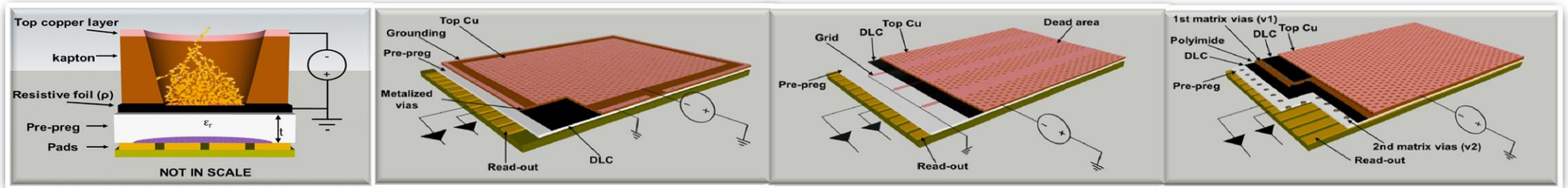
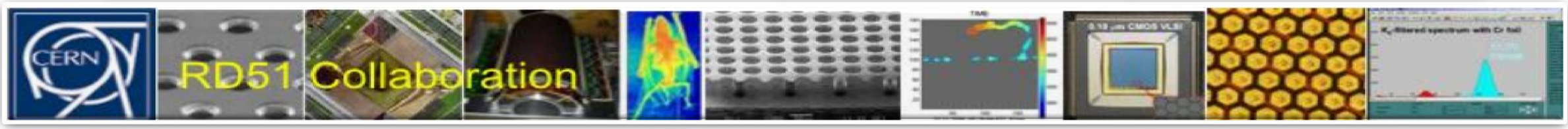
Status of the R&D on μ-RWELL

G. Bencivenni[1]

R. De Oliveira[2], G. Felici[1], M. Gatta[1], M. Giovannetti[1], G. Morello[1], M. Poli Lener[1]

1. Laboratori Nazionali di Frascati – INFN, Frascati - Italy
2. CERN, Meyrin - CH





Outline

- Detector architecture & principle of operation
- The low rate layout
- High rate layouts
- Space resolution studies
- Technology transfer
- Summary

Motivations

The R&D on μ-RWELL aims for a step-forward in terms of

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

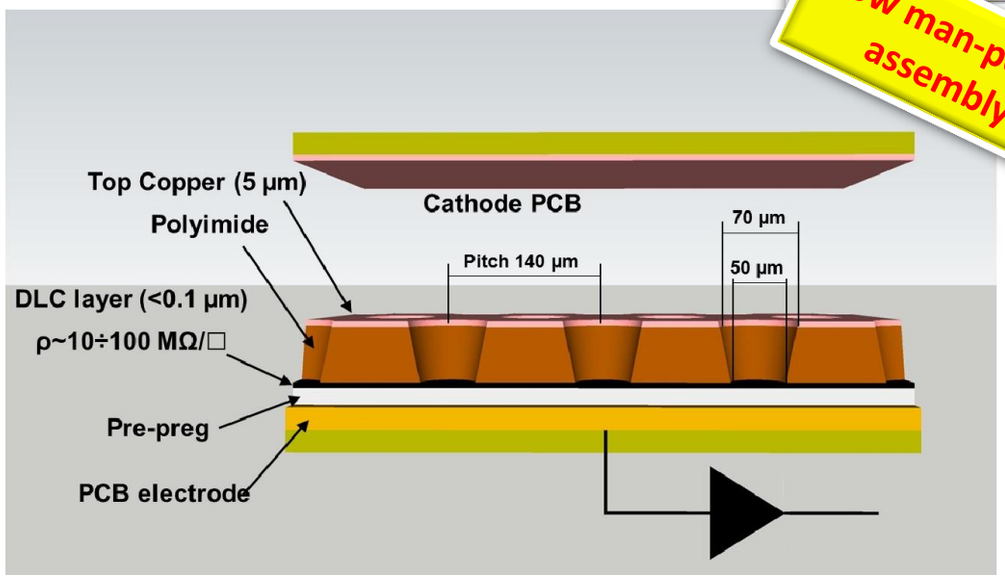
a MUST for large scale applications in fundamental research at future colliders, for large area applications and for technology dissemination beyond HEP

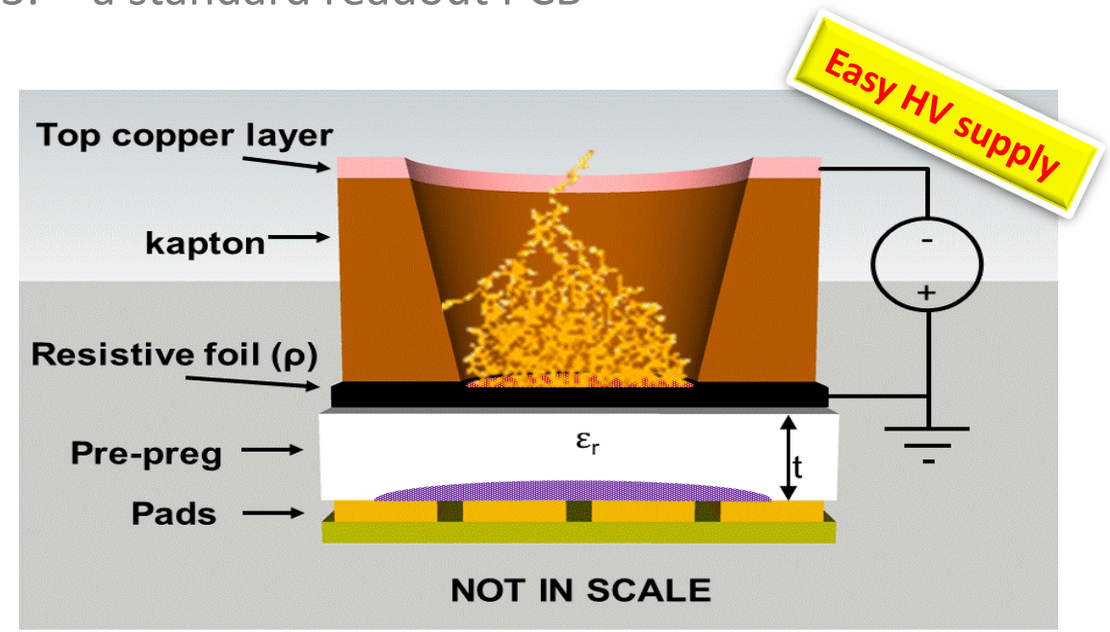
The architecture

The μ-RWELL is a simple device composed of only two elements: the μ-RWELL_PCB & the cathode

The μ-RWELL_PCB is realized by coupling:

1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression w/surface resistivity ~ 50÷200 MΩ/□
3. a standard readout PCB





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

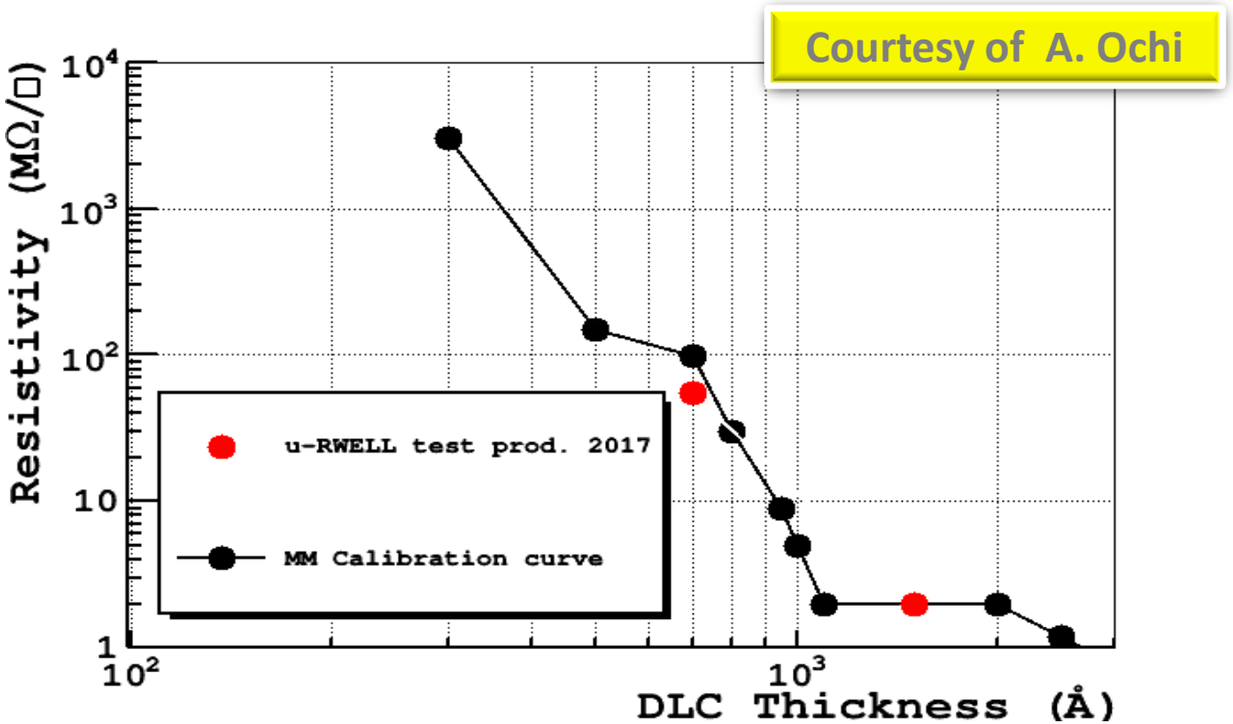
The charge induced on the resistive layer is spread with a *time constant*, $\tau = \rho \times C$
[*M.S. Dixit et al., NIMA 566 (2006) 281*]

$$C = \varepsilon_0 \times \varepsilon_r \times \frac{S_{pad}}{t} \approx 36\,pF \times S(cm^2)$$

The resistive layer: DLC sputtering

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

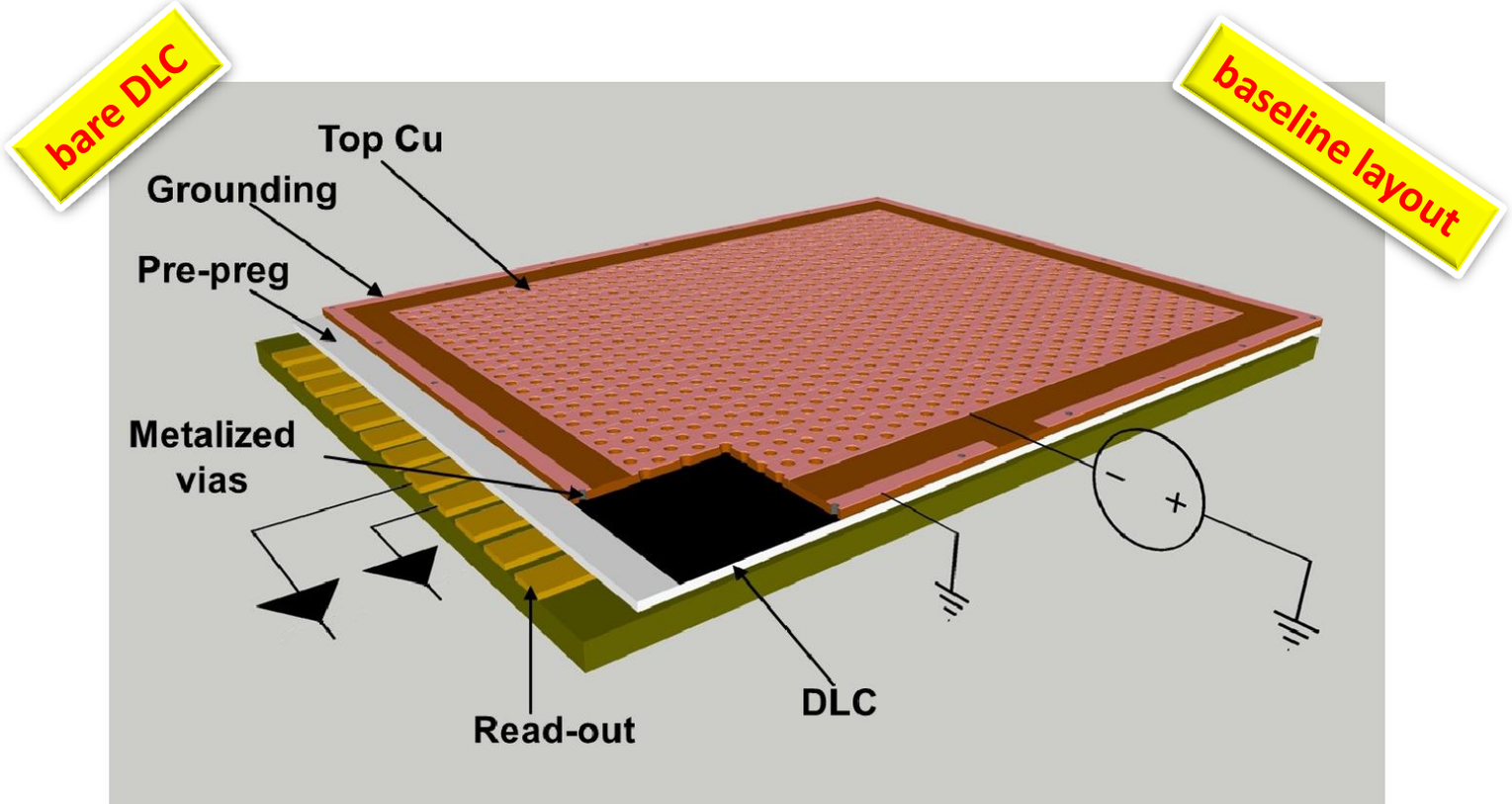
1 - Large area bare DLC deposition is performed in Japan by the Be-Sputter (Kobe)
The DLC uniformity on large foils, 1.2×0.6 m^2, is at level of ± 30% .



2 - Recent developments, at **USTC – Hefei (PRC)**, brought to the manufacturing **of DLC+Cu sputtered Apical® foils**, where an **additional layer of few microns of Cu above the DLC** coating is deposited.

This new technology open the way towards <u>improved high rate µ-RWELL layouts.</u>

The Low Rate Layout



Single Resistive Layer (SRL): a simple **2-D current evacuation** scheme through a **simple DLC film** with a conductive **grounding all around the perimeter** of the active area.

For **large area detectors** the **path of the current towards the ground connection** could be large and strongly dependent on the particle incidence point, giving rise to **detector response inhomogeneity → limited rate capability** (~5÷10 kHz/cm^2 for a ~50x50cm^2 detector tile).

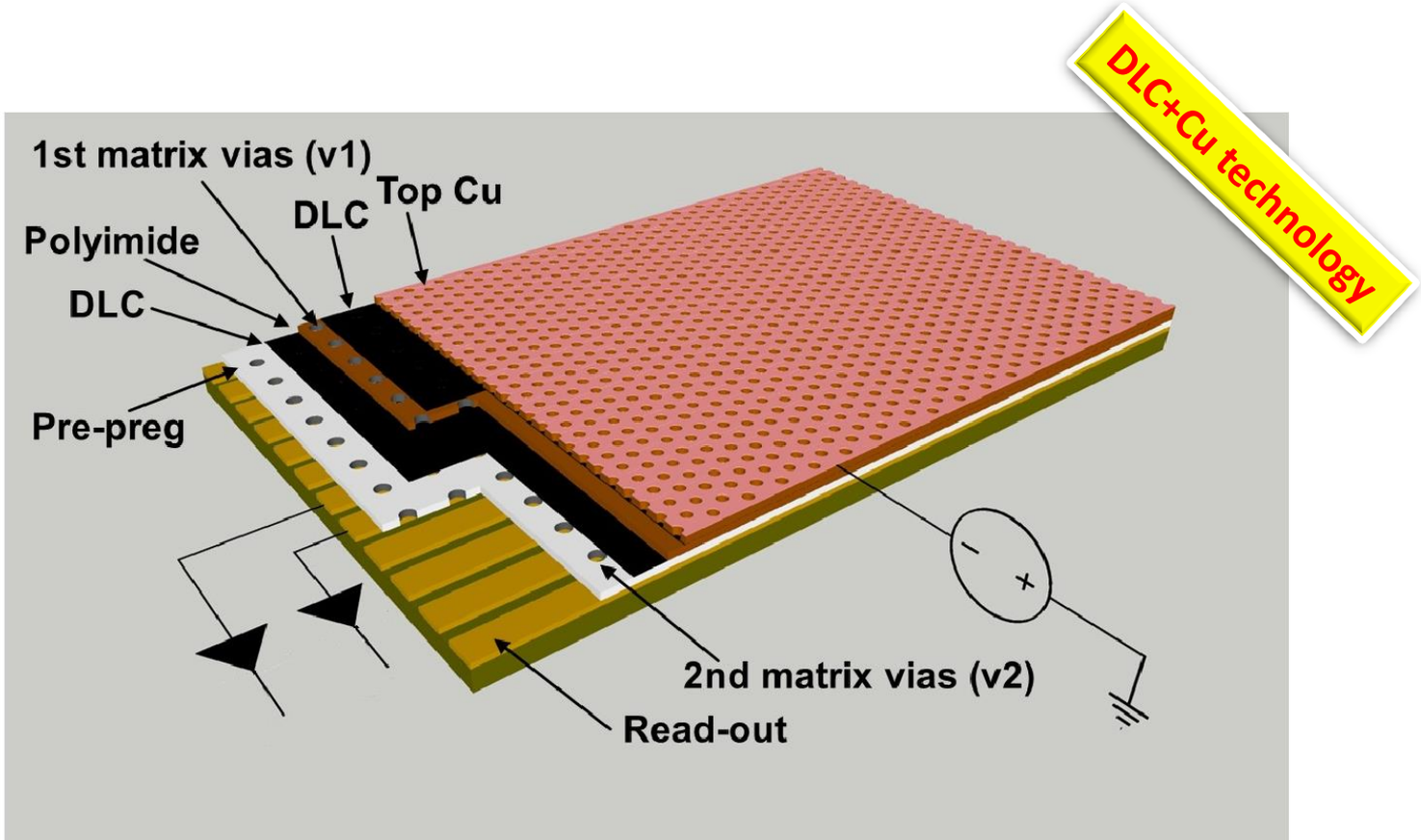
Towards high rate layouts

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

Two layouts *(but other ideas are under evaluation)* with a "dense" grounding network scheme have been designed and implemented:

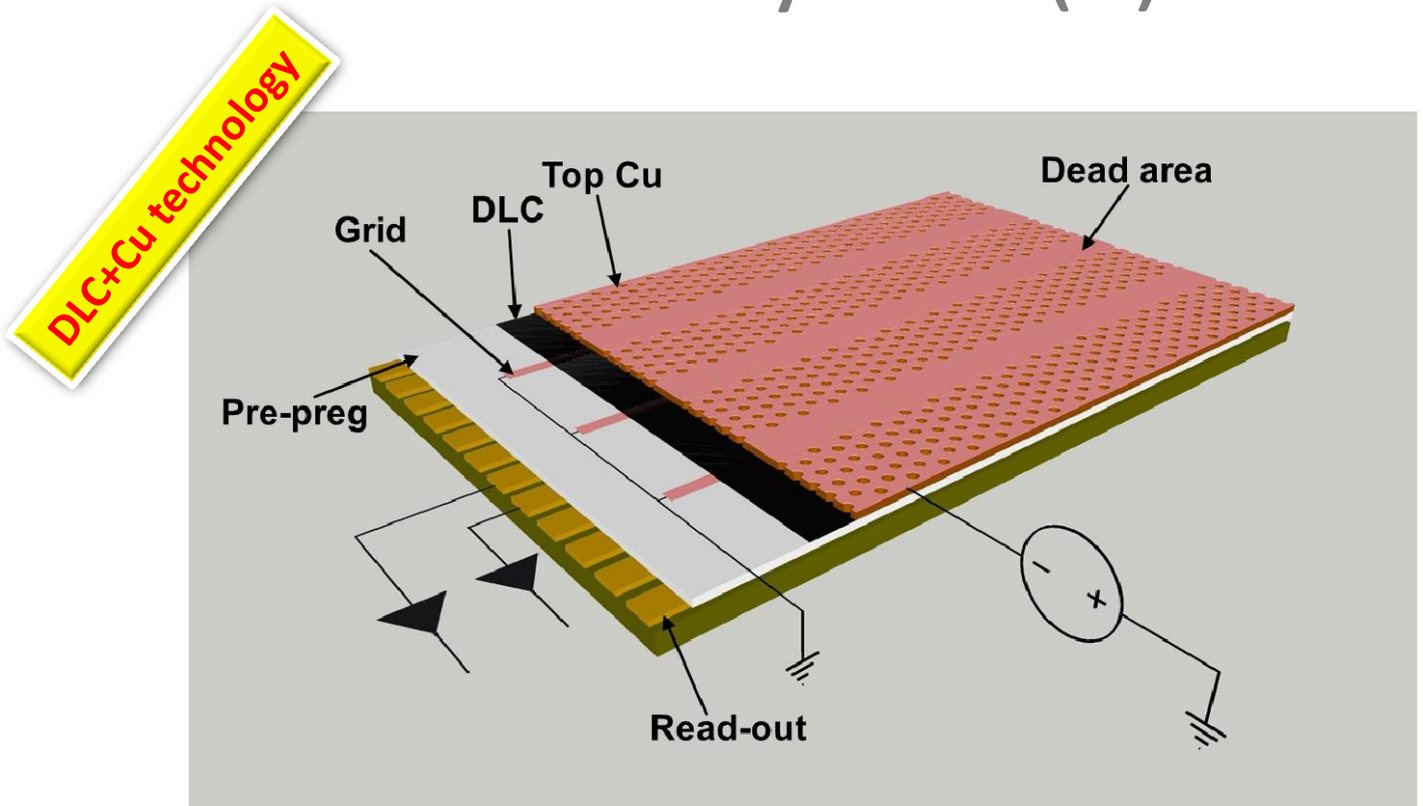
- the **Double Resistive layer** (**DRL**) with a sort of 3-D grounding scheme
- the **Single Resistive layout with a grounding grid** (**SG**) patterned on the resistive stage

HR layouts (I)



Double Resistive Layer (DRL): 3-D current evacuation scheme based on **two stacked resistive layers** connected through a **matrix of conductive vias** and **grounded through a further matrix of vias to the underlying readout** electrodes. The **pitch of the vias** can be done with a density **less than 1/cm²**. Realized with Sequential Build Up (SBU) technology.

HR layouts (II)



The **SG** is a **simplified HR layout** based on the **Single Resistive layer** with a **2-D grounding** by means a **conductive strip lines grid** patterned on the DLC layer.

The **conductive grid lines** can be screen-printed or **etched** by photo-lithography (*using the DLC+Cu deposition technology developed at USTC – Hefei*), with a **strip pitch of the order of 1/cm^2**.

The **conductive grid** can **induce instabilities due to discharges over the DLC surface**, thus requiring for the **introduction of a small dead zone** on the amplification stage.

The main application: LHCb

Detector requirements for HI-Lumi LHCb

- Rate ≥ 1 **MHz/cm²** on detector single gap
- Max **input capacitance** (double gap) **≤ 100 pF**
- Efficiency (double gap) **> 97%** within a BX (25 ns)
- Pad **cluster size < 1.2**
- **Long-term stability** up to **1,6 C/cm²** accumulated charge in 10 y of operation (M2R1 – with detector operated at G=4000)

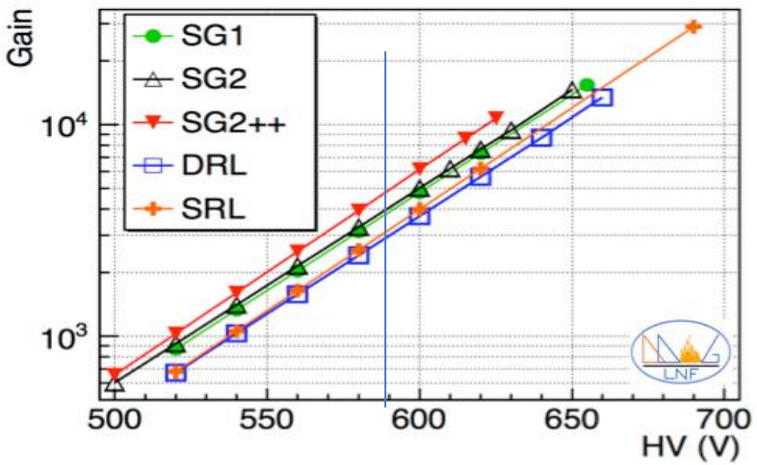
Detector size

- **R1÷R2**: **288** detectors, size **30x25** to **74x31 cm²**, **45 m²** det. - **65 m² DLC+Cu**
- **R3:** **384** detectors, size **120x25** to 149**x31 cm²**, **145m²** det. - **207 m² DLC**
- ~~**R4** : **1536** detectors, size 120**x25** to **149x31 cm²**, **582 m²** det. - **831 m² DLC**~~

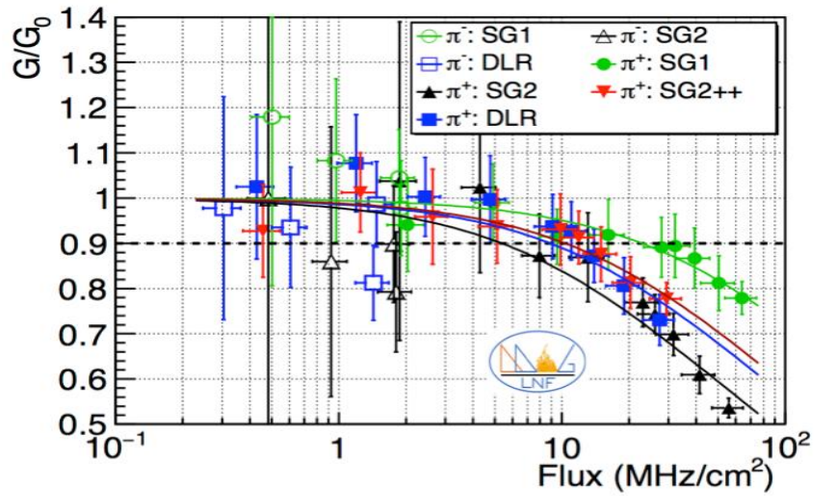
NO-RWELL

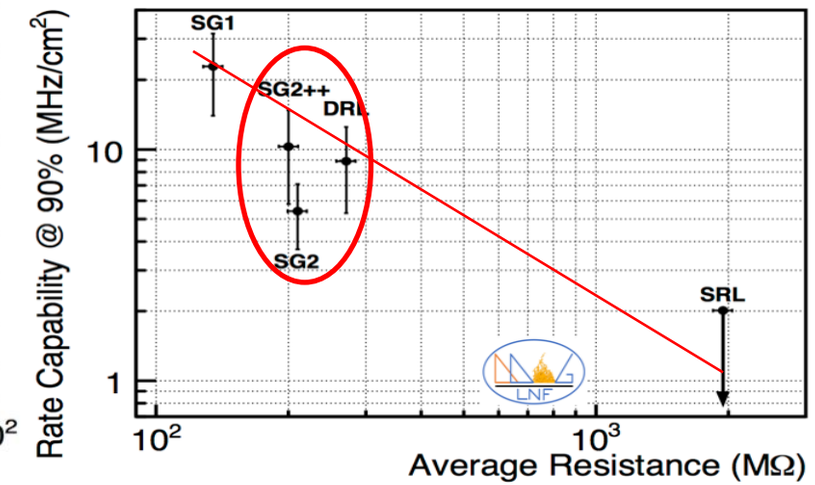
Detector performance

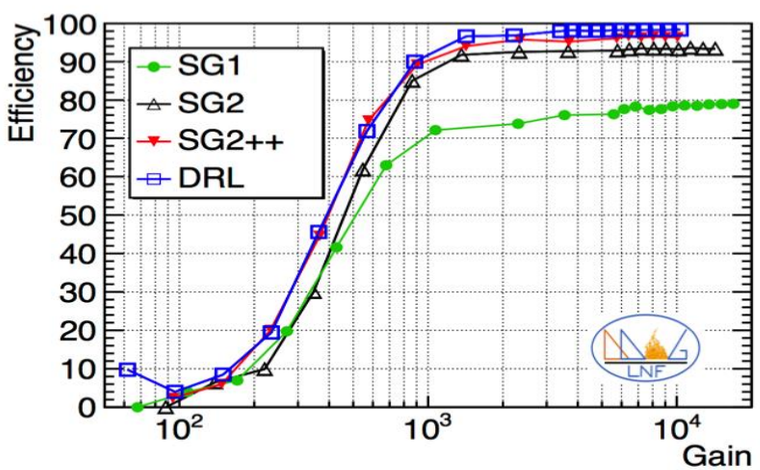
Gain up to ~ 10^4

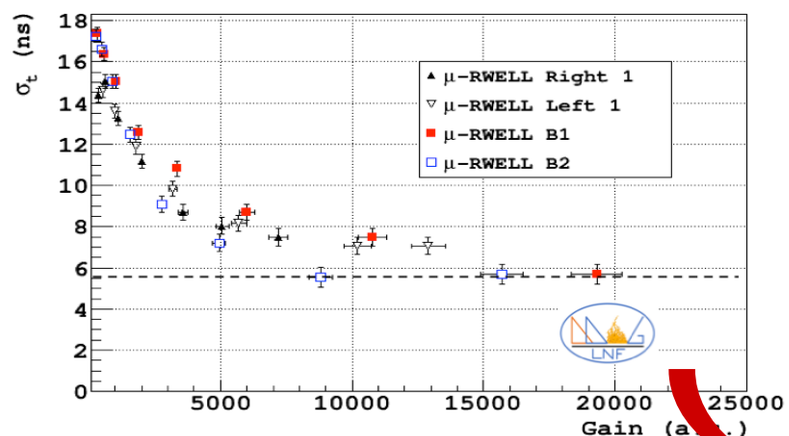


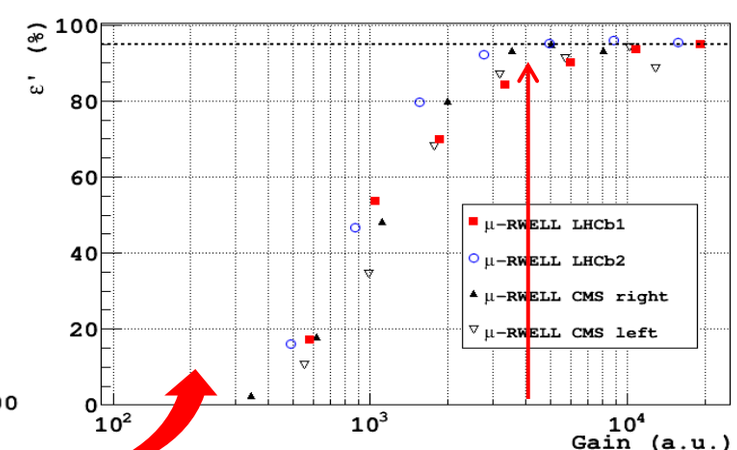
Rate capability (@ G = 4000) ~ 10 MHz/cm^2











Efficiency(SG2++ & DLR) ~ 98%

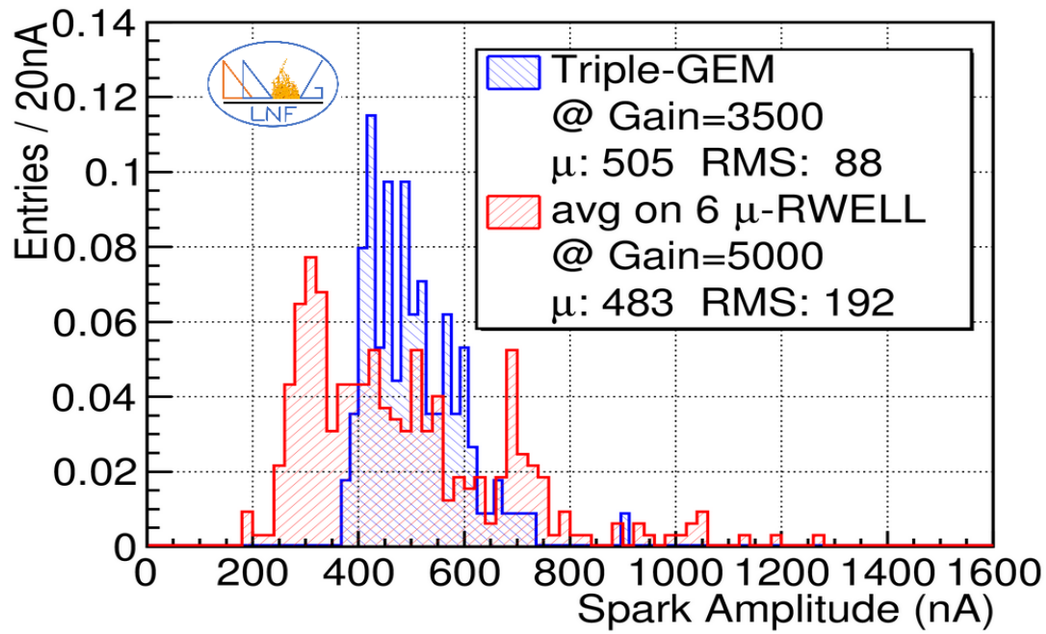
σ_t ~ 5- 6 ns (single gap)

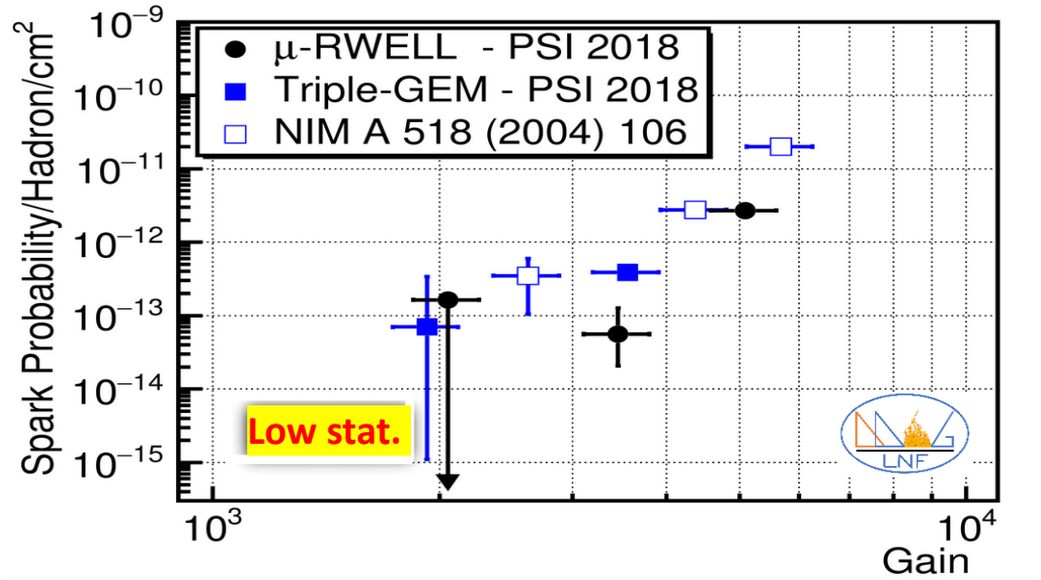
Efficiency in 25 ns (single gap)

Discharge studies

The μ-RWELL discharge probability measured at the PSI, and compared with the measurement done with GEM at the same time and in the 2004 (*same gas mixture* ***Ar:CO$_2$:CF$_4$ = 45:15:40***).

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





A "discharge" has been defined as the current spike exceeding the steady current level correlated to the particle flux (~90 MHz on a ~5 cm^2 beam spot size).

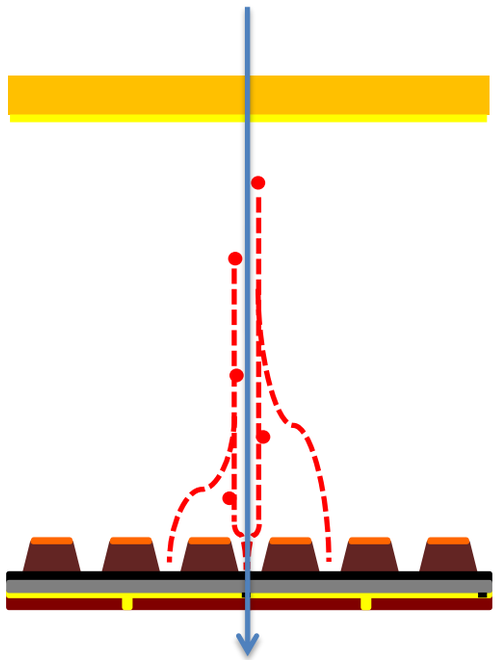
The discharge probability for μ-RWELL comes out to be similar to the one measured for GEM.

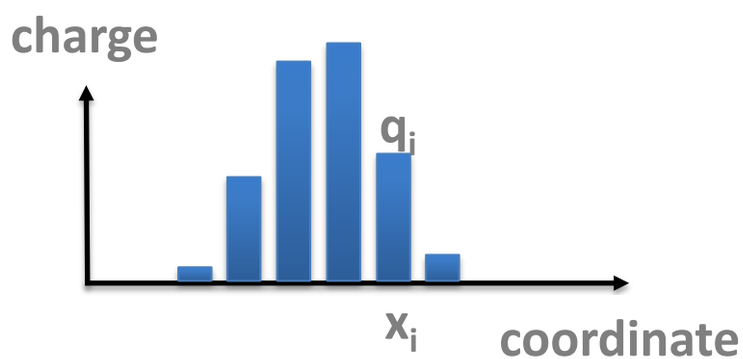
Moreover its discharge amplitude seems to be lower than the one measured for GEM.

Space resolution: orthogonal tracks

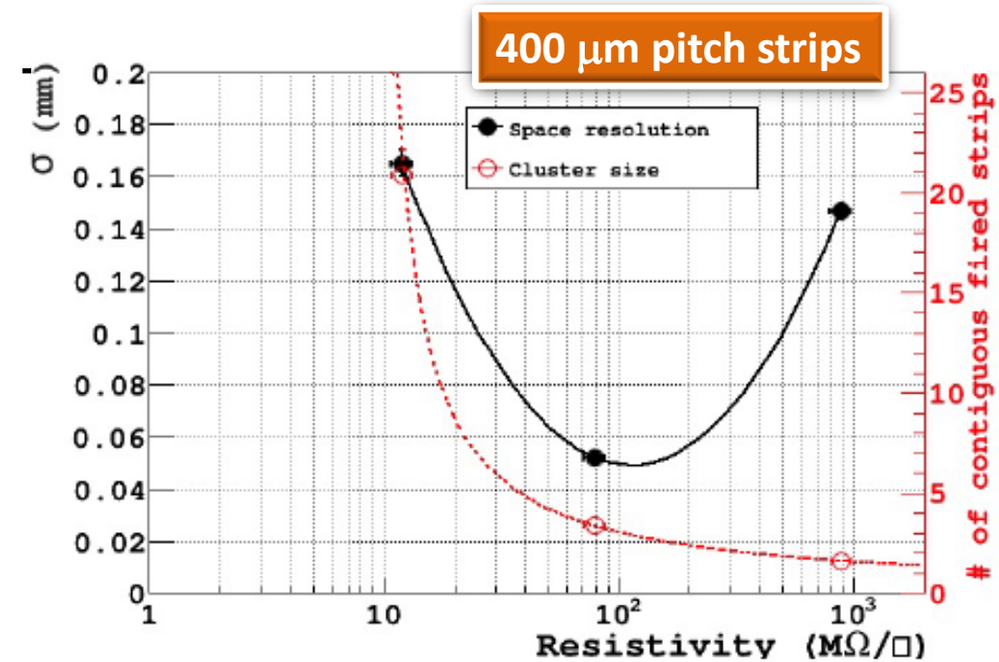
The presence of **the resistive layer** affects also the **charge spread** on the readout strips and consequently the space resolution of the detector.

With the **charge centroid (CC)** analysis (for orthogonal tracks) the track position is determined as a weighted average of fired strips.





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

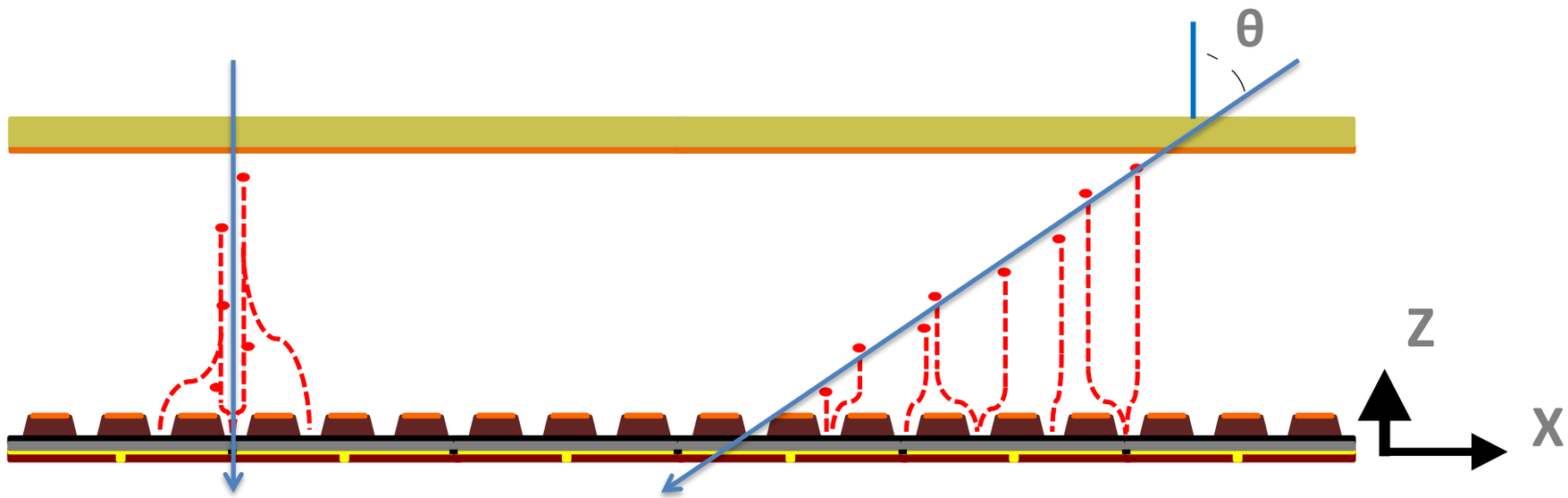


The space resolution exhibits a minimum around 100 MΩ/□:

- at **low resistivity** the **charge spread increases** and then σ is worsening
- at **high resistivity** the **charge spread is too small** (cluster-size → 1 fired strip) then the CC method becomes no more effective (σ → pitch/√12)

Orthogonal vs inclined tracks

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



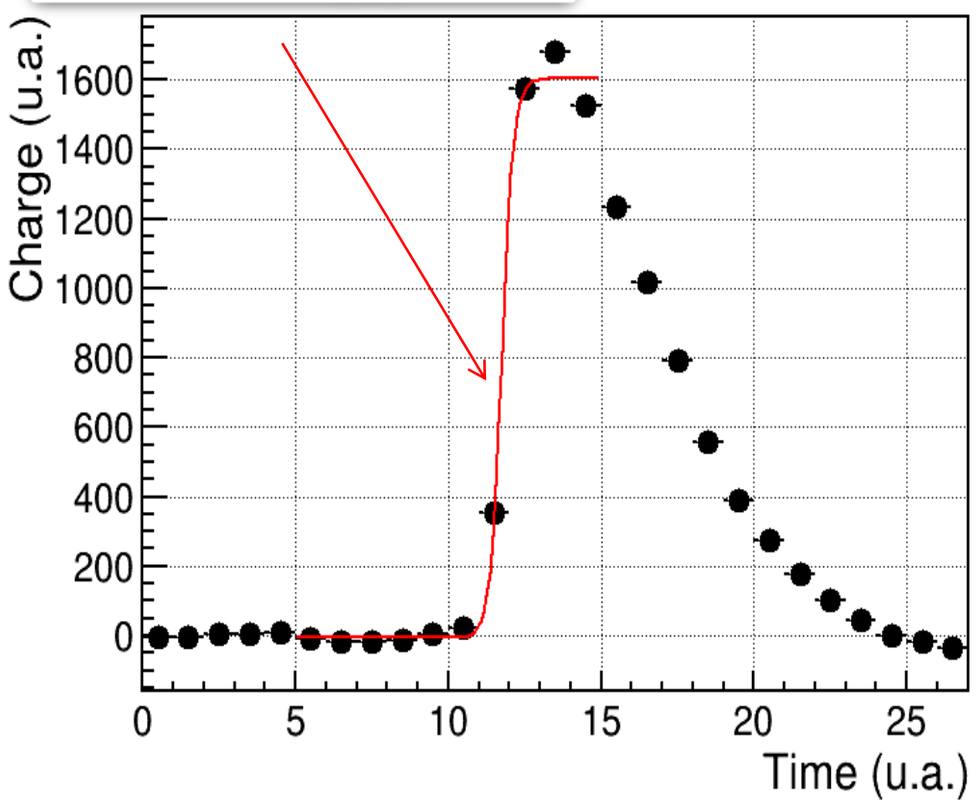
In the **u-TPC mode (*),** from **the knowledge** of the **drift velocity** and the **measurement of the arrival time** of electron clusters on the readout, **each ionization cluster is projected inside the conversion gap** and the **track segment** in the drift region **is reconstructed.**

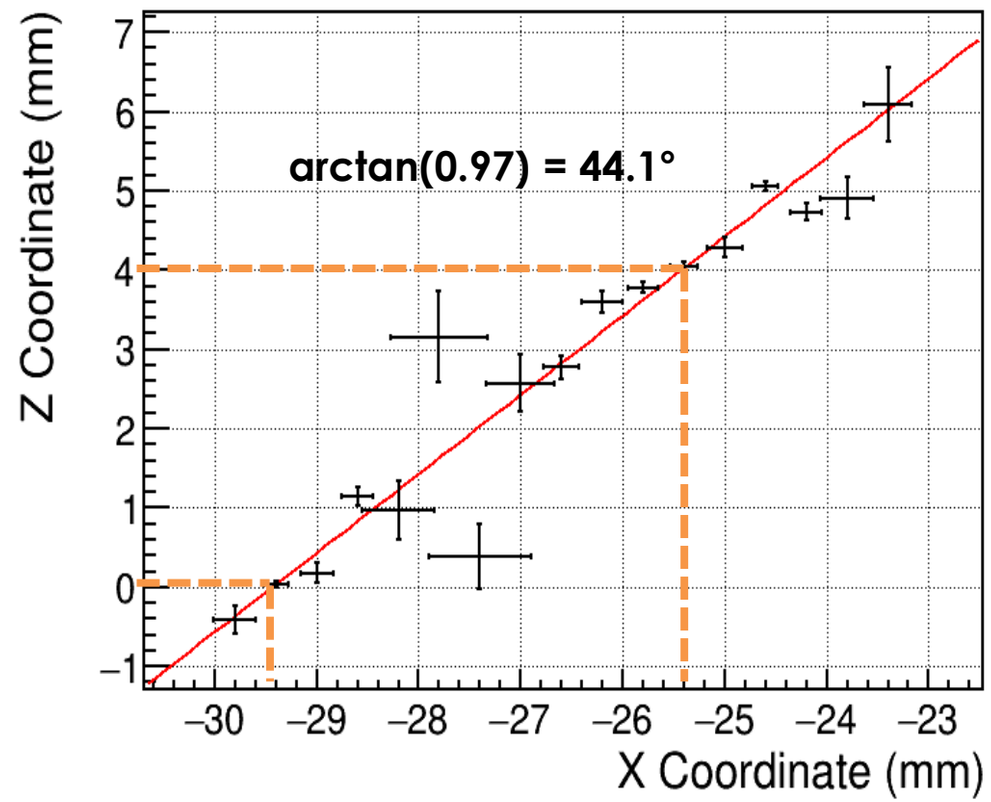
(*) introduced for MMs by T. Alexopoulos (NIM A 617 (2010) 161)

Track reconstruction with μ-TPC mode

$$f(t) = f_0 + \frac{q_k}{1 + e^{-(t-t_k)/\tau}}$$

Ar:CO_2:CF_4 45:15:40, Ed=0.5kV/cm, HV=600V, Gain ~10^4





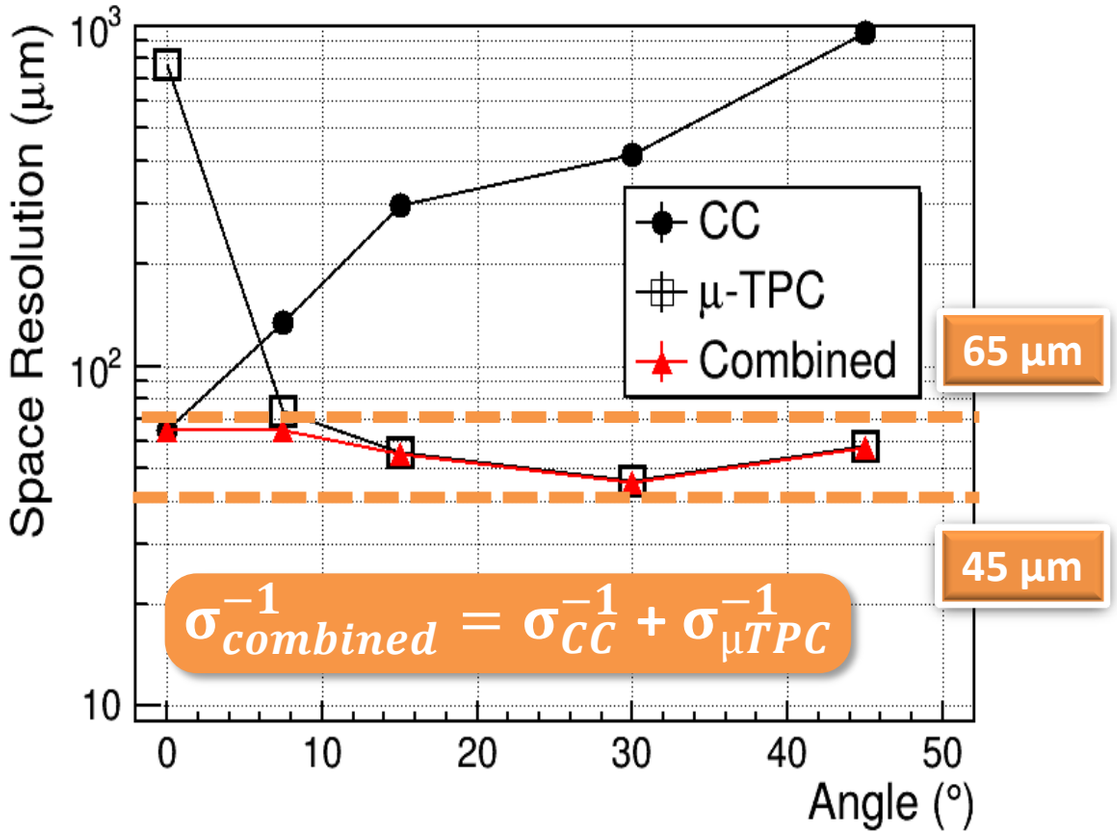
μTPC for a 45° track

The **fit of the rise-time of the signal (with a Fermi-Dirac)** gives the **arrival time of drift electrons** (*corresponding to the inflection point of the fitting curve*).

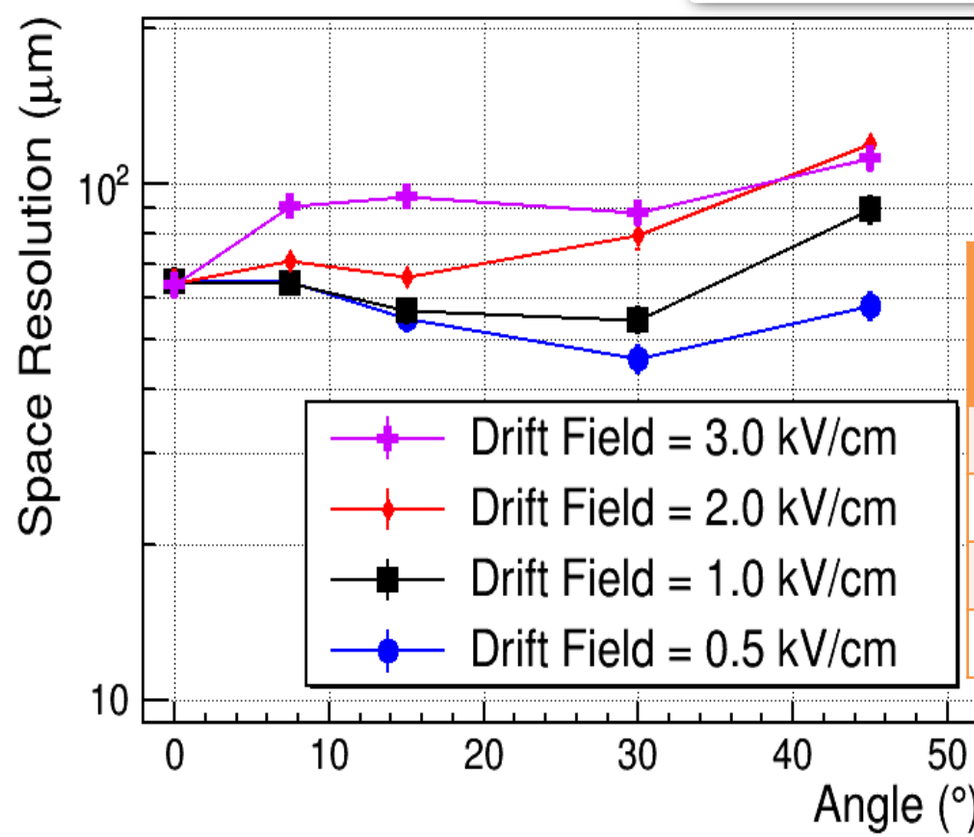
From the knowledge of the **drift velocity**, **the track inside the drift gap is reconstructed**.

Global Spatial Resolution

Ar:CO_2:CF_4 45:15:40, Ed=0.5kV/cm, HV=600V, Gain ~10^4



400 µm strip pitch



Drift Velocity (µm/ns)
95
74
40
20

Tuning the drift field an **almost flat distribution over a wide incidence angle range** is obtained with the **µTPC mode**. The smaller the drift field, the smaller the drift velocity, making easier for the FEE to discriminate between different clusters by their arrival times. The measurements were taken using APV25.

Status of the technology

- The whole R&D has been performed at the CERN PCB-Workshop (Rui de Oliveira)

- The detector is based on **Sequential Build Up (SBU) technology,** this means that the **Technology Transfer** to industry is **easy** → cost effective mass production

- All manufacturing process of the detector components are in our hands apart the **DLC** sputtering:
  - **large area (bare) DLC** foil sputtering at **Be-sputter in Japan:** 60×120 cm^2
  - **R&D on DLC+Cu** sputtering (@ **USTC – Hefei – PRC):** 30×30 cm^2 → 30×120 cm^2

Things to do

- **Looking for DLC/DLC+Cu production in Europe**
- **Validation test of DLC + aging studies**

Technology Transfer

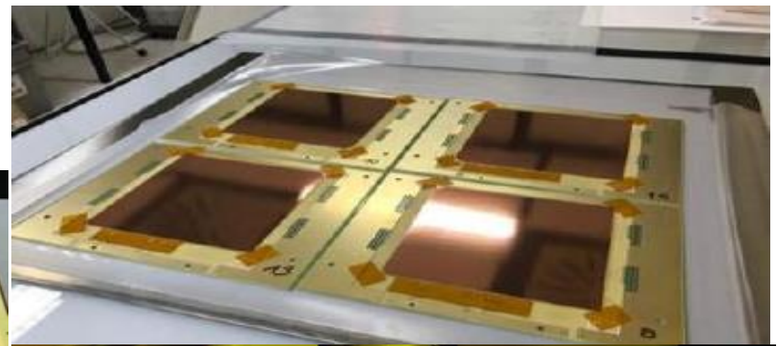
The **engineering and industrialization** of the μ-RWELL technology is one of the main goal of the project

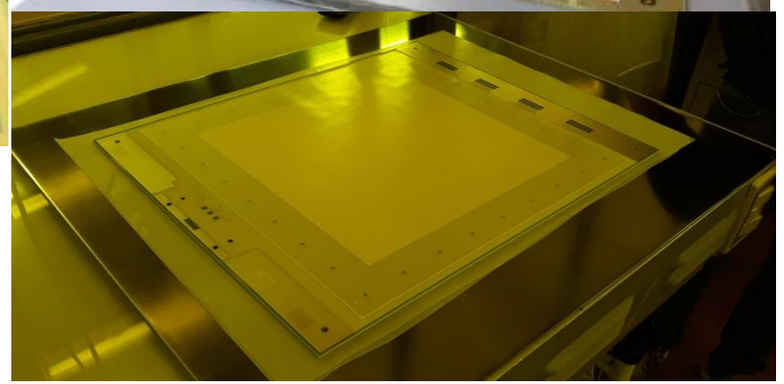
Production tests of the SRL layout @ ELTOS:

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

1.2x0.5m^2 μ-RWELL

1.9x1.2m^2 μ-RWELL





Large area tests @ ELTOS:

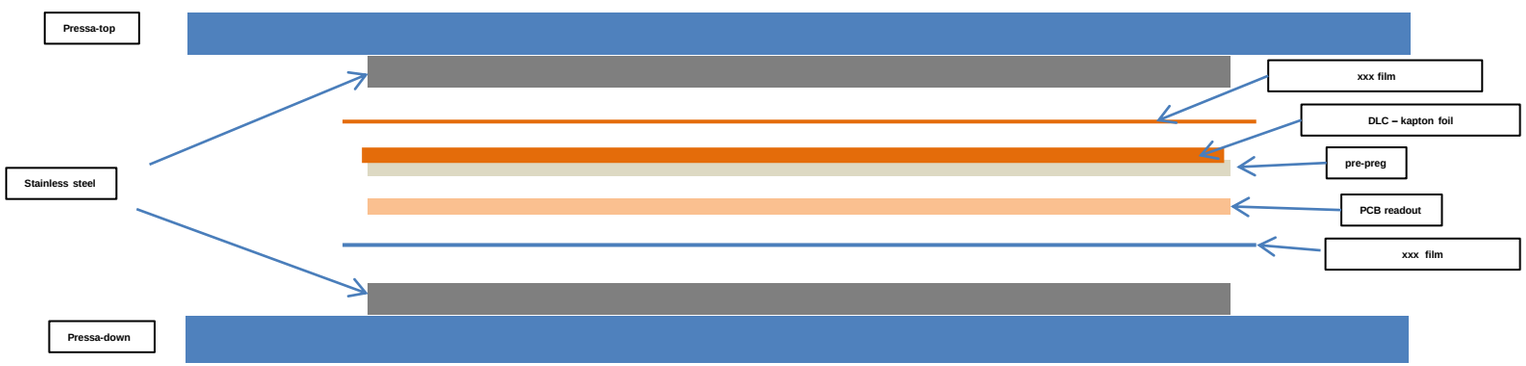
- 1.2×0.5m^2 with strip r/o
- 1.9×1.2m^2 with strip r/o - (w/PCB splicing of tile w/size 40×50 cm^2)
- 33×33 cm^2 with strip r/o

Kapton etching done @ CERN

The micro-RWELL @ ELTOS

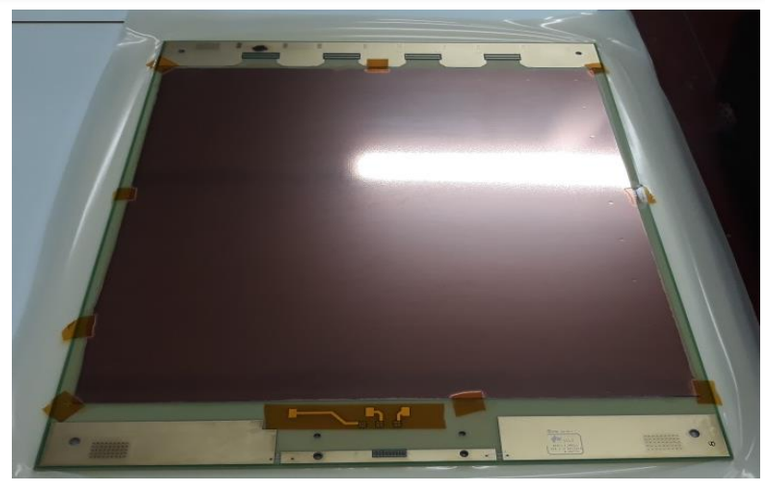
ELTOS performs the **coupling of the DLC-foil with the readout PCB** (only for the **SRL layout**).
The **max size of the μ-RWELL-PCB** that can be produced by ELTOS is about **60×70 cm²**.
Up to 8 PCBs of such size can be manufactured at the same time.

The manufacturing procedure is slightly different from the one used by Rui, but works fine.



Discussion in progress on a possible R&D on PI etching in ELTOS

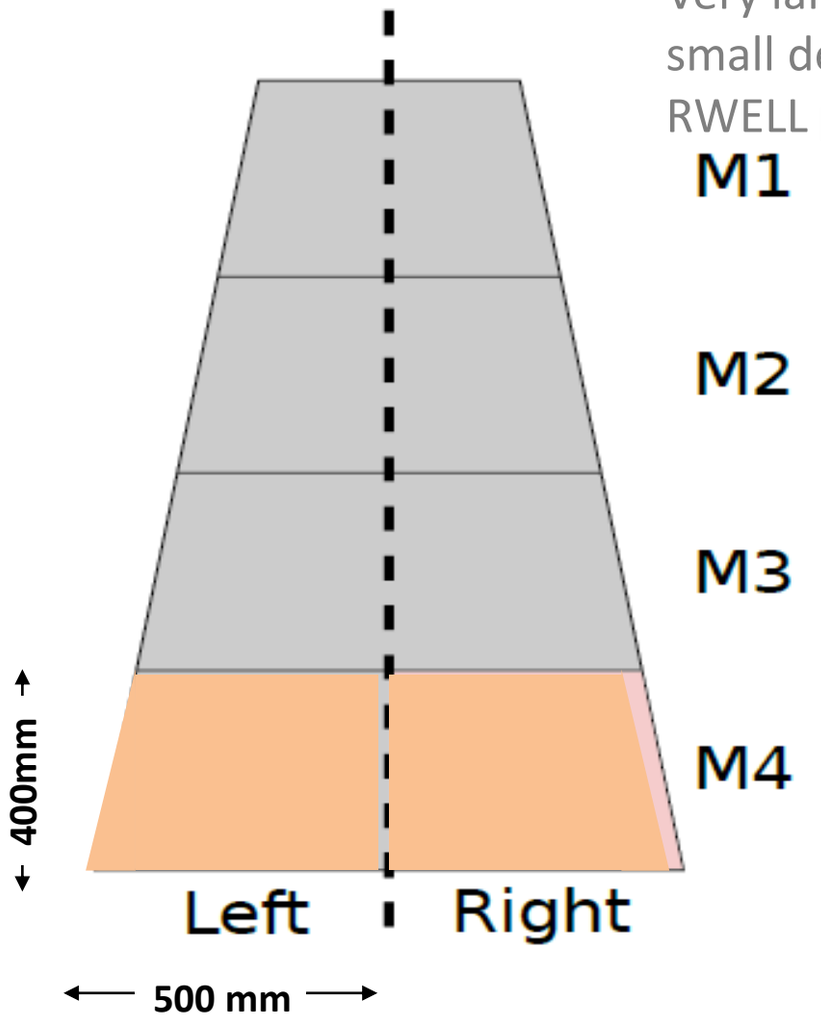
33×33 cm² active area SRL - RWELL



Large area detectors

PHD thesis L.Borgonovi – INFN-Bo

Very large area detectors can be realized by splicing detector tiles with small dead zone (< 1mm), as demonstrated with the large GE2/1 RWELL proto for CMS .

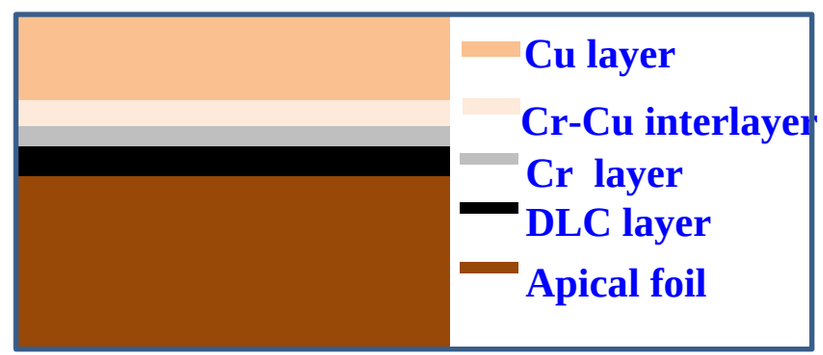


M4 μ-RWELL detector on the movable platform in the H4 beam

GE2/1 RWELL detector: ELTOS + CERN (Rui) manufacturing

DLC production in Europe

- Possible solution: installation of a magnetron sputtering machine at CERN (co-funded by CERN, LNF-INFN and possibly by other European Institutions …)
- The machine should have the following features:



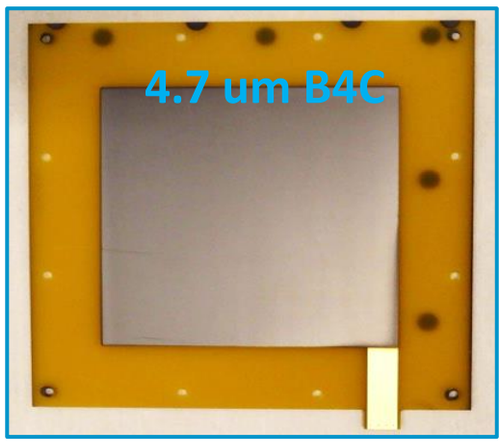
- Chamber size: Φ800mm×900mm
- Max foil size with good DLC uniformity: ~ 50×200 cm^2
- Equipped w/automatic shutter, allowing the DLC and Cr/Cu coating in the same batch

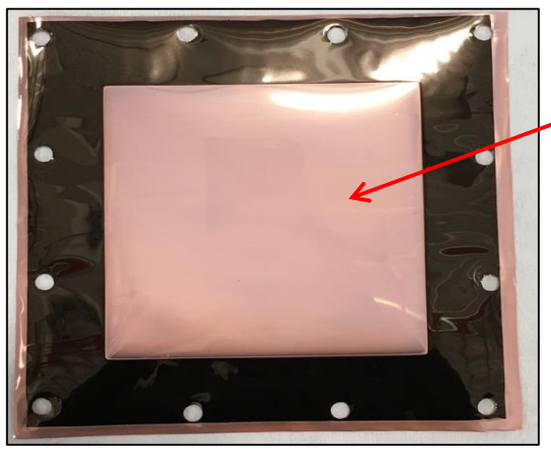
Linköping Coatings Workshop

Chung-Chuan Lai, Per-Olof Svensson, Linda Robinson

Detector Group - European Spallation Source ERIC -Linköping, Sweden

Experts in sputtering deposition (especially B4C)





Recently they showed interest in the R&D on DLC/DLC+Cu deposition

Max deposition size: 650×650 mm²

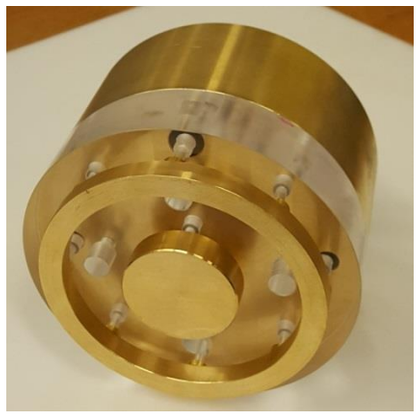
DLC & detector aging studies

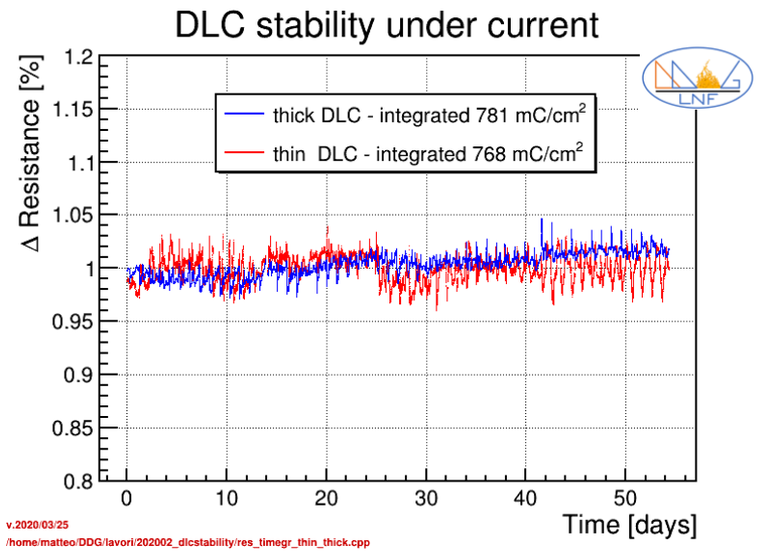
DLC & detector long-term stability, that for **HR applications,** must be verified **up to 1-2 C/cm^2 ,** are clearly mandatory

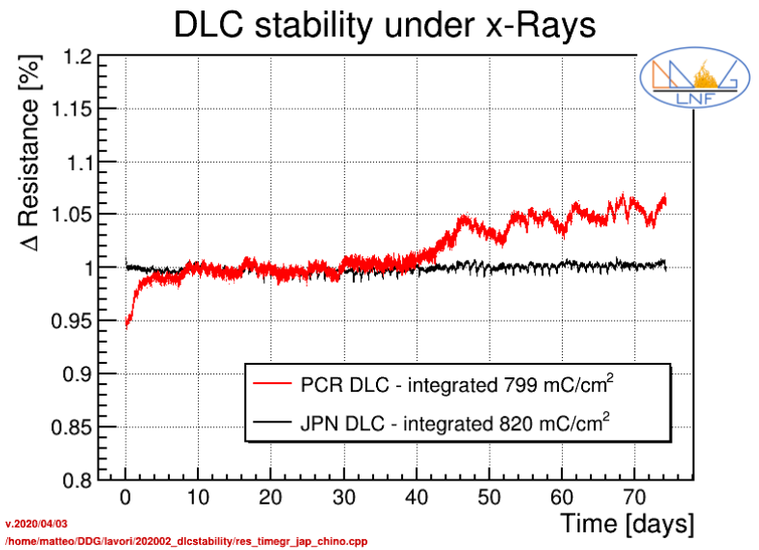
- **long term test of DLC foils** (thin vs thick) **under high current**
- **long term test of DLC foils under X-ray irradiation**
- **aging test of detectors** with different radiation (gammas, X-ray, mip)

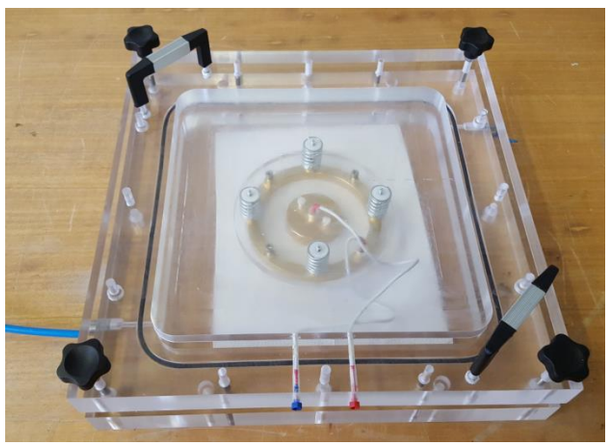
DLC stability tests

$$R = \rho_s * ln(\frac{R_{out}}{R_{in}}) / 2\pi$$

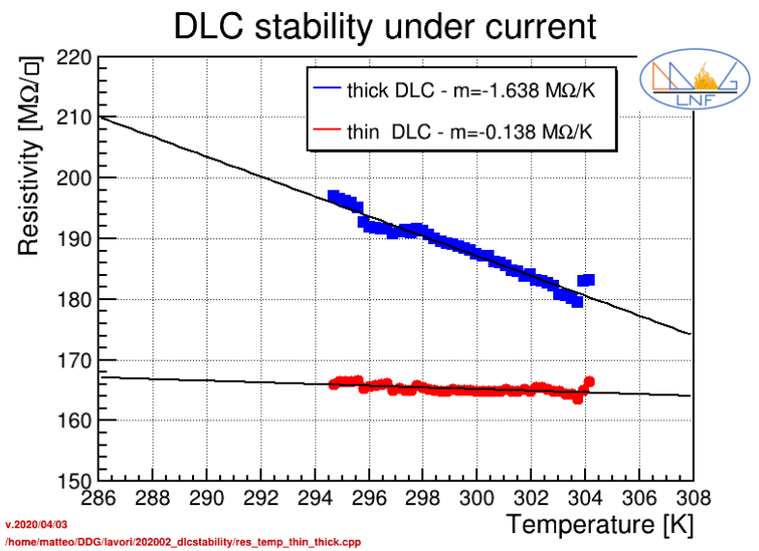






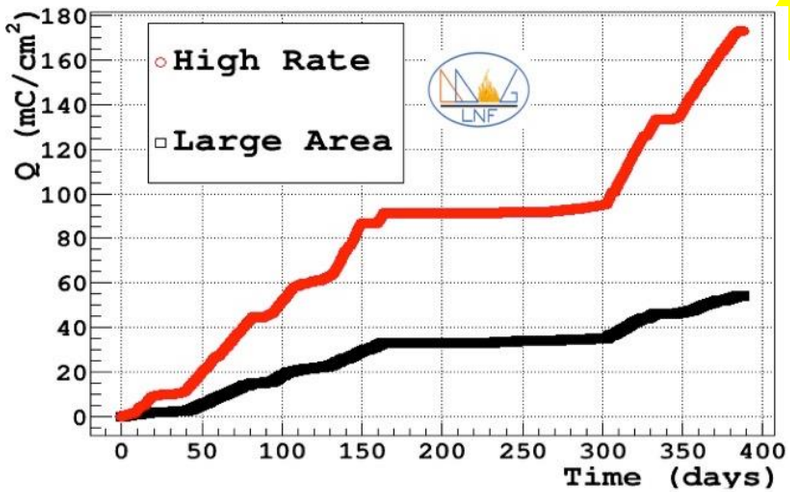


- The DLC resistivity is measured/monitored with the usual annular probe
- Its long term stability ($\Delta\rho$ < 10%) tested under different conditions (with & without X-ray irradiation), simulating an integrated charge of the order 0,8 mC/cm^2.
- The temperature dependence of the DLC resistivity has been also measured



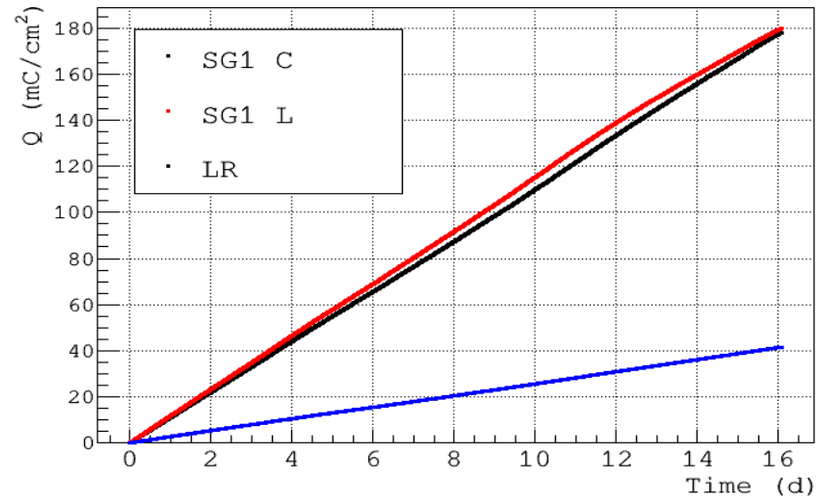
Detector aging

GIF++ - Full area, Flux ~ 200 kHz/cm²



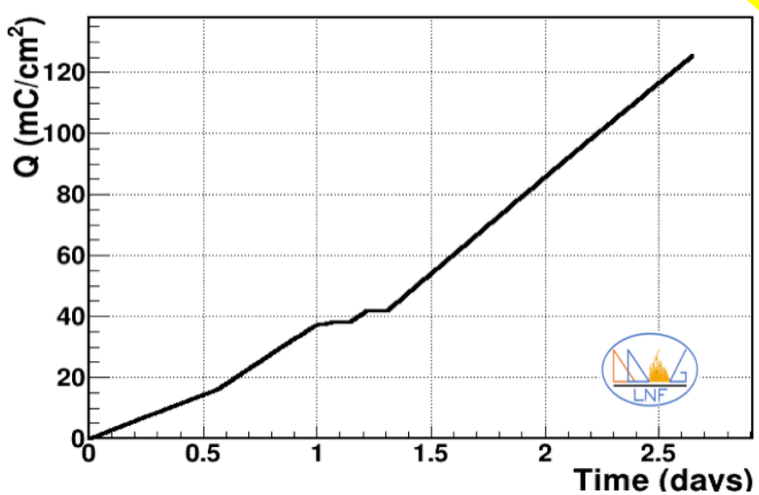
175 mC/cm²

X-Ray gun- spot 50 cm² - Flux up to ~ 1,2 MHz/cm²



180 mC/cm²

PSI-1, beam spot ~ 9 cm² , Φ ~ 10 MHz/cm²



125 mC/cm²

Several irradiation tests have been performed with different radiation:

- 662 keV gammas (GIF++)
- 5,9 keV X-Ray (LNF – lab)
- 350 MeV/c pions/protons (PSI)

Detector features

The μ-RWELL is a single-amplification stage resistive MPGD characterized by:

Very simple design/assembly-procedure

- only two components, the main one including readout & gas amplification stage
- no critical & time consuming assembly steps
  - no gluing
  - no stretching
  - easy handling
- suitable for large area with PCB splicing technique w/small dead zone
- the flexible version is a valuable and simplified option for cylindrical detectors

Cost effective & mass-production technology

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

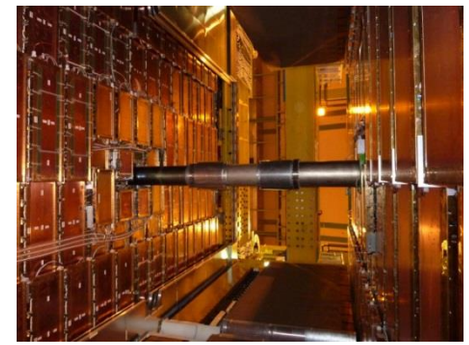
Easy to operate

- very simple voltage supply is required → only 2 independent HV channels or trivial passive divider

SUMMARY

The detector performance

- gas gain ≥ 10^4
- rate capability ≥ 10 MHz/cm^2 *(w/HR layouts)*
- space resolution < 65µm *(over a large incidence angle of the tracks)*
- time resolution ~ 5.7 ns



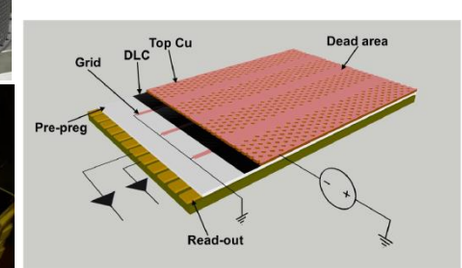
The experiments

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

- upgrade of the **LHCb** Muon apparatus
- EU project **ATTRACT-URANIA** as neutron detection
- EU project **CREMLINplus** as Cylindrical Inner Tracker at the SCTF

Future plans

- Production tests of the HR version of the detector at CERN
- Technology Transfer to industry (ELTOS)
- Import DLC technology in Europe
- Long term stability studies under irradiation

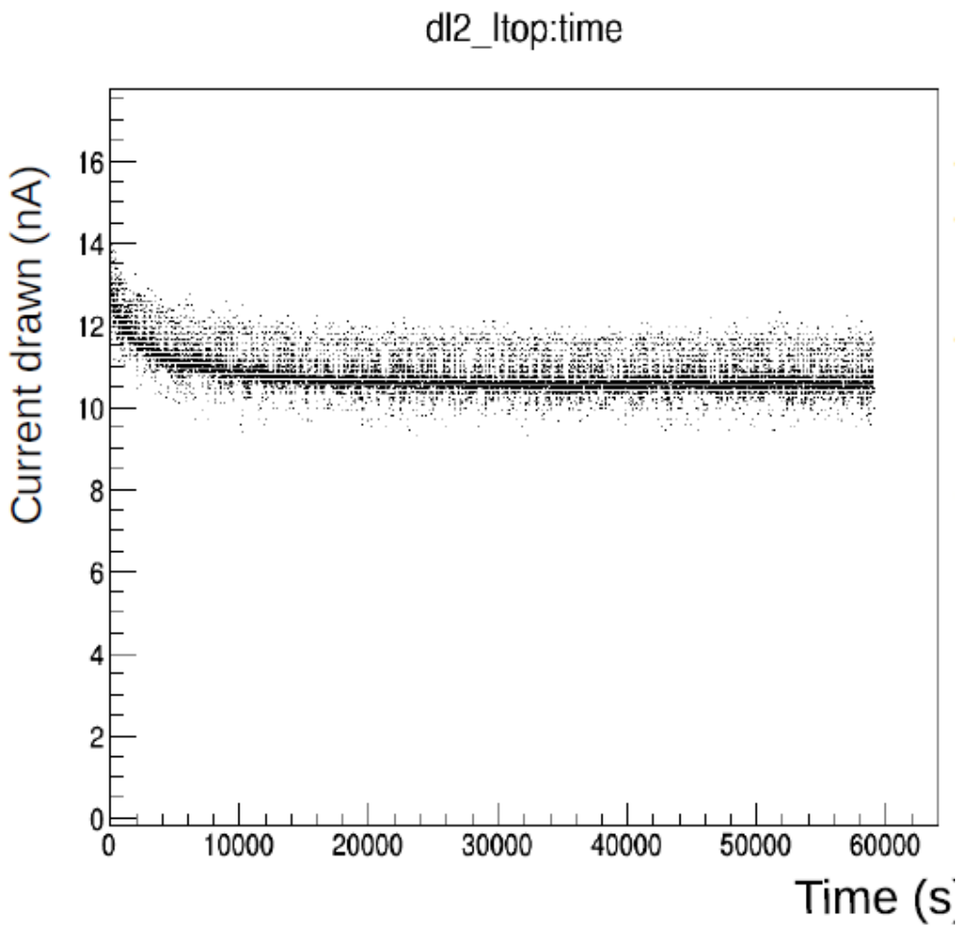


References

- G. Bencivenni et al., *The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD*, 2015 *JINST* **10** P02008
- G. Bencivenni et al., *The μ-RWEL detector*, 2017 *JINST* **12** C06027
- G. Bencivenni et al., *Performance of μ-RWELL detector vs resistivity of the resistive stage*, *Nucl. Instrum. & Meth.* **A 886** (2018) 36
- G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* **14** P05014
- A. Ochi et al., *Carbon sputtering Technology for MPDG detectors*, PoS(TIPP2014)351 (2014)

Spares Slides

Charging – up



- Charging up as observed @ G = 3000.
- The Gain drop is of the order of 15%.
- The measurement has been done on a 10x10 cm^2 active area irradiated with a thermal neutron flux of 750 Hz/cm^2 at the HOTNES neutron facility of the ENEA – Frascati.
- ~16 h monitoring
- ~ 1 h charging-up drop time

# Det.	Layout	Active area [cm²] readout	DLC type	DLC resistivity [MΩ/□]	Gain	Comments
1	Low Rate	5x5 Single PAD	Screen Printing & Dot	100/100	$8x10^3$	first detector 2009
1	Low Rate	5x5 STRIP	DLC JAP	880/N.A.	$3x10^4$	
1	Low Rate	5x5 STRIP	DLC JAP	80/N.A.	10^4	
1	Low Rate (CMS GE1-1)	1200x500 STRIP	DLC JAP	16 sectors: <70>	$8x10^3$	**Only 4 sectors working TB Nov. 2016 - GIF++**
1	Low Rate (CMS GE2-1)	600x470 STRIP	DLC JAP	N.A.	$> 5 x10^3$	
1	Low Rate (CMS GE2-1)	600x470 STRIP	DLC JAP	N.A.	-	**Never Working**
21	#21 Low Rate	10x10 PAD/STRIP	DLC JAP	<108>/N.A.	$>8x10^3$	**#2 detector in short: 1 is recovered, 1 is under HV recovery**
Tot	**24 Low Rate**					

~10 ÷12 % failure on LR layout

+ n. 32 LR 10×10 cm² to be built for uRANIA
+ n. 6 LR 33×33 cm²

# Det.	Layout	Active area [cm²] readout	DLC type	DLC resistivity [MΩ/□]	Gain	Comments
7	High Rate Single Res. Layer (buried resistor/grid)	10x10 PAD/STRIP	DLC JAP	N.A/<56>	$>8x10^3$	
2	High Rate Double Res. layers	10x10 PAD	2 DLCs JAP	N.A./<54>	$> 10^4$	
2	High Rate Single Res. Layer (grid) - SG2++	10x10 PAD	DLC PRC/Cu	N.A./64	10^4	Production 2018
4	High Rate Single Res. Layer (grid)- SG2++	10x10 PAD	DLC PRC/Cu	N.A./<27>	$>=4x10^3$	Production 2019; **1 det. In short and under HV recovery**
2	High Rate Double Res. layers -SBU	10x10 2D-STRIP	DLC PRC/Cu	N.A./N.A.	$4x10^3$	**TB PSI 2019 – Current instability under irradiation**
Tot	**17 High rate**					

+ n. 20 SG2 10 × 10 cm² under construction by Rui

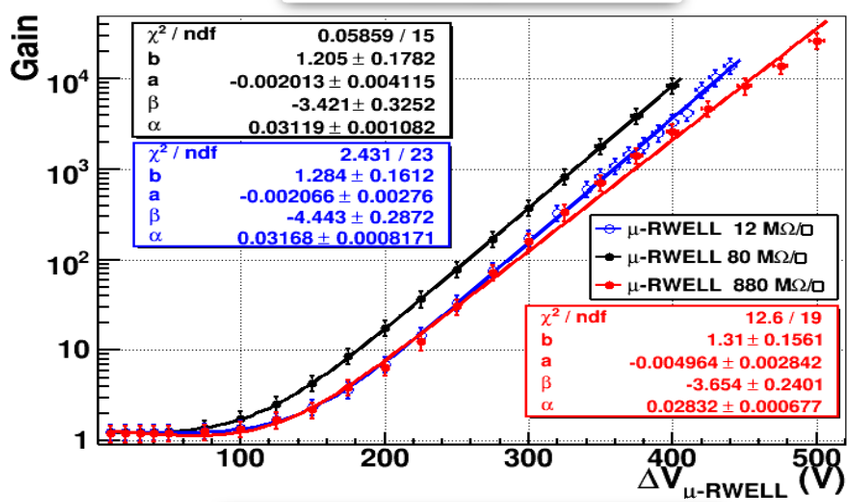
small production test in order to check: quality, yield …

+ some medium size SG2 (30×25 to 74×31 cm²)

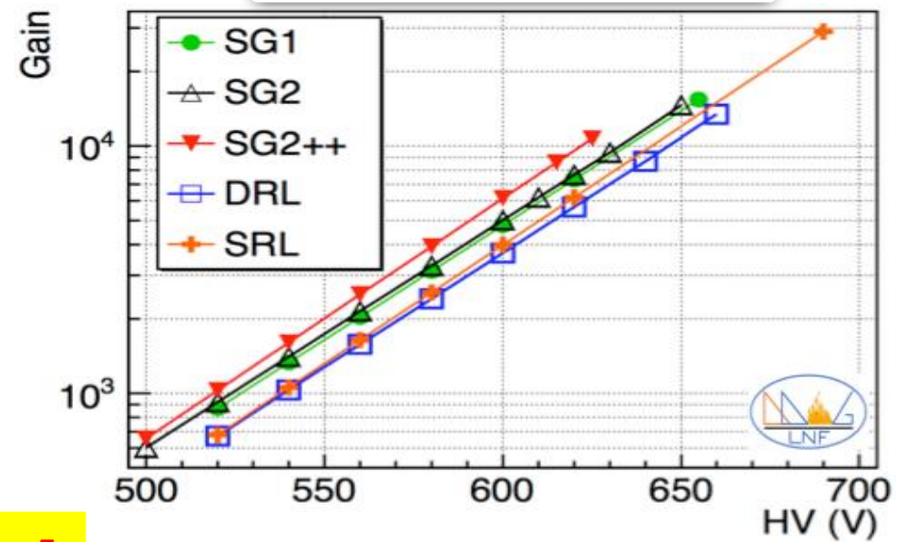
~ 5 ÷15 % failure on HR layout

Detector Gain

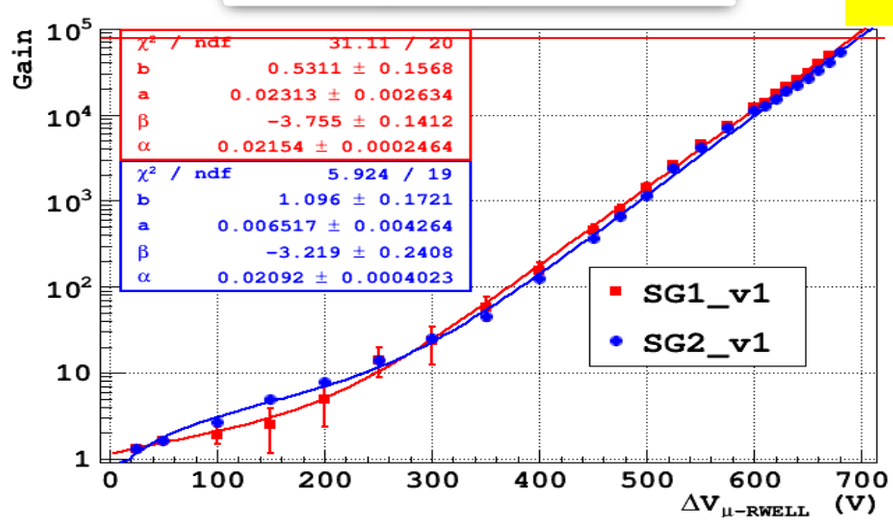
Ar/iC$_4$H$_{10}$= 90/10



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



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



$G > 5\times10^5$

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

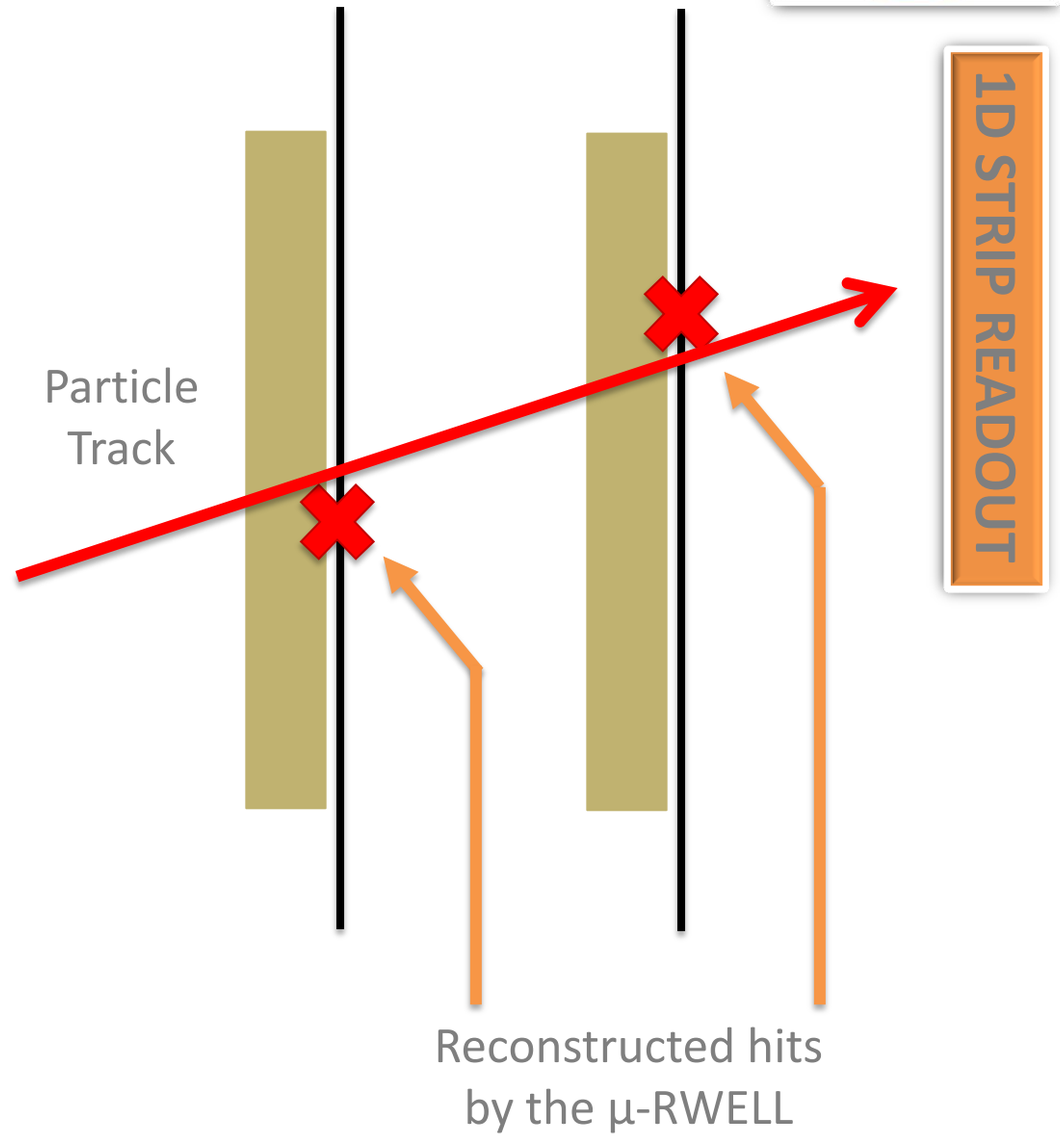
Gas gain measured with X-rays (5.9 keV), for several gas mixtures.

Spatial Resolution

- The spatial resolution can be evaluated avoiding trackers contribution with at least **two μ-RWELL** chambers in the same operating condition. The reasonable assumption is that they have the same spatial resolution.
- For a fixed incidence angle, **the residuals** were evaluated event by event as the difference of the coordinate of the two hits.
- Thus the resolution of the μ-RWELL is:

$$\sigma_{\mu RWELL} = \frac{1}{\sqrt{2}} \sigma_{residual}$$

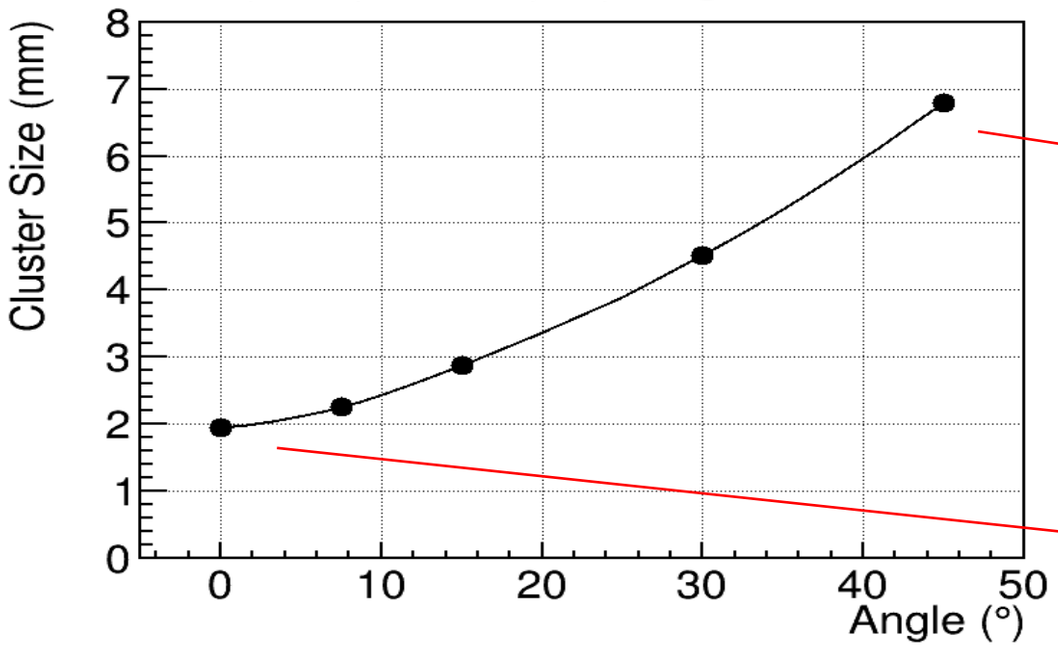
- Residuals distribution were studied both for CC reconstructions than for μTPC ones.

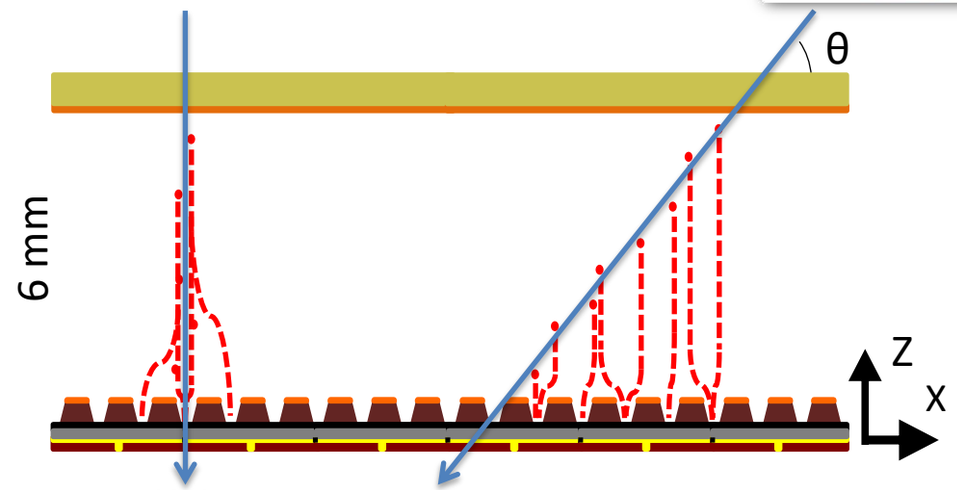


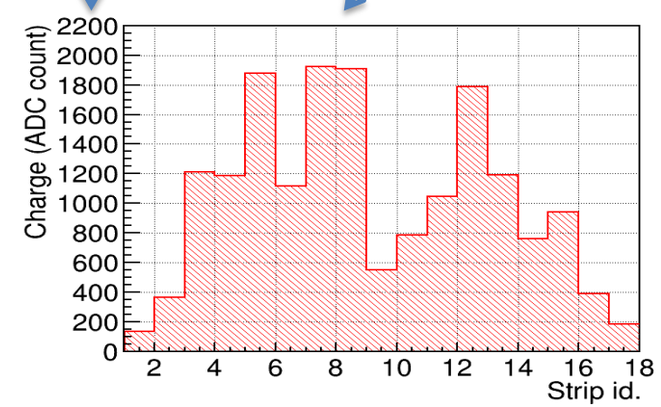
Cluster Size

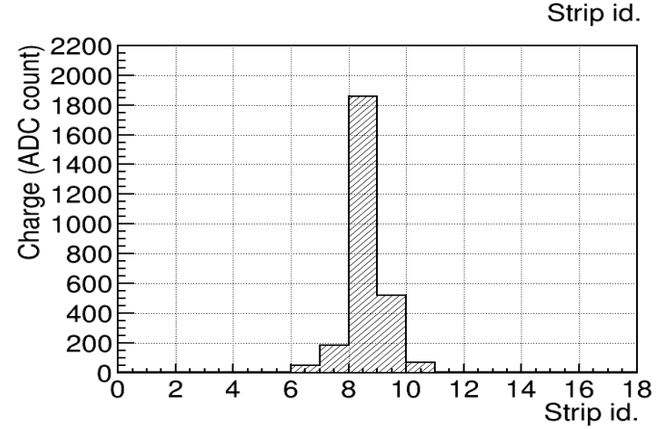
H4 beam area (RD51) Muon beam momentum: 150 GeV/c
μ-RWELL with 400 μm pitch strips readout by APV25 -
drift gap 6 mm

Ar/CO2/CF4=45/14/40 @ G=5000





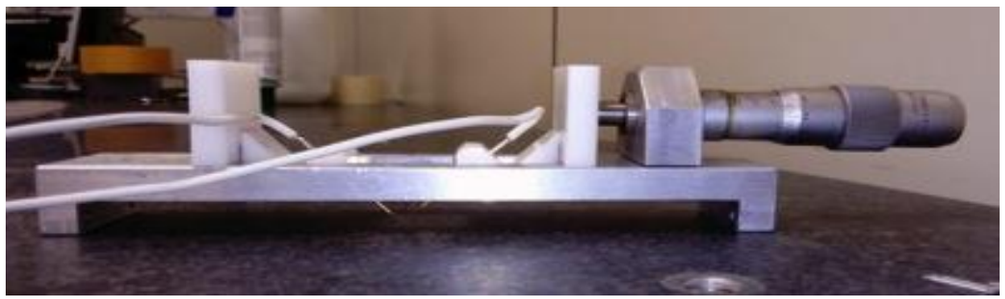


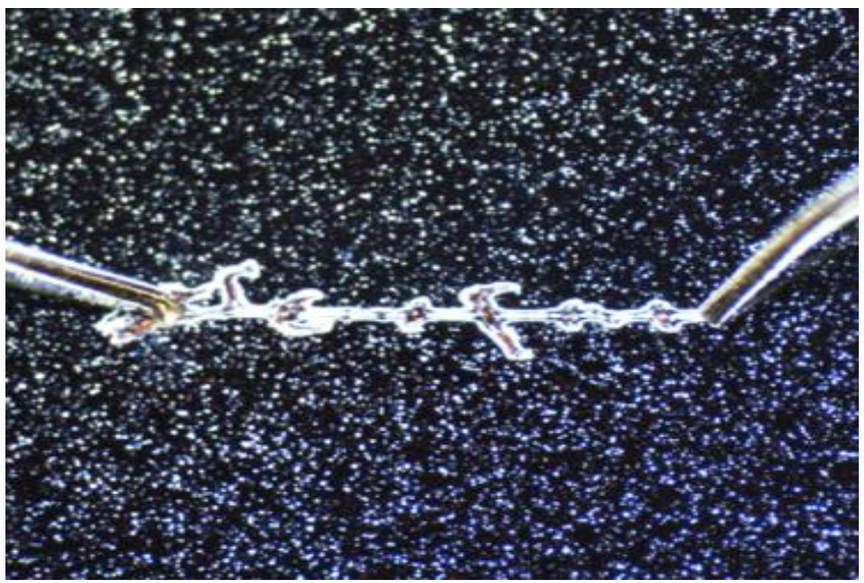


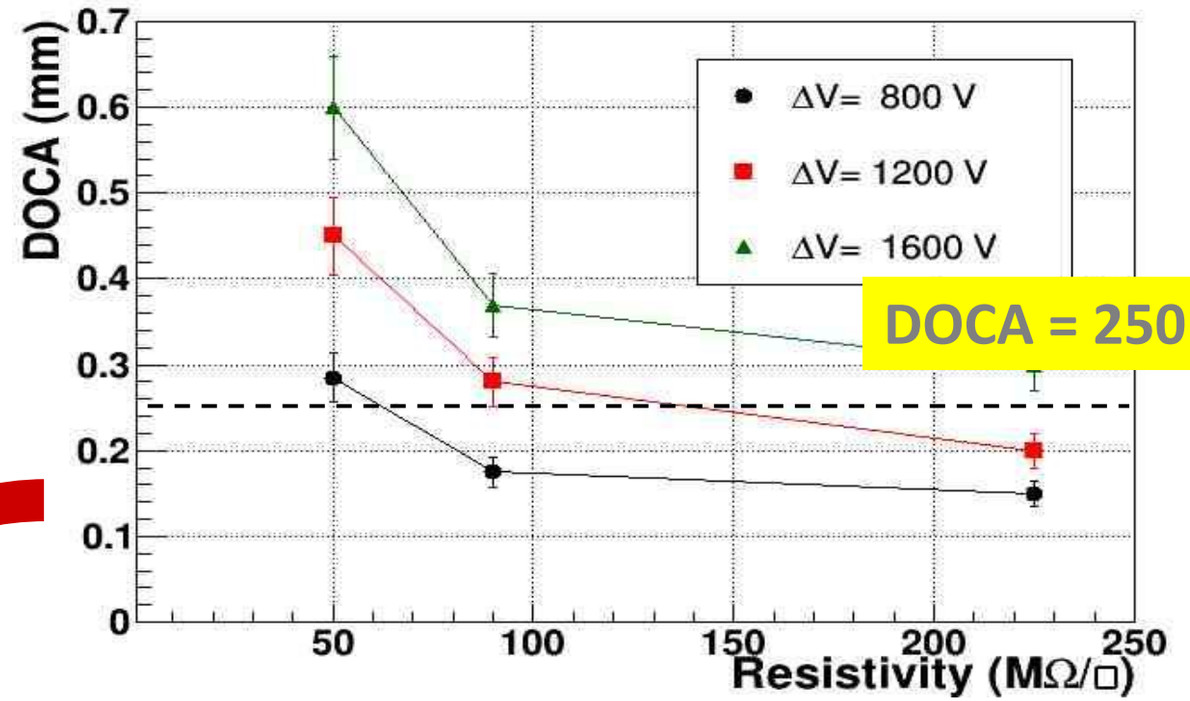
With a 3 mm drift gap as foreseen for LHCb, the CS should be smaller

Conductive Grid: optimization

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







DOCA = 250 μm

ρ > 60 MΩ/□ → DOCA < 250 μm

Large area detectors

PHD thesis L.Borgonovi – INFN-Bo

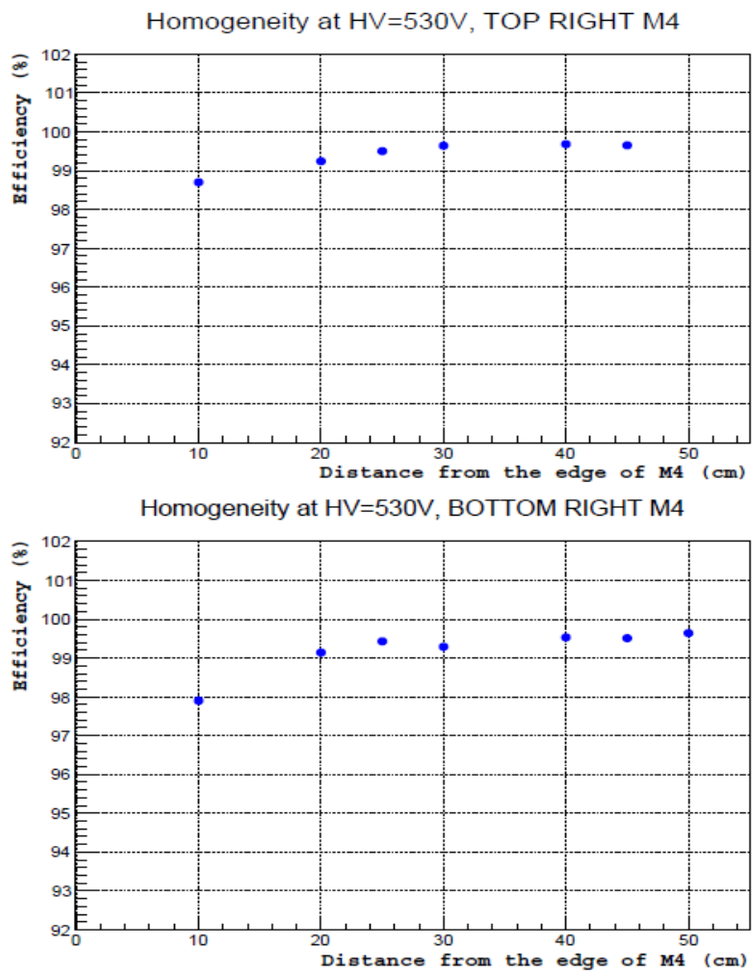


Figure 1.17: First estimation of the efficiency for the top (top), and bottom (bottom) region of the M4-right tested.

GE2/1 RWELL performance

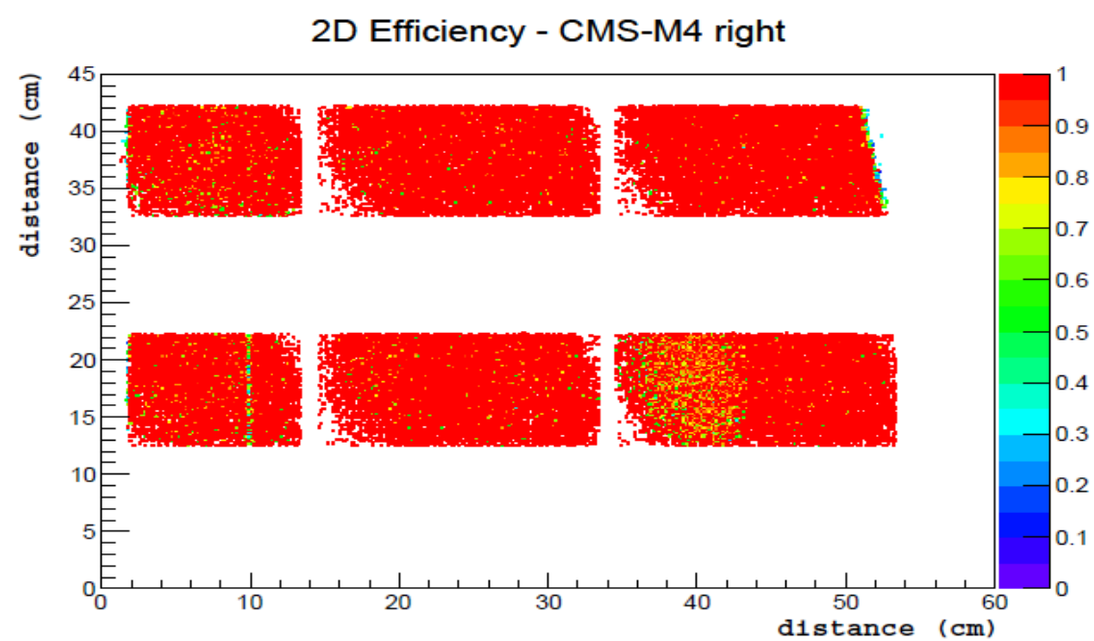


Figure 1.18: Efficiency of the M4-right μ-RWELL detector.

Milestones of the Project

- **2009** - first idea of the μ-RWELL detector (Blind-GEM at that time) has been developed in parallel/collaboration with GDD and Rui.
- **2014/15** – start of the R&D on μ-RWELL
- **2015/18** – R&D funded by Commissione Nazionale V – INFN in the framework of MPGD-NEXT program
- **2017/20** – TT to industry funded by Commissione Nazionale I – INFN in the framework of RD-FA program
- **2018/20** – R&D on advanced DLC deposition (DLC+Cu) by Common Project RD51 – CERN program
- **2019/20** – R&D on μ -RWELL for thermal neutron detection funded by EU – ATTRACT in the framework of the URANIA project
- **2020/23** – R&D on Cylindrical μ -RWELL funded by EU – CREMLIN-PLUS program
- **2019/20** – proposal for R&D + TT of micro-RWELL technology in the framework of AIDA++ (funded 2021/24)