The micro-RWELL detector for the phase-2 upgrade of the LHCb Muon system

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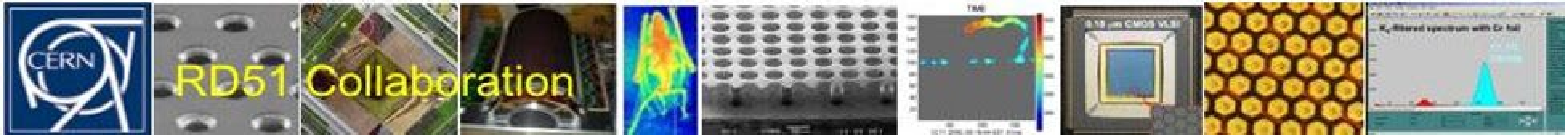
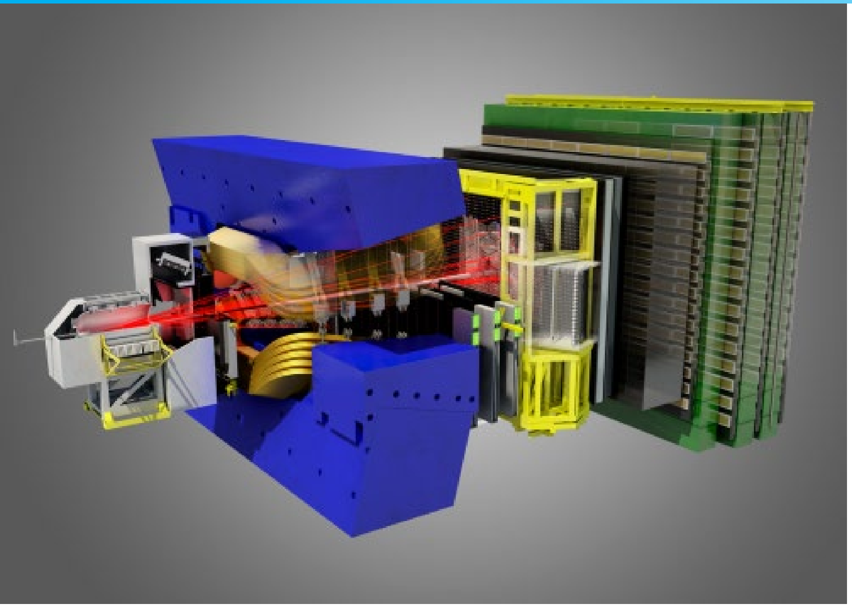
on behalf of the LHCb Muon Group

1. Laboratori Nazionali di Frascati dell'INFN
2. CERN

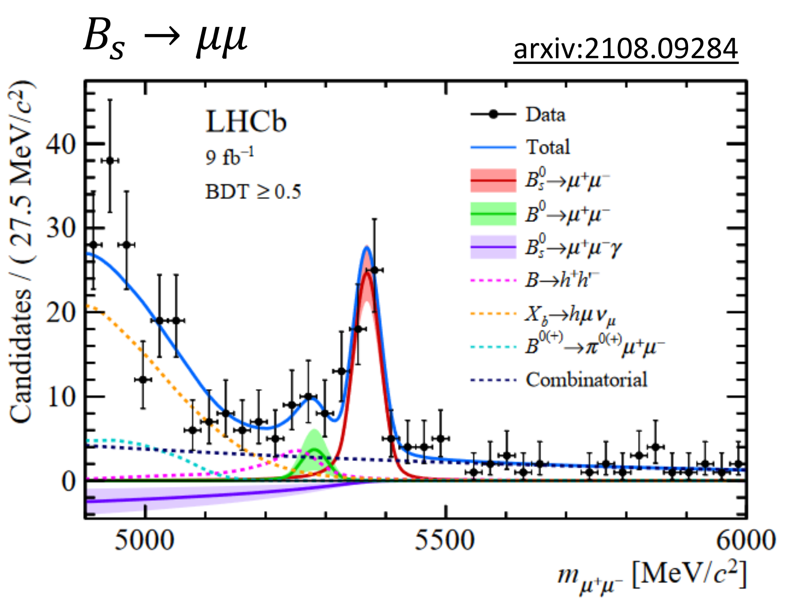
PM2021 - 15th Pisa Meeting on Advanced Detectors
May 27th, 2022

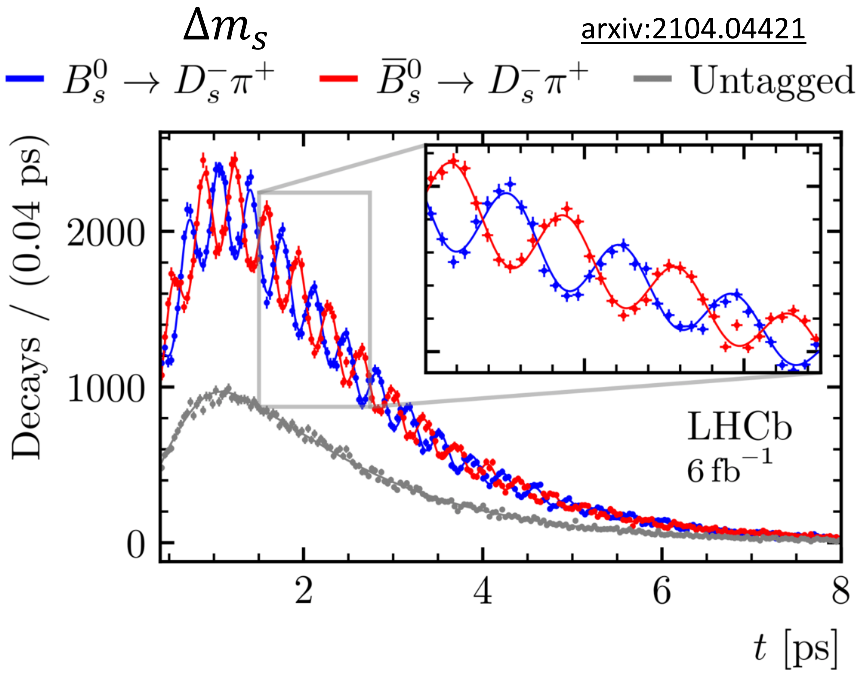


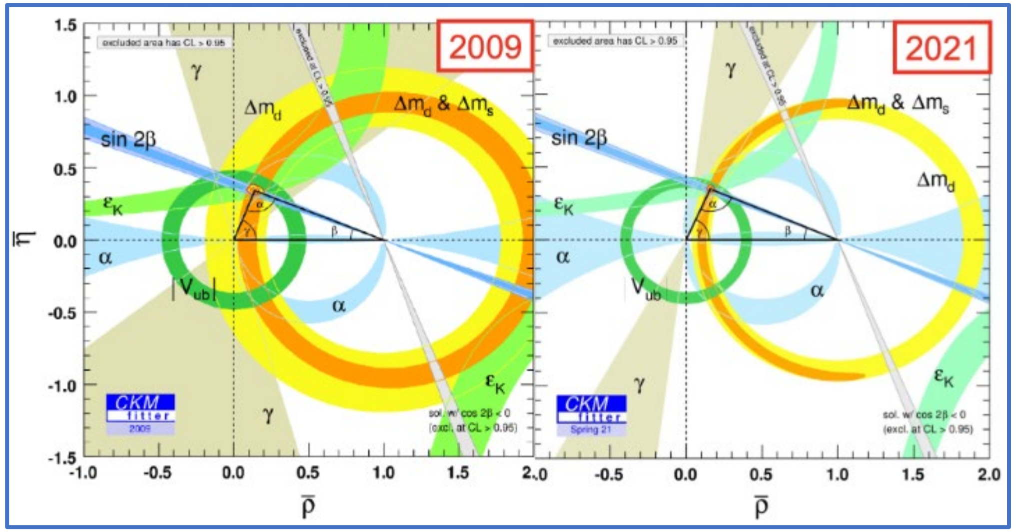
LHCb experiment at CERN: (very) few highligths

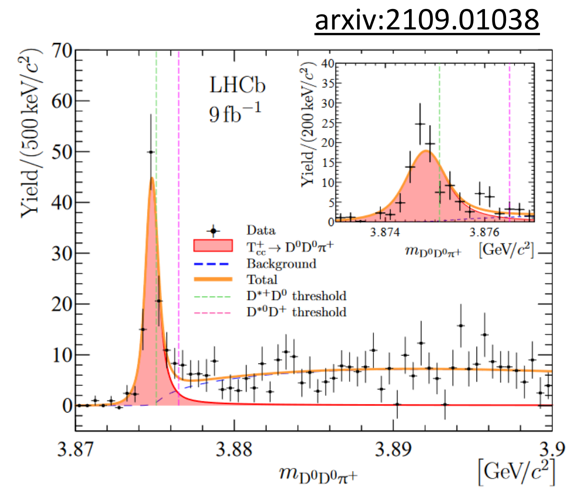


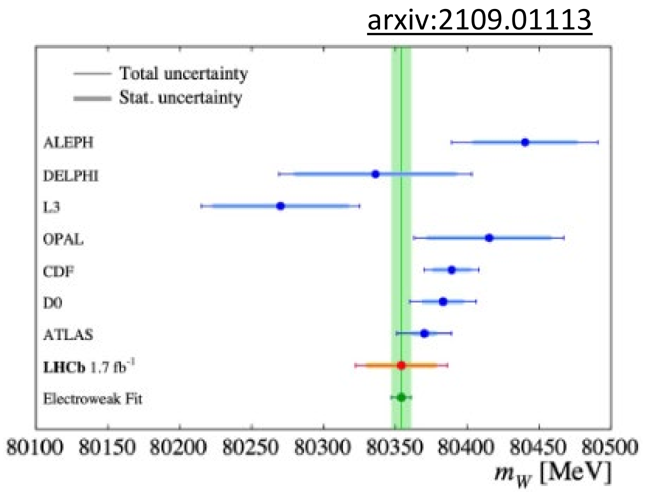
Excellent vertex/track reconstruction and PID



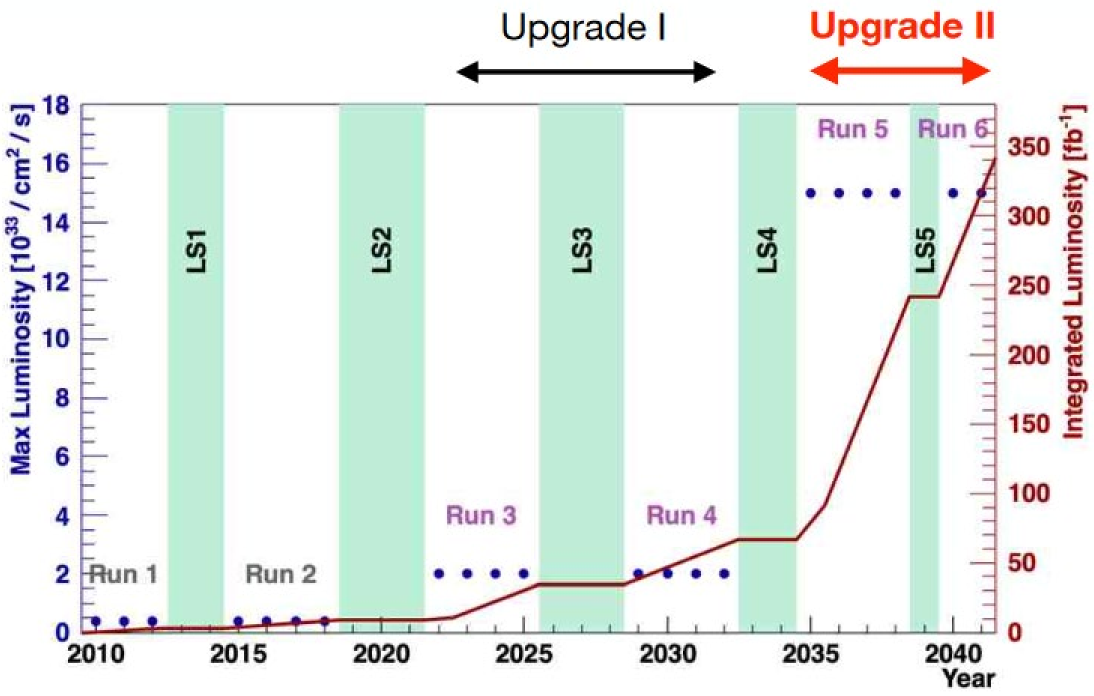




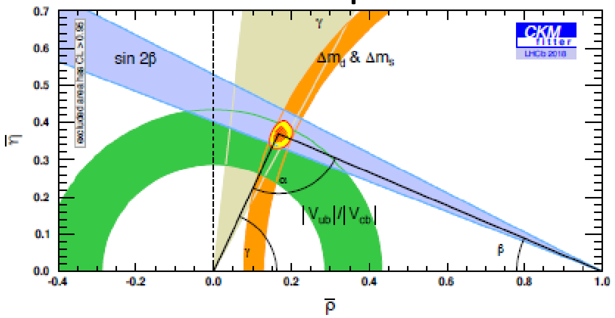




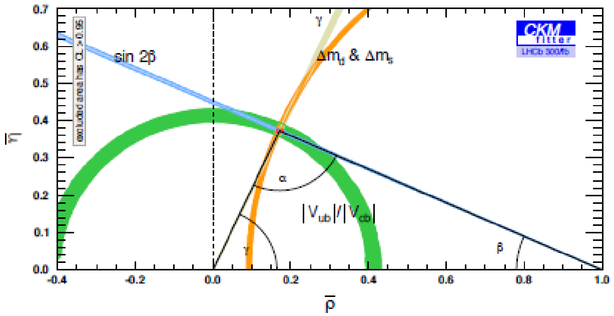
The LHCb Upgrade II (Run 5-6)



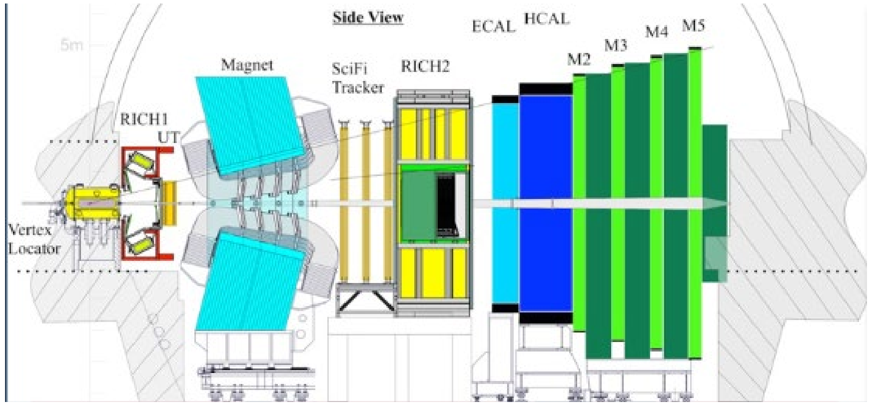
2018 inputs



300 fb-1 (2038)

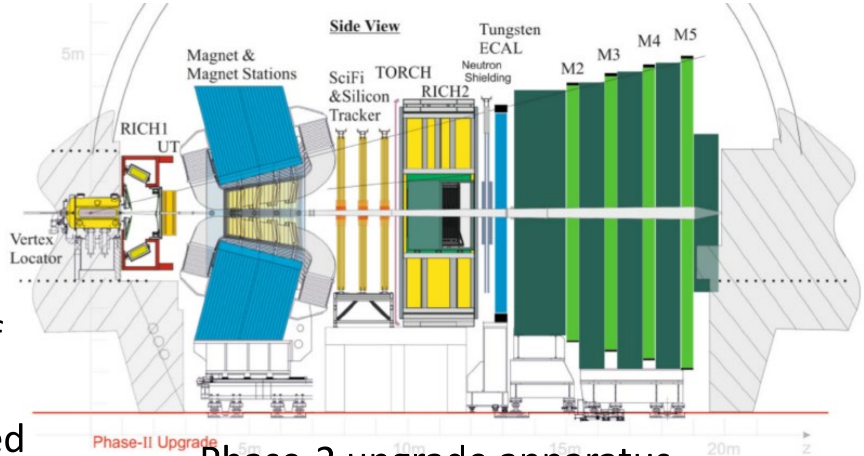


Huge improvement of LHCb constraints to the apex of the unitarity triangle



Current LHCb apparatus

- 4D-tracking in VELO
- Large Tracking Detector based on MAPS (downstream)
- Extensive use of timing of RICH and ECAL
- HCAL removed → replaced with shielding



Phase-2 upgrade apparatus

https://cernbox.cern.ch/index.php/s/4axD3HOyfjLDMTC

The LHCb Upgrade II (Run 5-6)

The Muon system **(MWPC+GEM)** during Run1 & Run2 (**1÷4 x 10^{32} cm^{-2} s^{-1}**) exhibited tracking **inefficiency**, from dead time, **at level of 1% in Run1 and 2% in Run2→ REMARKABLE!**

Increase in luminosity has consequence

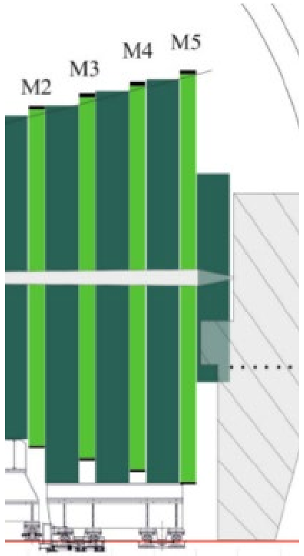
- Rate up to 1 MHz/cm^2 per single detector gap; 700 kHz per electronic channel
- large **increase in dead time induced inefficiency** (in most region of the detector the reconstructed hits are obtained by crossing large area X & Y strips)
- **increased** rate of **ghost hits** from accidental crossing of X-Y channels
- **increased pion misidentification**

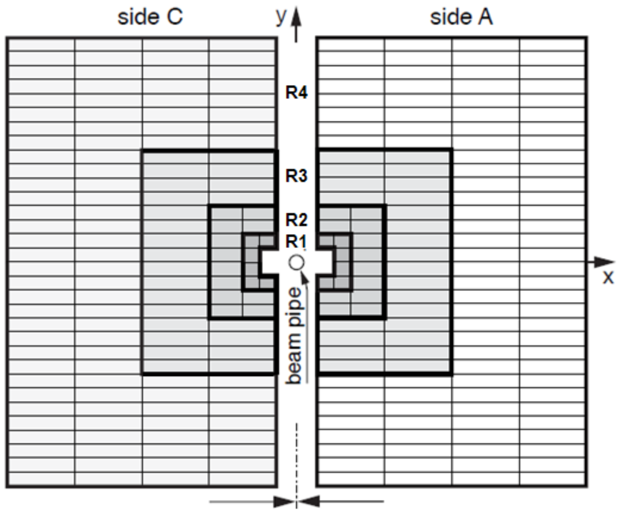
Requirements:

- Max input capacitance (double gap) ≤ 100 pF
- Efficiency (double gap)>95% within a BX (25 ns)
- Pad cluster size < 1.2
- **Stability for 10 y of operation**

PROPOSED SOLUTION: micro-RESISTIVE WELL technology

Each MWPC will be replaced with a **stack of 4 detectors** in the region **R1 and R2**: a total of **576 detectors**, size 30x25 to 74x31 cm^2, 90 m^2 det.





Maximum expected rate

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

Preliminary

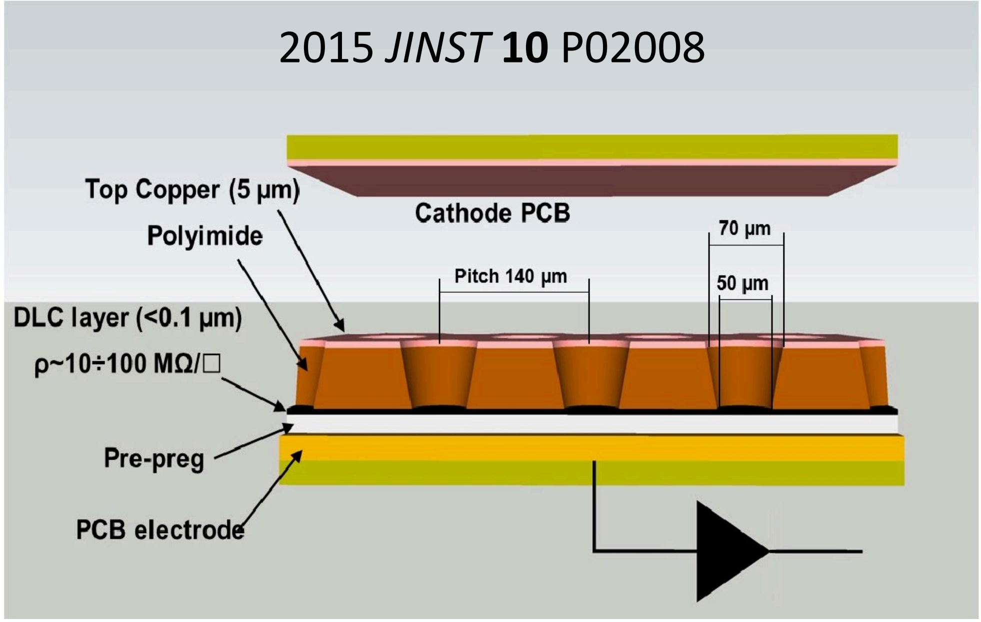
Area (m^2)	M2	M3	M4	M5
R1	0.9	1.0	1.2	1.4
R2	3.6	4.2	4.9	5.5
R3	14.4	16.8	19.3	22.2
R4	57.6	67.4	77.4	88.7

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

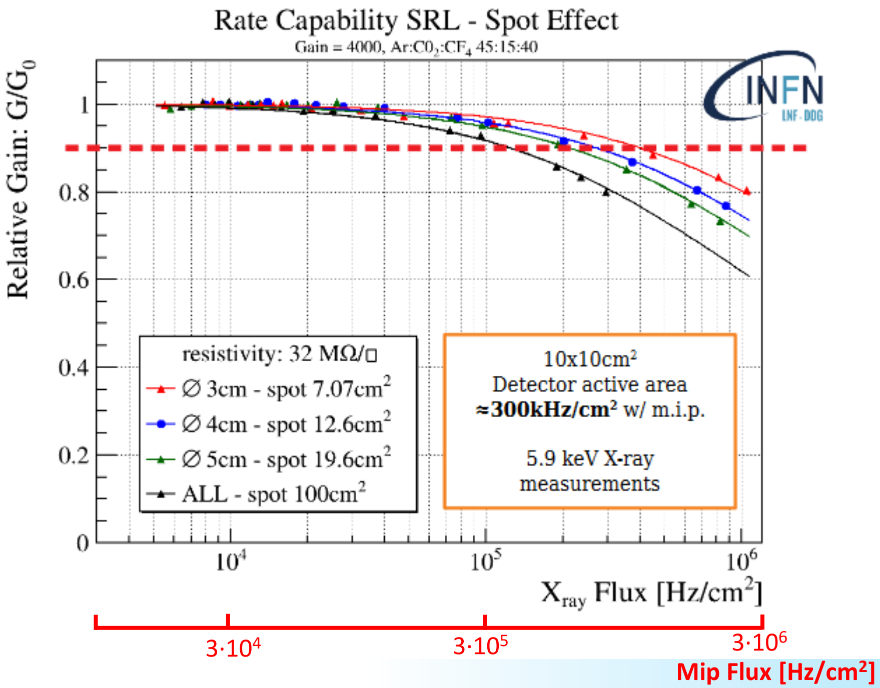
The µ-RWELL technology at a glance

Developed in collaboration with CERN-EP-DT-MPT workshop
The features can be summarized:

- **Spark suppression**: presence of a resistive layer (Diamond-like Carbon) to quench sparks amplitude (like MM)
- **Compactness**: amplification stage (geometry like WELL and GEM) embedded in the PCB readout → multi-layer PCB std. industrial technology →mass production



But the resistive layer introduces a local gain drop as the rate increases



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

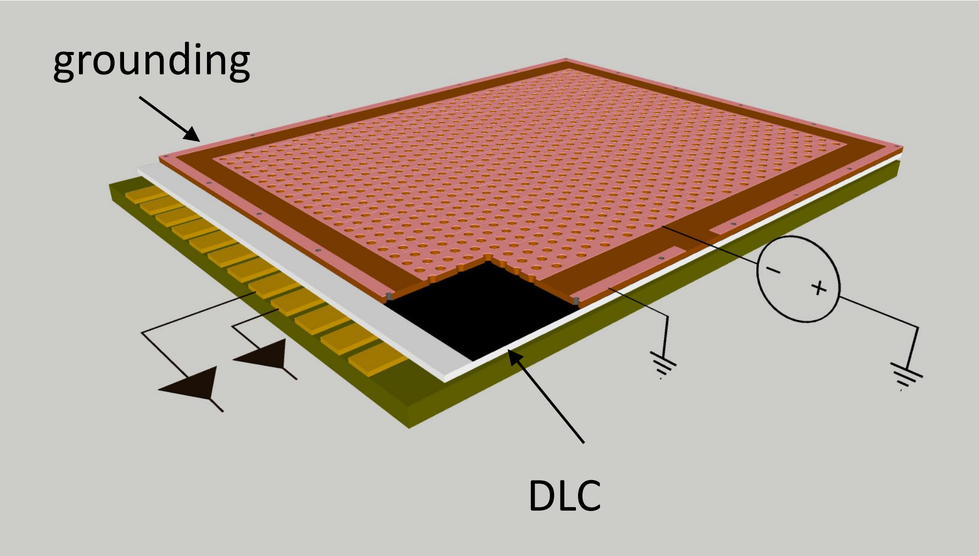
Naïf model for the **average resistance Ω** between the charge point collection and the perimetrical grounding line

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

α from the fit to the gain vs. applied ΔV
N_0 from GARFIELD++ simulation
r radius of the X-rays spot
d average distance to the ground

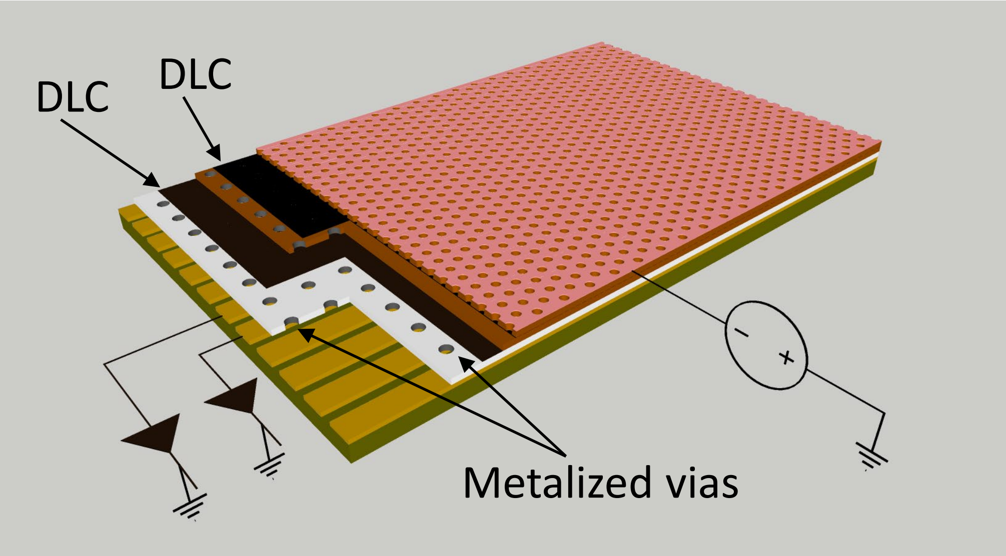
The µ-RWELL technology: the evolution

The **parameter *d*** becomes foundamental to produce detector for high rates purposes
An extensive R&D has been conducted to optimize the DLC grounding to make the detector stand up to 1 MHz/cm^2



Single **L**ayer

- Single DLC layer
- Large *d*
- Low rate purposes (up to 100 kHz/cm^2)
- Easy for industry



Double **L**ayer

- Stack of DLC foils interleaved by kapton
- *d* ~1 cm
- High rate purposes (>10MHz/cm^2)
- Complex manufacturing

…

The µ-RWELL technology: the evolution

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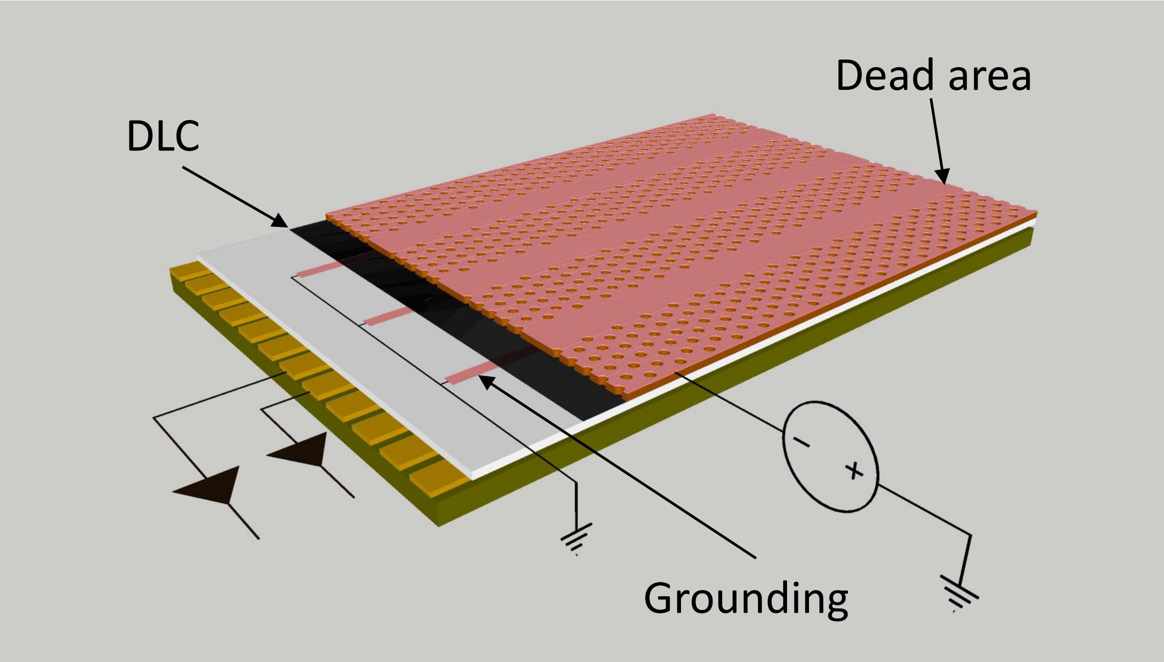
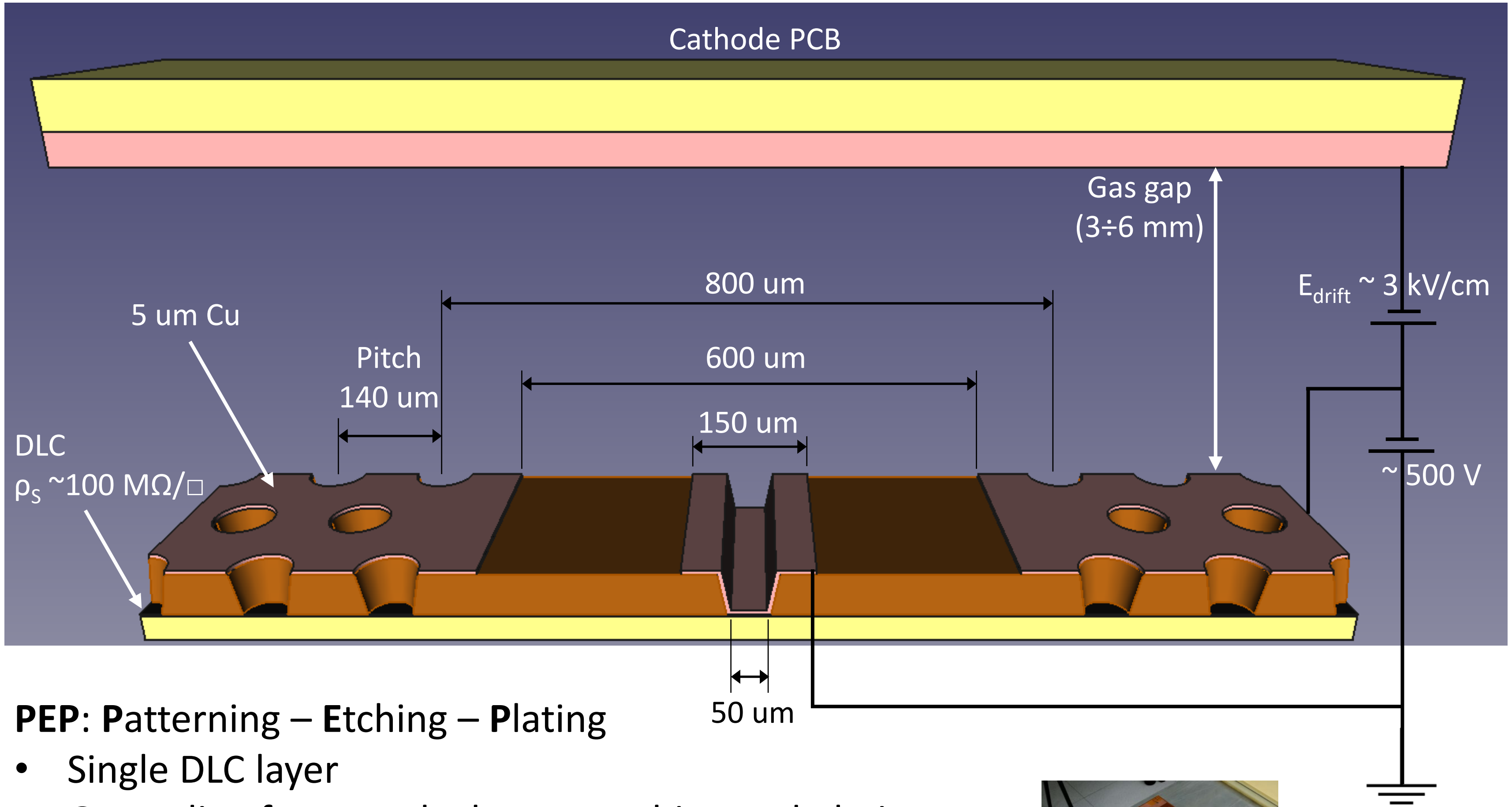


…

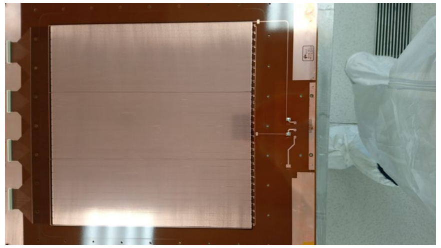
Silver **G**rid

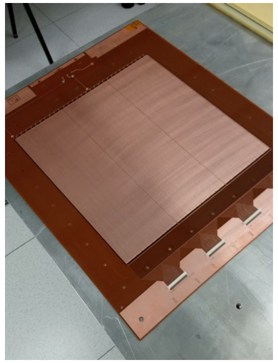
- DLC with Cu laminated
- *d* ~1 cm
- High rate purposes (>10MHz/cm^2)
- Not difficult for companies, BUT more complex Cu+DLC sputtering and the alignment of the grounding lines with the dead areas on the top of the amplification stage (more difficult for large size detector)

The µ-RWELL technology: the evolution



PEP: **P**atterning – **E**tching – **P**lating
- Single DLC layer
- Grounding from top by kapton etching and plating
- No alignment problems
- Scalable to large sizes





ACTIVE AREA 30 x 30 cm^2

«Less is more»
Ludwig Mies van der Rohe

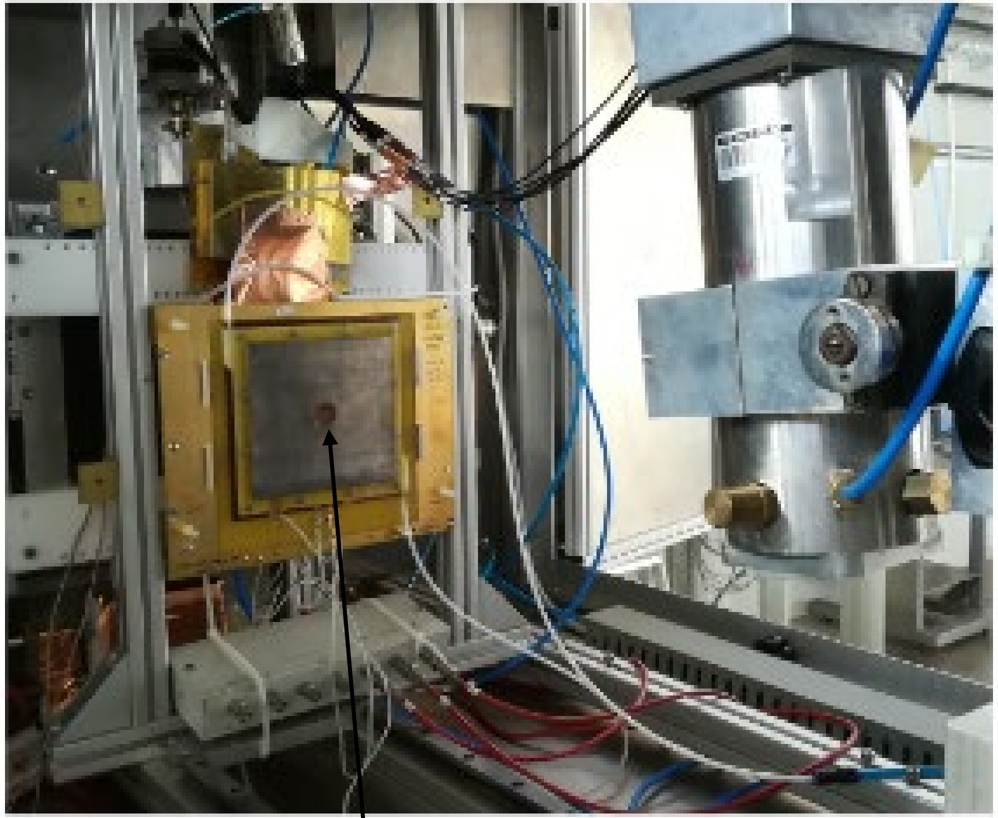
Geometrical PARAMETERS

Layout	GND pitch [mm]	Dead Area [mm]	DOCA [mm]	Geom. Acceptance
PEP1	6 // 8	1	0.475	66%
PEP2.1	8.9	0.8	0.375	91%
PEP2.2	17.8	0.8	0.375	95.5%

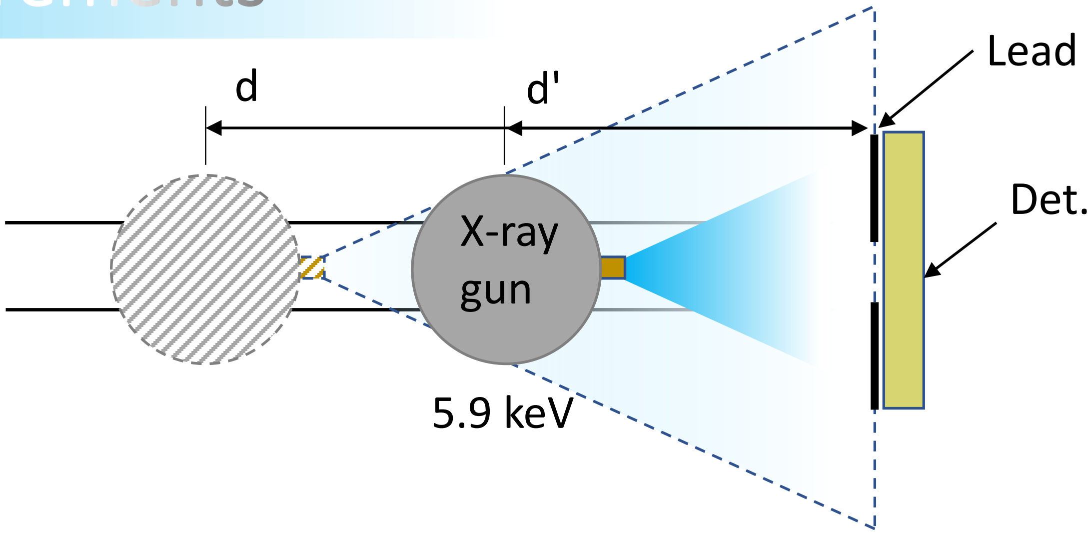
DOCA (Distance of Closest Approach): the minimum distance between a grounding line and an amplification channel.

The µ-RWELL technology: X- rays measurements

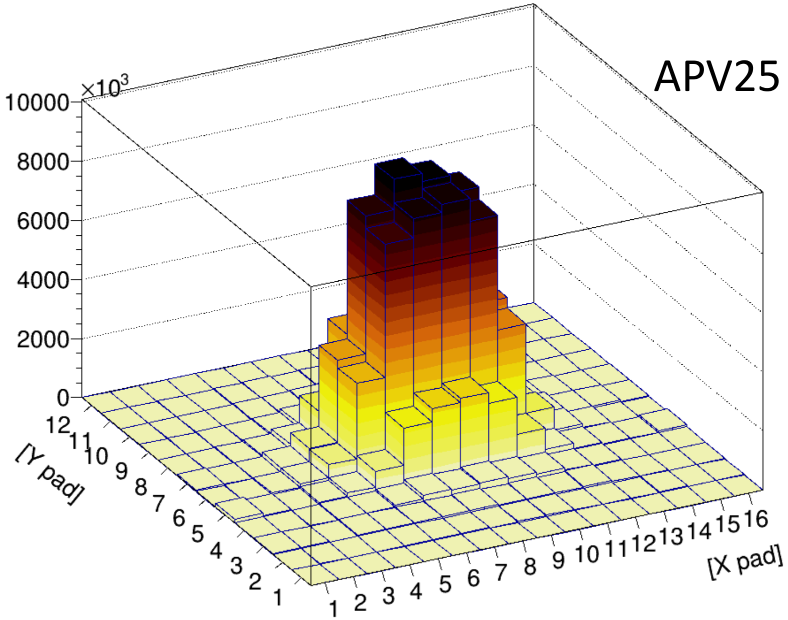
Setup



A lead square shielding, with length **L larger than the active area** and a circular window (*r*) is plugged on the cathode where ***r*** is **larger than the grounding pitch**.
The thickness of the lead is 1 mm (~ 500 X_0)

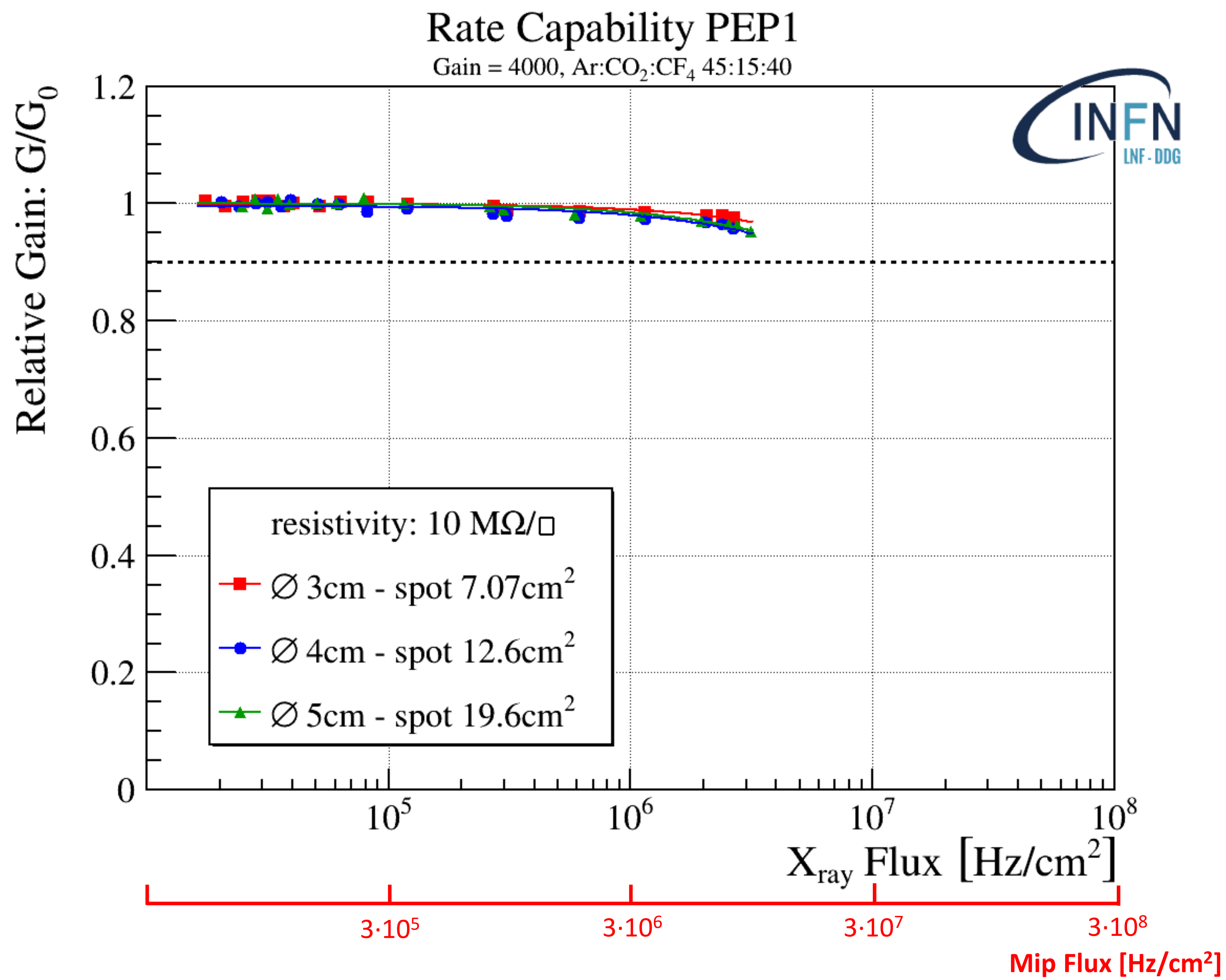


Gun installed on rail to **change the distance** from the detector → to **change the X-rays rate**



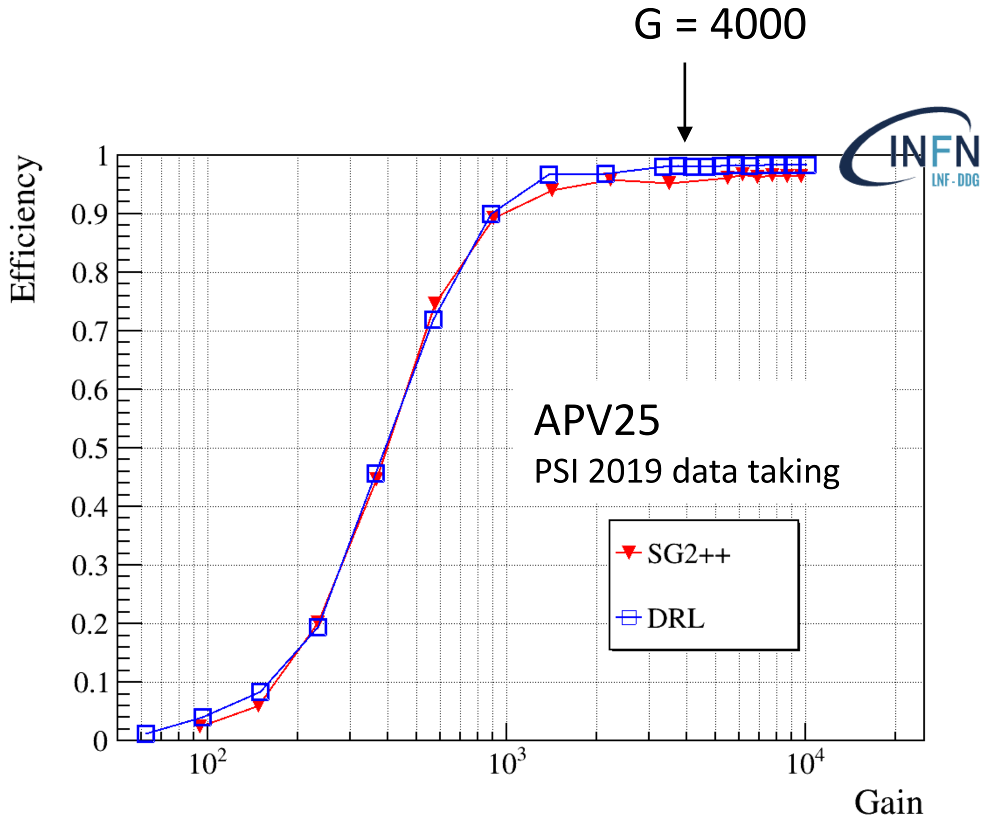
Spot nearly uniform on the irradiated area

The μ-RWELL technology: X- rays measurements



Rate capability defined as the rate where the detector loses 10 % of gain

It shoudn't affect the detection efficiency once chosen a working point well above the efficiency knee!

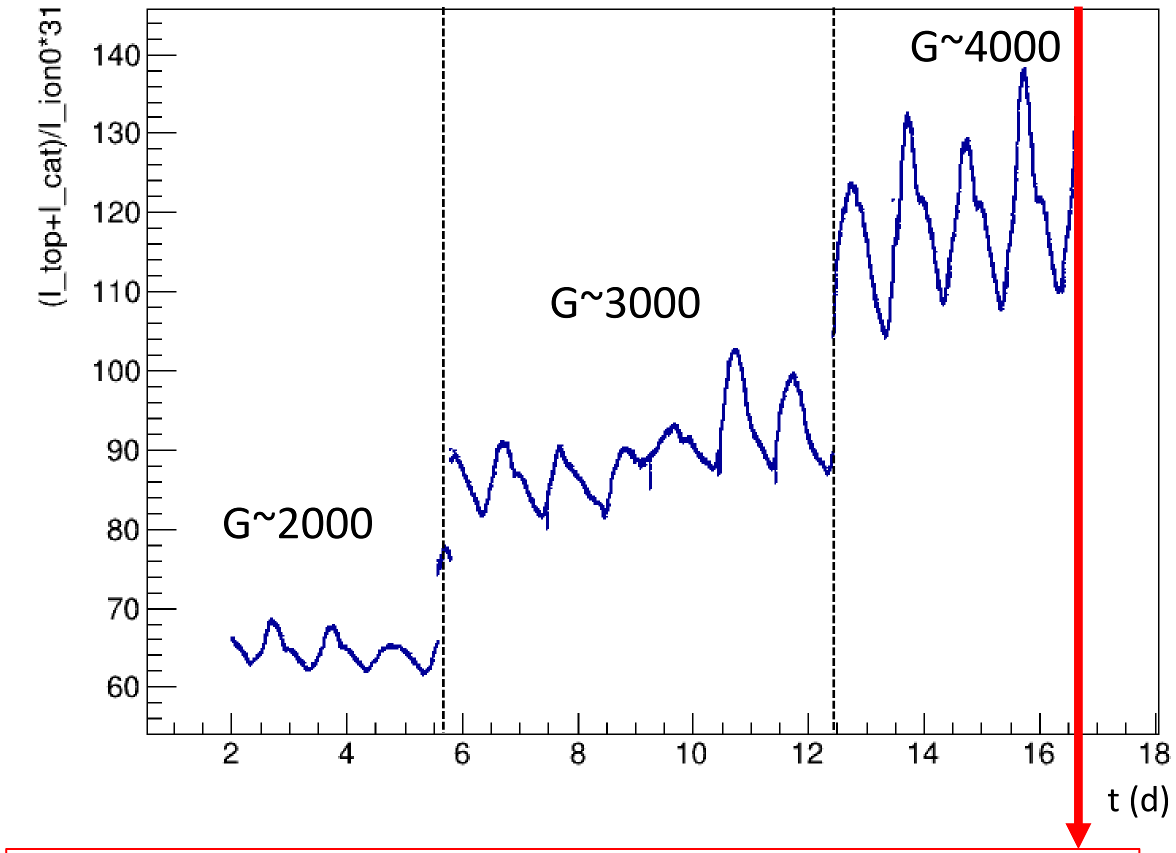


Because of the common effort in the scientific community to reduce the F-based components, we are changing our mixture to $Ar:CO_2:iC_4H_{10}$ 68:30:2 and starting the stability measurement

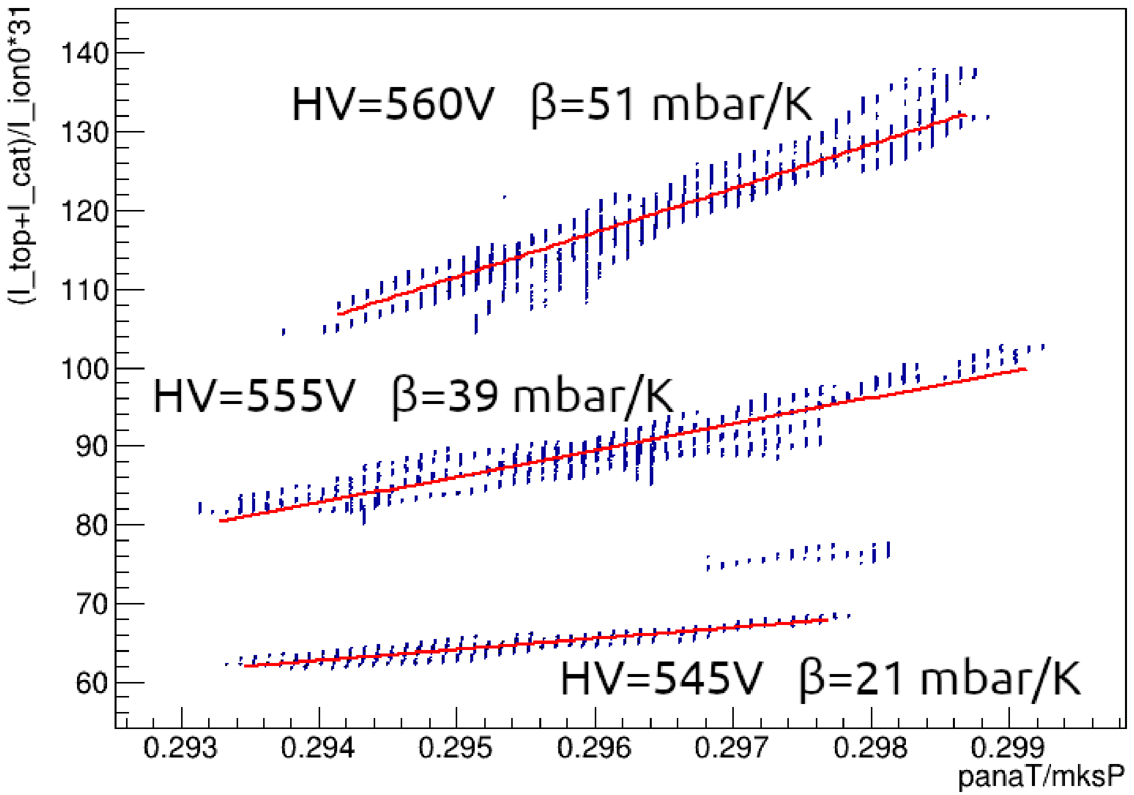
The μ-RWELL technology: X- rays measurements

Once fixed a distance for the gun (→ $\phi_{X\text{-rays}}$ = 60 kHz/cm^2 equivalent to ϕ_{mip} = 550 kHz/cm^2), the current drawn by the detector has been monitored to evaluate the stability of its daily average.

Parallel acquisition of the T and P gas parameters to apply the corrections $e^{\frac{\beta T}{P}}$
$H_2$0 concentration down to 500÷600 ppm



5 mC/cm^2 integrated so far with a gas gap of 6 mm **1 C/cm^2 after 10 years at LHCb** (0.75 MHz/cm^2 mip) and 3 mm gas gap

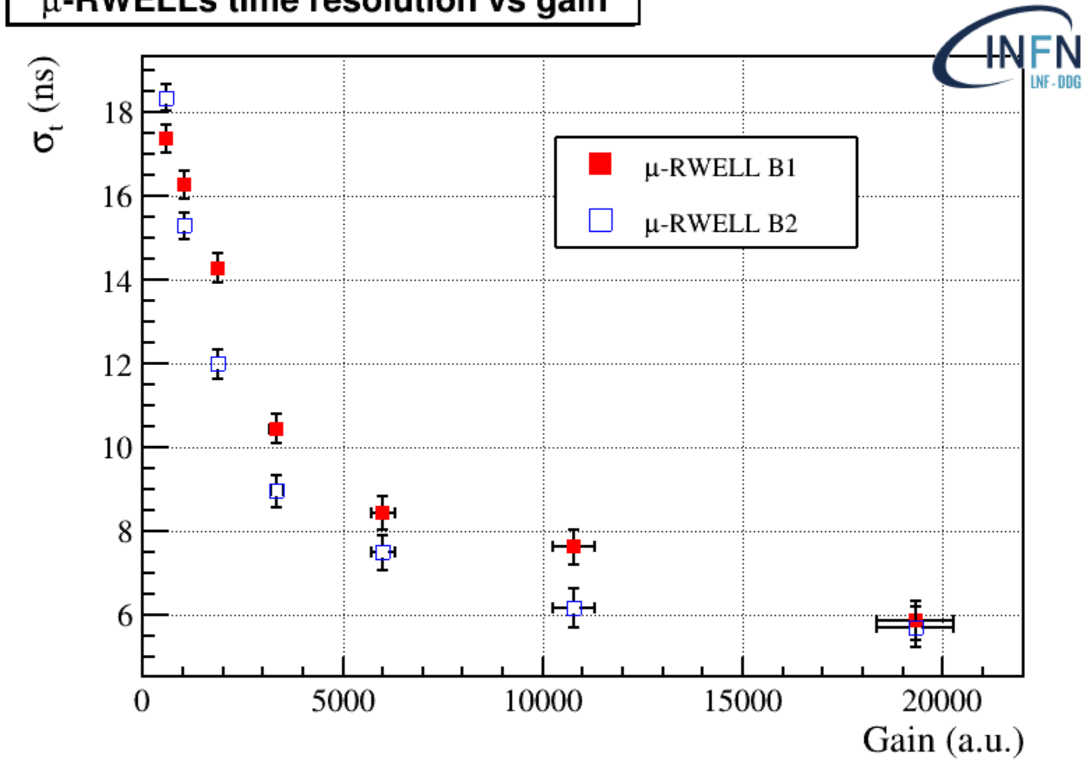


The increasing average of the current matches the trend of T/P

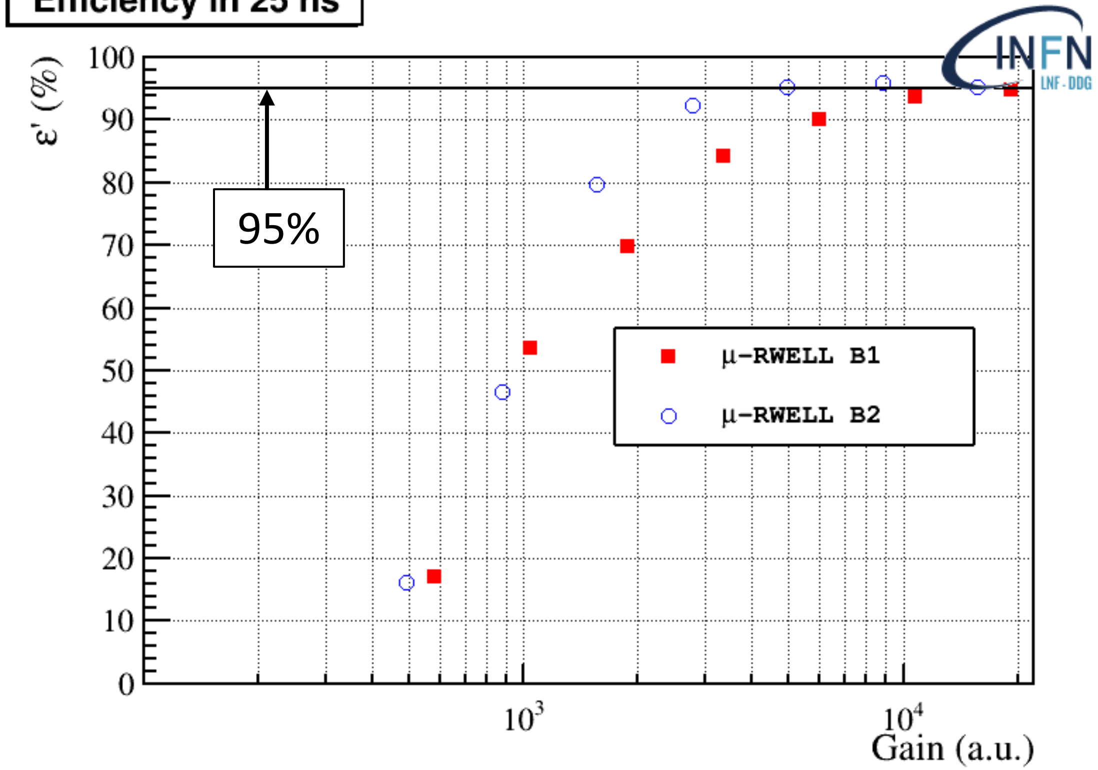
The μ-RWELL technology: the time resolution

The technology must guarantee a good time resolution and full efficiency in the 25 ns window

μ-RWELLs time resolution vs gain



Efficiency in 25 ns



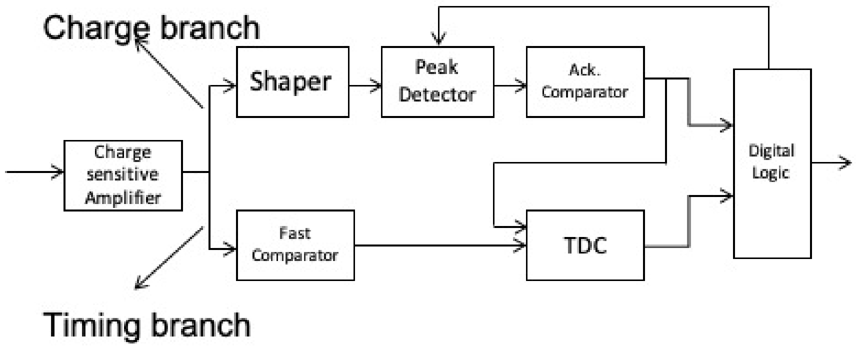
- A first measurement of the time resolution has been done at H8C Cern North Area.
- The detectors were operated with **$Ar:CO_2:CF_4$ 45:15:40** gas mixture (the same used by GEM @LHCb) and equipped with VFAT2. A saturation due to FEE is visible at high gain
- There is room to improve the resolution, improving the FEE

The μ-RWELL technology: the FEE for LHCb

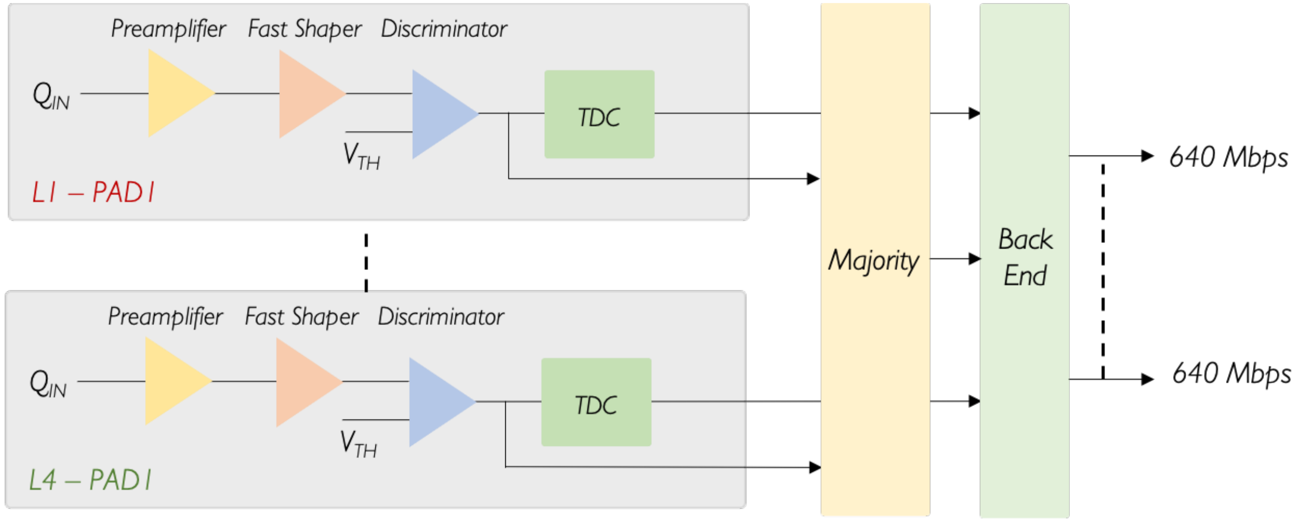
New ASIC design

- A new design based on FATIC2 (for FATIC see Anna Stamerra's talk) device is going on @ Bari (G. de Robertis/F. Loddo/F. Liciulli)
- Besides the majority logic the new device is able to make single channel time (shaping time from 25 to 100 ns) and charge measurements
- Better timing resolution if compared with the single majority time measurement

FATIC2 Block diagram

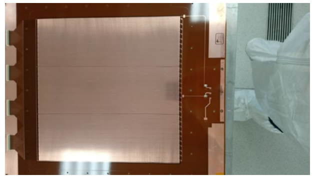


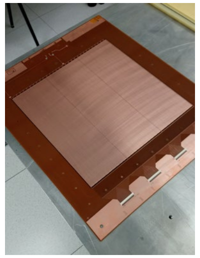
New ASIC block diagram



The μ-RWELL technology: TT

From slide 2 & 8:





- 576 detectors
- Up to 90 m^2 to be covered
- **Need for industry!!!**

The three stages are embedded in a single PCB, produced by **standard ridig-flex PCB manufacturing (even involving mixed multi-layer).**

MEMENTO:
Amplification stage +
Resistive stage +
Readout plane =
μ-RWELL_PCB

Start!

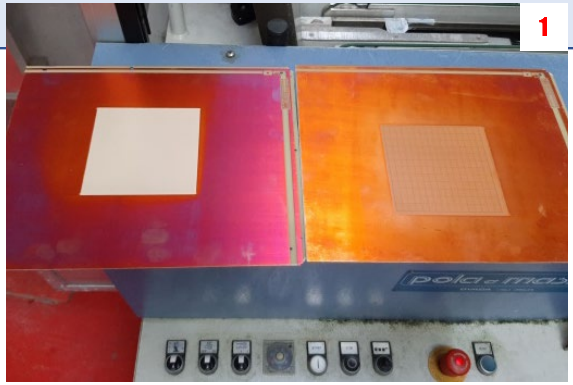
INFN LNF Istituto Nazionale di Fisica Nucleare

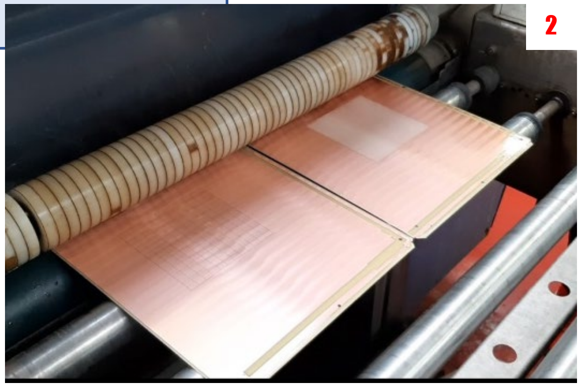
AIDA innova EU-project;

μ-RWELL techn. transf.

ELTOS

PCB production





DLC sputtering know-how

DCL foil prod.*

CERN INFN Istituto Nazionale di Fisica Nucleare

Completed μ-RWELL_PCB shipping

CERN

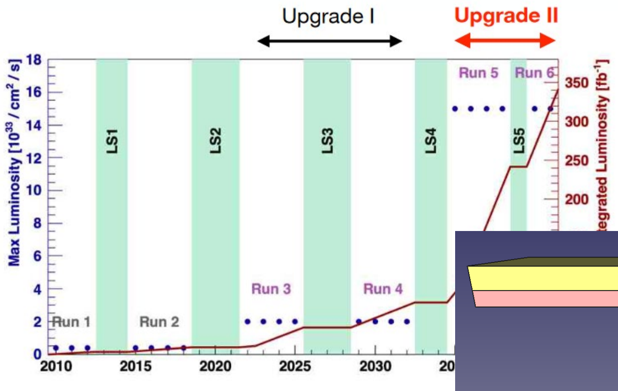
Detector manufacturing

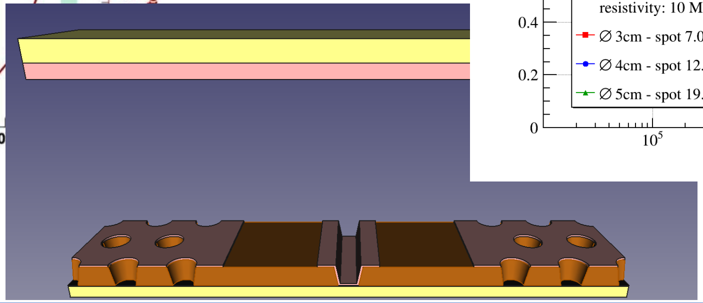
PCB shipping

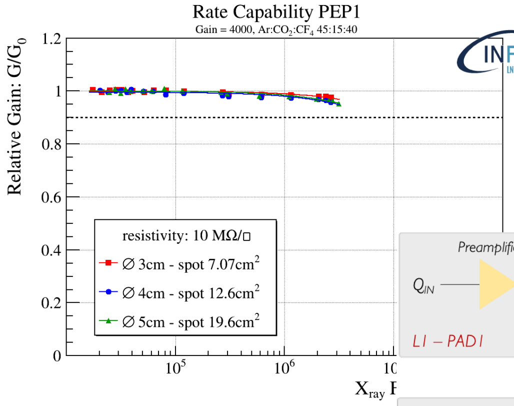
***DLC Magnetron Sputtering machine co-funded by INFN-CSN1**

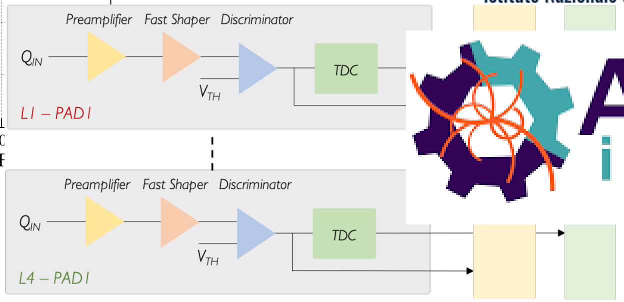
Summary & outlook

- In view of the **phase-2** upgrade the LHCb collaboration demands detectors with **rate capability up to 1 MHz/cm²** and with good stability during operation
- We proposed this technology, **micro-Resistive WELL**, for the upgrade
- The most recent version of **the detector fulfills the requirement** on the rate capability; stability test is ongoing
- **A new FEE** is being developed introducing a new ASIC (FATIC2)
- Due to the relative simplicity of the technology, **the technology is being trasferred to the industry** for the mass production









- Eco-gas mixture studies to be done
- Slice test
- Mechanical improvement of some detector components (i.e. replacing FR4 with PEEK)
- TT to be continued with ELTOS company

Addendum

LHCb is NOT the ONLY collaboration focusing its attention to this technology. The micro-Resistive WELL is involved also in

1. **FCC_ee**: the muon system of the IDEA apparatus for a Future Collider (see R. Farinelli poster)
2. **CLASS12** @ JLAB: the upgrade of the muon spectrometer
3. **EURIZON (under EU approval)**: the Inner Tracker based on cylindrical micro-RWELL for a super Charm-Tau factory (coll. with LOSON S.r.l)
4. **X17 @ n_TOF EAR2**: for the amplification stage of a TPC dedicated to the detection of the X17 boson
5. **UKRI:** neutron detection with pressurized ^{3}He-based gas mixtures
6. **TACTIC @ YORK Univ.:** radial TPC for detection of nuclear reactions with astrophysical significnace
7. **URANIA-V**: a project funded by CSN5 for neutron detection, an ideal spin-off of the EU-founded ATTRACT-URANIA (see M. Giovannetti poster)
8. **Muon collider:** hadron calorimeter (Anna’s talk)

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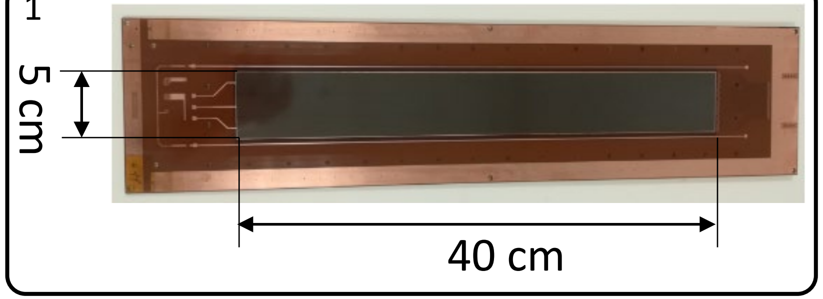

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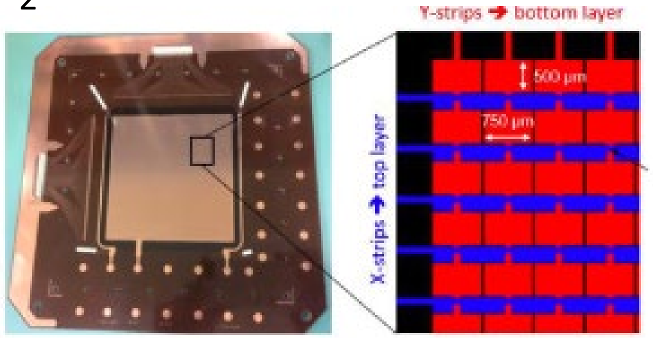

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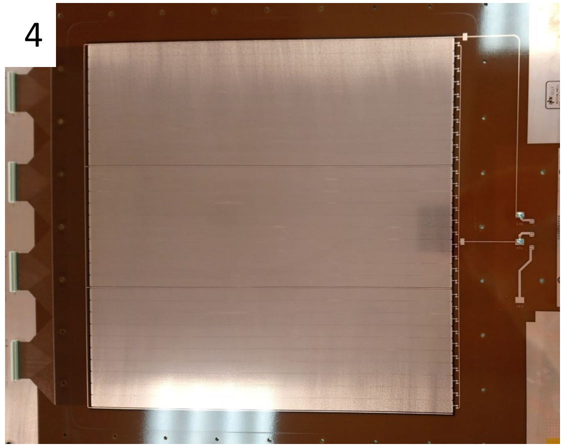

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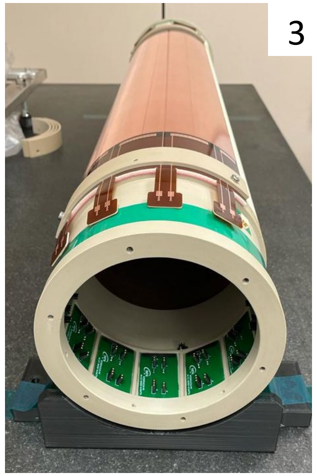

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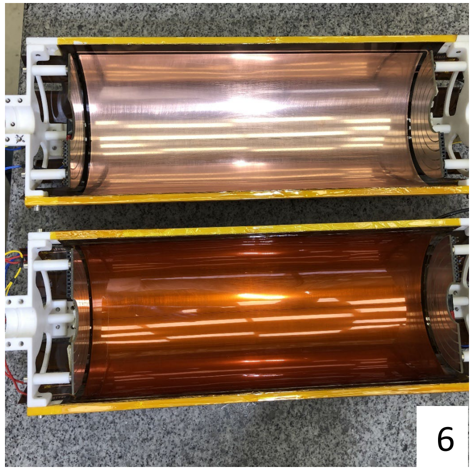

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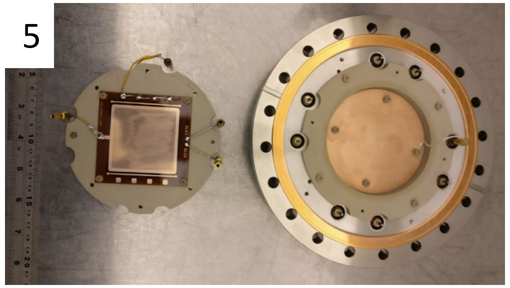

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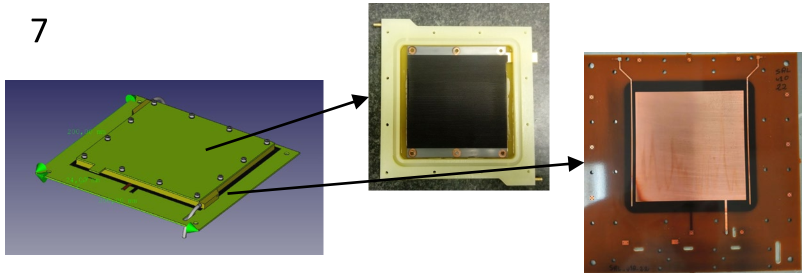

SPARE

LHCb experiment at CERN: (very) few highligths

[5] LHCb collaboration, R. Aaij *et al.*, *Observation of CP violation in charm decays*, Phys. Rev. Lett. **122** (2019) 211803, arXiv:1903.08726.

[6] LHCb collaboration, R. Aaij *et al.*, *First observation of CP violation in the decays of B_s^0 mesons*, Phys. Rev. Lett. **110** (2013) 221601, arXiv:1304.6173.

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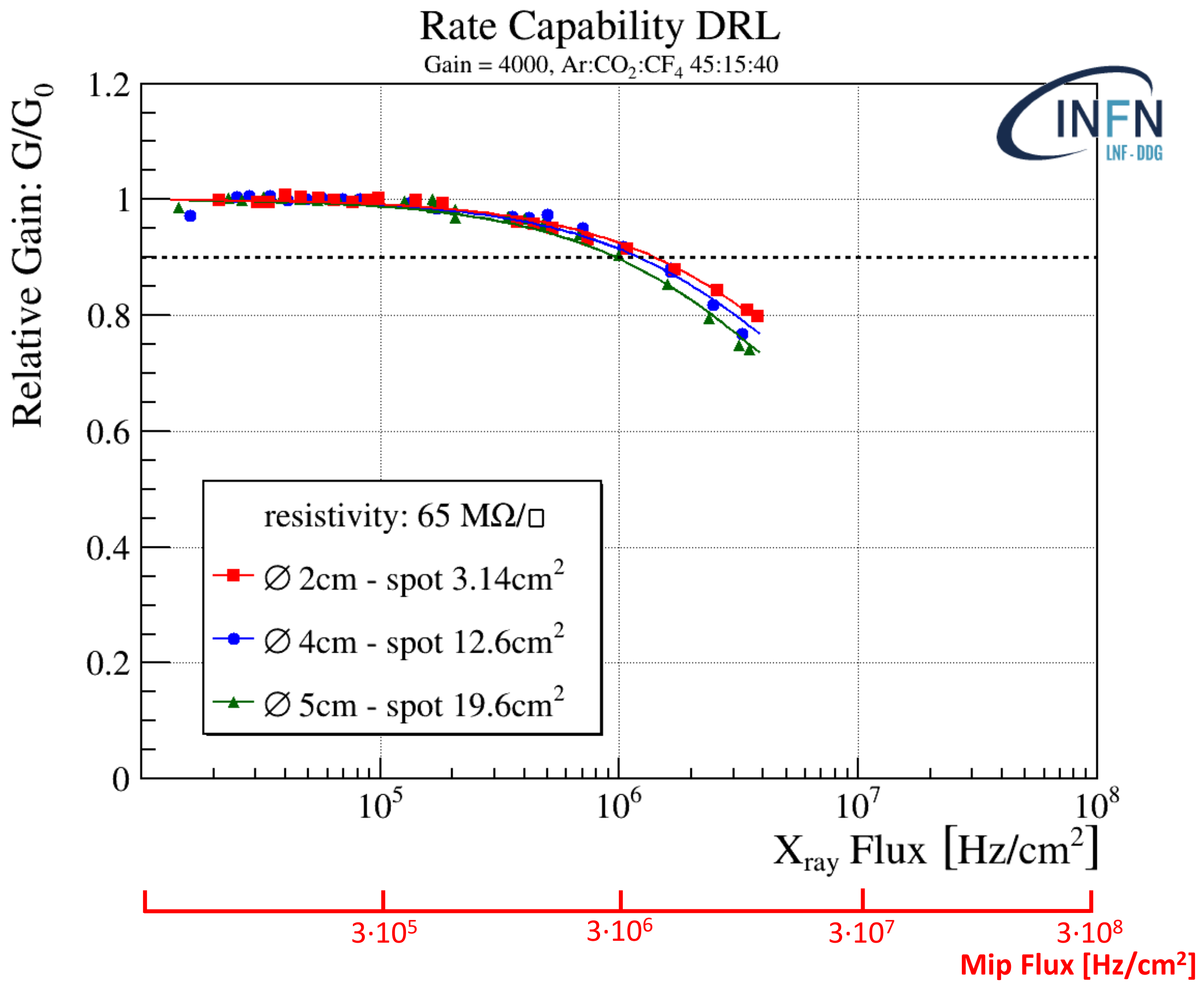
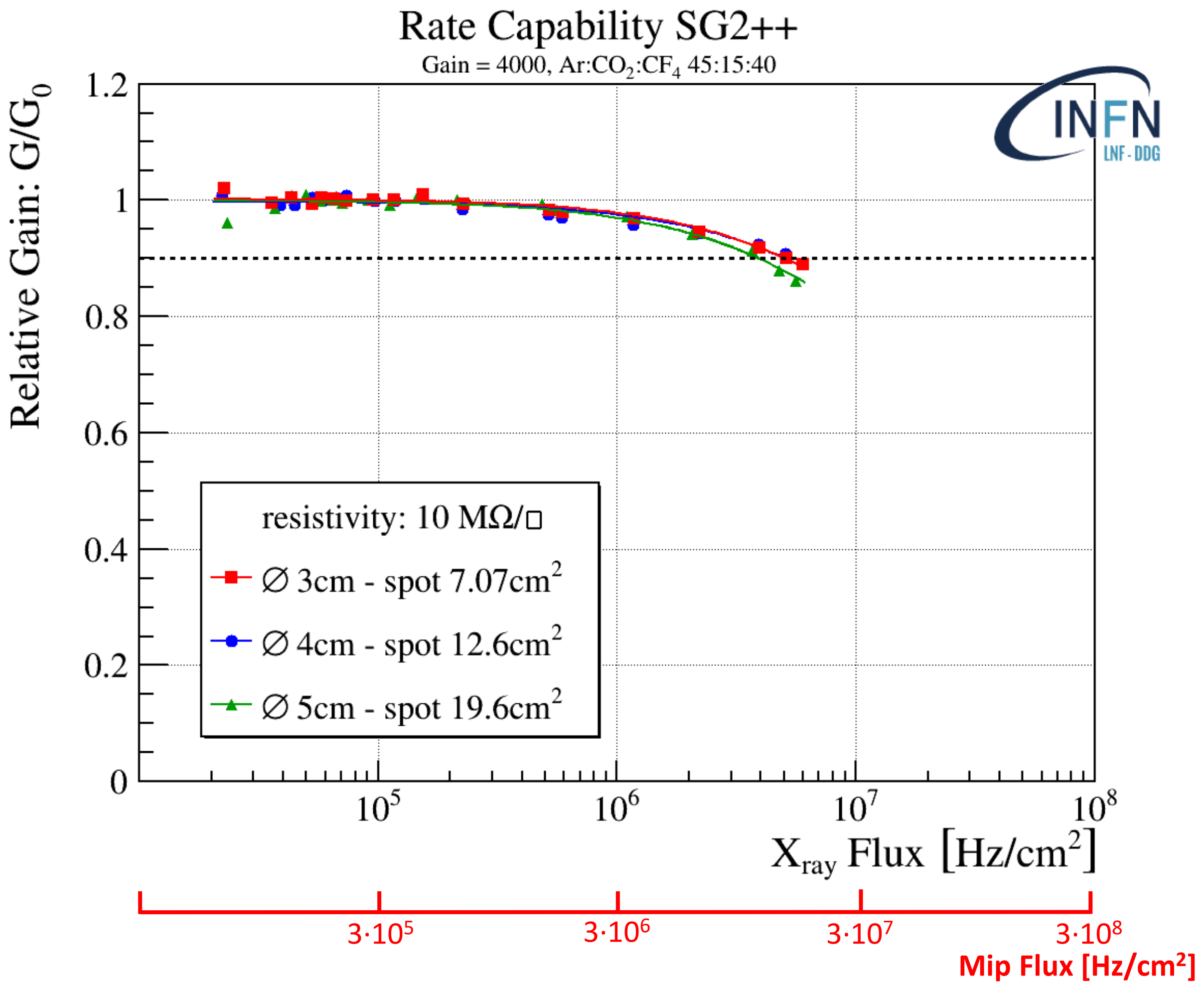
The μ-RWELL technology: X- rays measurements

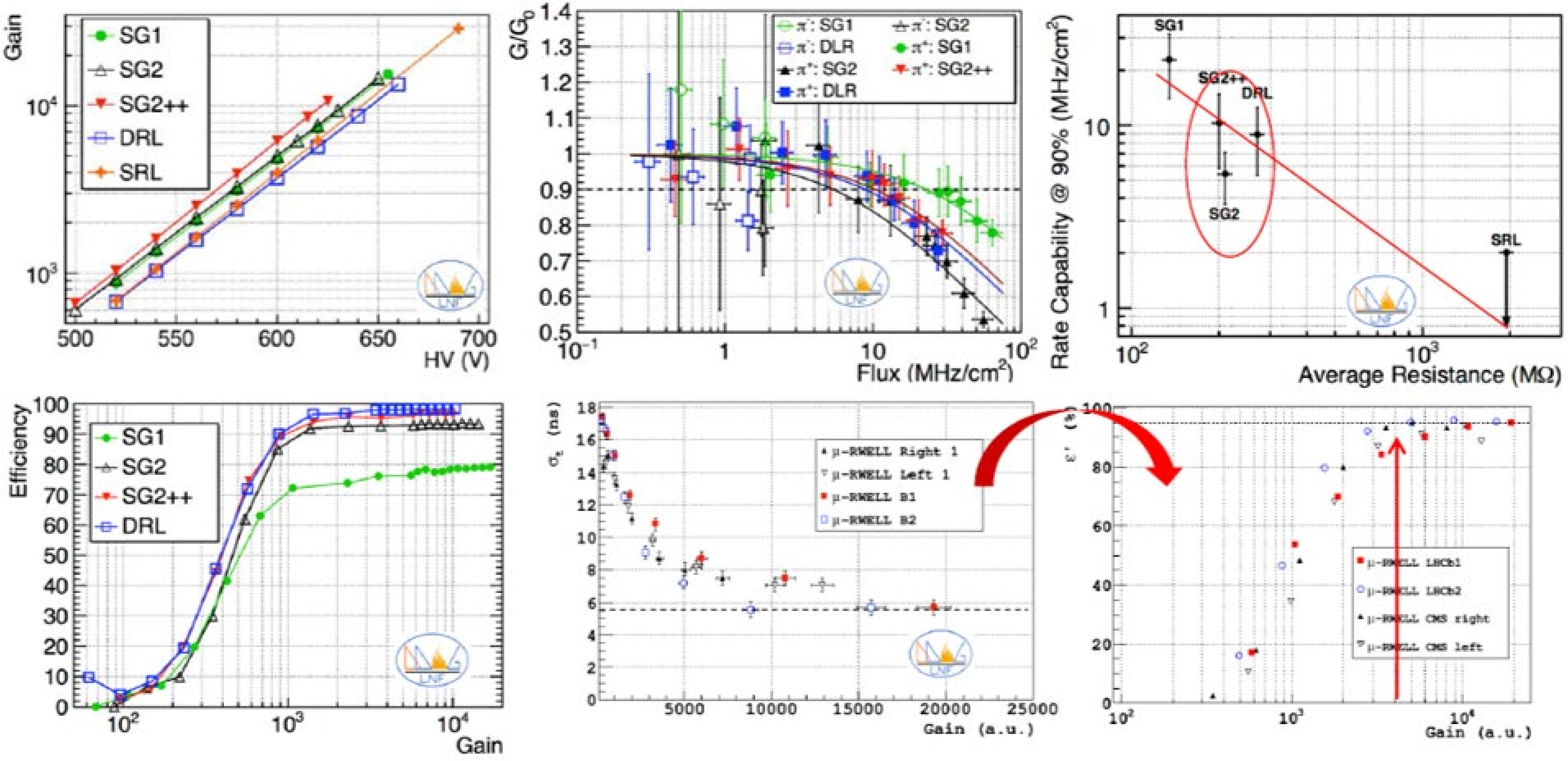




The μ-RWELL techology: measurements

Gain up to ~ 10^4

Rate capability (@ G = 5000) ~ 5-10 MHz/cm^2



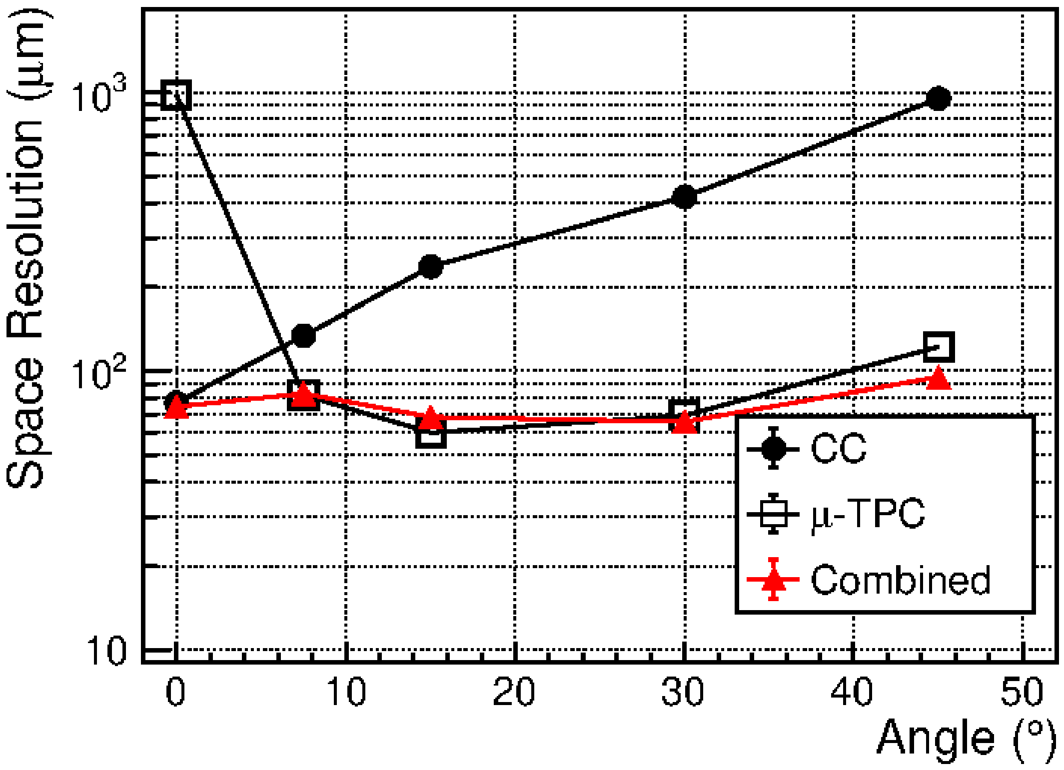
Efficiency ~ 98%

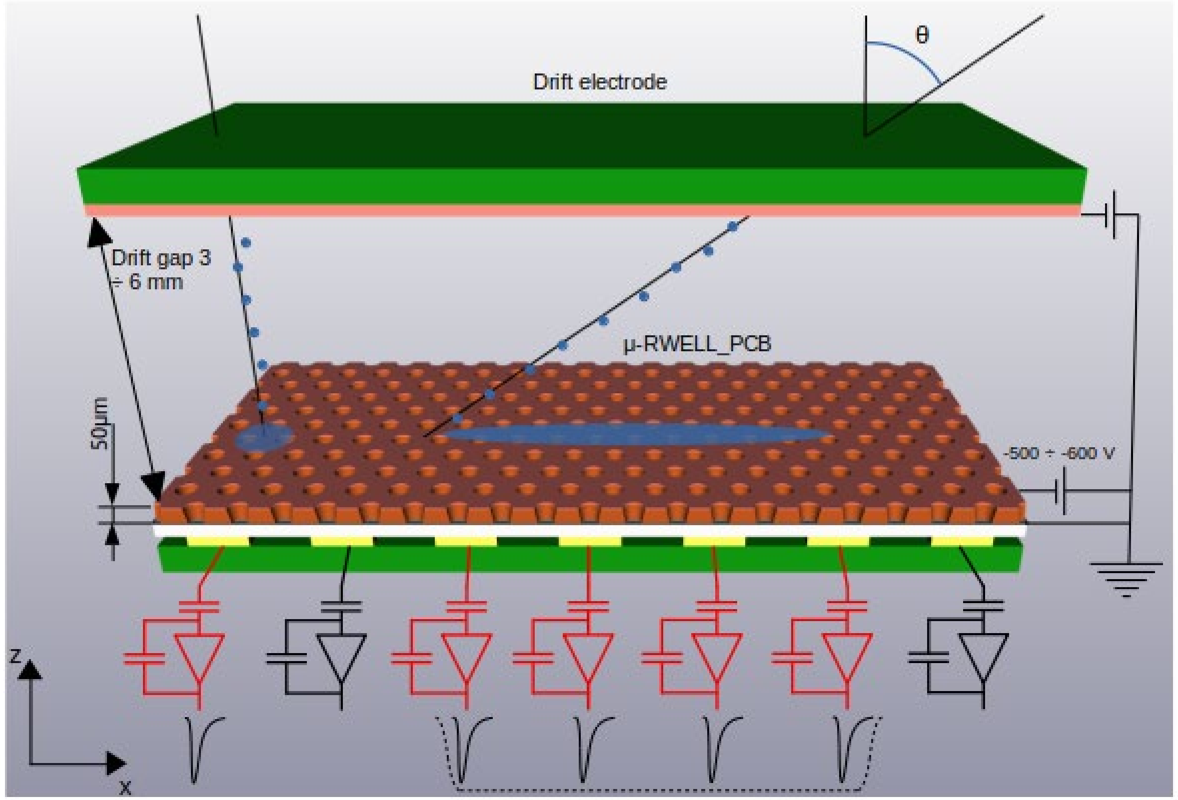
σ_t ~ 5-6 ns

Efficiency in 25 ns

2020 *JINST* **15** C09034

The µ-RWELL techology: measurements





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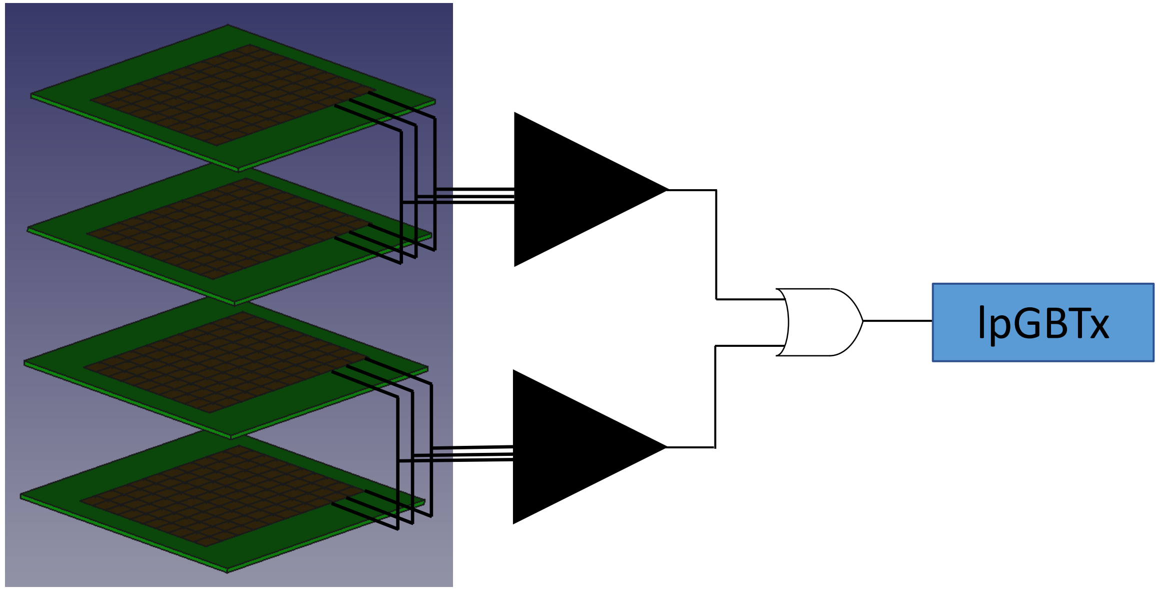
The µ-RWELL technology: the FEE for LHCb

Present readout electronics:

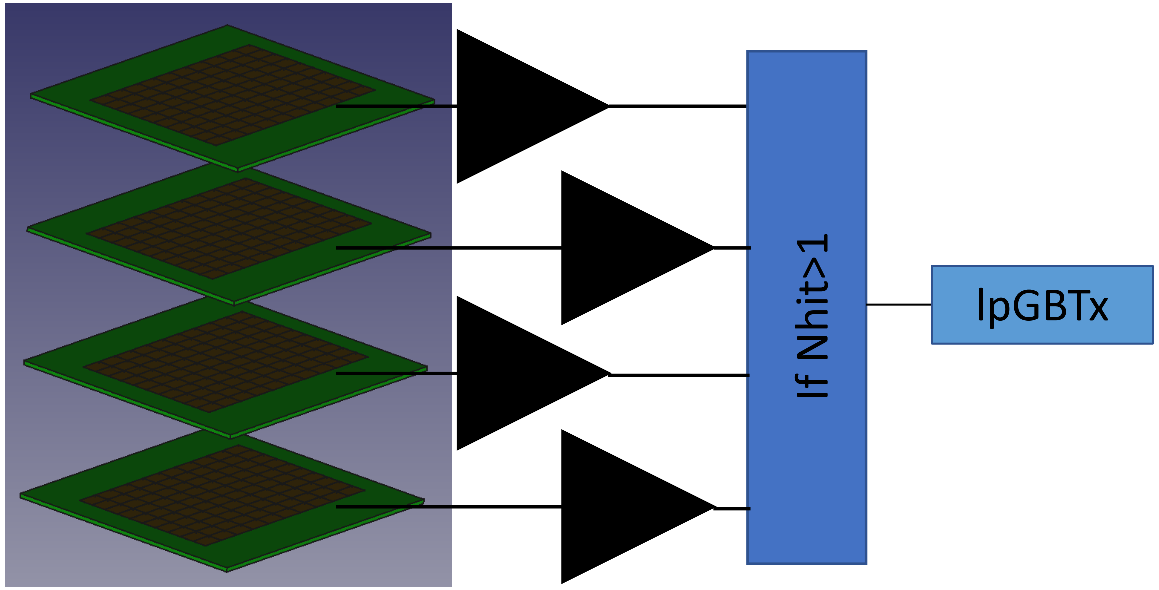
- The detector is made of **four gaps**
- **The corresponding pads** belonging to two different gaps are connected (**physical OR**)
- A **logical OR** of the two discriminated signal is then implemented

➡ The four gaps OR generate a very high rate due of single-GAP background signal (low energy particles)



New front-end electronics:

- background sensitivity reduction by requiring Nhit > 1 at front-end level (majority logic).
- Side effect : Nhit > 1 requirement can generate some inefficiency (MC studies are going on)
- **New front-end electronics** should be used to instrument also R3/R4 detectors (different pad density and pad capacitance)



μ-RWELL operation in ^{3}He based gas mixtures

Aim

- Neutron scattering applications
- Small area (100x100mm^2)
- High Efficiency(>70% at 25meV)
- High Position resolution (<0.5mm FWHM)

- Stopping gas to stop the range of the proton and triton of the reaction

$$n + {}^3He \rightarrow {}^1H + {}^3H + 770\ keV$$

- Measurements of the gain with a gas mixture containing 1 bar of ^{3}He and 1 to 6 bar of CF_4
- To date only MWPC and MSGC could operate at those gas pressures

Science and Technology Facilities Council

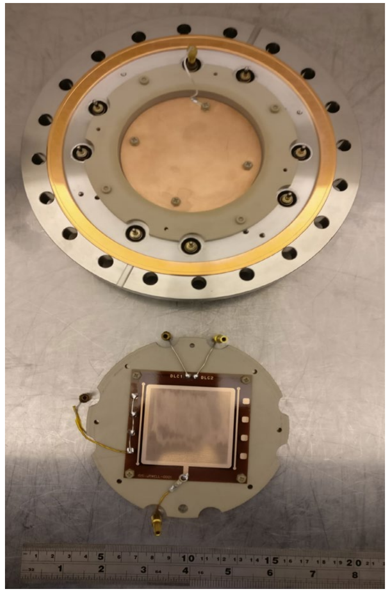
ISIS Neutron and Muon Source

R. Hafeji
D. Raspino
E.M. Schooneveld
N.J. Rhodes

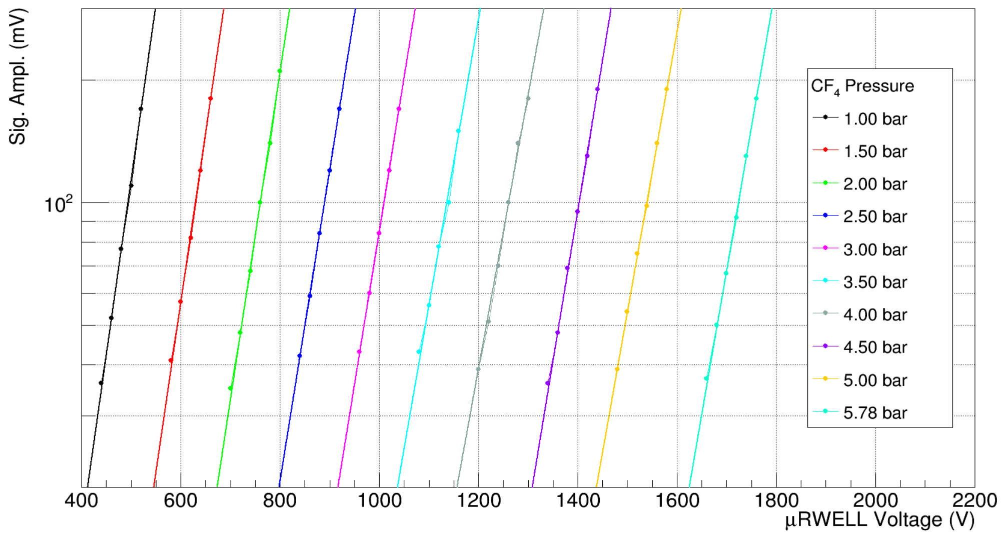
Setup

- 50x50 active area
- Active volume 16mm thick
- Sealed vessel

  (up to 7bar pressure)
- Neutrons from AmBe Source



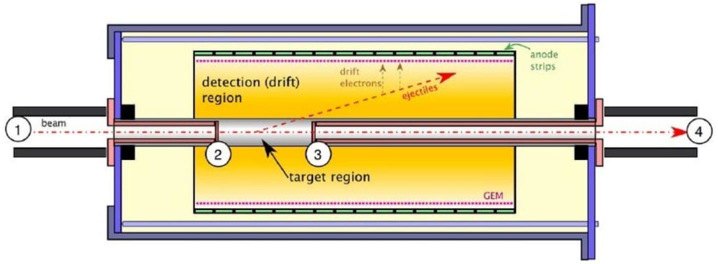
μRWELL with 1bar ^{3}He and CF_4



µ-RWELL for TACTIC

TRIUMF **A**nular **C**hamber for **T**racking and **I**dentification of **C**harged particles

- Active-target detector with cylindrical geometry designed to study nuclear reactions with astrophysical significance
- Aims at efficient small reaction cross-section measurements at low energies
- Will use µ-RWELLs in a **curved cylindrical geometry** for detection of various reactions products of interest with a range of energies (tens of keV to few MeV)
- Total length of detection region (shaded yellow): 251.9 mm and radius: 53 mm
- µ-RWELLs are currently installed inside and first alpha signals were seen. Future tests with reference sources and with a stable beam are planned.



TEST

- Time projection chamber with planar geometry
- Test chamber dimensions: 150 mm x 480 mm x 120 mm
- Distance between cathode and µRWELL surface (drift gap): 30 mm
- µ-RWELL active area dimensions: 35 mm x 251.85 mm; µ-RWELL overall dimensions: 336 mm x 80 mm; Foil thickness: 0.2 mm
- Anode is segmented into 60 pads of width 4.2 mm
- Designed to test MPGDs and electronics for TACTIC