Activity Report of the LNF Detector Development Group - DDG

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1 Introduction

The Detector Development Group (DDG) has a long-standing experience in the research, design and construction of both conventional gaseous detectors—such as Plastic Streamer Tubes, Glass Spark Counters and Large Drift Chambers—and Micro-Pattern Gaseous Detectors (MPGDs) for large-scale high-energy physics experiments. In particular, MPGD-related R&D activities, including GEM-based and novel detector architectures, have been carried out over the past two decades within the framework of the LHCb experiment at CERN. This effort initially led to the development of planar GEM detectors for the muon trigger system and was later extended to the design and construction of Cylindrical-GEM detectors for the Inner Tracker of the KLOE-2 experiment at DAΦNE (LNF).

Currently, DDG is primarily engaged in the R&D of the micro-Resistive WELL (μ-RWELL) detector for the Phase-II upgrade of the LHCb muon system, as well as in the development of detector technologies for the muon system of the IDEA apparatus at FCC_ee. In parallel, DDG remains actively involved in the joint CERN–INFN project aimed at exploiting the Magnetron Sputtering Machine for the deposition of functional materials on substrates relevant to detector fabrication.

The main results achieved in 2025 within the principal research lines are summarized below:

- μ-RWELL detectors for operation in high-rate environments (LHCb);
- μ-RWELL-based solutions for tracking applications (RD-FCC).

In addition, the DDG group is actively contributing to the development and characterization of detector concepts based on both μ-RWELL and surface Resistive Plate Counter (sRPC) technologies for neutron detection, with a focus on applications in the field of homeland security.

2 μ-RWELL for high rate environment - LHCb

The μ-RWELL technology [1] has been selected as a candidate solution for the realization of the innermost regions of the muon detection system in the Phase-II upgrade of the LHCb experiment at the High-Luminosity LHC (HL-LHC). The installation of the detectors is foreseen during the Long Shutdown 4 (LS4) of the LHC, with the start of data taking planned for Run 5, currently expected to begin in 2032.

The performance requirements set by the LHCb Collaboration for any technology proposed for the muon system are extremely demanding, particularly in terms of detection efficiency within

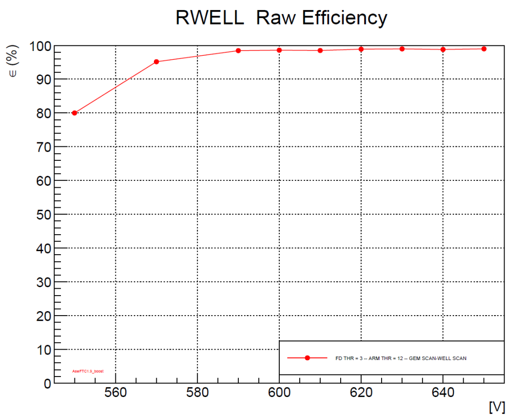

Figure 1: Efficiency for μ-RWELL layout as function of HV.

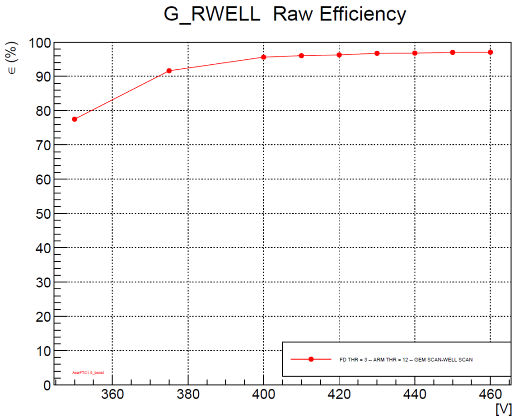

Figure 2: Efficiency for G-RWELL layout as function of HV.

the 25 ns bunch-crossing time window. Efficiencies well above 90% are required, together with a time resolution better than 5 ns. Following the definition of the grounding layout (PEP-DOT scheme), the DDG group focused on producing full-size M2R2 detectors (600×250 mm^2), upgrading the μ-RWELL design with a GEM pre-amplification stage (G-RWELL), and testing the third-generation front-end electronics FATIC3 developed by INFN-Ba.

Detectors of various sizes were tested at the CERN-PS T10 East Area with a 5 GeV secondary muon and pion beam and the FATIC3 electronics, ensuring fast response and compliance with stringent timing requirements.

Results show that both μ-RWELL and G-RWELL layouts deliver efficiency plateaus above 95% (Figs. 1, 2) and time resolutions around 5 ns (Figs. 3, 4), fully ensuring compliance with the 25 ns efficiency requirement above 90% (Figs. 5, 6). The results show that both layouts achieve the stringent LHCb requirements.

3 μ-RWELL for the muon system for FCC-ee - RD_FCC

The μ-RWELL technology is considered as a candidate solution for the muon detection system of the IDEA detector 2), proposed for the FCC-ee future lepton collider 3). The muon system is composed of a cylindrical barrel and two endcaps, ensuring full detector coverage, and includes multiple detection layers integrated within the iron yoke of the solenoidal magnet.

Simulation studies show that multiple scattering dominates the spatial accuracy of muons from Z^0 decays, leading to spatial resolution of a few millimeters at the first muon layer, while muons from long-lived particle decays inside the calorimeters exhibit significantly better precision, at the level of a few hundred microns. To achieve the required momentum reconstruction performance for long-lived particles, a spatial resolution of about 200 μm is needed.

To meet these requirements, a modular muon system based on μ-RWELL detectors has been adopted. Each detector tile has an active area of 50×50 cm^2 and a two-dimensional strip readout. Depending on the strip pitch, the achievable spatial resolution ranges from approximately 100 to

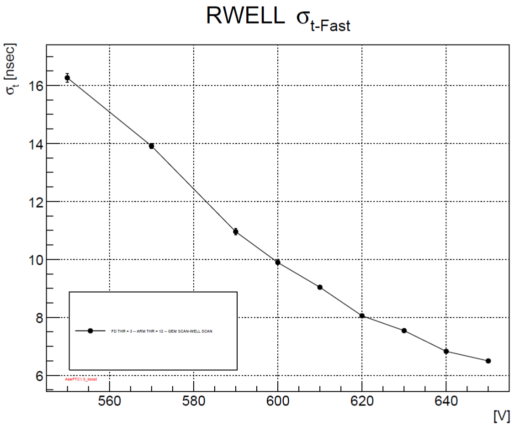

Figure 3: Time resolution of the μ-RWELL layout as function of the HV.

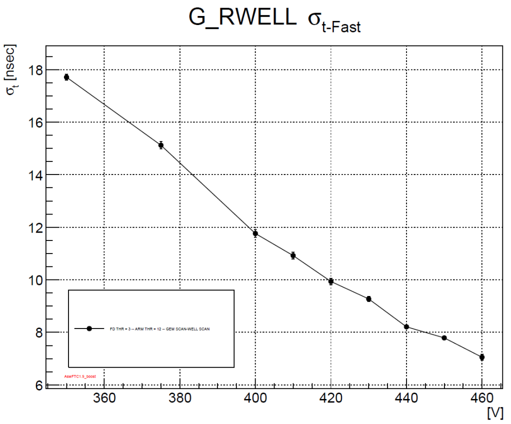

Figure 4: Time resolution of the G-RWELL layout as function of the HV.

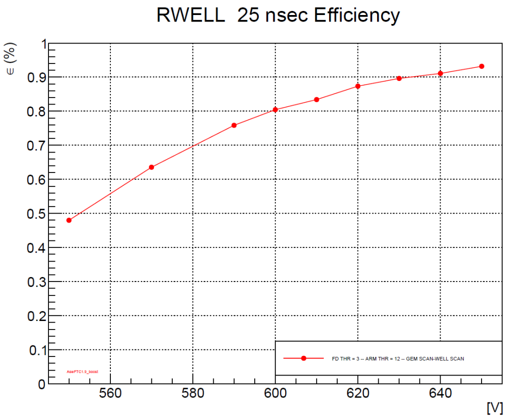

Figure 5: Efficiency in 25 ns for μ-RWELL layout as function of HV.

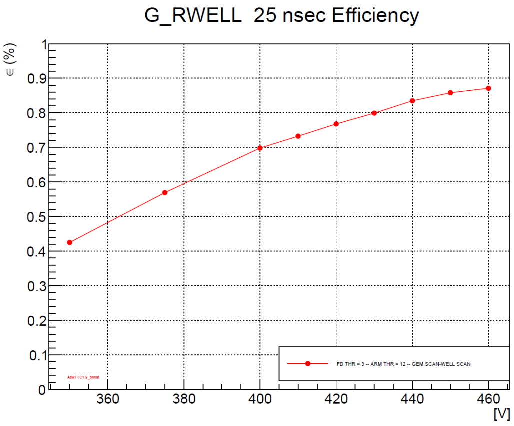

Figure 6: Efficiency in 25 ns for G-RWELL layout as function of HV.

500 μm, corresponding to several hundred to a few thousand readout channels per tile.
Since the µ-RWELL technology has not yet been employed in a full-scale detector, an extensive R&D program is ongoing to address integration aspects. This activity is carried out in synergy with the DRD1 collaboration 4), with particular focus on the development of dedicated front-end electronics based on a custom ASIC.

3.1 R&D on the detector

In the past years, the R&D activity has been devoted to several key studies aimed at consolidating the µ-RWELL technology for application in the muon system. In particular, the work concentrated on the optimization of the DLC resistivity and of the strip pitch, with the goal of reducing the overall number of readout channels while preserving the spatial resolution required for the muon detector. In parallel, significant effort was dedicated to the development of a two-dimensional readout layout ensuring efficient and stable detector operation.
Building on the results obtained in previous years, the R&D in 2025 was focused on optimizing several µ-RWELL layouts. The work aimed to find the optimal balance between spatial resolution, detection efficiency, operational stability, and the number of front-end electronics channels, which directly affects both system complexity and cost.
The layouts explored are summarised below and the performances are reported in Fig. 7 and 8:

- **2x1D chambers (X-Y):** Two µ-RWELL chambers, each segmented with 1D strips and rotated 90° to each other, provide 2D tracking by combining signals from the two detectors. Achieved a spatial resolution $\sigma = 150 - 200$ μm with efficiency plateau around 96% at $\Delta V_{\mathrm{WELL}} \approx 520$ V.

- **Capacitive Sharing (CS) layout:** Charge is distributed across multiple pad layers through capacitive coupling, reducing the number of readout channels while maintaining high spatial resolution. Similar residuals to the 1D+1D layout were reached, but the efficiency plateau required higher voltage ($\sim +100$ V) due to charge division.

- **TOP readout plane:** A single detector module with strips on top (WELL copper) and bottom (PCB) provides independent 2D charge collection. Resolution ~ 150 μm was achieved, but efficiency plateau is limited to $\sim 70\%$ due to inactive regions from the amplification stage segmentation.

- **µRGroove layout:** An evolution of the TOP design with GROOVE amplification channels, providing intrinsic 2D readout without geometrically dead regions. The bottom coordinate benefits from DLC charge spreading, yielding residual $\sigma \sim 85$ μm and efficiency plateau $\sim 96\%$ at 620 V. Some localized inefficiencies arose from discharges on the top electrodes.

From these studies, several important lessons have emerged. The 2x1D layout, while conceptually simple, requires precise alignment and matched gas gains for two independent modules, leading to higher production cost, increased material in the tracking volume, and compounded inefficiencies. The CS layout demonstrates that charge sharing can reduce the number of readout channels while maintaining high resolution, but it necessitates higher operating voltages. The TOP

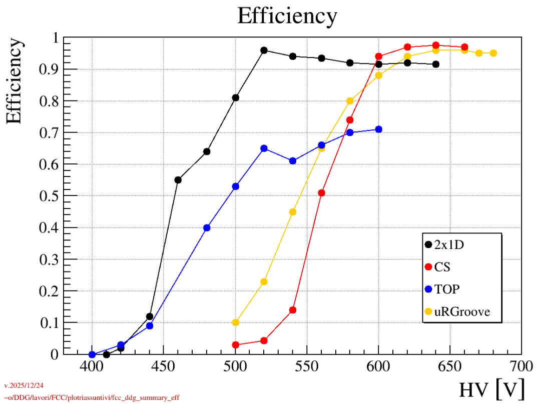

Figure 7: Efficiency curves for 2x1D, CS, TOP and μRGroove prototypes.

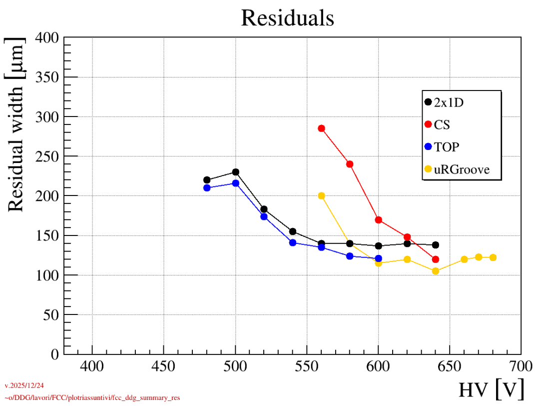

Figure 8: Residuals plots for 2x1D, CS, TOP and μRGroove prototypes.

layout shows that independent 2D readout in a single module is feasible, yet inactive regions limit efficiency and the top coordinate suffers from narrower charge distributions. Finally, the μRGroove design confirms that intrinsic 2D readout without dead regions is achievable, with improved resolution along the bottom coordinate, although the top coordinate still does not benefit from DLC charge spreading. Overall, these results provide clear guidance for selecting and optimising the next-generation μ-RWELL readout geometries.

4 ATHENA

Aside the field of micro-pattern gaseous detector, the DDG group is involved in the development of the surface Resistive Plate Counters (sRPC). Differently from classical RPC, where the bulk resistivity plays the main role of discharge quencher, sRPC exploits the resistivity of a Diamond-Like Carbon (DLC) thin layer. The main idea is to borrow the charge evacuation scheme from DLC-based high-rate-oriented detectors to obtain an RPC-like device for expositions up to 100 kHz/cm^2. Morevoer, thanks to the experience derived form the EU-funded URANIA/URANIAV projects, the group investigated the possibility to adapt sRPC technology to neutron detection with the introduction of a converter plane, specifically ^{10}B$_4$C. From previous tests conducted on micro-Resistive WELL detectors, which belong to the family of micro-pattern gaseous detectors, the introduction of a 2-3 μm of boron pushes the thermal neutron detection efficiency (capture + signal amplification) around 4%, exploiting the reactions:

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

The charged particles escaping the ^{10}B$_4$C layer enter the active volume of the detector, create electron avalanches and then induce signals on the properly segmented readout plane. The project has been developed in several stages, starting with the assembly of the detectors (fig. 9) and ending with a final test hosted at the iTRAP Laboratory of the Joint Research Centre in Ispra (VA) ; over

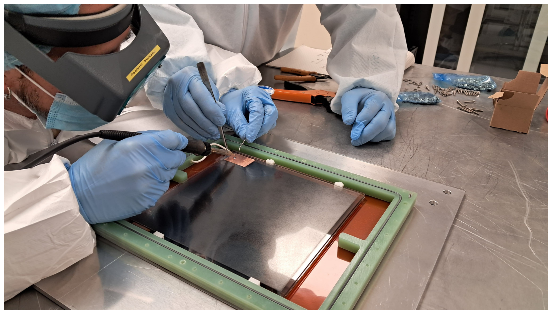

Figure 9: Construction of a boron-coated sRPC.

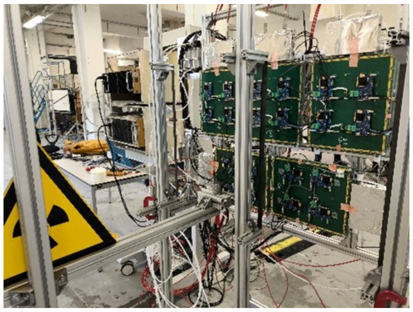

Figure 10: The matrix of sRPC for the test.

the two weeks from March 31, 2025, to April 11, 2025, the Non-Destructive Assay (NDA) team of the JRC, specifically Dr. A. Favalli and Dr. M. Looman, actively collaborated in the execution of the test. Their contributions included the following preparatory operations:

- Performing preliminary simulations of our detector systems irradiated with (1) a ^{252}Cf spontaneous fission neutron source and (2) with thermal neutrons
- Certifying the gas system used during the test for flushing the sRPC detectors
- Designing and building a mechanical support structure to accommodate multiple polyethylene (PE) layers
- Providing a setup system for both static and dynamic measurements, ensuring maximum reliability
- Handling all bureaucratic authorizations required for access to the JRC premises and the iTRAP facility

During the test, the JRC team further supported us by:

- Supplying various calibrated radioactive sources, including ^{252}Cf neutron sources, ^{137}Cs and ^{60}Co gamma sources, among others, for our measurements.
- Assisting with data acquisition and providing daily support to help us interpret the results obtained

This collaboration significantly contributed to the successful realization of the experimental test.

4.1 Data taking campaign

Five detectors, 20x20 cm^2 active area each, have been installed side-by-side (fig. 10) and equipped with dedicated front-end electronics, based on CREMAT-110 shaper. The matrix of devices has been then placed in front of the source. The runs should verify the counting capability of the detectors, in a given time gate, at different working points. The data-taking campaign can be divided into two main items: static and dynamic measurements.
Static measurements (source placed at 25 cm from ^{10}B$_4$C plane embedded into the detectors) (fig. 11) are here listed:

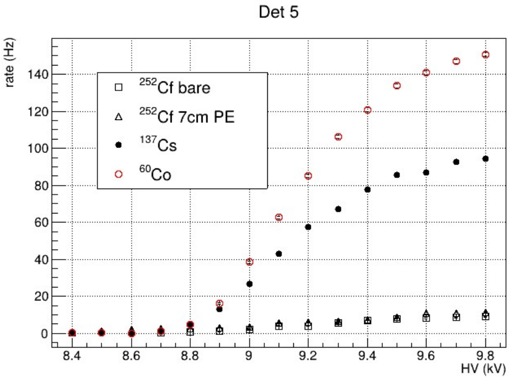

Figure 11: Counts measurements done with ^{252}Cf, ^{137}Cs and ^{60}Co.

- Background stability
- Gamma detection efficiency with ^{137}Cs and ^{60}Co gamma sources
- Neutron detection efficiency with a ^{252}Cf spontaneous fission neutron source:
  - with Pb shield to absorb gamma rays, and without polyethylene (PE) to minimize the neutron moderation
  - with Pb shield and various PE thickness

The dynamic measurements were focused to evaluate the neutron detection efficiency with ^{252}Cf source moving at a speed of 1.2 m/s on a rail at 25 cm from the neutron conversion plane and changing the thickness of PE. The measurements have been definitively fruitful to understand the two working points of the detector for which we have:

1. the plateau of the gamma efficiency
2. the maximum of the ratio neutron to gamma efficiency.

The dynamic measurements have been useful to understand present weak points of the technology to be improved and, once done, to undergo further tests at the iTRAP facility.

5 List of Conference Talks & Posters by DDG - LNF Authors in Year 2025

1. G. Bencivenni, ”Advancements in resistive MPGD: From μ-RWELL technology to high performance Hybrid Layouts”, VCI2025, Vienna, Feb. 17-21 2025
2. M. Giovannetti, ”Technology Transfer at ELTOS of high-rate µ -RWELL”, 4th DRD1 Coll. Meeting, CERN, Feb. 24-28, 2025
3. M. Poli Lener et al., ”The µ-RWELL technology for the IDEA Muon System”, Circular Electron-Positron Collider (CEPC) International Workshop, European Edition 2025, Barcelona, Spain, June 16-19 2025.
4. M. Giovannetti, ”G-RWELL update: detector construction & beam test results”, 117th LHCb week, Beijing, China, 22-26 Sept. 2025.

5. M. Giovannetti, "The G-RWELL technology for LHCb Muon Detector at HL-LHC", 6th DRD1 Collaboration Meeting, Warsav, Poland, Oct. 6-10 2025
6. M. Poli Lener et al., "The μ-RWELL technology for the IDEA Muon System", RD FCC collaboration meeting, 16-17 December 2025.

6 Publications

1. M. Giovannetti et al.,, The micro-RWELL for future HEP challenges and beyond, 8th International Conference on Micro Pattern Gaseous Detectors 2024 (MPGD2024), Hefei, China, JINST 20 (2025) C05002,
   (DOI: https://doi.org/10.1088/1748-0221/20/05/C05002)
2. M. Giovannetti et al., uRANIAV: resistive gaseous devices for thermal neutron detection, Position Sensitive Neutron Detector conference (PSND24), Oxford, UK, J. Phys.: Conf. Ser. 3130 (2025) 012011,
   (DOI: https://doi.org/10.1088/1742-6596/3130/1/012011)
3. E. Di Fiore et al., The μ-RWELL technology for the muon system at the IDEA experiment, 17th Vienna Conference on Instrumentation (2025), Vienna, Austria, NIM A 1082 (2026) 170960,
   (DOI: https://doi.org/10.1016/j.nima.2025.170960)
4. G. Bencivenni et al., Advancements in resistive MPGD: From μ-RWELL technology to high performance Hybrid Layouts, 17th Vienna Conference on Instrumentation (2025), Vienna, Austria, NIM A 1080 (2025) 170623,
   (DOI: https://doi.org/10.1016/j.nima.2025.170623)
5. E. Sidoretti et al., The Hybrid μ-RWELL for ePIC Endcap Tracking, 17th Vienna Conference on Instrumentation (2025), Vienna, Austria, NIM A 1080 (2025) 170622,
   (DOI: https://doi.org/10.1016/j.nima.2025.170622)
6. R. Farinelli et al., μ-RWELL muon system and pre-shower for FCC-ee, 8th International Conference on Micro Pattern Gaseous Detectors (2024), Hefei, China, JINST 20 (2025) C06064,
   (DOI: https://doi.org/10.1088/1748-0221/20/06/C06064)

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9. R. Cardarelli et al., *Performance of RPCs and diamond detectors using a new very fast low noise preamplifier*, 2013 JINST P01003.
10. G. Bencivenni, G. Morello, M. Poli Lener, *Brevetto Italia n.102020000002359, INFN (submitted the 10th Sept. 2019 - registered the 6th Feb. 2020) "Elettrodo piano a resistività superficiale modulabile e rivelatori basati su di esso.*
11. A. Valentini, RD51-NOTE-2020-006.
12. Kordas, et al., 15^th Vienna Conference on Instrumentation, Feb. 18-22, 2019.
13. S.A. Korff, Electron and Nuclear Counters, D. Van Nostrand Company -Inc, Fourth Avenue, New York, USA, 1955.
14. G. Bencivenni et al., *The micro-RWELL layouts for high particle rate*, 2019 JINST 14 P05014.