DLC-based MPGDs

G. Bencivenni
on behalf of the DLC – Community
in particular
Yi Zhou , Lev Shekhtman, Kondo Gnanvo, Mauro Iodice, Paul Colas, Atshuiko Ochi, Eraldo Oliveri, Piotr Gasik & Laura Fabbietti, Piet Verwilligen, Xu Wang
& Rui de Oliveira

Introduction

In this special session on the use of DLC in MPGDs the emphasis should be given to the current status of each R&D focusing on the following topics:

- main **requirements on the DLC/DLC+Cu** production (resistivity, size, uniformity, etc …)
- requirements for the **manufacturing of the detectors**
- Any **other production-related aspects**

While **dedicated presentations on DLC production centers** are foreseen.

In the following I collected slides from the **groups working on the different technologies**.
At the end of the review I will try **to summarize the common requests of each technology.**

Rui in his presentation, on **"Production processes and problems on resistive MPGDs"**, together with the **Experts on DLC production** will **give more technical answers/comments to each question**.

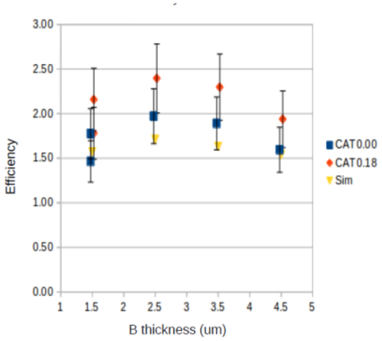
List of contributions

1. μ-RWELL @ LNF-INFN
2. μ-RWELL @ USTC
3. μ-RWELL @ Budker Inst.
4. Cyl-RWELL @ Virginia Univ.
5. Pixel-MM @ RM3+ …
6. MM-TPC @ Saclay
7. μ-PIC @ Kobe Univ.
8. Resistive GEM @ CERN
9. Resistive (TH)-GEM @ TUM
10. FTM @ INFN-Bari
11. DLC-photocathodes for Picosec

1 - μ-RWELL @ LNF

G. Bencivenni ,G. Felici, M. Gatta, M. Giovannetti, G. Morello, M. Poli Lener

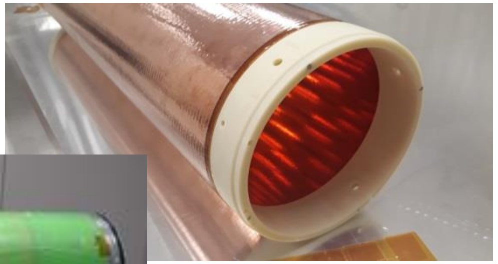
The activity of the DDG-LNF is focused on the following topics



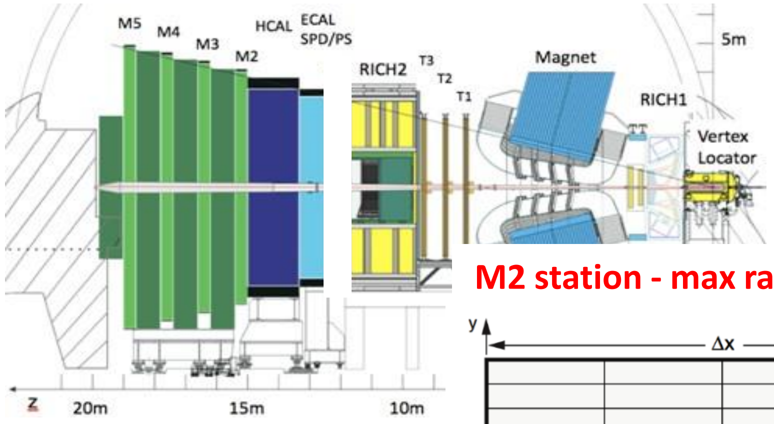
- R&D on **μ-RWELL for high rate applications** - **LHCb Muon** apparatus upgrade
- **thermal neutron detection** based on μ-RWELL technology (LNF + INFN Ferrara + ESS Linkoping – in the framework of the **ATTRACT –uRANIA - EU project**

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

- **R&D on Cylindrical-RWELL** detector (LNF + INFN Ferrara), in the framework of the **CREMLINplus - EU Project**
- **μ-RWELLs** are also proposed for **Muon apparatus and pre-shower @ CepC**
- + other new ideas …



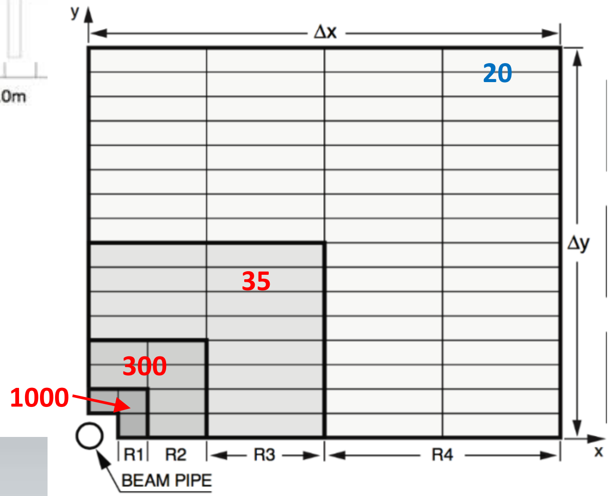
µ-RWELL for the upgrade of Muon Apparatus @ LHCb



Detector requirements:

- **Rate > 1 MHz/cm²** on detector single gap (innermost region)
- **Rate per electronic channel up to 700 kHz**
- Max **input capacitance (double gap) ≤ 100 pF**
- **Efficiency (double gap) > 97%** within a BX (25 ns)
- Long-term stability **up to 2C/cm²** accumulated charge in 10 y of operation (M2R1 with detector operated at G = 4000)
- **Pad cluster size < 1.2** (innermost region: **pad size 3×8 mm²**)

M2 station - max rate (kHz/cm²)



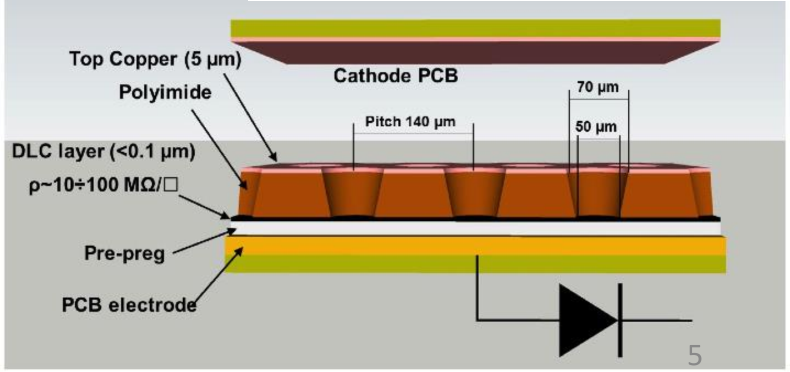
Detector size:

- **R1÷R2**: **288 detectors**, size **30x25 to 74x31 cm²**, **45 m²** det. active area → **high rate**
- **R3:** **384 detectors,** size **120x25 to 149x31 cm²**, **145m²** det. active area → **low rate**
- ~~R4 : 1536 detectors, size 120x25 to 149x31 cm², 582 m² det. - 831 m² DLC~~

Proposed solution:

The **µ-RWELL,** composed of two elements: the µ-RWELL_PCB & the cathode
The µ-RWELL_PCB is realized by coupling:

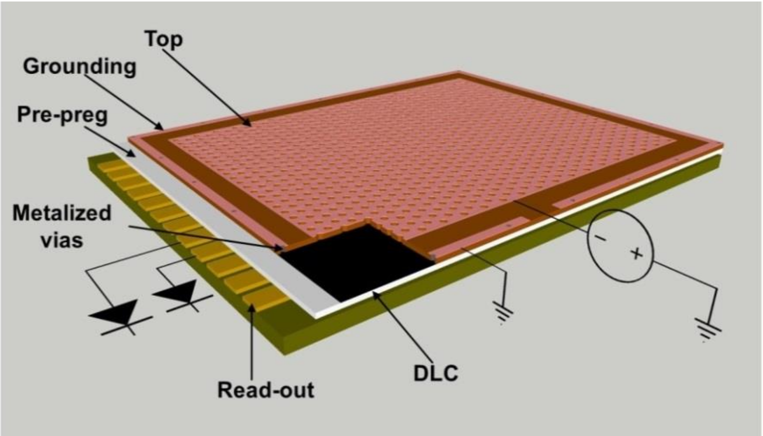
- a **WELL patterned Apical® foil** acting as amplification stage
- a **resistive layer** for discharge suppression **w/surface resistivity ~ 50÷100 MΩ/□**
- a standard **readout PCB with pad readout**

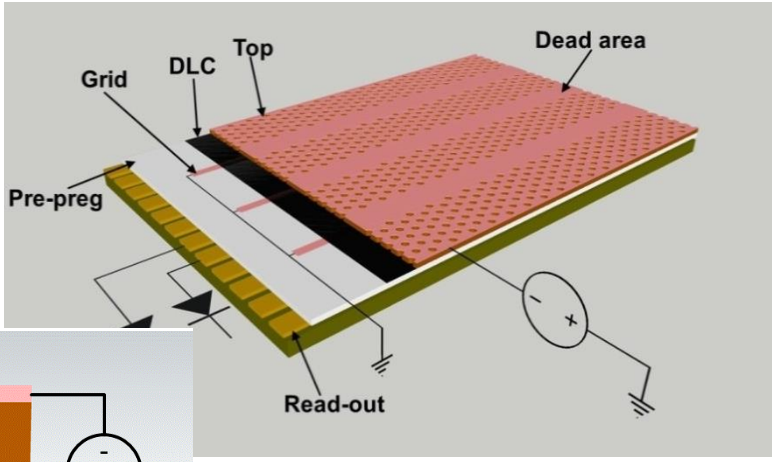


The Low & High rate μ-RWELL layouts

- The **low rate layout for R3** (large size) → the **Single Resistive Layer (SRL)** layout is a simple **2-D current evacuation scheme** based on a **single DLC layer** with a **conductive grounding all around the perimeter of the active area**

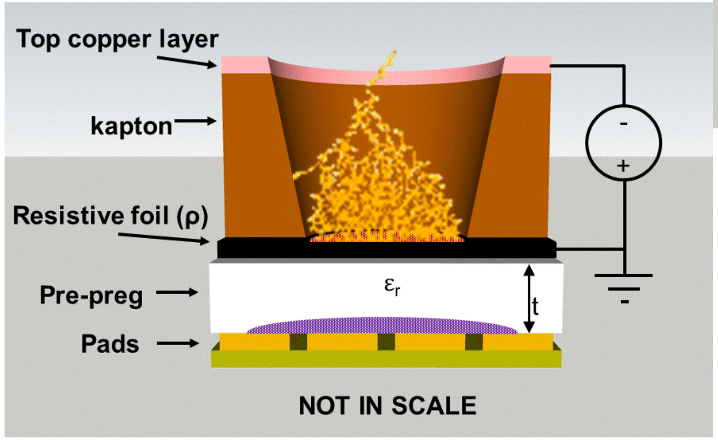
- The **high rate for R1& R2** (small & medium size) → the **SG2++ layout is a simplified HR layout based on the SRL with a 2-D grounding** by means a **conductive strip lines grid patterned on the DLC layer**. The conductive grid lines can be screen-printed or etched by photo-lithography (using **the DLC+Cu deposition technology – by USTC, Zhou Yi)**





<u>**Requirements on DLC**</u>

- **bare DLC w/resistivity 50-100 Mohm/sq → 200 m^2**
- **DLC+Cu w/resistivity 50-100 Mohm/sq → 65 m^2**



Status of the technology

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

- All detector manufacturing process/components are in our hands.
- **DLC** sputtering:
  - **large area (bare) DLC** foil sputtering at **Be-sputter in Japan**
  - **R&D on DLC+Cu** sputtering (@ **USTC – Hefei - PRC)**

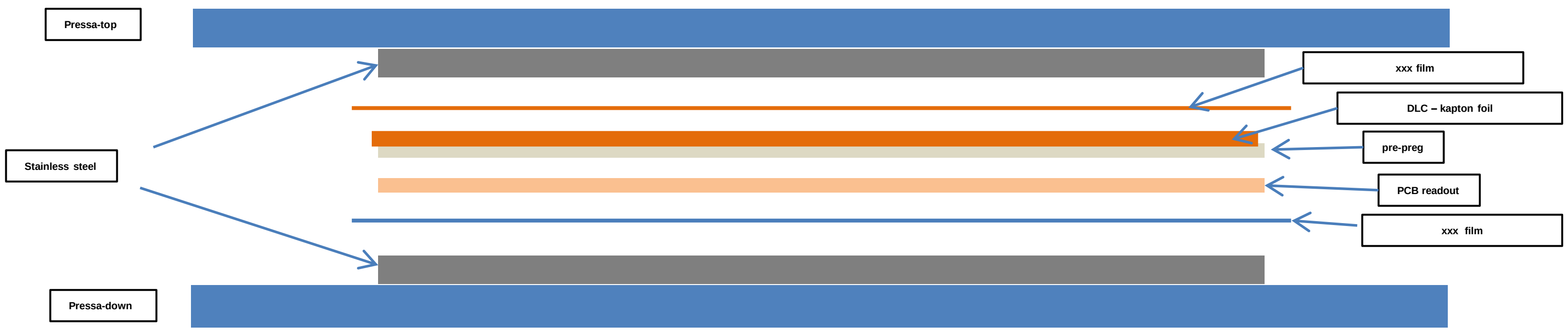
Things to do

- **large area DLC+Cu sputtering needed**
- **Validation test of DLC + aging studies**

The micro-RWELL @ ELTOS

ELTOS performs the **coupling the DLC-foil with the readout PCB** (at the moment only for the **SRL**).
The **max size of the μ-RWELL-PCB** that can be produced by ELTOS is about **600×700 mm²**. **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.



33×33 cm² active area SRL - RWELL

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

State of the u-RWELL prototypes production

# 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

DLC studies

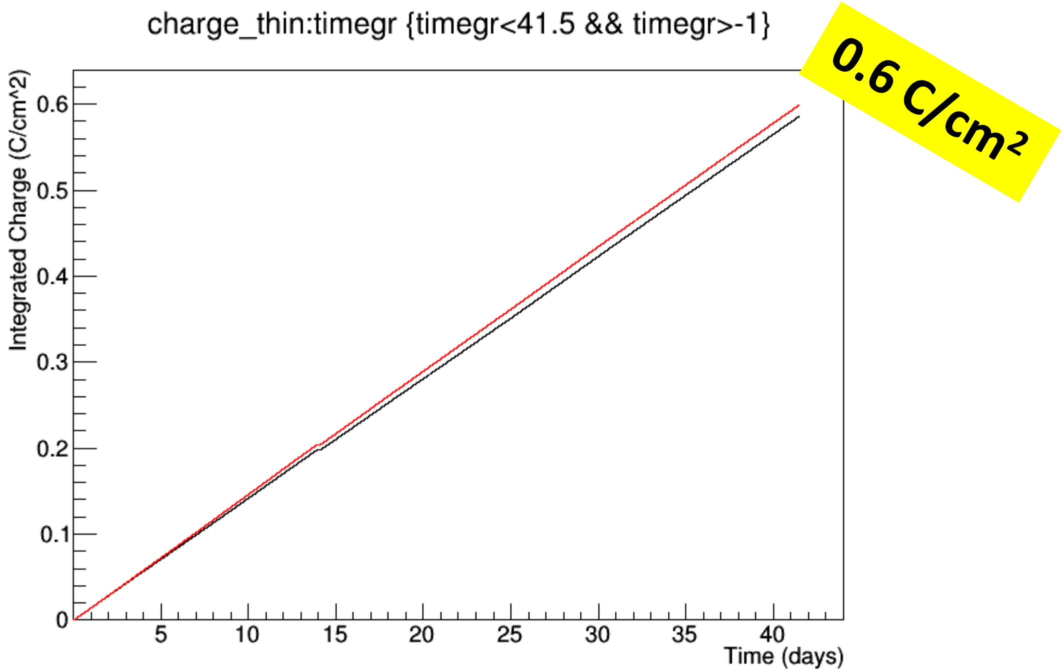
Considering the demanding requirements of the Muon apparatus at the upgraded LHCb (phase2):

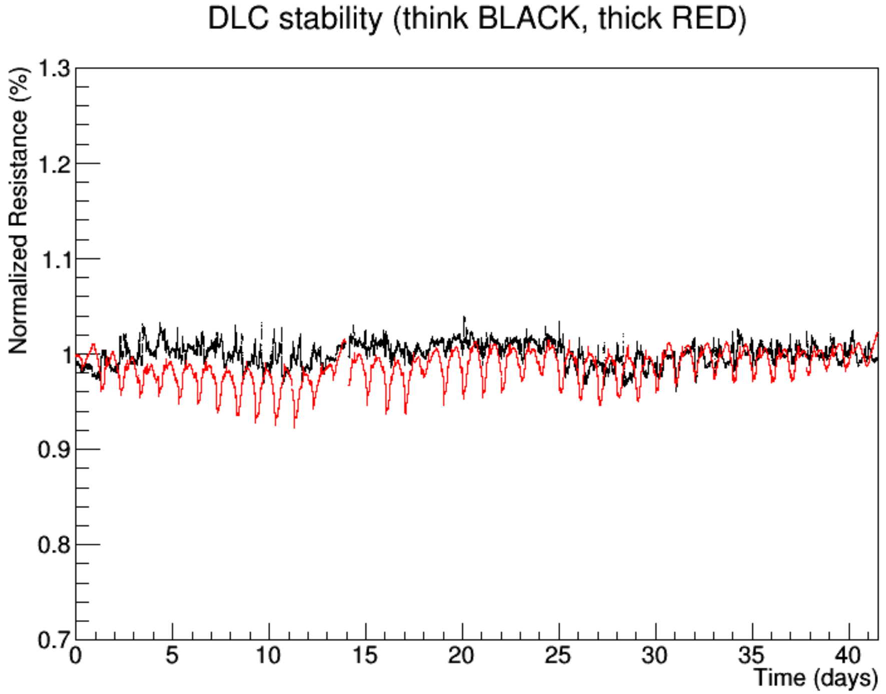
- **detector and DLC stability** must be verified **up to 2 C/cm^2** (integrated charge in 10 y of operation in M2R1 for a detector gain of 4000)

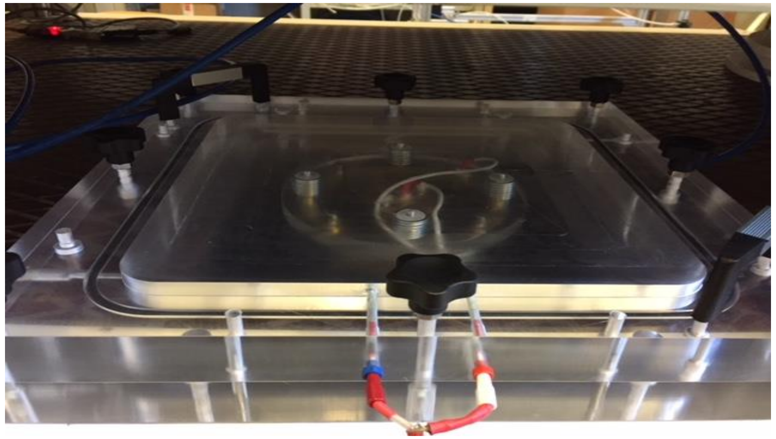
- **long term test of DLC foils** (thin vs thick) **under high current**
- **long term test of DLC foils under X-ray irradiation**
- **aging test of detectors** with different radiation (**gammas, X-ray, mip**)

- ***main task in the RD51 CP on resistive MPGD***
- ***main topic of discussion in the LHCb-Muon community***

DLC stability under current draw

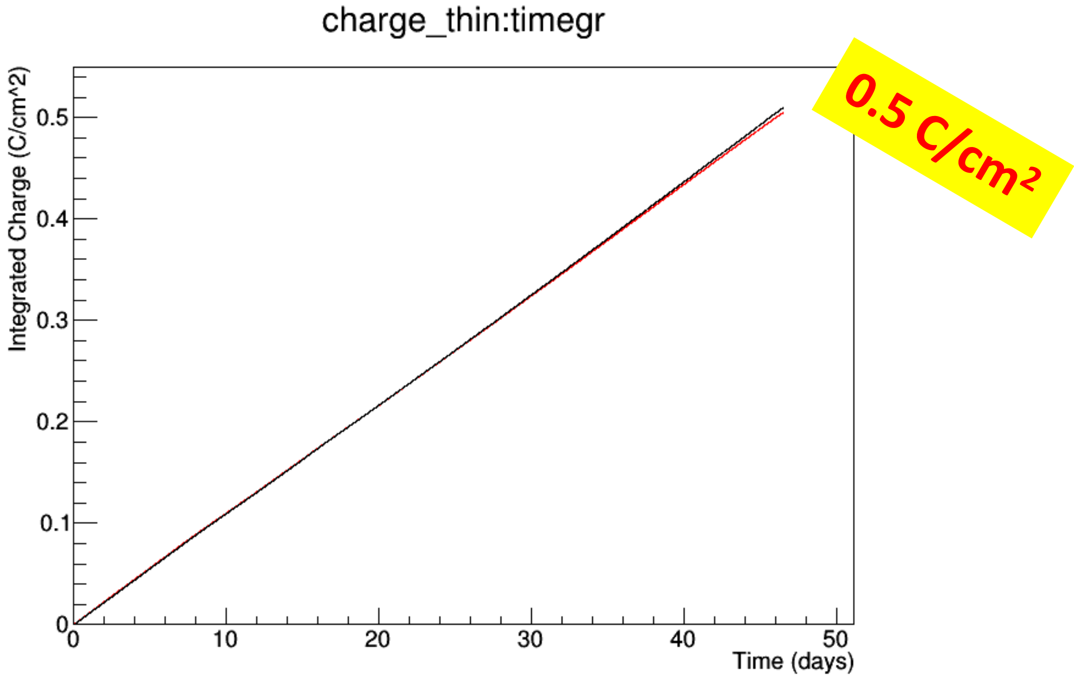


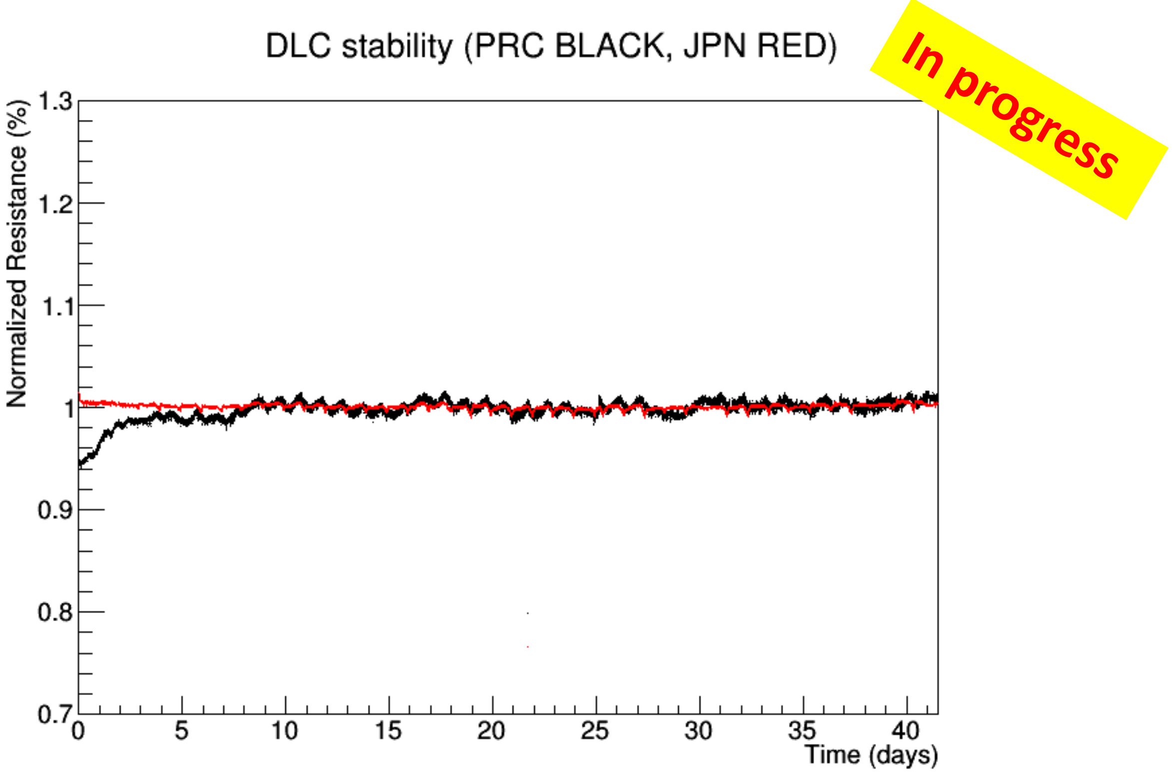


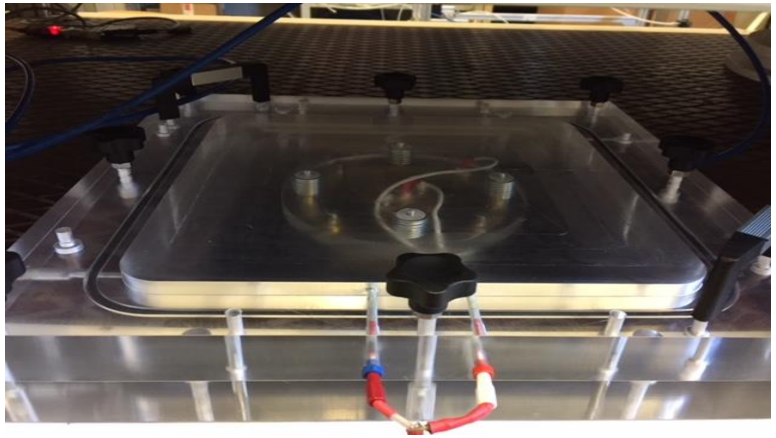


The HV and the current drawn by the DLC foil is recorded together with the ambient parameters (T,P, RH).

DLC stability under X-ray irradiation



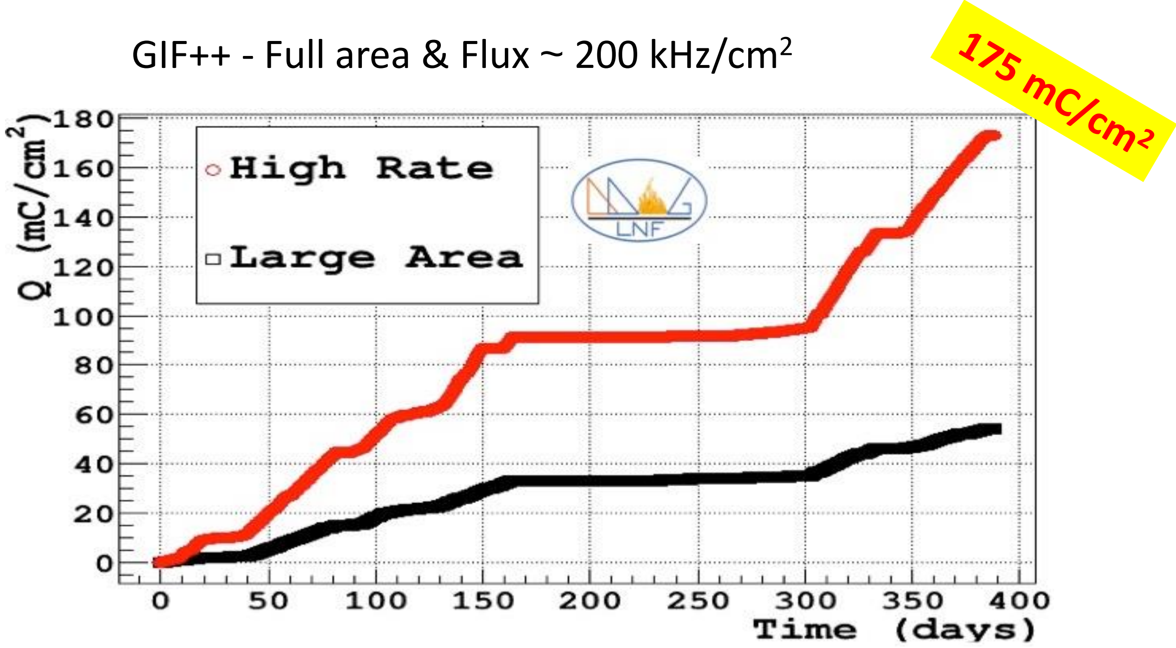




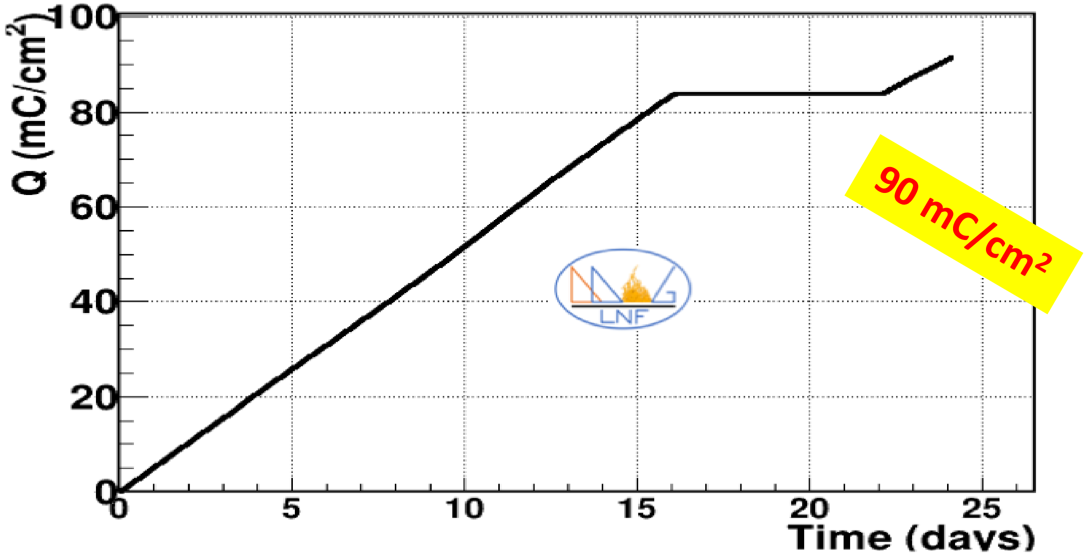
A long term test on DLC irradiated with X-rays has been recently started. We are looking at the DLC stability as a function of the radiation dose (Chinese-DLC vs Japan-DLC)

Detector aging studies

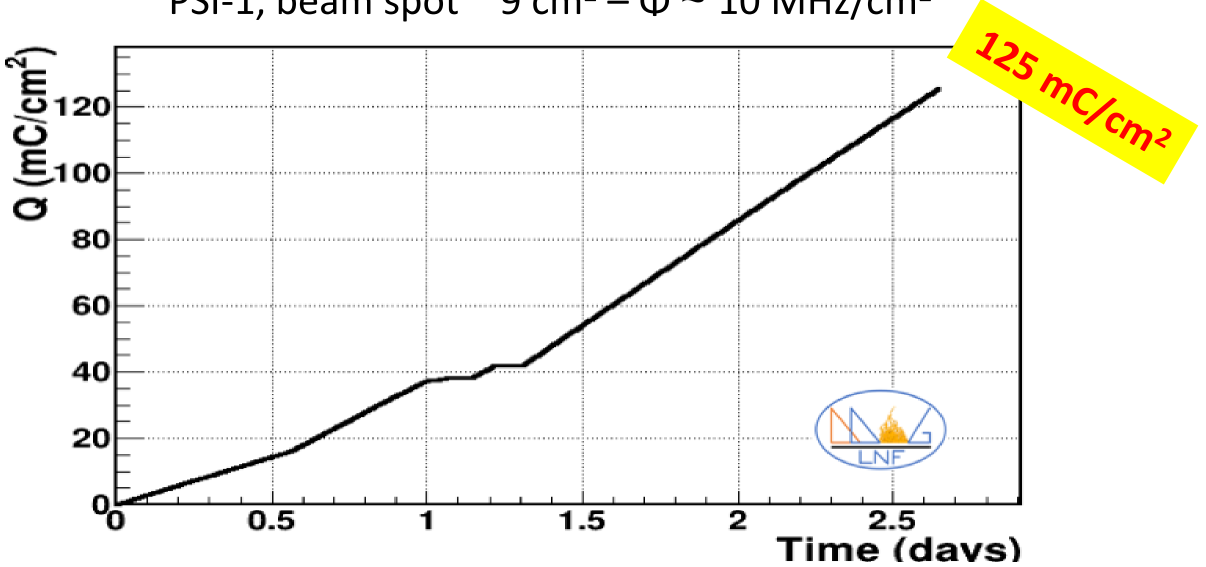
GIF++ - Full area & Flux ~ 200 kHz/cm^2



X-Ray gun- spot 50 cm^2 Φ ~ 700 kHz/cm^2



PSI-1, beam spot ~ 9 cm^2 – Φ ~ 10 MHz/cm^2



- Unfortunately **our proposal to irradiate** some detectors in parasitic mode for several (4-6) months **at PSI has not been accepted**
- We are then focusing our efforts on the **slice test at LHCb (2021-2022)**

Issues & requirements for detector production

- **Control of DLC resistivity**
  - monitoring the DLC resistivity after detector production
    - LR layout → adding conductive bars (vias) on the top of the uRWELL amplification stage
    - HR-SG layout → the grid can be easily used to measure the resistivity
- **Decrease of DLC resistivity** for the DLC+Cu foils after Cu sputtering as well as during successive manufacturing steps done by Rui (pressing phase of the DLCed kapton on the PCB, pressure or/and temperature ???)
- **Need to define a QC standard for the produced chambers:**
  - HV=650 V & I<1 nA in controlled atmosphere, Nitrogen RH< 10 % ???
- **Need of a manufacturing data sheet of each detector** with the details of each production step (DLC resistivity after each step, geometrical parameters – outer and inner well diameter – temperature and pressure cycles during the PCB pressing, technical procedure for removal of Cu/Cr/DLC…, etc)
- **Implementation of a sort of production database** of the u-RWELL could supply the interesting information of the production yield
- Defining a **standard design of LR & HR-SG** prototype detectors (work in progress !!! with Rui)

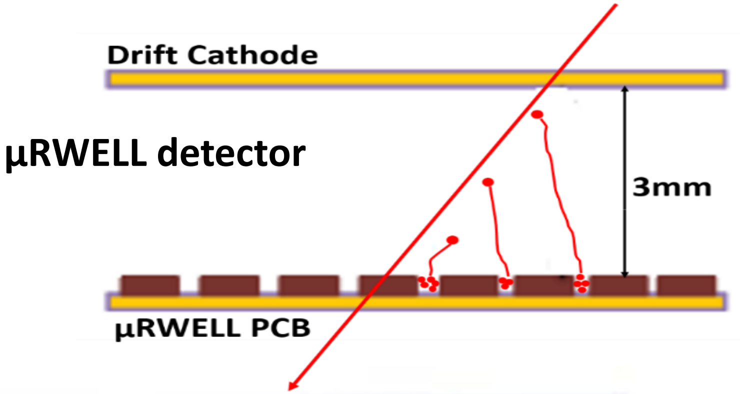
2 - μ-RWELL @ USTC

Zhou Yi
USTC (PRC)

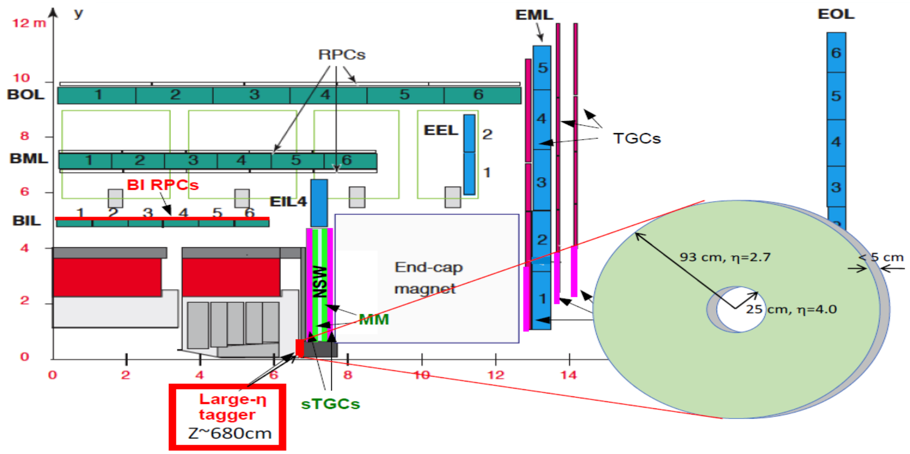
Motivation of µRWELL R&D

µRWELL: a novel MPGD combines features of MM and GEM

- **Compact** & high granularity
- **Spark protected**
- Without gluing & stretching, **fast assembling**
- Easy to make a **cylindrical detector**



Application



High-eta muon tagger

Cylindrical µRWELL for STCF inner tracking

- **ATLAS phase-2 upgrade: µRWELL is a candidate detector for high-eta muon tagger**
- **STCF: Cylindrical µRWELL detector for inner tracking detector**

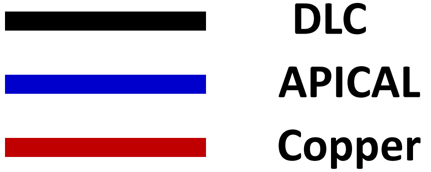
DLC electrode

Diamond-like Carbon (DLC): A high-quality resistive material, applied as resistive electrode to suppress the discharge in μRWELL.
Magnetron Sputtering: an effective way for DLC coating at low-temperature,

Technical challenge in DLC deposition

- The resistivity of **DLC depends on many preset parameters** (thickness, chamber vacuum degree, APICAL roughness …), a lot of calibration work needed before mass production in every batch
- **The resistivity change of DLC after copper coating may be caused by the high temperature during copper deposition**
- **Transition layer (Cr) between DLC and copper is needed in order to improve the adhesion between DLC and copper. The optimization of the transition layer is still on going.**

DLC/APICAL substrate

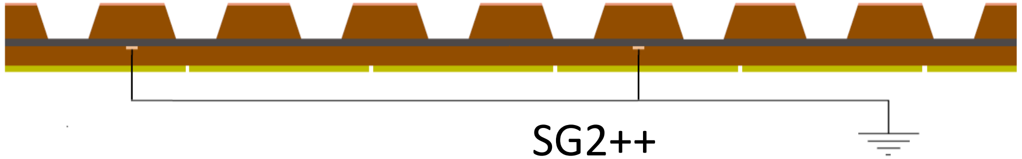


Copper/DLC/APICAL substrate

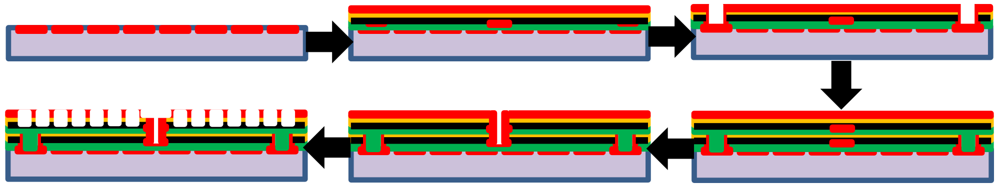
High-rate μRWELL

Two different high-rate μRWELL have been presented and fabricated based on Copper/DLC/APICAL.

1. **1-DLC layer μRWELL with fast grounding lines (SG2++)**
2. **2-DLC layers μRWELL by Sequential Build Up method (SBU)**



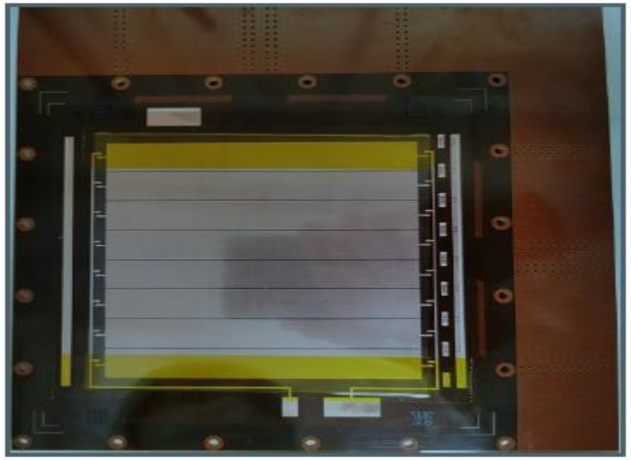
SG2++



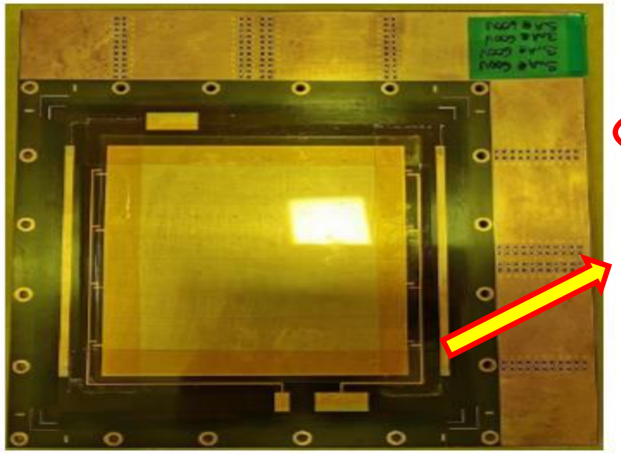
SBU

A **high pressure of 20 kg/cm²** was applied in order to glue DLC/APICAL substrate and PCB board, which may have **unknown influence to the DLC resistivity this effect should be understand in the next step.**

- An **SG2++ μRWELL and an SBU μRWELL** prototypes have been built at CERN
- These two detectors were tested with 8-keV copper X-rays, **the highest gain is about 1000 and then the discharge appears.**



SG2++ μRWELL PCB



SBU μRWELL PCB

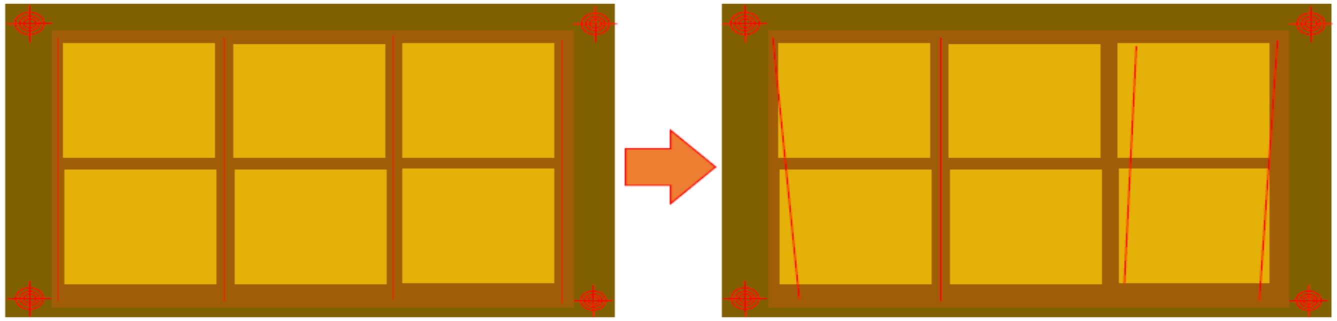
The **resistivity of DLC is several MΩ/☐**, much less than the expected value (before fabrication: 50 MΩ/☐). **We guess that the resistivity of DLC coating decreased a lot after copper coating and gluing process,** which results to the lower maximum HV.

Large area μRWELL

Large area μRWELL have to be developed to satisfy different applications, for example, STCF inner tracking require the μRWELL detector size is ～m^2.

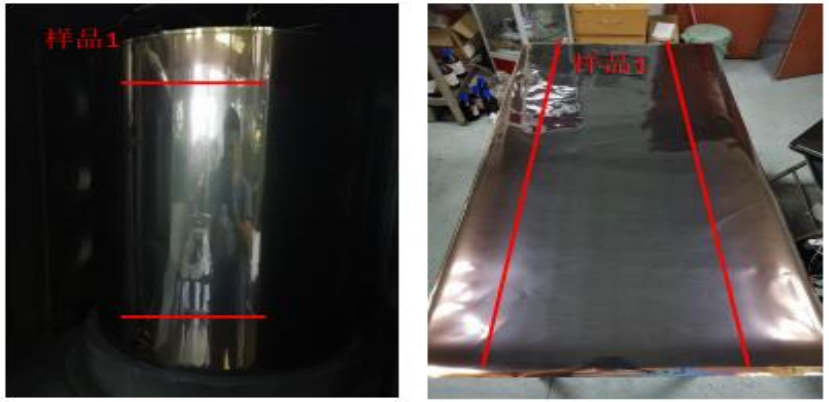
Existing problems in large area μRWELL manufacturing

alignment problem w/SG and DRL on large area



- **Large area APICAL foil have a large deformation**
- For SG2++, after gluing onto the readout PCB, it is impossible to see the fast grounding lines, **so it is quite difficult to align the mask for APICAL etching**
- The DRL – SBUcould also have alignment problems

R&D on large area DLC sample by Hauzer coating system



Large area DLC sample (1.2m×0.6m)

- Calibrate the relationship between DLC resistivity and preset parameters (temperature, vacuum degree, thickness…) of Hauzer coating system
- **A batch of large area DLC sample have been made, the resistivity shows a large value on the top and bottom side, for 1.2m × 0.4m, the resistivity uniformity is 25% (sigma/mean)**

The resistivity repeatability and uniformity should be improved in the next step.

3 - μ-RWELL @ Budker Institute

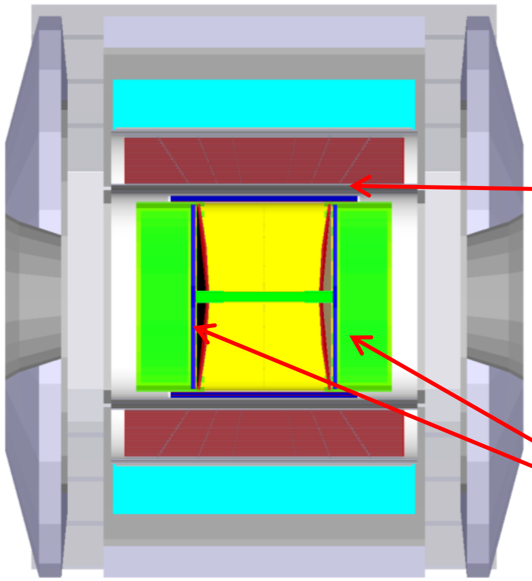
Lev I. Shekthman
N.A. (at the moment !!!)

3 - μ-RWELL @ Budker Institute

GOAL: upgrade of the CMD-3 Tracking System

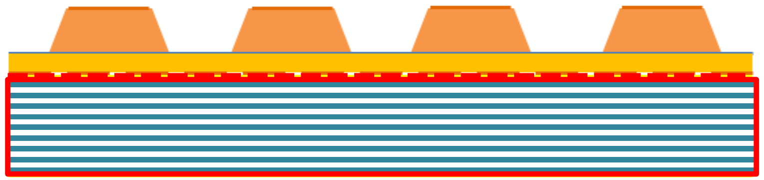
E.Batalov, G.Fedotovich, A.Kozyrev, V.Kudryavtsev, A.Ruban, **L.Shekhtman**

Budker INP SB RAS, Novosibirsk, Russia
Novosibirsk State University, Novosibirsk Russia



Cylindrical Z-chamber

End-cap discs



- top electrode, copper foil with holes, thickness 5μ
- WELLs with typical diameter about 50 μ
- resistive layer on kapton foil
- Two readout layers
- Multilayer PCB, rooting signals to connectors at the edge

Detectors design

End-cap discs

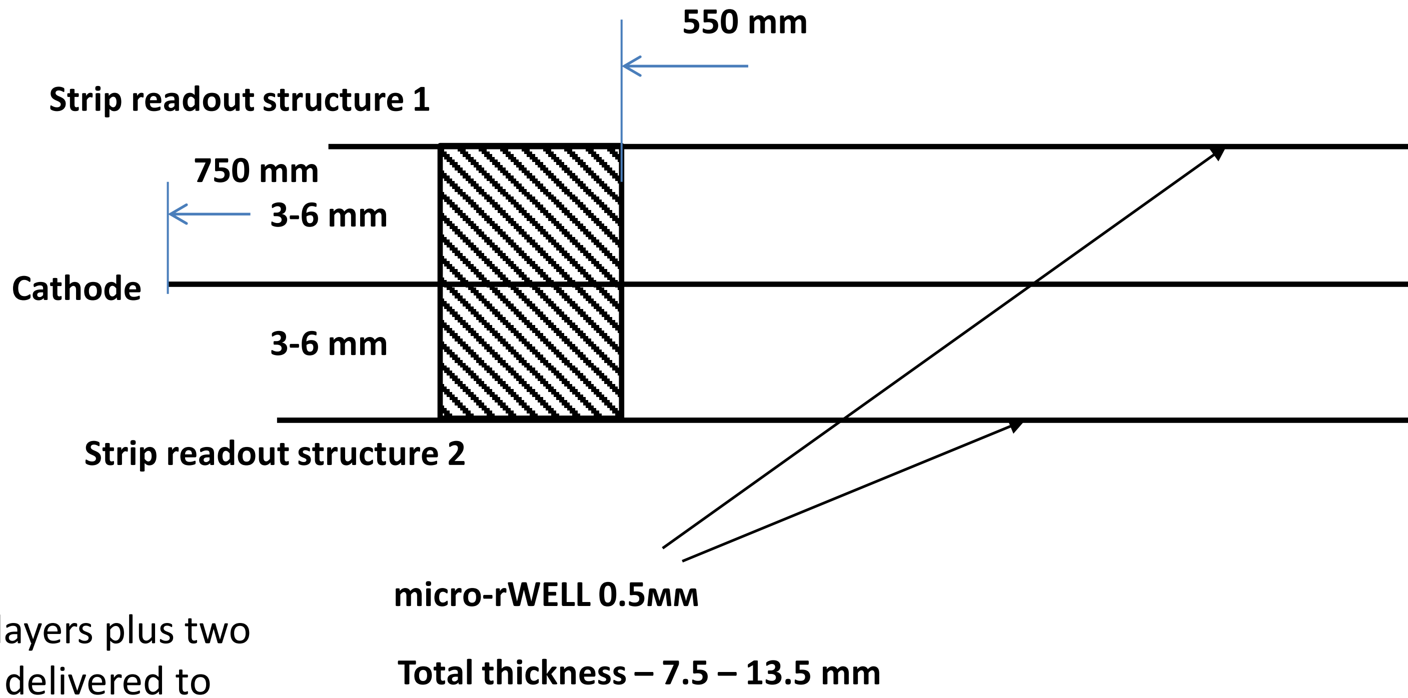
Inner dia.: 100 mm - Outer dia.: 580 mm

Current status of end-cap discs

- **two uRWELL discs** with necessary design of the readout layers plus two GEMs of the same size have been produced at CERN and delivered to Novosibirsk in December 2019
- **inner and outer rings** and **cathodes** have been produced
- ready for assembly

Z-chamber CMD-3

Cylinder diameter: 617-643 mm , length : 550 - 750 mm



4 - Cylindrical µRWELL R&D for an EIC Detector

Kondo Gnanvo

University of Virginia

R&D Cylindrical µRWELL as EIC Central Tracker

Two options under study

Low rate layout

Low mass & large area

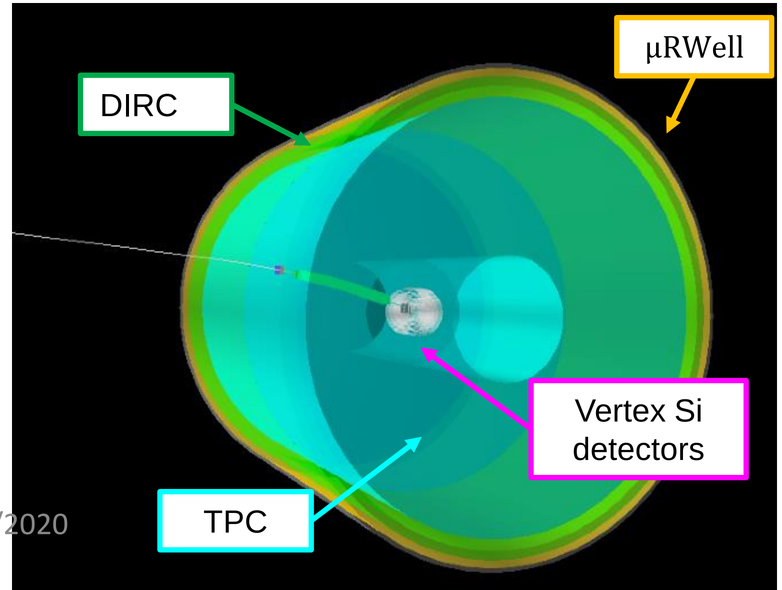
DLC optimization

- **R&D on Low-mass Cylindrical µRWELL** for application as EIC tracker in the barrel region (3 Institutes **Florida Tech, UVa and Temple U.)**
  - **Single layer option: Additional layer to TPC to provide fast signal tracking and direction vertex seed** (in µTPC mode) for both TPC and DIRC
  - **Multi layers option: Full barrel tracker ⇨ up to 6 layers** for the barrel region as an alternative for the TPC for a second EIC detector
- **EIC relatively low rate experiment** ⇨ performance of **standard µRWELL** with **simple DLC structure** should be OK

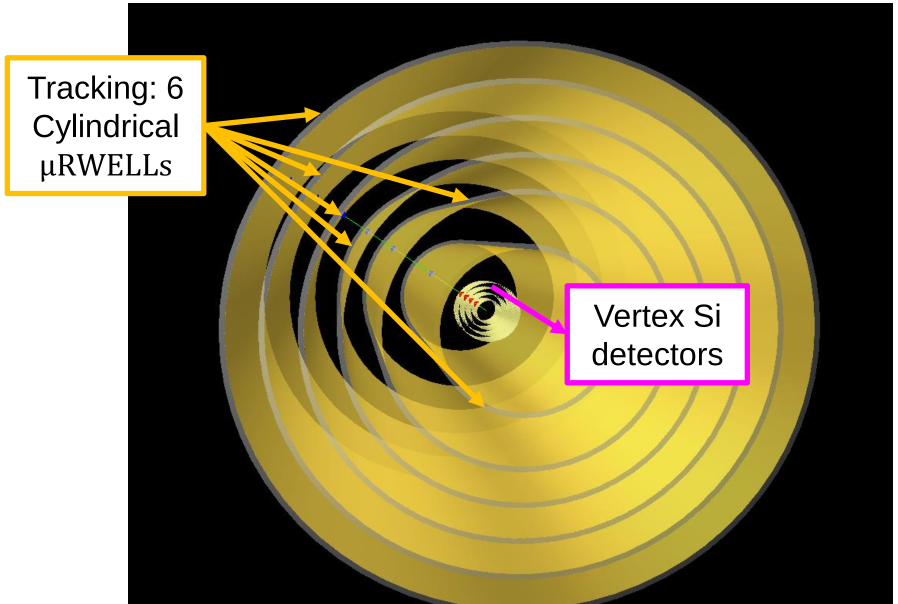
Challenges:

- Minimization of µRWELL material **is a must ⇨ Low-mass µRWELL** is where most of our R&D will be concentrated on (DLC layer is not an issue i
- Investigate **splicing method** for large area capability ⇨ That is where most of our R&D will be concentrated on **(DLC layer is concerned here**)
- Develop **2D readout layer (U-V strips)** with low channel count and high spatial resolution performance ⇨ **Optimization DLC layer characteristics (charge sharing capabilities vs. mitigating spark rate probability and energy**)

Single uRWELL layer option



multi uRWELL layers option



EIC Central Tracker: Real size Cylindrical µRWELL prototype

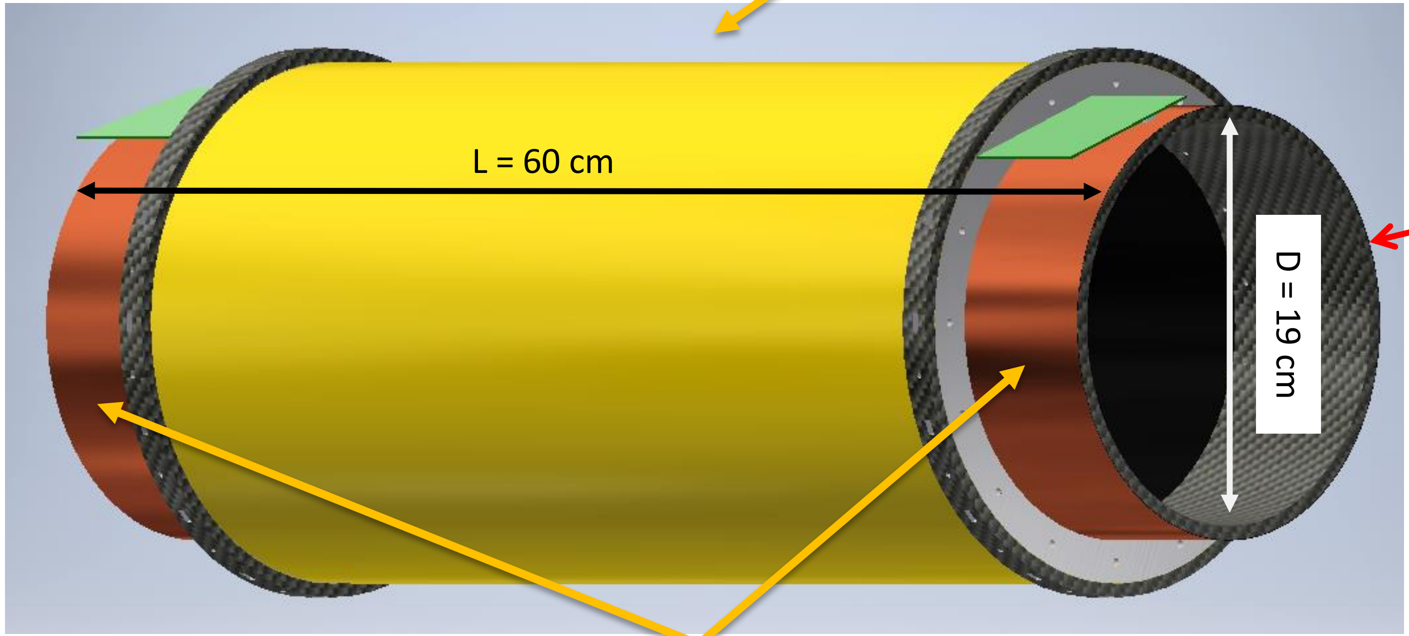
- **Goal**: Build an **"EIC size cylindrical µRWELL prototype" by July 2022** that will operate with large drift gap (20 mm) in µTPC mode
  - Develop low-mass µRWELL foil With 2D U-V stereo angle strip readout
  - Implement splicing technique for large area and small dead area
- **Our interest in DLC technologies:**
  - **Long term stability of DLC (ageing etc …),**
  - Issues with splicing µRWELL foils that the community can think of …

µTPC mode

DLC stability

Current design

"Drift Foil" (kapton foil, 50 µm)

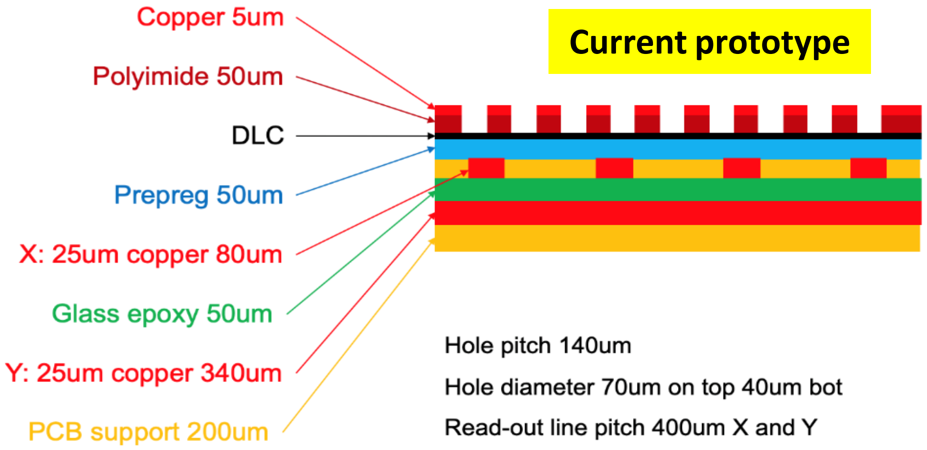


"µRWELL, DLC & Readout foil composite"

Real size proto

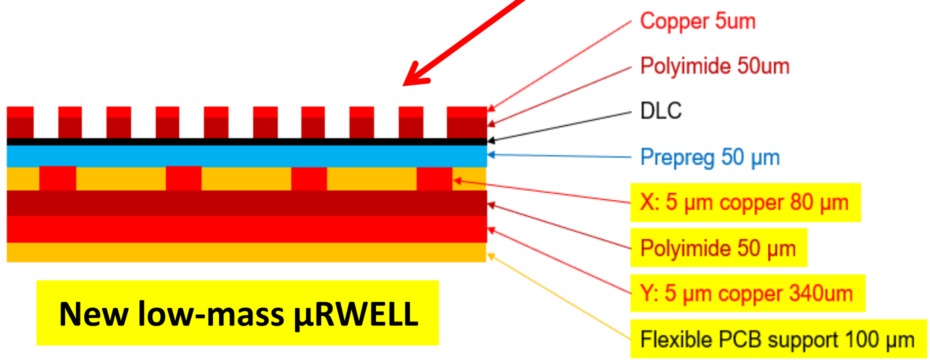
R&D Low-mass uRWELL foil

Current prototype



Hole pitch 140um
Hole diameter 70um on top 40um bot
Read-out line pitch 400um X and Y

Low mass r/o



New low-mass µRWELL

5 - Pixel-MM for HR applications

M. Alviggi[b,c], M.T.Camerlingo[a,f], V. Canale[b,c], M. Della Pietra[b,c], C. Di Donato[b,d], P. Iengo[e], M.Iodice[a], F. Petrucci[a,f], G. Sekhniaidze[b]

[a]INFN Roma Tre, Rome, Italy, [b]INFN Napoli, Naples, Italy, [c]Università di Napoli Federico II, Naples, Italy, [d]Università di Napoli Parthenope, Naples, Italy, [e]European Center for Nuclear Research, CERN, Geneva, Switzerland, [f]Università di Roma Tre, Rome, Italy,

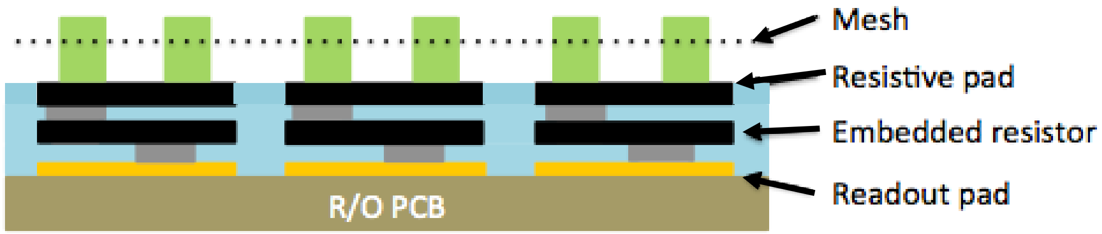
GOAL: Development of **resistive Micromegas** aimed at operation under very high rates ~**10 MHz/cm²**

- **R&D BASIC STEPS**
  - **Optimisation of the spark protection resistive scheme**
  - **Implementation of Small pad readout** (allows for low occupancy under high irradiation)
- From existing R&D we aim at **reducing the pad size from ~1cm² to < 3mm²**
- **Possible applications**
  - **ATLAS** very forward extension of muon tracking (**Large eta Muon Tagger** – option for future upgrade),
  - **Muon detectors** at Future Accelerators
  - Hadron sampling **calorimetry**

Small Pad Micromegas – Experience with DLC

Two different implementations of the Resistive layer

PAD-Patterned resistive layer



PAD-P Version 2 **(NO DLC):**

(version 1 was a test with full screen-printing soon abandoned)

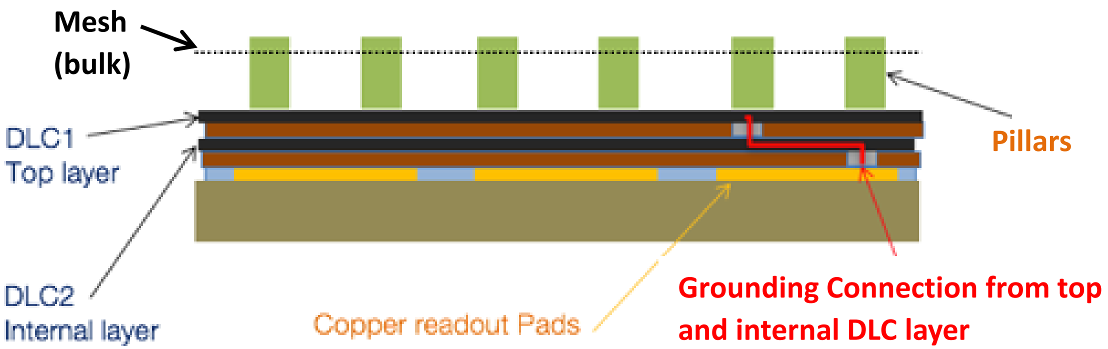
- Embedded resistors by Screen-Printing
- Resistive pads by paste filling of photoimaging created vessels

PAD-P Version 3 (under construction – not tested):

- Embedded resistors by **DLC** pad-patterned etching
- Resistive pads by paste filling of photoimaging created vessels

???

Double **DLC** (Diamond Like Carbon) uniform resistive layer



DLC Version 1:

- Double **DLC** layer a' la uRWell with connections vias to ground

DLC Version 2:

- Same as version 1 using **copper-clad DLC** adopting the sequential Build up construction process (**DLC-SBU**)

Prototypes Construction – DLC Version 1

PAD-P Version 2 (September 2016) [first Version 1 July 2015 – full screen print was abandoned]

- NO DLC used
- Independent resistive pads with embedded resistors
- Resistance for each resistive pad to anode pad in the range R = 3-7 MOhm

First tests w/Japanese DLC (NO Cu deposition)
Classical double layer - NO SBU technology

DLC Version 1 (DLC50 August 2017 – DLC20 May 2018) :

- Double **DLC** layer
- DLC Production: JAPAN (Atsuhiko) [to be confirmed by Rui]
- Two prototypes with resistivity values APPROXIMATELY:
  - 50-80 MOhm/sq → DLC50
  - 20 MOhm/sq → DLC20

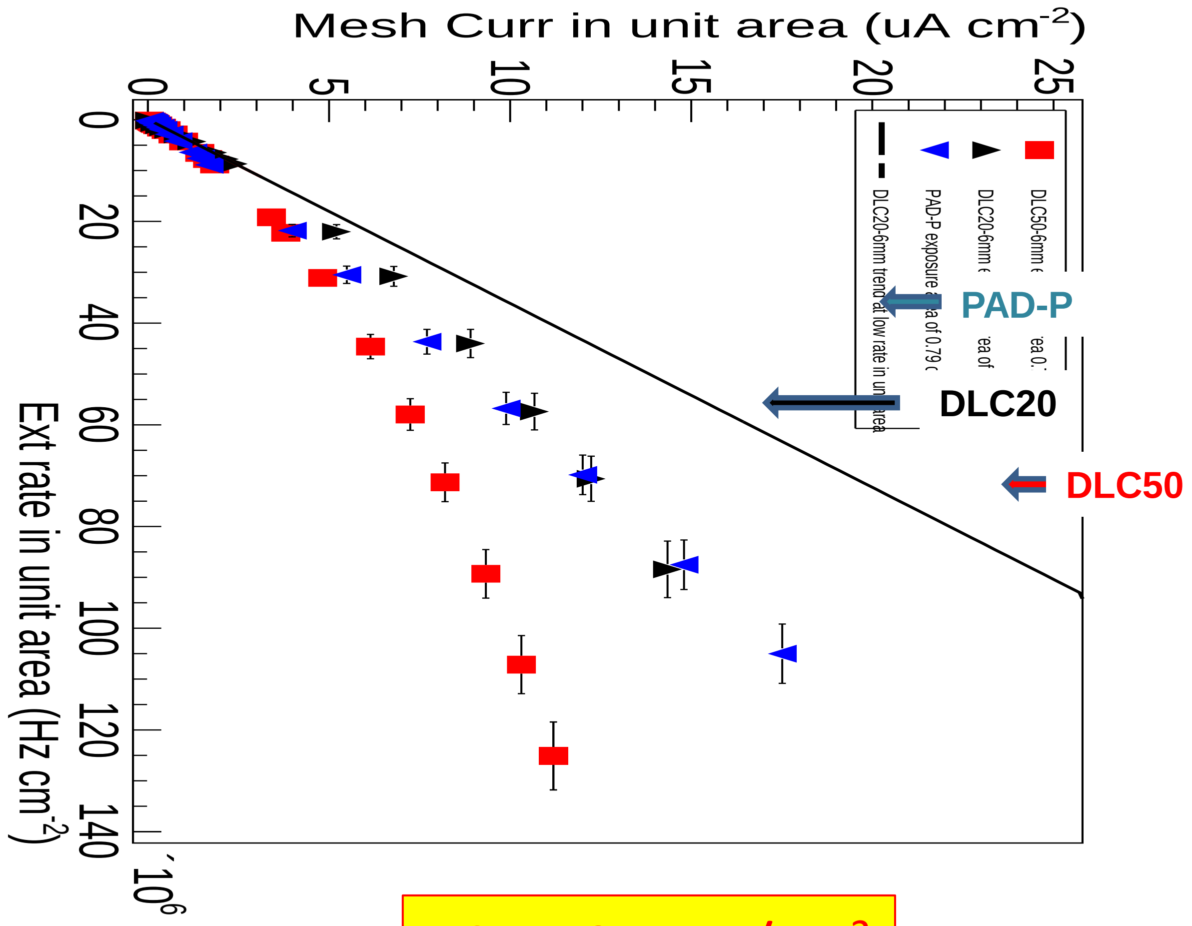
Large uncertainty on DLC resistivity

- No systematic measurements on the foils nor on final detectors → large uncertainties on resistivity

DLC20 and DLC50: X-ray measurements

Deviation from linearity under X-rays at very high rates

- Nominal ~20 MΩ/sq Vs nominal 50-70 MΩ/sq
- Deviation from linearity dominated by Ohmic Voltage drop
- As expected DLC 50 has a more pronounced drop
- A comparison is also done with PAD-P Pad-Patterned prototype



RC ~10 MHz/cm^2

Prototypes Construction – DLC Version 2

DLC Version 2 (July 2019) :

- Same as DLC version 1 using now **copper-clad DLC (USTC – PRC)** adopting the Sequential Build Up construction process (DLC-SBU)
- The advantage is to better control the precision drilling for the vias: **easier photolithographic construction process**
- **improving of the centering of the pillars with the silver vias (every 6 mm)**

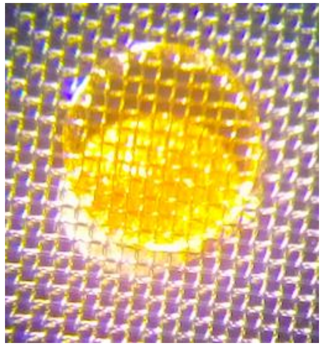
2nd test w/USTC - DLC+Cu SBU technology

Easy production, NO silver paste application for vias metalizaztion

Producer: Yi Zhou

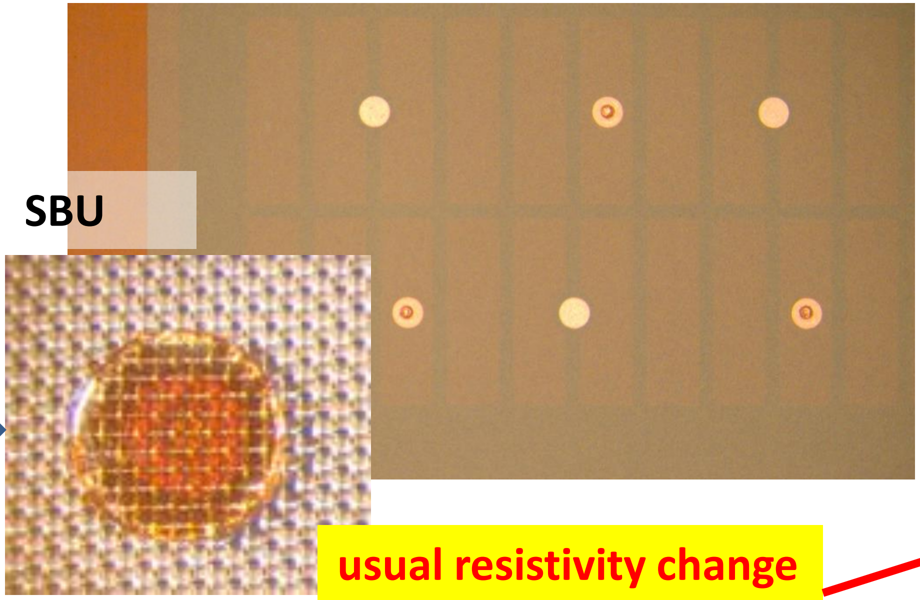
Copper-clad DLC process requested on polished APICAL:

- DLC deposition : target 50 MΩ/sq
- Copper: at least 5 μm



DLC20/50

SBU



usual resistivity change during manufacturing

Built TWO "ideally" identical prototypes: SBU1 and SBU2

Both used the same DLC with a declared resistivity of 60 MΩ/sq

Results after construction:

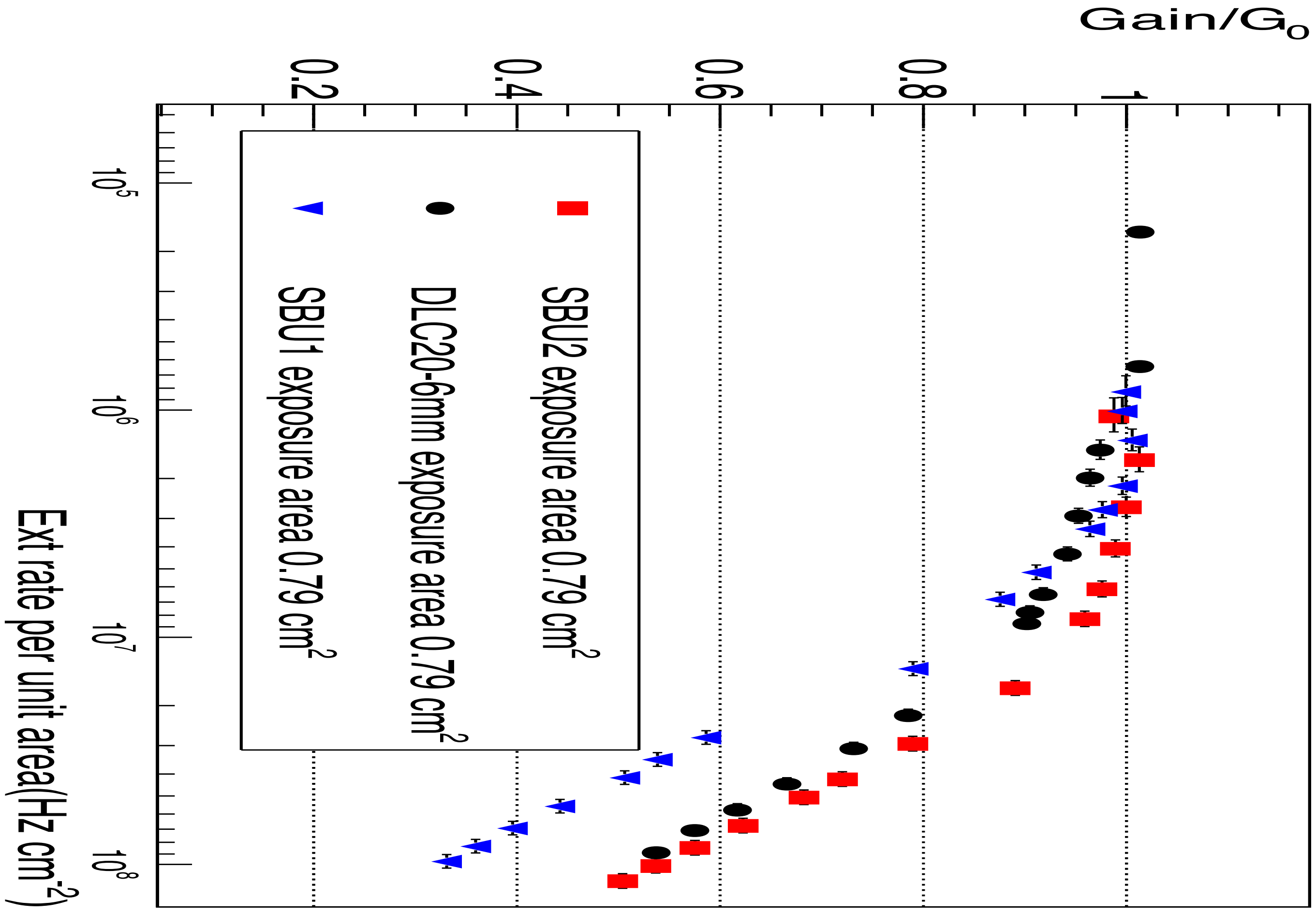
For both, SBU1 and SBU2 the resistivities are:

- **Bottom (embedded) layer: 35 MΩ/sq**
- **Top layer 5 MΩ/sq !!!**

NOT YET UDERSTOOD THE CAUSE OF THIS DRAMATIC DECREASE OF RESISTIVITY

DLC-SBU1 and DLC-SBU2: X-ray measurements

RC ~ 10 MHz/cm^2



Gain drop under X-rays at very high rates

- DLC-SBU1 Vs DLC-SBU2 expected to behave similarly
- **More significant drop in SBU1 indicate however a higher resistivity**
- A comparison is also done with DLC20 prototype

Prototypes Construction – PAD-P Version 3

PAD-P Version 3 (February 2020)

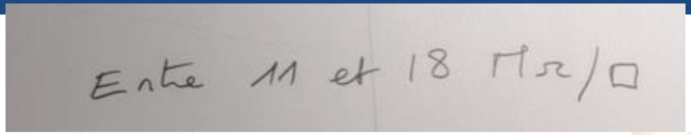
- Reproduction of a pad-patterned prototype
  - First attempt using the same technique of PAD-P Version2: Failed due to bad control of resistive paste resistivity after screen printing and pressing
- **Use a DLC foil for the embedded resistor etched to form individual pads**
- DLC Production: ??? [Rui, Olivier?? See photo]
- **Prototype now under construction:**

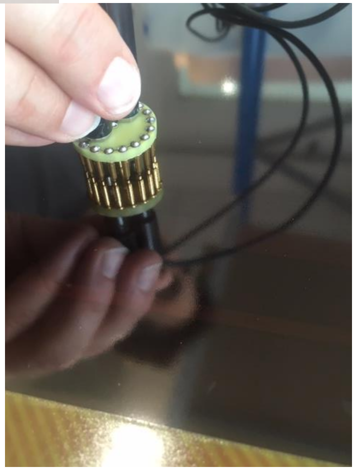
  Started from a foil with **R = 11 – 18 MOhm/sq**

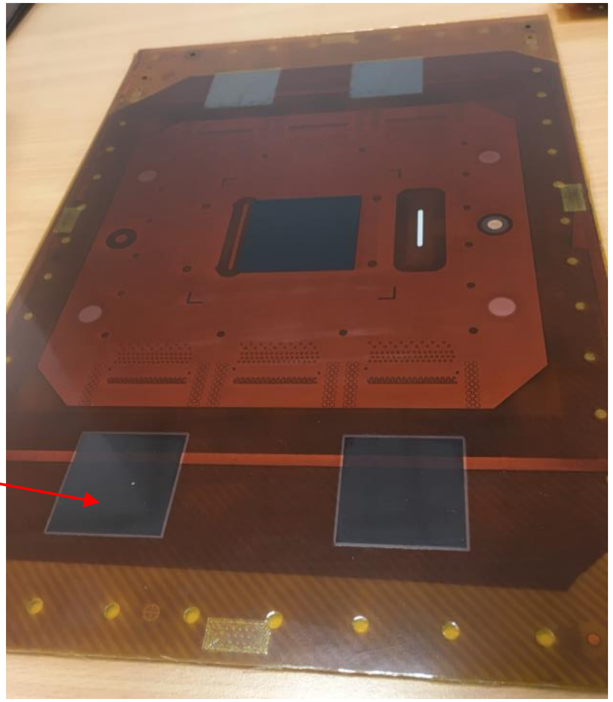
  In theory a reduction by more than half is expected after the TWO pressing steps (step1: DLC, step2: the photoimageable coverlay)

  Measurements in the open squares after second pressing was ~15 MOhm/sq

  → No reduction in resistivity!







Construction still in progress

NO resistivity change during manufacturing (?)

SUMMARY – pixel MM

- As several times reported in RD51 weeks and at Conferences **both resistive schemes for small-pad micromegas (pad-patterned and uniform layers DLC) result in very good performance** with complementary advantages (best configuration depends on the conditions and requirements)
- We can **take advantage of the Copper-clad DLC to ease the precision of construction**

HOWEVER:

- **We greatly suffered for no-control of the resistivity** (also availability of foils of a given value was very difficult)
- **Weak control of evolution during the production process** (e.g. after pressing)
  - Not only an issue with DLC, also with screen-printing the situation is not better (possibly depending on the paste)

FUTURE PROSPECTS – Main Requirements:

- From all tests done so far, for our typical layout **the optimal surface resistivities are**:
  - About **10 MΩ/sq for the embedded resistors** of the PAD-Patterned prototype (no need for copper-clad
  - About **20 (30 ?) MΩ/sq copper-clad for the uniform double DLC layer**
  - Size: actual **size is below 10x10 cm^2.** Eventually we would **like to scale to 30x30 cm^2 (40x40 cm^2?)**

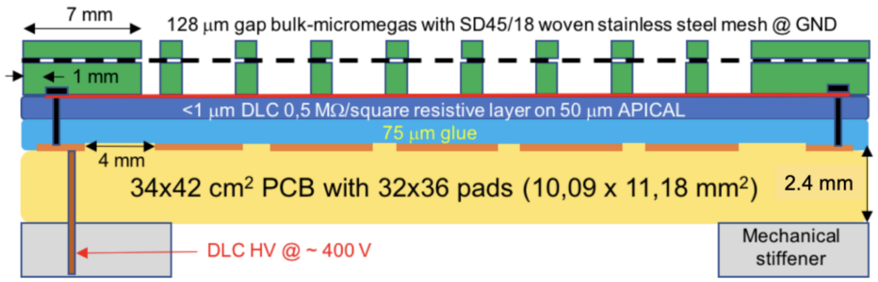
6 - MM-TPC @ Saclay

P. Colas

TPCs for ILC and T2K

- **Requirements from physics:**
  - **ILC:** mainly a point resolution of 100 μm (at all drift distances) and 5% dE/dx resolution
  - **T2K** : mainly dE/dx resolution (8%) and point resolution better than 700 μm
- **Use of DLC in Micromegas TPCs to**
  - **Stabilize Micromegas**
  - **Spread the charge to improve point resolution and save electronic channels**

The **charge spreads** according to a diffusion equation, where the **τ** parameter **is equal to RC**, the **resistive-capacitive continuous network**. **R surface resistivity per unit of surface**, and **C capacitance per unit of surface**



$$C = \frac{\varepsilon_0 \ \varepsilon_r}{d}$$

$$\frac{\partial \rho}{\partial t} = \frac{1}{RC}\left[\frac{\partial^2 \rho}{\partial r^2} + \frac{1}{r}\frac{\partial \rho}{\partial r}\right]$$

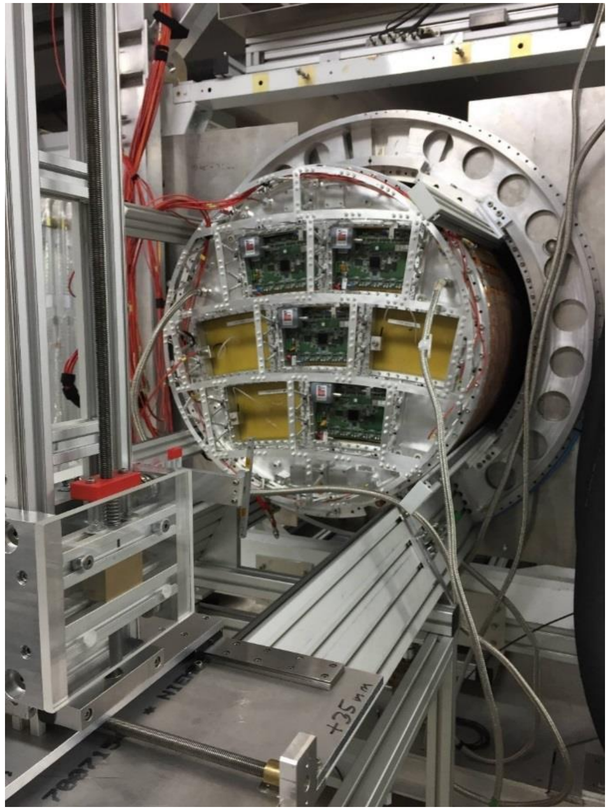
$$\Rightarrow \rho(r,t) = \frac{RC}{2t} e^{\frac{-r^2 RC}{4t}}$$

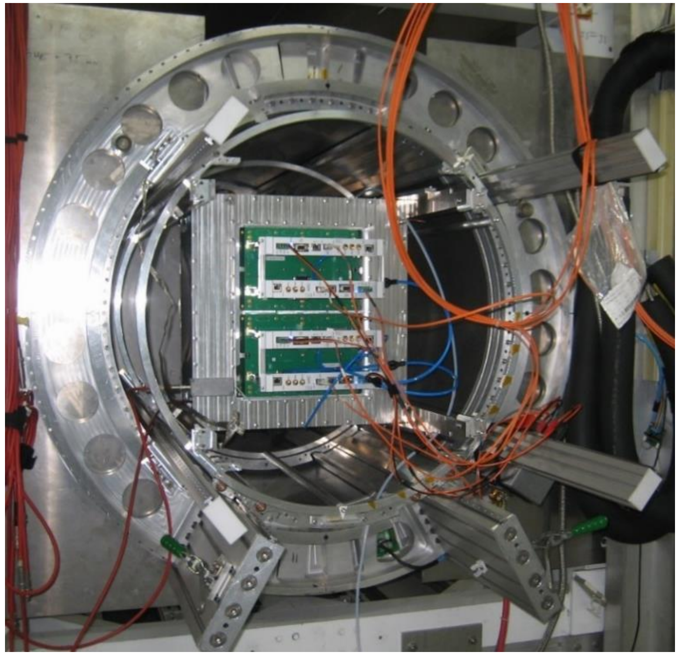
RC ~ 100 ns/mm² allows **a charge spread** over a **few mm²** for an **integration time of the electronics of O(100 ns)**

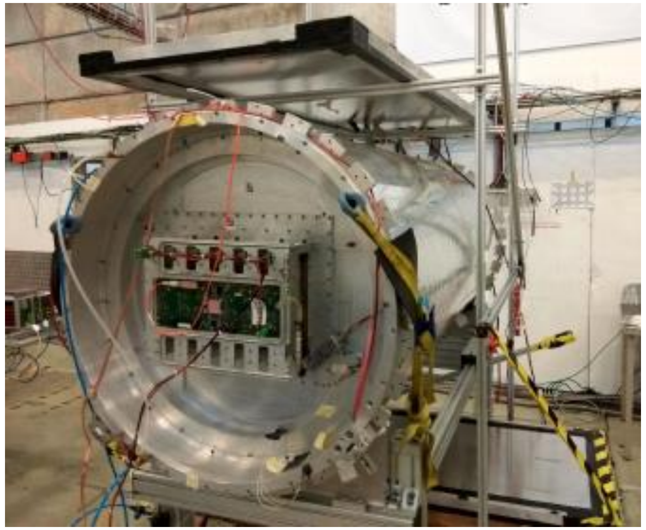
M.S. Dixit et.al., NIM A518, 721 (2004) , M.S. Dixit & A. Rankin, NIM A566, 281 (2006)

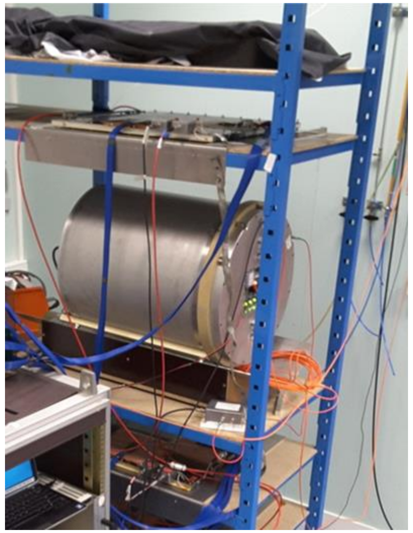
Many tests in recent years

Beam test at DESY in 2015 (LCTPC, 2DLC modules)
Cosmic-ray test at Saclay in 2017 (T2K)
Beam test at CERN in August 2018 (T2K)
Beam test at DESY in November 2018 (LCTPC)
Cosmic-ray test in Saclay since January 2019 (LCTPC/FCC)
Beam test at DESY in June 2019 (T2K)
Cosmic test at CERN since December 2019 (T2K)

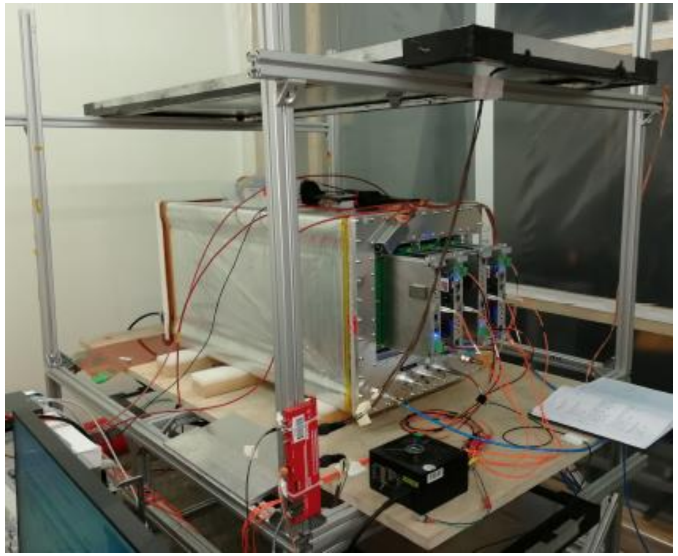








N. 5 TPC of 15, 58, 60, 100 and 150 cm length with 1000 to 2000 channels. All with DLC charge spreading



Overal conclusion: extremely reliable and stable operation

Requirements & Issues with DLC

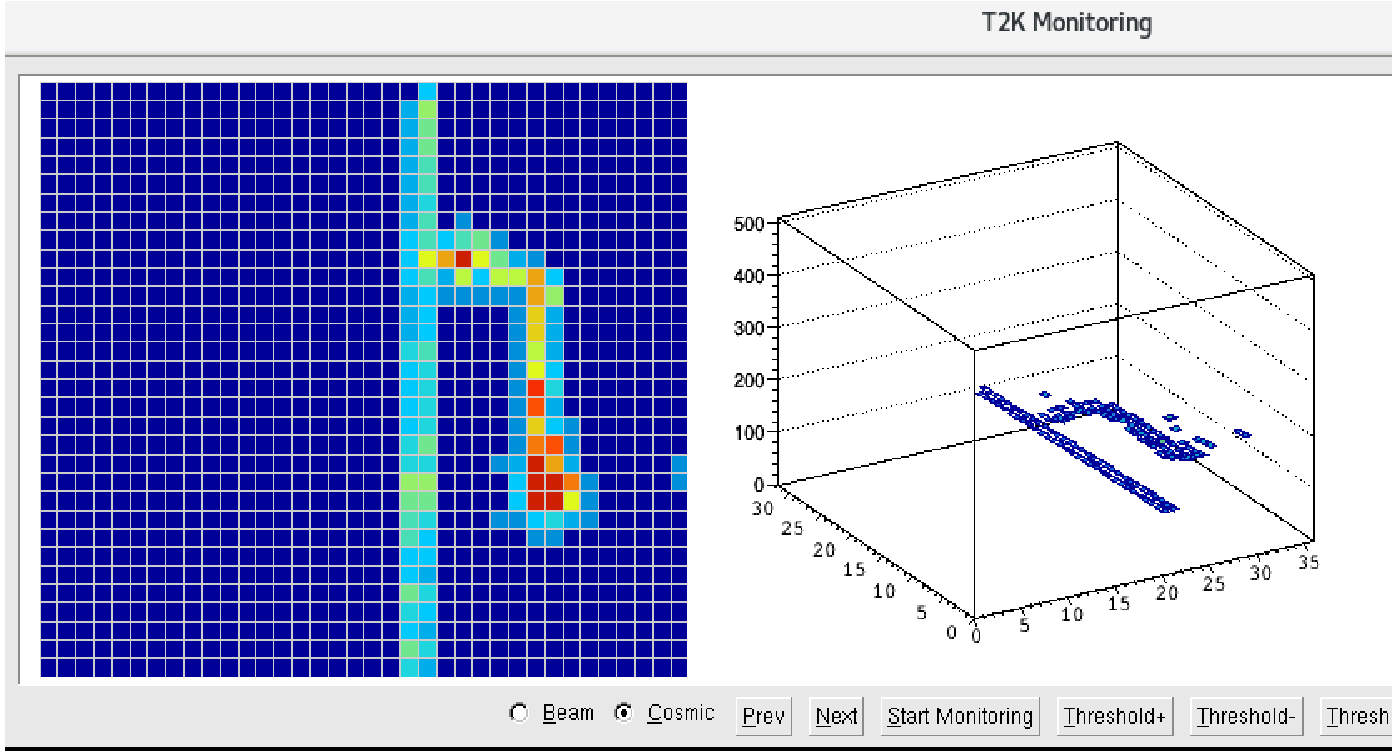
Requirements on resistivity

- **400 ± 200 kOhm/sq** for **T2K** (w/1cm pad size)
- **2.5 MOhm/sq** for **ILC** (w/3 mm pad size)
- **Resistivity lower than 200 kOhm/sq would still be OK** for T2K, but it's not clear that **the spark protection still effective**
- In addition, **such a low resistivity** as that required for T2K **seems difficult to achieve (?)** and **the uniformity, as Rui will show, is not excellent so far.**

Streaks of chemicals in one of the DLC foils and micro-scratches on another.

Surface quality problems … can affect in some cases detector operation (???)

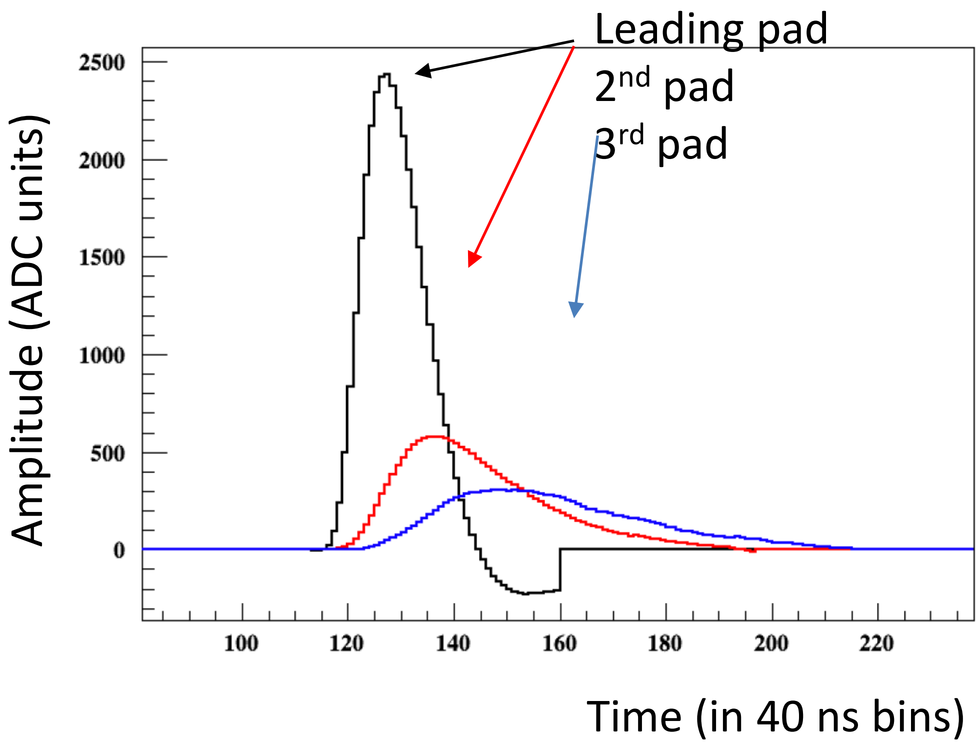
Charge spreading is visible on the events



Details on Charge spreading

- **Wave forms**
  - They carry information on RC, and

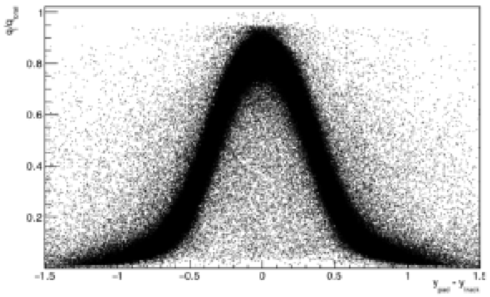
  can be used to assess the uniformity of RC

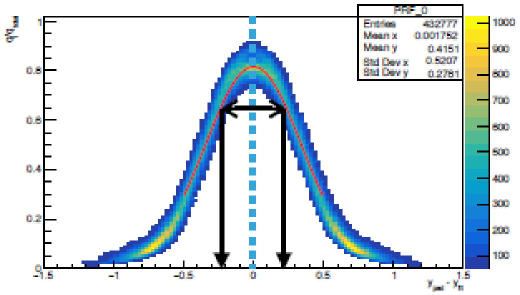


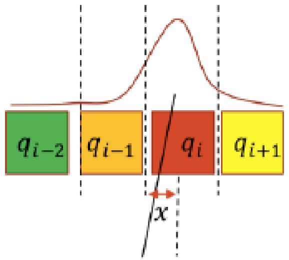
- **Pad Response Function (PRF)**
  - Relates the pulse height fraction to the position of the track

  within the pad

PRF scatter plot:







$$PRF(x_{track} - x_{pad}) = \frac{q_{pad}}{q_{cluster}}$$

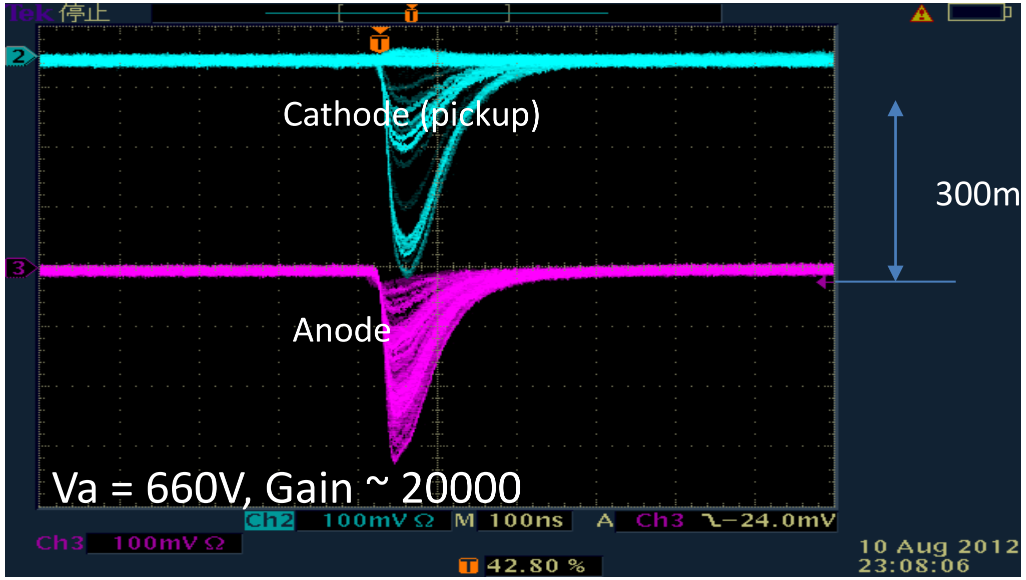
7 - μ-PIC with DLC cathode

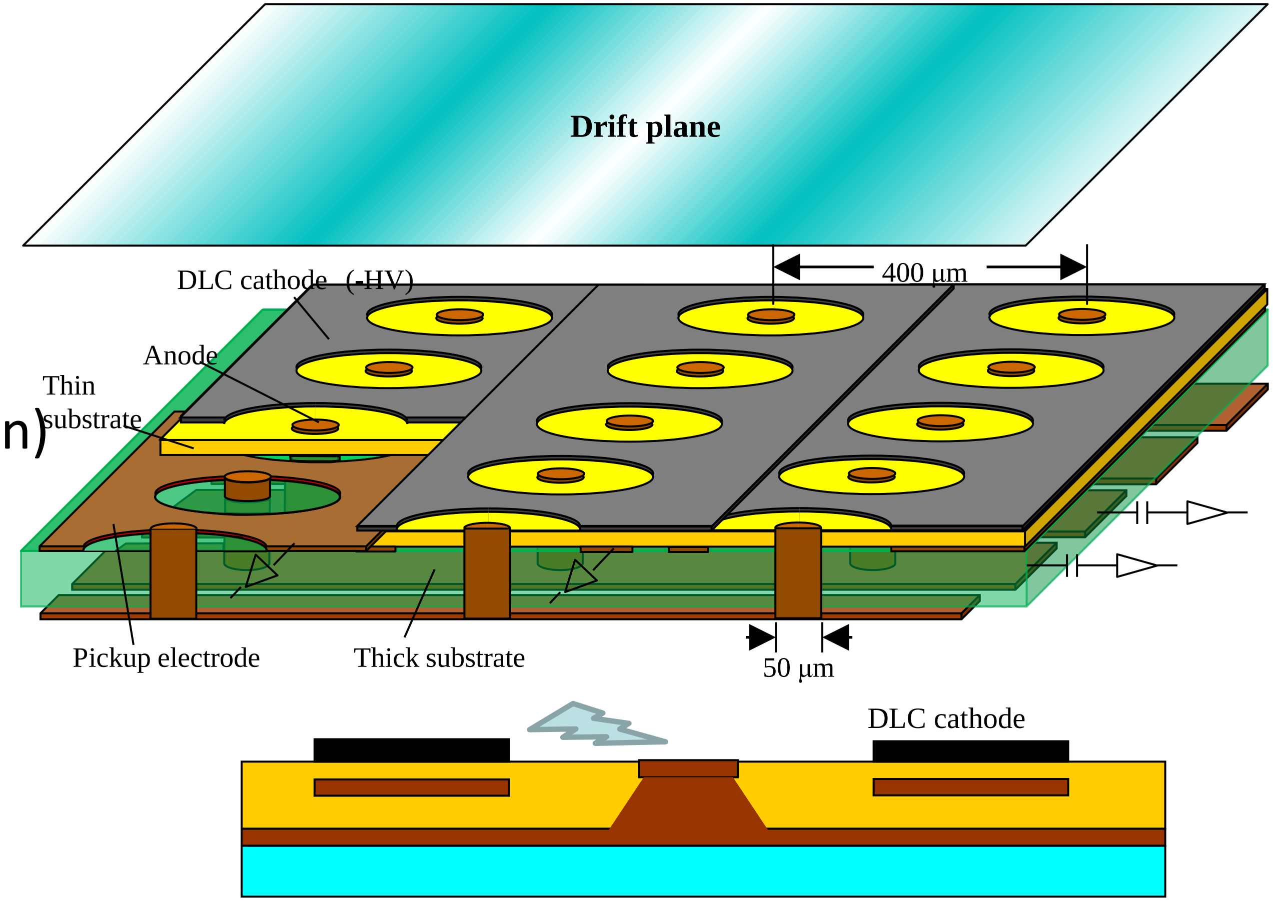
Atsuhiko Ochi
Kobe University

μ-PIC with DLC cathode and capacitive readout

Detector design

- All cathodes are made of DLC
- Pickup electrodes are placed under cathodes and insulator
- We have two dimensional signals (opposite sign)



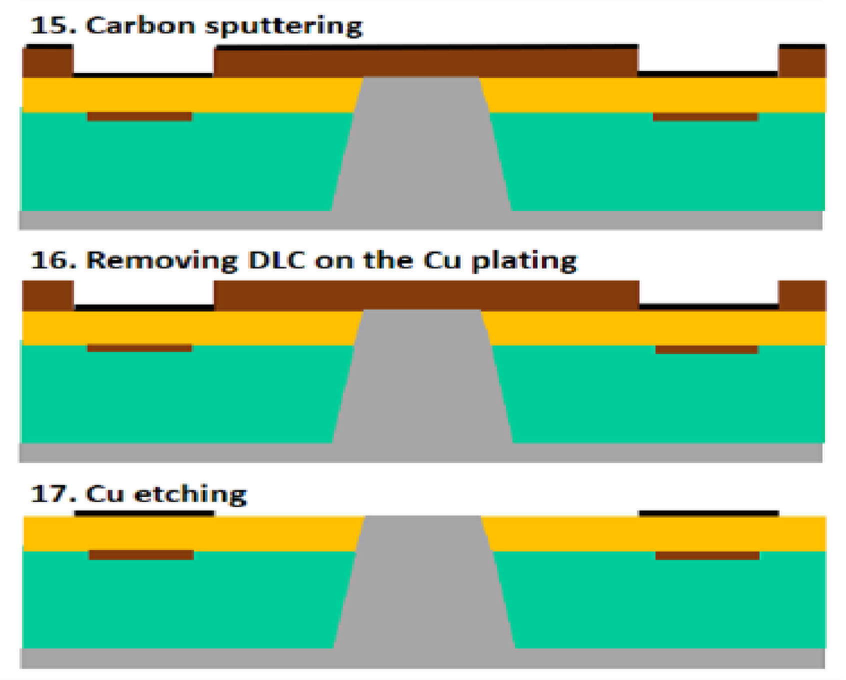


- There is no floating electrodes
- There is no charge spreading
- **Fine DLC pattern needed (< 10um precision)**

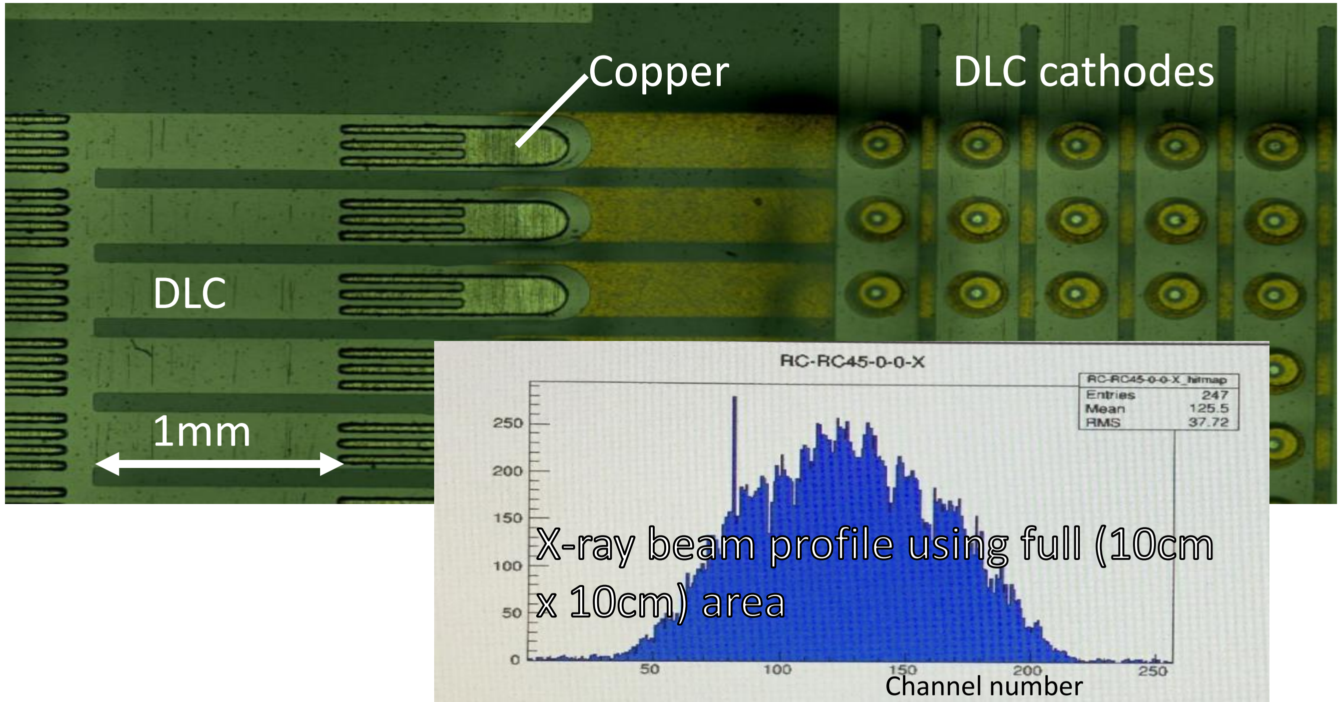
See also NIM A951 (2020) 162938

Fine patterning process of DLC using liftoff method

- <u>Fine DLC patterning is performed by using copper lift-off</u>



- Fine pattern makes possible the good connection to DLC



DLC resistivity requirements

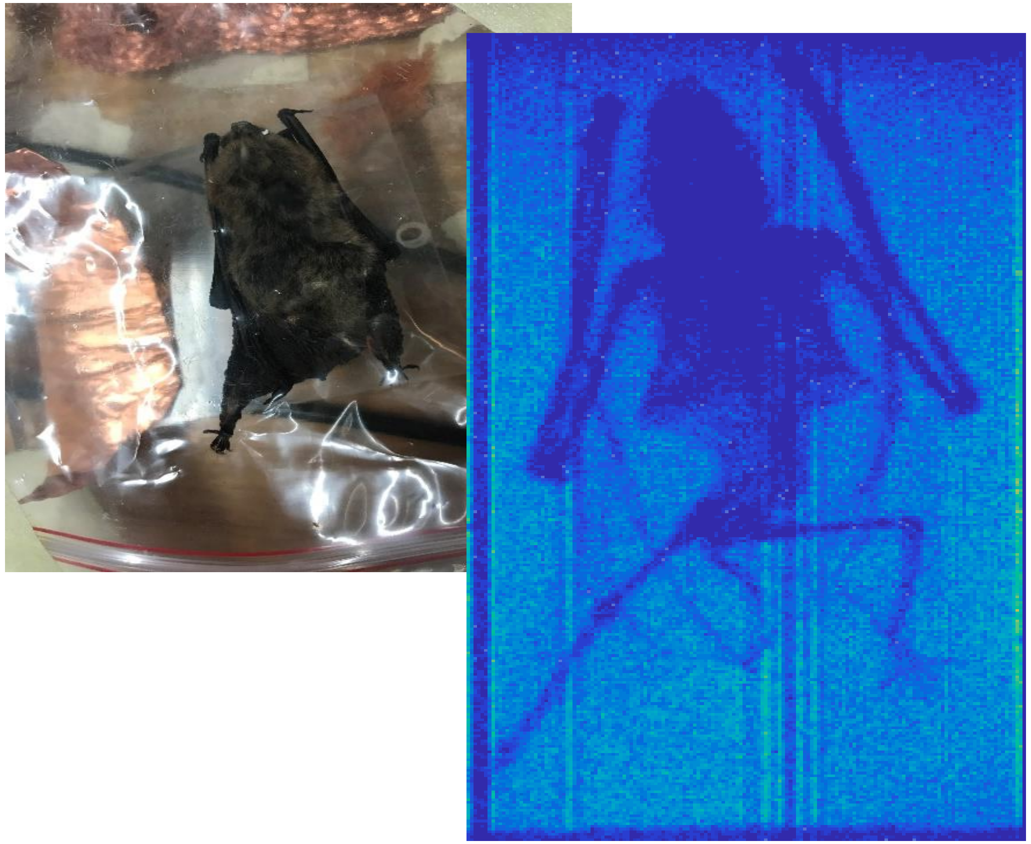
- As for u-PIC detector, a wide target range of **DLC resistivity 0.1 ÷ 10 MOhm/sq** is foreseen depending on the application:

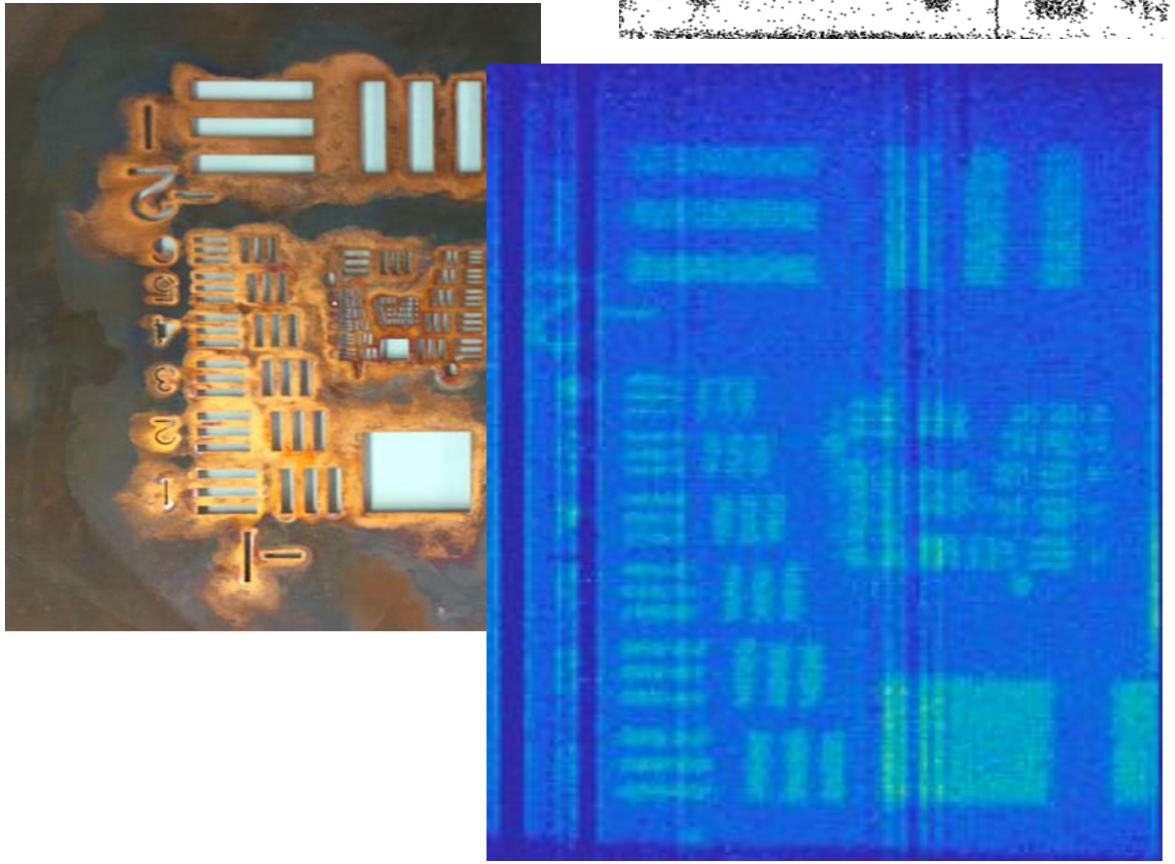
- For **high luminosity physics experiments** (e.g. HL-LHC muon tagger) or intense X-ray imaging, it should be in the range of **0.1 ÷ 1MOhm/sq**

- For gamma-ray camera, or non accelerator physics (e.g. dark matter search), a resistivity of **1 ÷ 10MOhm/sq** or more is appropriate

Optimization of this parameter is in progress

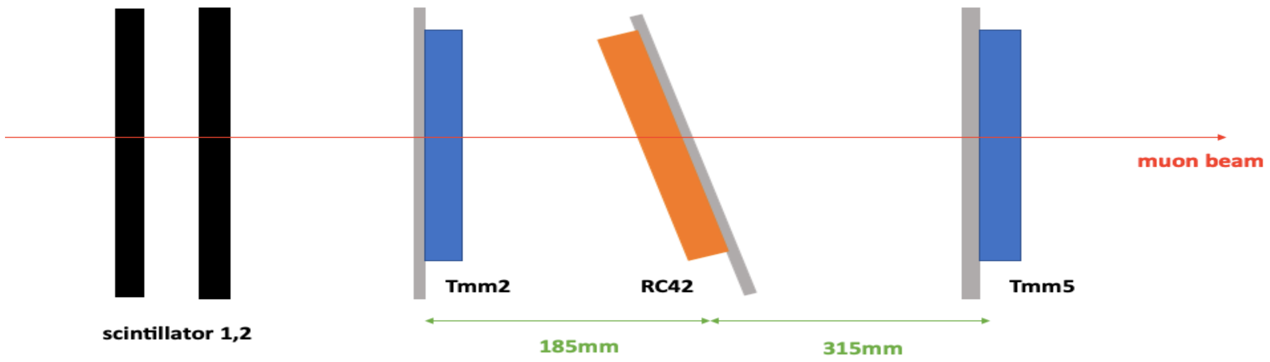
Imaging using DLC - μ-PIC

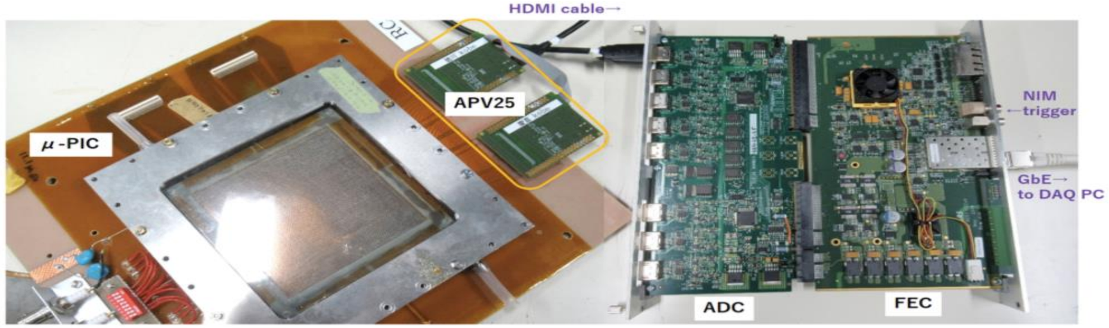




Position resolution @ RD51 test beam

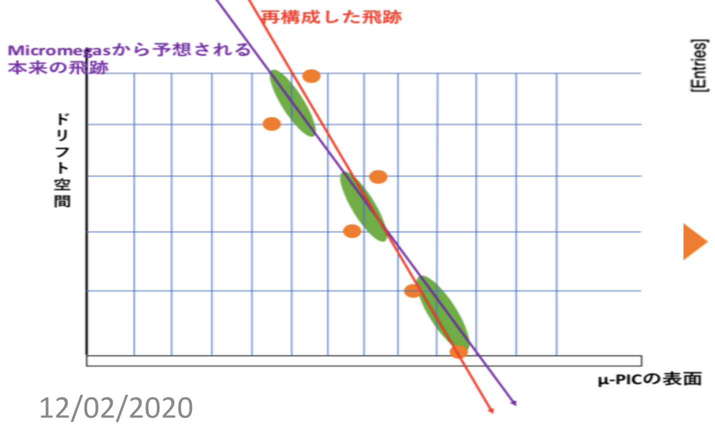
- Test beam using CERN SPS 150GeV muon (H4 beamline)

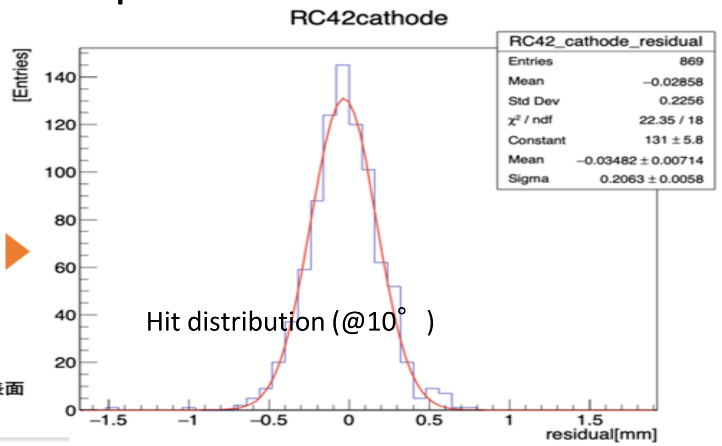


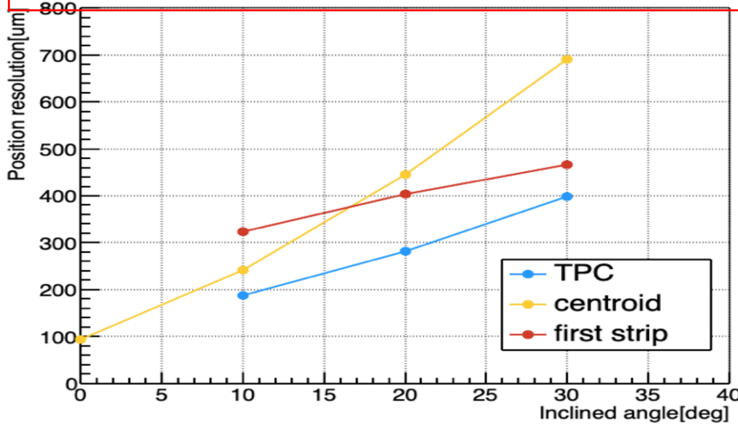


- Center of mass method, first hit method, TPC method have been applied, using residual position from telescope chamber
- TPC is best way for inclined setup

Best position resolution for charged particle < 100 μm







8 - Resistive GEM

CERN GDD & MPT, USTC

Two topics under study

- DLC on GEM Sectors

F. Sauli, Restoring efficiency in gem sector separations, rd51 collaboration meeting -22/10/19, https://indico.cern.ch/event/843711/contributions/3573003/attachments/1930931/3198380/SECTORS.pdf

- DLC GEM

M. Lisowska, Preliminary measurements on 10x10 Cu-Apical-DLC GEM, RD51 coll. Meet. Oct. 2019 https://indico.cern.ch/event/843711/contributions/3608165/attachments/1931749/3199663/Preliminary_measurements_on_10x10_Cu-Apical-DLC_GEM.pdf

Important aspects:

- Adhesion
- Making GEM holes in DLC
- Control of layer resistivity
- Uniformity

⇐ focusing on

DLC coating for sectored GEMs

GEM foil divided in sectors (100 cm^2) in order to reduce the stored energy

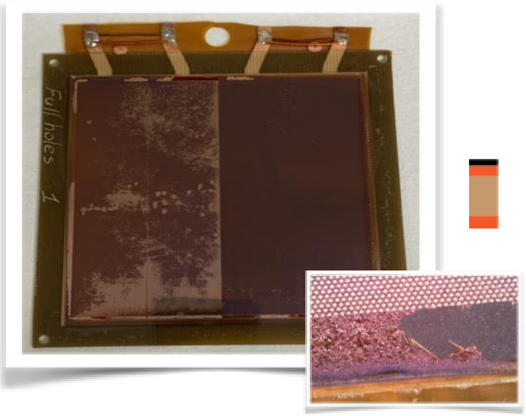
DLC layers may be used to resistively decouple GEM sectors to reduce the stored energy for discharge protection and **preserve the electric field uniformity.**

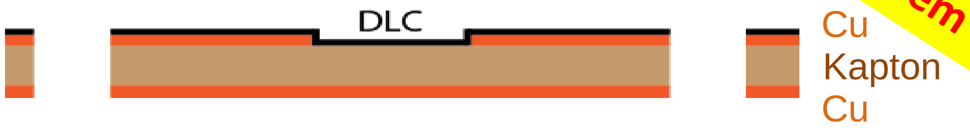
DLC adhesion problem !!!

Two different approaches

1st trial:
DLC on Cu GEM electrode

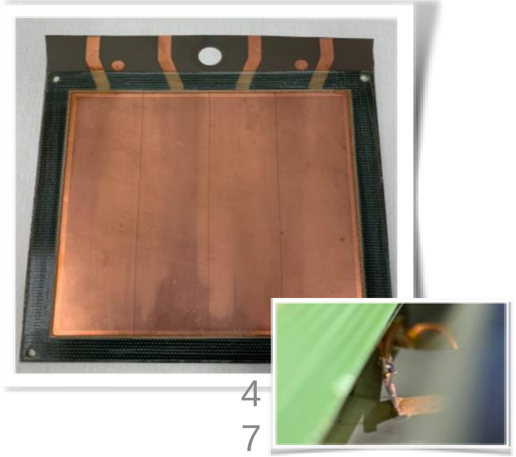
DLC coating of standard GEM suffered **from poor adhesion of DLC on Cu**

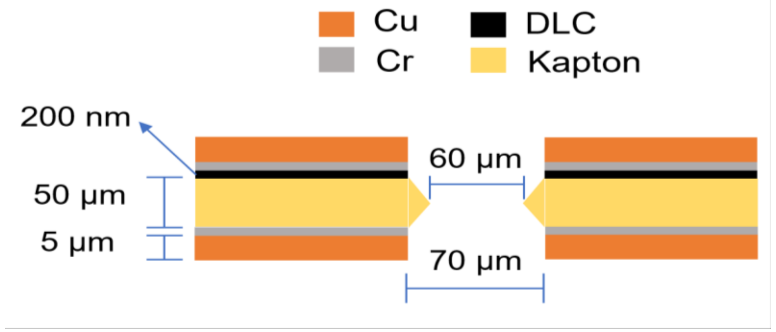




2nd trial:
Cu on DLC

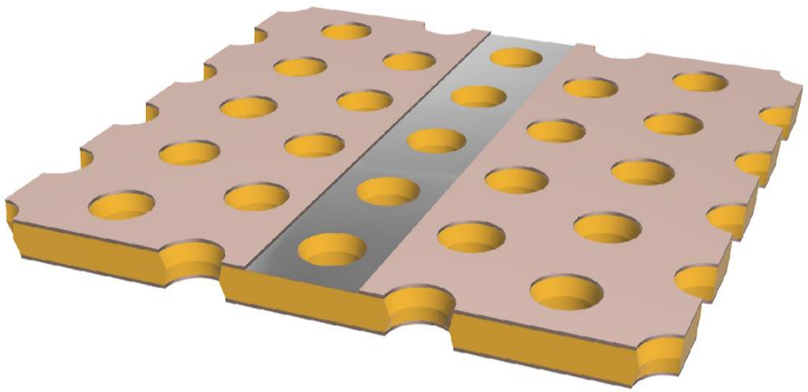
Producing GEM from DLC-coated Kapton foil and exposing DLC only in the intra-sector gap regions





DLC coating for sectored GEMs

DLC layers in sector gaps preserve the electric field line uniformity. This can minimise distortions in the vicinity of the gap.



1

A single-sided sectored GEM with DLC connecting sectors was produced.

2

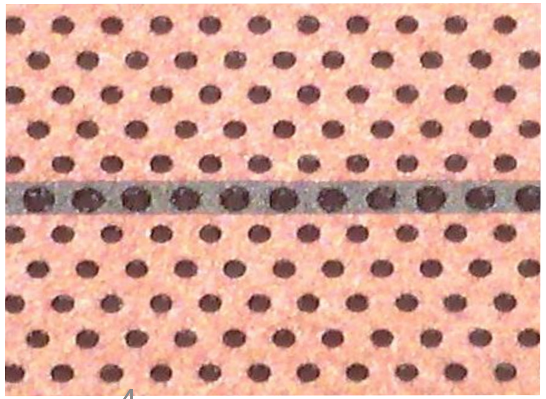
1GΩ/sq DLC sheet resistivity resulted in 3MΩ resistance between neighbouring sectors.

3

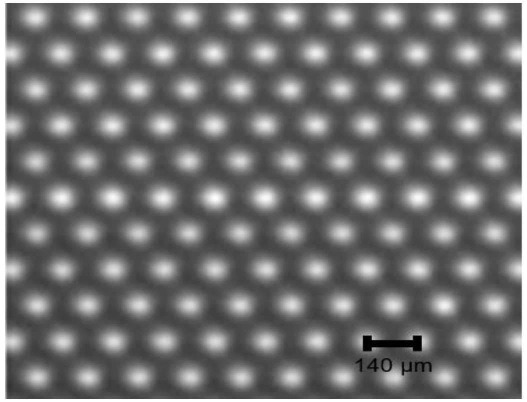
Distortions in the gap region are minimised and an almost uniform response of the GEM is observed.

This may be **beneficial for demanding imaging applications while preserving the protective effect of sectored GEM electrodes.**

Microscope image of sector gap with exposed DLC layer



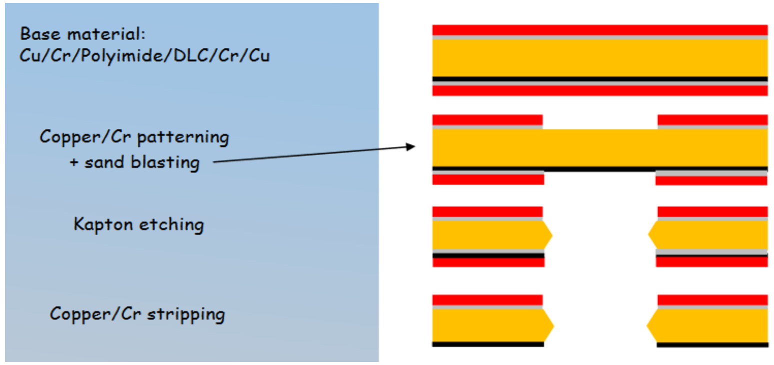
Optically read out image of gap region under X-ray irradiation



Sectors on top

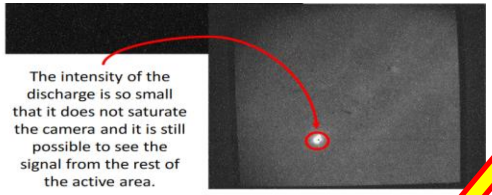
What we have so far

Single DLC GEM



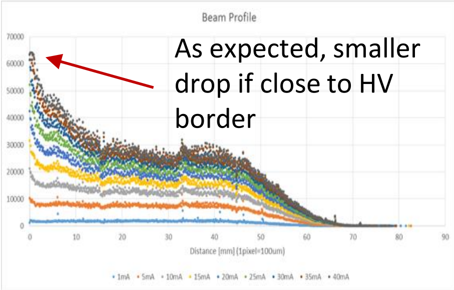
High Resistivity

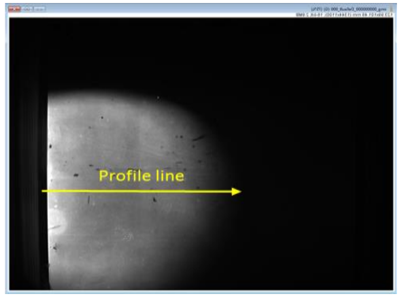
The High Resistivity (about 100 MΩ/□), ensuring a large quenching effect, offers the possibility to limit the energy in discharges (i.e. you can run even in presence of local discharges…)



… but it was limiting the rate capabilities: non uniform drops of gain depending on where the charge is collected.

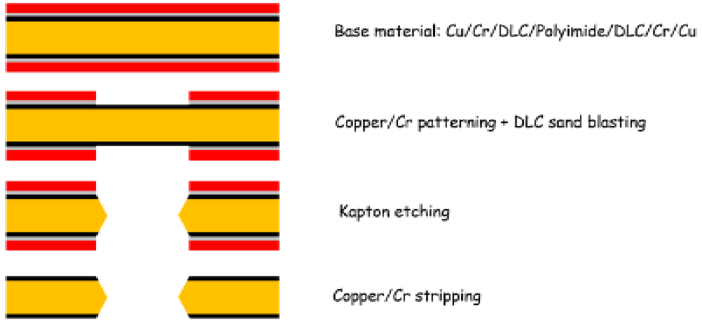
M. Lisowska, Preliminary measurements on 10x10 Cu-Apical-DLC GEM, RD51 coll. Meet. Oct. 2019 https://indico.cern.ch/event/843711/contributions/3608165/attachments/1931749/3199663/Preliminary_measurements_on_10x10_Cu-Apical-DLC_GEM.pdf





What we are aiming

Double DLC GEM



Low Resistivity

Studying the minimum value of resistivity offering proper quenching and proper attenuation of energy released by the GEM during discharges.

Trying to limit rate issues

DLC adhesion problem !!!

First trial but issues with copper layer adhesion.

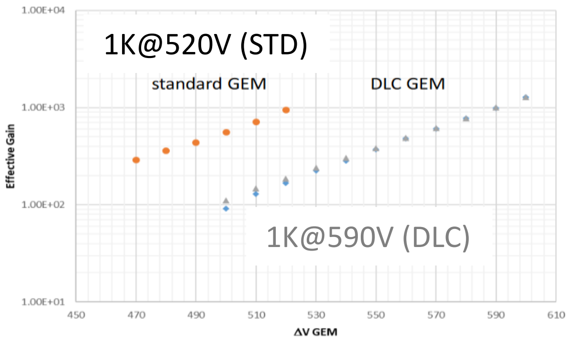
R. De Oliveira, Resistive Protections, CERN MPT, RD51 October2019 https://indico.cern.ch/event/843711/contributions/3607915/attachments/1931703/3199572/2019_RD51_october_MPT.pdf

What we learnt so far on <u>single side DLC with high resistivity</u>

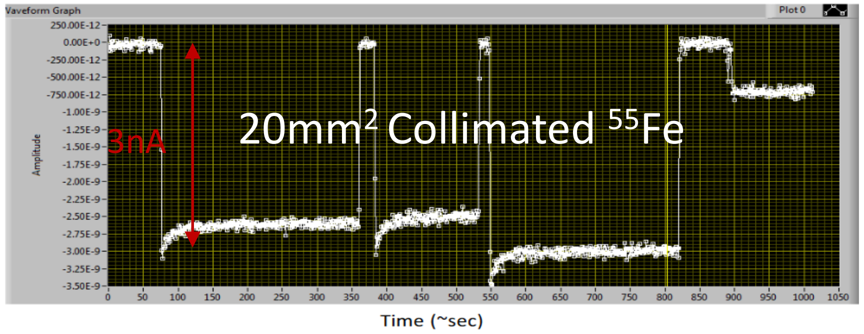
- Larger HV to get same gain (hole geometry,..)
- **Charging up stronger…**
- Uniformity to be optimized…
- Maximum gain driven by local defect for the GEM we tested…

→ Most of them **driven by GEM production and room for process optimization**

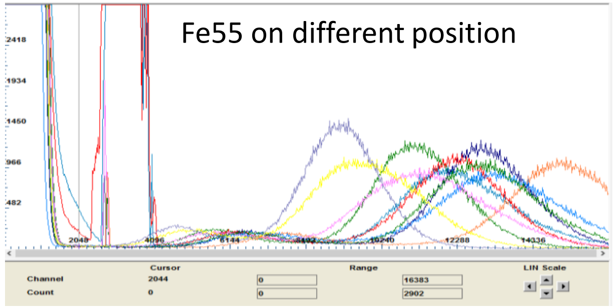
<u>Useful to understand how DLC properties can affect GEM production steps</u>



Effective Gain



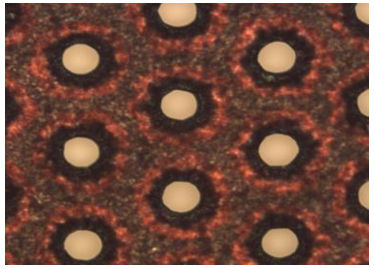
Charging Up

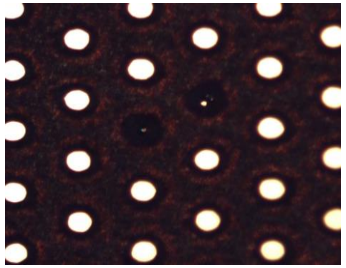


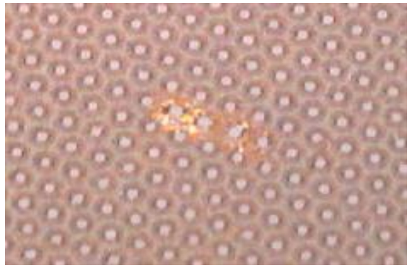
Uniformity

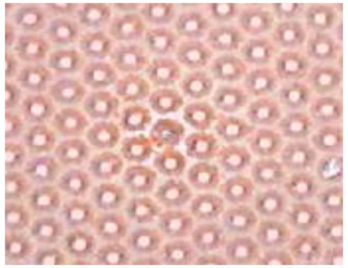
M. Lisowska, Preliminary measurements on 10x10 Cu-Apical-DLC GEM, RD51 coll. Meet. Oct. 2019
https://indico.cern.ch/event/843711/contributions/3608165/attachments/1931749/3199663/Preliminary_measurements_on_10x10_Cu-Apical-DLC_GEM.pdf

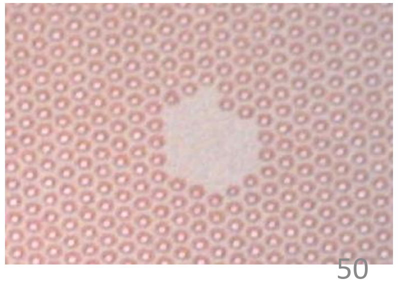
Few Pictures…











9 - Resistive (TH)-GEM @ TUM

TU Munich, Physics Department E62

Dense and Strange Hadronic Matter

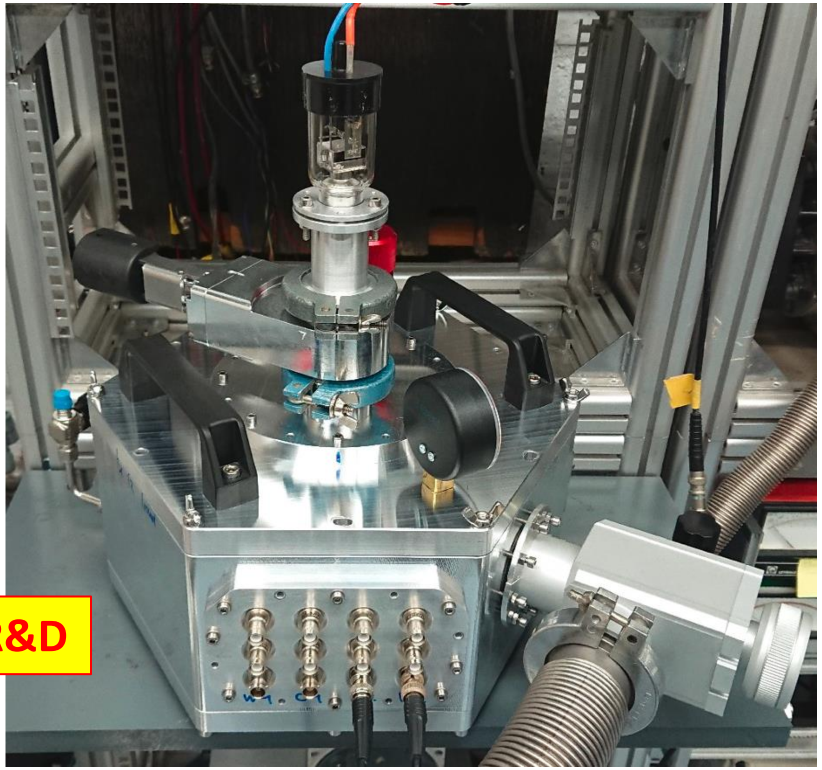
Laura Fabbietti
Piotr Gasik (currently GSI/Darmstadt)
Thomas Klemenz
Berkin Ulukutlu
Lukas Lautner
Tobias Waldmann

R&D on DLC based MPGD

i. photocathode coating for new gaseous photo-detector
ii. resistive layer for MPGD stability improvements

i) (TH)GEM-based photodetector @ TUM

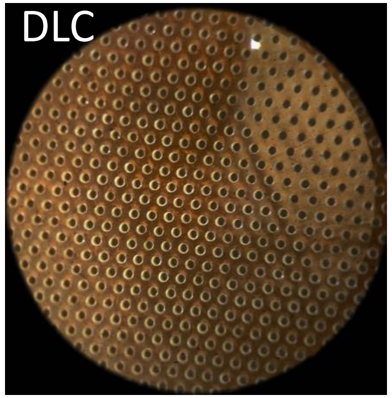
- **New gaseous photodetector** developed at TUM
- A prototype **for the future deep underwater neutrino experiments**
- **Study different photo-cathode materials**
- Search for the visible-light sensitive technology
- Prove technology for future break through developments for neutrino physics

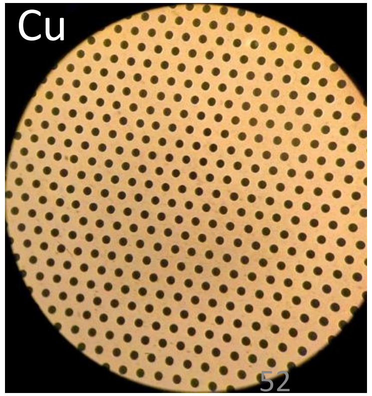


… early stage R&D

Current status and plans

- Calibration runs ongoing
- QE studies of different GEM coatings
  - Reference CsI coated THGEMs (in-house coating)
  - DLC GEMs and THGEMs have been produced at CERN, using Chinese DLC foils

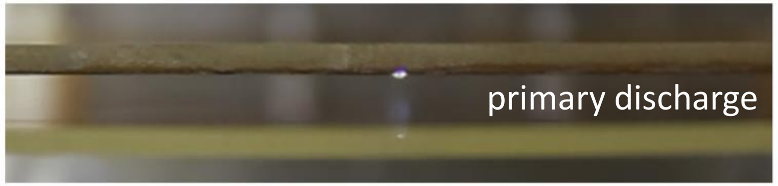




ii) R&D on (TH)GEM stability @ TUM

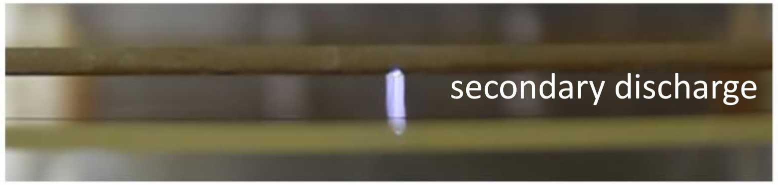
Primary discharges

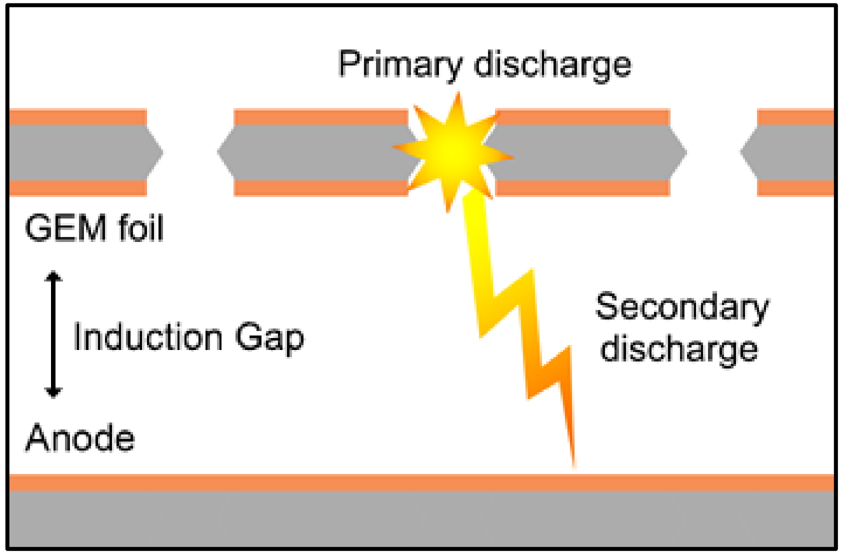
- Electrical breakdown inside a GEM hole after the critical charge limit is reached
- $Q_{crit} \approx 10^6 - 10^7$ e^-/hole
  - P. Gasik et al. NIM A 870 (2017) 116



Secondary discharges

- Occurs with an $\mathcal{O}$(10 μs) time delay after a primary discharge in the gap below discharging GEM
- Pose a threat to the detector integrity
- Mechanism still not clear. Recent hypothesis: cathode thermionic emission
  - A. Deisting et al. NIM A 937 (2019) 168
  - A. Utrobicic et al. NIM A 940 (2019) 262





Mitigation strategies

- S. Bachmann et al. NIM A 479 (2002) 294
- L. Lautner et al. JINST 14 (2019) P08024

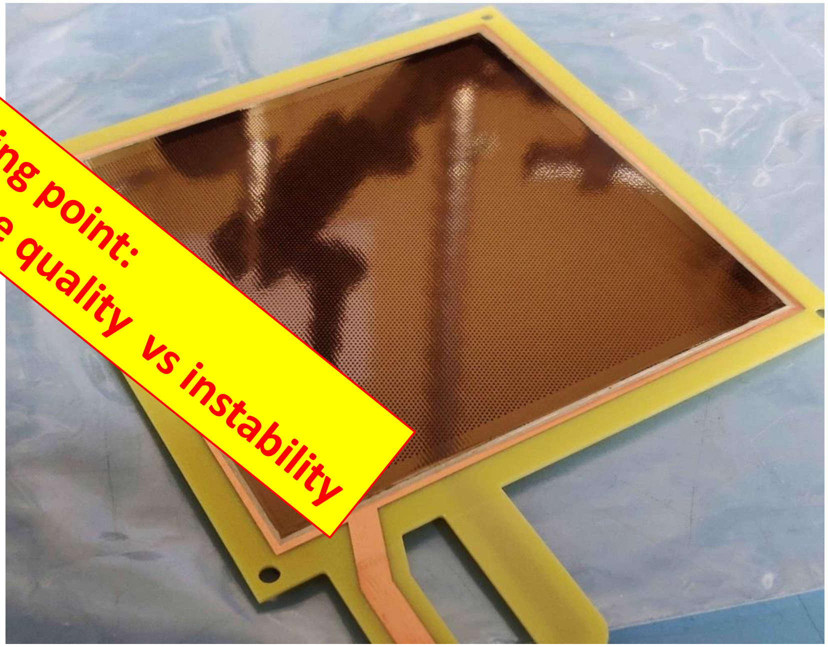
- HV settings optimisation
- GEM segmentation
- RC scheme optimisation
- NEW approach: new GEM electrode materials

DLC (!!!)

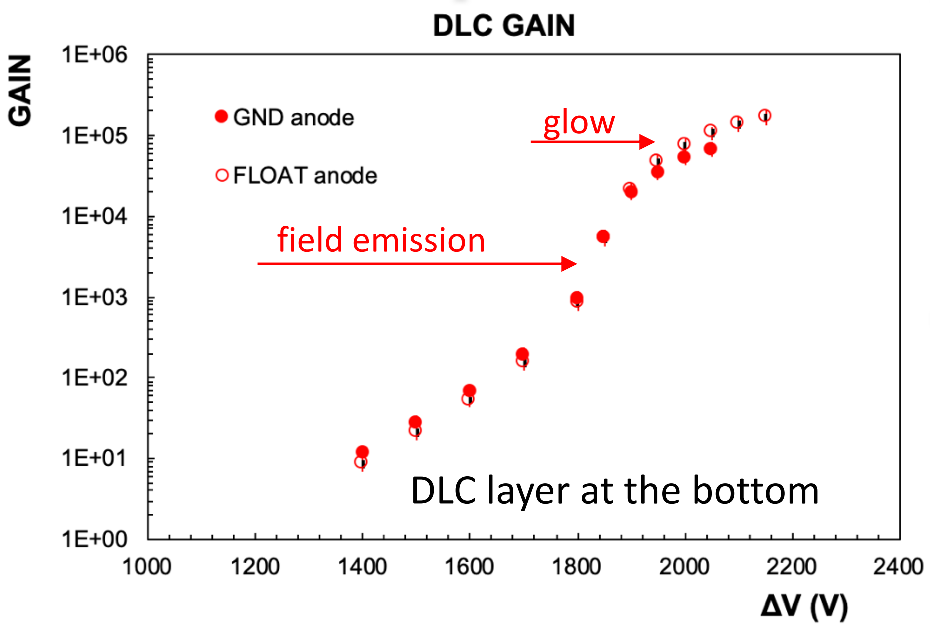
DLC THGEM @

- **<u>THGEM with single-side DLC coating</u>** (CERN EP-DT workshop)
- **$\rho_s \approx 20$ MΩ/sq**
- Measure secondary discharge probability
- **No primary discharges observed with the given ρ_s**
- **Increase of the induction field at high gains leads to instabilities due to field emission (DLC imperfections ???)**
- Further studies after **DLC surface cleaning**; also with lower resistivity

Interesting point: DLC surface quality vs instability



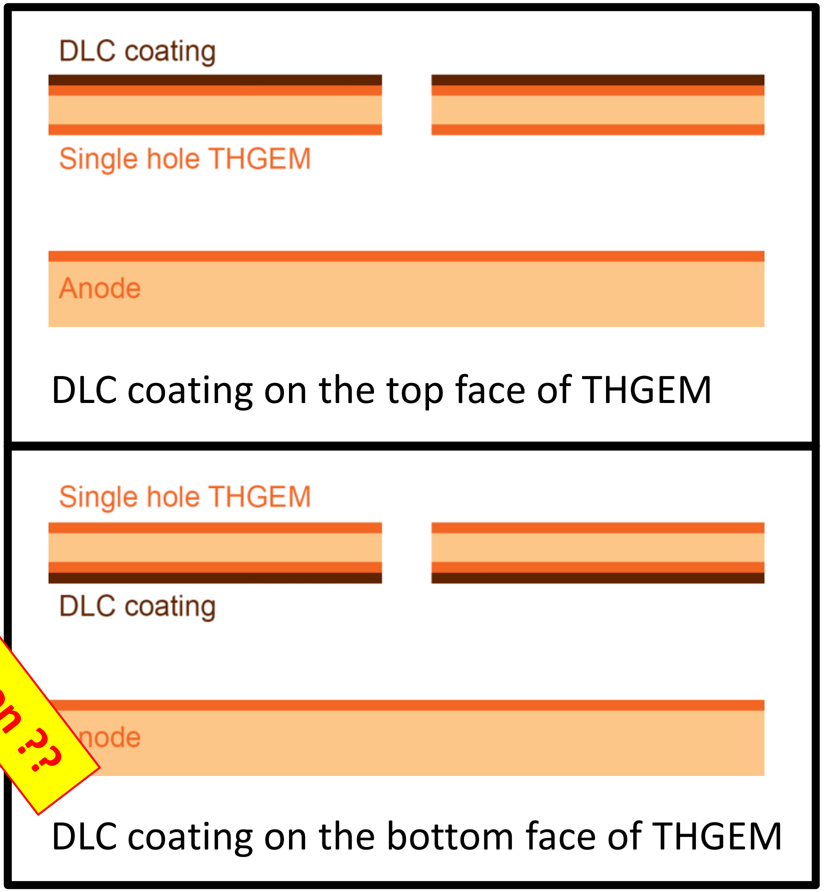
which kind of cleaning ???



Single-hole DLC THGEM

- THGEM with a DLC coating on one side, $\rho_s \approx 20\ M\Omega/sq$
- Single drilled hole with cylindrical shape and no rim
- **With DLC coating on GEM_{top}**
  - **No discharges observed (high $\rho_s \approx 20\ M\Omega/sq$)**
- **With DLC coating on GEM_{bottom}**
  - **Gap instabilities (electron extraction due to changing induction field)**
  - **More systematic studies ongoing**
- Ultimately we want to study:
  - Influence of the DLC coating on primary/secondary discharge formation
  - Study secondary discharge mechanism with spectroscopy studies (see next slide)

again electron field emission ??

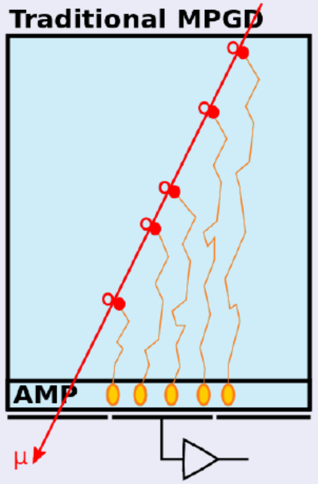


10 - FTM @ INFN-Bari

Piet Verwilligen – INFN Bari

FTM: principle of operation and detector design

Fast Timing MPGD Principle



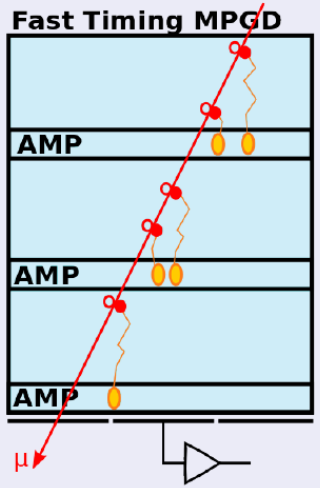
σ_t driven by distance fluct's

$\sigma_t \propto 1/(\lambda v_{\text{drift}})$
$\lambda = \#$ primary cls / mm

electron-ion pairs created close to amplification structure result in fast signals

Fast Timing MPGD: split drift volume in N layers, each with own amplification structure

$\sigma_t \propto 1/(\lambda v_{\text{drift}} N)$

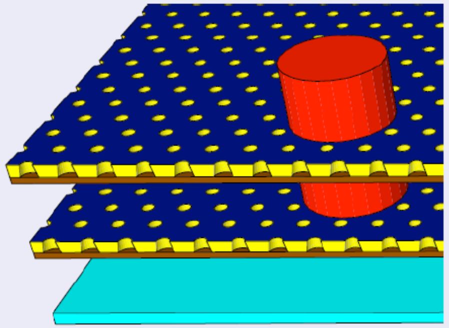


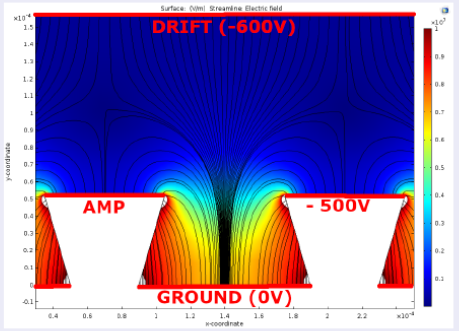
- resistive structure ⇒ signal from any layer induced in readout
- resistive structure ⇒ limits development of discharges
- time resolution improves with N = number of layers

Exploiting **micro-gas-gap** the **jitter** of the distance the **ionization clusters** produced in the gas from the amplification stage **is "artificially" reduced**. The e-I pairs close to amplification stage result in fast signal. The **efficiency is recovered** by using many, **O(10), micro-gas-gap** detector layers. The **full resistive structure should allow signal transparency** (same concept as MGRPC, and PST …)

Two Layer FTM Prototype :: Design

2-layer prototype

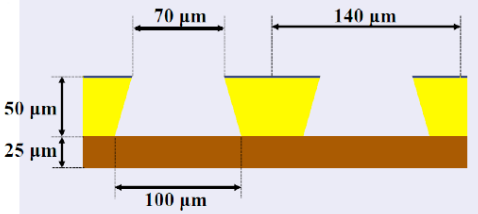




Single layer specifications:

- Drift layer: 250 μm drift layer (Red: Dupont Coverlay spacers)
- Gain layer: 50 μm kapton (Yellow: GEM foil: 70 μm hole, 140 μm pitch)
- Resistive kapton: 25 μm (Brown: Dupont high resistivity Kapton XC)
- Resistive coating: 10–100 nm (Blue: Diamond Like Carbon: DLC)

2-layer prototype



Resistivity requirements

For FTM we would like to have the lowest R that allows for good signal transparency, obtaining as such the highest rate capability, w/o too much charge spread

- Choice of resistivity for an application is a trade-off between various effects:
  - **rate capability:** high resistivity $\Rightarrow$ Large Voltage drop $\Rightarrow$ Low Rate Capability
  - **charge spread:** low resistivity $\Rightarrow$ Large charge spread (need good optimum)
  - **signal transparency:** higher resistivity gives better signal transparency
- **Want to explore MPGDs w/ $R_S = 100\,\mathrm{k}\Omega/\square$—$1\,\mathrm{G}\Omega/\square$, first try $100\,\mathrm{M}\Omega/\square$**

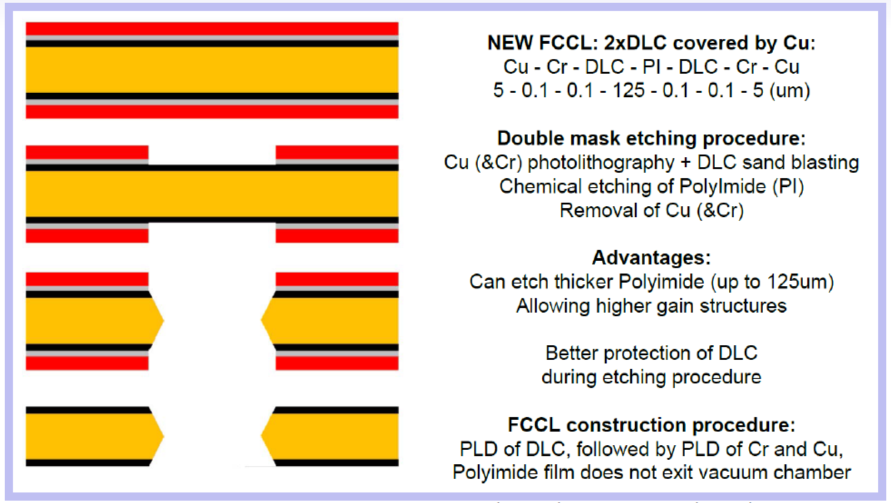
- **Effective Voltage** due to current I and material with resistance $R_e = \rho l/A$:

$$V_{\mathrm{eff}} = V_{\mathrm{app}} - IR_e$$

- with particle **rate** R: $I = \langle q \rangle R$
- **Voltage drop** $\Delta V = \langle q \rangle R \rho l/A$
- E-field $\downarrow$ $\Rightarrow$ detector $\epsilon \downarrow$

$\rho_s \sim 0.1 \div 1\ \mathrm{G}\Omega/\square$

Problems w/DLC coated PI



Idea developed during MPGD-Next by R. De Oliveira (CERN) & M. Maggi (INFN); already adopted by USTC Colleagues (China - Magnetron Sputtering)

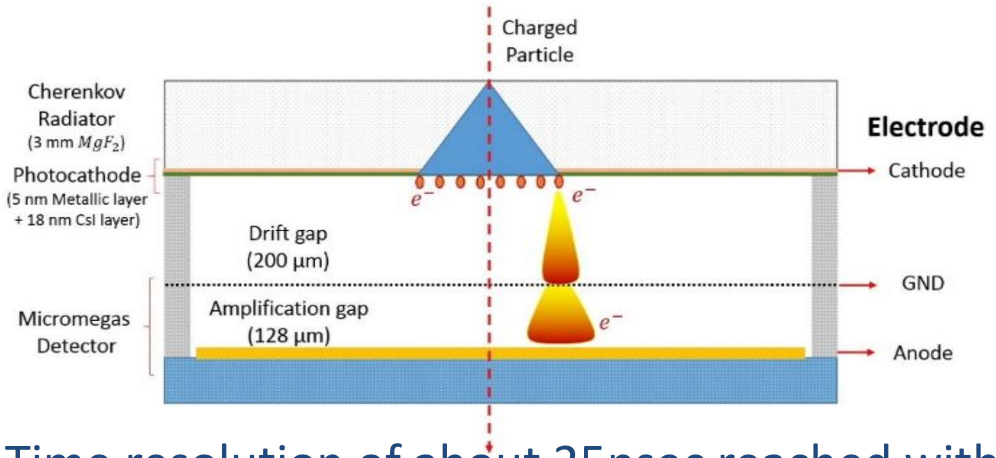
- **Production μRWELL:**
  - DLC coated PI film glued on PCB
  - good protection DLC during etching
- **Production FTM:**
  - DLC coated PI film without glueing
  - Rui uses thin film for protection DLC
  - not good enough . . . DLC delaminates
- **New FCCL: Cu-DLC-PI-Cu:**
  - produced by Yi Zhou at USTC
  - same prob: DLC delaminates
  - holes with large diameter = low gain
- **Problem with adhesion DLC to Polyimide**
- **Prompted Collaboration to investigate DLC**
  - INFN BA: Ion Beam Deposition
  - INFN LE: Pulsed Laser Deposition & Char

Main problem: DLC delamination !!!

DLC (et al.) based UV Photocathode as alternative of CsI

Xu Wang
PICOSEC

PICOSEC MM detector and its photocathode



Time resolution of about 25psec reached with MIPs using:

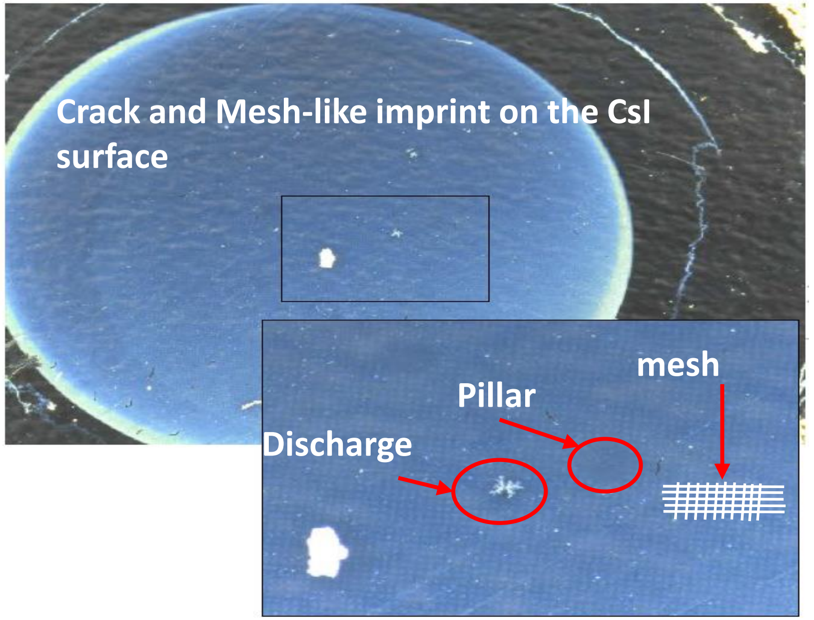
- a Cherenkov radiator
- UV CsI photocathode
- <u>a two stages micromegas with amplification in both gaps</u>

"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", J. Bortfeldt et. al. NIM A, 2018

PROMISING RESULTS (beam and lab) OBTAINED BY THE PICOSEC COLLABORATION (production @ USTC/Saclay) WITH DLC, B4C,.. BASED PC

<u>Challenge of CsI photocathode</u>

1. **High hygroscopic characteristic** of CsI strongly affects its storage, mounting and handling. Dry environment to be granted ALWAYS.

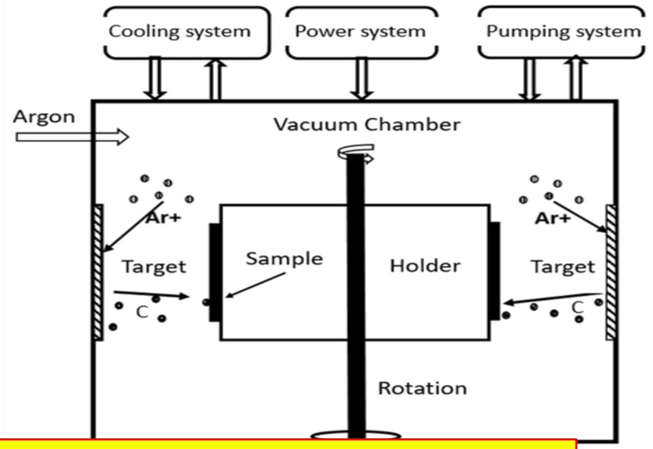


2. Typical QE losses because of **ion feedback**

3. **Discharges: PICOSEC works with pre-amplification**, i.e. the photocathode is exposed to discharges

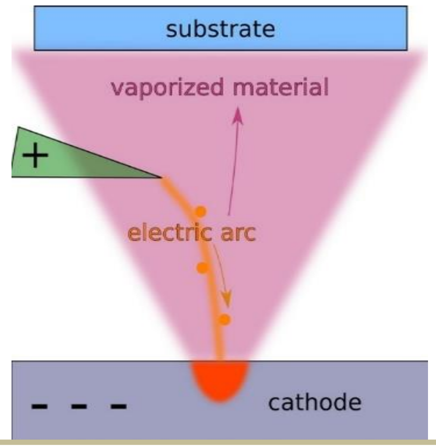
Production of DLC-based photocathode

Magnetron Sputtering Deposition

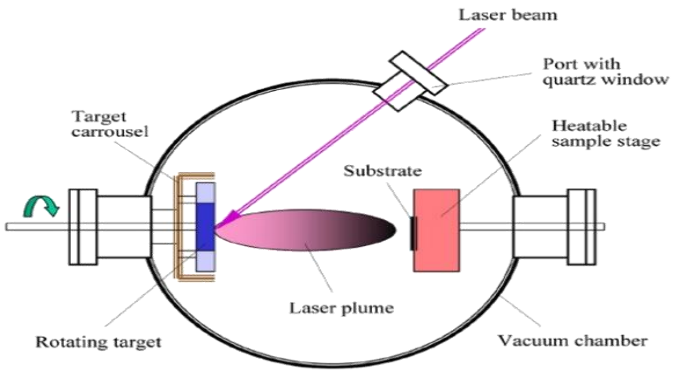


The main method we use now

Vacuum Cathodic Arc Deposition



Pulsed Laser Deposition



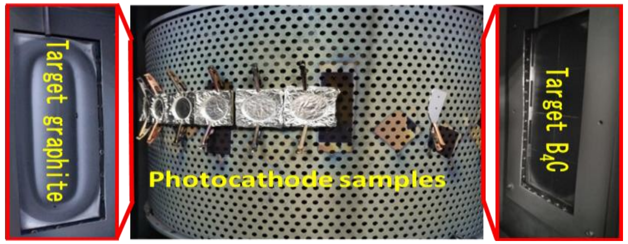
Studies linked to DLC-based photocathodes:

- Thickness and chemistry optimization of the film
- <u>Boron doping</u>
- <u>Surface treatment of photocathodes</u>
- Resistivity of DLC-based photocathode layer
- Large area, aiming to $10\times10 cm^2$
- Different deposition methods

Technical aspects to be studied in detail

Several aspects to be understood: deposition processes affect the samples' performance, cleanliness of the chamber, vacuum degree, …

Aspects to be considered/studied/investigated

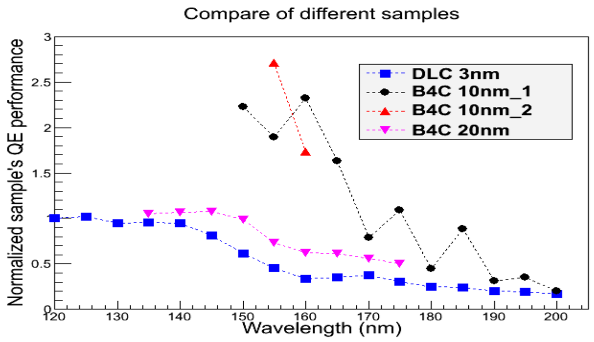


1. (Boron) Doping

Pure graphite target and pure Boron target can be used together to prepare a certain boron-carbon ration. **Higher QE performance is excepted after Boron doping. To be explored.**

Pure boron target sputtering currently not available (RF power)

Pure B4C film has been therefore studied and better QE performance compared to DLC has been obtained in the lab under UV exposure.



2. Surface Treatment

Surface treatment to form a negative electron affinity is very helpful for electron emission, which has already been studied in the field of bialkali photocathode.

Higher QE performance is excepted after surface treatment of the DLC-based photocathode film.

Hydrogen plasma “sputtering” or **atomic layer deposition (ALD) of alumina** could be investigated. Currently, **more experience and professional guidance are urgently needed.**

aging/stability of treatment/deposition to be verified

3. Protective coating

Methods to protect CsI with DLC thin layers. Not clear if feasible/possible.

(*non exhaustive*) SUMMARY

A **quite large MPGD Community** is (becoming) active on **resistive gaseous detectors** (*also GEMmers !!!*).

DLC (*this unknown-black coating …*) **should be understood better and its production should be taken under control**. The **resistivity required** by various technologies **ranges from few hundreds kΩ/sq up to 1 GΩ/sq**.

The most F.AQ. looking for (positive) answers seem to be:

- **Control** of DLC resistivity
- DLC resistivity **uniformity**
- DLC **surface quality** characterization/control
- Resistivity **changes during** detector **manufacturing**
- DLC **stability** under current/irradiation
- **Adhesion** problems (DLC on PI, Cu on DLC …)
- … ???

Using a statement done by Xu: *"… more experience and professional guidance are probably needed … (???) "*

For sure a better *information exchange* between *users* and *manufacturers* will help a lot in doing significant steps forward in the technology

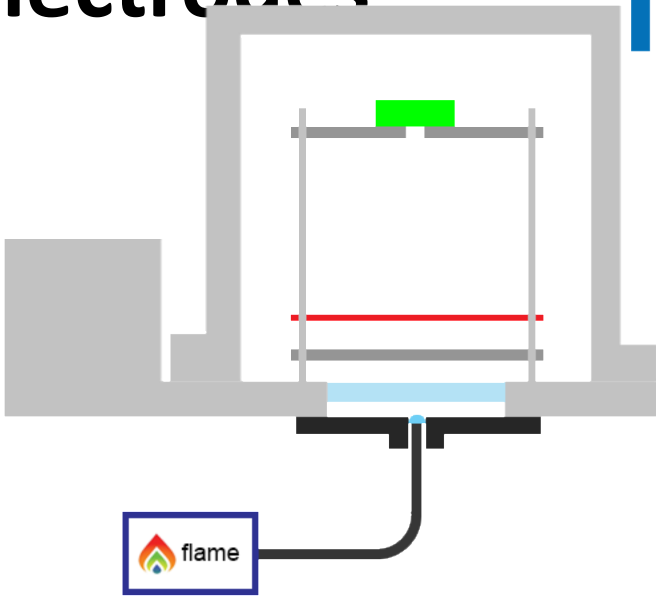
Back-up slides

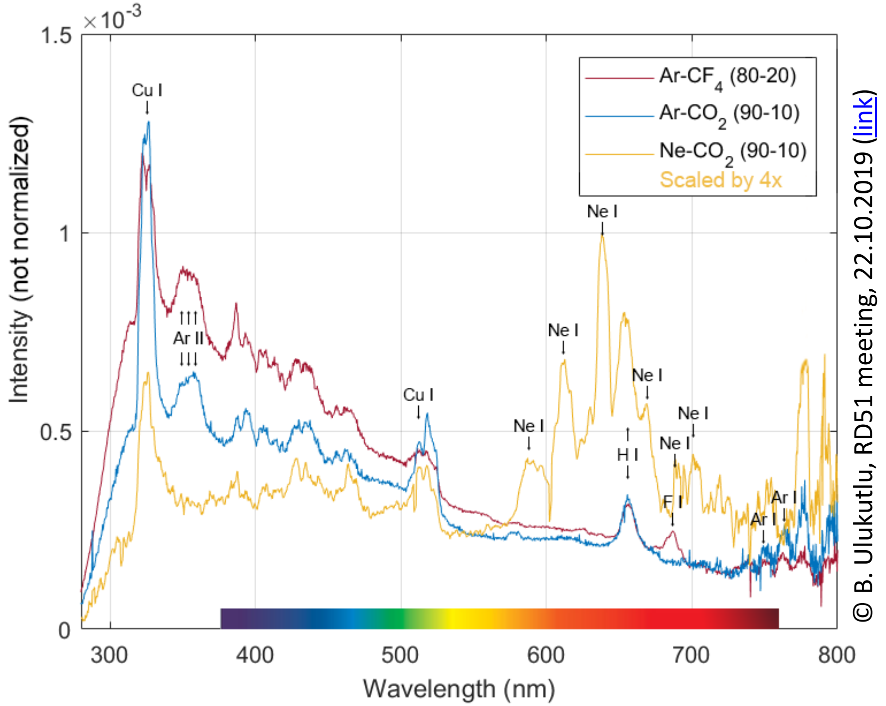
Preliminary table
To be integrated/corrected with inputs coming from other groups/activities

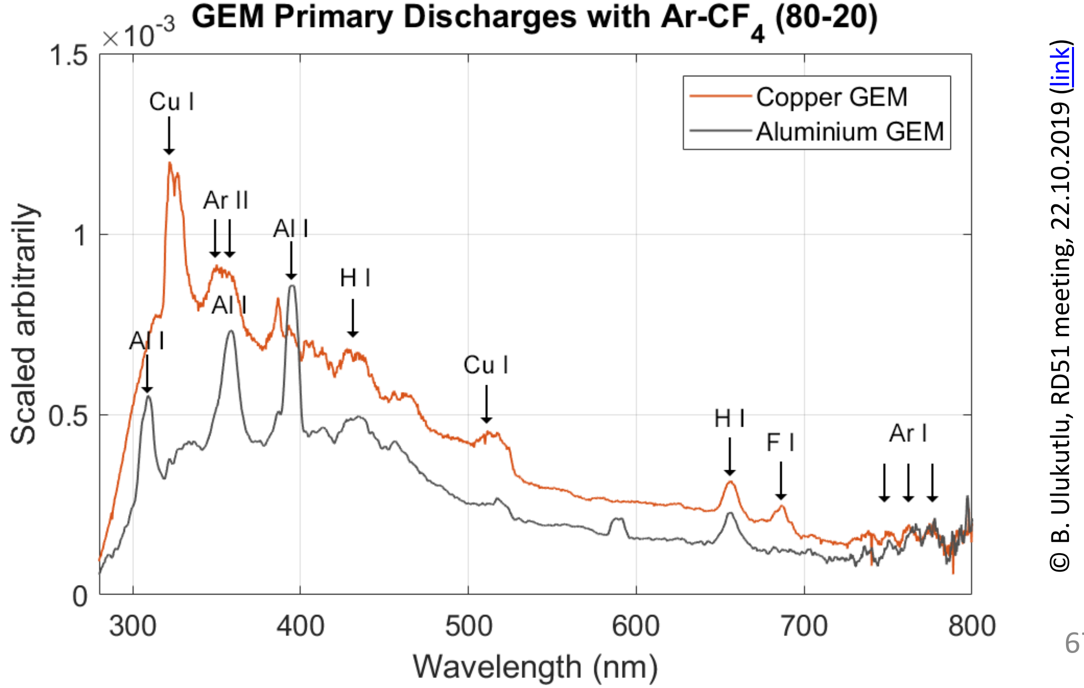
	Magnetron Sputtering Deposition	Vacuum Cathodic Arc Deposition	Pulsed Laser deposition
Available Machines	Teer (CHN) / Hauzer (CHN)	Hauzer (CHN)	A small machine (CHN)
Control of Parameters, cleanliness	High / High	High	Medium
Different deposition (graphite, B, B4C)	Yes (For B, need some upgrade now) / Yes (except B)	Yes	Yes
Doping	Yes	Yes	Yes (Limited by target, not flexible enough)
Uniformity on $10*10cm^2$	Good / Good	Good	Impossible(up to 2cm)
Control of Resistivity	High/ High	Medium	No study
Surface treatment	No / No	No	No
Compatible with protection layers on CsI	No	No	No
Remarks	The always used method	DLC structure(more sp3 structure)	Some R&D study

Spectroscopy studies w/different GEM electrodes

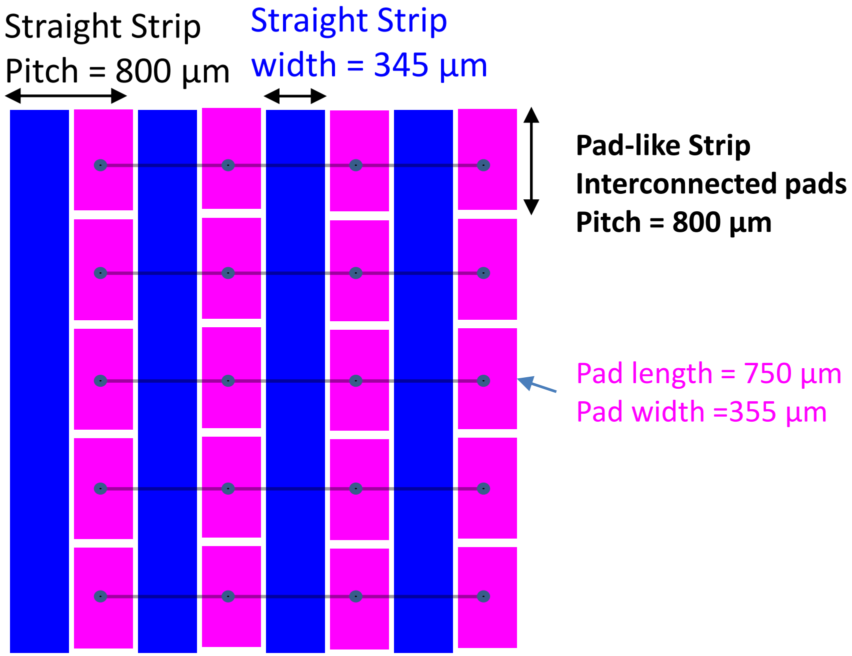
- Studying discharge formation and evolution through the light emission spectra
- Secondary discharge studies with exotic THGEMs. Measurements with DLC coated THGEM ongoing
- See more by B. Ulukutlu (TUM) at RD51 Collaboration meeting, 22.10.2019 (link)



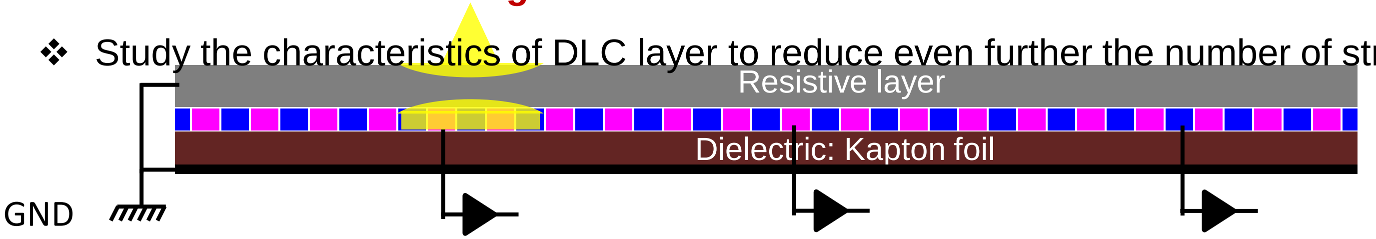




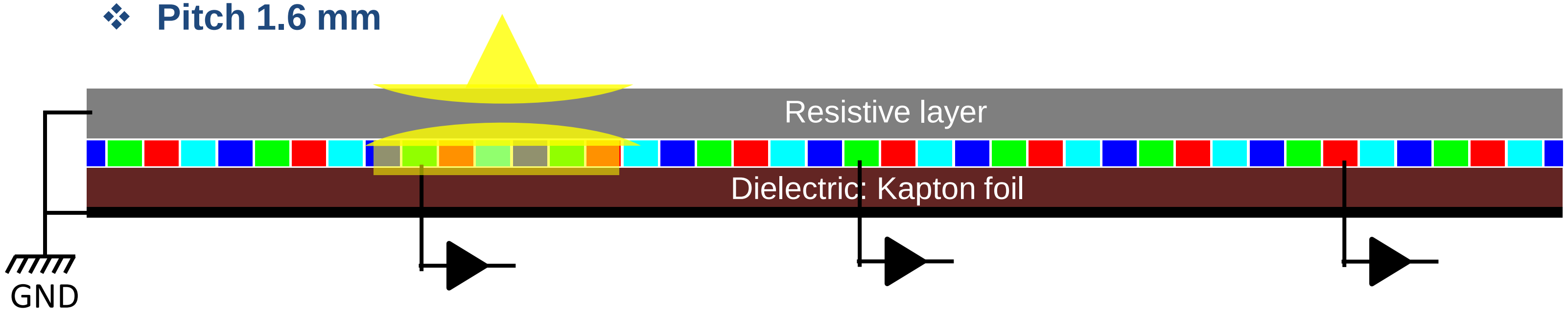
Generic R&D: Resistive Strip Readout for GEMs

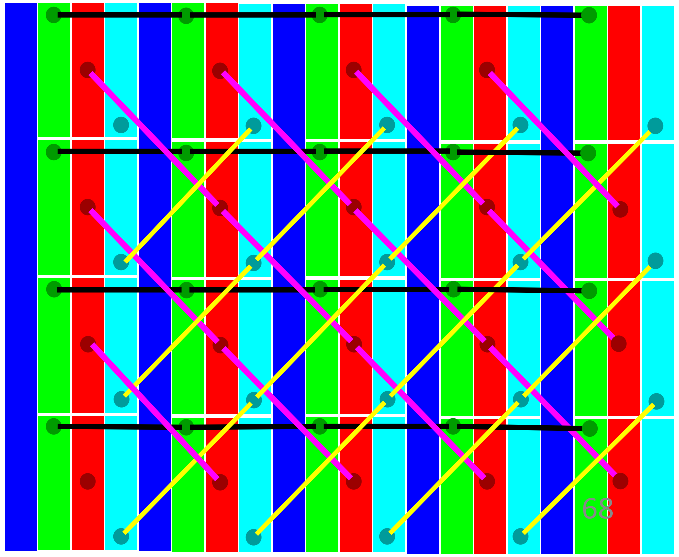


- **Idea**: Develop 2D X-Y readout strips with **resistive layer (DLC)** on top for charge sharing
  - X-Strips width 345 µm & Y-Pad-Strip readout width 355 µm
  - **Pitch 800 µm**
  - Prototype under production with Rui ⇨ Half the number of COMPASS X-Y readout
- **Our interest in DLC technologies:**
  - Study the characteristics of DLC layer to reduce even further the number of strips



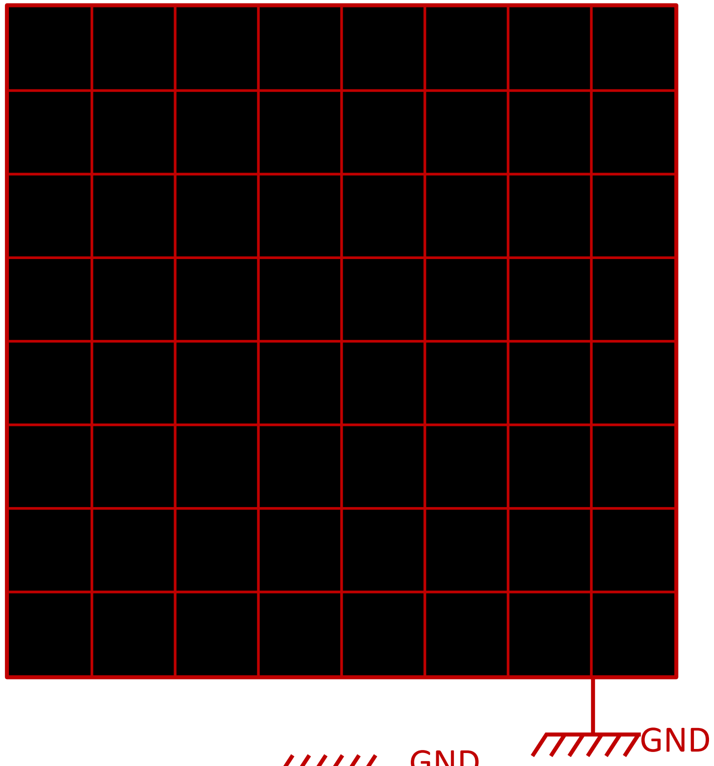
- **Going one step further**: just for fun ⇨ explore 4D X-Y / U-V pad-Strips readout strips **with resistive layer on top for charge sharing**
  - **X-Strips 345 µm and Y-Pad-like strip**
  - **Pitch 1.6 mm**





Generic R&D: Resistive Cascade Pad Readout for GEMs

(Original idea from Rui's of course)

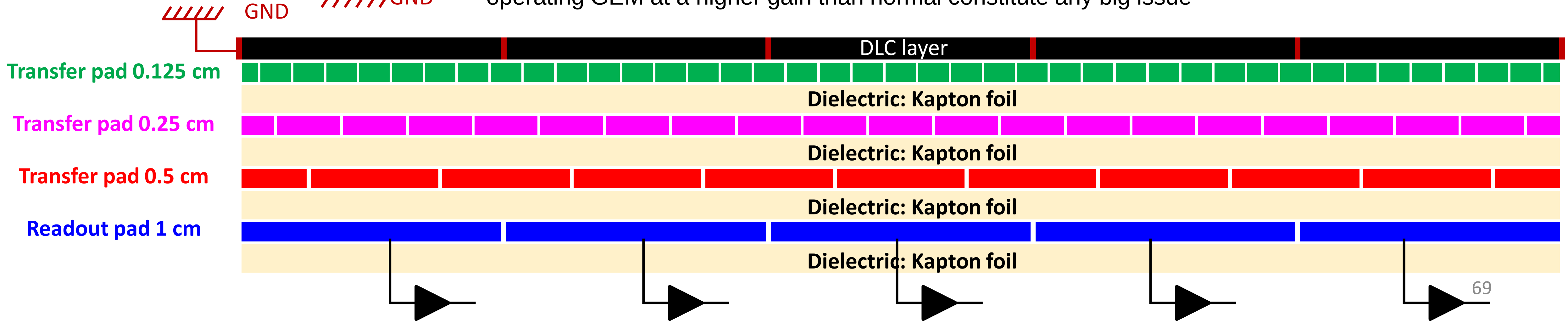


Idea: Develop a high performance large pad readout ⇨ prototype under production 1 cm^2 pads

- ❖ **Only 100 pads to cover 10 × 10 cm^2 triple GEM detector**
- ❖ Charge sharing through **capacitance coupling** with a cascade of **transfer pad layers** with ever decreasing pad size on top of the pad readout layer
- ❖ Pad size of upper layer is half the pad size of the layer below ⇨ ensuring the charge sharing scheme
- ❖ **DLC layer on top of the upper transfer pad layer** to provide the initial charge spread as well as the evacuation of the charge from the GEM amplification

Concern & potential issues:

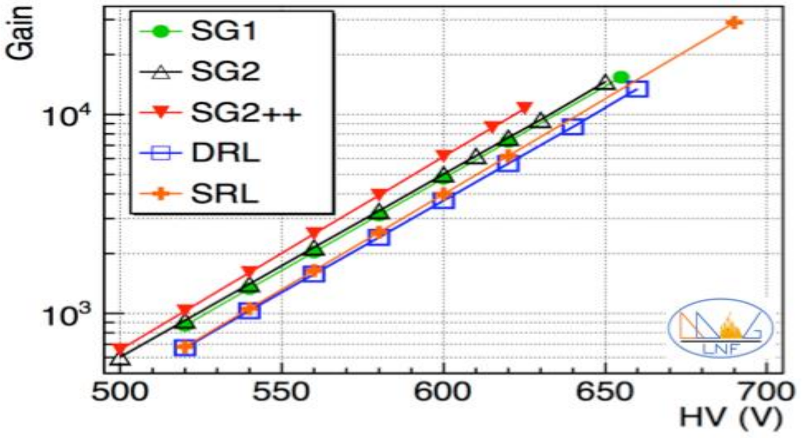
- ❖ Capacitance noise from readout pads & upper transfer pad layers could make this design ineffective
- ❖ Charge sharing from 4 stages would require the GEM amplification to be pretty large ⇨ Does operating GEM at a higher gain than normal constitute any big issue

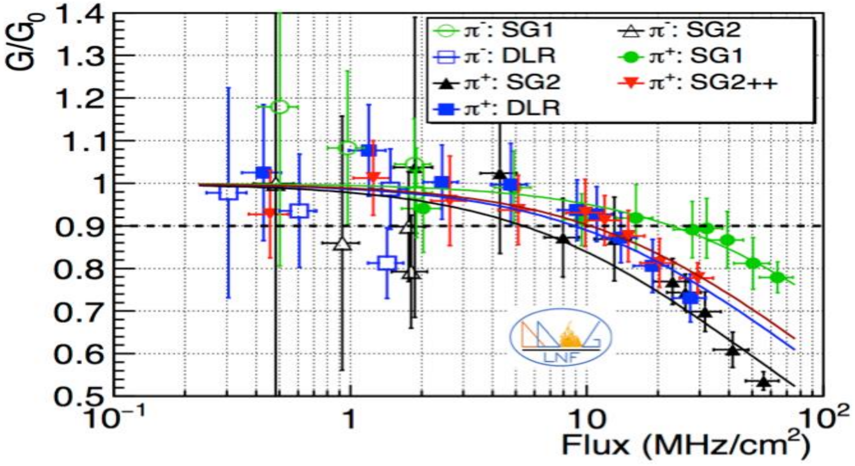


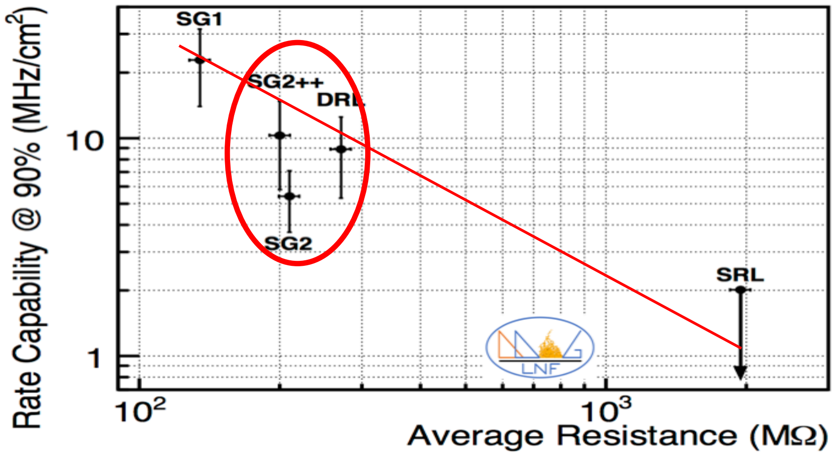
uRWELL performance

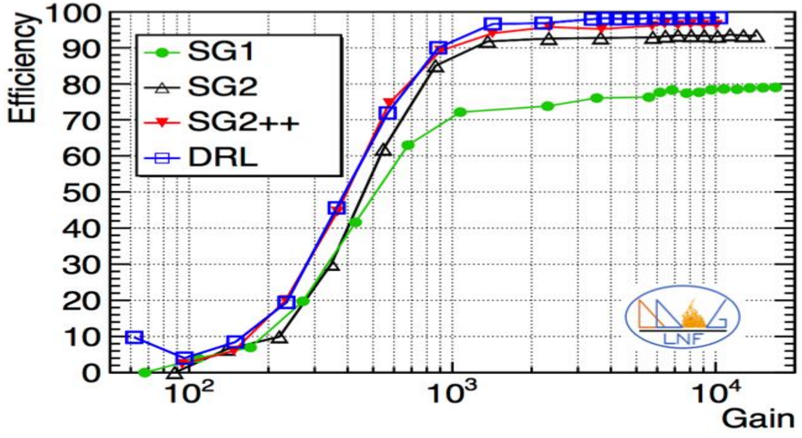
Gain up to ~ 10^4

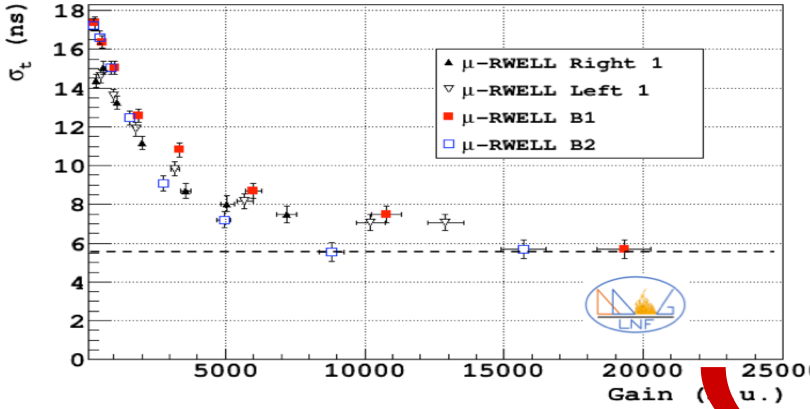
Rate capability (@ G = 4000) ~ 10 MHz/cm^2

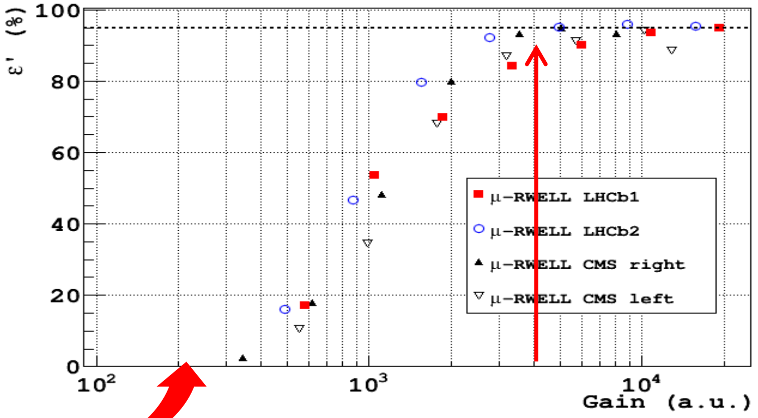












Efficiency ~ 98%

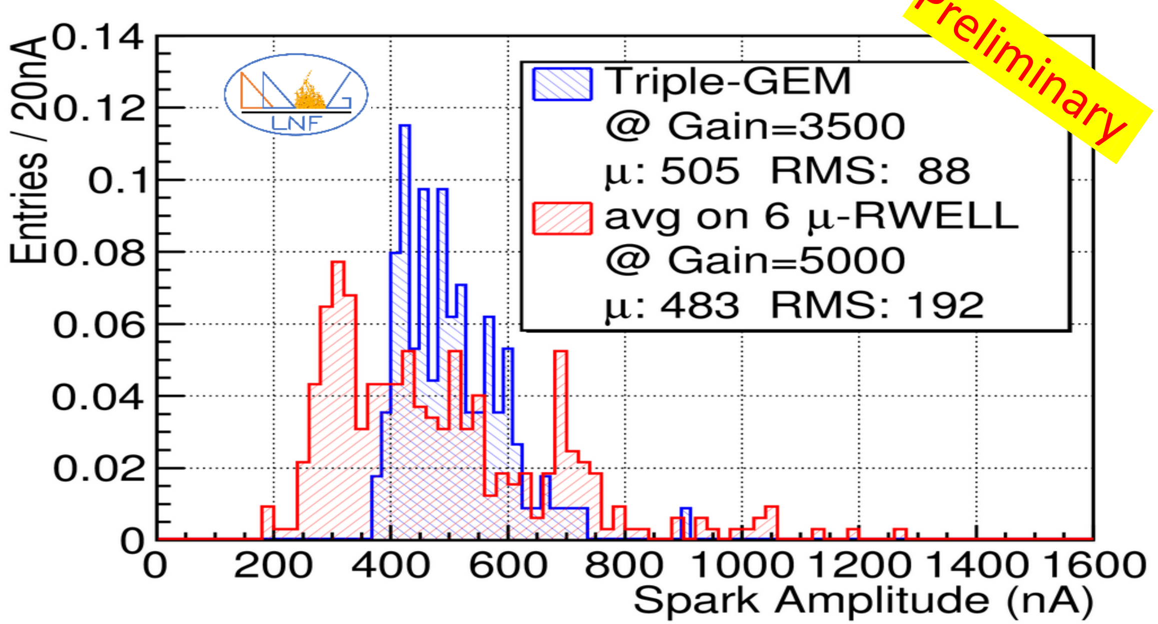
σ_t ~ 5- 6 ns (single gap)

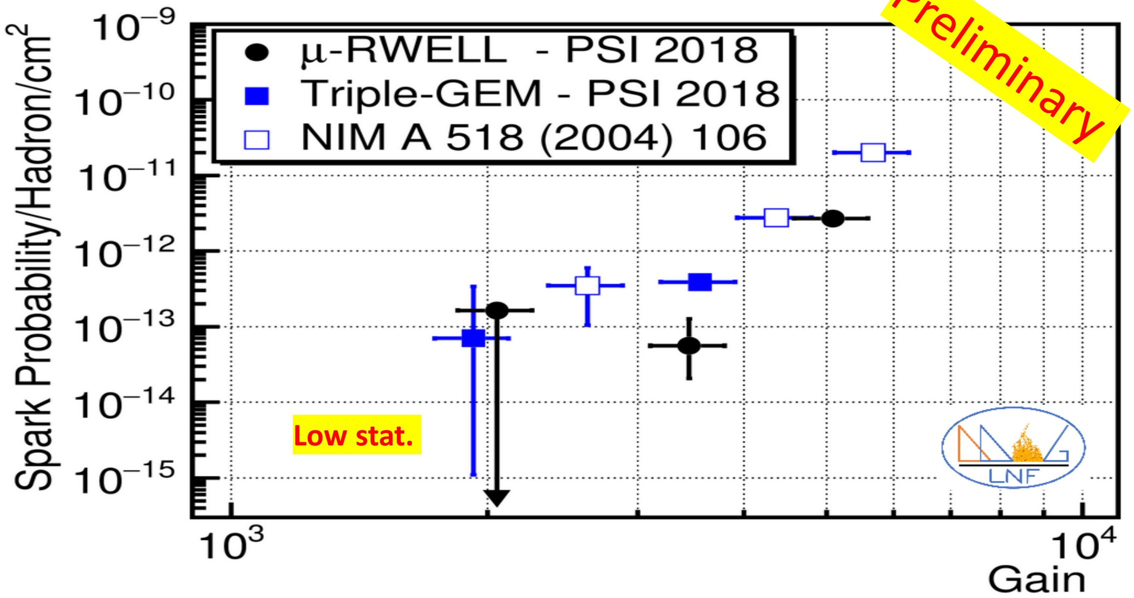
Efficiency in 25 ns (single gap)

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 slightly lower than the one measured for GEM.

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