ICHEP 2022

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

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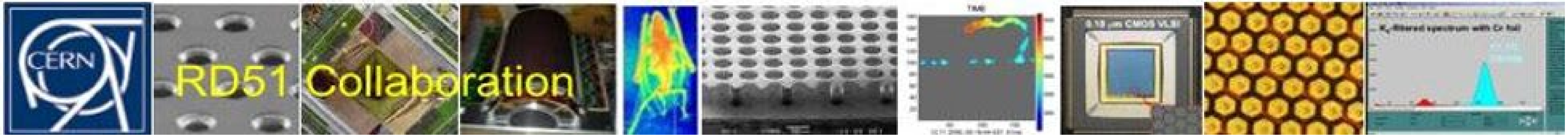
on behalf of the LHCb Collaboration

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

Bologna, July 8th, 2022

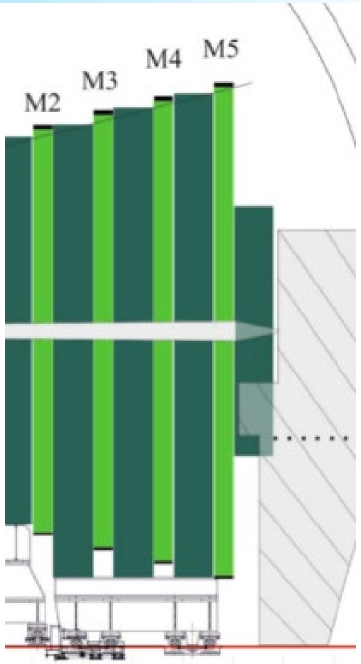


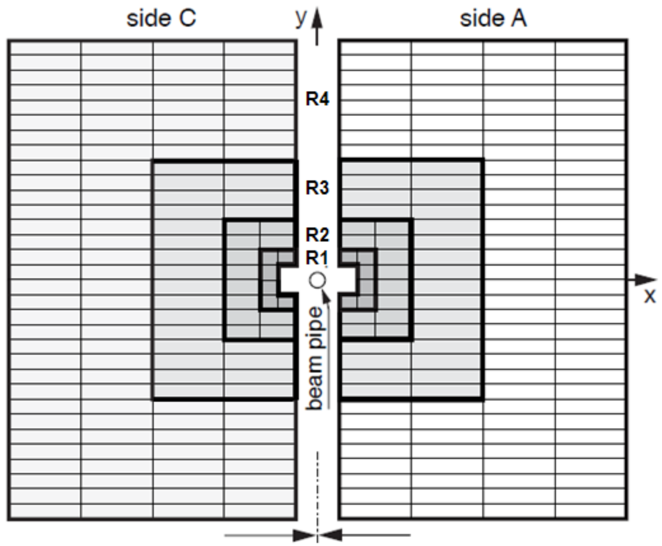
The LHCb Upgrade II (Run 5-6)

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!**

Requirements for Run 5-6 (2035-2042):

- Rate up to 1 MHz/cm^2 per single detector gap; 600 kHz per pad
- Efficiency (station)>95% within a BX (25 ns)
- Max input capacitance (double gap) ≤ 100 pF
- **Stability for 10 y of operation (up to 1 C/cm2)**





PROPOSED SOLUTION: micro-RESISTIVE WELL technology

Each MWPC will be replaced with a **stack of 4 gaps** in the region **R1 and R2**

- **R1÷R2: 576 gaps, size 30x25 to 74x31 cm^2, 90 m^2 det., 130 m^2 DLC**
- R3: 768 gaps, size 120x25 to 149x31 cm^2, 290m^2 det.
- R4 : 3072 gaps, size 120x25 to 149x31 cm^2, 1164 m^2 det.

For R3 and R4 region this technology is not a suitable solution due only to the large input capacitance of the detector.

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

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

Preliminary

See L. Paolucci's talk "The LHCb Muon Detector Upgrades", July 9th, Parallel Session on Operation, Performance and Upgrade (Incl. HL-LHC) of Present Detectors

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

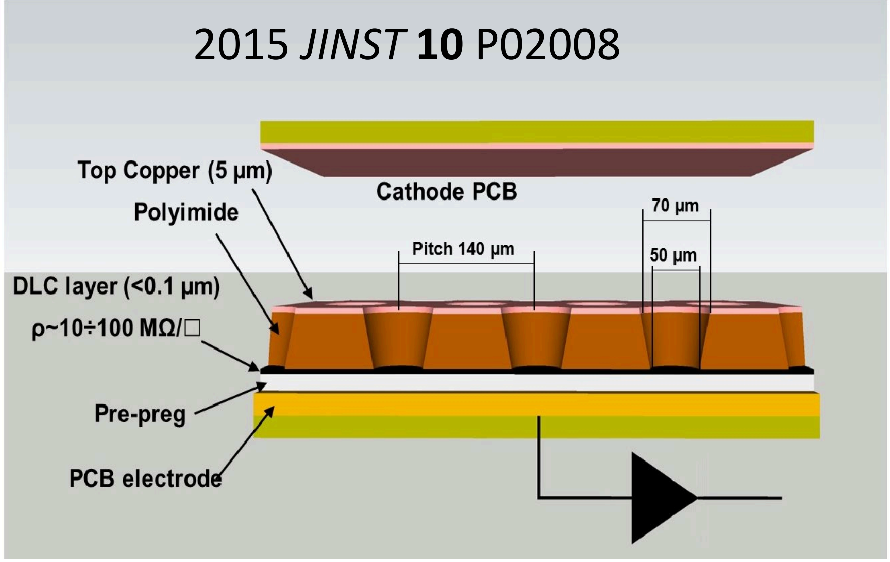
The µ-RWELL technology at a glance

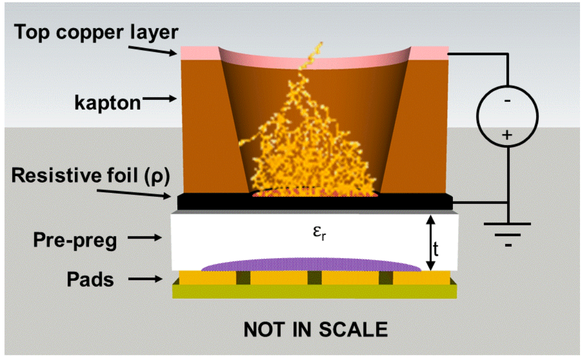
Developed in collaboration with CERN-EP-DT-MPT workshop

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





The "WELL" acts as a multiplication channel for the ionization produced in the gas of the drift gap

The charge induced on the resistive layer is spread with a time constant, $\tau \sim \rho \times C$

[M.S. Dixit et al., NIMA 566 (2006) 281]:

- ρ → the DLC surface resistivity
- C → the capacitance per unit area, depending on the distance between the DLC and the readout plane

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

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

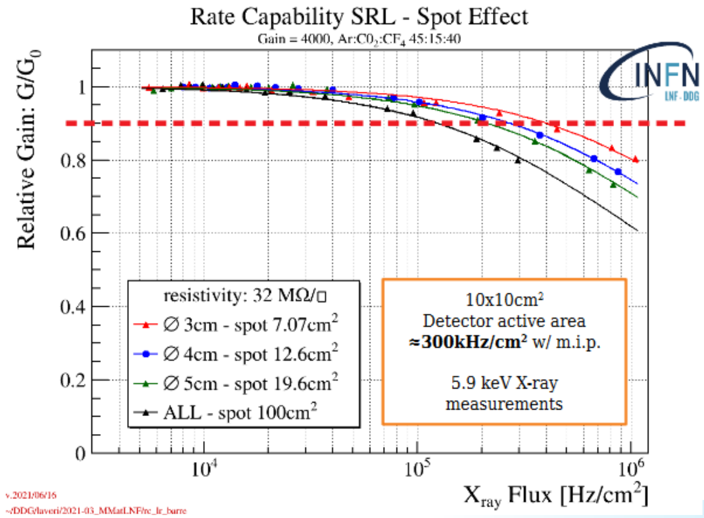
$$\Omega(r) = \frac{p_0(r)}{\alpha e N_0 G \pi r^2} = \rho_S \frac{d - \frac{r}{2}}{\pi r}$$

α from the fit to the gain vs. applied ΔV

N_0 from GARFIELD++ simulation

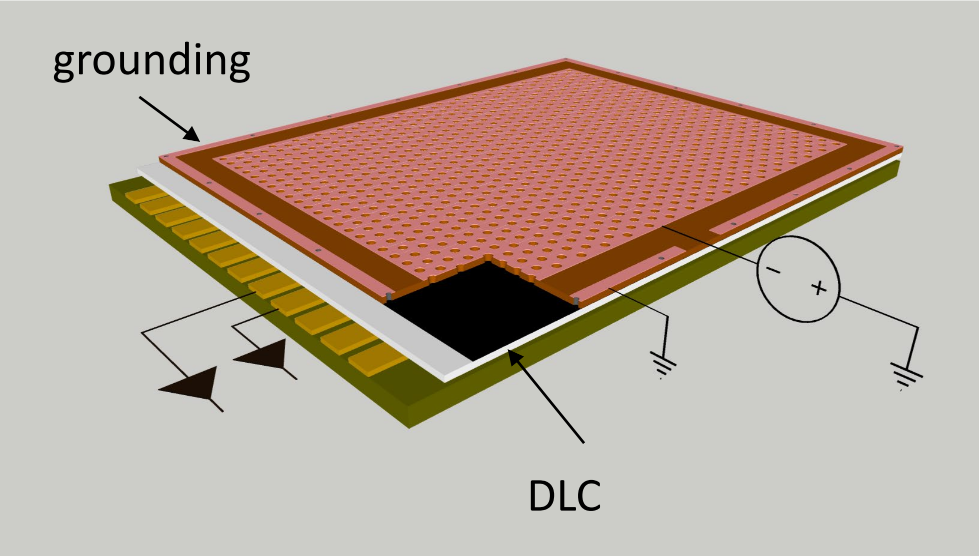
r radius of the X-rays spot

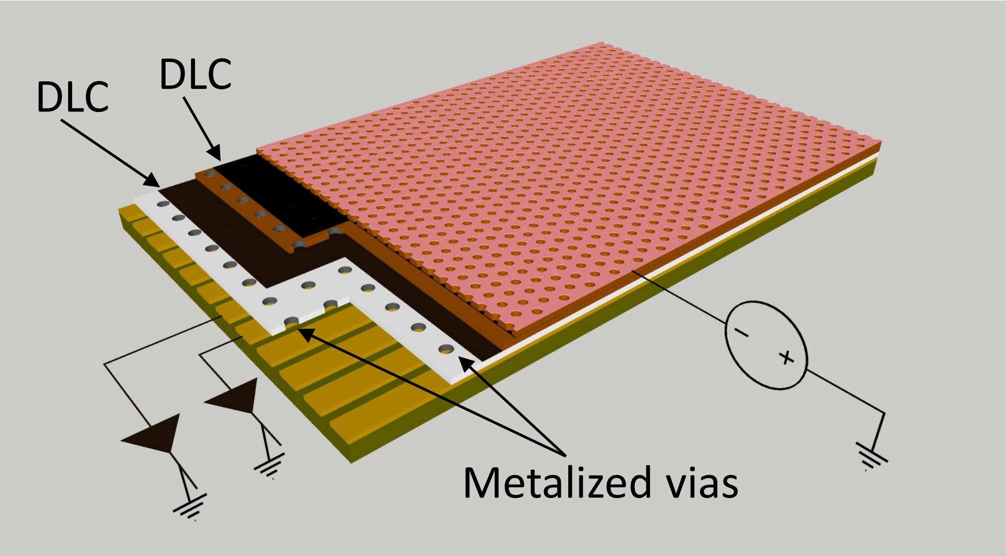
d average distance to the ground



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 several MHz/cm^2





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Single **L**ayer

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

Double **L**ayer

- Stack of DLC foils inteconnected by a matrix of conductive vias
- *d* ~1 cm
- High rate purposes (>10MHz/cm^2)
- Complex manufacturing

The µ-RWELL technology: the evolution

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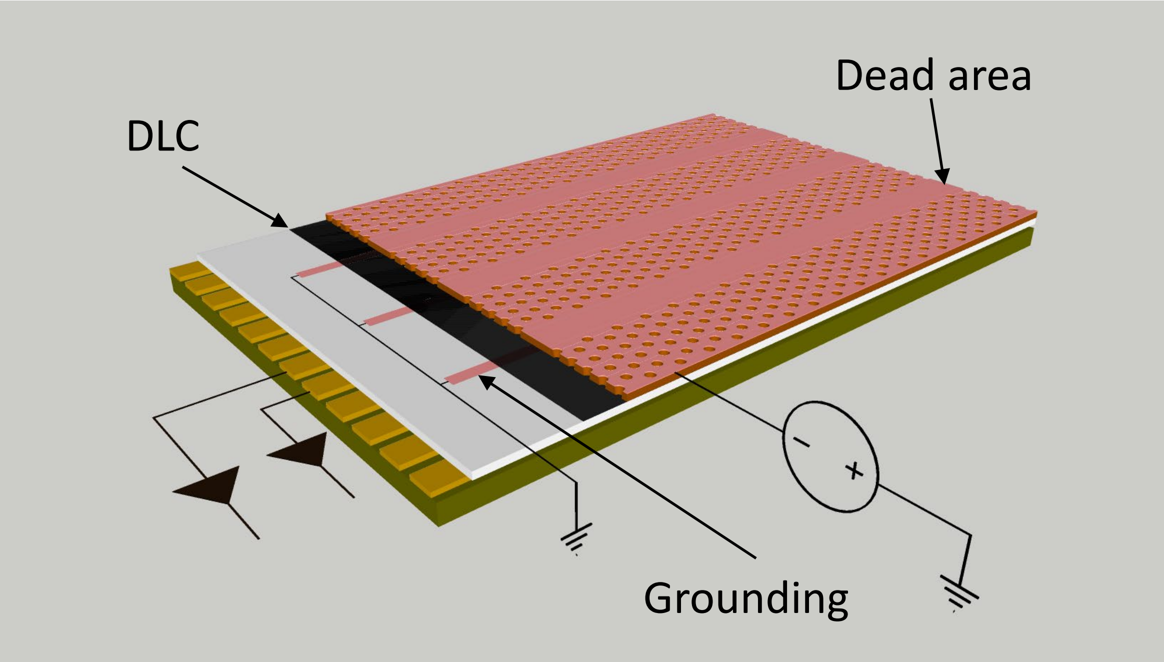


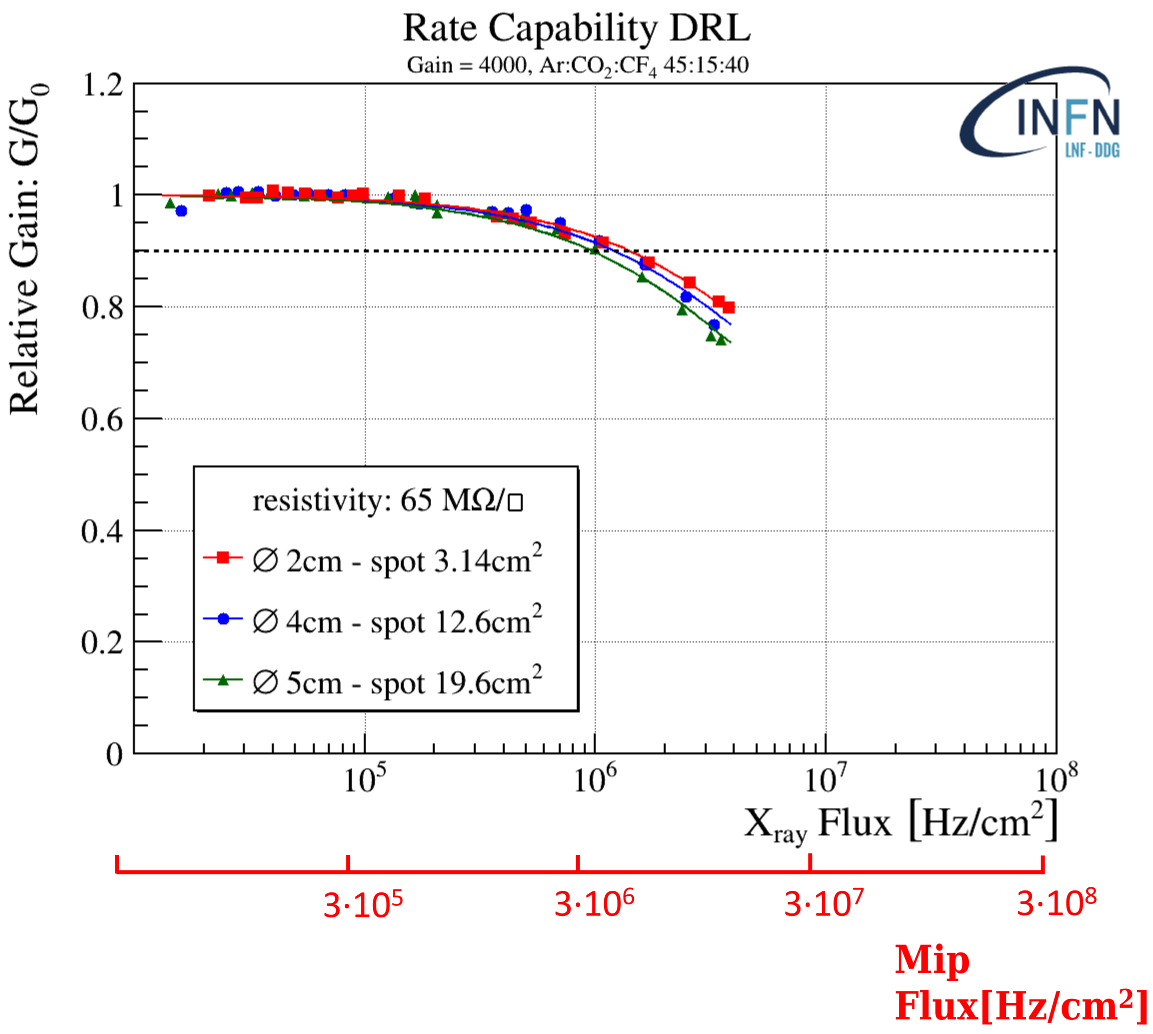
…

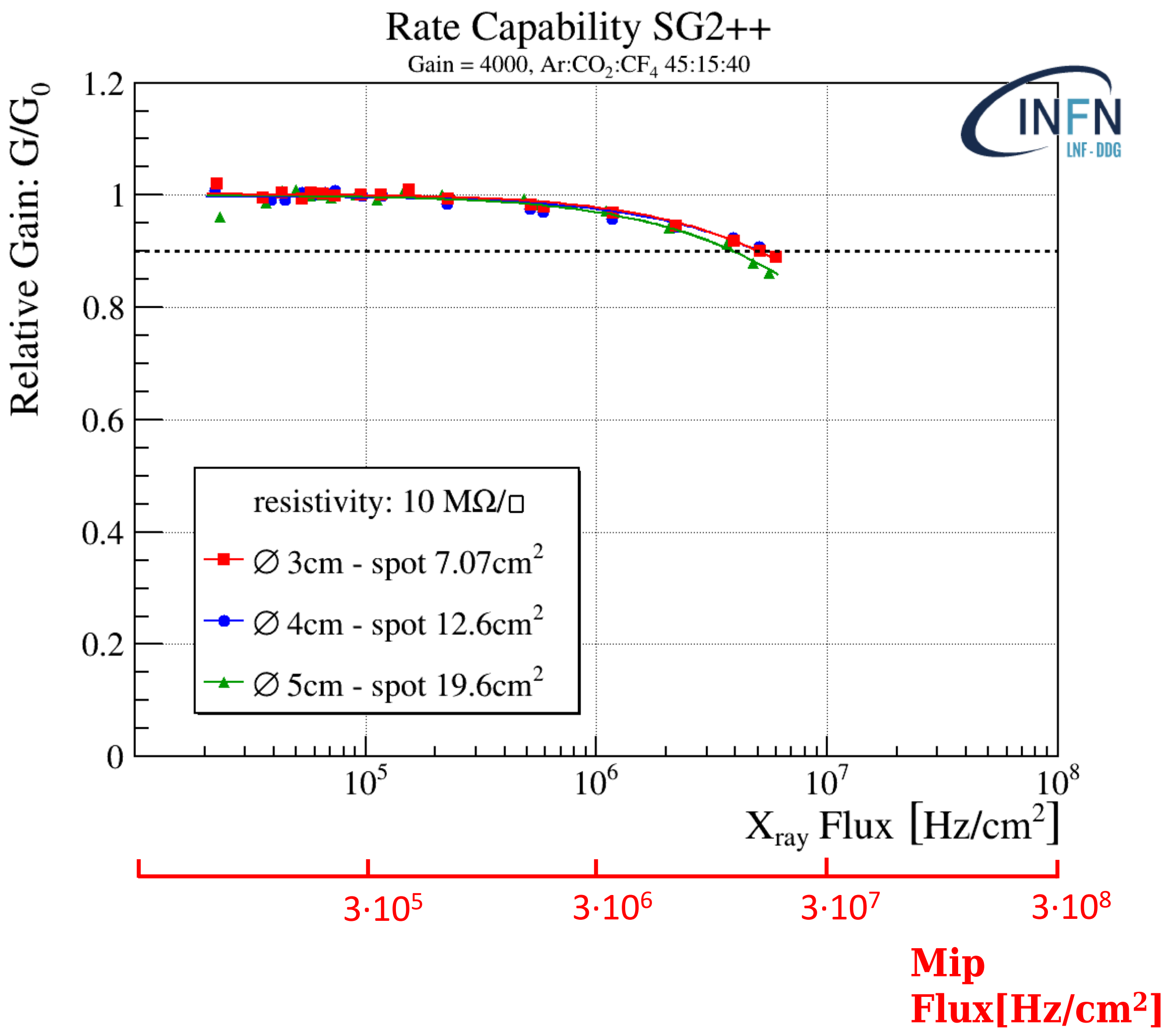
Silver **G**rid

- DLC grounded by coated Cu strips below
- d ~1 cm
- High rate purposes (>10MHz/cm^2)
- Complex Cu+DLC sputtering; difficult alignment of the grounding lines with the dead areas on the top of the amplification stage (expecially for large size detector)

High-rate layouts: performance with X-rays

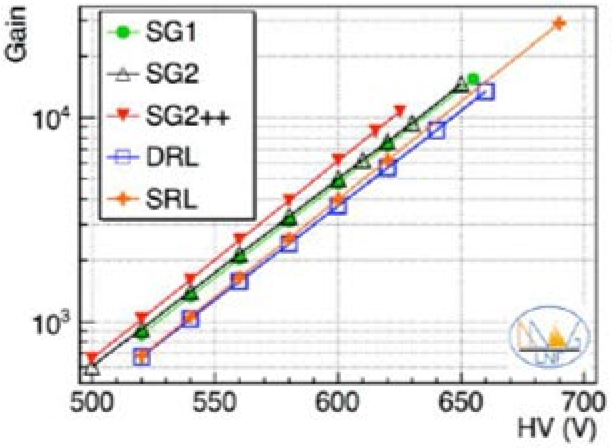
Energy of X-rays: 5.9 keV; ionization three times larger than a Mip in 6 mm gas gap



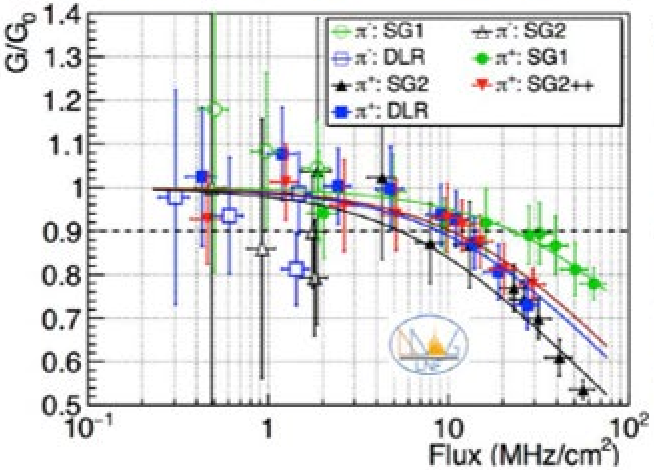


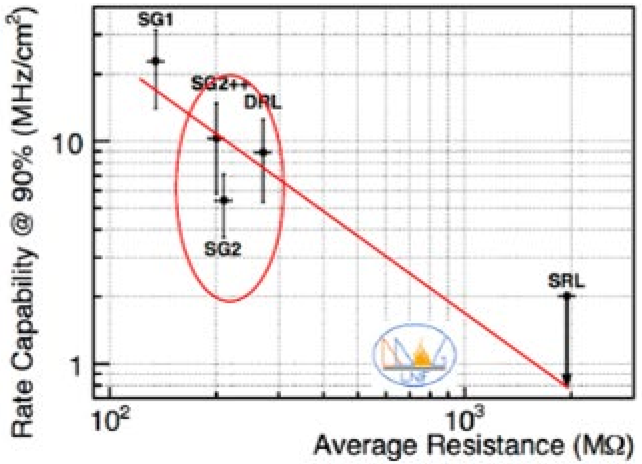
The µ-RWELL techology: measurements

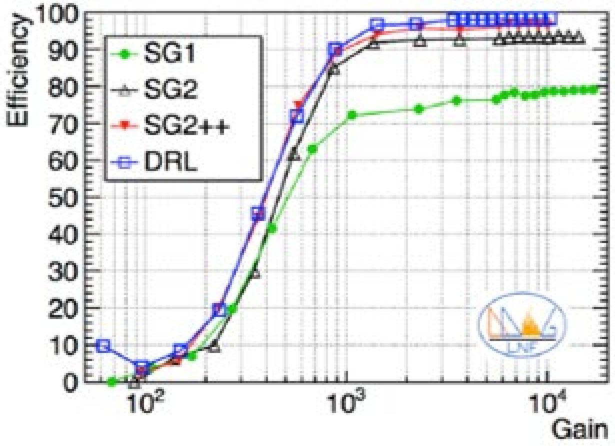
Gain up to ~ 10^4

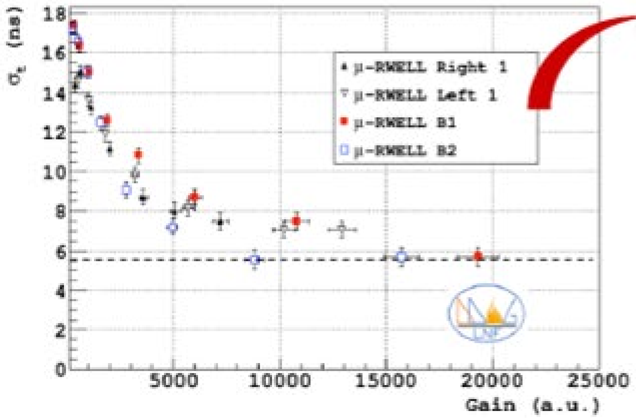


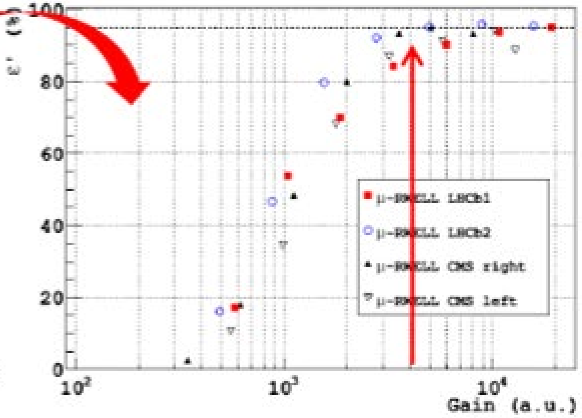
Rate capability (@ G = 5000) ~ 5-10 MHz/cm^2











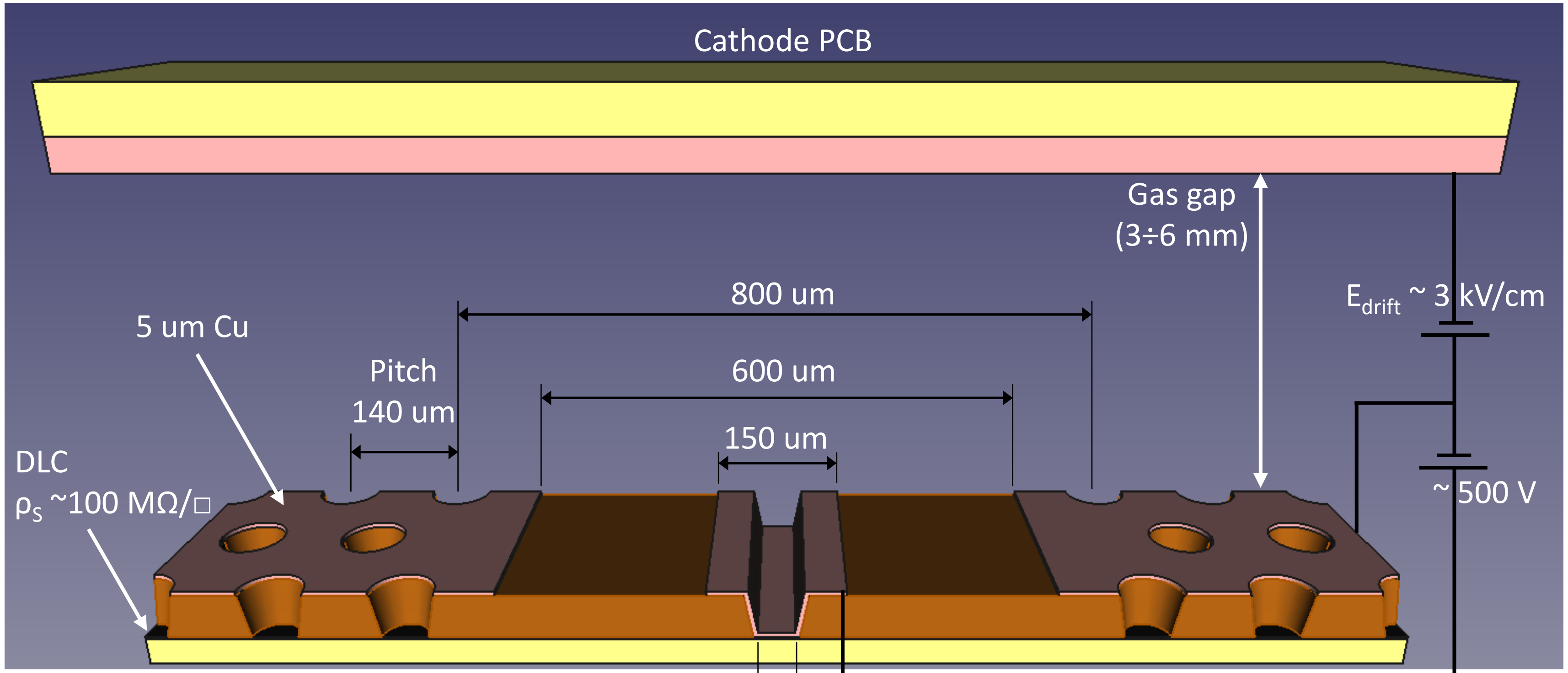
Efficiency ~ 98%

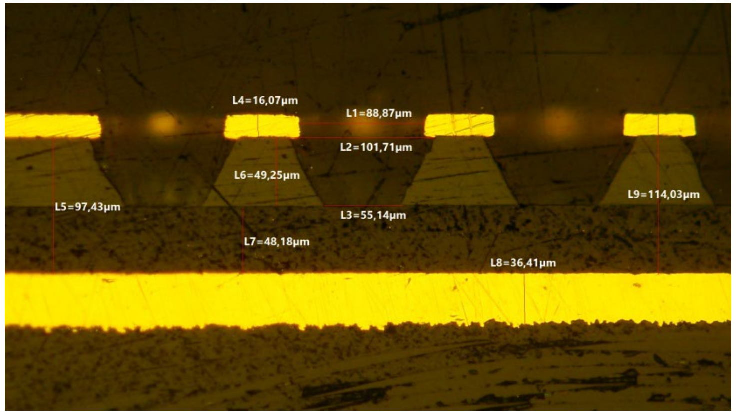
σ_t ~ 5-6 ns

Efficiency in 25 ns

2020 *JINST* **15** C09034

The µ-RWELL technology: the evolution





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%

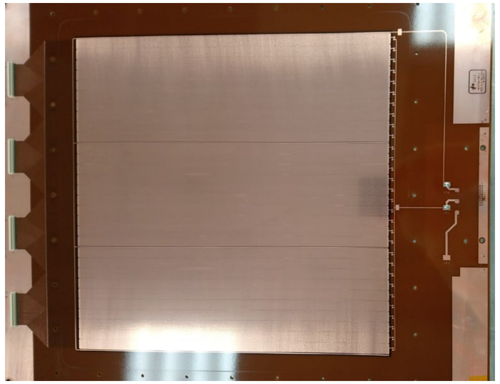
DOCA (Distance of Closest Approach): the minimum distance between a grounding line and an amplification channel.

PEP: **P**atterning – **E**tching – **P**lating

- Single DLC layer
- Grounding from top by Cu and kapton etching and plating
- No alignment problems
- Scalable to larger sizes

Present prototype: 30 x 30 cm^2

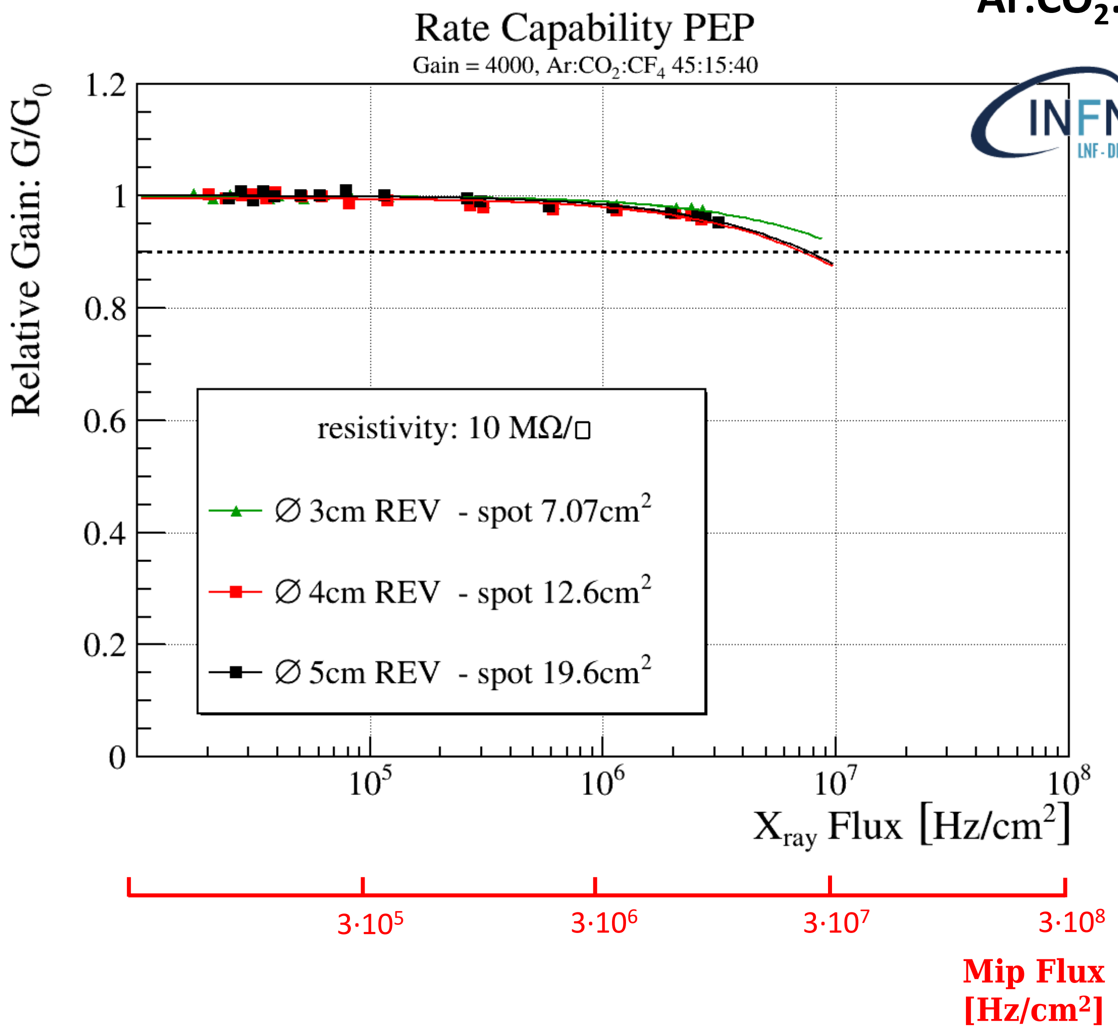
In construction 50 x 50 and 150 x 50 cm^2

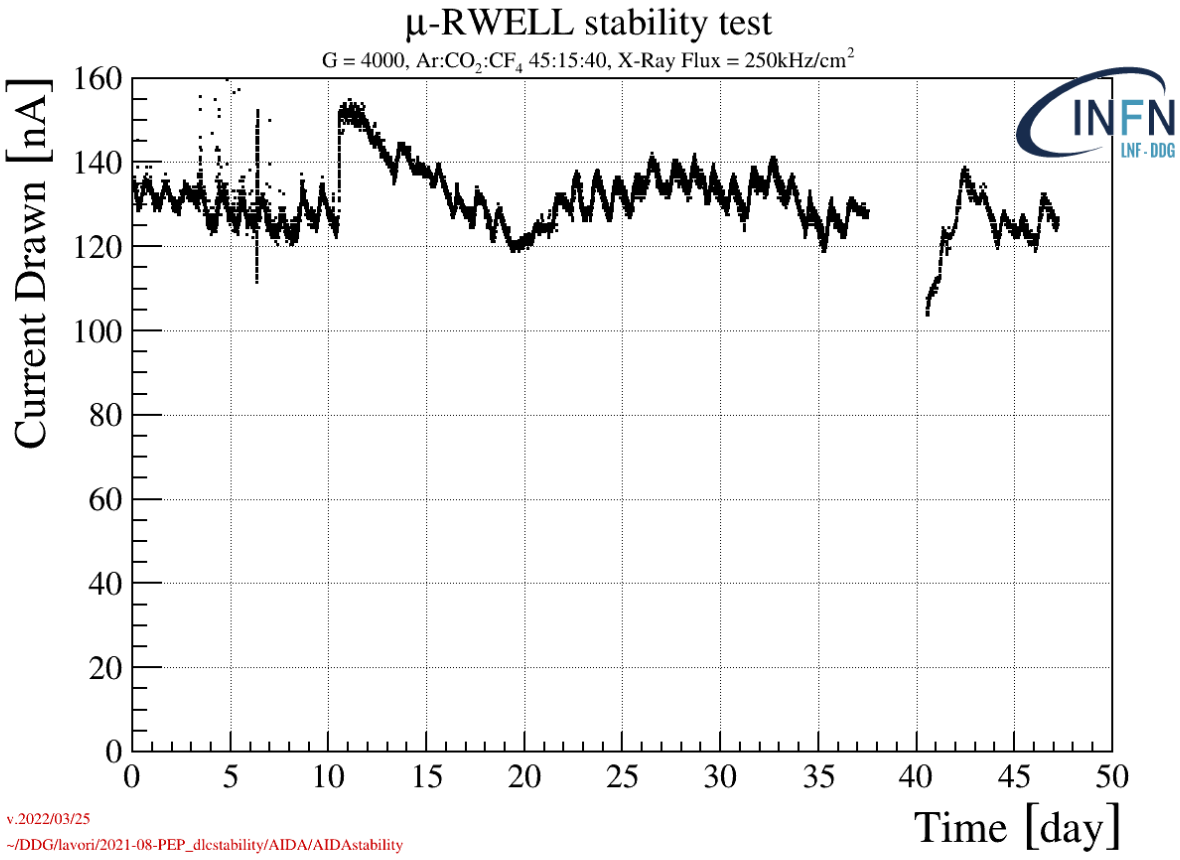


ACTIVE AREA
30 x 30 cm^2

The μ-RWELL technology: X- rays measurements

$Ar:CO_2:CF_4$ 45:15:40





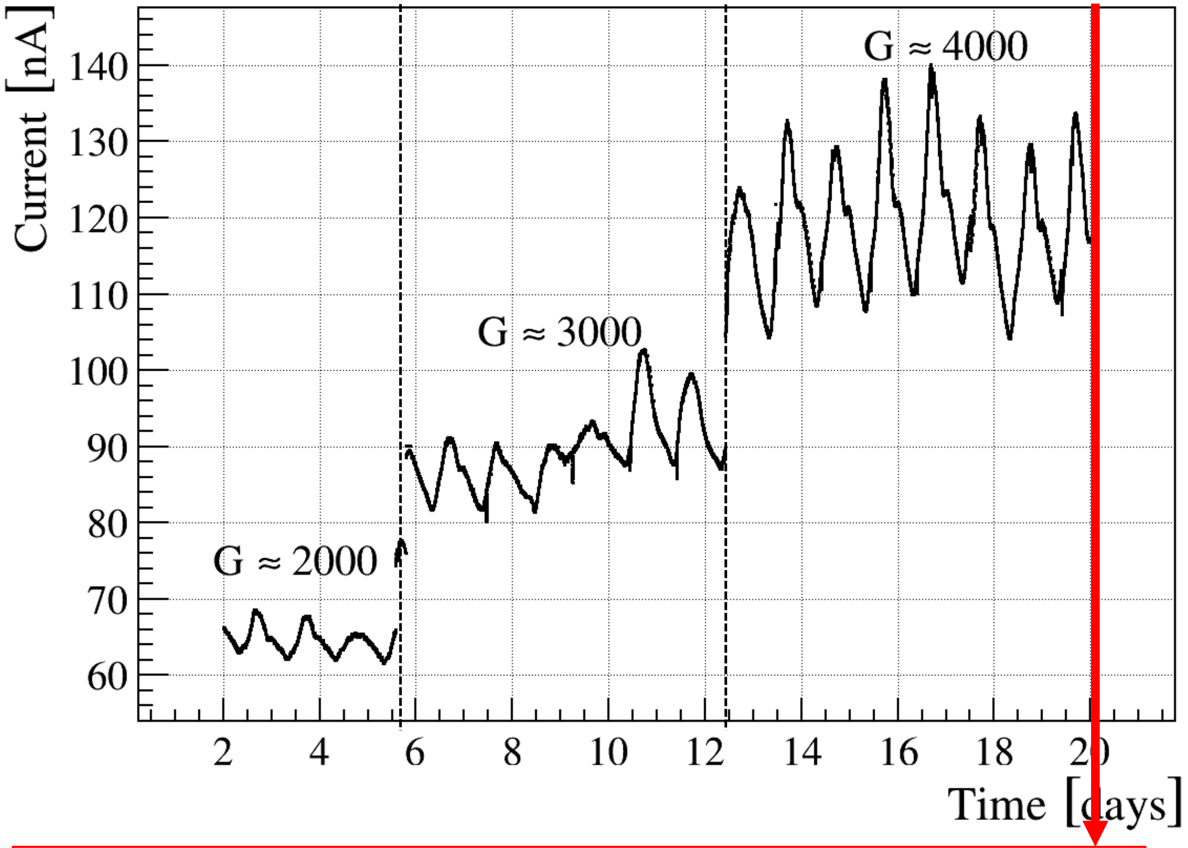
Because of the common effort in the scientific community to reduce the F-based components, we are changing our mixture to $Ar:CO_2:iC_4H_{10}$ 68:30:2 and starting the stability measurement

The μ-RWELL technology: X- rays measurements

Parallel acquisition of the T and P gas parameters to apply the corrections $e^{\frac{\beta T}{P}}$

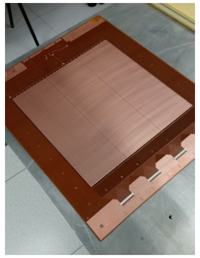
H_20 concentration down to 500÷600 ppm

$Ar:CO_2:iC_4H_{10}$ 68:30:2



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 μ-RWELL technology: TT



- 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!

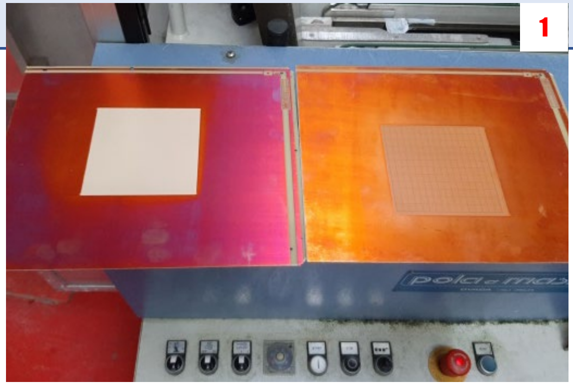
INFN LNF Istituto Nazionale di Fisica Nucleare

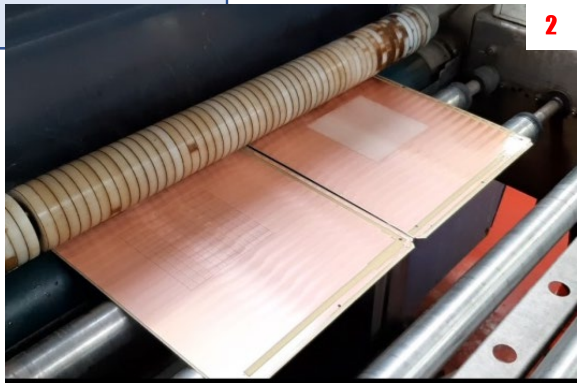
AIDA innova EU-project;

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

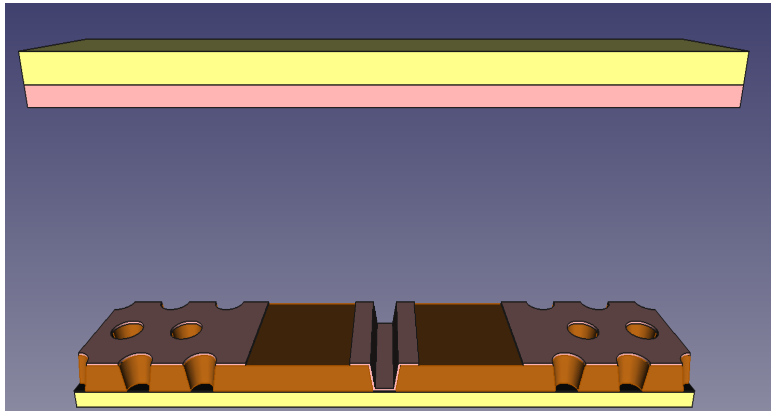
Detector manufacturing

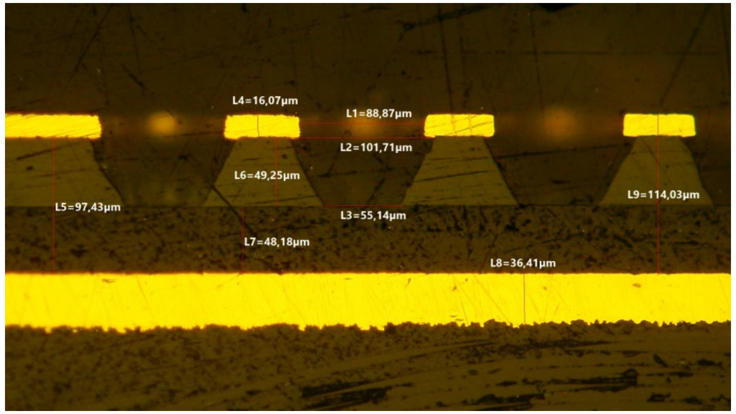
PCB shipping

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

Summary & outlook

- In view of Run 5-6 the LHCb collaboration demands detectors with **rate capability up to several MHz/cm²** and with good stability during operation
- We proposed this technology, **micro-Resistive WELL**, for the LHCb Run 5-6
- The most recent version of **the detector fulfills the requirement** on the rate capability; stability test is ongoing
- 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
- Stability tests (X-ray, gamma/neutron irradiation)
- 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 (R. Farinelli's talk "The u-RWELL technology at the IDEA detector", this session)
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
8. **Muon collider:** hadron calorimeter

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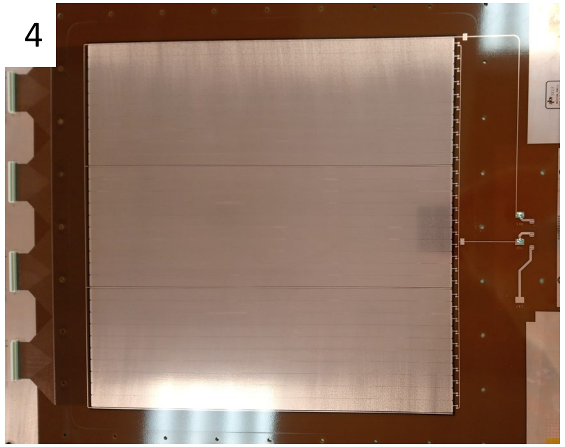

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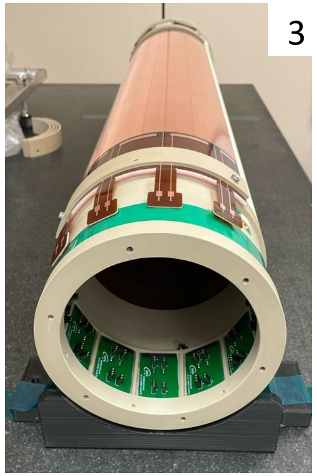

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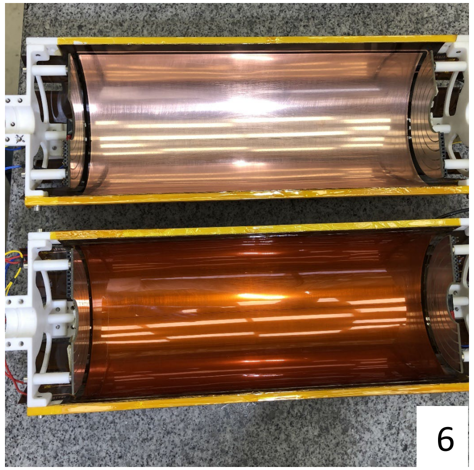

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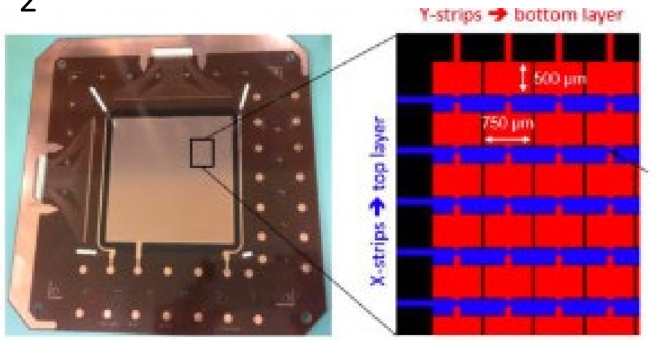

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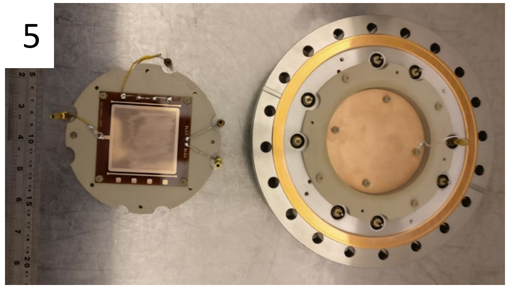

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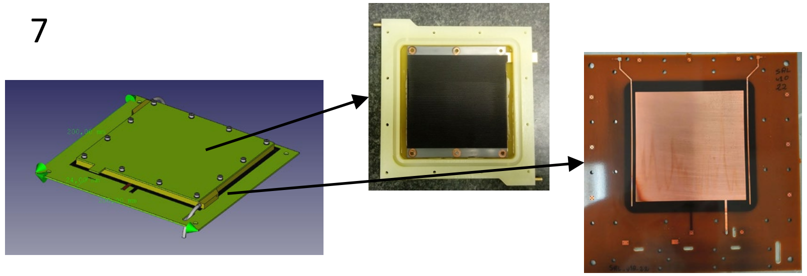
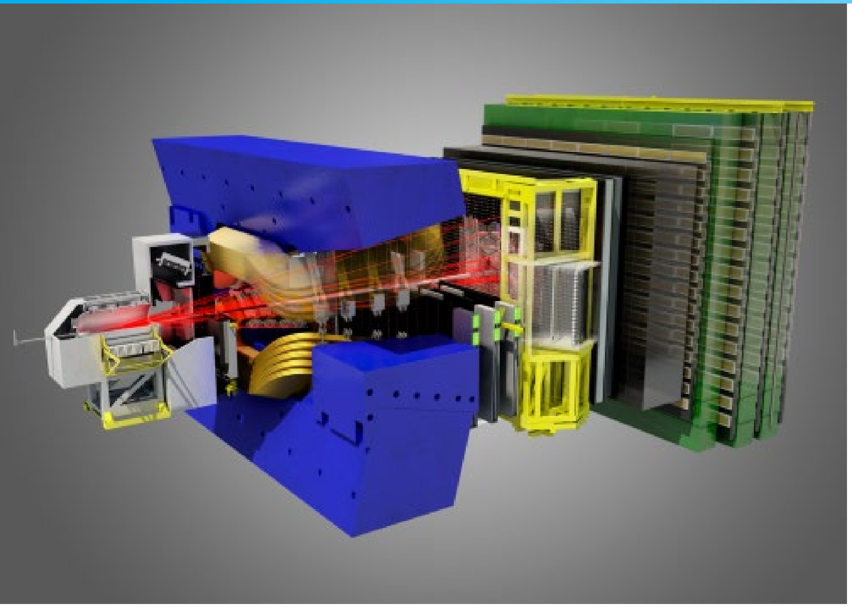


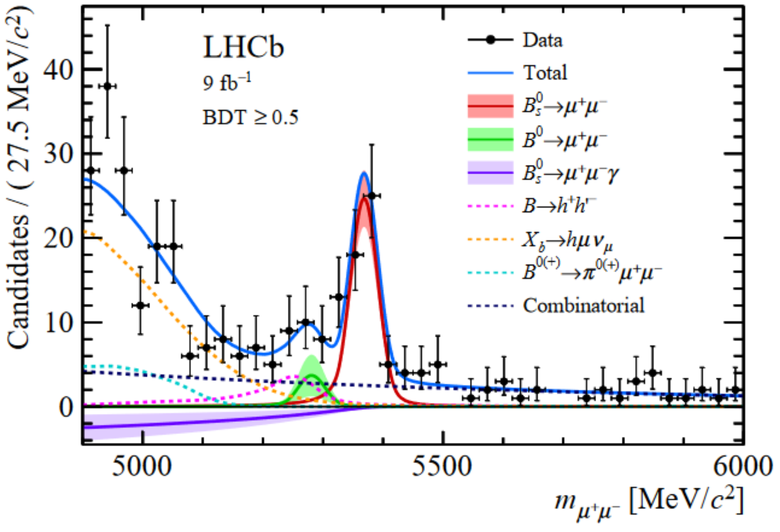
SPARE

LHCb experiment at CERN: (very) few highligths

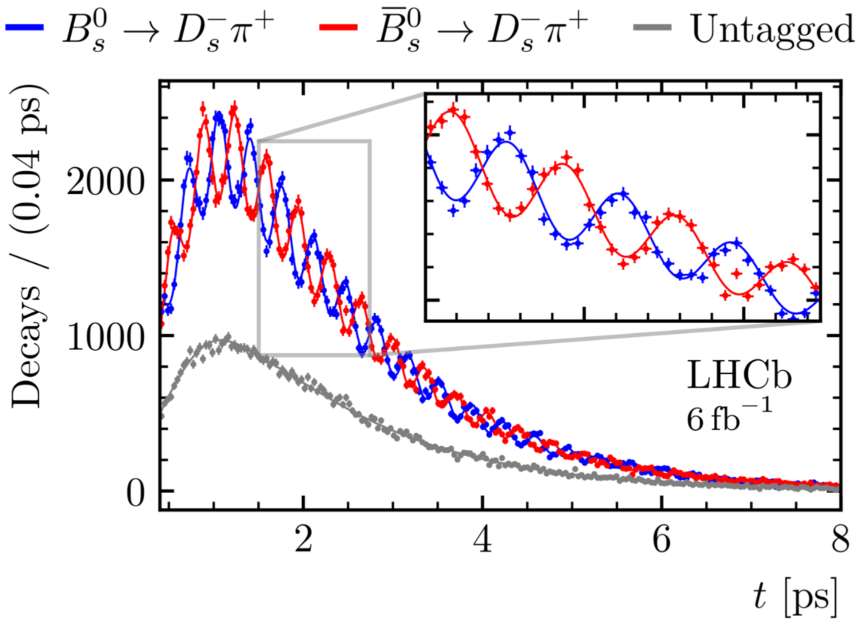


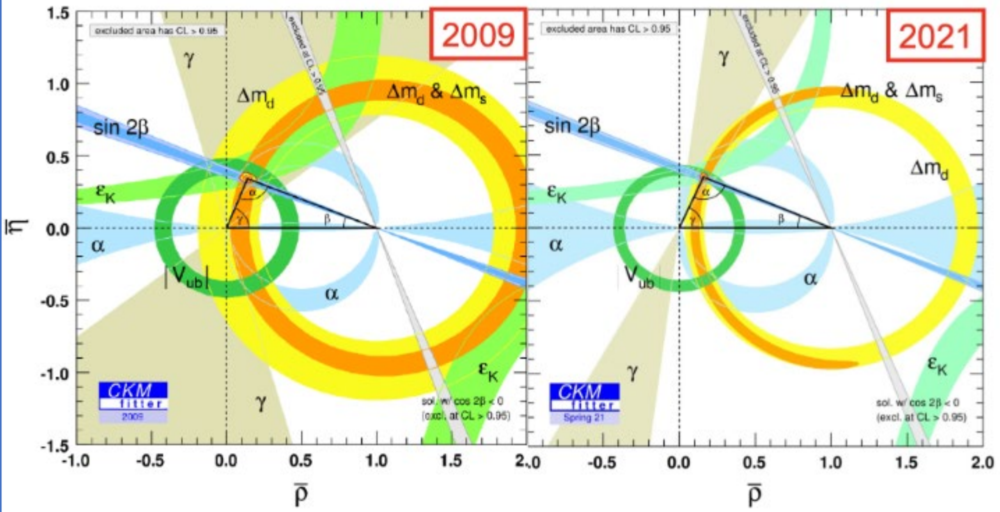
Excellent vertex/track reconstruction and PID

$B_s \to \mu\mu$ arxiv:2108.09284

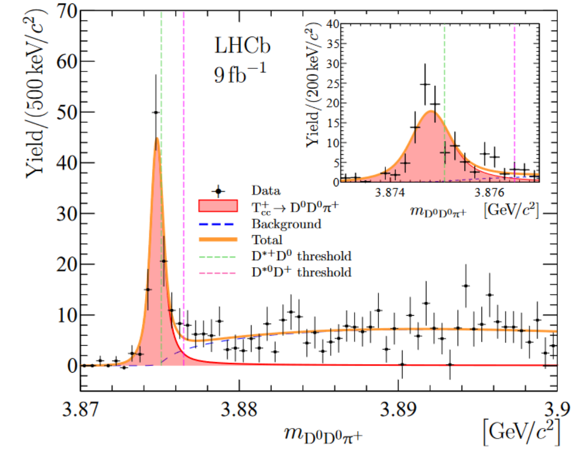


Δm_s arxiv:2104.04421

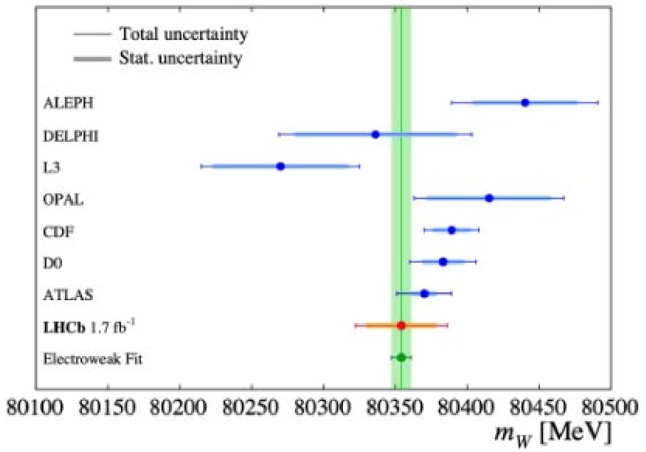




arxiv:2109.01038

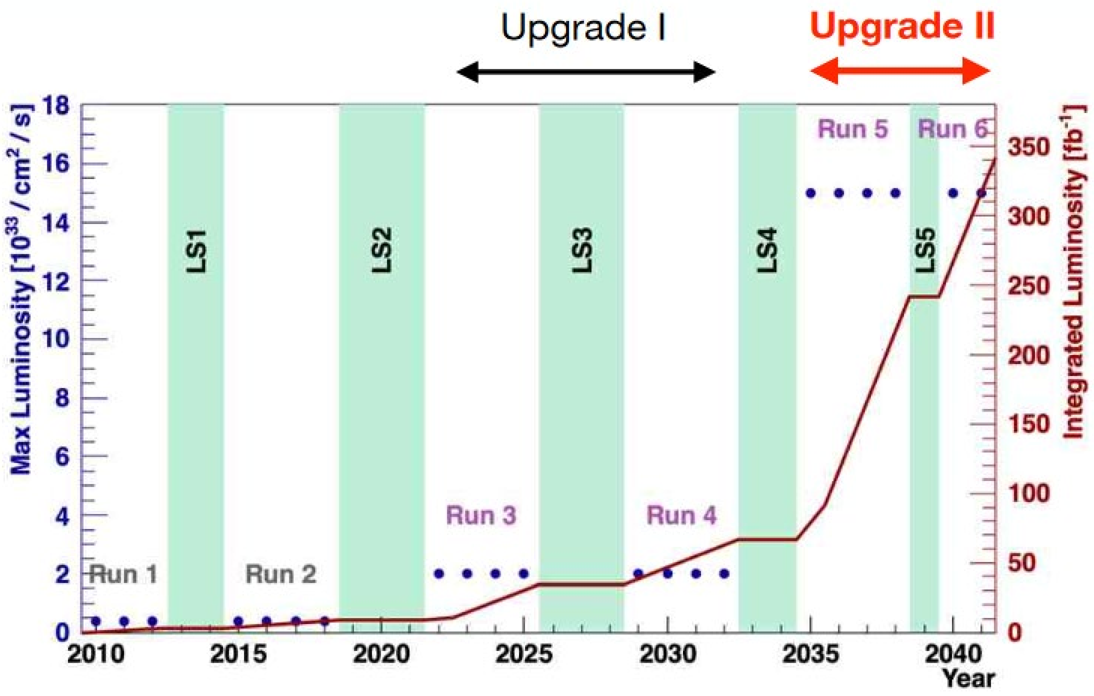


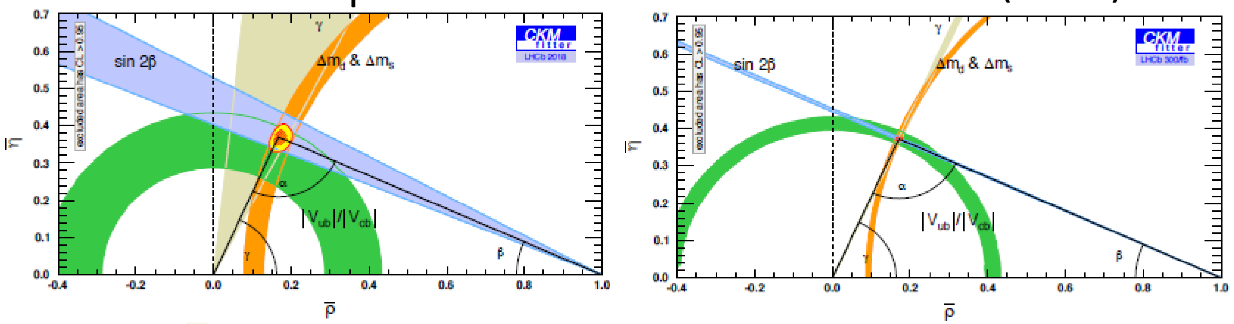
arxiv:2109.01113



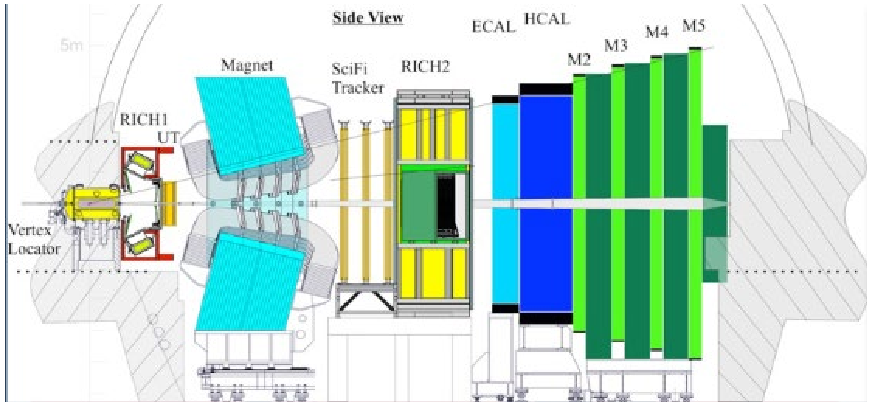
See also spare

The LHCb Upgrade II (Run 5-6)



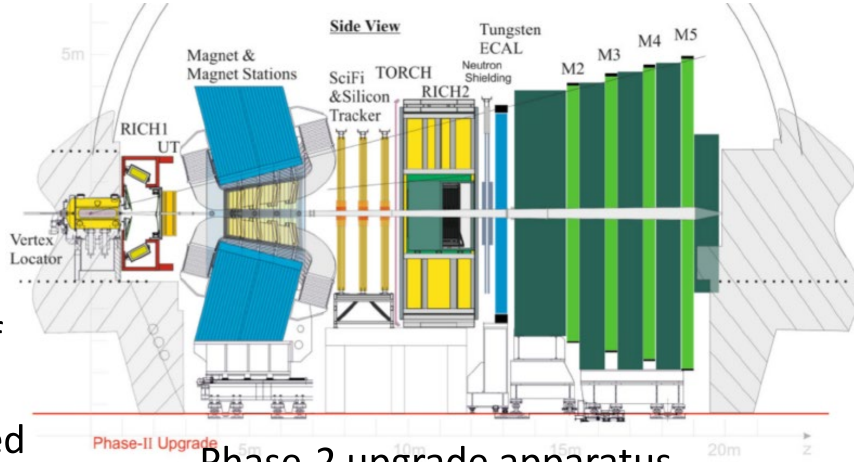


Huge improvement of LHCb constraints to the apex of the unitarity triangle



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

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.

[7] LHCb collaboration, R. Aaij *et al.*, *Observation of CP violation in two-body B_s^0-meson decays to charged pions and kaons*, JHEP **03** (2021) 075, arXiv:2012.05319.

[8] LHCb collaboration, R. Aaij *et al.*, *Updated measurement of time-dependent CP-violating observables in $B_s^0 \to J/\psi K^+K^-$ decays*, Eur. Phys. J. **C79** (2019) 706, Erratum ibid. **C80** (2020) 601, arXiv:1906.08356.

[9] LHCb collaboration, *Updated LHCb combination of the CKM angle γ*, LHCb-CONF-2020-003.

[10] LHCb collaboration, R. Aaij *et al.*, *Combination of LHCb results on the CKM angle γ and charm decays*, LHCb-PAPER-2021-033, in preparation.

[11] CMS and LHCb collaborations, V. Khachatryan *et al.*, *Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data*, Nature **522** (2015) 68, arXiv:1411.4413.

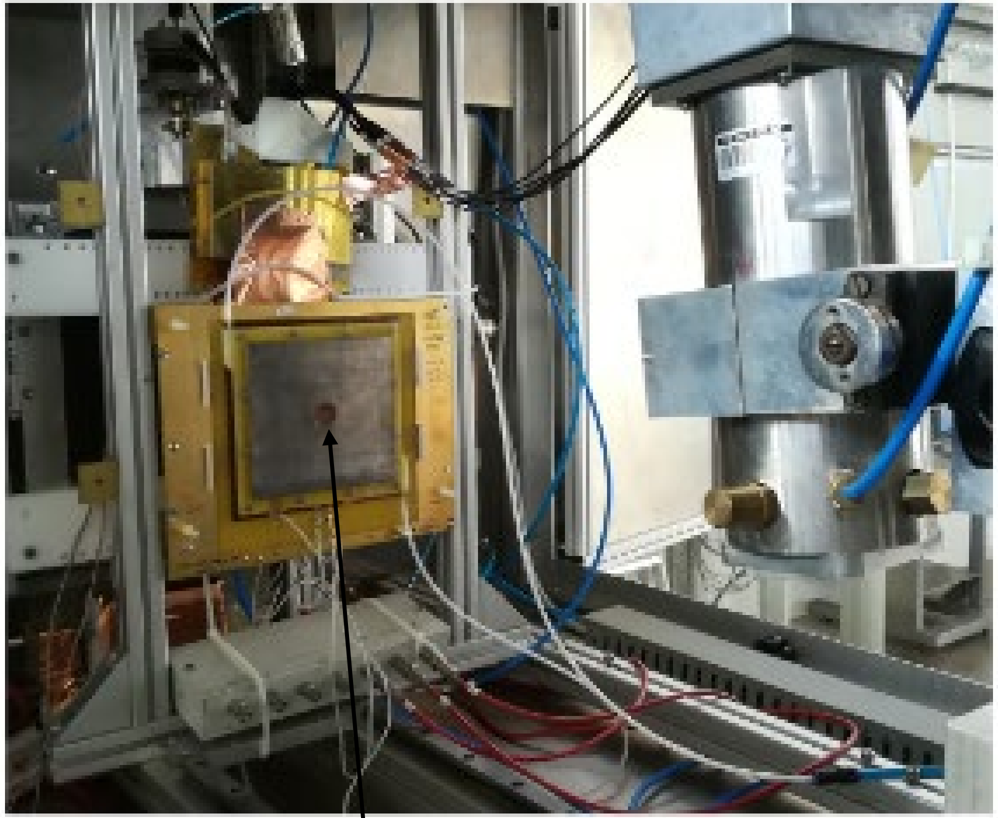
[12] LHCb collaboration, R. Aaij *et al.*, *Test of lepton universality in beauty-quark decays*, arXiv:2103.11769, submitted to Nature Physics.

[13] LHCb collaboration, R. Aaij *et al.*, *Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity*, JHEP **02** (2016) 104, arXiv:1512.04442.

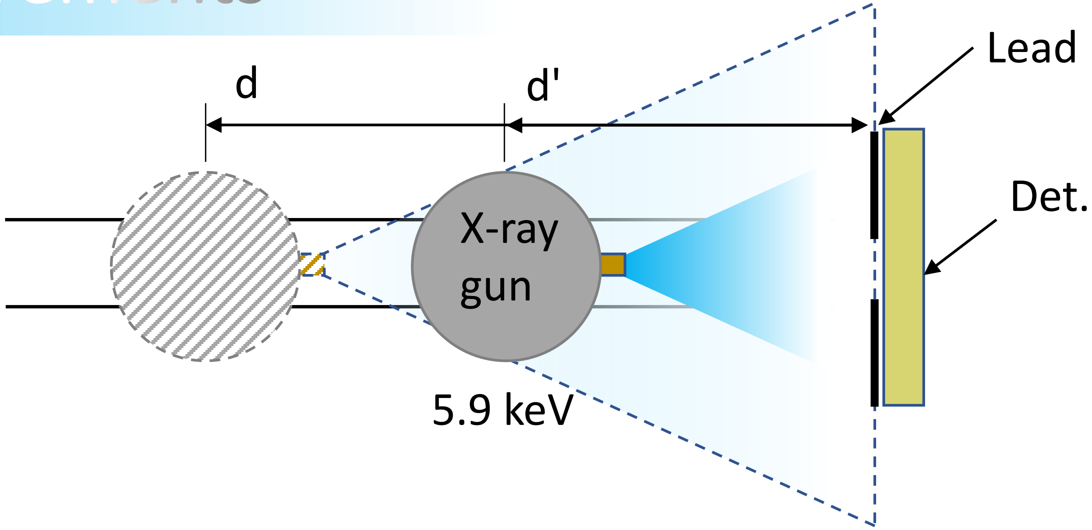
[14] LHCb collaboration, R. Aaij *et al.*, *Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$ decays*, Phys. Rev. Lett. **115** (2015) 072001, arXiv:1507.03414.

The μ-RWELL technology: X- rays measurements

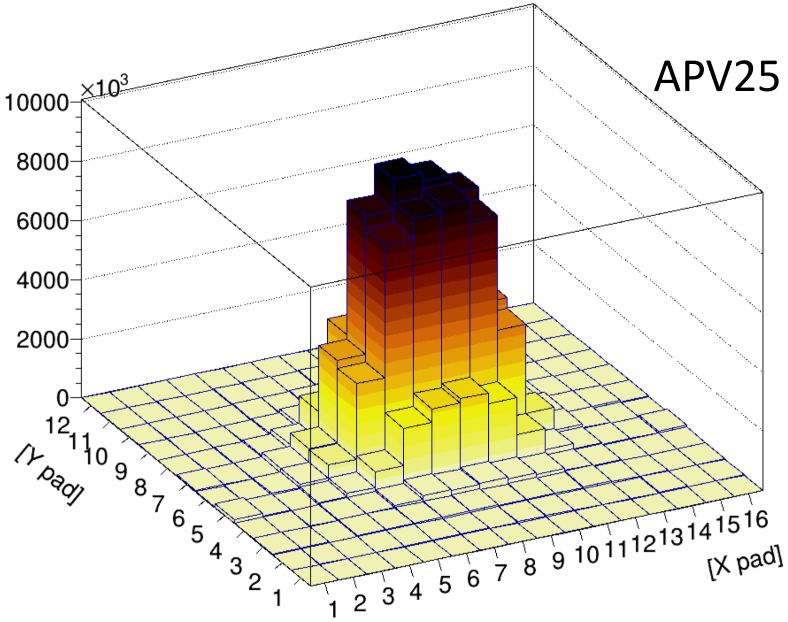
Setup



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)

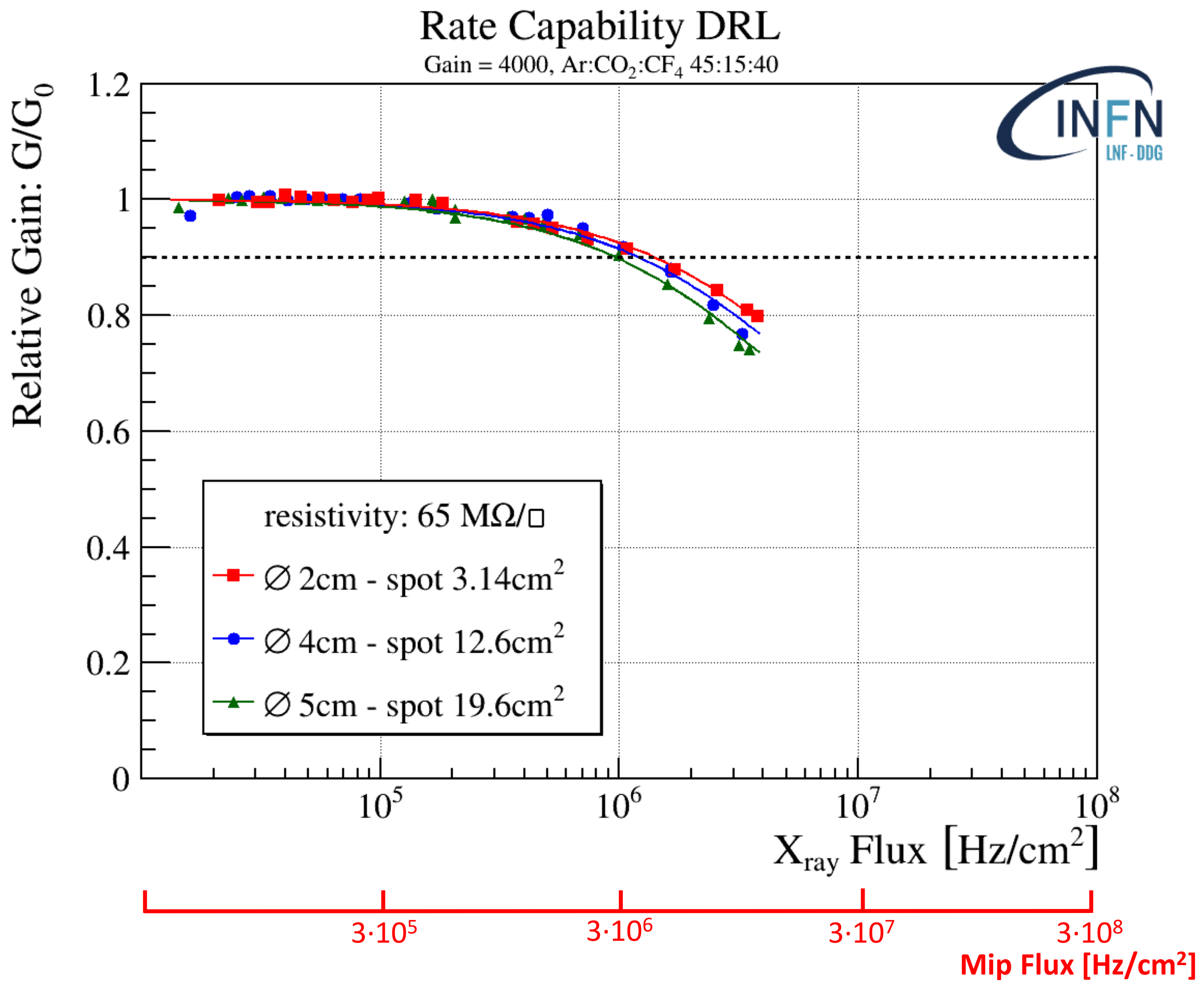


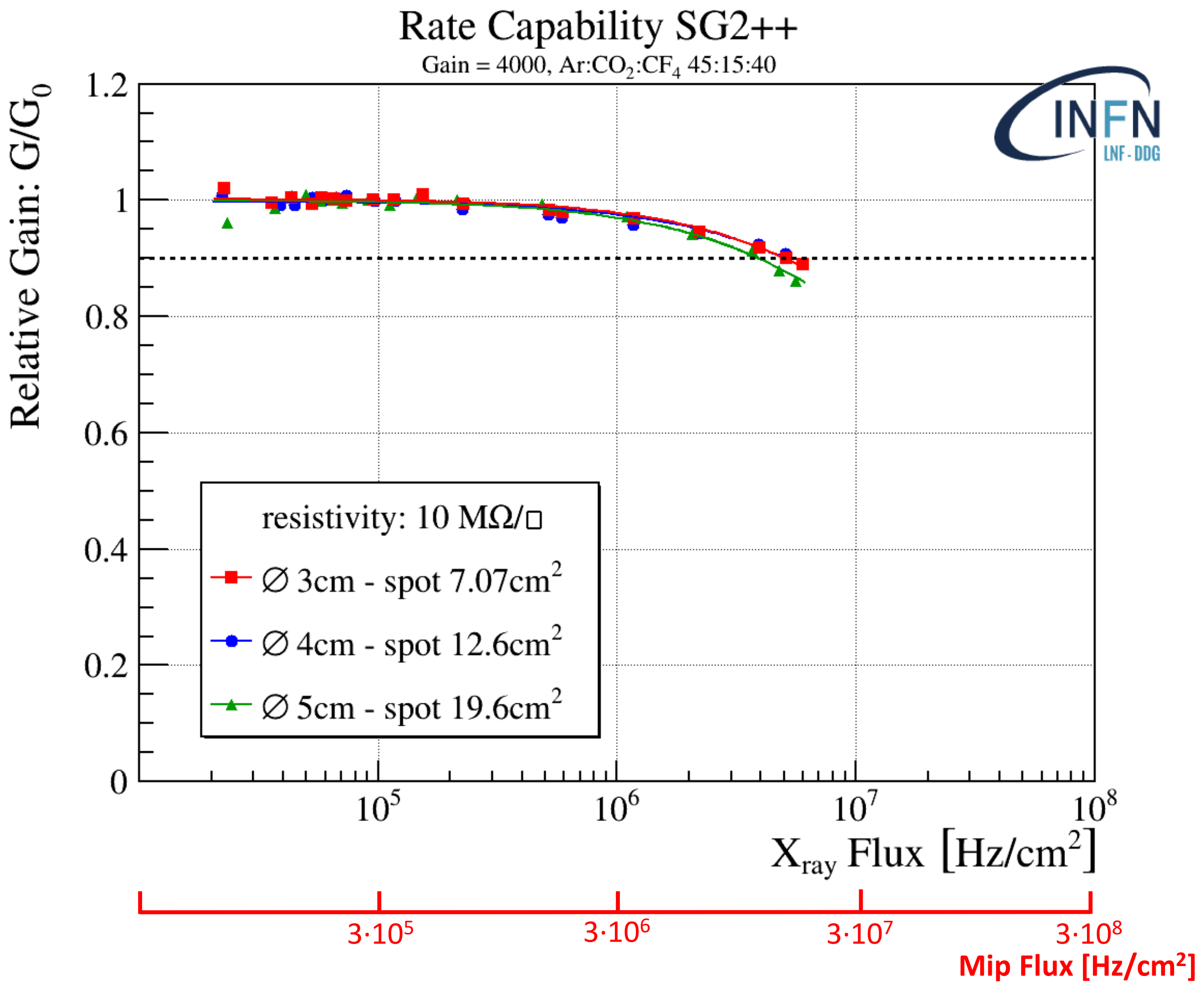
Gun installed on rail to **change the distance** from the detector → to **change the X-rays rate**



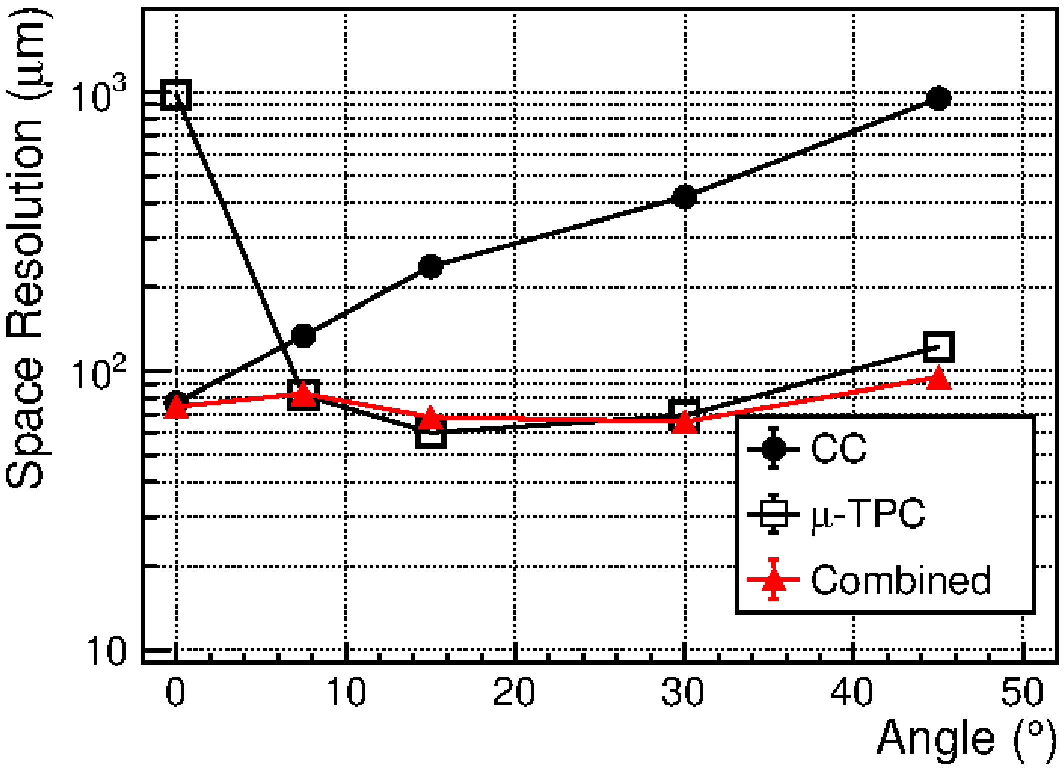
Spot nearly uniform on the irradiated area

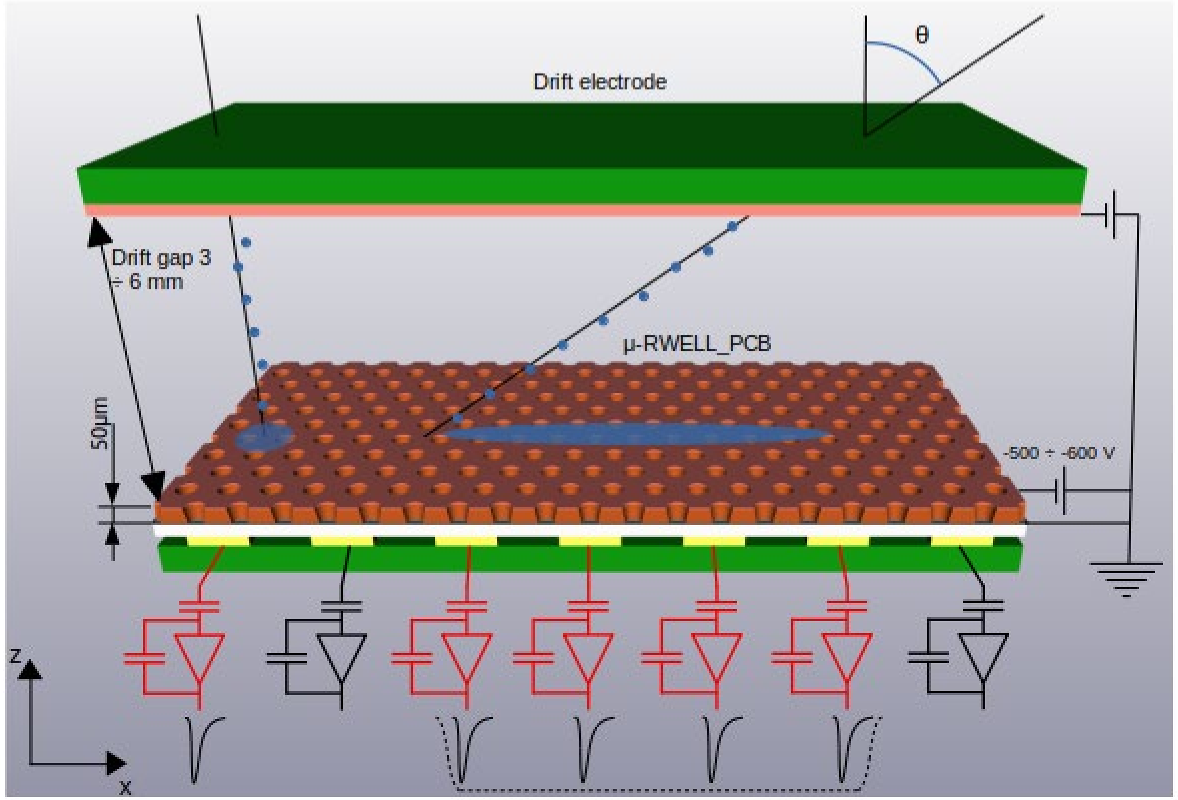
The µ-RWELL technology: X- rays measurements





The μ-RWELL techology: measurements





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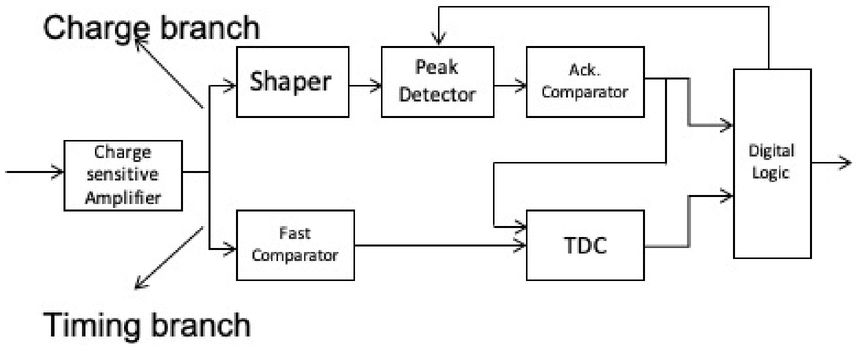
The µ-RWELL technology: the FEE for LHCb

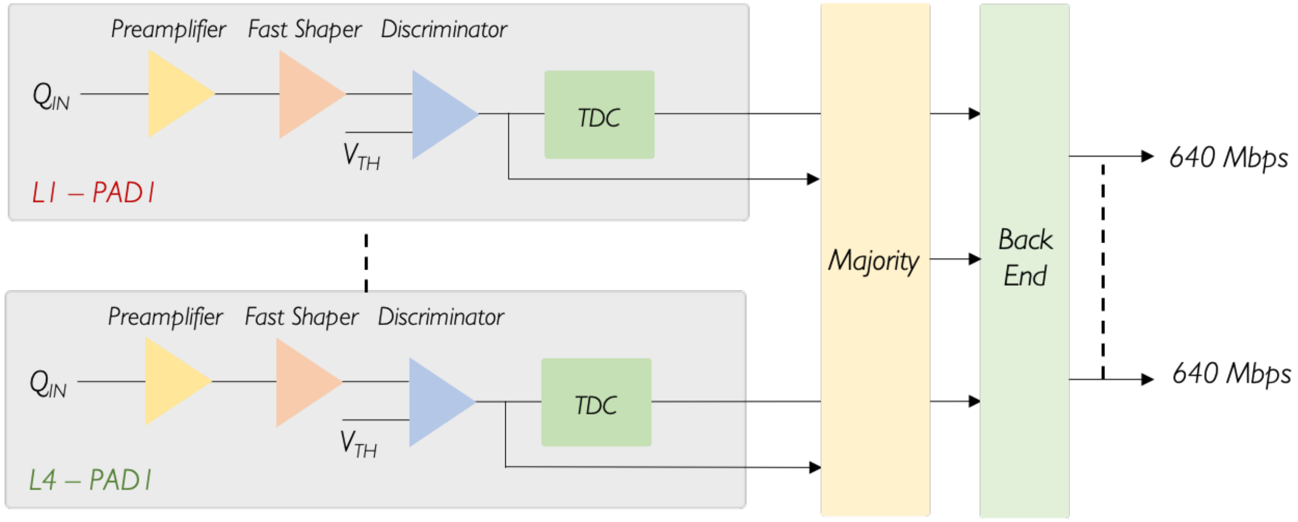
New ASIC design

- 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 can 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

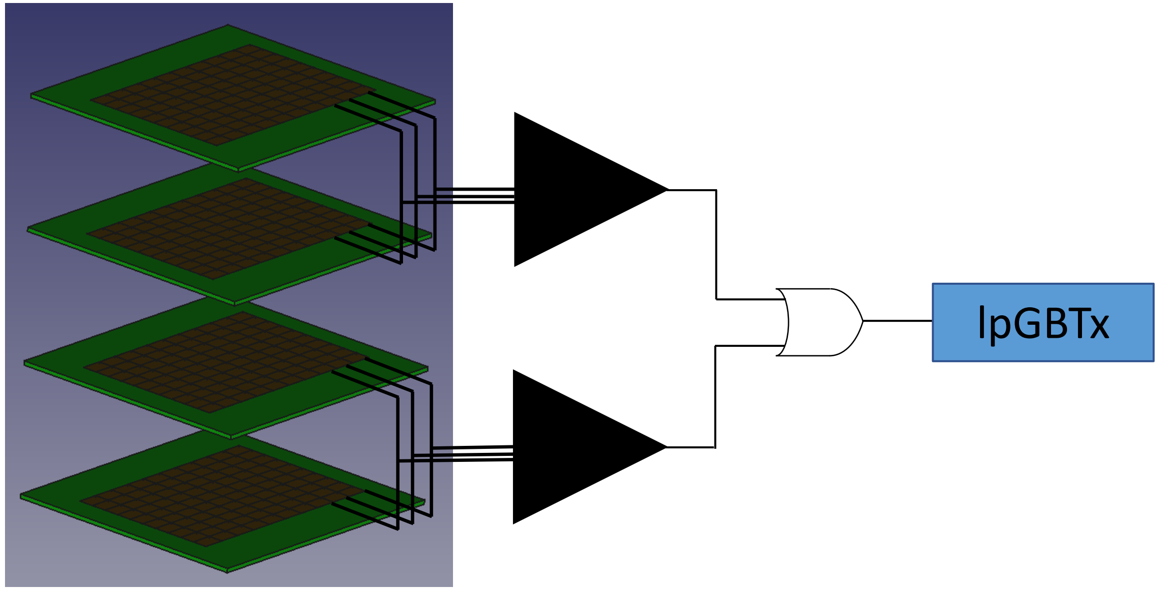


The μ-RWELL technology: the FEE for LHCb

Present readout electronics:

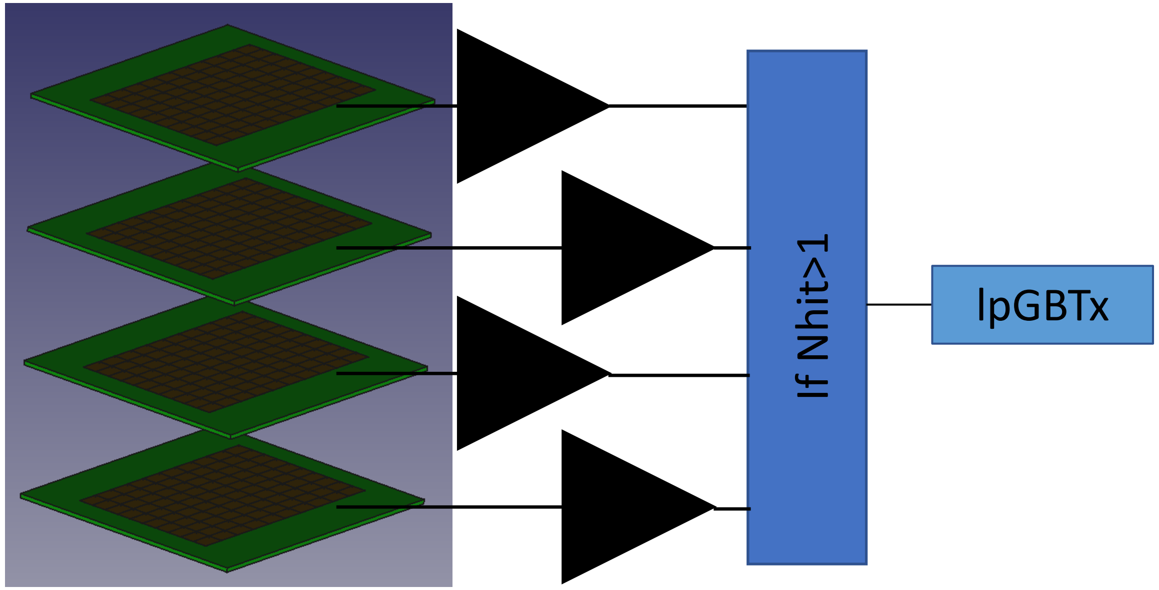
- The detector is made of **four gaps**
- **The corresponding pads** belonging to two different gaps are connected (**physical OR**)
- A **logical OR** of the two discriminated signal is then implemented

➡ 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

UKRI Science and Technology Facilities Council

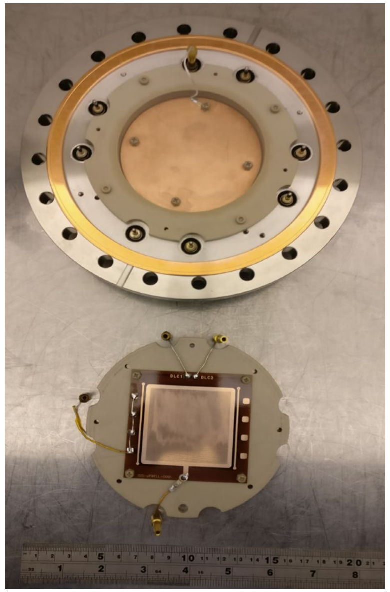
ISIS Neutron and Muon Source

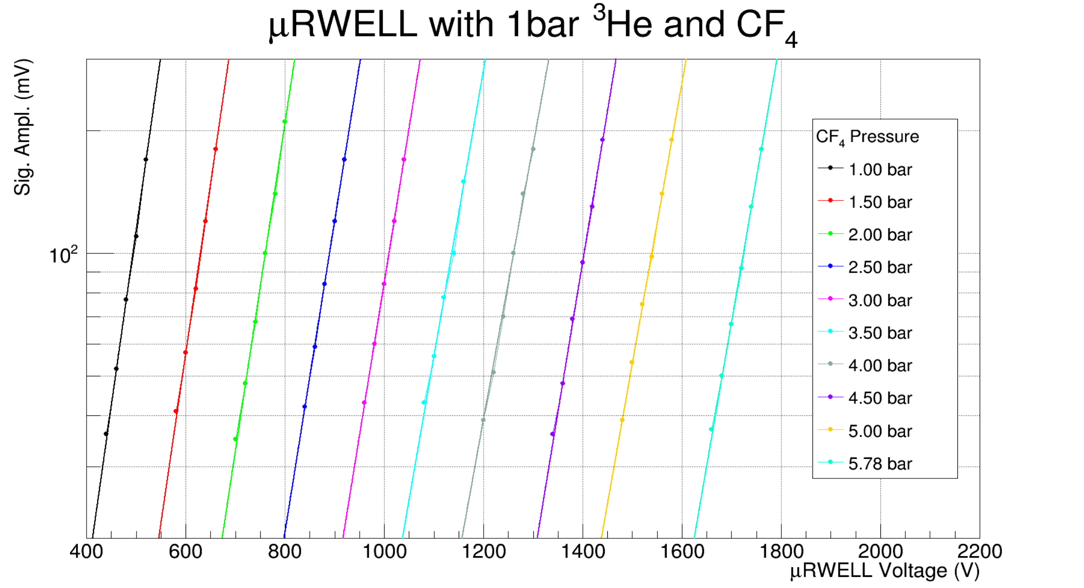
R. Hafeji
D. Raspino
E.M. Schooneveld
N.J. Rhodes

Setup

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

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



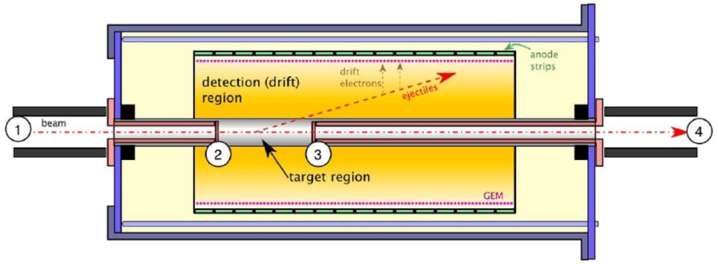


μ-RWELL for TACTIC

UNIVERSITY of York

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