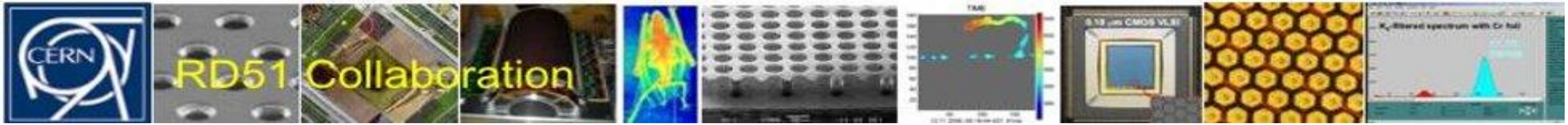
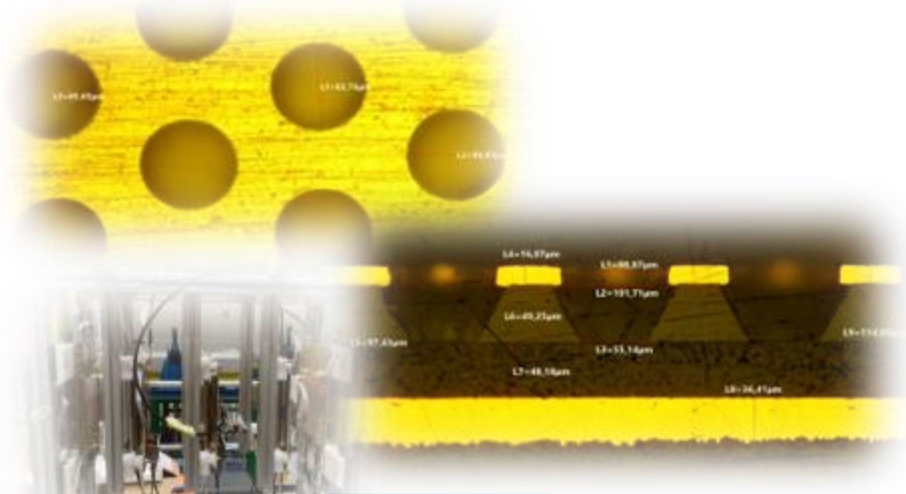


The micro-RWELL for high-rate

Design, Construction, Performance



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],
M. Pinamonti[3], R. Pinamonti[3], M. Poli Lener[1], R. Tesauro[1]

1 – Laboratori Nazionali di Frascati – INFN, Frascati (IT)
2 – CERN, Meyrin (CH)
3 – ELTOS SpA, Arezzo (IT)

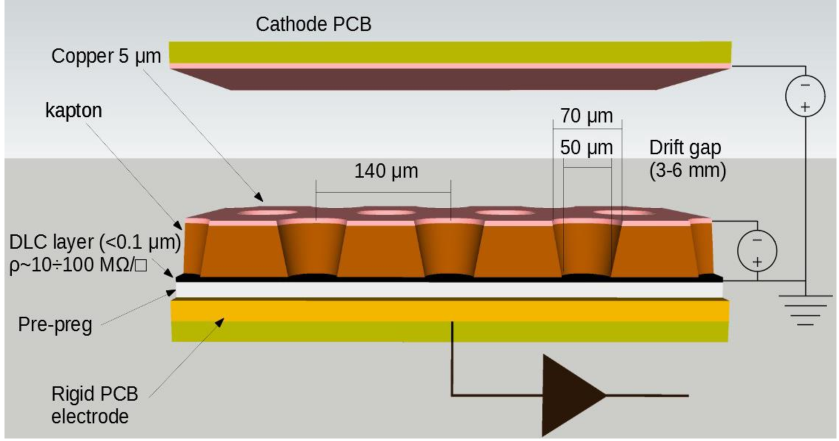
INFN LNF - DDG

LHCb

AIDA innova

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:

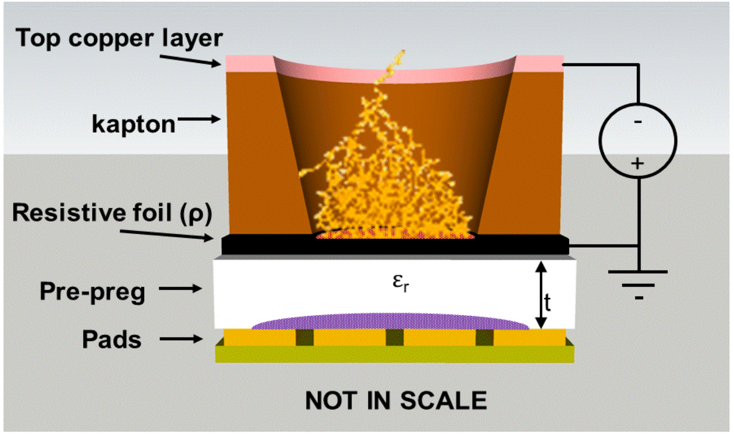
- **Cathode**
- **μ-RWELL PCB:**

– 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

R. Bellazzini et al., The WELL detector, Nucl. Instrum. Meth. A 423 (1999) 125.



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.**

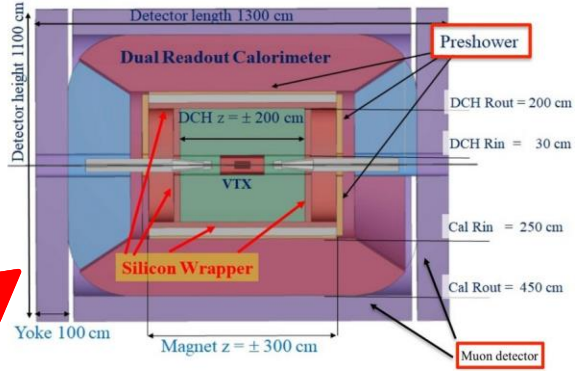
Drawback: the capability to **stand high particle fluxes** is **reduced**, but **largely recovered** with appropriate **grounding schemes** of the **resistive layer.**

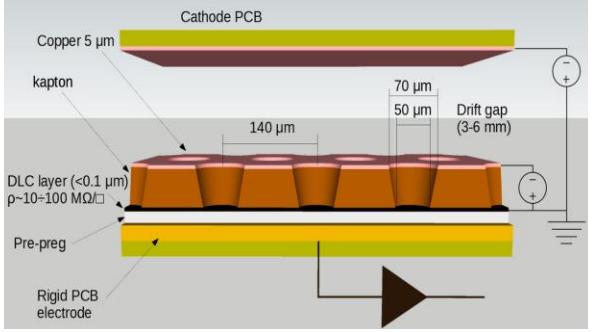
DDG – LNF R&D projects

LHCb

- rate up to **1 MHz/cm²**
- **576 detectors** w/**pad r/out** ≥ **9×9mm²**
- size 300x250 to 740x310 mm² active area
- **90 m²** detectors
- **500x0.6 m²** DLC

IDEA
FCC-ee

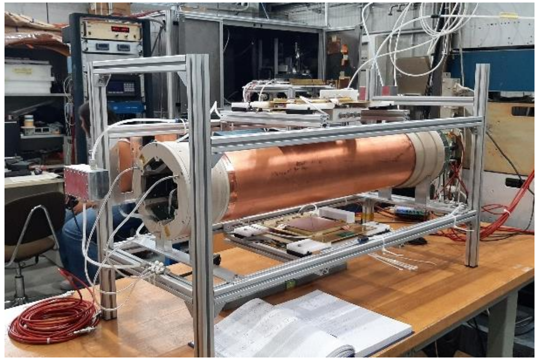




uRANIA

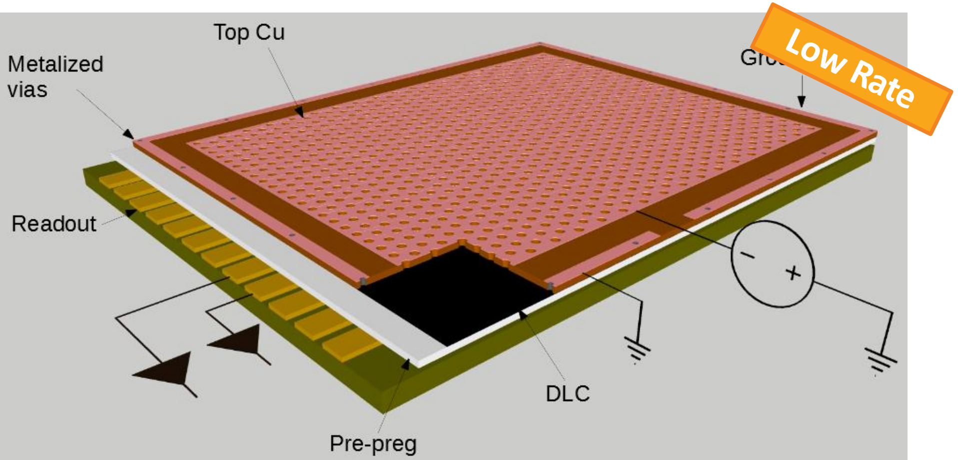
$$n+{}^{10}_{5}B\begin{cases} {}^{7}_{3}Li(1.02MeV)+\alpha(1.78MeV) & 6\% \\ {}^{7}_{3}Li(0.84MeV)+\alpha(1.47MeV)+\gamma(0.48MeV) & 94\% \end{cases}$$

EURIZON

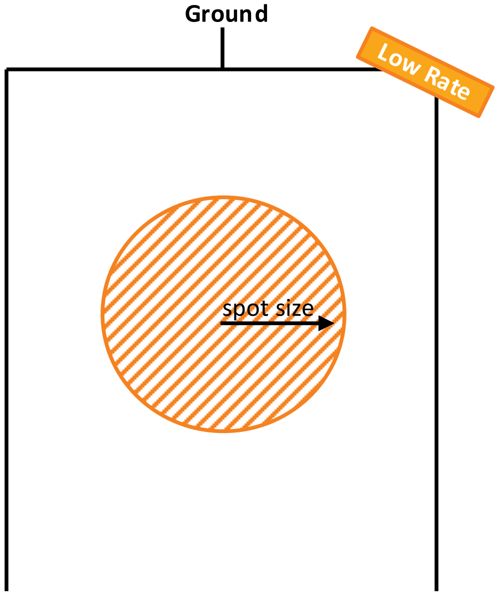


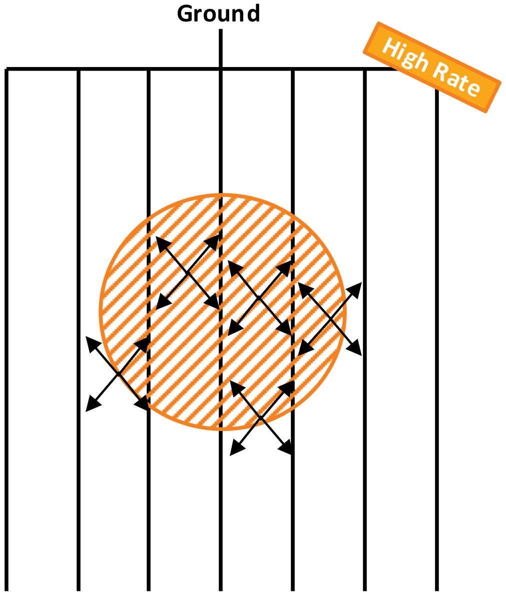
High-rate layout: principle of operation

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





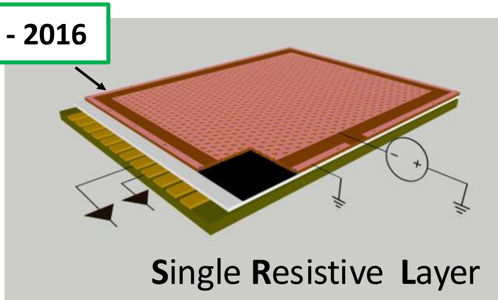
Segmenting the DLC with **conductive micro-strips/dots with a** typical **pitch of 1cm:** a sort of tiling of the active area using a set of smaller SRL.

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

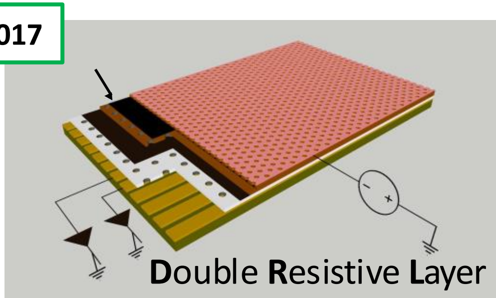
2014 - 2016



Single **R**esistive **L**ayer

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

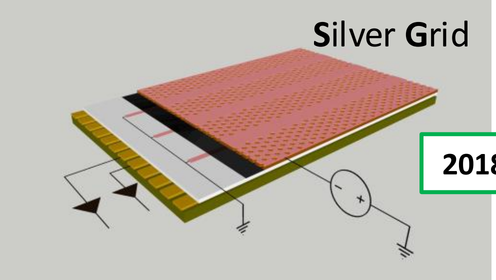
2017



Double **R**esistive **L**ayer

- **Two stacked resistive layers** with a **double matrix of conductive vias**
- **3-D current** evacuation
- Rate capability **> 10MHz/cm^2**
- **Complex manufacturing not easily engineered**

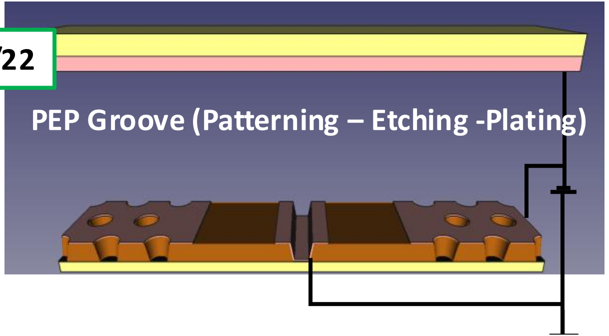
2018 - 2020



Silver **G**rid

- **Single DLC layer**
- **2-D current evacuation** through **conductive grid on the DLC layer**
- rate capability **> 10MHz/cm^2**
- **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**

PEP layouts comparison

2022

PEP-Groove:

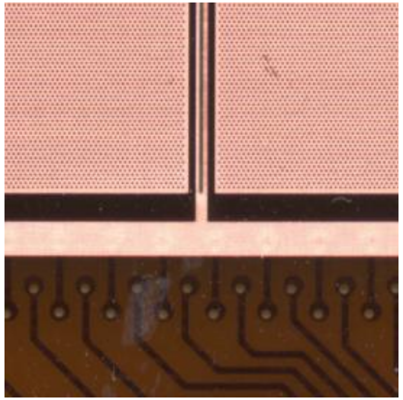
DLC grounding through conductive groove to ground line

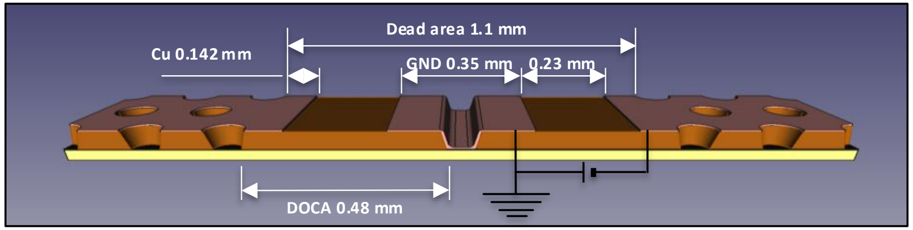
Pad R/O = 9×9mm^2

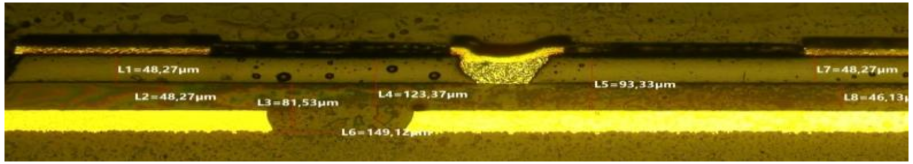
Grounding:

- Groove pitch = 9mm
- width = 1.1mm

→ 84% geometric acceptance







2023

PEP-DOT:

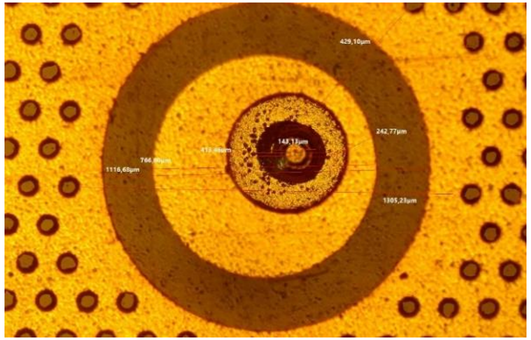
DLC grounding through conductive dots connecting the DLC with pad r/outs

Pad R/O = 9×9mm^2

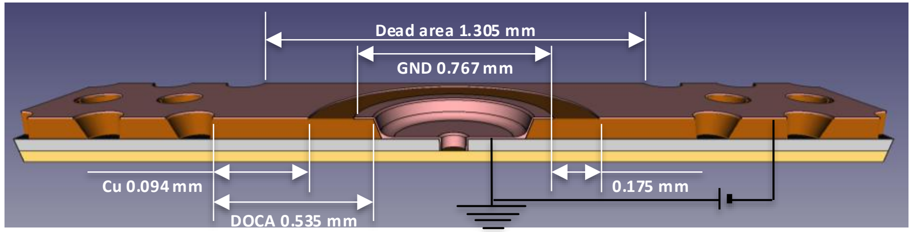
Grounding:

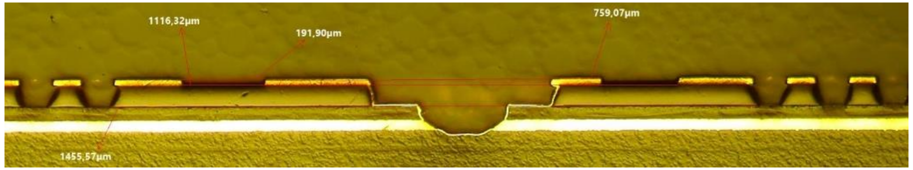
- Dot pitch = 9mm
- dot rim = 1.3mm

→ 97% geometric acceptance



DOT → plated blind vias

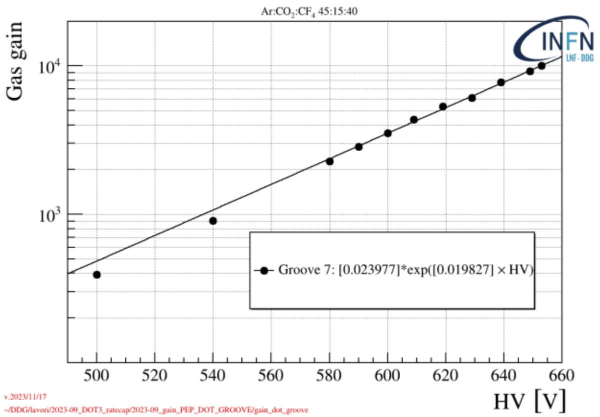




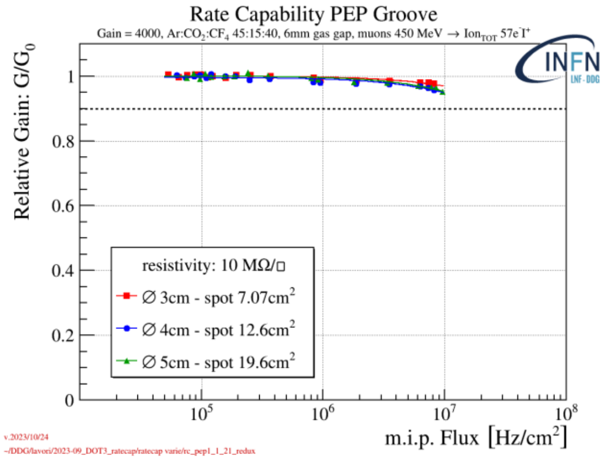
Groove vs DOT (X-ray characterization)

2022

PEP-Groove layout



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



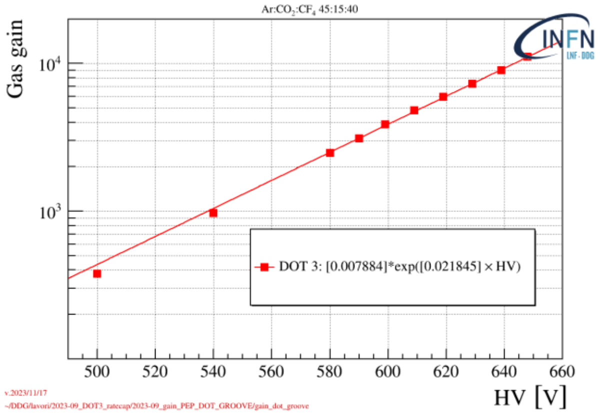
v.2023/10/24
~/DDG/lavori/2023-09_DOT3_ratecap/ratecap varie/rc_pep1_1_21_redux

Both layouts exhibit **satisfactory performance:**

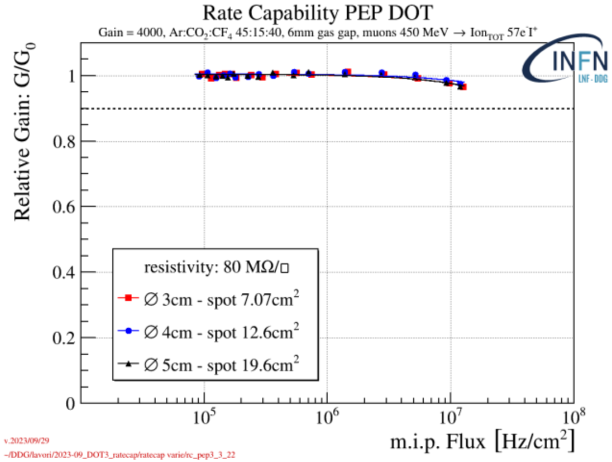
- **gas gain** up to **10^4**
- **rate capability** (@ 90% gain drop) > **10 MHz/cm^2 ,** measured with **different irradiation spot size.**

2023

PEP-DOT layout



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

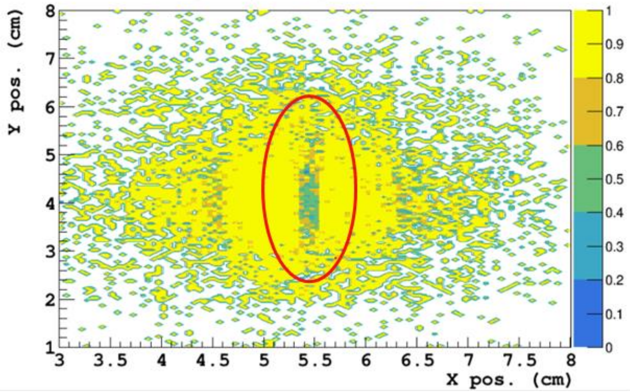


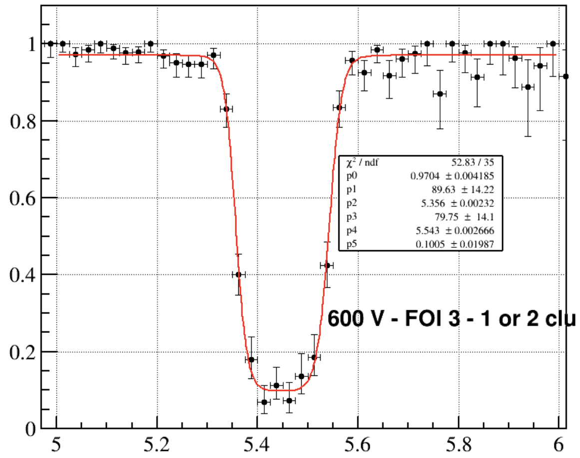
v.2023/09/29
~/DDG/lavori/2023-09_DOT3_ratecap/ratecap varie/rc_pep3_3_22

Groove vs DOT (test beam characterization)

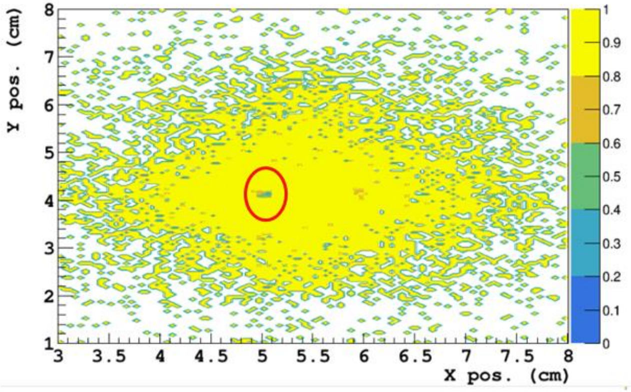
APV25 based Fee

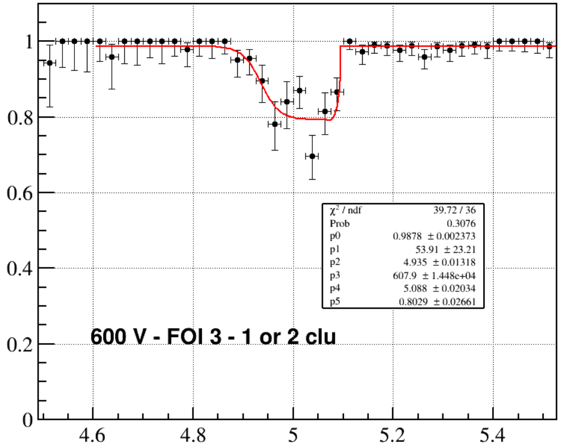
PEP-Groove layout

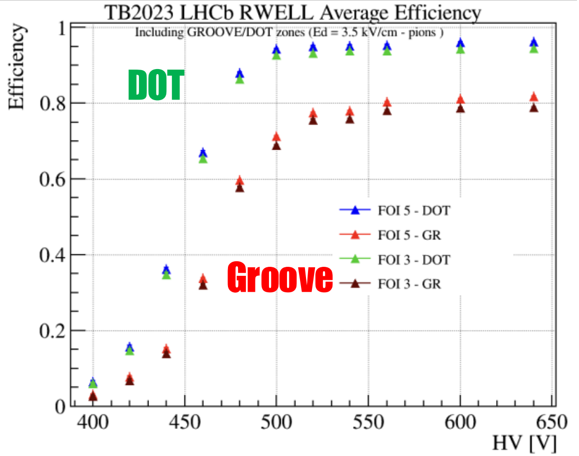


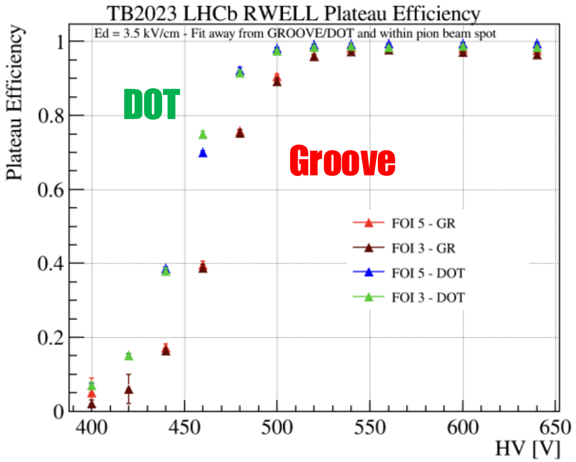


PEP-Dot layout



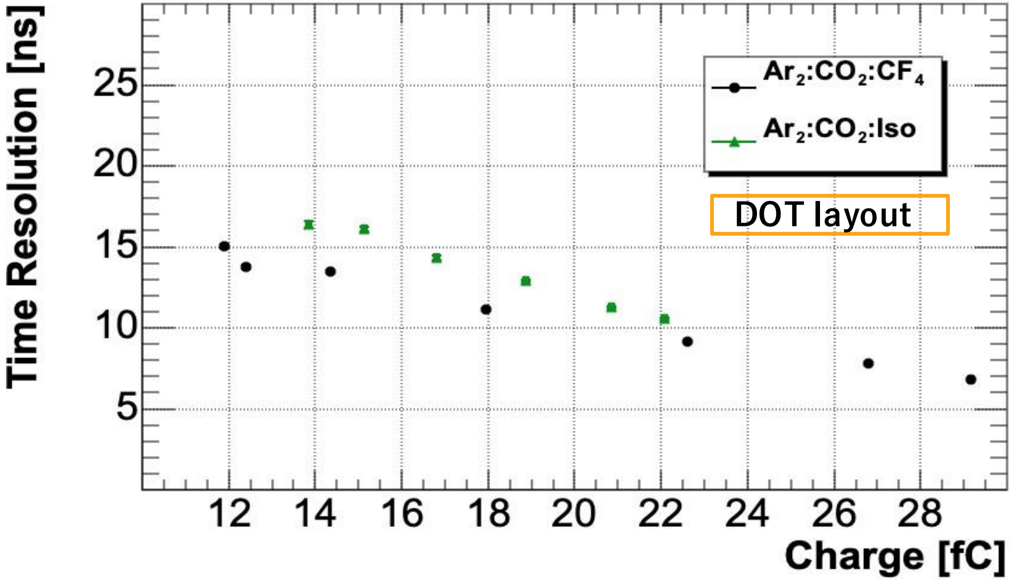




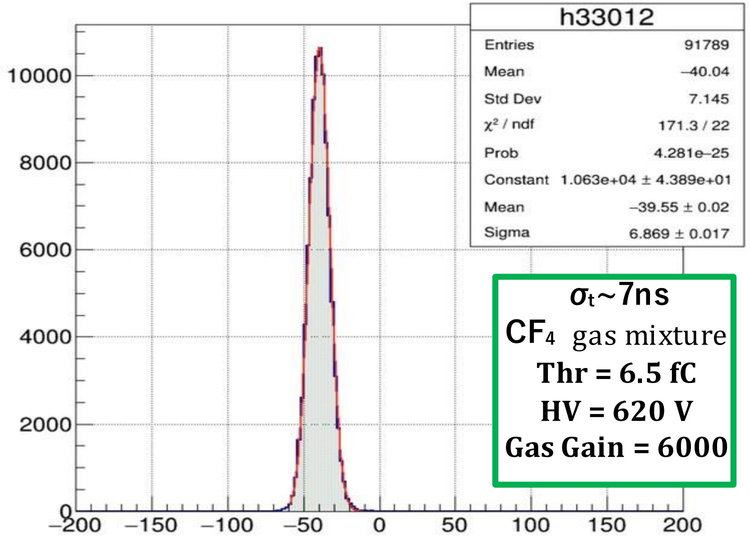


PEP DOT – time performance (preliminary)

FATIC 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 **preliminary version of the FATIC chip** (developed by Bari Group) in the framework of the R&D for the **LHCb-Muon upgrade**. A new **test beam foreseen next Nov. '24** with **an updated version of the ASIC**, aiming to reduce the **FEE thr down 3 – 3.5 fC**

Manufacturing high-rate layouts

The **PEP-DOT layout is a rigid-flex PCB** using an **SBU technology-based PCB**, that is **compatible with standard industrial processes**.

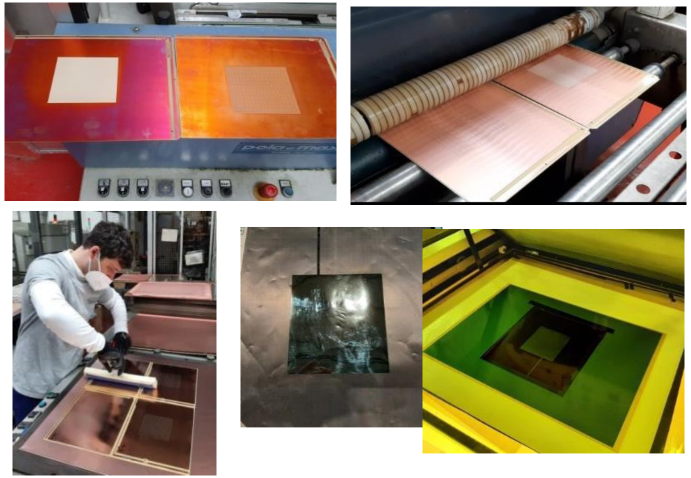
The **ELTOS** is the industrial partner **involved in the manufacturing of the µ-RWELL**.

This presents a significant advantage, in view **of large-scale production for the Muon upgrade at LHCb.**

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

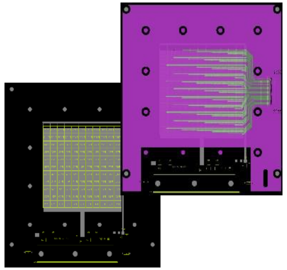
The Company has a **large experience in the construction of MPGDs,** including technologies such as **Thick-GEM (THGEM)** and **MicroMegas**.

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.**



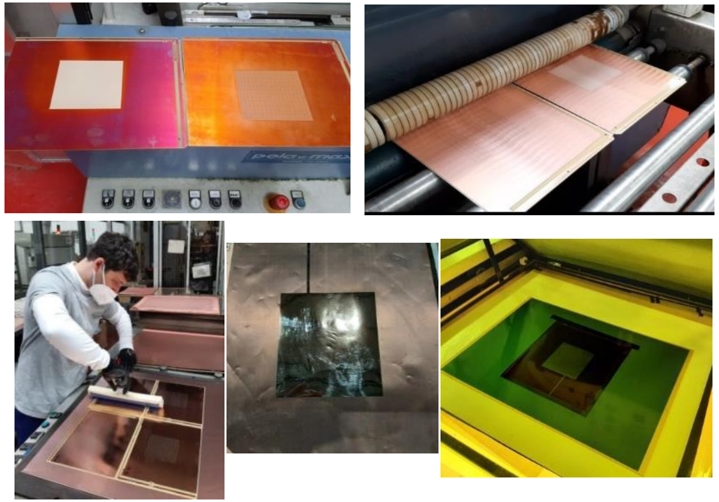
Detector Manufacturing flow chart

LAYOUT design



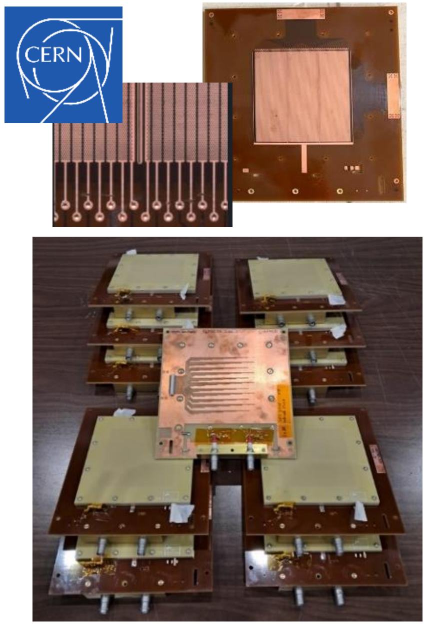
DLC foil production

PCB production



Feedback from tests

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

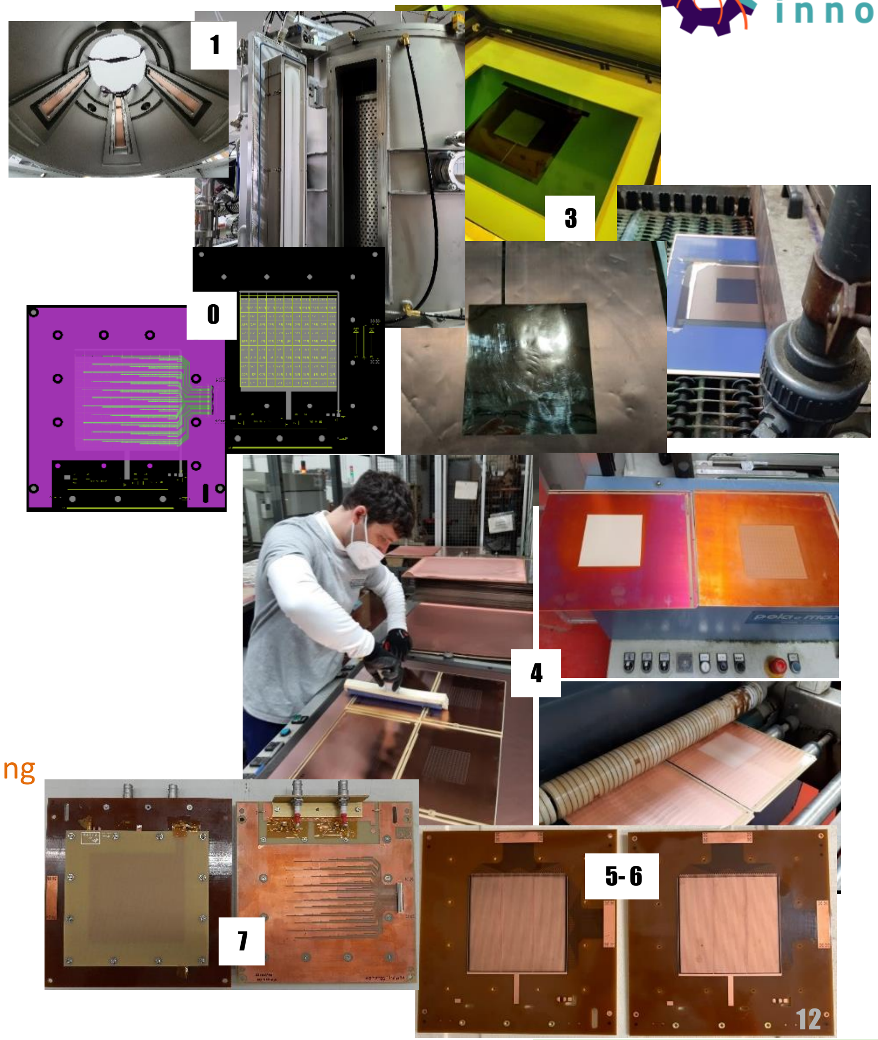
Step 3 – DLC patterning by **ELTOS**
- photo-resist → patterning with BRUSHING-machine

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

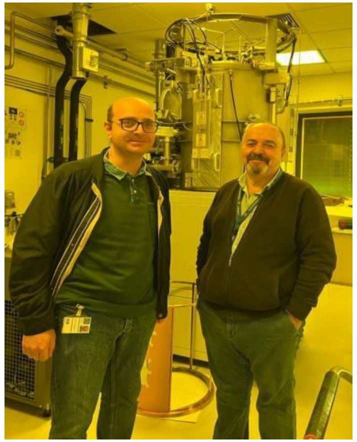
Step 5 – Top copper patterning by **CERN**
- Cu amplification holes image and HV connections by Cu etching

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 **1.7m×0.6m**
- **Rigid substrates** up to **0.2m×0.6m**

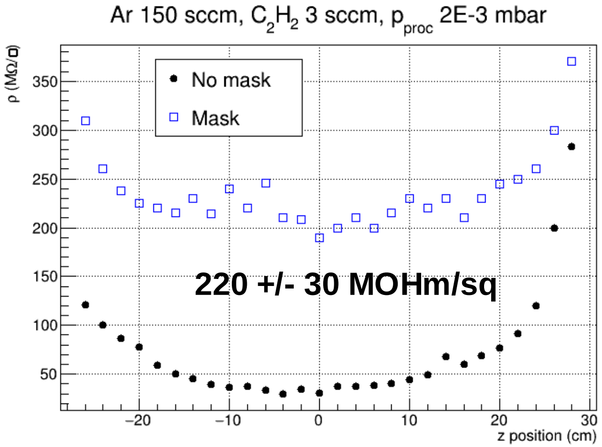
In **2023,** the activity on CID focused on the **tuning** of the **machine on small foils:** very **good** results in terms of **reproducibility and uniformity.**

In **2024**, the challenge is the **sputtering of large foils.**

C.I.D.

The graphite target

The three external cathodes



220 +/- 30 MOHm/sq

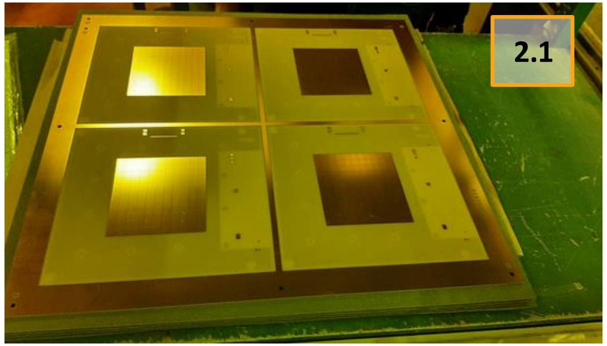
Detector manufacturing at ELTOS (I)

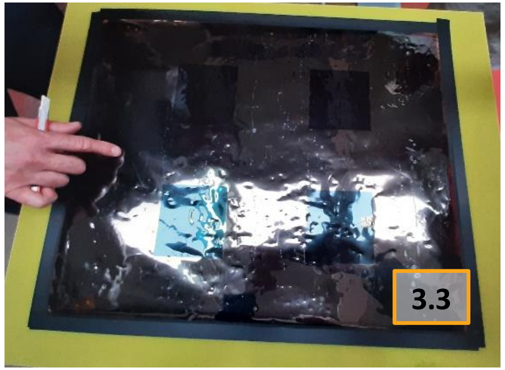
Step 2 (@ ELTOS)

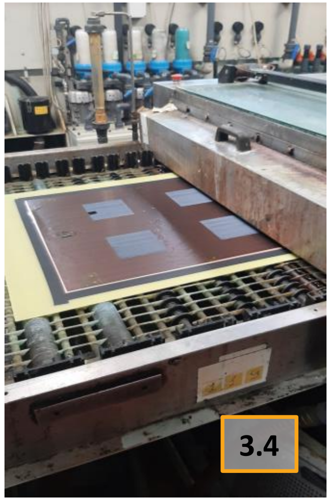
1) **PCB production**

Step 3 (@ ELTOS)

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







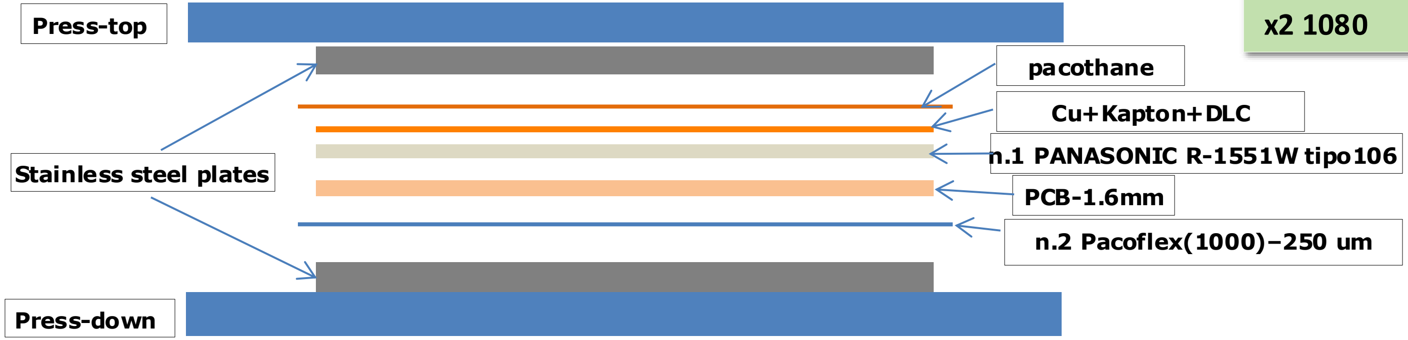
Detector manufacturing at ELTOS (II)

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



Press-top

Stainless steel plates

pacothane

Cu+Kapton+DLC

n.1 PANASONIC R-1551W tipo106

PCB-1.6mm

n.2 Pacoflex(1000)−250 um

Press-down

Electrical Hot Cleaning

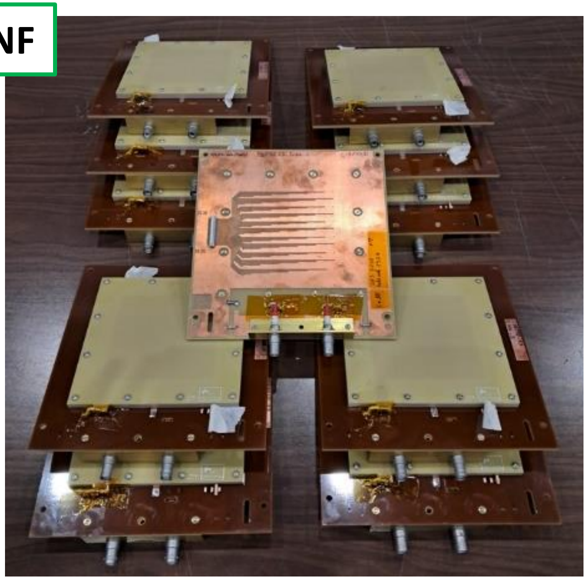
@ CERN

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

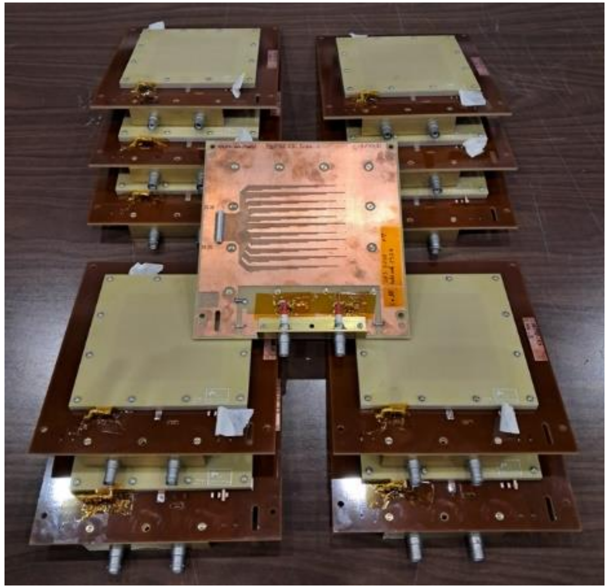


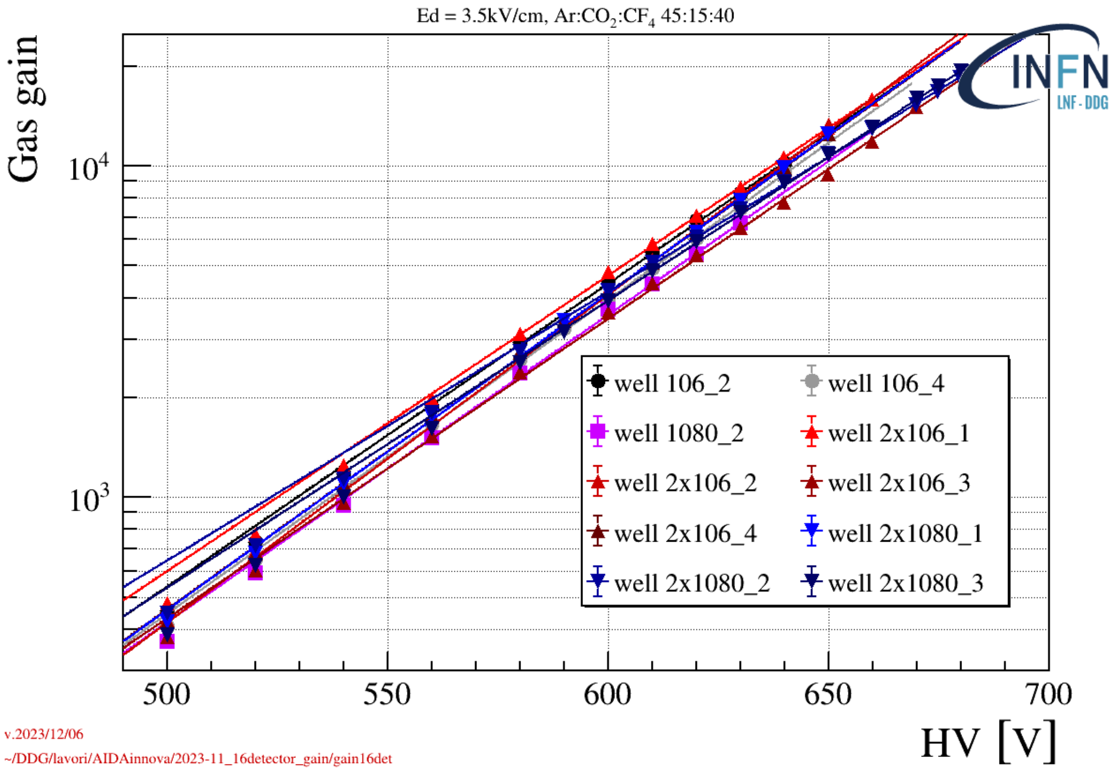
The 16 co-produced prototypes have been tested with X-rays:

- **15/16 are fine**
- **1/16 needs re-cleaning**

Production yield > 93%

Co-production pilot results (I)

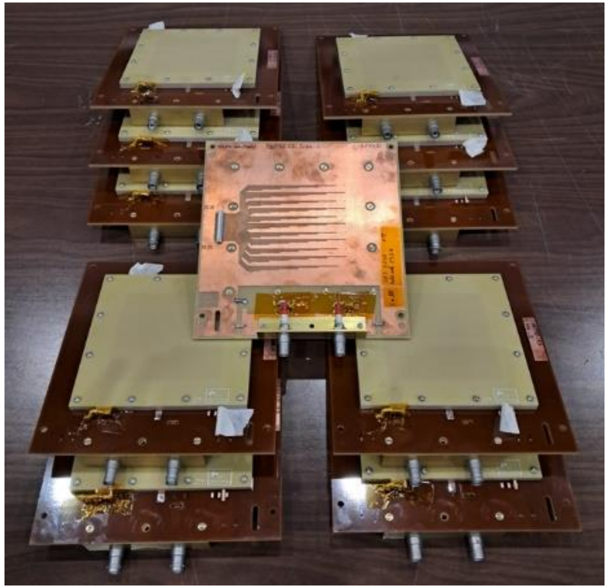


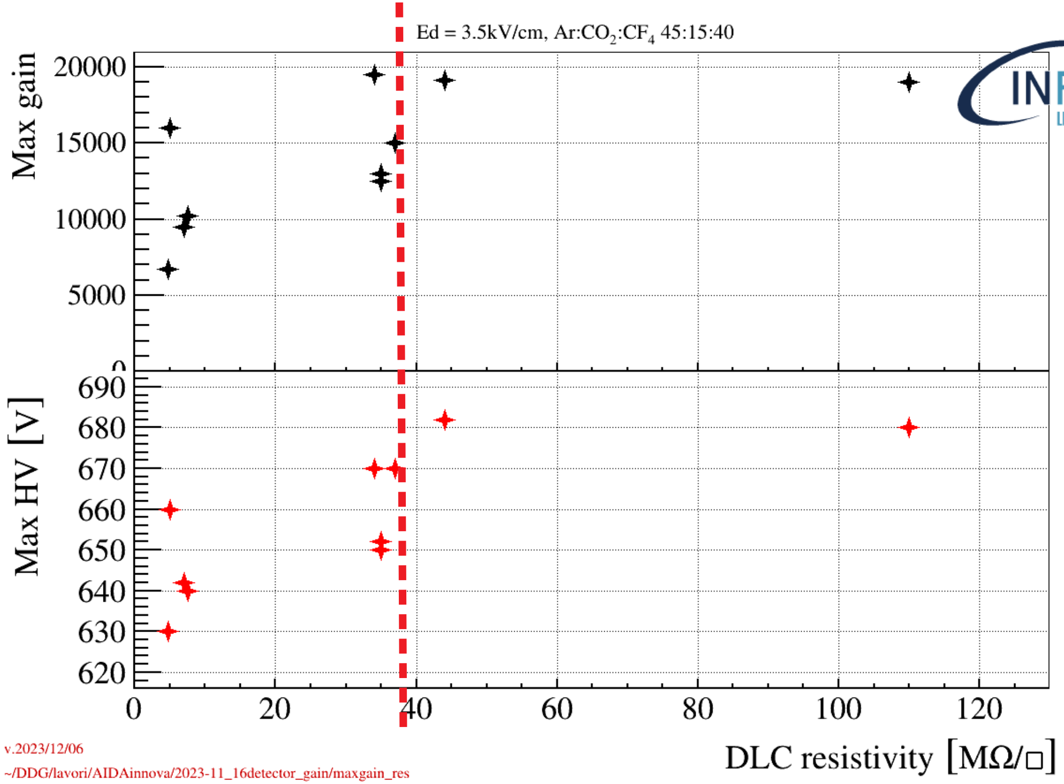


Characterized with **X-ray gun** → **Gas gain** measurement

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

Co-production pilot results (II)

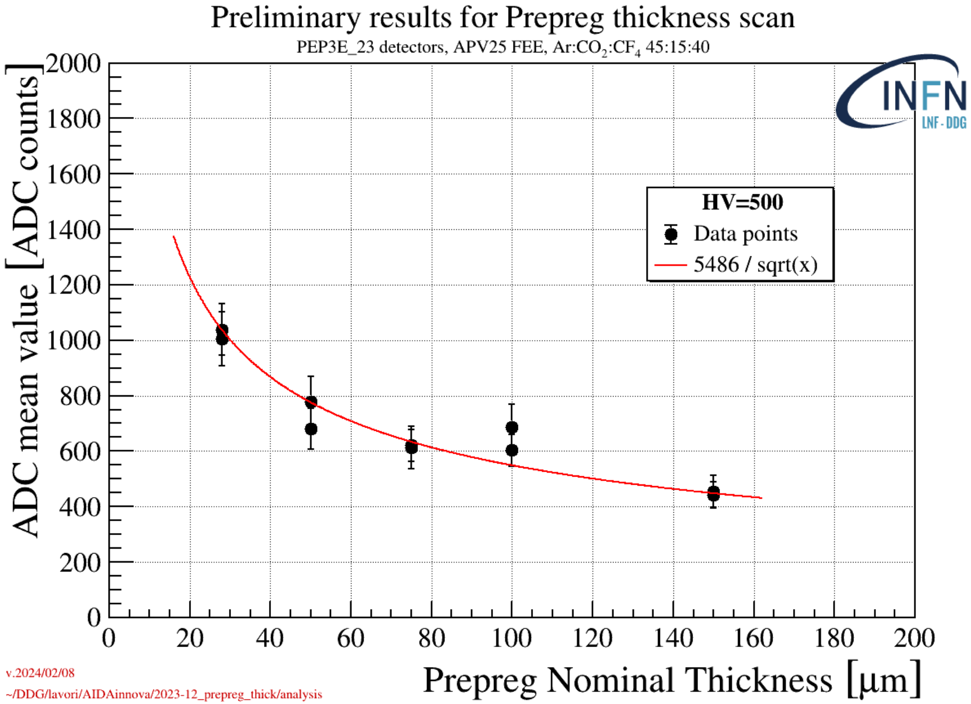




- **16** co-produced protos have been delivered and tested
- **10/16 (LNF) + 5/16 (CERN)** are fine
- **1/16 should be re-cleaned**

The **gain** is maximized for **ρ ≥ 30 - 40 MOhm/square**

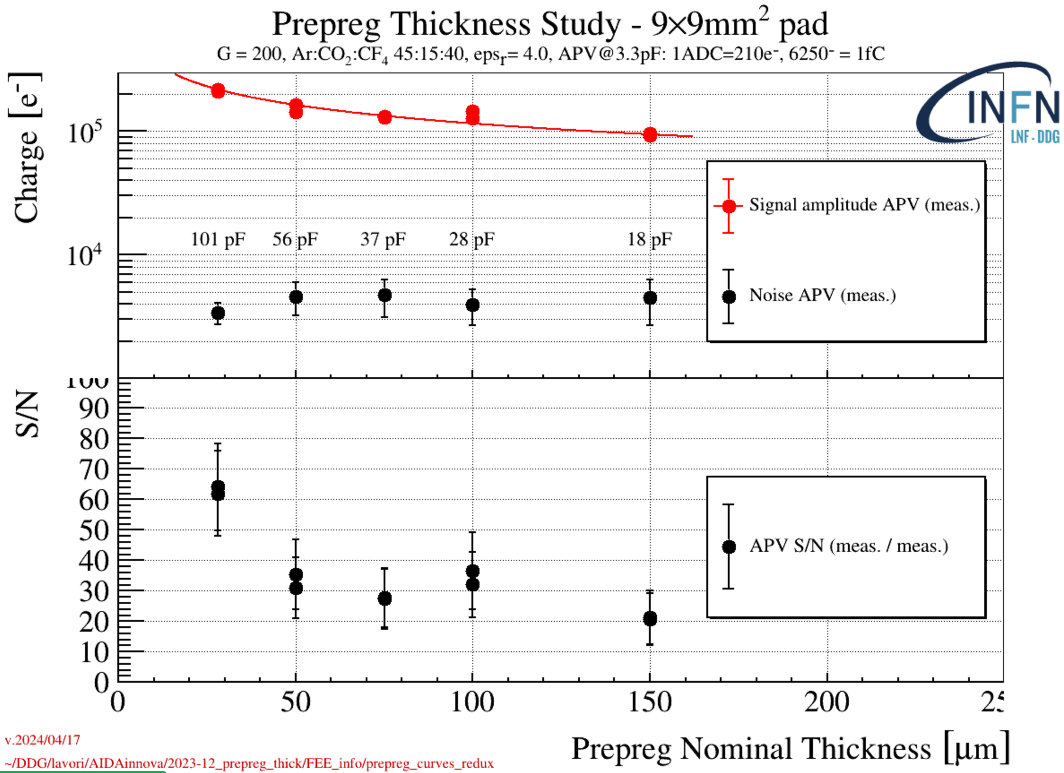
Prepreg thickness optimization



Preliminary results for Prepreg thickness scan

PEP3E_23 detectors, APV25 FEE, $Ar:CO_2:CF_4$ 45:15:40

v.2024/02/08
~/DDG/lavori/AIDAinnova/2023-12_prepreg_thick/analysis



Prepreg Thickness Study - 9×9mm^2 pad

G = 200, $Ar:CO_2:CF_4$ 45:15:40, eps_r = 4.0, APV@3.3pF: 1ADC=210e$^-$, 6250$^-$ = 1fC

v.2024/04/17
~/DDG/lavori/AIDAinnova/2023-12_prepreg_thick/FEE_info/prepreg_curves_redux

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

Summary

The **R&D** on **high-rate layouts for the LHCb upgrade** has been completed:

- the **PEP-DOT** layout shows good performance**:** gain of **10^4, 98%** efficiency, **> 10 MHz/cm^2**, **7ns** time resolution
- **General parameters** of the detector have been set to **maximize stability and gain**:
    - **$\rho \geq 50$ MOhm/square, DOCA = 0.5 – 0.6mm (dead-zone ~ 1.3mm)**
    - **prepreg thickness ~ 28µm**
    - Amplification stage optimization by reducing the **well pitch:** 140µm, 110µm, 90µm
- **Large size**:
    - **M2R1-LHCb (25x30 cm^2** active area): **delivered May '24**, X-ray characterization in June/July, test beam in **Nov. '24**.
    - **M2R2-LHCb (30x70 cm^2 active area): design** by the end of **2024, production** beginning in **2025**

The **detector manufacturing process** is nearly finalized:

- Several construction **steps are performed by ELTOS**
- **Detector finalization** (Kapton etching, electrical hot cleaning, etc.) is **carried out at CERN**
- The **DLC sputtering machine**, C.I.D., **will provide the base material**, once the sputtering parameters are optimized


429,10μm
242,77μm
143,13μm
413,46μm
766,60μm
1116,68μm
1305,23μm

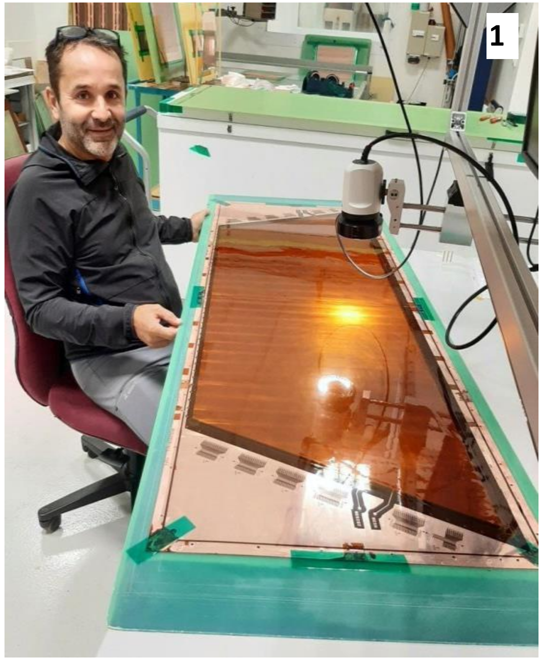
Many thanks

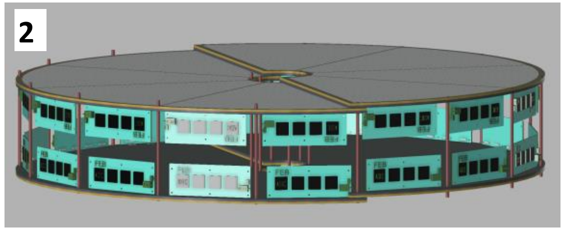
SPARE SLIDES

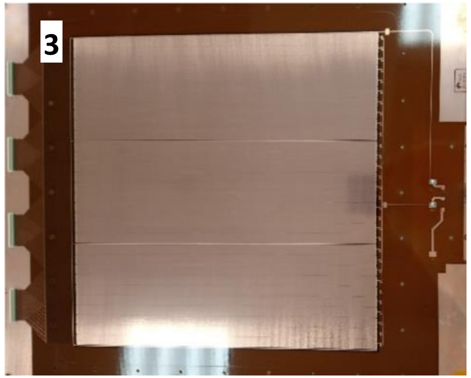
Technology spread

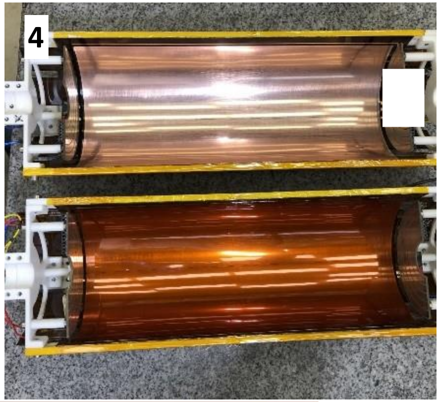
In the last years there has been a significant spread of the technology among several research groups working on Nuclear and Sub-Nuclear experiments

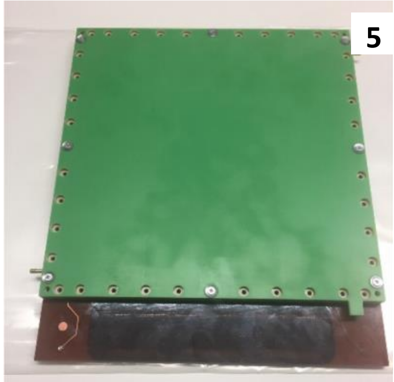
1. **CLAS12 @ JLAB (USA):** the upgrade of the muon spectrometer
2. **EPIC @EIC (BNL - USA):** endcap tracker disks based on a hybrid GEM+μRWELL technology
3. **X17 @ n_TOF EAR2 (CERN)**:TPC with a μRWELL based amplification stage, for the detection of the X17 boson
4. **TACTIC @ YORK Univ. (UK):** radial 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


1

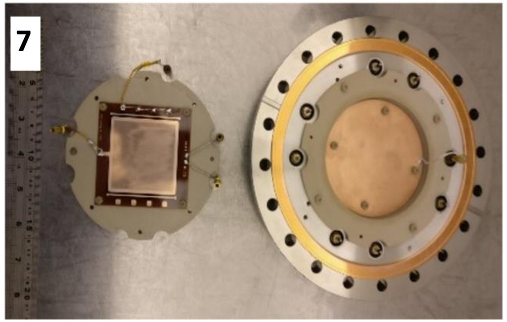

2


3


4


5


6


7

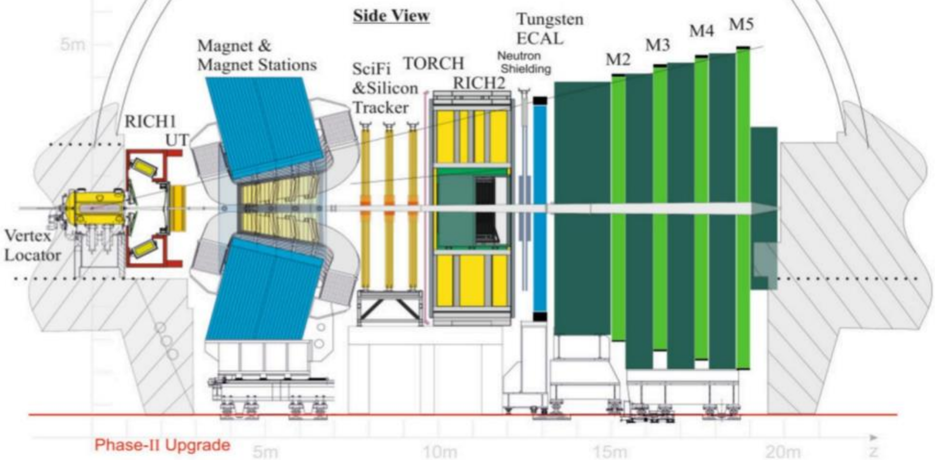
μ-RWELL at LHCb

Inner region @ Run5 – Run6 **detector requirements**[1]

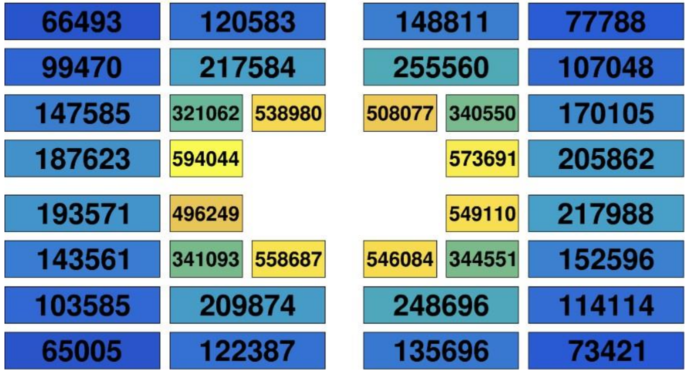
- Rate up to **1 MHz/cm^2** on detector single gap
- Rate up to **700 kHz** per electronic channel
- **Efficiency quadrigap >=99%** within a BX (25 ns)
- Accumulated charge in 10y at M2R1 up to **1C/cm^2**

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

- **R1÷R2: 576 detectors,** size 30x25 to 74x31 cm^2, **90 m^2** detectors **– 130 m^2** DLC



Chamber rates on M2R1-R2 (Hz/cm^2)



66493	120583		148811		77788
99470	217584		255560		107048
147585	321062	538980	508077	340550	170105
187623	594044			573691	205862
193571	496249			549110	217988
143561	341093	558687	546084	344551	152596
103585	209874		248696		114114
65005	122387		135696		73421

[1] CERN-LHCC-2021-012; LHCB-TDR-023 http://cds.cern.ch/record/2776420?ln=it

Spot Effect for SRL – Manufacturer plot

From the model of the resistive stage of a µ-RWELL:

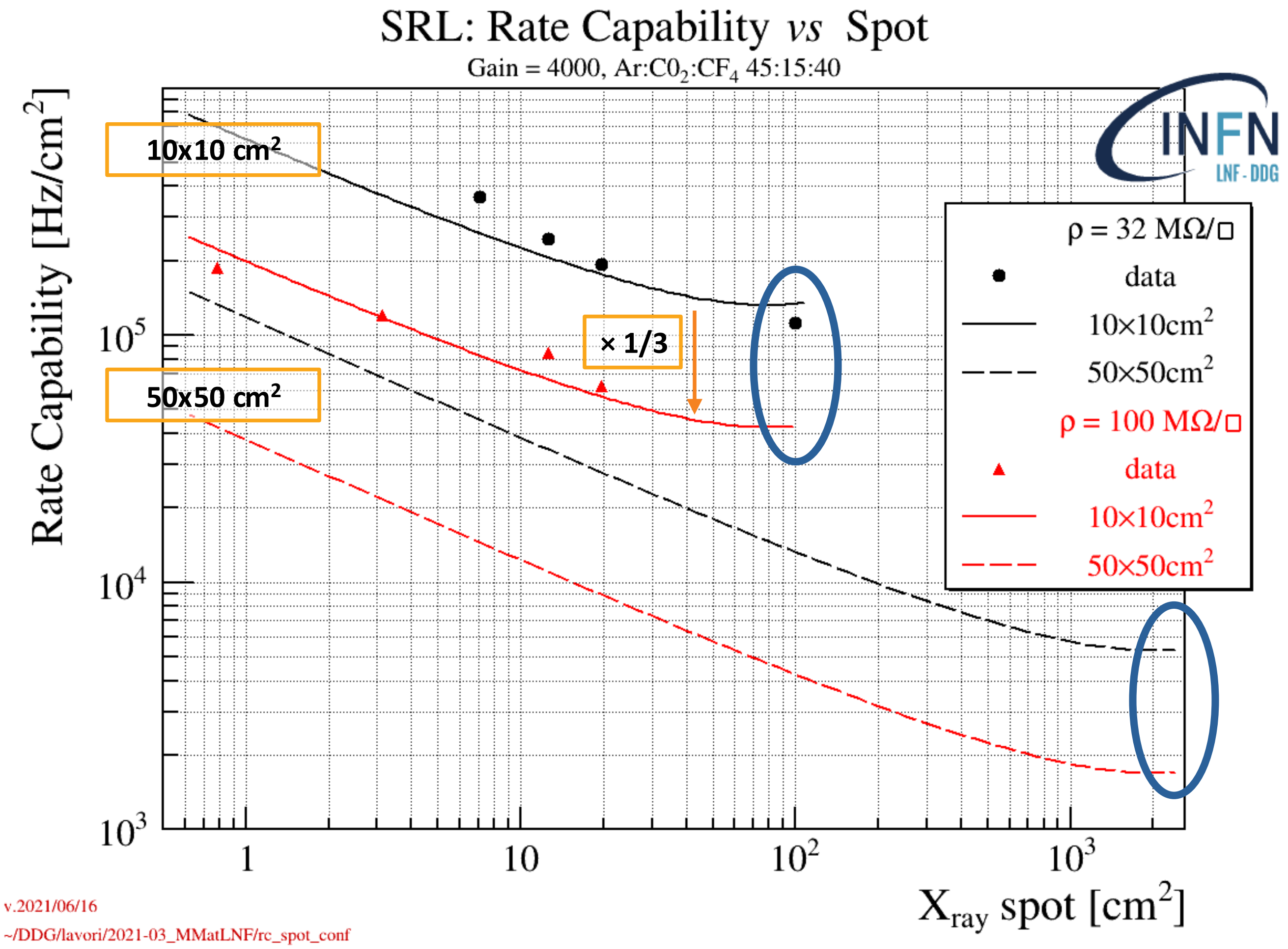
1. detectors with **same size** but **different resistivity** exhibit a **rate capability** scaling as the **inverse of their resistivity.**

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

3. By using a **DLC ground sectoring every 10 cm**, **large (50x50 cm²) detectors** could achieve **rate capability** up to **100kHz/cm²** (with X-ray)

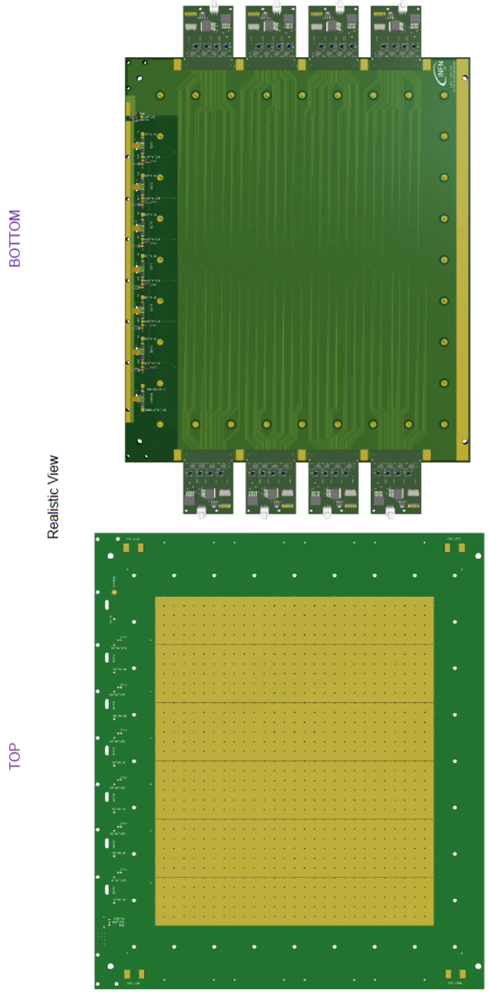
$$\phi_{90\%} \approx \frac{1}{\rho_S \cdot r\,(d - r/2)}$$

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

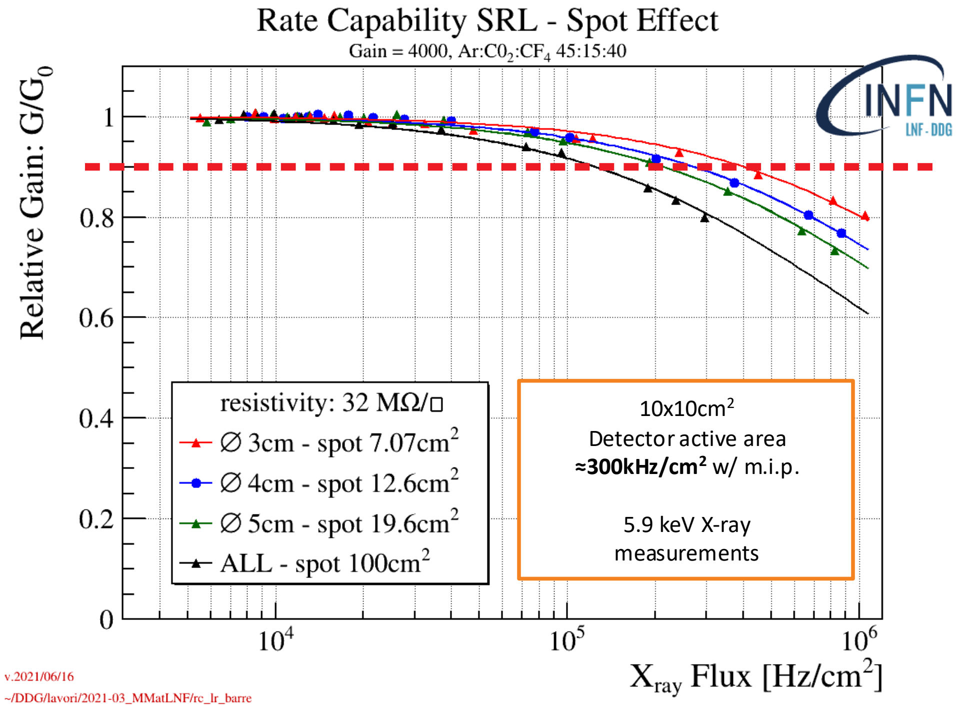


High-rate μ-RWELL – R&D plans

- ✓ M2R1 design – delivered May 2024
- M2R1 X-ray characterization (June- July 2024)
- Electronic integration, FATIC3 chip based (Sept. 2024)
- Test beam (NA – H8C CERN or T10-PS) M2R1 with FATIC3 (Nov. 2024)
- R&D plans:
    - amplification stage optimization (gain vs well-pitch)
    - optimization coupling DLC_foil - R/out PCB
    - test of Hybrid layout → G-RWELL
    - electrical cleaning optimization (w/Rui)
    - irradiation study a GIF++ (w/CERN Gas Group)



The SRL resistive model



10x10cm^2
Detector active area
≈**300kHz/cm²** w/ m.i.p.

5.9 keV X-ray
measurements

v.2021/06/16
~/DDG/lavori/2021-03_MMatLNF/rc_lr_barre

FLOW:

DATA

$\frac{G}{G_0} \to p_0$ →

Extrapolation

$\Omega \to \phi_{90\%}$

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

Prediction

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

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

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

← $\Delta V_{drop\ 10\%}$
from the gain
measurement

Validation

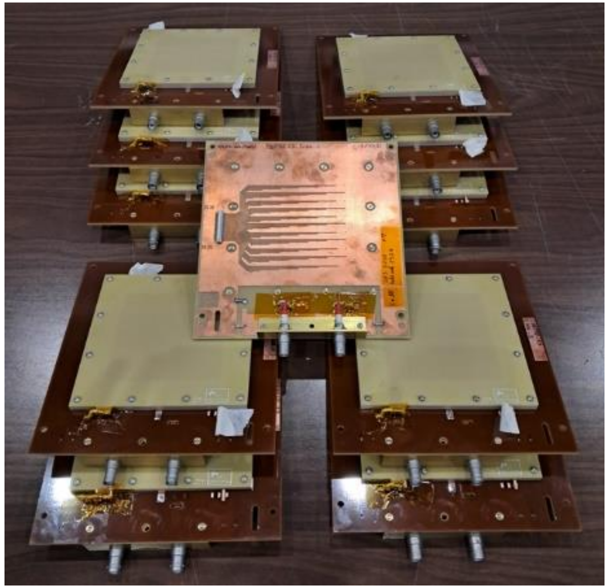
$$\frac{G}{G_0} = \frac{-1+\sqrt{1+4p_0\phi}}{2p_0\phi}$$

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

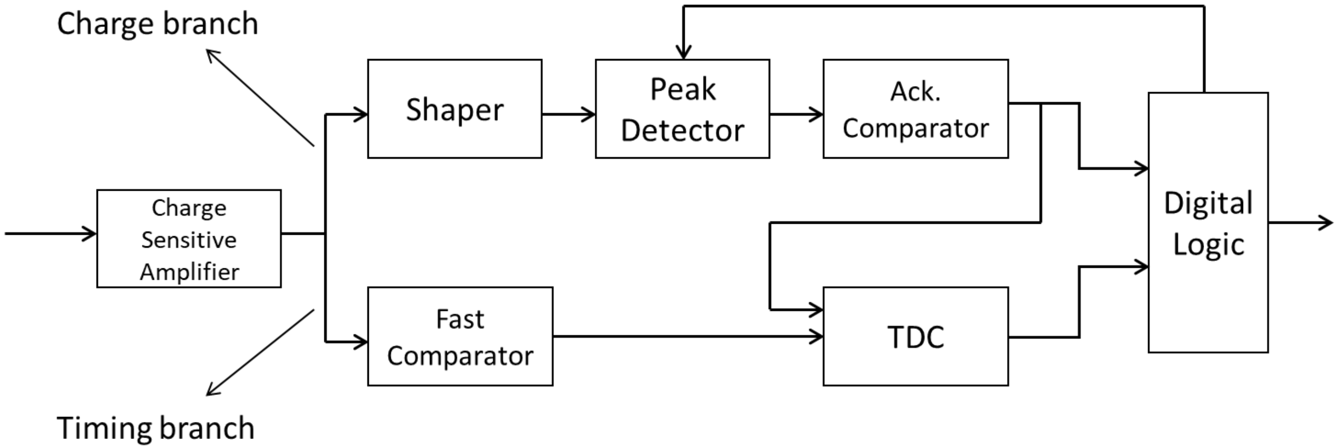
Co-production pilot test



Detector #	Prepreg type	DLC resistivity	Production status	Max HV/Gain	comments
106_1	1x 106		Cleaning		@ CERN
106_2	1x 106	7.5	Delivered	640/10000	
106_3	1x 106		Cleaning		@ CERN
106_4	1x 106	7	Delivered	640/9500	
1080_1	1x1080		Cleaning		@ CERN
1080_2	1x1080	4.8	Delivered	630/6700	
1080_3	1x1080	5	Delivered	n.a.	To be re-cleaned
1080_4	1x1080		Cleaning		@ CERN
2x106_1	2x106	35	Delivered	660/16000	
2x106_2	2x106	37	Delivered	650/13000	
2x106_3	2x106	35	Delivered	670/15000	
2x106_4	2x106	34	Delivered	650/12500	
2x1080_1	2x1080	33	Delivered	670/19500	
2x1080_2	2x1080	110	Delivered	680/19000	
2x1080_3	2x1080	44	Delivered	680/19000	
2x1080_4	2x1080		Cleaning		@ CERN

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

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

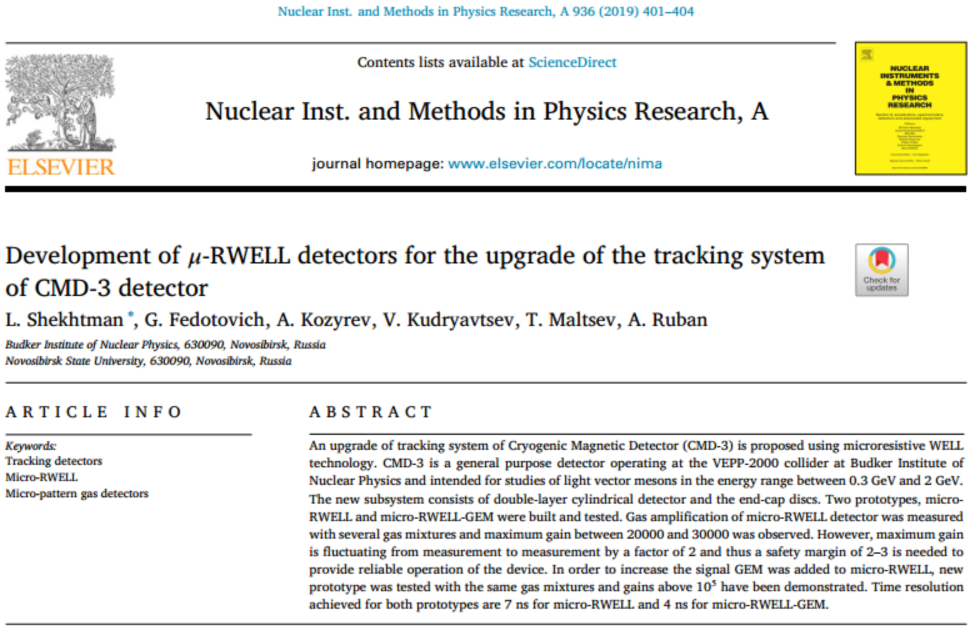
Timing branch:

- ✓ 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

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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

L. Shekhtman *, G. Fedotovich, A. Kozyrev, V. Kudryavtsev, T. Maltsev, A. Ruban

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
Novosibirsk State University, 630090, Novosibirsk, Russia

ARTICLE INFO

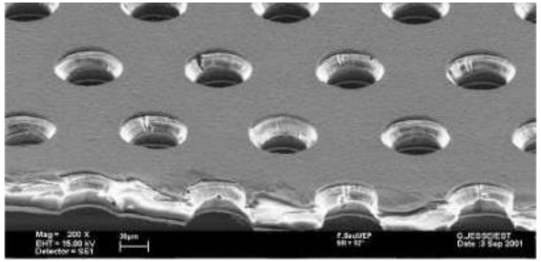
Keywords:
Tracking detectors
Micro-RWELL
Micro-pattern gas detectors

ABSTRACT

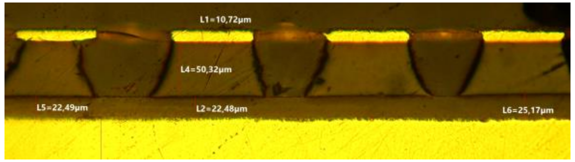
An upgrade of tracking system of Cryogenic Magnetic Detector (CMD-3) is proposed using microresistive WELL technology. CMD-3 is a general purpose detector operating at the VEPP-2000 collider at Budker Institute of Nuclear Physics and intended for studies of light vector mesons in the energy range between 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**



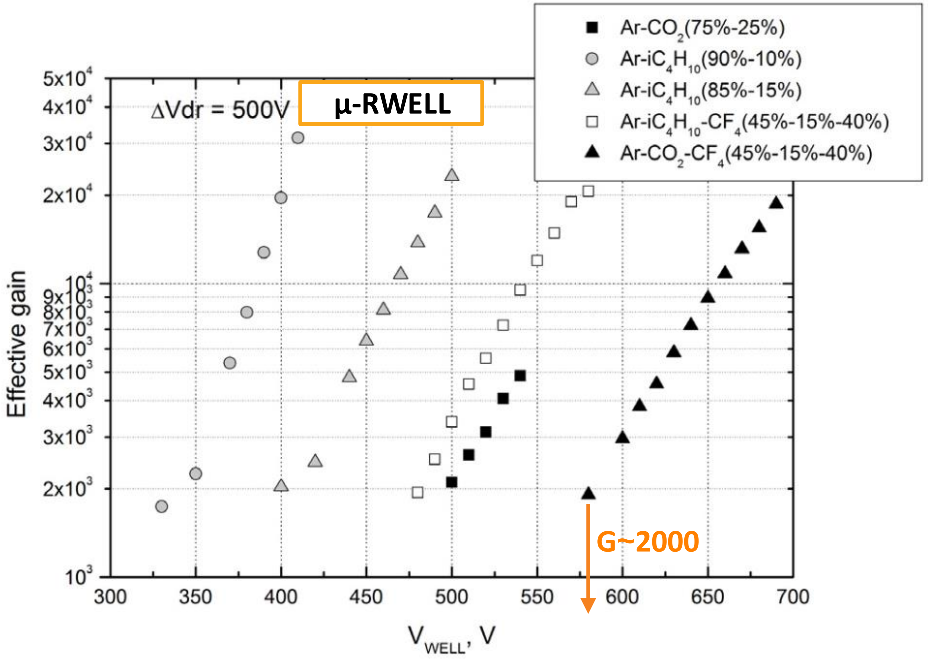
Transfer Gap: Shekhtman **3mm** – LNF+Roma2 **3mm**



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).

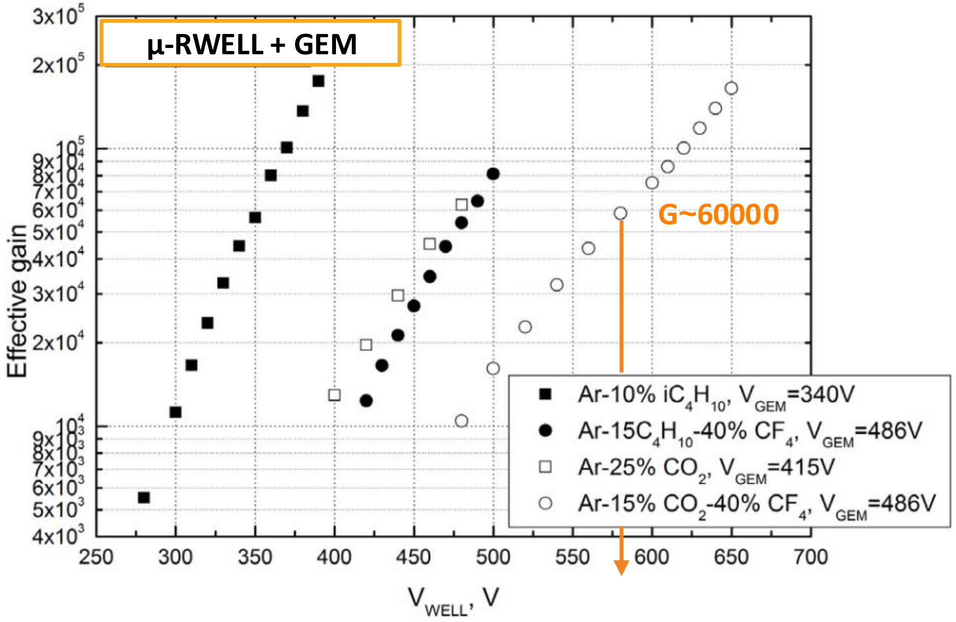
μ-RWELL + GEM: gas gain



μ-RWELL

G~2000

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.



μ-RWELL + GEM

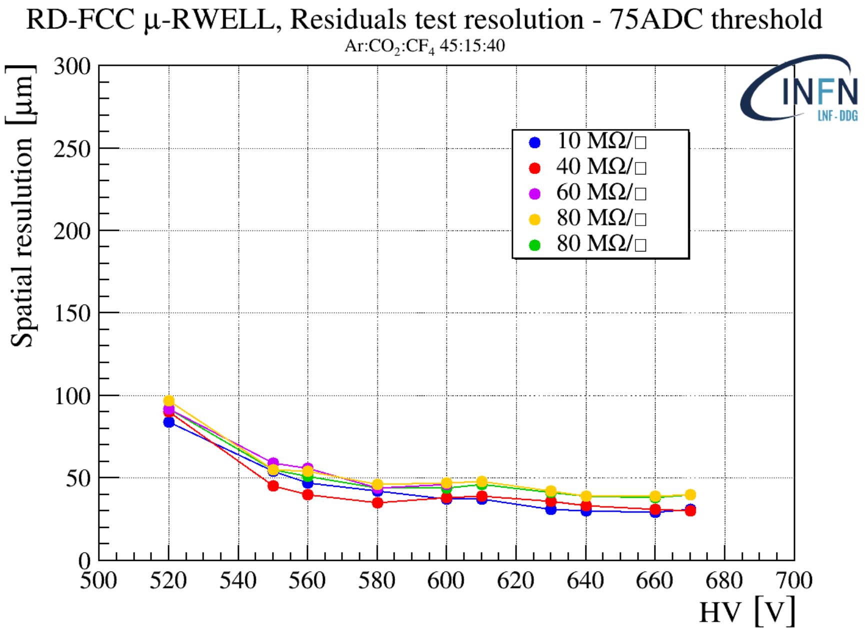
G~60000

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.

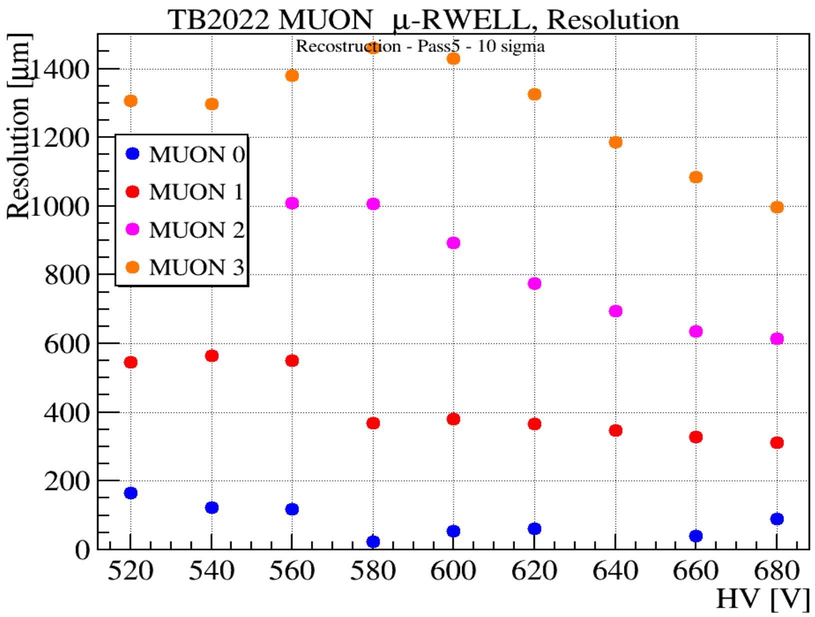
L. Shekhtman, Nuclear Inst. and Methods in Physics Research, A 936 (2019) 401–404

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.

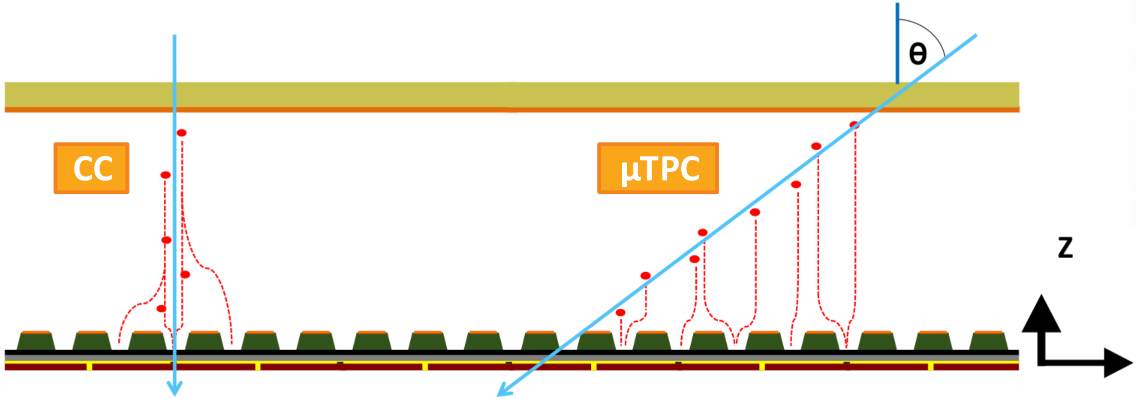
Increasing the R/O pitch will result in a **reduction of the spatial resolution**

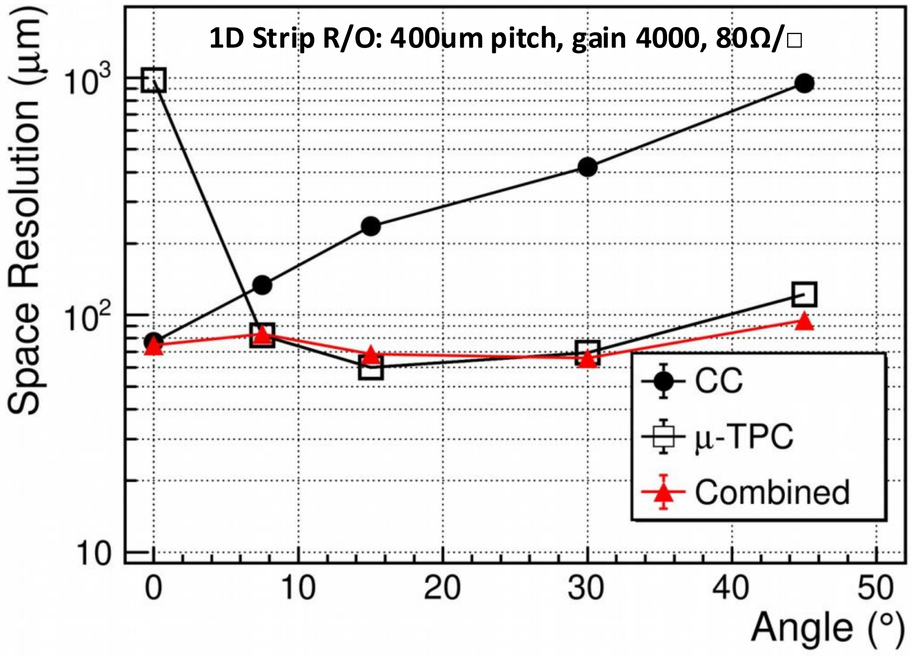
In collaboration with G. Cibinetto, R. Farinelli, L. Lavezzi, M. Gramigna, P. Giacomelli, E. De Lucia, D. Domenci, A. D'angelo, M. Bondi, M. Scodeggio, I. Garzia, M. Melindi

1-D tracking (inclined tracks)

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

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





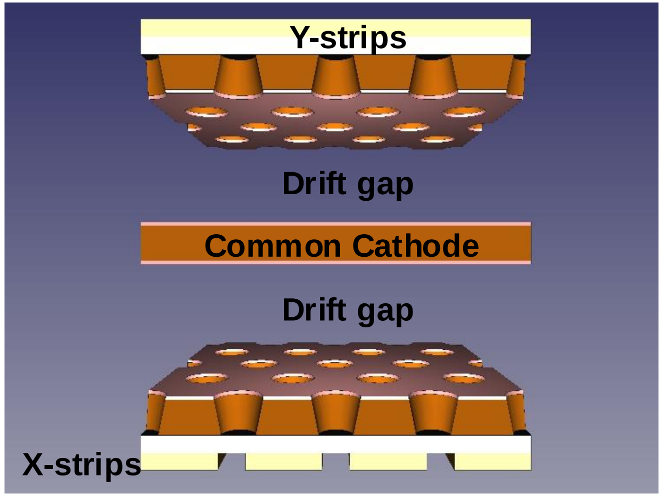
Combinig the CC and µTPC reconstruction (through a wheighted average) **a resolution well below 100 µm** could be reached over a wide incidence angle range.

[1] introduced for ATLAS MMs by T. Alexopoulos

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

2-D Tracking layouts

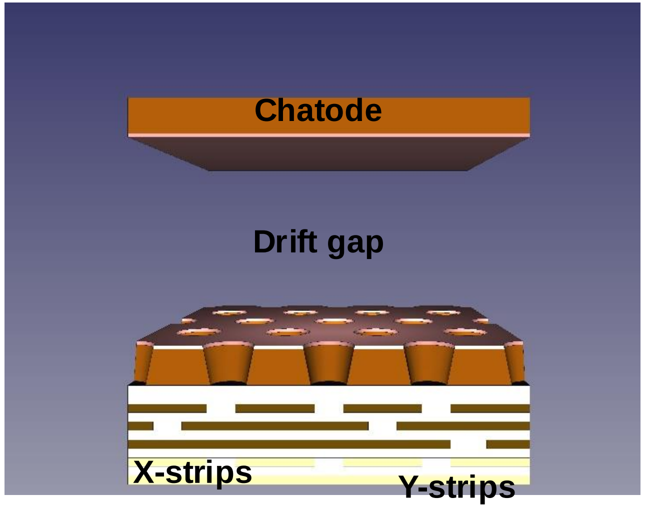
N.2 u-RWELLs 1D (2⊗1D)



Operation at **lower gas gain** wrt the «COMPASS» R/out (X-Y r/out decoupled)

Tested @ TB2022

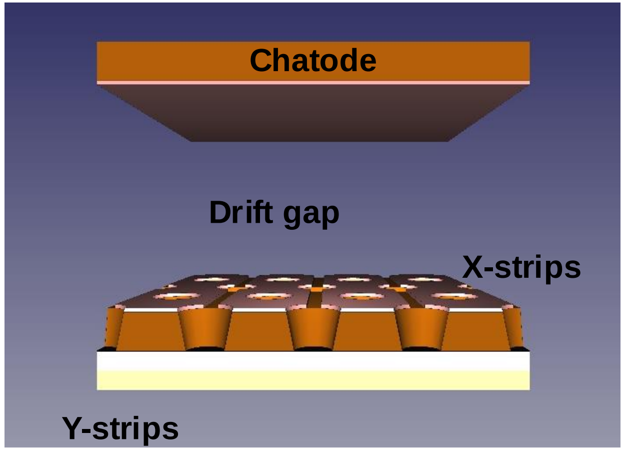
u-RWELL - Capacitive Sharing r/out



The **charge sharing performed through the capacitive coupling between a stack of layers** of pads and **the r/out board.**
Reduce the FEE channels, but the **total charge is divided between the X & Y r/out.**

Tested @ TB2023

u-RWELL TOP r/out

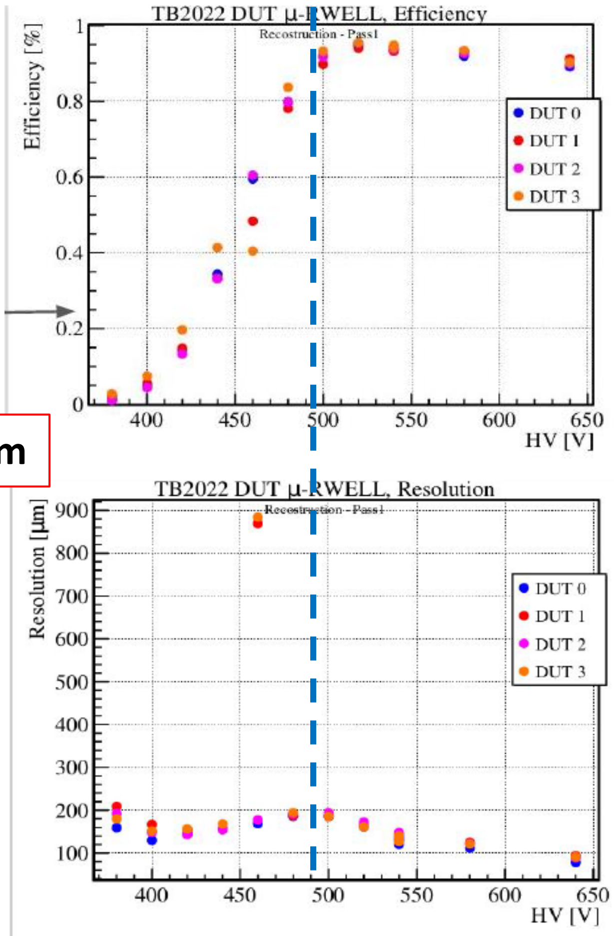


The **TOP-readout layout** allows to work at **low gas gain** wrt the «COMPASS» r/out (X-Y r/out decoupled).

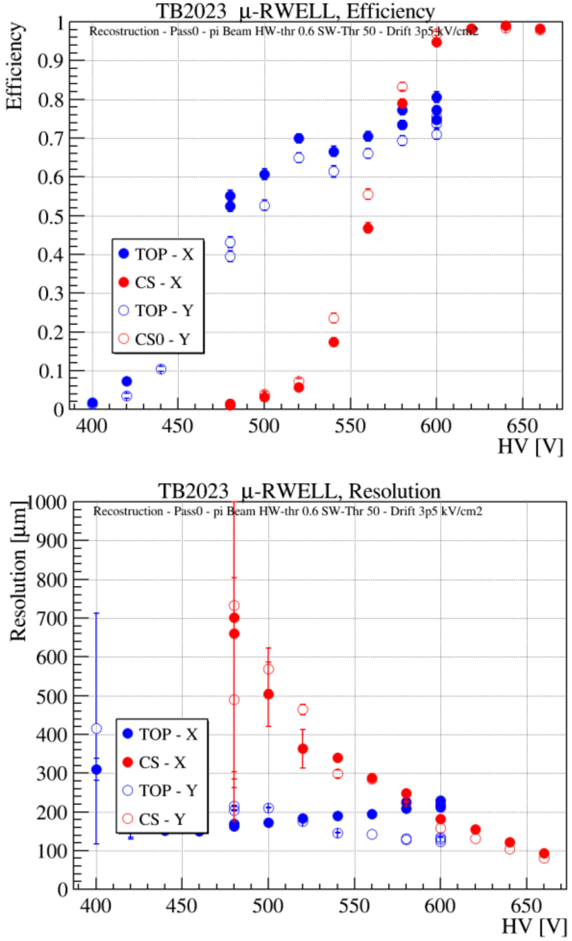
X coordinate on the TOP of the amplification stage introduces **dead zone in the active area.**

Tested @ TB2023

Tracking performance



1D Pitch = 0.8 mm



CS pitch 1.2 mm

- due to the charge spread the working point is shifted to high voltage/gain
- Spatial resolution improves at high gain reaching 150 um with a strip pitch of 1.2 mm

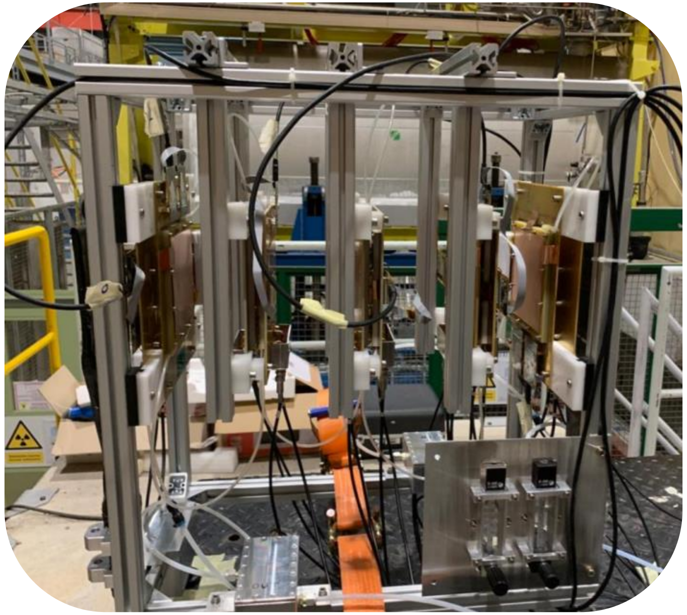
Top-r/out pitch 0.8 mm

- low-voltage/gain operation but low efficiency level due to the geometrical dead zone on the segmented amplification stage

Tracking: R&D plans

R&D on tracking µ-RWELL for muons systems at future colliders

- Finalization of the analysis of the 2022-2023 beam tests:
    - 2 ⊗ 1D layouts
    - 2D → 1D ⊕ top-readout
    - 2D w/Capacitive Sharing
- R&D plans:
    - amplification stage optimization (gain vs well-pitch)
    - new PCB-RWELL multi-task layout (1D, 2D, Hybrid layouts)
    - hybrid µ-RWELL → GEM ⊕ RWELL
    - TB-2024 (sinergy with INFN - **Roma2**)

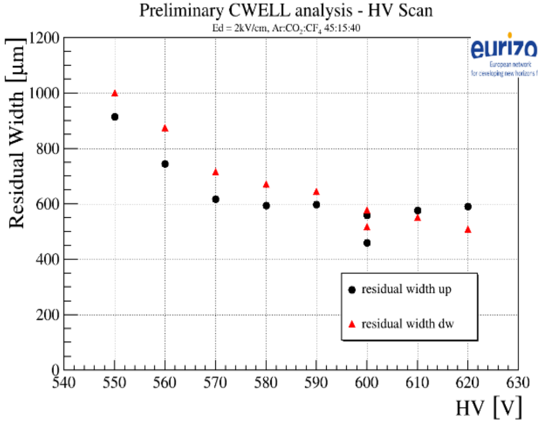


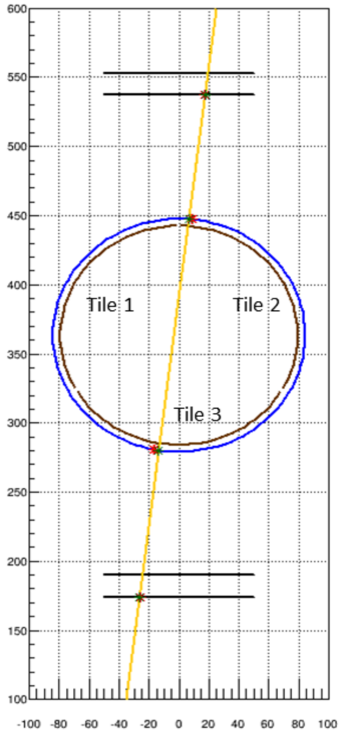
Low X_0 Cylindrical µ-RWELL

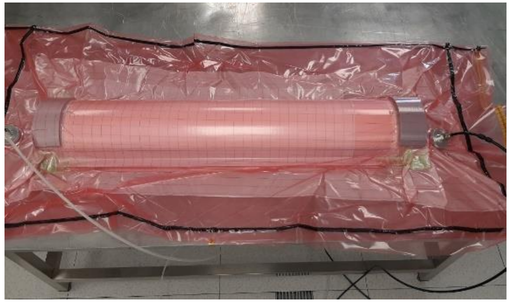
Exploiting the **flexible characteristic of the amplification stage** of the µ-RWELL, as well as the readout (to which it is coupled through the resistive DLC stage), we developed **a low-mass (0.6% X0) modular Inner Tracker for low-energy positron-electron colliders**, exploiting the **innovative Cylindrical µ-RWELL (C-RWELL) technology.**

Three roof-tile layout

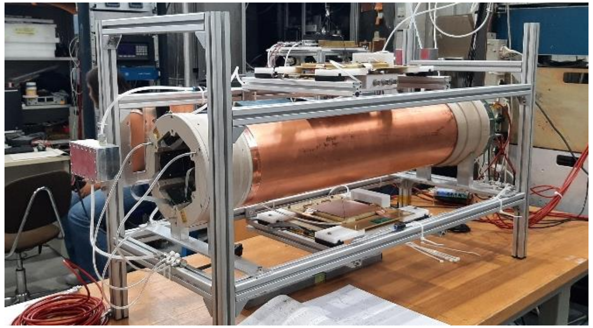
Roof-tiles assembly







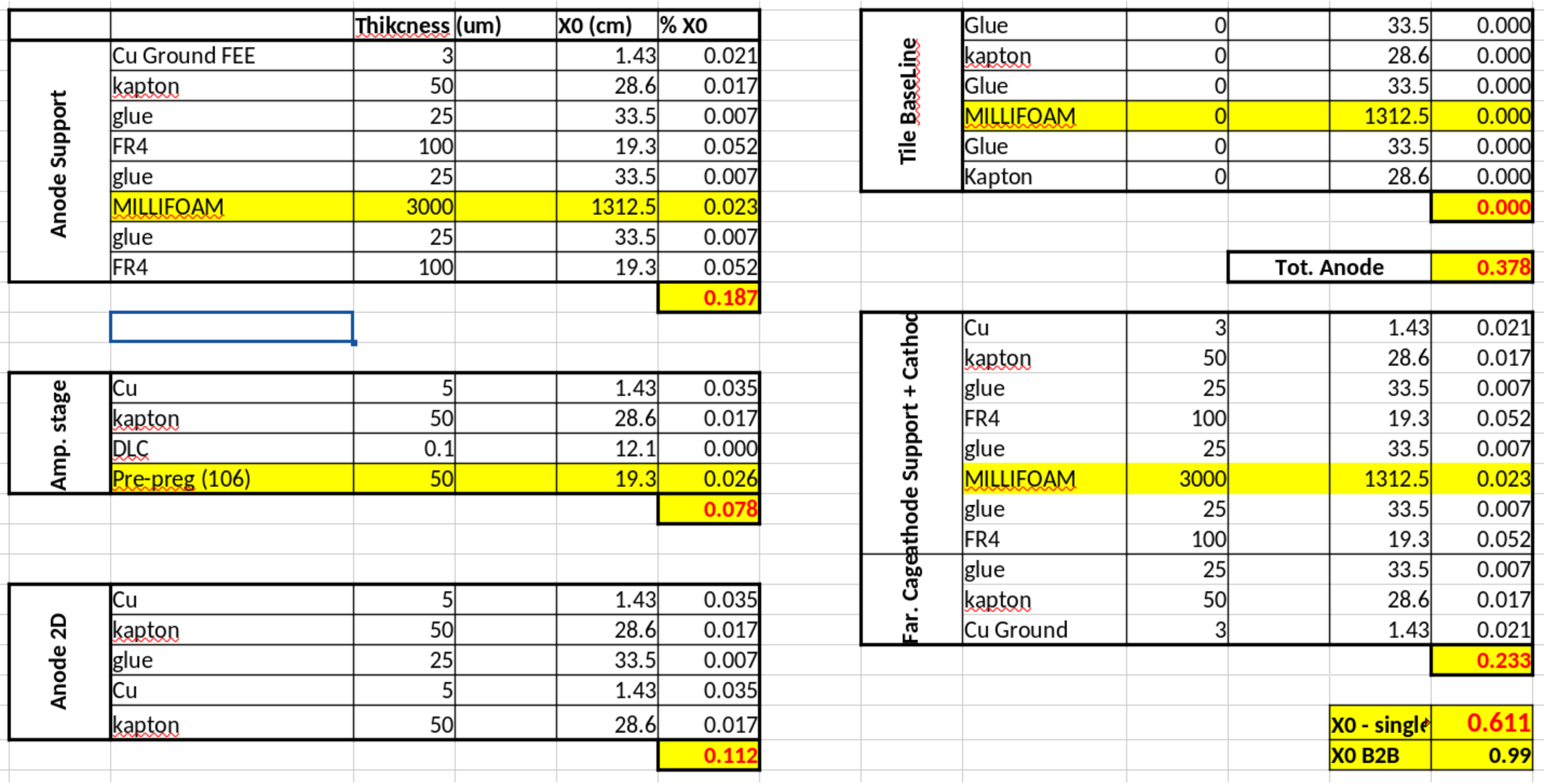
Vacuum bag technology



C-RWELL test with cosmics

Dinner with Huong

Low Mass µ-RWELL



		Thikcness (um)	X0 (cm)	% X0
Anode Support	Cu Ground FEE	3	1.43	0.021
	kapton	50	28.6	0.017
	glue	25	33.5	0.007
	FR4	100	19.3	0.052
	glue	25	33.5	0.007
	MILLIFOAM	3000	1312.5	0.023
	glue	25	33.5	0.007
	FR4	100	19.3	0.052
				0.187

Amp. stage	Cu	5	1.43	0.035
	kapton	50	28.6	0.017
	DLC	0.1	12.1	0.000
	Pre-preg (106)	50	19.3	0.026
				0.078

Anode 2D	Cu	5	1.43	0.035
	kapton	50	28.6	0.017
	glue	25	33.5	0.007
	Cu	5	1.43	0.035
	kapton	50	28.6	0.017
				0.112

Tile BaseLine	Glue	0	33.5	0.000
	kapton	0	28.6	0.000
	Glue	0	33.5	0.000
	MILLIFOAM	0	1312.5	0.000
	Glue	0	33.5	0.000
	Kapton	0	28.6	0.000
				0.000

Tot. Anode	0.378

Cathode Support + Cathod	Cu	3	1.43	0.021
	kapton	50	28.6	0.017
	glue	25	33.5	0.007
	FR4	100	19.3	0.052
	glue	25	33.5	0.007
	MILLIFOAM	3000	1312.5	0.023
	glue	25	33.5	0.007
	FR4	100	19.3	0.052
Far. Cage	glue	25	33.5	0.007
	kapton	50	28.6	0.017
	Cu Ground	3	1.43	0.021
				0.233
			X0 - single	0.611
			X0 B2B	0.99