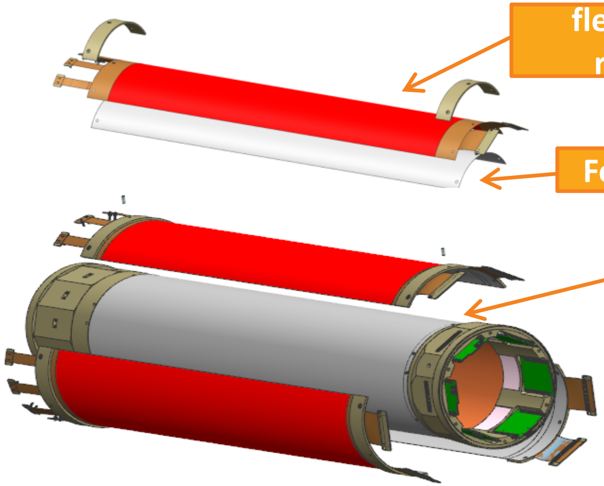
Cathode

Prototype cross section

µ-RWELL

Detector size

- external diameter ≈20cm
- global length ≈ 100cm
- active length≈ 60cm



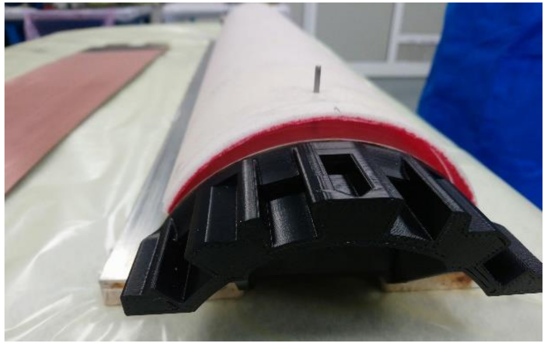
flexible µ-RWELL + readout (CERN)

Foam root-tile (LOSON)

Structural anode cylinder

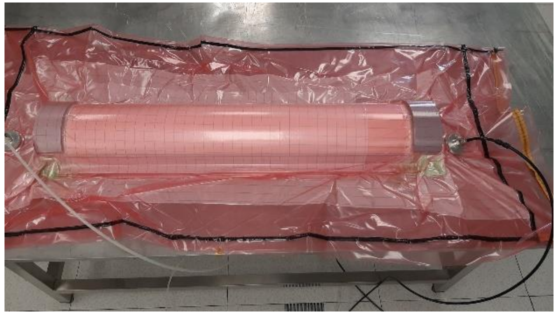
The roof tile assembly

The roof tile is composed of a **Structural Adhesive Film (30 µm)** coupled to **a layer of Millifoam® (2 mm)** where the flexible PCB is glued, under vacuum, with epoxy.



The **roof tile Millifoam®** support

The **flexible µ-RWELL PCBs** produced at CERN-EP-DT MPT Workshop. Each foil is divided in four HV sectors



Gluing the µ-RWELL-PCB onto the roof tile, followed by an epoxy curing cycle under vacuum.

The final roof tile is coupled to the anode support

The final assembly

The final assembly didn't require a highly sophisticated sliding machine, thanks to the large distance (10 mm) between the roof tiles and the internal surface of the cathode. **The tile gluing and the detector assembly took 14 days.**

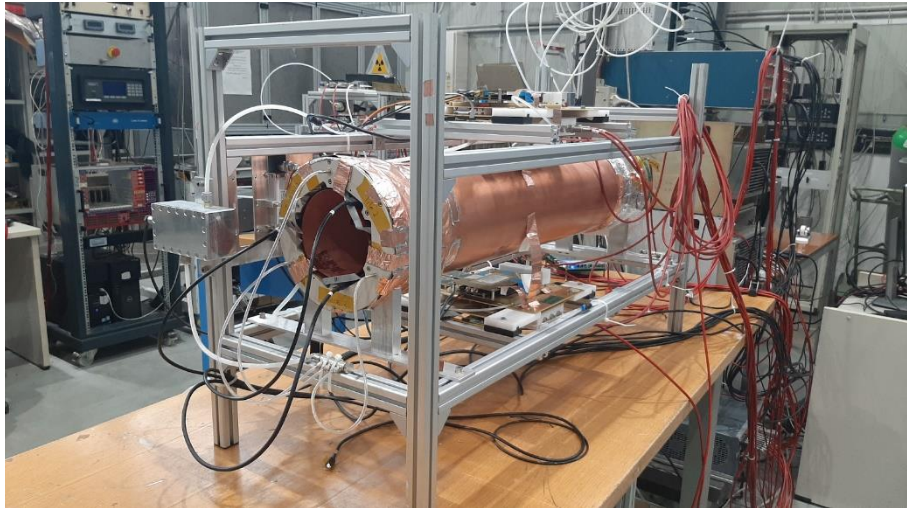
The assembly

The detector completed

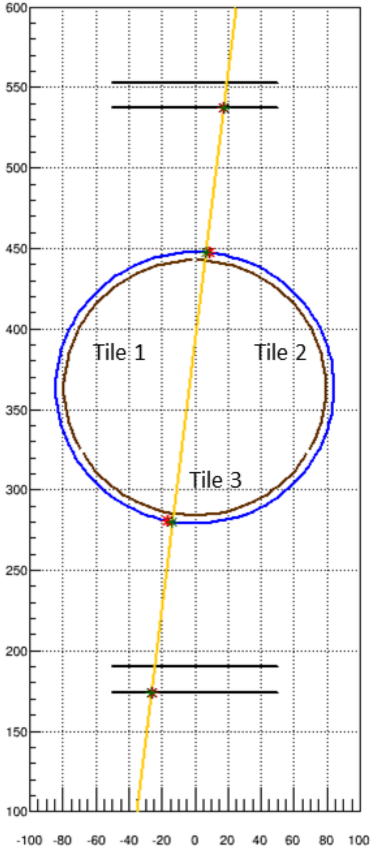
Vietnamese dinner with Huong (in Rome)

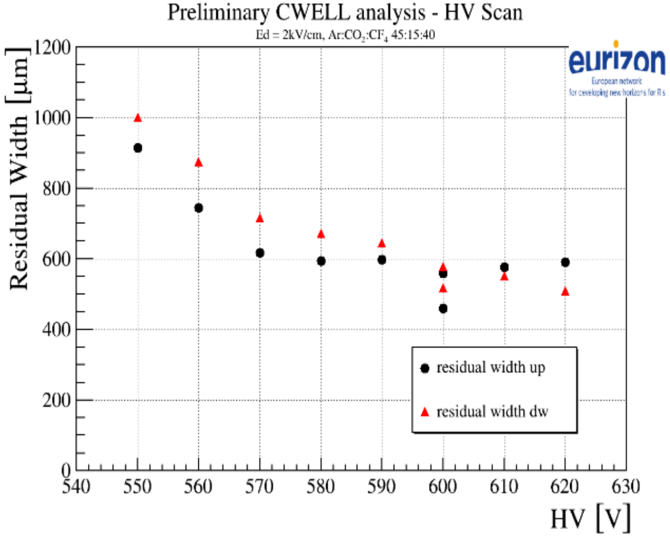
Cosmic ray test

We set up a **tracking system** with four 1D μ-RWELL (400 μm strip pitch → ~100 μm **tracking** resolution)
All detectors were equipped with **APV25** and flushed with **$Ar/CO_2/CF_4$ 45/15/40.**



C-RWELL test with cosmics.





The technology remains in the drawer because the **collaboration with the SCTF group in Russia** has obviously been **stopped by the war.**

Technology Transfer to Industry

Manufacturing high-rate layouts

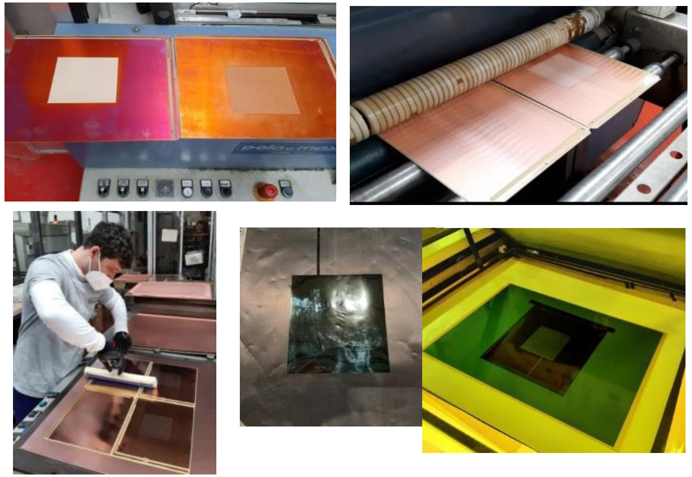
The **µ-RWELL_PCB is a rigid-flex PCB** based on **SBU technology**, that is **compatible with standard industrial processes**.

The **ELTOS** is the industrial partner **involved in the manufacturing of the µ-RWELL**.

The **ELTOS SpA** was founded in 1980 in Arezzo, Italy.

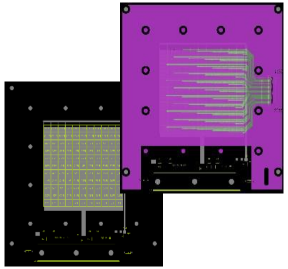
The Company has a **large experience in the construction of MPGDs,** including technologies such as **Thick-GEM (THGEM)** and **MicroMegas**.

The **involvement of a private industry** in this R&D **opens the way** for the use of µ-RWELL technology **across various fields of applications.**



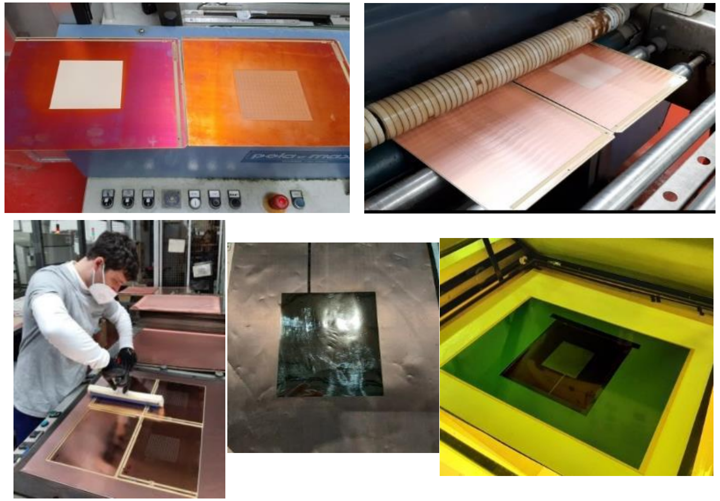
Detector Manufacturing flow chart

LAYOUT design



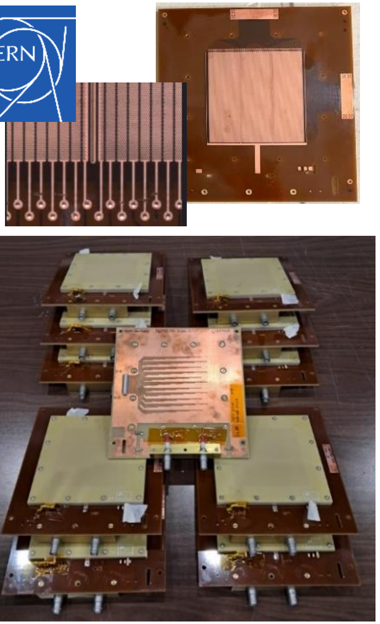
Feedback from tests

PCB production



DLC foil production

Final detector manufacturing



Detector manufacturing steps

Step 0 – Detector PCB design @ **LNF**

Step 1 – CERN_INFN DLC (C.I.D) sputtering machine installed @ **CERN**
- In operation since Nov. 2022
- Production by **LNF-INFN** technical crew

Step 2 – Producing readout PCB by **ELTOS**
- pad/strip readout

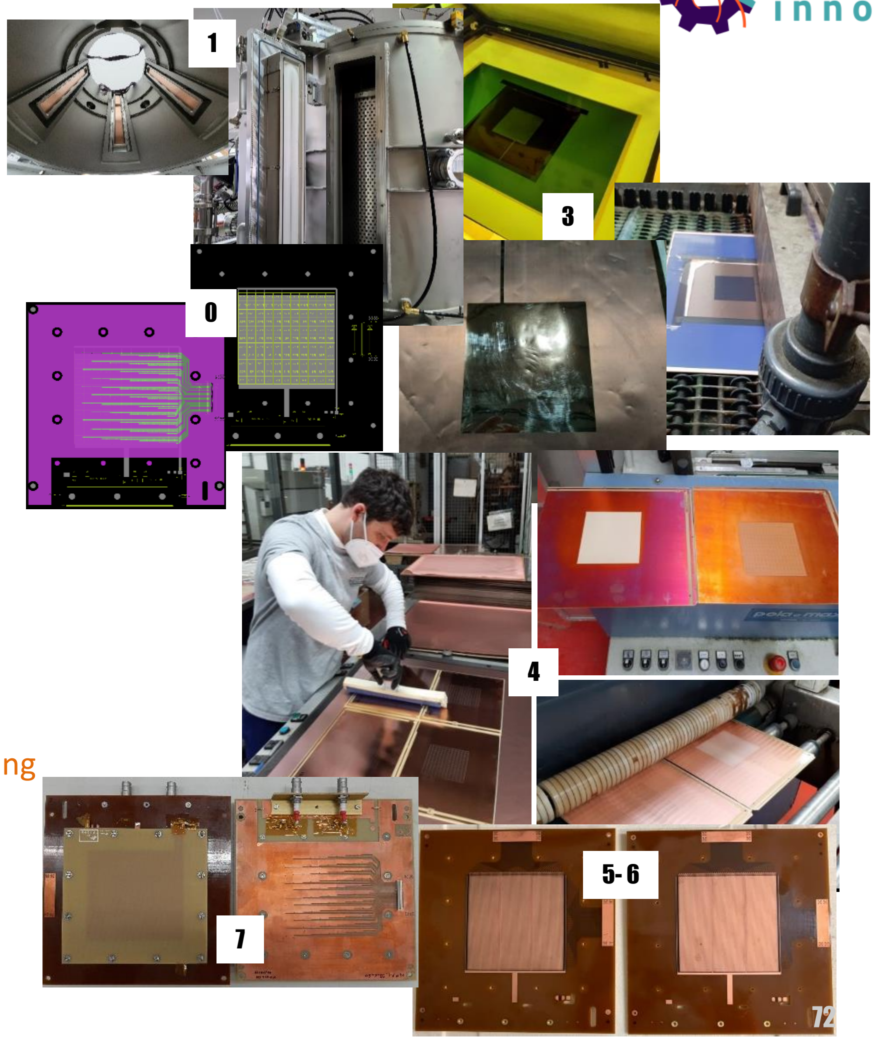
Step 3 – DLC patterning by **ELTOS**
- photo-resist → patterning with BRUSHING-machine

Step 4 – DLC foil gluing on PCB by **ELTOS**
- Large press available, up to 16 PCBs workable simultaneously

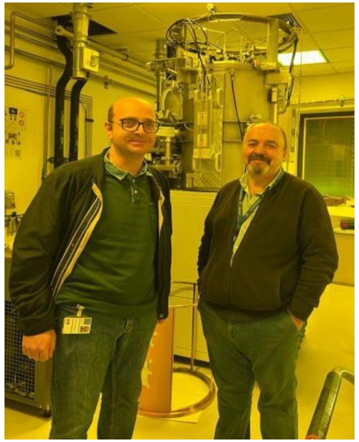
Step 5 – Top copper patterning by **CERN**
- Cu amplification holes image and HV connections by Cu etching

Step 6 – Amplification stage patterning by **CERN**
- PI etching → amplification-holes

Step 7 – Electrical cleaning and detector closure @ **CERN**



DLC sputtering



The **CID** (CERN-INFN-DLC) sputtering machine, a **joint project between CERN and INFN**, is used for preparing the **base material of the detector**. The potential of the DLC sputtering machine is:

- **Flexible substrates** up to **1.7×0.6m2**
- **Rigid substrates** up to **0.2×0.6m2**

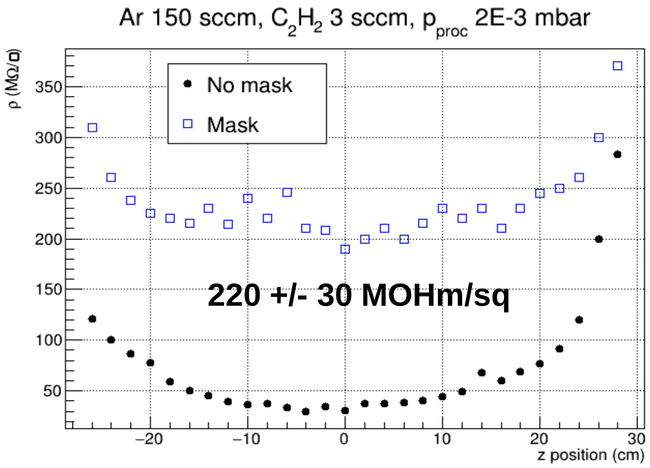
In **2023,** the activity on CID focused on the **tuning** of the **machine on small foils with good** results in terms of **reproducibility and uniformity.**

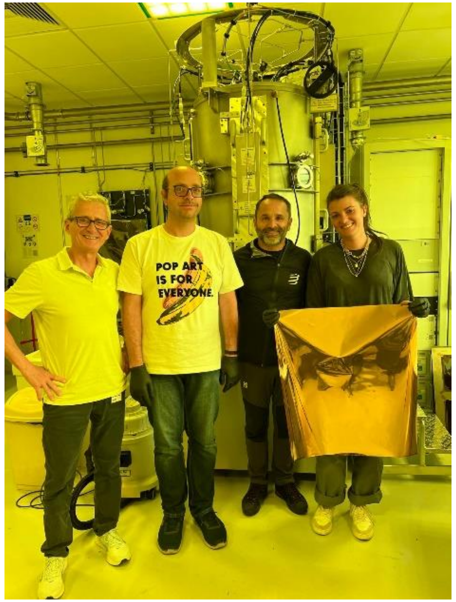
In **2024**, the challenge has been the **sputtering of large foils**:

- **DLC+Cu sputtering on 0.8×0.6m2 successfully done (May/June 2024)**
- **DLC on 1.7×0.6m2 large 0/50/0 Apical foils successfully done (June 2024)**
- **DLC on 1.7×0.6m2 large 5/50/0 Apical foils still to be done (July 2024)**

The graphite target

The three external cathodes





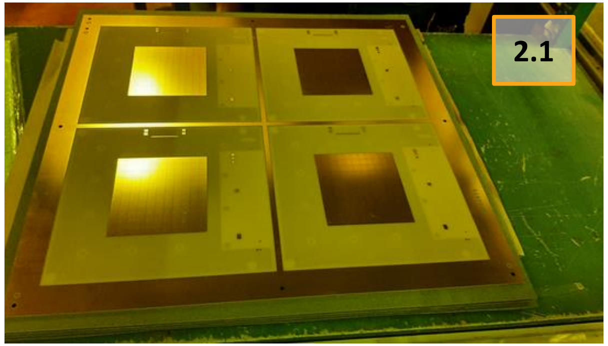
Detector manufacturing at ELTOS (I)

Step 2 (@ ELTOS)

1) **PCB production**

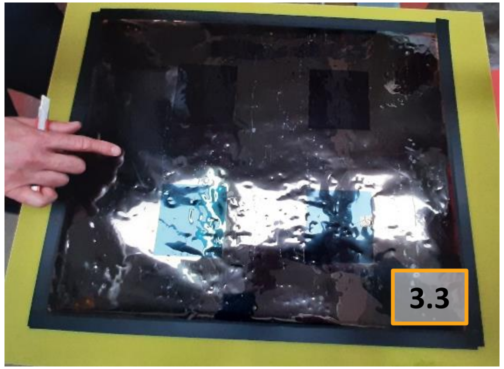
Step 3 (@ ELTOS)

1) Photoresist lamination for DLC protection
2) Photoresist UV-exposure
3) Photoresist developing
4) **DLC patterning** with brushing machine


2.1


3.1


3.2


3.3


3.4

Detector manufacturing at ELTOS (II)

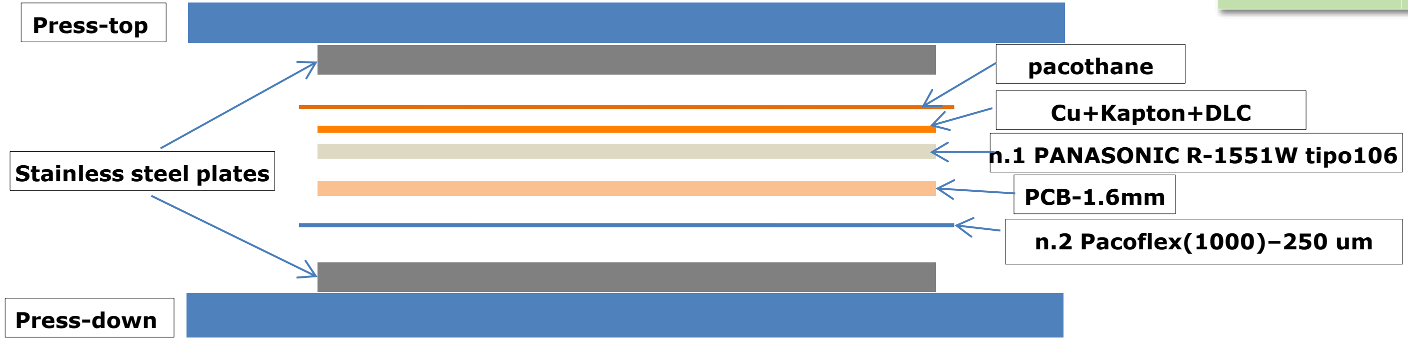
Step 4: The final manufacturing operation carried out at ELTOS is the **coupling of the DLC foil and the PCB through a layer of prepreg**.

N. 16 prototypes of micro-RWELL were made **with 4 different prepreg thicknesses (⊕1 special).**

The test, beside **validating the whole manufacturing process (ELTOS ⊕ CERN)**, allowed for **the study of the dependence** of the **induced signal amplitude** as a **function of the readout capacitance** wrt the amplification stage.

Pre-preg	Δx [μm]
106	50
1080	75
x2 106	100
x2 1080	150

Main parameters:
Pressure 180 N/cm^2
Temperature 210 °C



Electrical Hot Cleaning

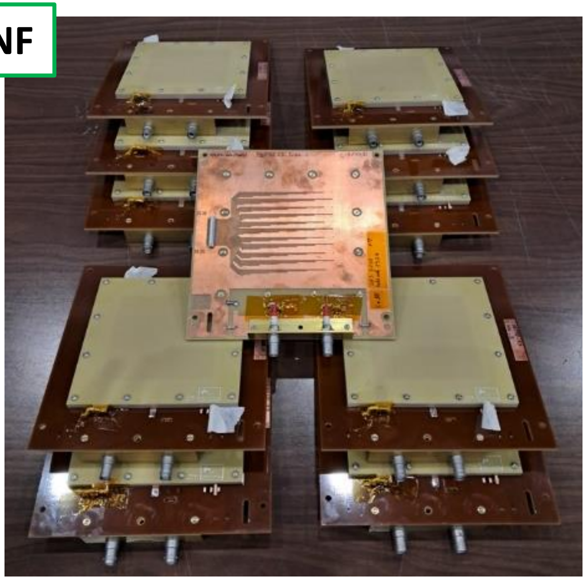
@ CERN

At the end of the manufacturing process at CERN, a **conditioning procedure** is performed:

- Standard **PCB washing**
- **Electrical cleaning in dry air** (**90°C** in an oven) from **300 V to 680 V** (each step with current < 1 nA)
- **Detector closure** and final **test at 600 V in ambient air**

Pilot co-production test

@ LNF

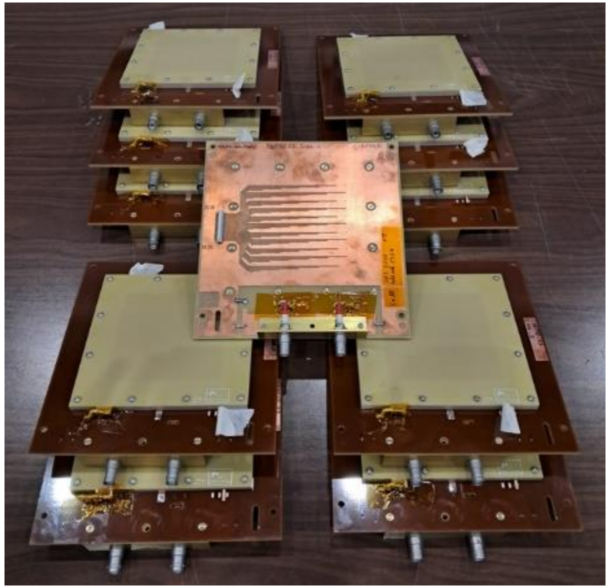


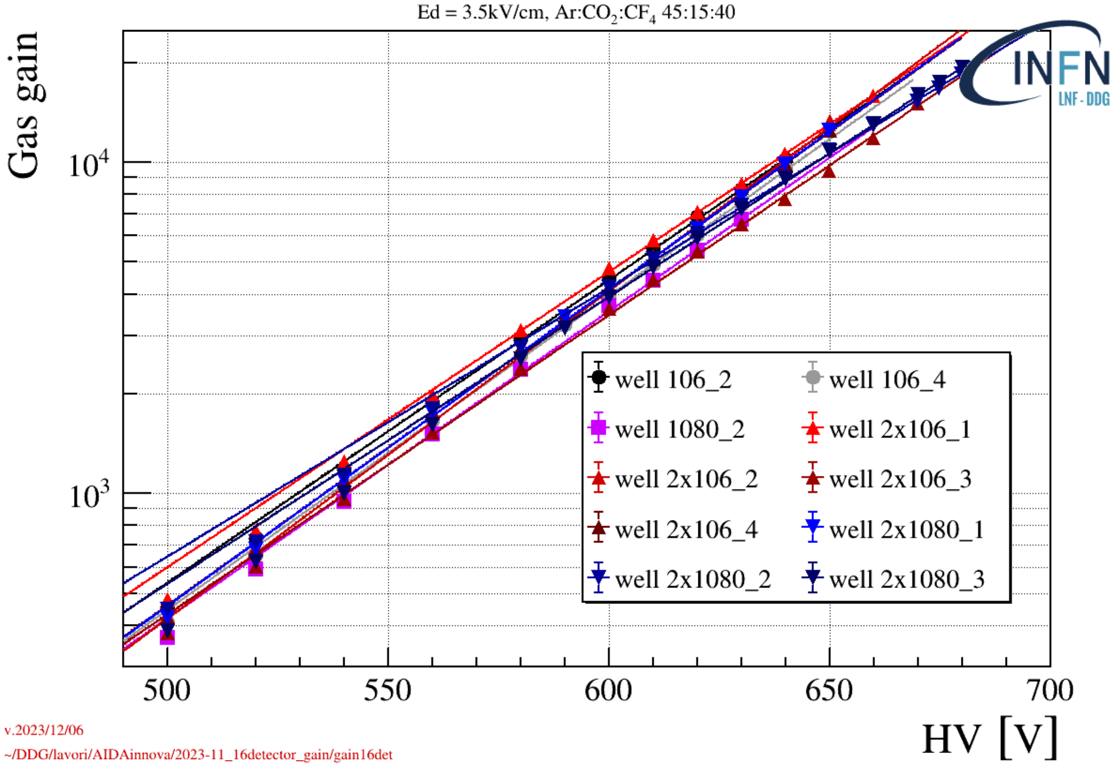
The 16 co-produced prototypes have been extensively tested with X-rays:

- **15/16 are fine**
- **1/16 needs to be re-cleaned**

Production yield > 93%

Co-production pilot results (I)

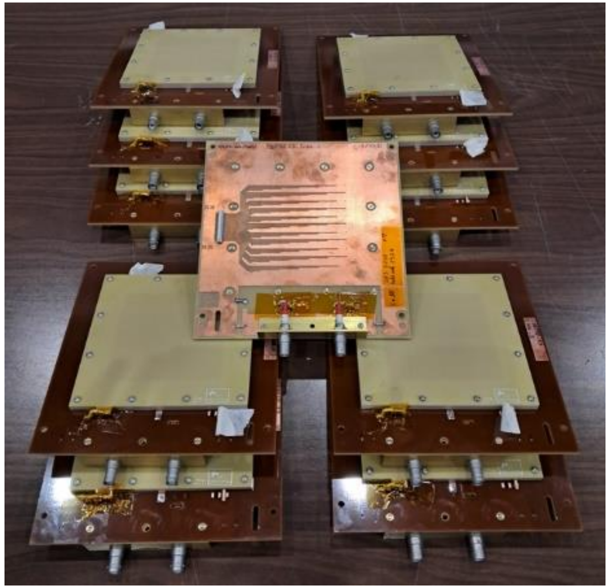




Characterized with **X-ray gun** → **Gas gain** measurement

- **16** co-produced protos have been delivered and tested
- **10/16 (LNF) + 5/16 (CERN)** are fine
- **1/16 should be re-cleaned**

Max-gain vs resistivity



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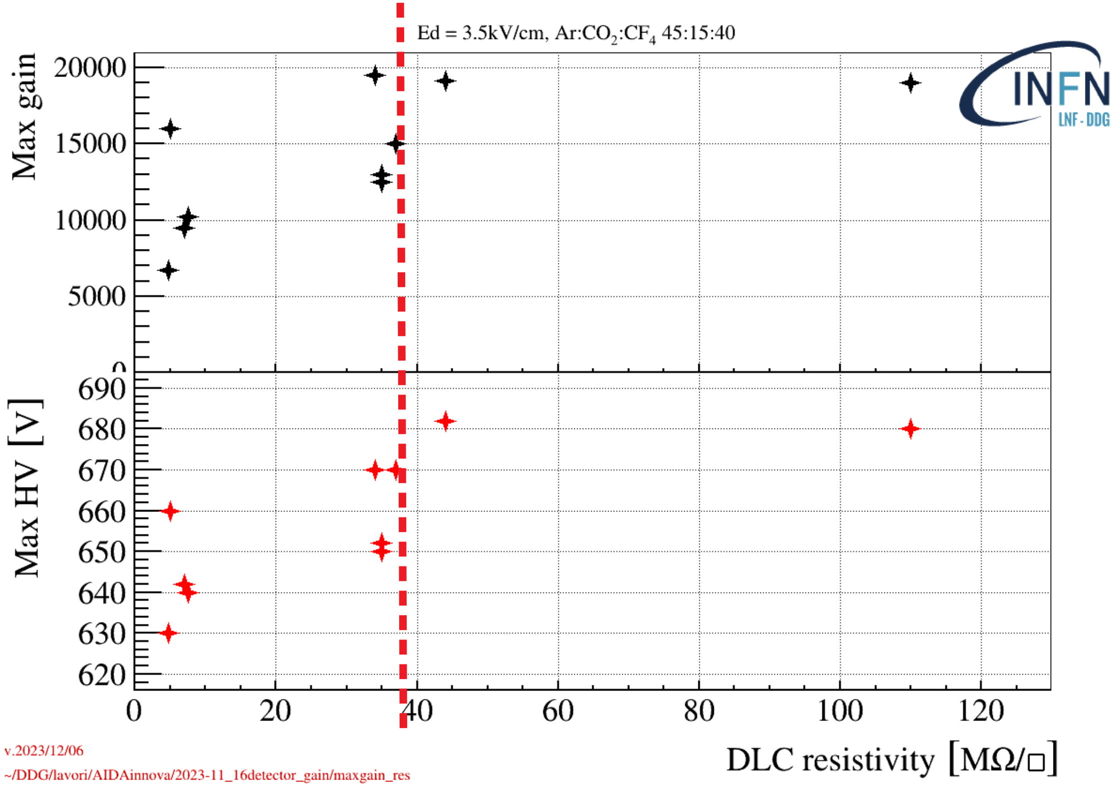
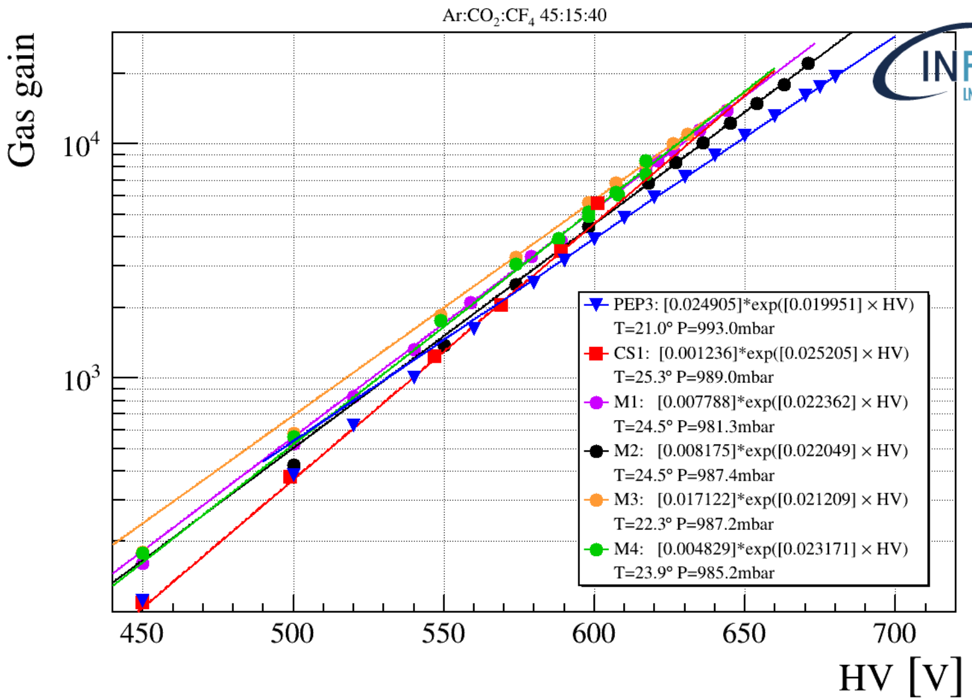
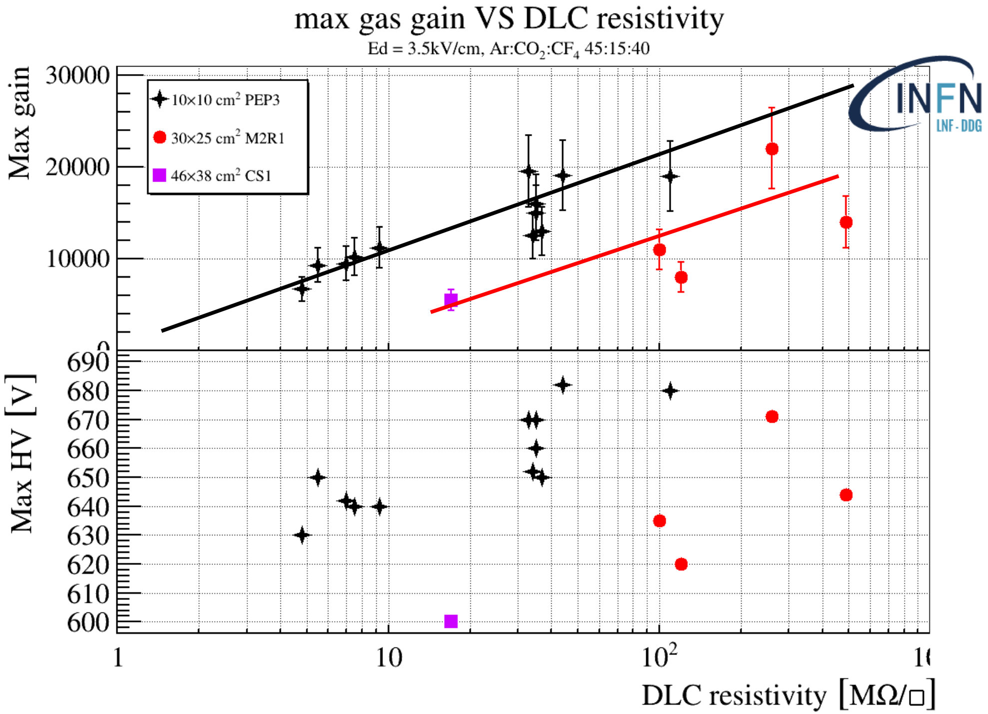


The **maximum gain** is larger for ρ ≥ **40 MOhm/square**

Max-gain: large size vs small size

CS_01 13 MOhm/sq, area **46x38 cm^2**
M2R1 260 MOhm/sq, area **30x25 cm^2**





For large-size detectors, the max-gain increases with the DLC resistivity, although, compared to the small-size detectors, the **gain curve for the larger size is shifted towards lower values.**