The G-RWELL technology

for LHCb Muon Detector at HL-LHC

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LNF – INFN [1]
Bari – INFN [2]
CERN [3]

Istituto Nazionale di Fisica Nucleare

6th DRD1 Collaboration Meeting, Oct. 7th 2025

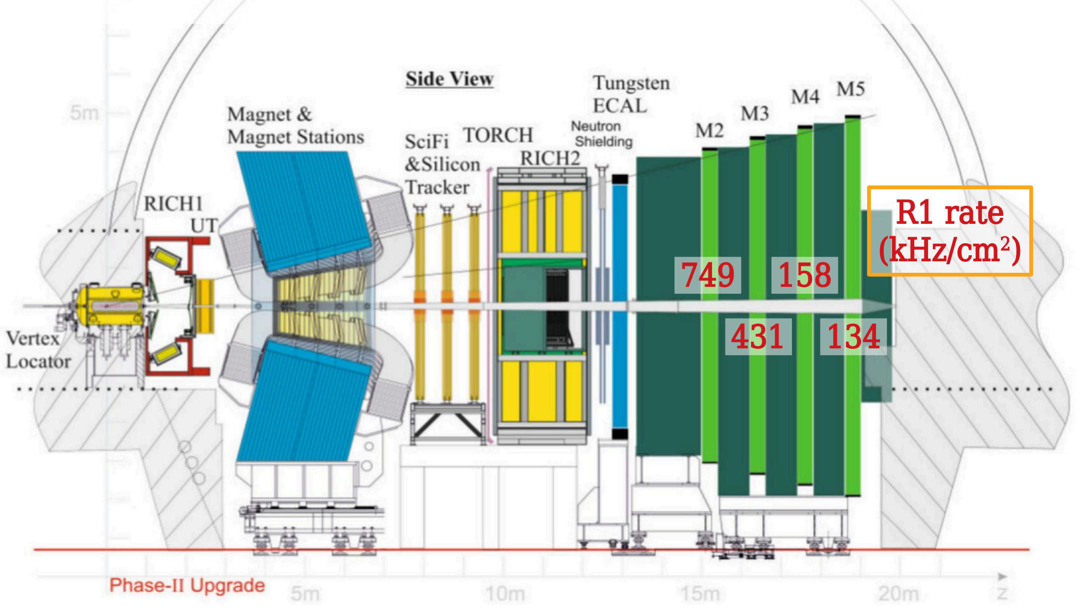
LHCb Upgrade II (Run5-6)

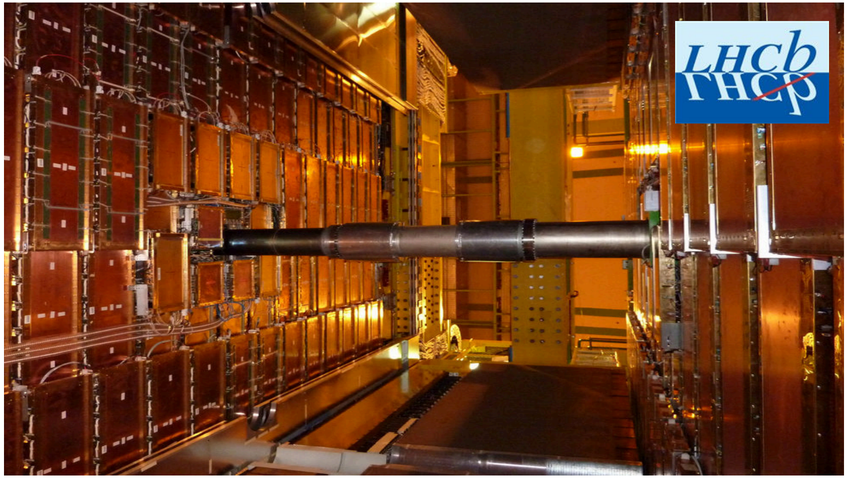
LHCb muon RUN 5-6 → Detector requirements:

- Rate up to **1 MHz/cm²** on detector single gap
- Rate up to **700kHz** for FEE channel
- Efficiency (4 gaps) > **98% within BX** (25 ns)
- Stability up to 1 C/cm² accumulated charge in 10y of operation

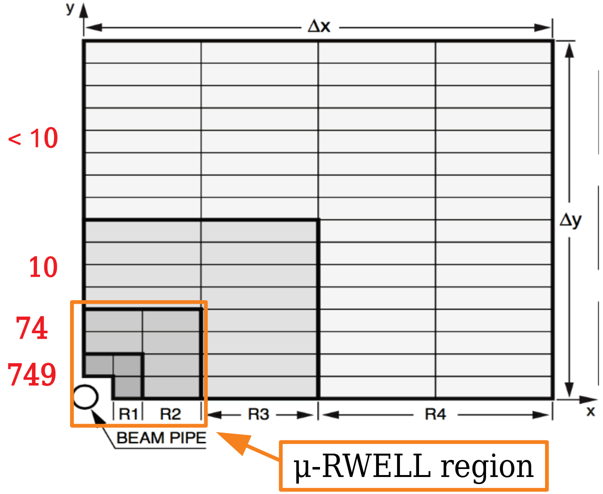
Detector size & quantity (4 gaps/chamber)

- R1 + R2 of M2-M5: **576 det.**, size 30x25 to 74x31 cm², **90 m² det**



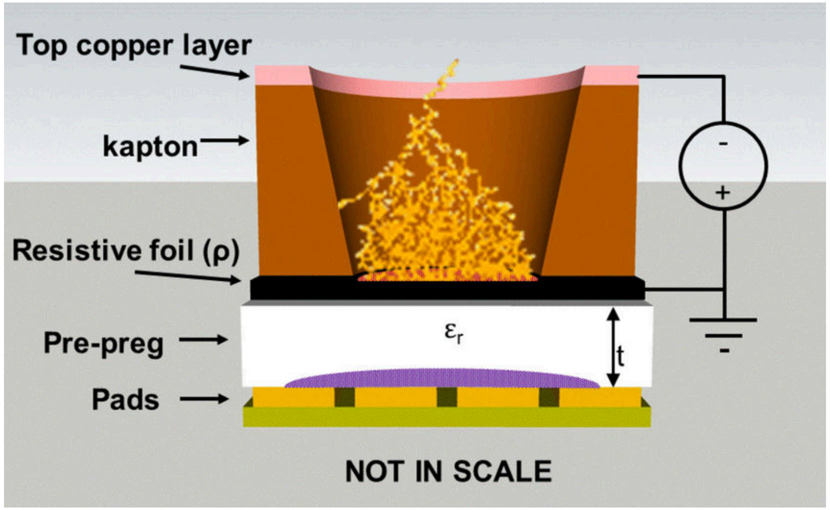


M2 station - max rate (kHz/cm²)

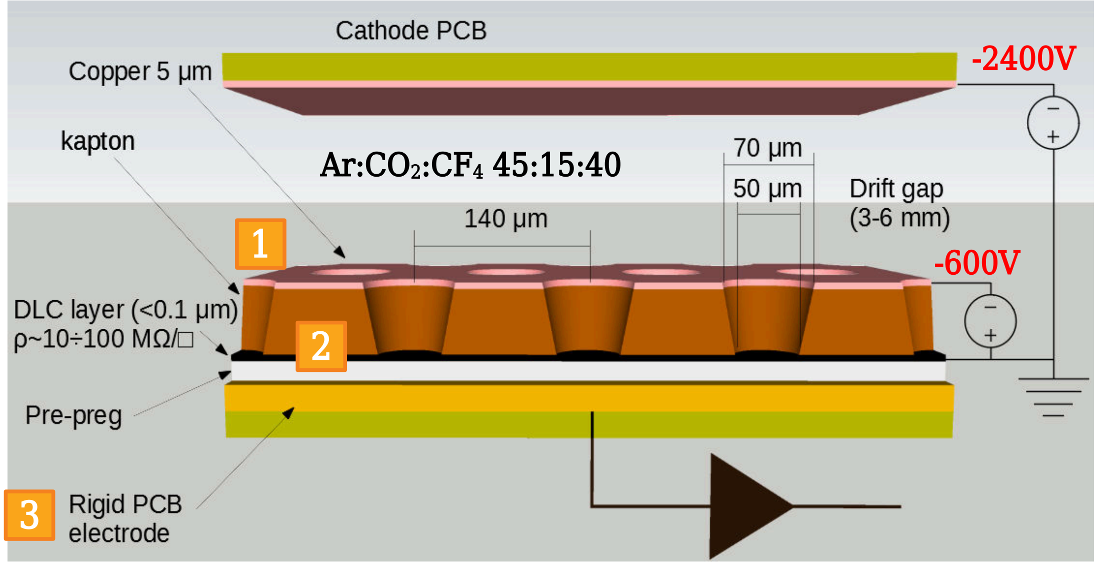


The µ-RWELL: detector scheme

The µ-RWELL is a Micro Pattern Gaseous Detector (MPGD) composed of only two elements: the µ-RWELL_PCB and the cathode. **The core is the µ-RWELL_PCB**, realized by coupling three different elements:



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

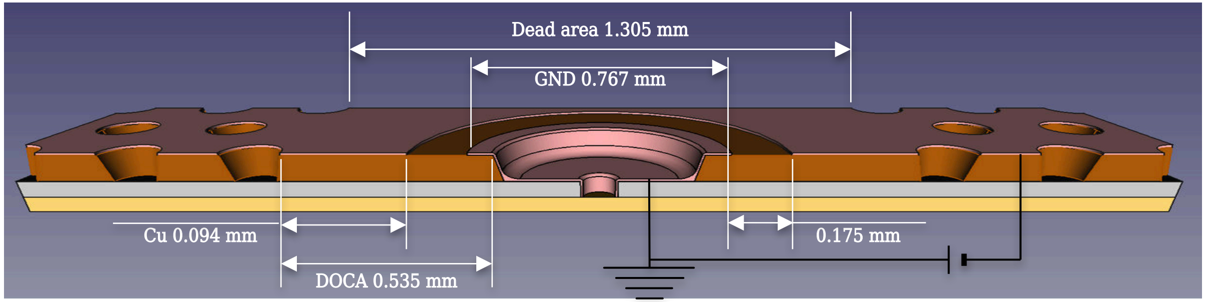


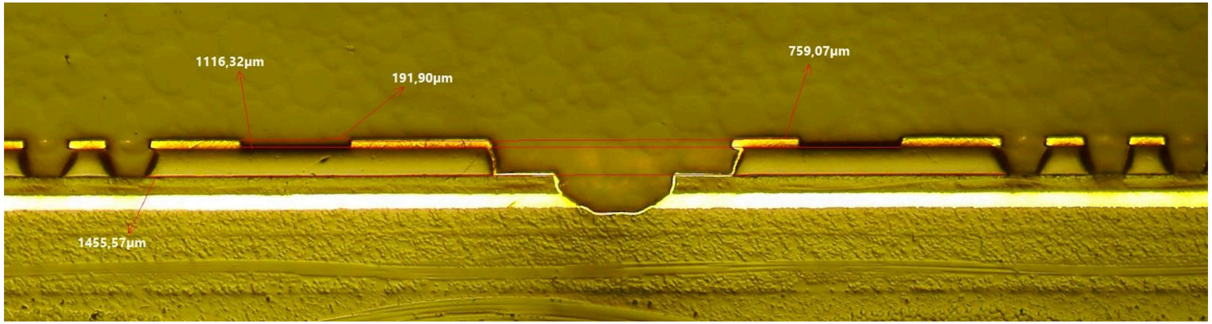
1. **a WELL** patterned kapton foil acting as **amplification stage** (GEM-like)
2. a **resistive DLC layer (Diamond-Like-Carbon)** for discharge suppression with surface resistivity ~ 50÷100 MΩ/□
3. a standard readout PCB

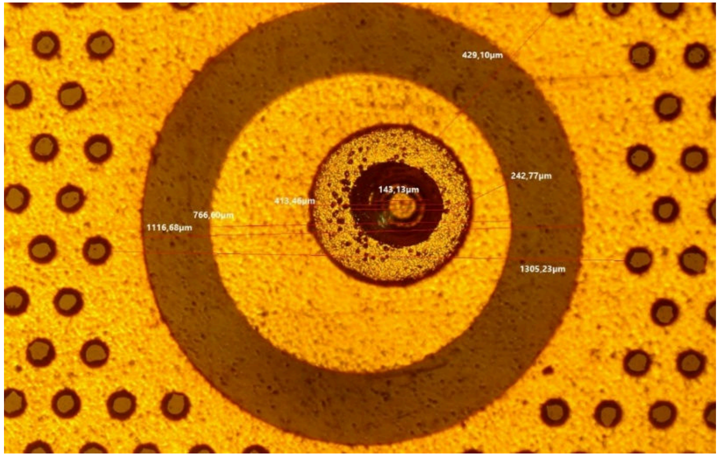
The PEP-DOT µ-RWELL

DLC-GND pitch [mm]	Dead Area [mm]	GND width [mm]	Insulation gap [mm]	DOCA [mm]
9	1.3 (1.6%)	0.767	0.175	0.535

- The most recent high rate layout:
  Patterning–**E**tching–**P**lating
- The DLC ground connection is established by creating **metalized vias from the top Cu layer through the DLC**, down to the pad-readout of the PCB
- The dead area is ~2%

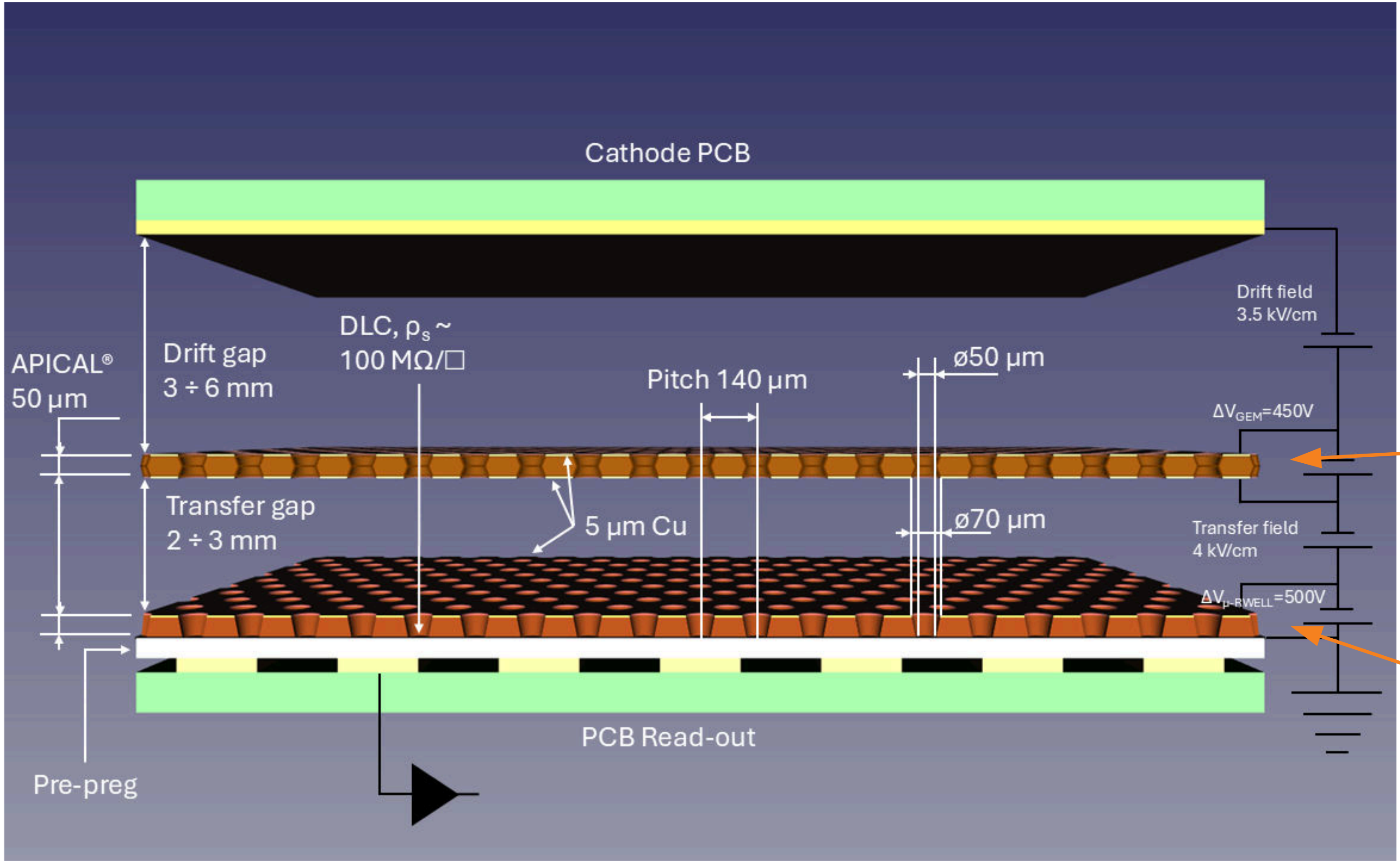






There have been a revival of "**S**ilver **G**rid" high rate **µ-RWELLs** but the PEP-DOT still remains the favorite option due to the **reduced dead area**.

The G-RWELL



	Drift [mm]	Transfer [mm]
2024	6	3
2025	6	2
LHCb U2	3	2

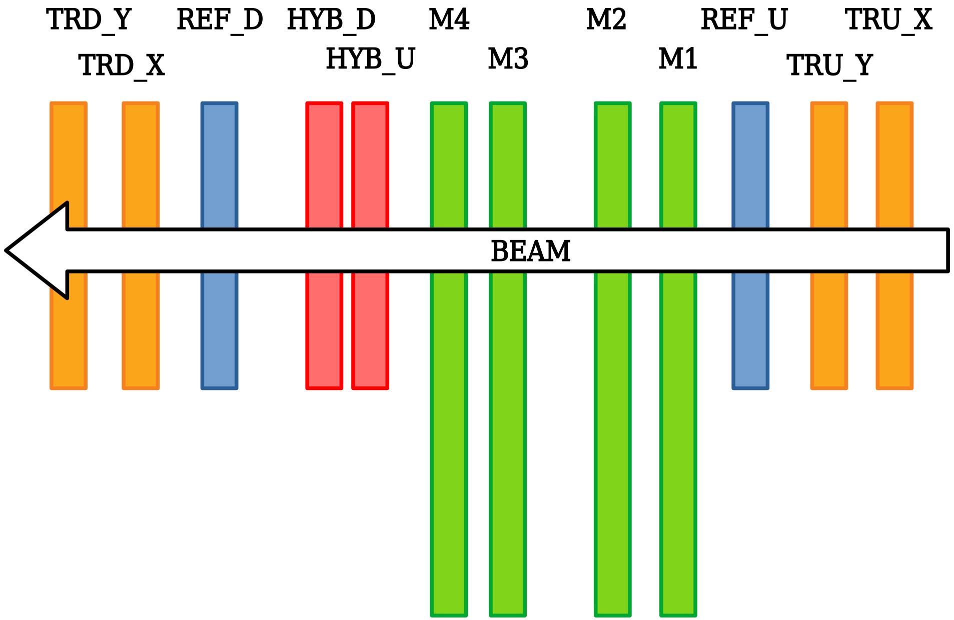
GEM detector
(preamplification)

+

µ-RWELL detector
(amplification)

2024 - Test Beam setup

Gas used: $Ar/CO_2/CF_4$ 45/15/40



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

Trackers: 10×10cm^2 - 1.2mm strip R/O (Capacitive Sharing)
Reference: 10×10cm^2 - 9×9mm^2 pad R/O
G-RWELL: 10×10cm^2 - 9×9mm^2 pad R/O
M2R1: 30×25cm^2, instrumented 15×13cm^2 - 9×9mm^2 pad R/O

TB area: PS-T10 w/ 5 GeV muons

FEE: **16 FATIC3** FEE boards (more info on FATIC3 and FATIC4 in L. Congedo's talk this week - link)

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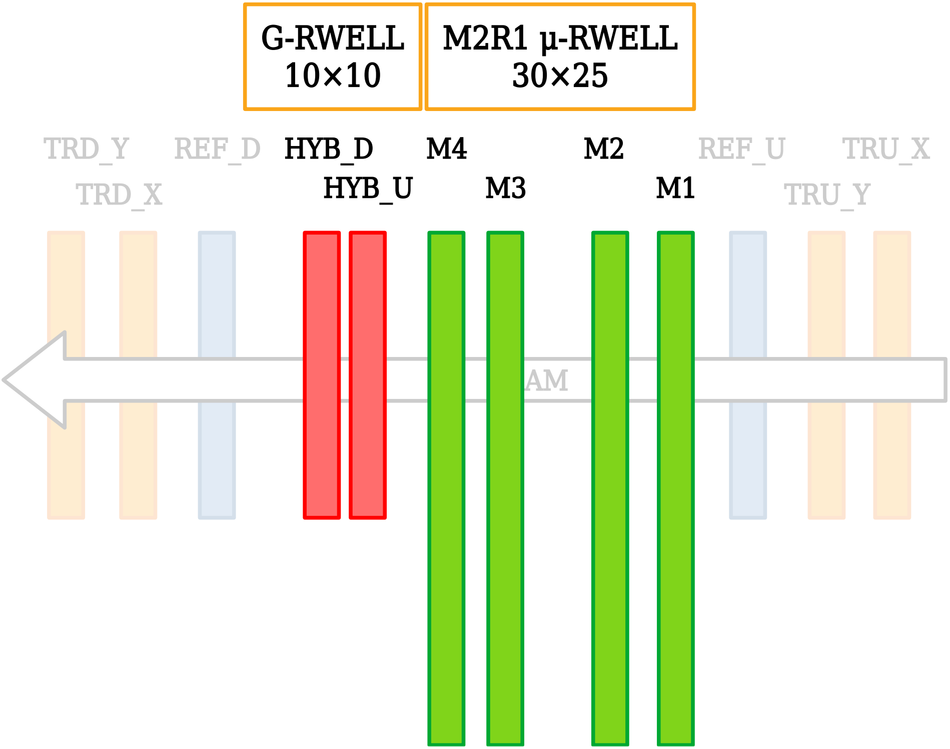

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A special dziękuję to INFN LNF, Rome2, and Bari LHCb groups for the support during the beam test.

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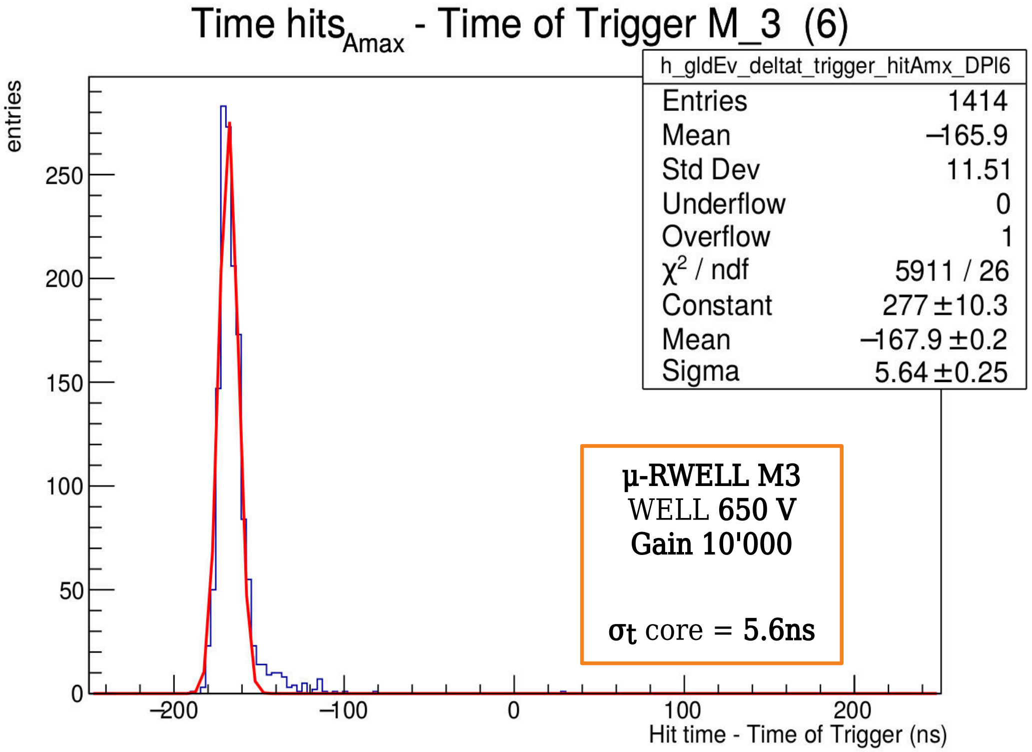
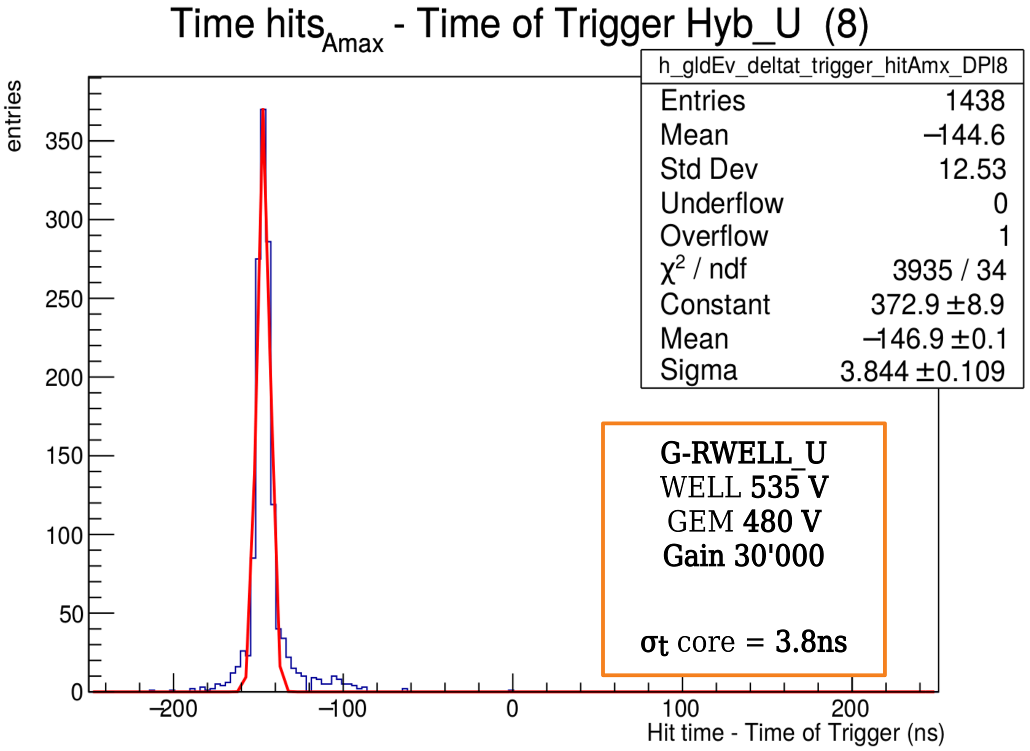
2024 - µ-RWELL vs G-RWELL – Time resolution





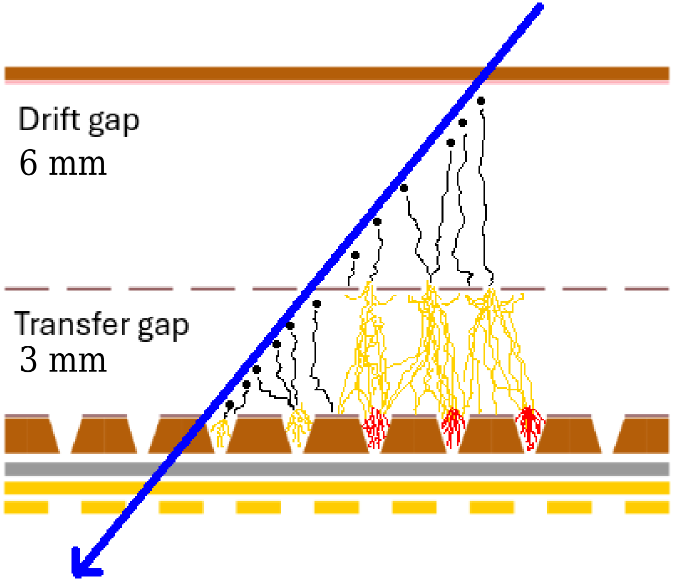
Time reference: one of the scintillator of the trigger (σ_t<1ns)

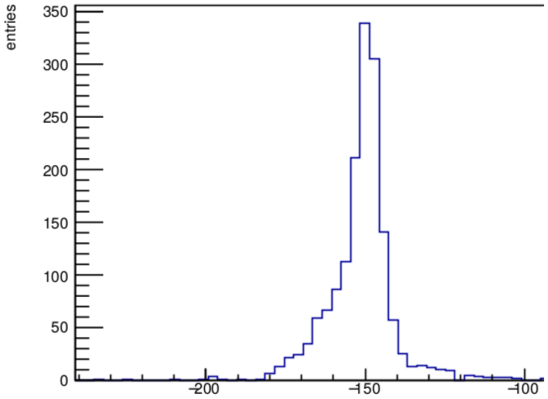
σ_t: gauss fit core of the Δ_t distribution

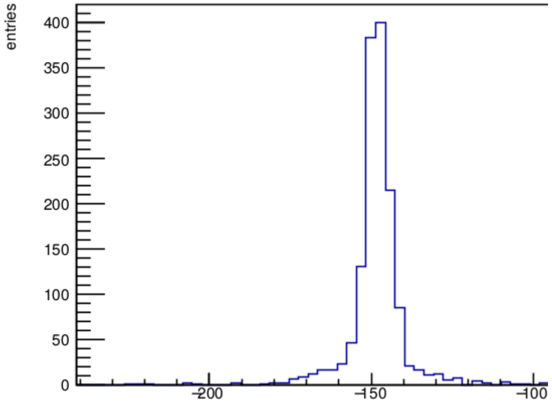
G-RWELL – Bigap effect

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

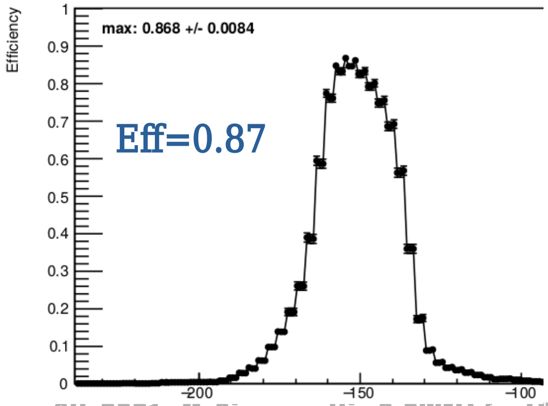
WELL **535** (gain 1000)
GEM **510** (gain 50)
Gain **50'000**
RUN_id 20241124_182541

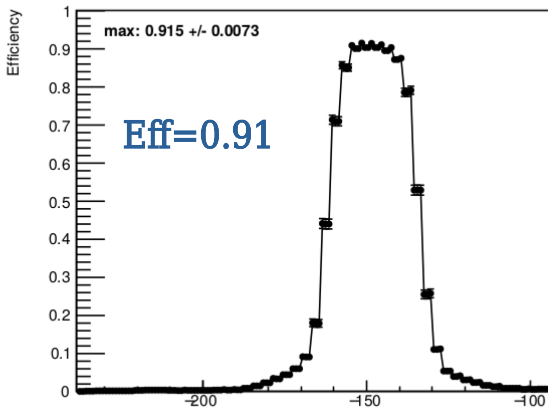






Time window: 25ns
T_fastest_hit - T_trigger

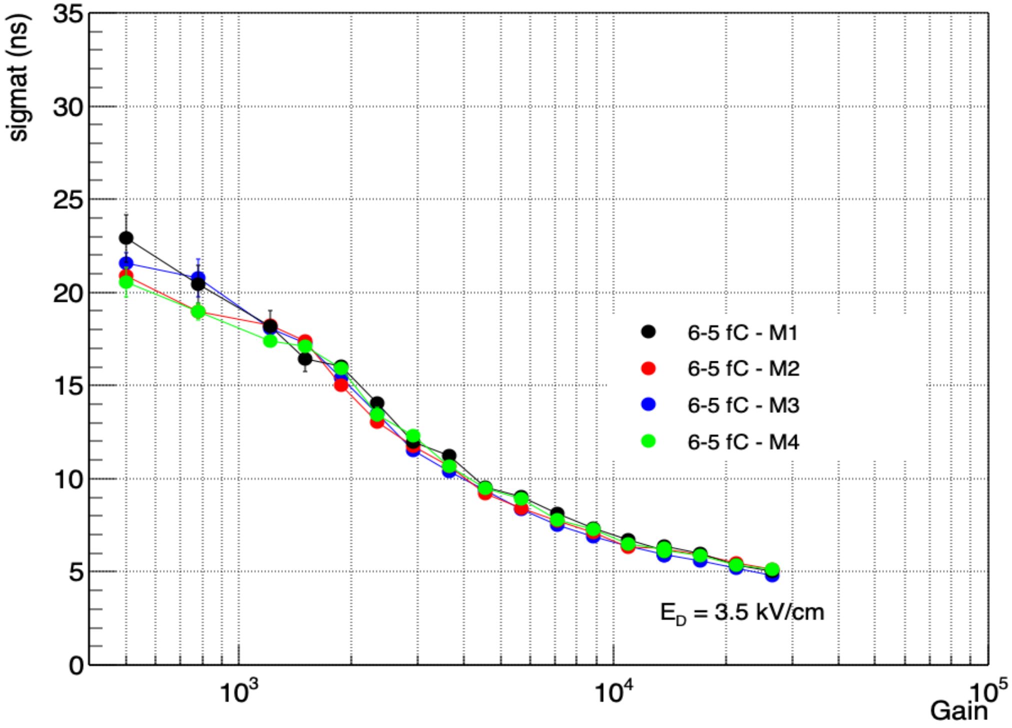




TDC sampling time: 3.125ns.
Window **steps**: 1ns.

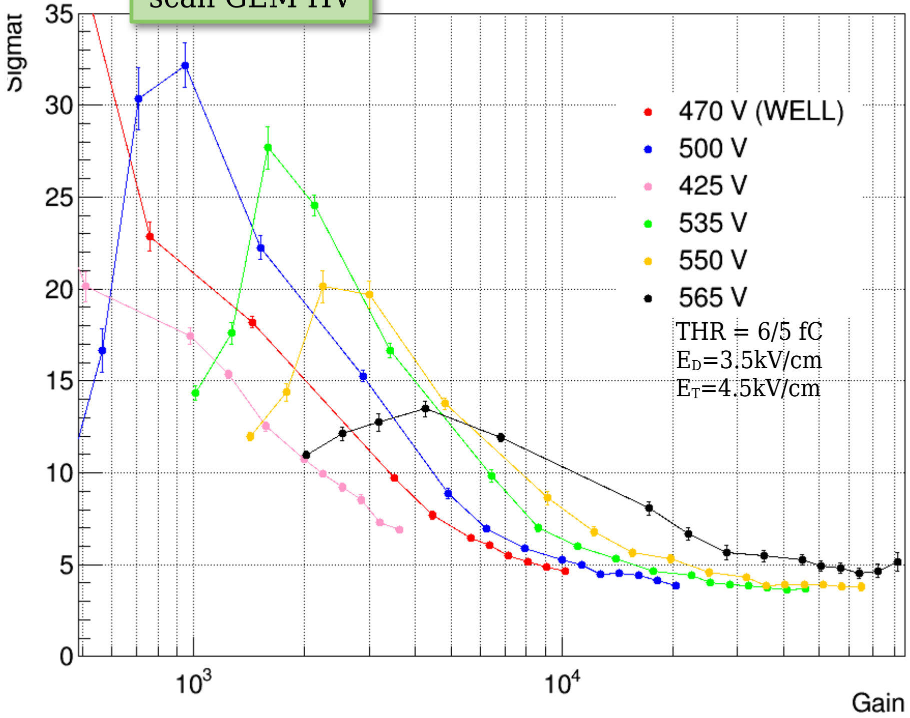
2024 - µ-RWELL vs G-RWELL – Time resolution [core]

µ-RWELL



Fixed WELL HV
scan GEM HV

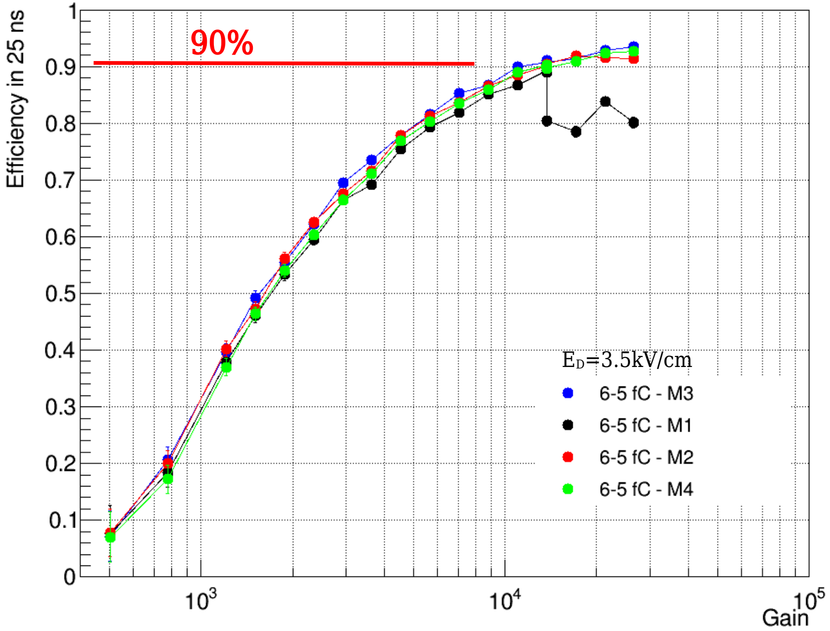
G-RWELL



The G-RWELL demonstrates better time performance than µ-RWELL at the same gain, thanks to higher efficiency on the first cluster.
For the same gas gain, differences varying HV_WELL → “Bigap effect”

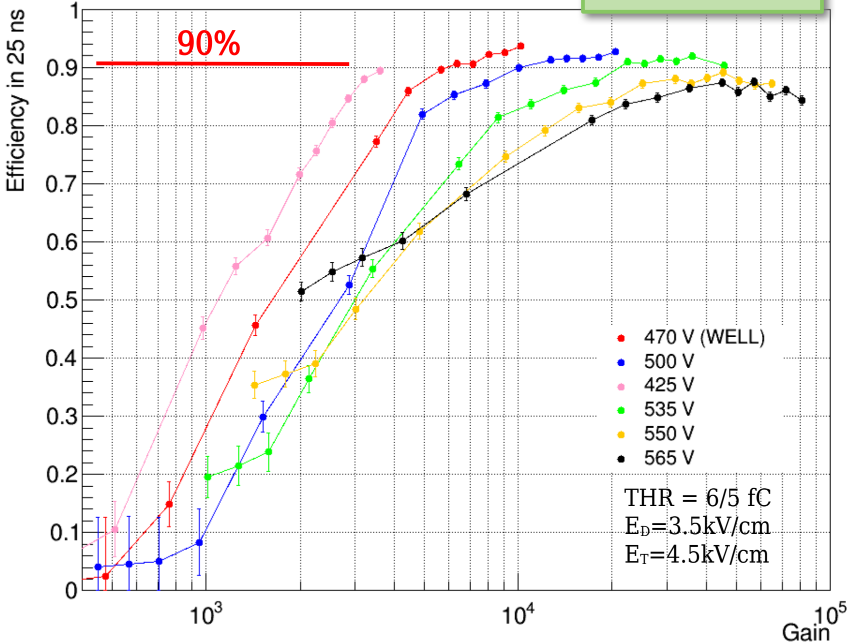
2024 - µ-RWELL vs G-RWELL – Efficiency in 25ns

µ-RWELL



G-RWELL

Fixed WELL HV
scan GEM HV

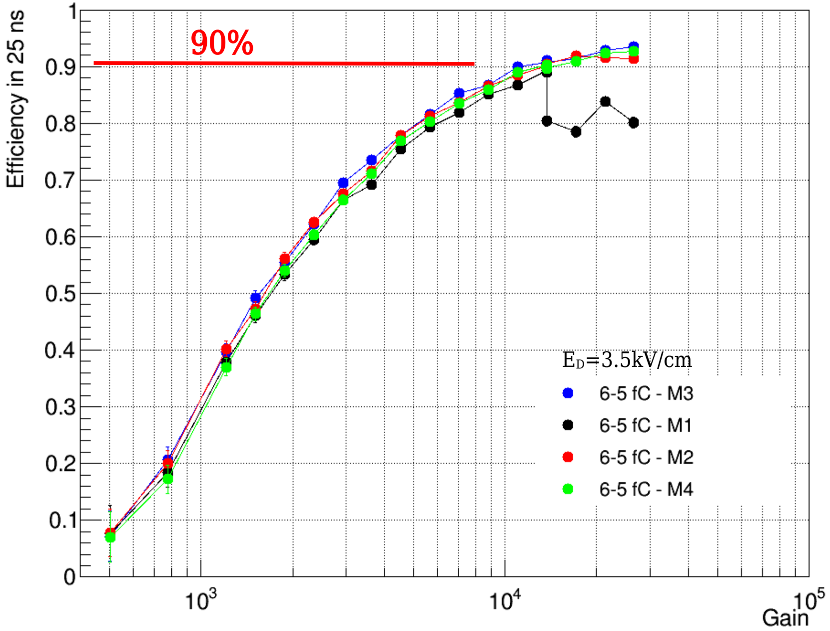


The best performance obtained for a µ-RWELL gain around 10^4, close to the typical **max gain** of the detector.

High gain curves have a lower plateau due to the **"bigap" effect**. The magnitude of this **effect depends** on the geometry of the detector (the **transfer** field and gap) and the **FEE threshold**.

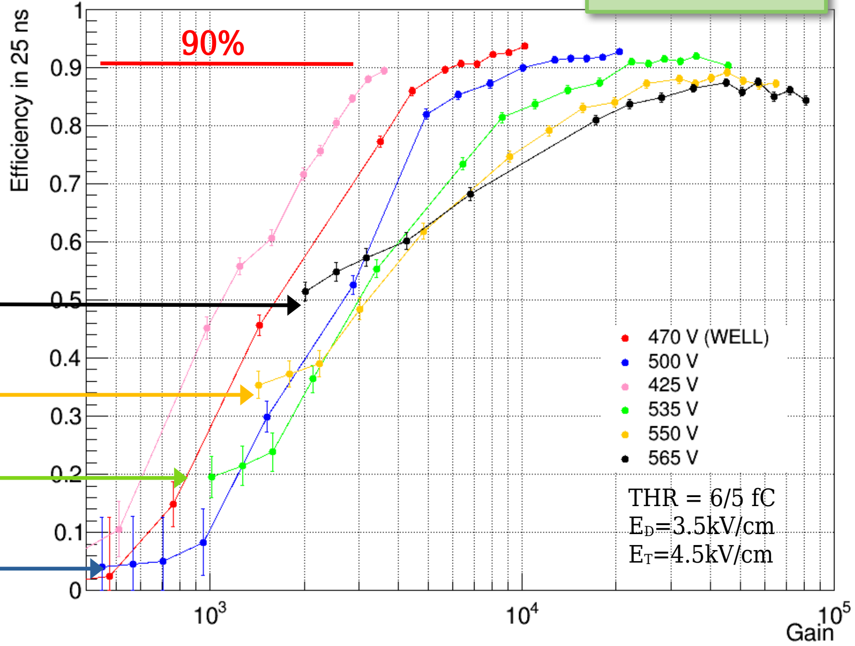
2024 - µ-RWELL vs G-RWELL – Efficiency in 25ns

µ-RWELL



G-RWELL

Fixed WELL HV
scan GEM HV



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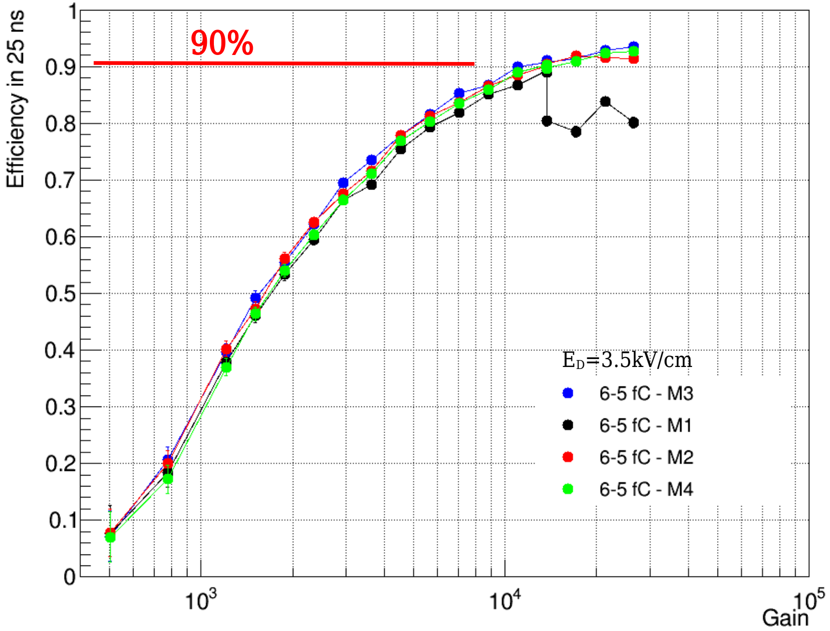
High gain curves have a lower plateau due to the **"bigap" effect**. The magnitude of this **effect depends** on the geometry of the detector (the **transfer** field and gap) and the **FEE threshold**.

Each LHCb station has 4 detectors (Majority 2over4 logic)
Eff(25ns)≥0.9 per single gap means **Eff(25ns)≥0.98** per station

The values for low gains should be the percentage of "bi-gap events". Nice catch Eraldo ;)

2024 - µ-RWELL vs G-RWELL – Efficiency in 25ns

µ-RWELL



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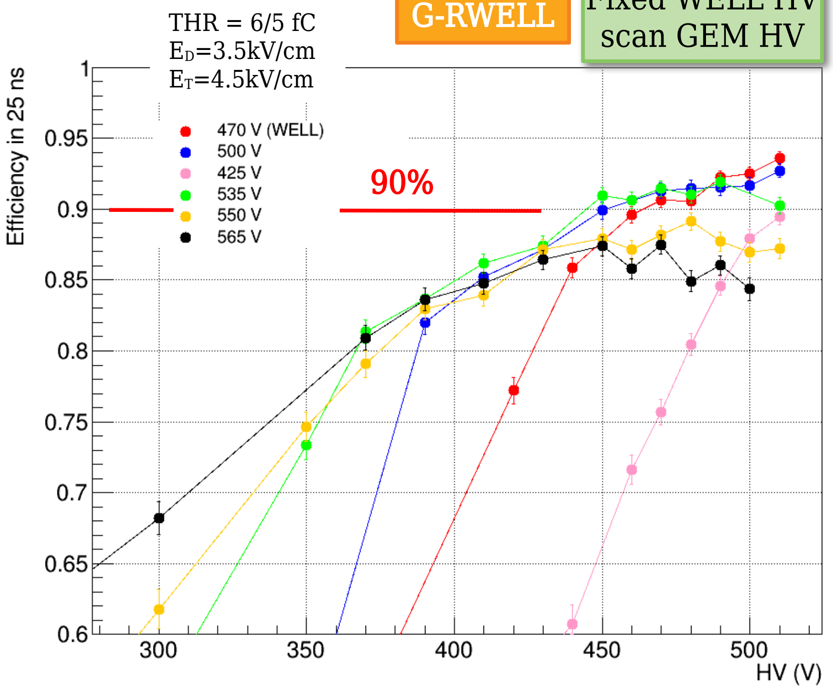
G-RWELL

Fixed WELL HV scan GEM HV

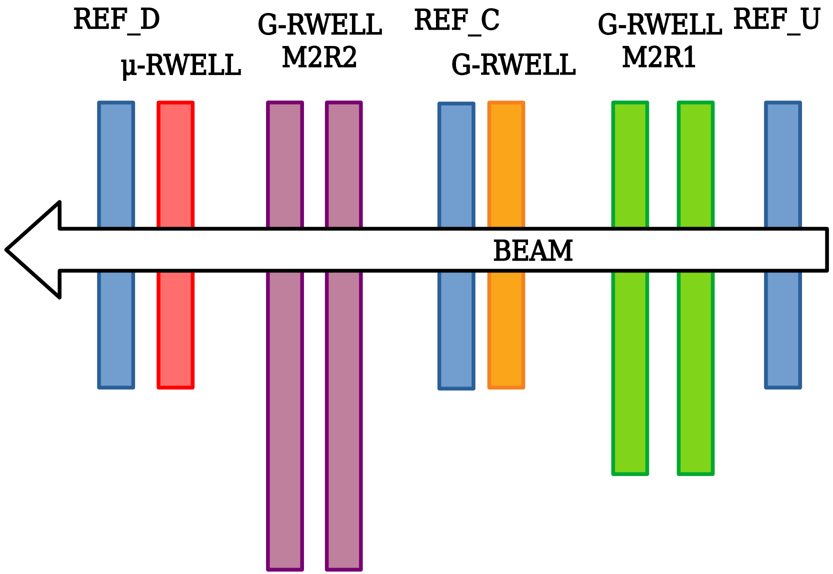


High gain curves have a lower plateau due to the **"bigap" effect**. The magnitude of this **effect depends** on the geometry of the detector (the **transfer** field and gap) and the **FEE threshold**.

Best performance:

- HV **µ-RWELL** = 500-535 V (**gain 500-1000**)
  HV **GEM** = 450 V (**gain 20**)

Next beam test: November 2025



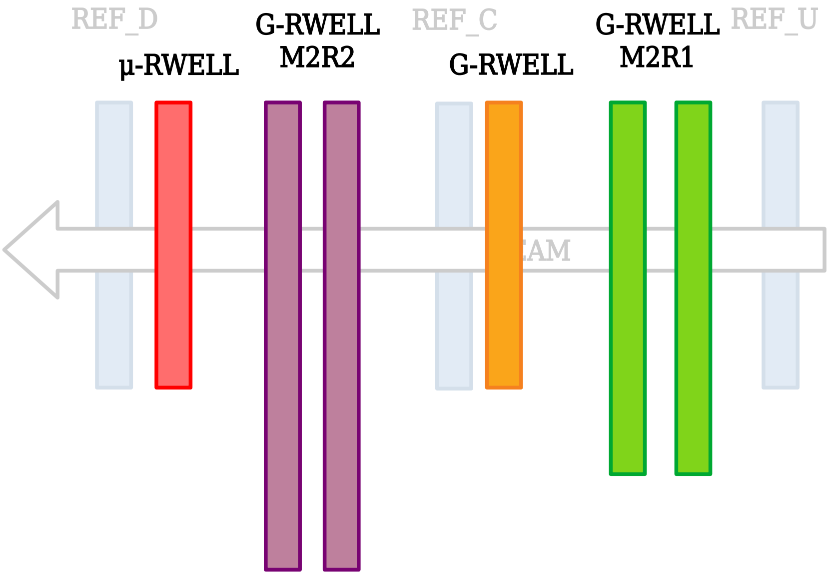
Reference: 10×10cm² - 9×9mm² pad R/O

μ-RWELL: 10×10cm² - 9×9mm² pad R/O
G-RWELL: 10×10cm² - 9×9mm² pad R/O – Transfer 3mm

M2R1: 30×25cm² - 9×9mm² pad R/O – Transfer 2mm
M2R2: 60×25cm² - 9×9mm² pad R/O – Transfer 2mm

TB area: PS-T10 w/ 5 GeV muons, FEE FATIC3

Next beam test: November 2025



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G-RWELL: 10×10cm^2 - 9×9mm^2 pad R/O – Transfer 3mm

M2R1: 30×25cm^2 - 9×9mm^2 pad R/O – Transfer 2mm
M2R2: 60×25cm^2 - 9×9mm^2 pad R/O – Transfer 2mm

TB area: PS-T10 w/ 5 GeV muons, FEE FATIC3

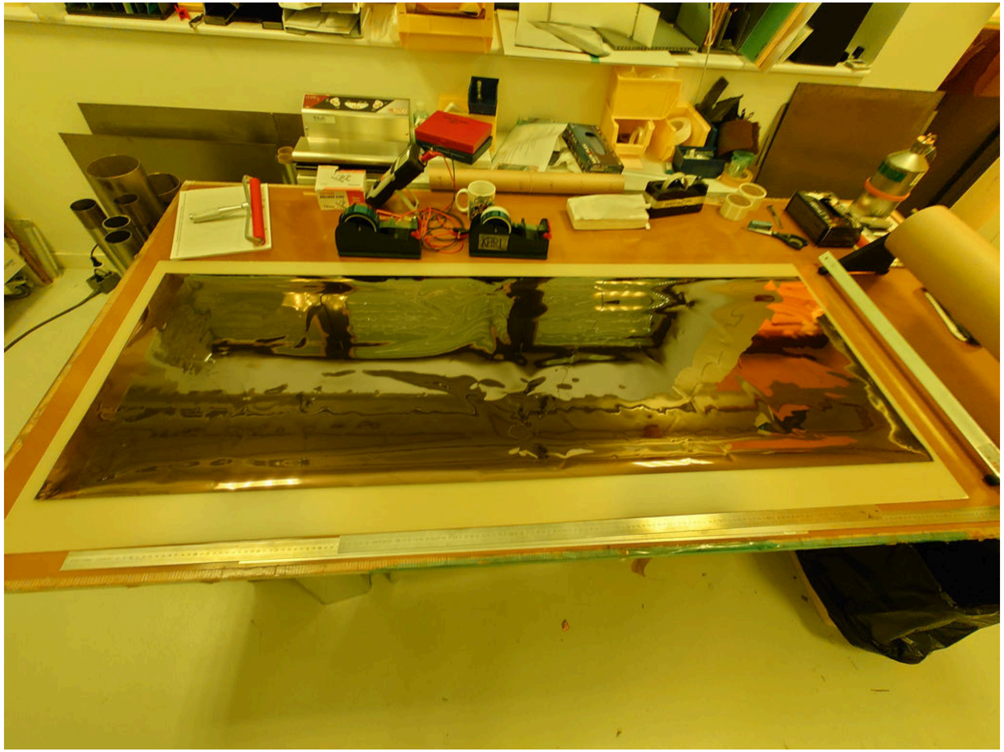
Dziękuję to the MPT team and in particular to Alexis for his help

DLC foil production

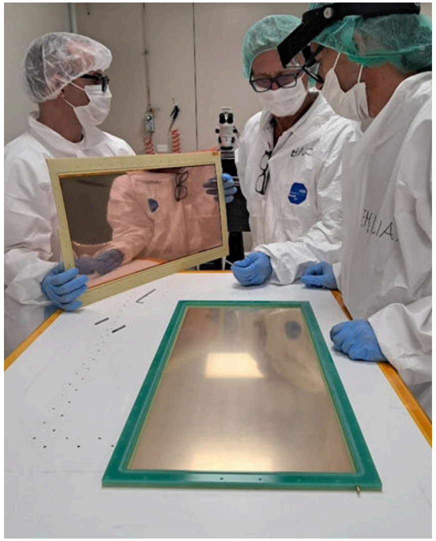
4 M2R2 foils, **ρ = 170 ± 40 MΩ/□**, type Kapton-Cu

Full report at the [WP1 3rd Mini Workshop – Task 8]

The CID team: Rui, Serge, Karl ([see talk]), Givi, Louise Gianfranco, Gianni, Gianluca

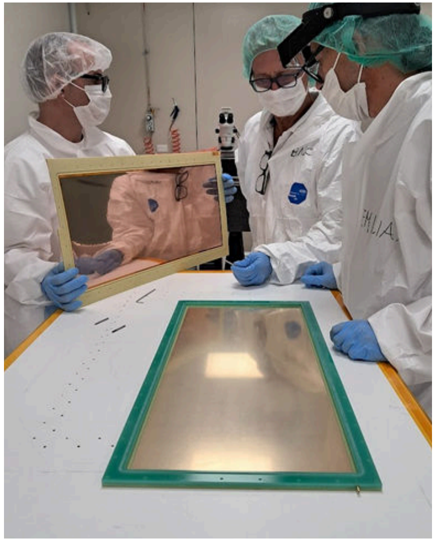


GEM gluing



Quality control:
testing the GEMs
with the **MEGGER**

GEM gluing



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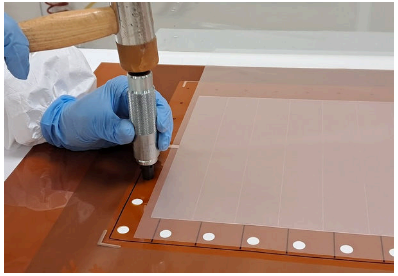
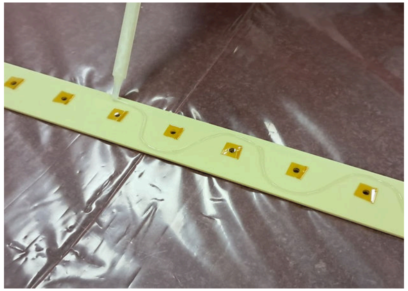
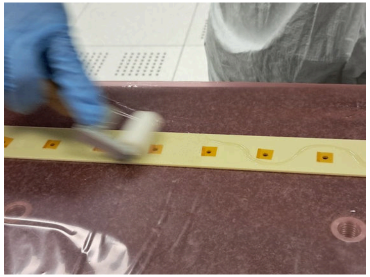
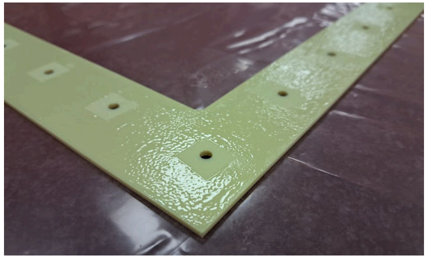


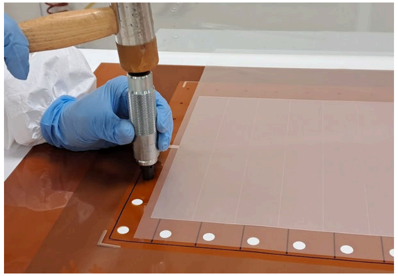


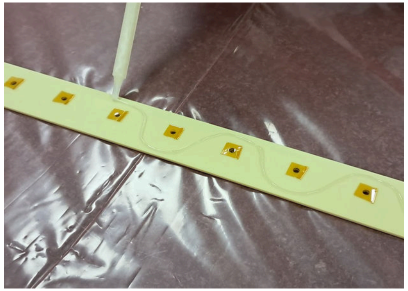


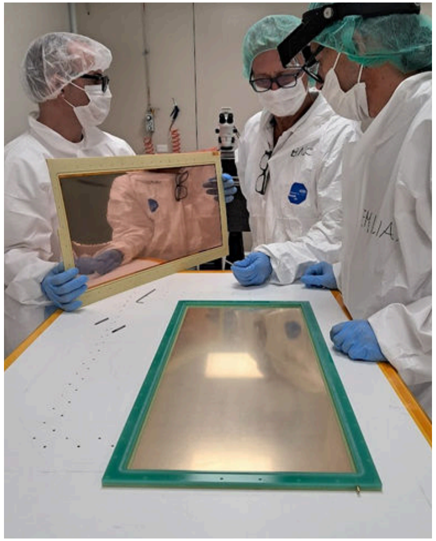


Thin glue film on the frames:
“S” pattern +“void area” around the holes, to prevent glue in the holes

GEM gluing







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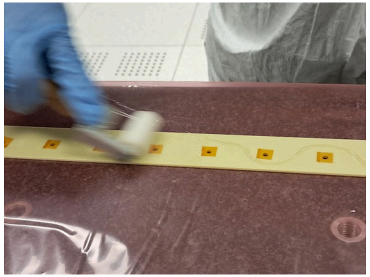
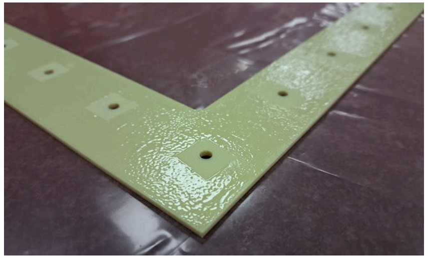
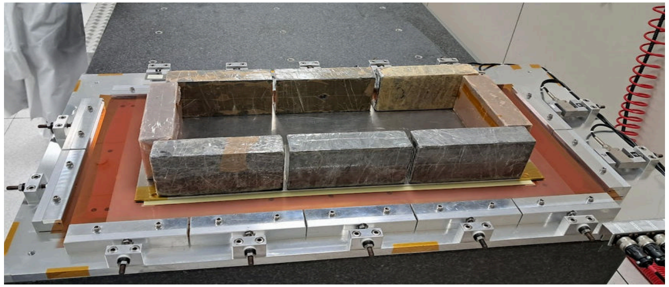


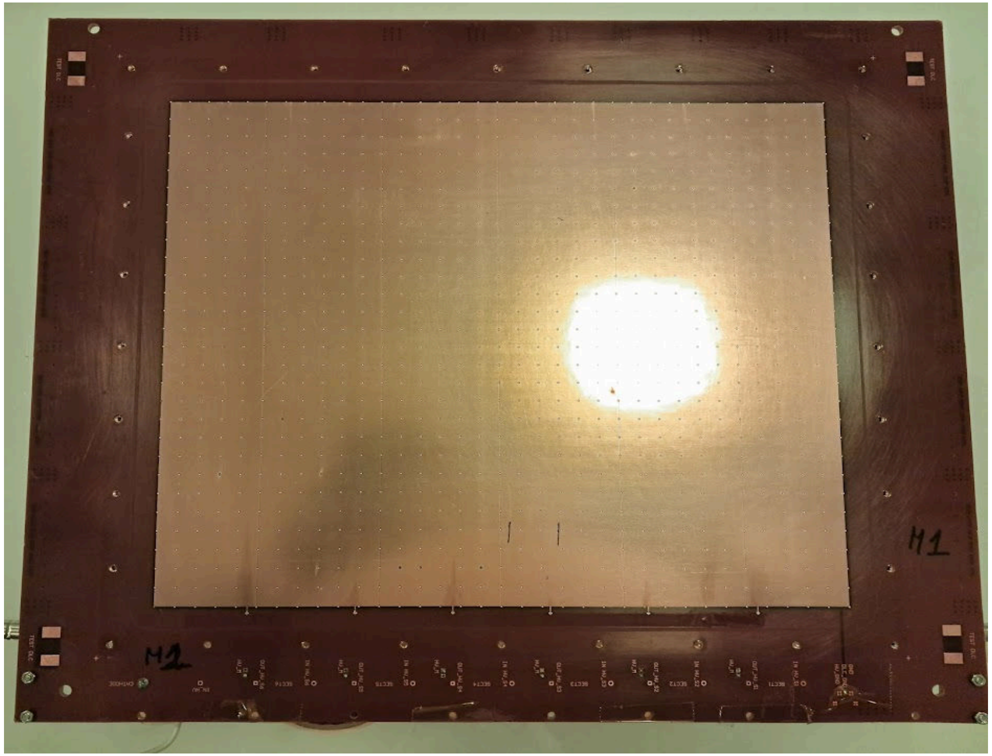


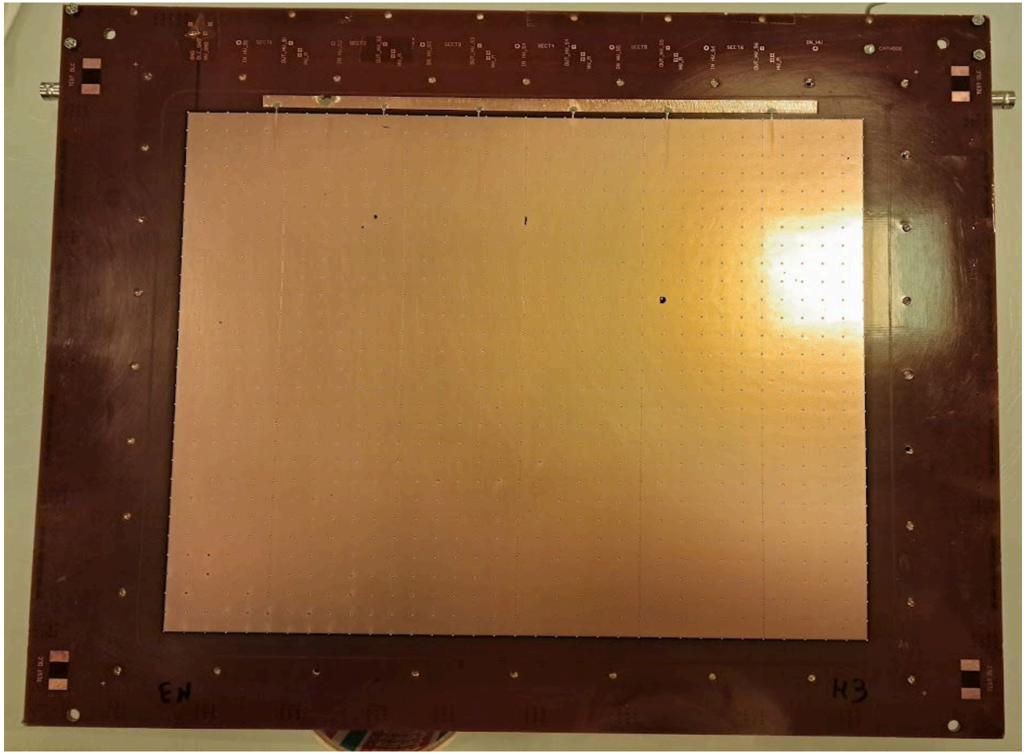
Thin glue film on the frames:
“S” pattern +“void area” around the holes, to prevent glue in the holes

Frame gluing:
- **the GEM is stretched**
- the frame is put on top
- pressure is applied evenly with the help of a steel plate



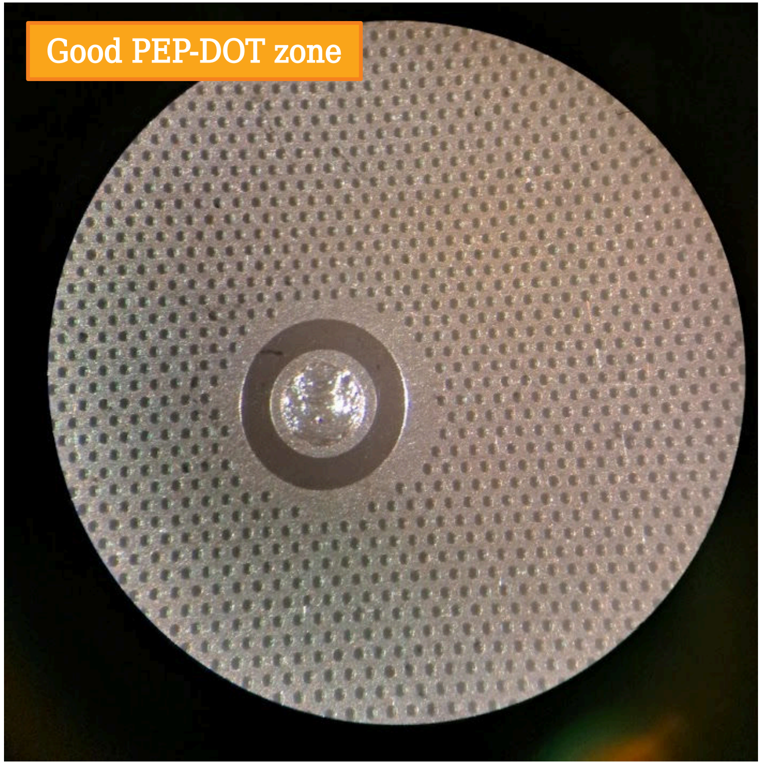
µ-RWELL preparation – 30x25 M2R1

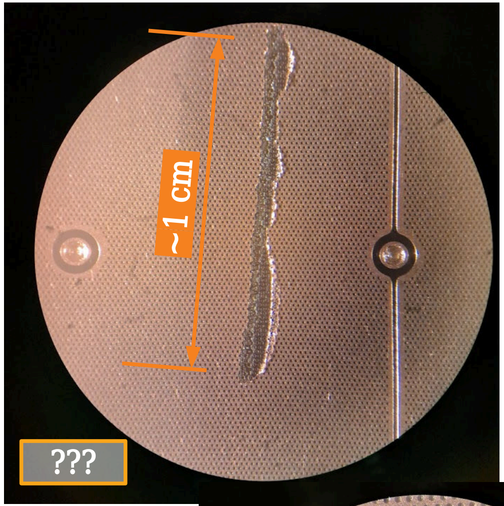


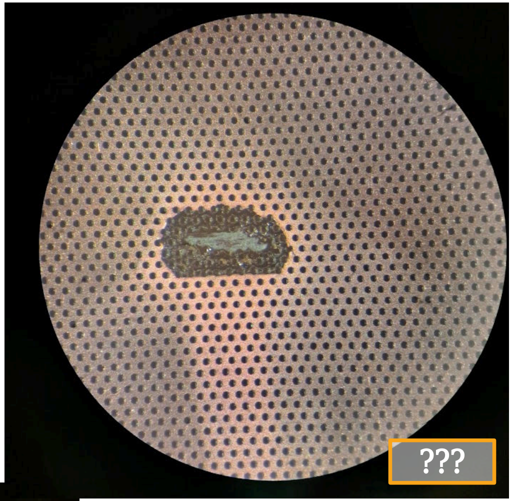


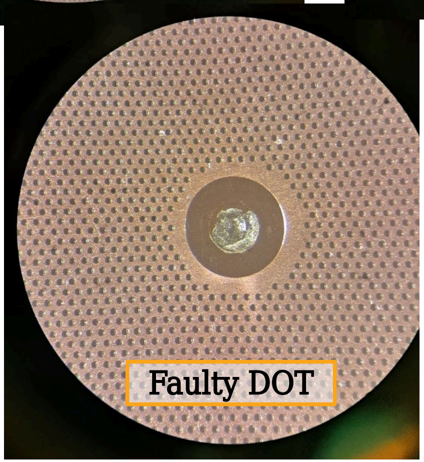
M2R1 µ-RWELL already tested in 2024
Opened for the GEM installation: **a lot of defects!**

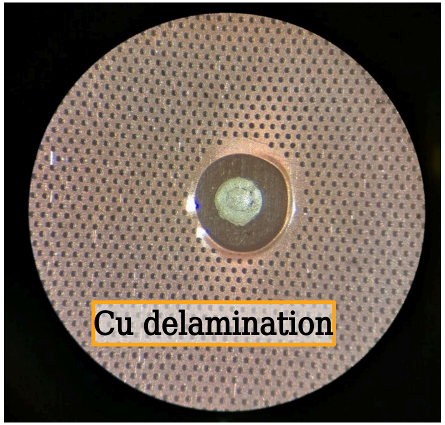
Bonus: 30x25 defects











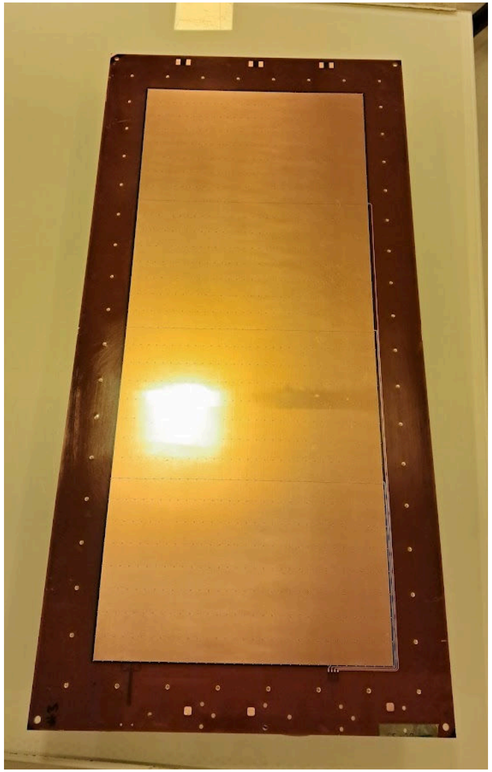
M2R1 µ-RWELL already tested in 2024
Opened for the GEM installation: **a lot of defects!**
Rui's comment: "but **they worked** and you didn't noticed."

M2R1 have been used as **stress test of cleaning** (water, soft/hard chemistry) and **conditioning** (hot cleaning), in order to gain knowledge for the M2R2 production (and µ-RWELLs in general).

µ-RWELL preparation – 60x25 M2R1

GEM 2mm frame o-ring gluing

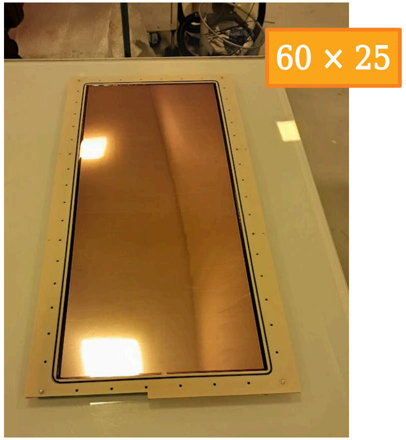
Low pressure cleaning with DI water

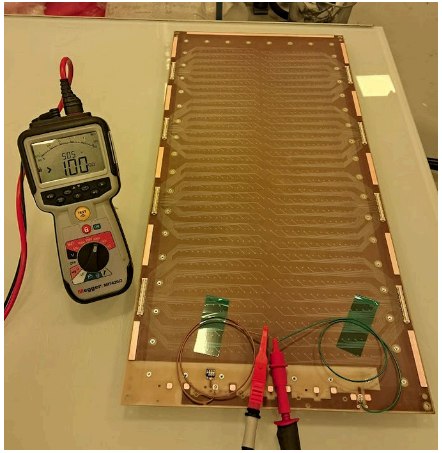


Water/Chemical cleaning possible also if **“Cathode-Frame-GEM-Frame” stack is glued**:
→ easier handling/ammebly
→ more dust protection for the GEM

Hoven / Dry box

GEM + µ-RWELL assembly





Megger Test to GEM and RWELL.

Assembly order: **CAT → GEM → WELL**
In order to prevent dust for entering the µ-RWELL (e.g. from bolt-FR4 friction).

Rui: after the installation, the GEM shouldn't be tested: a possible spark could vaporize metal on top of the µ-RWELL: this can only be recovered with chemical cleaning.

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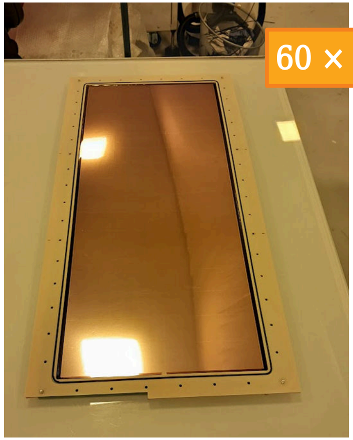
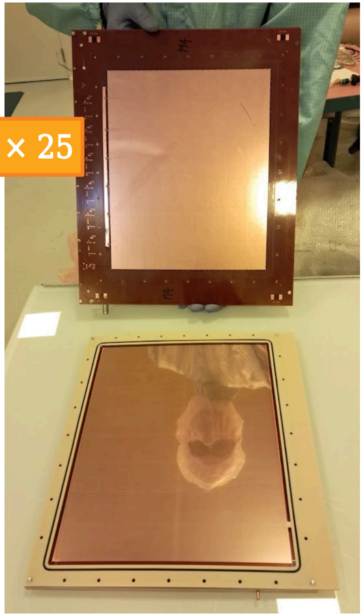
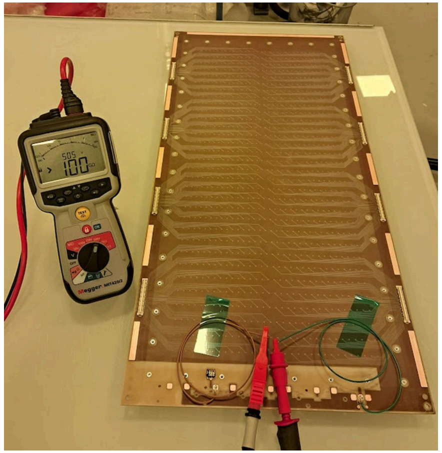


60 × 25



30 × 25



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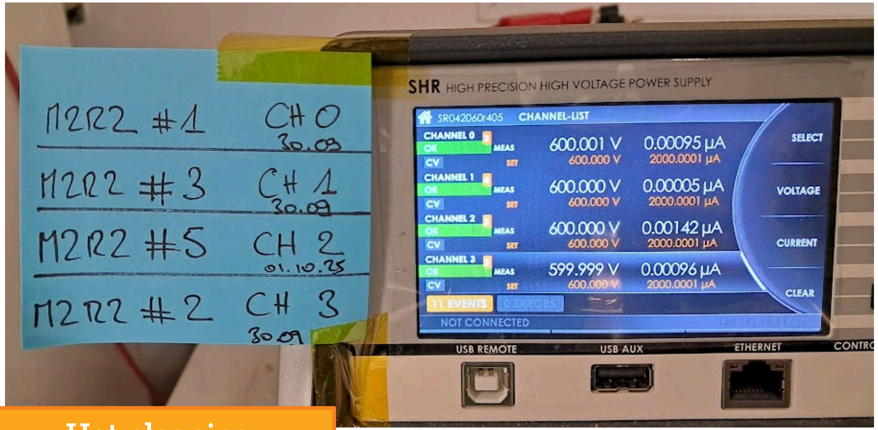
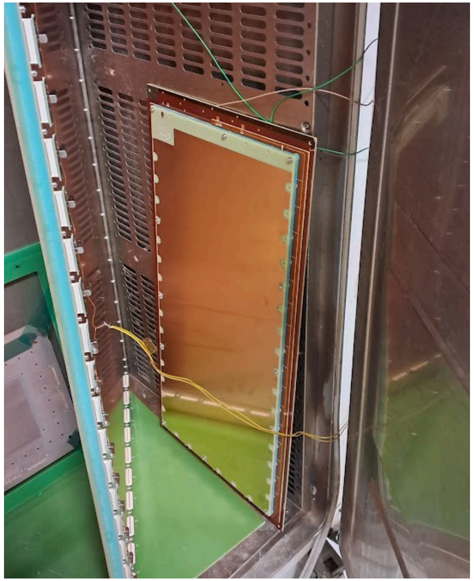
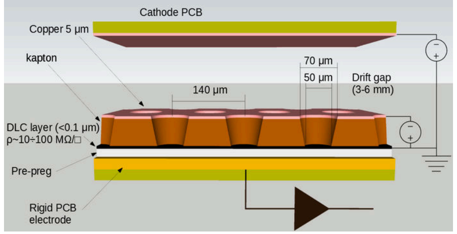


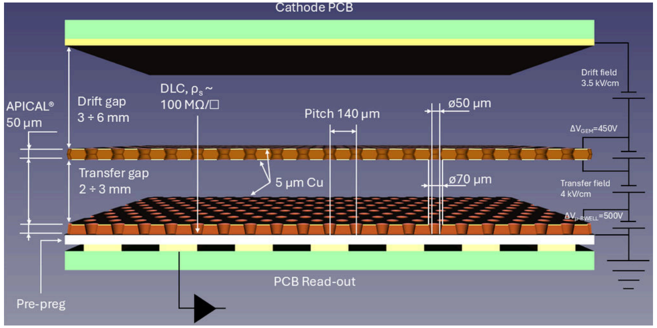
Hot cleaning

- **Fast power supply**: refresh rate >1Hz in order to notice sparks
- **High limitation: >1mA** – the spark should not be suppressed in order to fully burn the defects
- High temperature in order to remove moisture
  - Detector w/ cathode? <50°, because otherwise the Kapton will outgas and the deposits will remains inside
- Start at **250V**
  - Wait for current **<1nA**
- Increase 50V, wait again
- From 600V, decrease the steps to 20V
- Sometimes if the detector response is bad, you have to step back



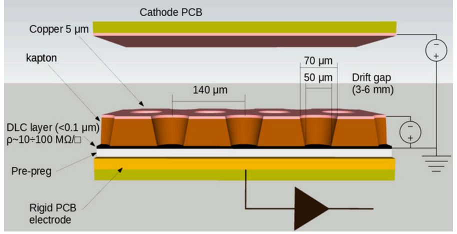
A quick summary table

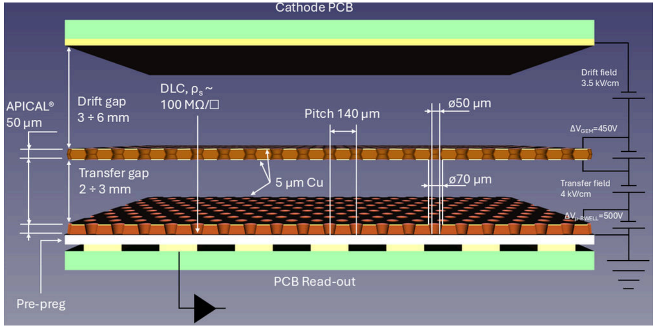




	µ-RWELL	G-RWELL
Application	Standard MPGD – the everyday use	**Very demanding scenarios** in which extremely high gas gain is needed: e.g. time resolution <5ns, 2D uTPC reconstruction
Complexity: **Production**	**Mid:** low rate µ-RWELL are standards, high-rate ones need a bit more care	**Low:** GEMs are the MPT-Workshop "best sell item"
Complexity: **Assembly**	**None:** in principle they are ready to use after delivery from the MPT	**Mid:** it's an additional manufacture step, they need to be stretched/glued (more manpower)
Stability	**Resistive**: stable by design **Single stage**: operational gain 6-8k	**Non-resistive**: permanent damage **Multi-stage**: gain up to 100k
Timing	Down to 5ns	Down to 3.8ns bigap effect → possible source of stress for the GEM
Tracking	G. Bencivenni et al., 2020 *JINST* **16** P08036	See Elena's talk on thursday
Scalability	As large as the DLC foil (for the CID 170x60cm^2)	As large as the µ-RWELL

A quick summary table





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Dziękuję !!

Spare

CERN-INFN DLC (CID) sputtering machine

The **CID** (CERN-INFN-DLC) sputtering machine, a **joint project between CERN and INFN.** It is used for preparing the **base material for DLC-based detectors**. And various deposition over electrodes (Cu, Al, $^{10}B_4C$,…). The potential of the DLC sputtering machine is:

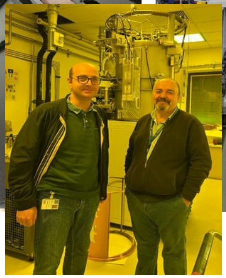
- **Flexible substrates** up to **1.7×0.6m²**
- **Rigid substrates** up to **0.2×0.6m²**

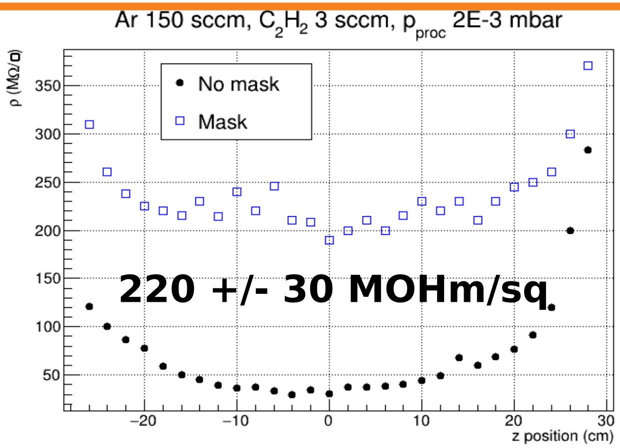
In **2023,** the activity on CID focused on the **tuning** of the **machine on small foils: good** results in terms of **reproducibility and uniformity.**

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

2024 highlights

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



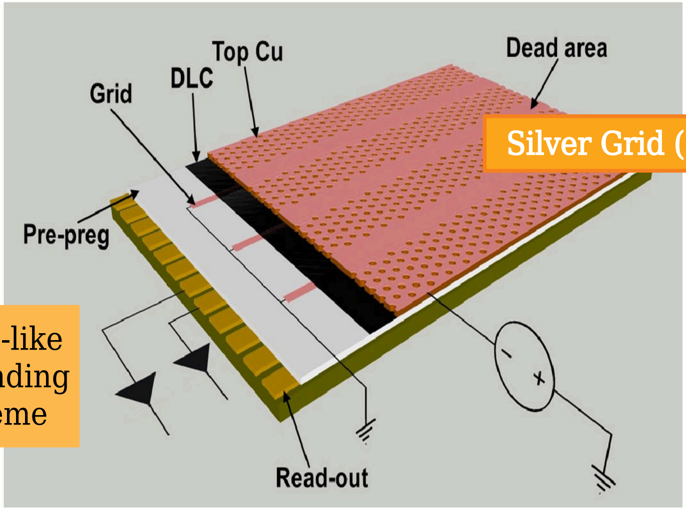


Many thanks to the CID team!!

The High Rate layouts

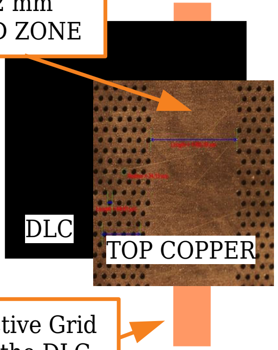
2017

Silver Grid (SG)



GRID-like Grounding scheme

1.2 mm DEAD ZONE



Conductive Grid Under the DLC

A **conductive grid** is patterned on the back of special DLC foils (**DLC + Cu technology: delicate manufacturing process**).

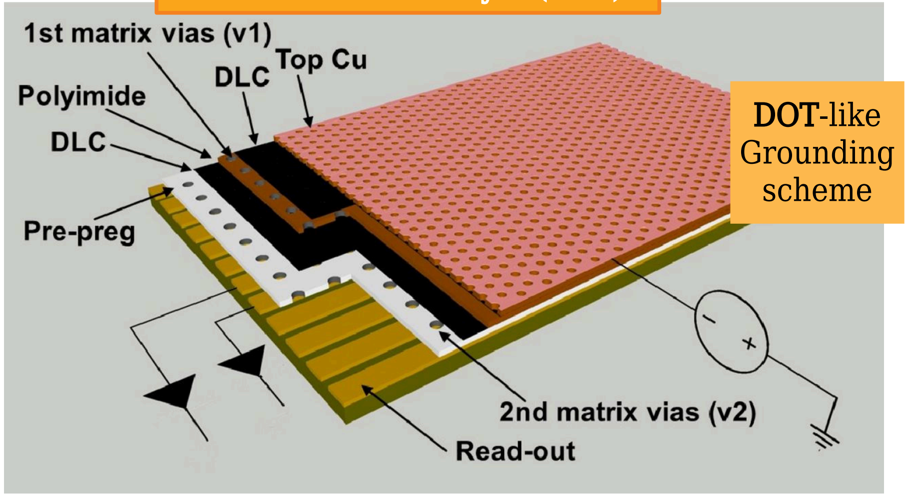
Necessity to introduce a **small DEAD AREA** above the grid, to avoid discharges (tuned to be 5% of the total area).

NOT SCALABLE to large size: distortions and alignment problems **during manufacturing.**

IS POSSIBLE to **check the resistance** of the layer after the detector is built

2018

Double Resistive Layer (DRL)



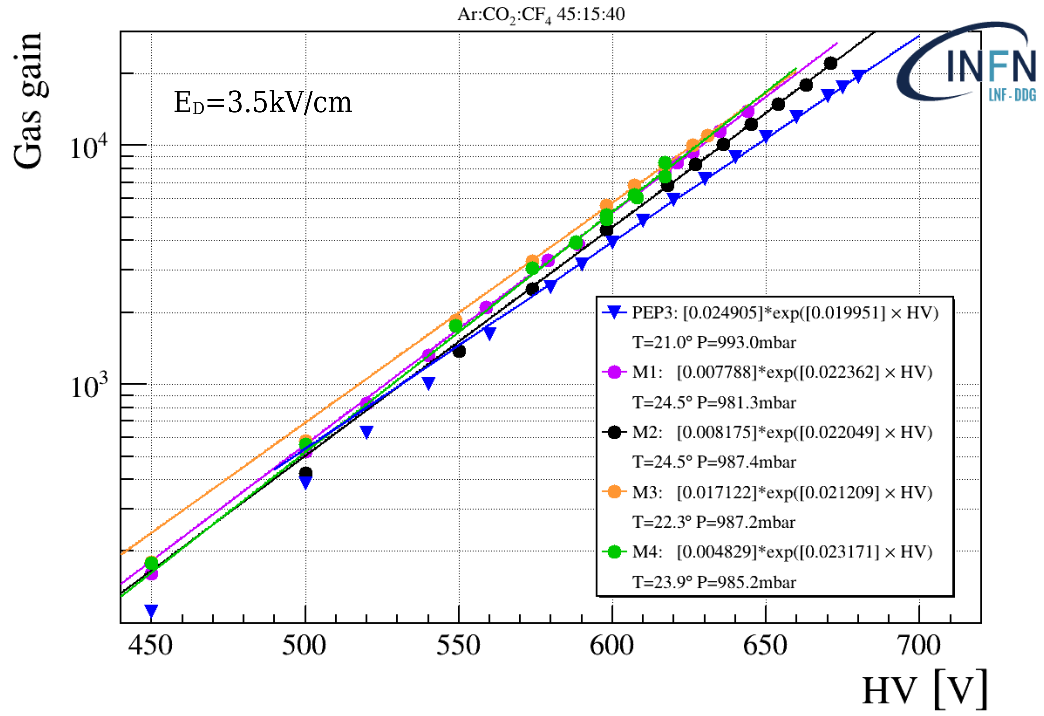
DOT-like Grounding scheme

Based on a **3-D** current evacuation scheme:
Two stacked resistive layer connected through a **matrix of conductive vias,** grounded through a further matrix of vias to the underlying readout electrodes.

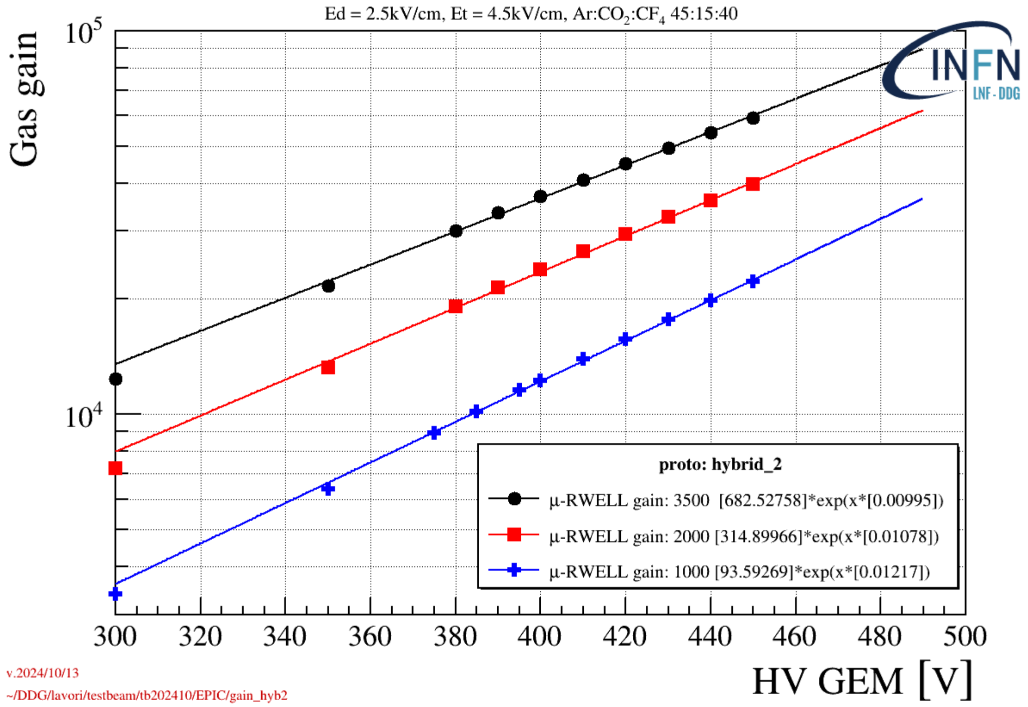
MORE COMPLEX to buid **than SG** but reliable (for now only 10x10 prototypes).
NOT POSSIBLE to check the resistance of the two layers after the manufacture.

Gas gain measurement – w/ X-rays

µ-RWELL



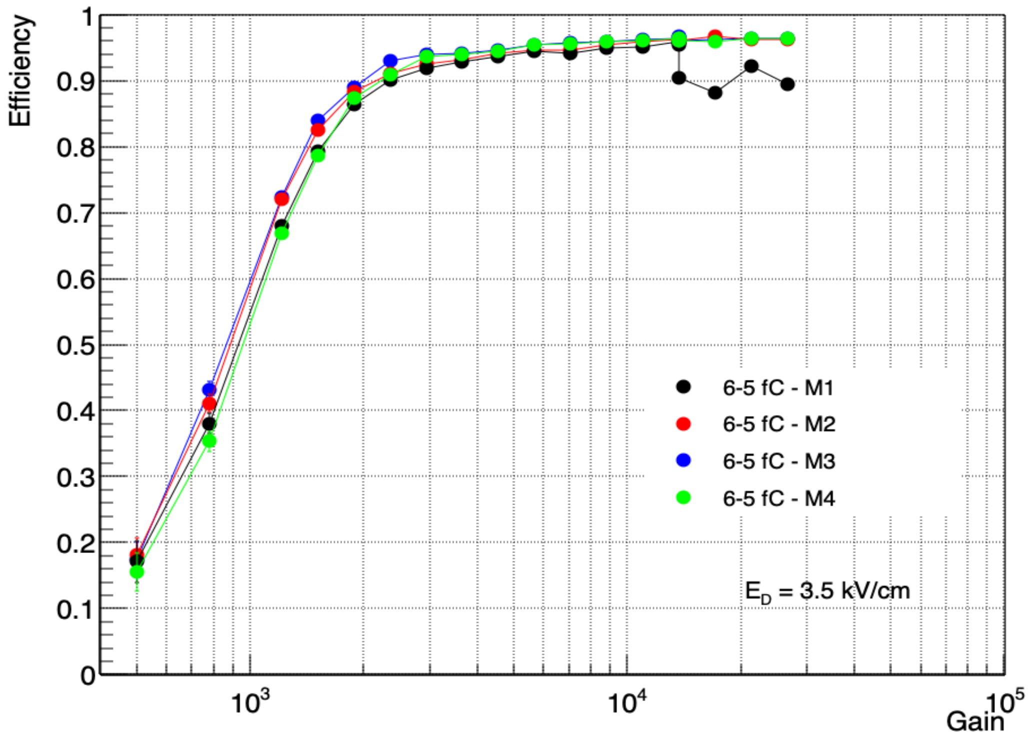
G-RWELL



A very stable detector: it doesn't show any hint of instabilities even at **60k.** During the '24 beam test we have data points even at **100k.**

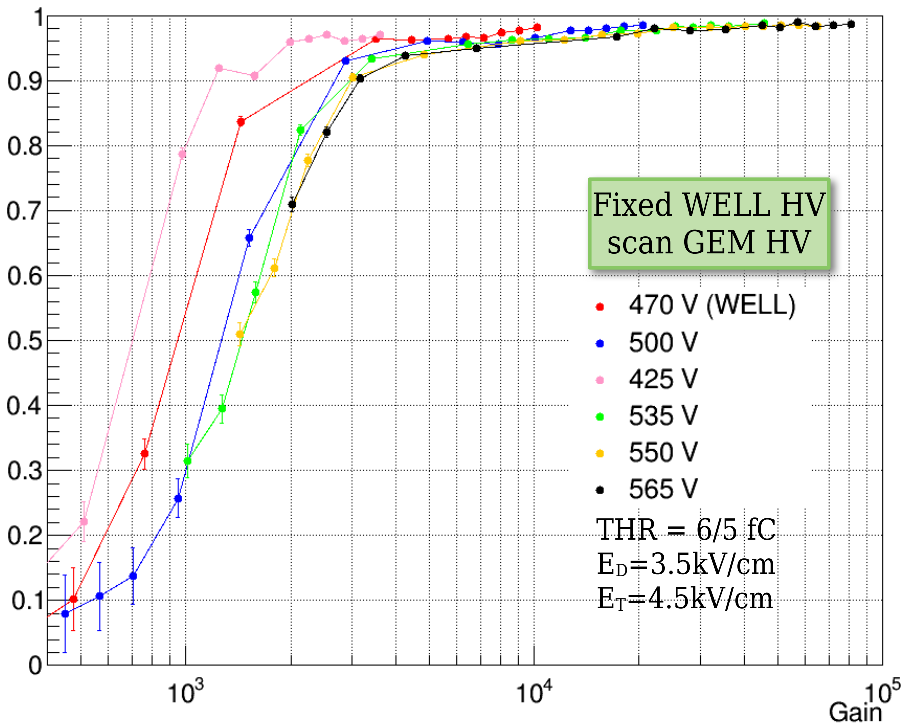
2024 - µ-RWELL vs G-RWELL – Efficiency

µ-RWELL



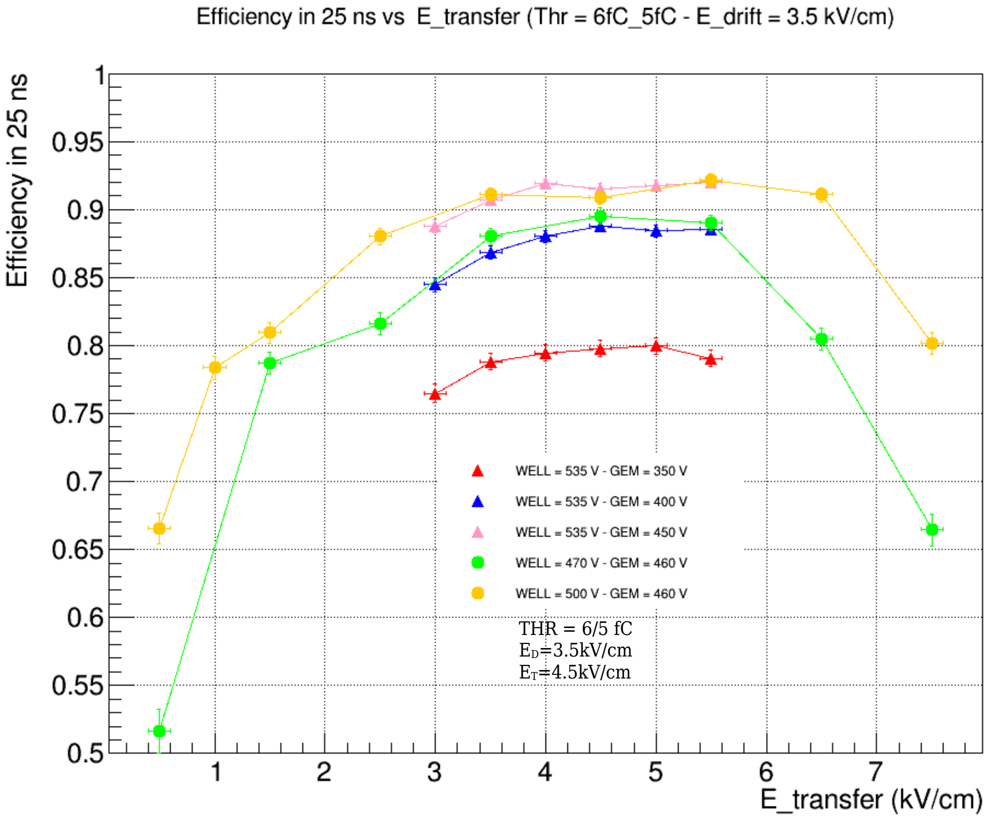
M1 behavior will be more clear during the second part of the talk.

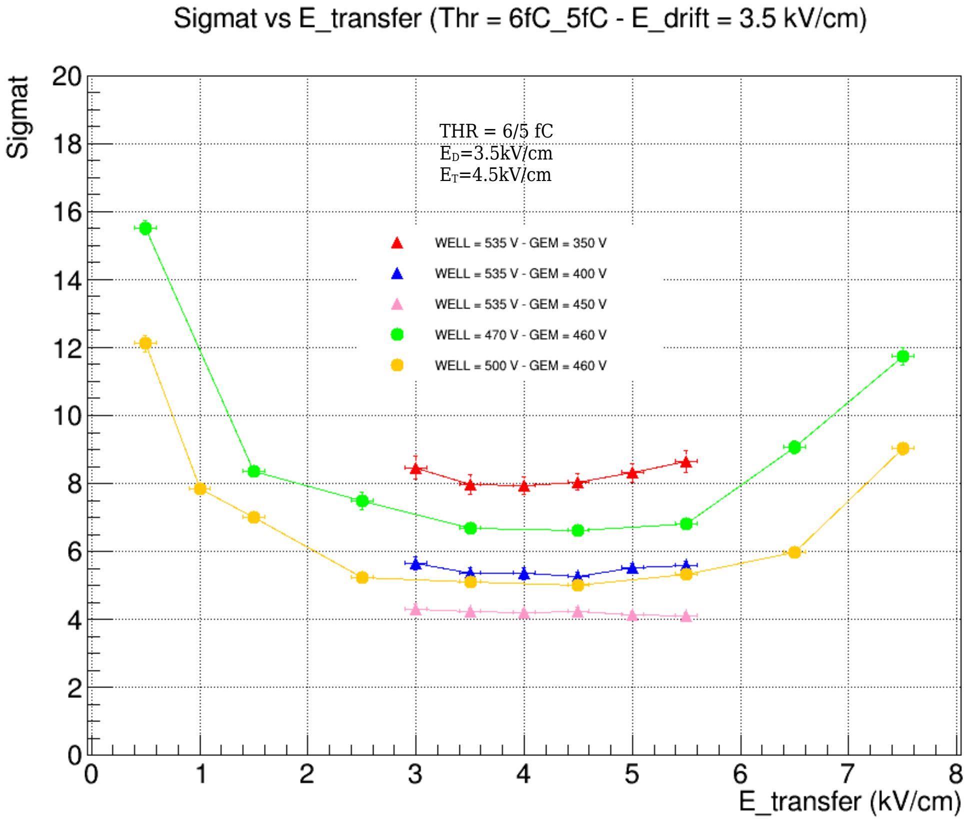
G-RWELL



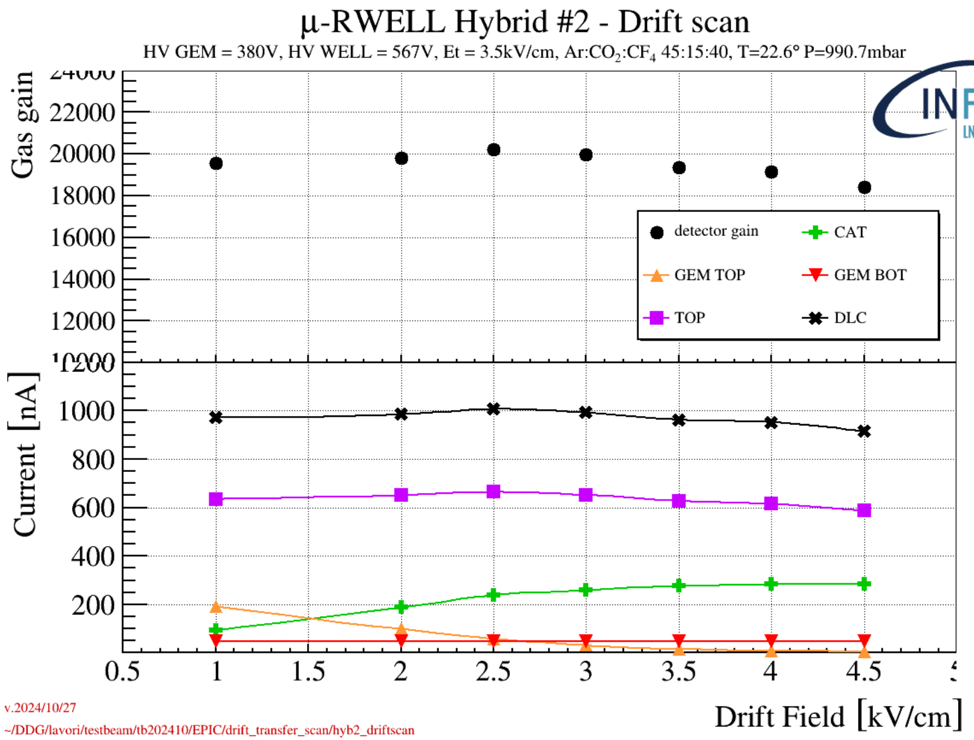
A plateau >98% is reached for a gas gain above 8000.
The gain for PINK (WELL 425) and RED (WELL 470) is extrapolated, so the curves doesn't overlap likely for this reason.

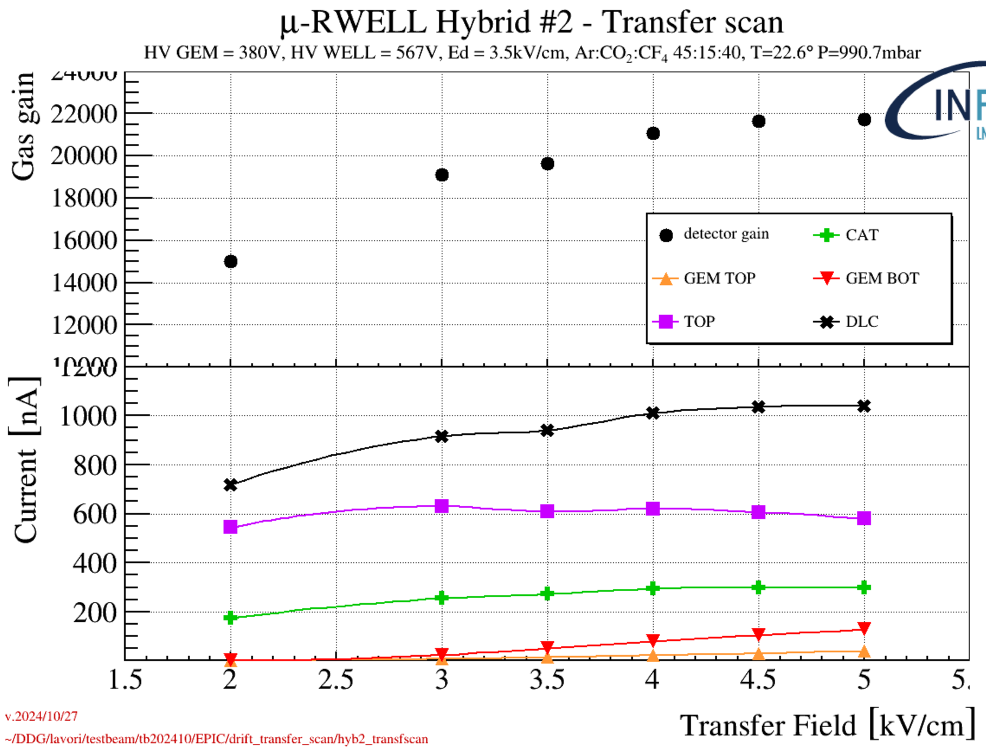
Transfer scan Hybrid HYB_U



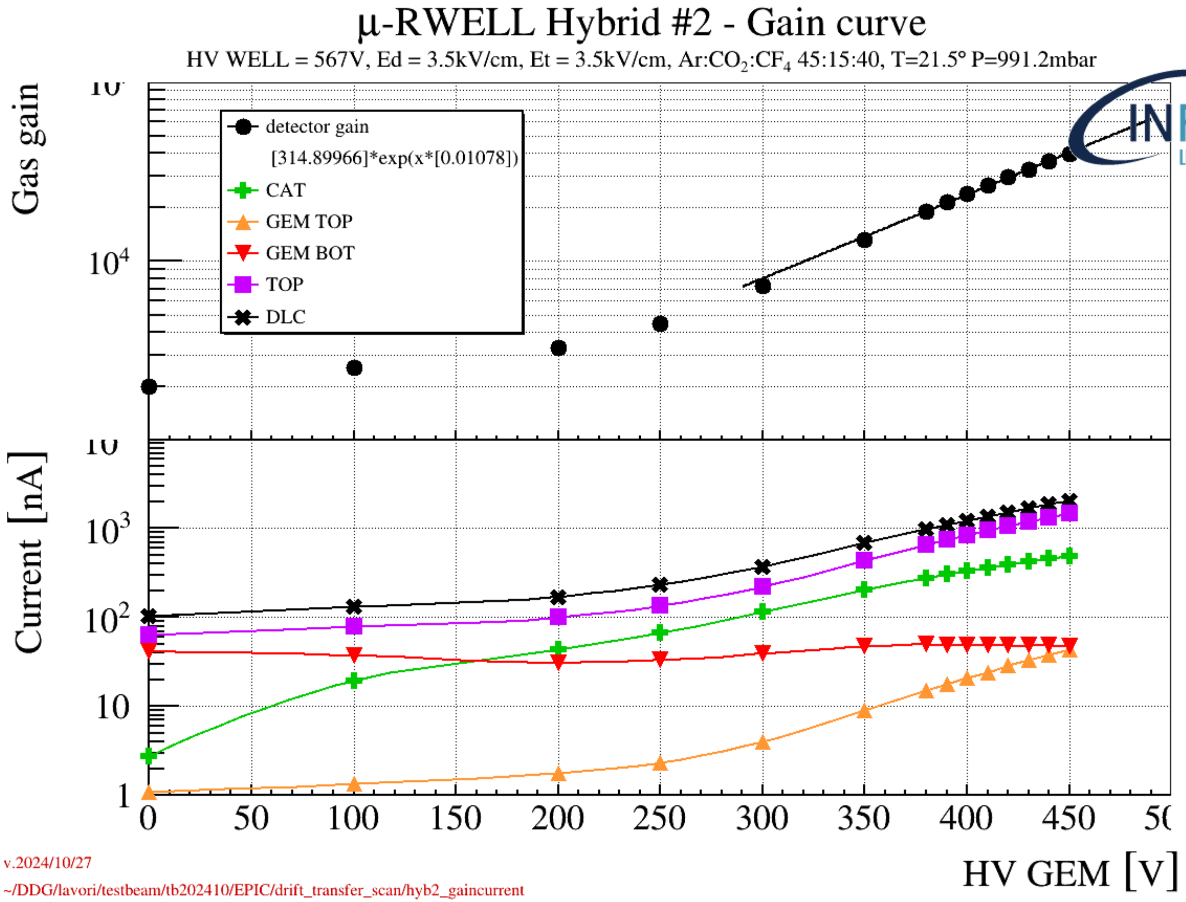


Hybrid – Ed Et scan

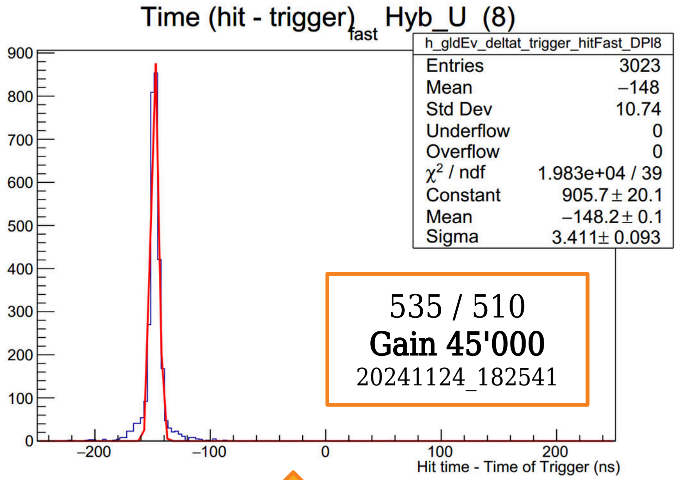


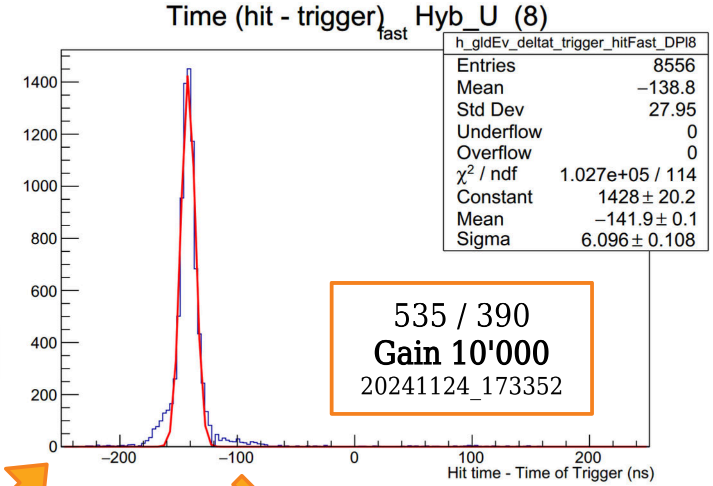


Hybrid – gas gain

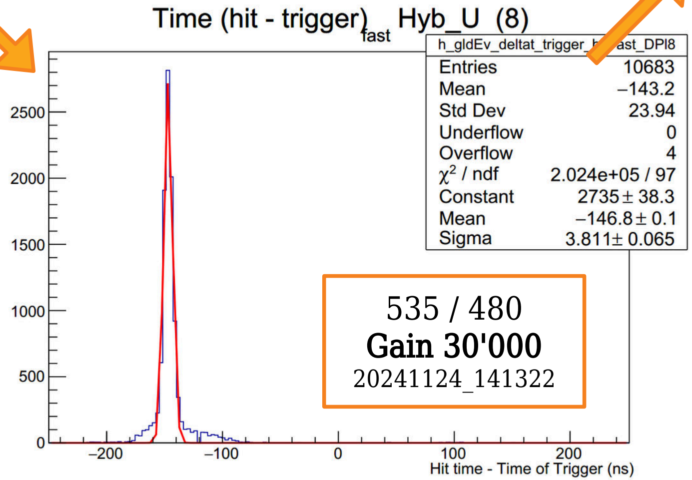


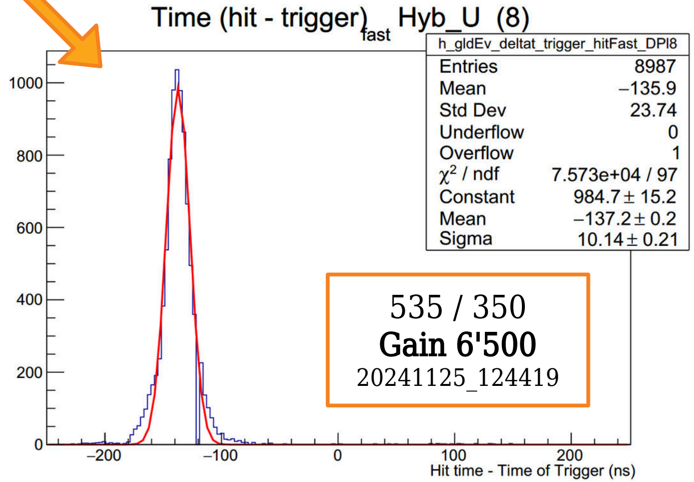
Time of Fastest Hits – HYB_U – HV scan





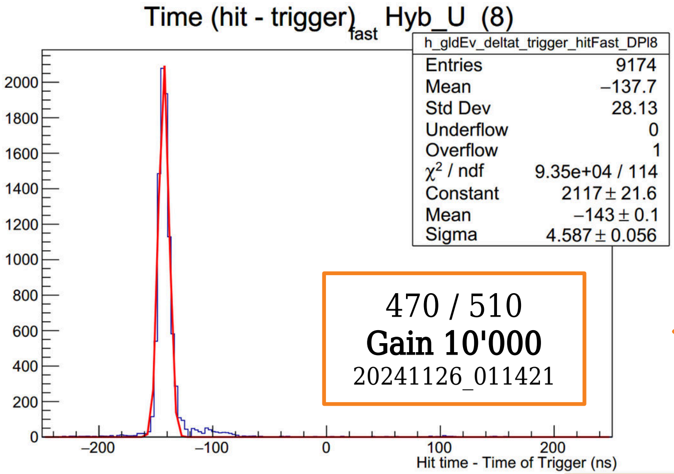
GEM SCAN

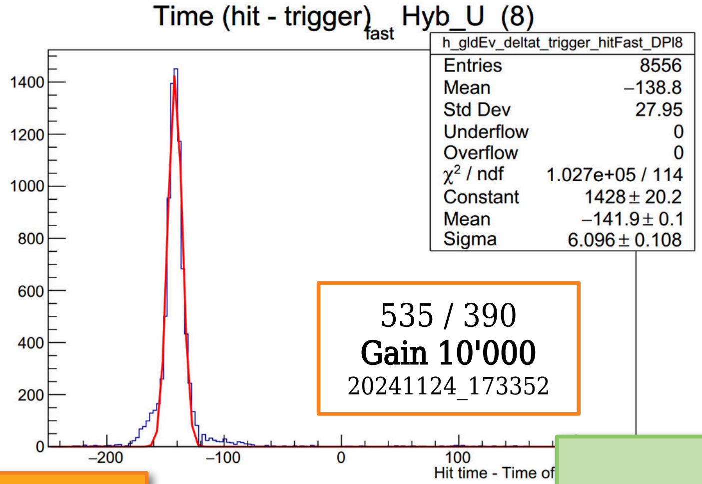




Delayed shoulder doesnt' depent on the gas gain: FEE noise?

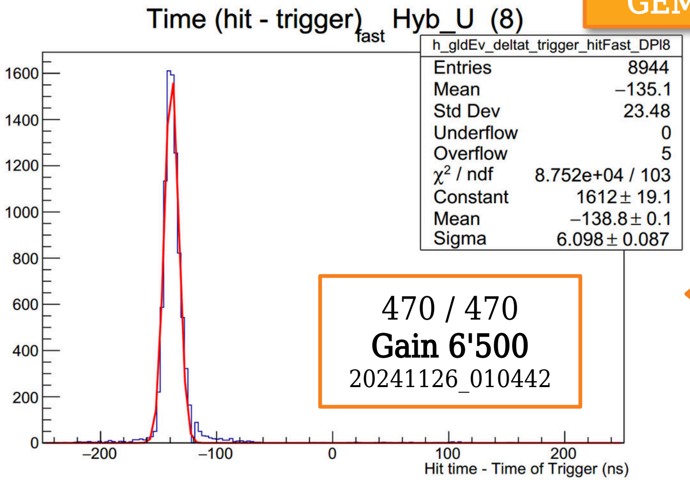
Time of Fastest Hits – HYB_U – biwell scan

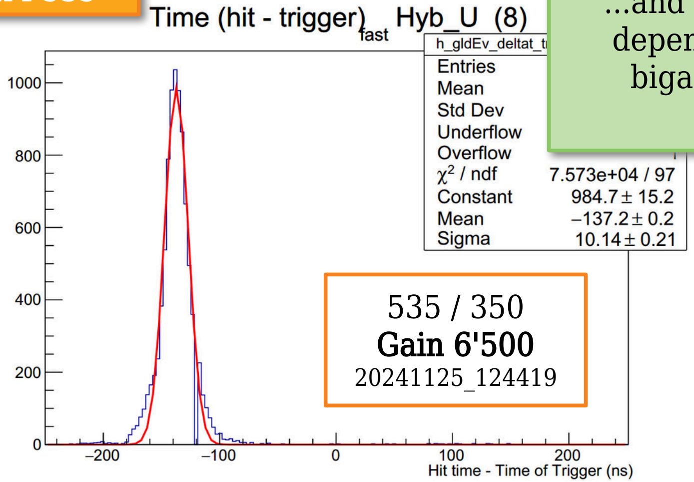




GEM 470

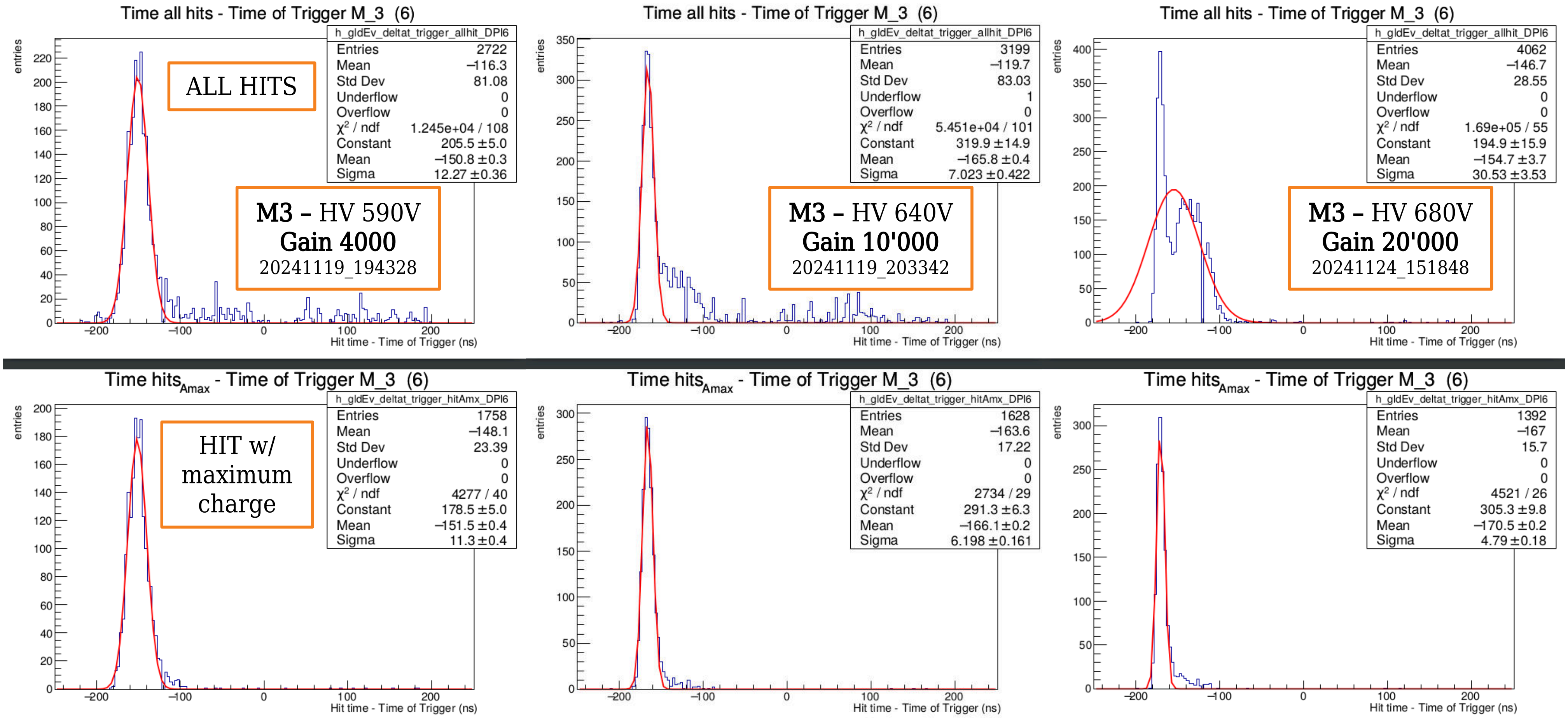
GEM 535





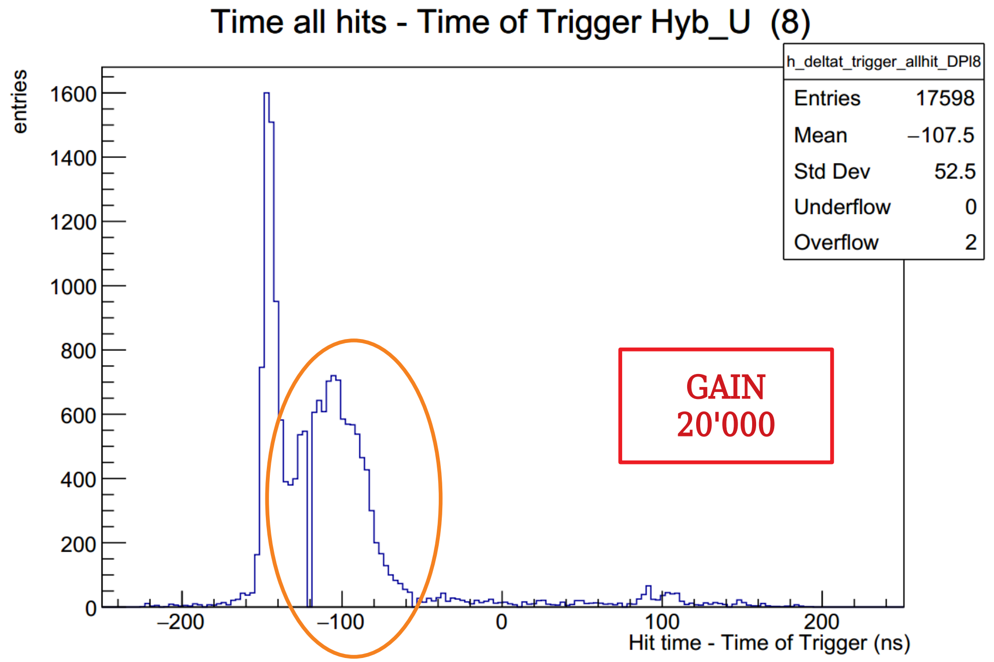
...and it doesn't depend on the bigap effect

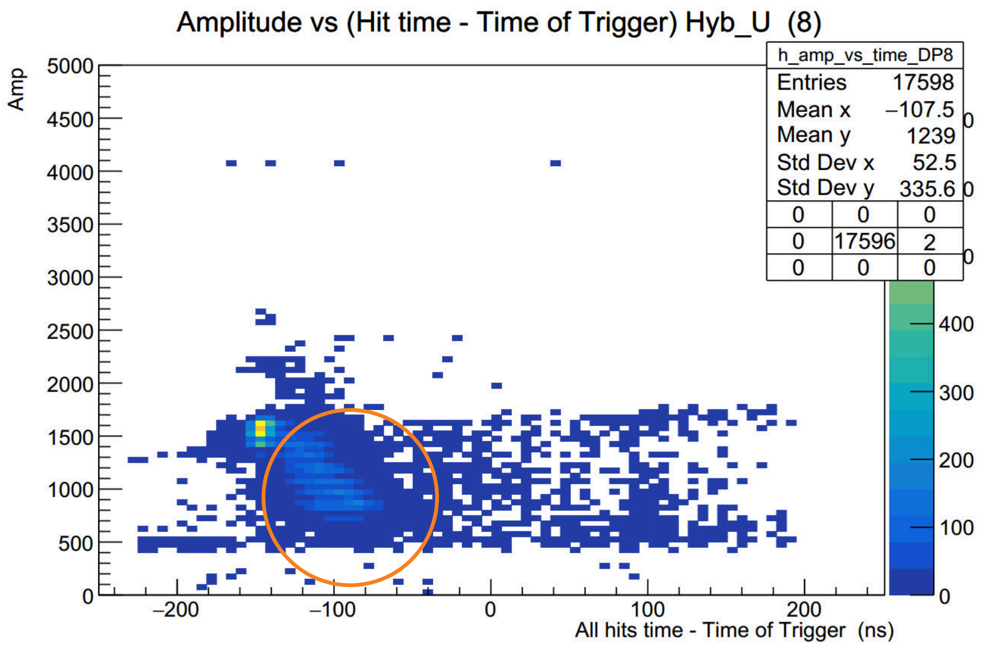
Time of all hits - M2R1



Delayed events - 50ns - T vs Q

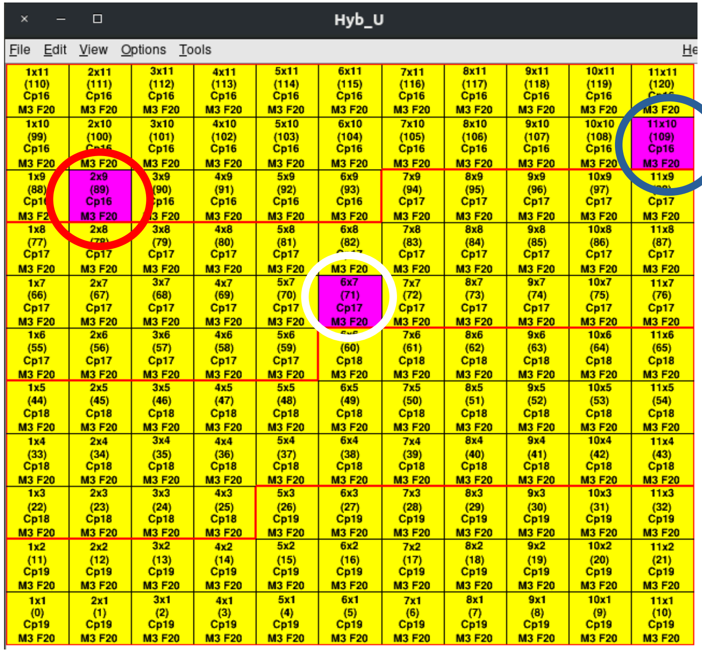
HYB 500/510 gain 20'000 DAQ_20241124_183044

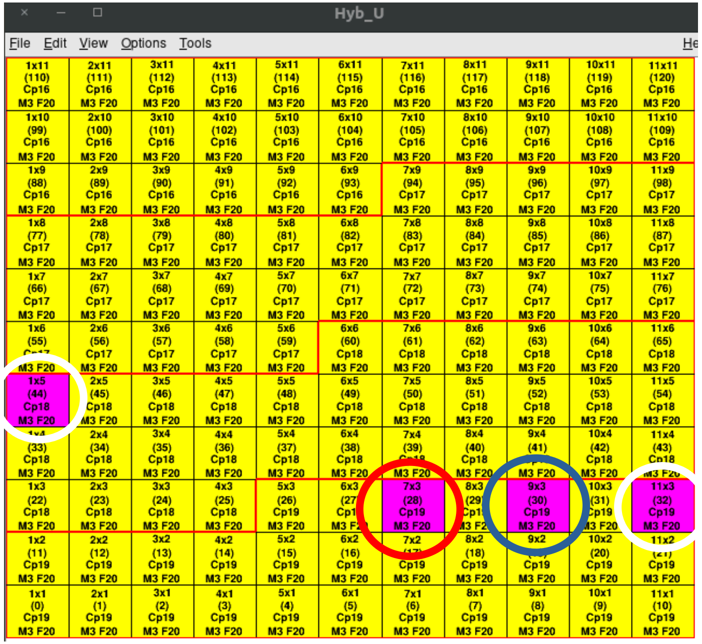




Delayed events - 50ns - Mappa HYBRID

HYB 500/510 gain 20'000 DAQ_20241124_183044





GREEN: bigap
RED: good
BLUE: delay
WHITE: double delay

```
Evento 5_1:
 REF_U:
   pad 2x9   (89)    Msc_1 Chip_9  chl_2      amp= 1504    dt= -140.62
Warning in <TCanvas::Constructor>: Deleting canvas with same name: REF_U
 Hyb_U:
   pad 11x10   (109)    Msc_3  Chip_16  chl_24     amp= 832    dt= -103.12
   pad 2x9   (89)    Msc_3 Chip_16  chl_26    amp= 1504  dt= -143.75
   pad 6x7   (71)    Msc_3  Chip_17  chl_20    amp= 480     dt= -65.62
Warning in <TCanvas::Constructor>: Deleting canvas with same name: Hyb_U
 REF_D:
   pad 2x10   (100)    Msc_1  Chip_12  chl_25      amp= 1568    dt= -150.00
```

```
Evento 9_1:
 REF_U:
   pad 7x3   (28)    Msc_1  Chip_11  chl_1      amp= 1440     dt= -146.88
Warning in <TCanvas::Constructor>: Deleting canvas with same name: REF_U
 Hyb_U:
   pad 1x5   (44)    Msc_3  Chip_18  chl_7      amp= 480     dt= 87.50
   pad 9x3   (30)    Msc_3  Chip_19  chl_5      amp= 1376    dt= -121.88
   pad 11x3   (32)    Msc_3  Chip_19  chl_7      amp= 800     dt= -71.88
   pad 7x3   (28)    Msc_3  Chip_19  chl_3      amp= 1504    dt= -146.88
 REF_D:
   pad 7x2   (17)    Msc_1  Chip_15  chl_10      amp= 1536    dt= -159.38
```

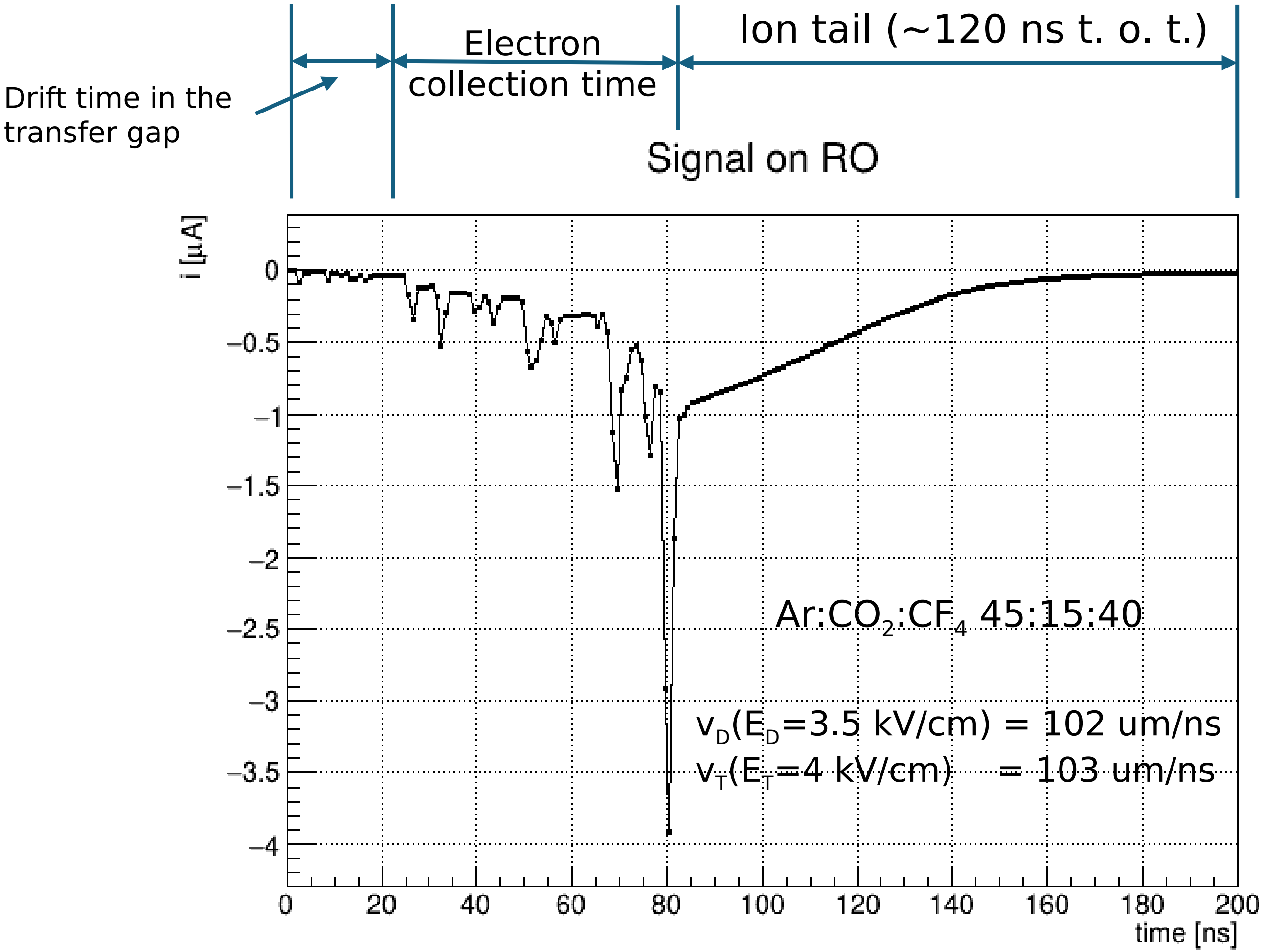
Garfield++ signal simulations

- **G-RWELL 6(drift)-3(transfer)**
- Ionisation from a **5 GeV muon** track
- tools: **COMSOL 6.3 + GARFIELD++**
- E_{drift} = 3.5 kV/cm
- ΔV_{GEM} = 450 V
- E_{transf} = 4 kV/cm
- $\Delta V_{u\text{-}RWELL}$ = 550 V

Expected collection time: 60ns
Expected ion tail: 120ns

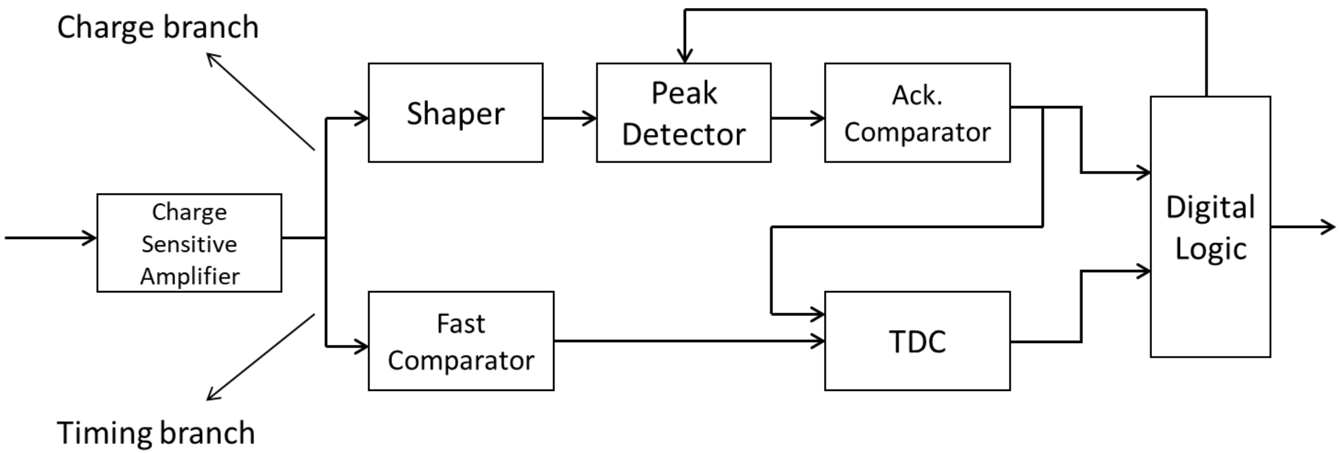
→ total induction: ~200ns

NO FEE implemented
(filters, shaping, or amplification)



Dziękuję Djunes for your kind help,
it was the spark that we needed

FATIC3 block diagram



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

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

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

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

Next steps

2026

- **Beam test with FATIC4** (dead time 100ns) at PSI with continuos high rate beam (1MHz/cm^2)
- PCB optimisation: noise and crosstalk suppression

2027

- **M2R1 Proto0 construction** with integration of:
  - HV connections (filters, distribution)
  - FEE (shielding, concentrator)
  - Gas (inlet/outlet)

2028

- **CERN MoU** for production
- Production of the **base material** with the CERN-INFN DLC machine
  - See more at (link)

2029-’32

- **Detector production** (more than 600 units, 90m^2)
- Quality control