Activity Report of the LNF Detector Development Group - DDG

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1 Introduction

The Detector Development Group (DDG) has long been involved in the R&D, design and manufacture of classical gaseous detectors (Plastic Streamer Tube, Glass Spark Counters, Large Drift Chamber) and MPGDs for large high energy physics experiments. In particular the R&D activity on MPGDs (GEMs and innovative architectures) has been performed for the last twenty years in the framework of the LHCb experiment (CERN) with the development of the planar GEM detectors for the muon triggering and successively in the design and construction of the Cylindrical-GEM detectors for the Inner Tracker of the KLOE-2 experiment at DAFNE (LNF). At the moment the DDG is mainly involved in the R&D of the micro-Resistive WELL (μ-RWELL) detector for the phase-2 upgrade of the Muon system at LHCb and in the development of the detectors for the muon system of the IDEA apparaus at FCC_ee. Moreover DDG is always active in the project established bewteen CERN and INFN to expolit the Magnetron Sputtering Machine for the sputtering of materials on substrates useful for detector production. In the following the main achievements of the 2024 on the main research lines are reported:

- μ-RWELL for high rate environment (LHCb)
- μ-RWELL for tracking (RD-FCC)

2 μ-RWELL for high rate environment - LHCb

The μ-RWELL technology [1] is envisaged to realise the innermost regions of the muon detection system for the phase-II upgrade of the LHCb experiment at the High Luminosity LHC (HL-LHC). The detector will be installed during the Long Shutdown 4 of the LHC (LS4), and it will start data taking during Run 5, currently scheduled for 2032.
The requirements from LHCb collaboration to any technology proposed for the muon apparatus are very stingent in terms of detection efficiency in the 25 ns bunch-crossing time window, well above 90%, requiring a time resolution below 5 ns. After having established the layout of the grounding scheme (PEP-DOT), the activity of the DDG group has been developed on

- production of full-size detectors for the M2R1 station (300x250 mm2 active area)
- upgrade of the technology through the use of a GEM foil as pre-amplification stage
- test of the third version of the front-end electronics under development by INFN-Ba

Four prototypes for the M2R1 station have been realized and first tested under X-rays. In fig. 1 it is reported the detector gain as a function of the HV applied to the amplification stage. The four curves are there compared to the gain of a standard 10x10cm^2 prototype, exhibiting a very similar behaviour. At the same time, studies on the upgrade of the technology have been carried on, but a preamble is needed before. In a gaseous detector the time resolution depends on the capability of the device to detect the closest cluster to the amplification stage. For this reason it is recommended to use a highly-clusterizing gas mixture, in our case Ar:CO_2:CF_4 45:15:40. Moreover, to cope with avalanche fluctuations, the nominal operational gain should be chosen to be high, a configuration quite dangerous for a single-amplification stage detector. Following the work reported in [2)], we realized two 10x10 cm^2 μ-RWELL with a pre-amplification stage consisting of a GEM foil, from now on called GRWELL. Similarly to what happens in a triple-GEM [3)], the total gain can be then "distributed" between the two stages with the advantage to maintain each stage at safe voltage difference, obtaining anyway high gain factors, even above $2 \cdot 10^4$ as shown in fig. 2. All the detectors have been then tested at the CERN-PS T10 East Area, irradiated by a 5 GeV secondary beam, and equipped with a new version of the FATIC3 front-end electronics, developed by INFN-Ba with the purpose to guarantee a fast answer to fulfill the reqeust on the time resolution. The absolute detection efficiency is shown in figg. 3, 4, where an efficiency plateau above 95% has been achived; for one of the M2R1-like detectors a problem on some readout channels causes the efficiency leak visible on the black curve. For the GRWELL the low values of the gain have been extrapolated and this explains why the curves don't exactly overlap. The test beam campaign has been completed through the measurements of the time resolution. The classical version of the μ-RWELL (fig. 5) achieves a time resolution of 5 ns at very high gains. Is it very evident from the comparison between figures fig. 5 and 6 how a better time resolution can be achieved with the GRWELL even at gain lower than for a μ-RWELL. With this feature a plateau of efficiency in 25 ns, above 90%, is reached with both architectures, but it is quite clear from figg. 7 and 8 how the efficiency request is achieved in safer conditions for the GRWELL.

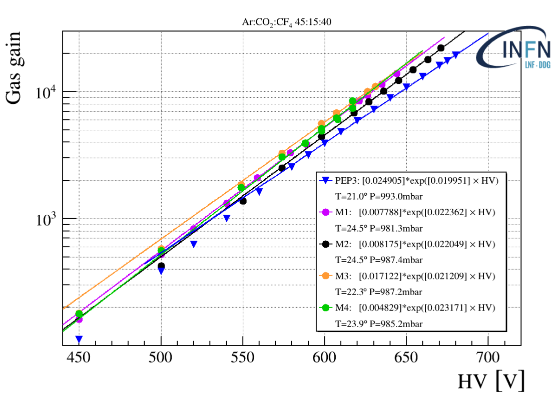


Figure 1: Gain of the four M2R1-like detectors (M1-4). A 10×10cm^2 detector (PEP3) has been added for comparison. The drift field is 3.5kV/cm.

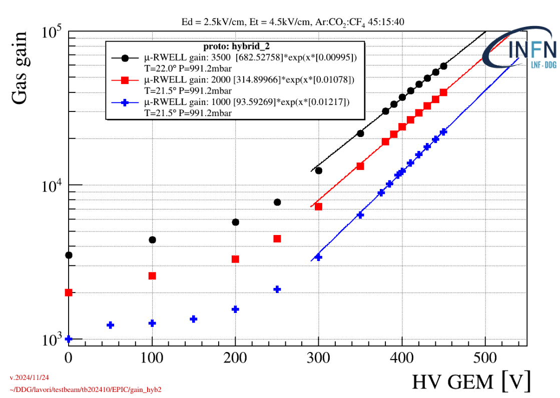


Figure 2: Gain of a G-RWELL detector, as a funcion of the GEM voltage, for different μ-RWELL gains.

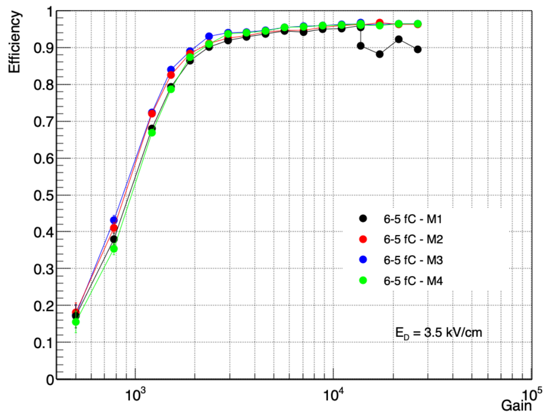


Figure 3: Efficiency for the M2R1-like μ-RWELL, as a funcion of the gas gain in fig. 1. The threshold used is 6fC, the plateau level of one of the detector suffers for some dead channels in the FEE (black curve).

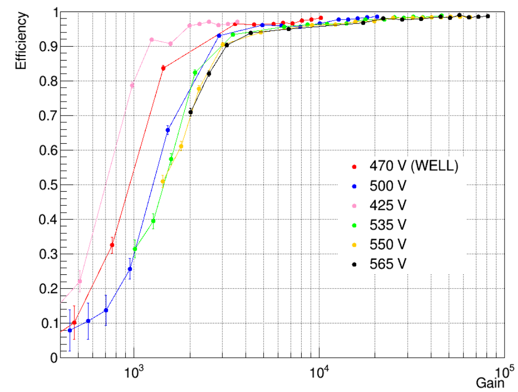


Figure 4: Efficiency for the G-RWELL, as a funcion of the gas gain in fig. 2, for different values of the μ-RWELL voltages. The threshold used is 6fC, the drift field is 3.5kV/cm, the transfer field is 4kV/cm. The 425V and 470V curves are shifted due to and extrapolation uncertainty at low gain of the μ-RWELL.

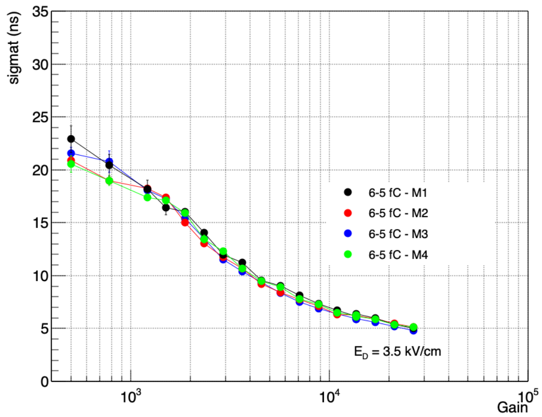


Figure 5: Time resolution of the M2R1-like μ-RWELL.

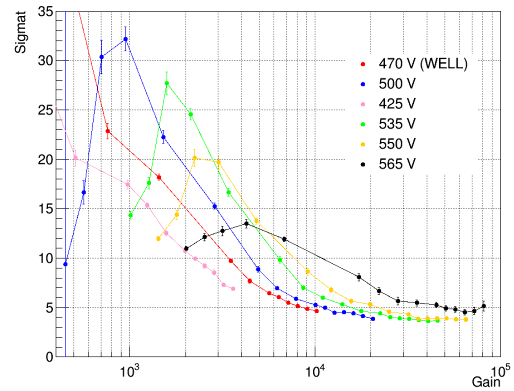


Figure 6: Time resolution of the G-RWELL for different values of the μ-RWELL voltages.

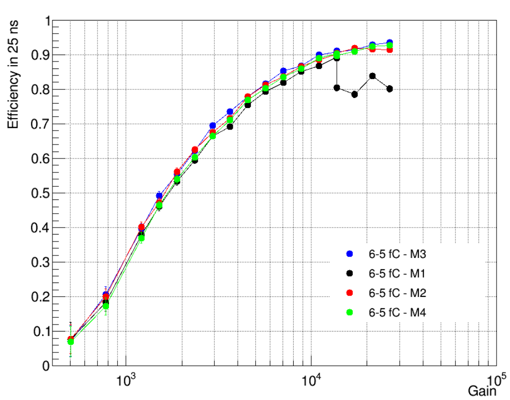


Figure 7: Efficiency in 25ns of the M2R1-like μ-RWELL. The plateau level of one of the detector suffers for some dead channels in the FEE (black curve).

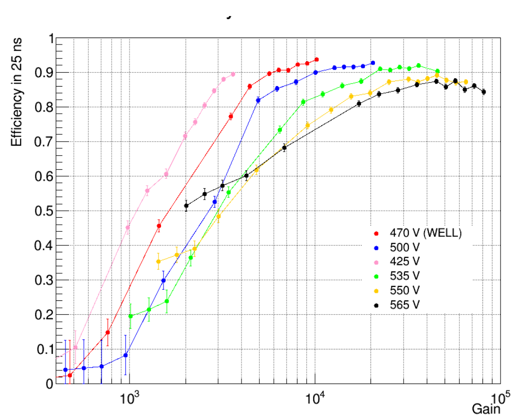


Figure 8: Efficiency in 25ns of the G-RWELL for different values of the μ-RWELL voltages.

3 µ-RWELL for tracking - FCC-ee

The µ-RWELL is proposed as active sensor for the muon detection system of the IDEA detector concept [4] designed for the FCC-ee [5] future large circular leptonic colliders.
The Muon detection system is composed by a central cylindrical barrel region closed at both ends by two endcaps to ensure hermeticity (Fig. 9 and 10). This apparatus will consist of three or more layers of detectors covering the barrel and endcap regions, housed within the iron yoke that encloses the solenoidal magnetic field. Preliminary simulation studies indicate that the multiple scattering of muons originating from Z^0 decays introduces a loss of positional accuracy of a few millimeters upon reaching the first muon detection layer. Conversely, muons decaying from long-lived particles within the calorimeter apparatus exhibit a significantly smaller loss of accuracy, of the order of hundreds of microns, at the first detection layer. In addition to the effects of multiple scattering, momentum measurement performance is also considered. A spatial resolution of a hundred microns is required to achieve the precision necessary for accurate momentum reconstruction of long-lived particles.
To fulfill the required spatial resolution, the muon apparatus will be equipped by µ-RWELL detectors. To take advantage of the industrial production capabilities of this technology, a modular design has been adopted for the muon detection layers. Each basic µ-RWELL tile features an active area of 50×50 cm^2 with a two dimensional strip readout. A strip pitch of approximately 0.4÷1.5 mm provides a typical spatial resolution in the range of 100÷500 μm, which corresponds in 2,500÷640 readout channels per tile.
The choice of detector tile size, strip pitch, and strip width represents a compromise among several factors: the largest µ-RWELL detector that can be industrially mass-produced, the maximum input detector capacitance tolerable by the Front-End Electronics (FEE) to maintain an adequate signal-to-noise ratio, the spatial resolution required by the IDEA experiment, and the costs of electronics for the readout channels, which need to remain within reasonable budget constraints.
Since the µ-RWELL technology has not yet been used to realize a full detector system, a rigorous R&D program will be undertaken in the coming years to address integration issues. R&D on the µ-RWELL is performed in synergy with Working Package 1 (WP1) of the Detector R&D Collaboration for Gaseous Detectors (DRD1) [6]. Another key aspect of the R&D program will be the design and development of a dedicated FEE based on a custom-made ASIC.

3.1 Layouts description and results

The R&D program has focused on two main objectives: optimizing the DLC resistivity and strip pitch to minimize the number of electronic channels while achieving the required spatial resolution for the muon apparatus; and developing a 2-D layout capable of efficient and stable operation. The study on DLC resistivity demonstrated stable and consistent performance within the resistivity range of 40÷80 M$\Omega/\square$. This finding relaxes any strict homogeneity requirement for DLC resistivity over a large-area µ-RWELL and enhances the reliability of performance uniformity across such an area. At lower DLC resistivity ($\leq 10\,\mathrm{M}\Omega/\square$), the efficiency plateau is reached at higher HV due to a slightly increased charge spread and threshold-related effects.
The study on strip pitch from 0.4 to 1.6 mm shows that as the pitch increases, the collected signal charge decreases due to geometric and threshold effects, requiring higher gain for full efficiency. Ad-

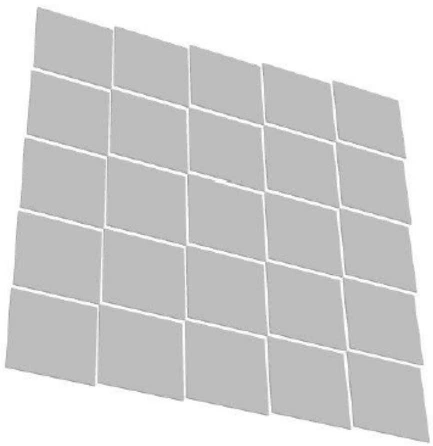


Figure 9: Geant4 visualization of 50×50 cm^2 μ-RWELL tiles in the muon apparatus.

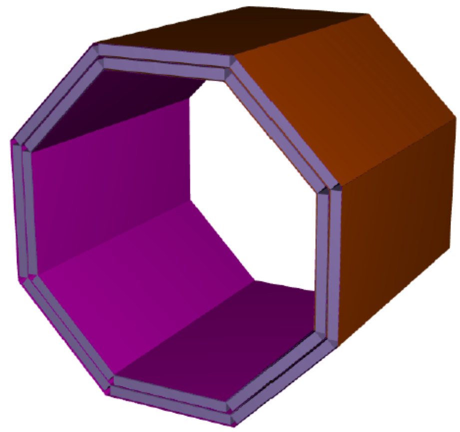


Figure 10: The barrel muon detection system for the IDEA detector.

ditionally, the number of fired strips decreases, bringing spatial resolution closer to the pitch/$\sqrt{12}$ limit.

Besides the tuning of the parameters (resistivity, strip pitch and strip width) still in progress, the first ideas for the two-dimensional readout of a μ-RWELL have been designed. A commonly used 2-D layout involves embedding two wo parallel layers of strips in the readout plane at a defined angle (e.g., XY or XV), as implemented in COMPASS triple-GEM detectors [3]. However, this approach, which equally shares the charge between the two views, requires a high detector gain and is therefore not optimal for a single-stage amplification detector such as the the μ-RWELL, as discussed in [2]. Alternative 2-D readout designs are being explored, as shown in fig. 11), with three layouts currently under study:

- two one-dimensional detectors, coupled through a common cathode. This is the simplest solution as it consists of using two standard detectors. They can operate at the usual gas gain with the readout strips completely separated. This layout is a feasible option thanks to the μ-RWELL overall small thickness, due to the compactness of the μ-RWELL_PCB.
- a single two-dimensional μ-RWELL, with the standard 1-D readout on the PCB plus a strip patterned top electrode for the second coordinate. The main advantage of this layout is that it does not require an increase of the detector gas gain.
- a single two-dimensional μ-RWELL based on the capacitive-sharing anode readout as described in [7]. This layout offers high spatial performance with a significant reduction of electronic channels required to read out a very large area apparatus.

The first versions of these designs were produced and tested. A dedicated test beam campaign evaluated the performance of the three layouts using a muon beam at the SPS-H8 beamline at CERN. The results, shown in Fig. 12, demonstrate good spatial resolution for all three layouts.

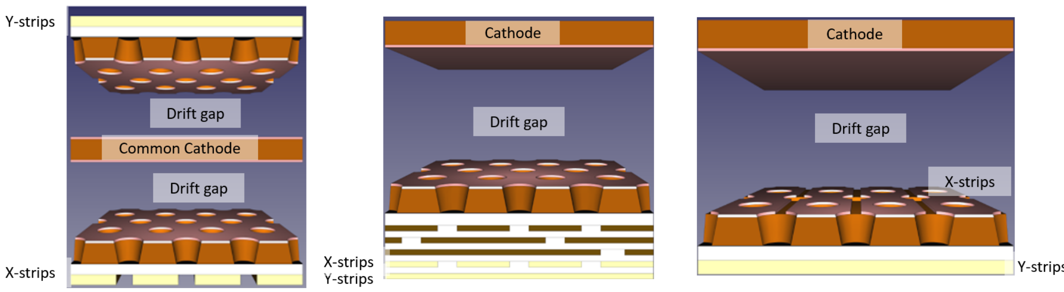
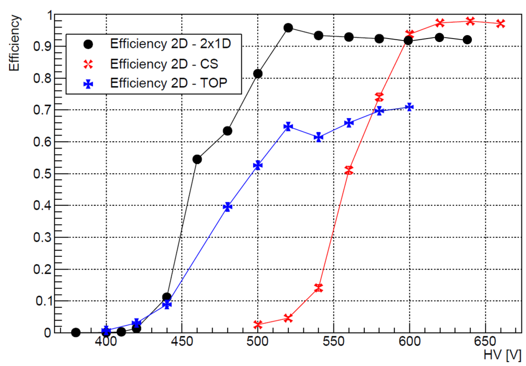
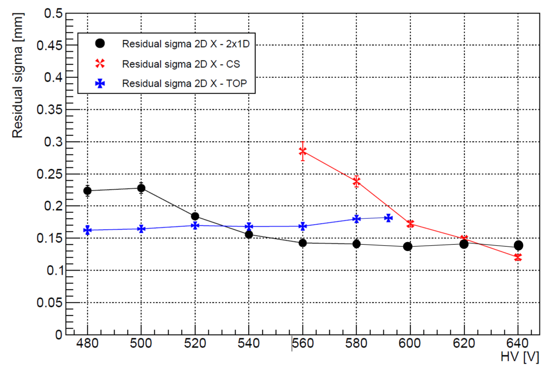


Figure 11: Sketch of the two-dimensional layouts. Left: the 2x1D readout. Center: the CS-readout. Right: the TOP-readout.



(a) Tracking efficiency for different HV.



(b) Residuals width for different HV.

Figure 12: Results of the 2D layouts test campaign.

However, the efficiency results reveal an efficiency plateau of approximately 70% for the second layout (blue lines), due to dead areas on the amplification electrode required for segmentation. The third layout (red lines) delivers very good performance despite requiring a higher high voltage (HV) on the amplification stage. The R&D for this activity will continue to optimize the layout configurations, ensuring 2-D readout performance while maintaining detector operational stability.

3.2 Electronics

The results shown in the previous section are evaluated with APV-25 electronics and SRS readout system [8, 9]. This readout system is widely used in the gas detector R&D community but it can not be used in experiments such as LHC or FCC due to a maximum trigger rate of about 1 kHz. Alternatives are needed to profit from the performance of the ASIC and a design optimized for the μ-RWELL and its final layout. A possible solution is identified in the TIGER/GEMROC system which is a compact, modular, scalable, and highly customizable [10]. TIGER is versatile for the readout of radiation sensors up to 50 fC and for high rates up to 60 kHz. Its output is passed to

two shapers optimized for time and charge measurement. The peak time of the shaper for the time branch was set to the expected charge collection time (60 ns) to enable measurements with low jitter. The shaper for the energy branch has a slower peak time (170 ns) for better charge resolution and ENC optimization.
A first integration test between μ-RWELL and TIGER was tested on a 10×10 cm^2 prototype. The average noise is 0.3-0.4 fC allowing the detector to operate at a threshold of about 1 fC. Further studies between TIGER and μ-RWELL integration are ongoing to confirm the expected performance achieved with APV/SRS system. In the future, an optimization of the TIGER parameters is planned to match the needs of the μ-RWELL layout chosen to optimize the performance of the 2-D readout.

4 List of Conference Talks by DDG - LNF Authors in Year 2024

1. G. Morello, *The Cylindrical Resistive WELL*, 60th International Winter Meeting on Nuclear Physcics, Bormio,I, January 22nd-26th 2024
2. G. Bencivenni, *The micro-RWELL for future HEP challenges*, 16th Pisa Meeting on Advanced Detectors, La Biodola, I, May 26th - June 1st 2024
3. M. Giovannetti, *uRANIA-V: resistive gaseous devices for thermal neutron detection*, PSND2024, Oxford, UK, April 8th-11th 2024
4. M. Poli Lener, *LHCb Muon Detector for the High Lumi at LHC*, ICHEP24, Prague, CZ, July 17th-24th 2024
5. M. Giovannetti, *The micro-RWELL for future HEP challenges and beyond*, MPGD2024, Hefei, PRC, October 14th-18th 2024

5 Publications

1. M. Giovannetti, *The μ-RWELL in High Energy Physics and beyond*, JINST **19** (2024) C02057 https://doi.org/10.1088/1748-0221/19/02/C02057
2. G. Bencivenni et al., *Build a $0.3 \times 0.3m^2$ prototype and the read-out plane with the new structure*, Horizon 2020 Research Infrastructures project AIDAinnova (g.a. 101004761), Milestone MS27 report, https://doi.org/10.5281/zenodo.13837399
3. M. Poli Lener, *LHCb Muon Detector for the High Lumi at LHC*, PoS **476** (2024) 902 https://doi.org/10.22323/1.476.0902
4. G. Bencivenni, *The μ-RWELL for future HEP challenges*, NIM **A 1069** (2024) 169725 https://doi.org/10.1016/j.nima.2024.169725
5. M. Poli Lener, *Irradiation effects on GEM detectors operated at RUN1 and RUN2 at the LHCb experiment*, NIM **A 1066** (2024) 169579

References

1. G. Bencivenni at al., *The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD*, JINST 10 (2015) P02008.

2. L. Shekhtman et al.,*Development of* μ*-RWELL detectors for the upgrade of the tracking system of CMD-3 detector*, Nucl. Instr. & Meth. **A 936** (2019) 401.

3. C. Altunbas et al., *Construction, test and commissioning of the triple-gem tracking detector for compass*, Nucl. Instr. & Meth. **A 490** (2002) 173.

4. The IDEA Study Group, *The IDEA detector concept for FCC-ee*, `https://arxiv.org/abs/2502.21223`.

5. Abada, A. et al., *FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1*, Eur. Phys. J. C79 (2019) 474.

6. A. Colaleo et al., *DRD1 Extended R&D Proposal*, `https://cds.cern.ch/record/2885937/files/DRDC-P-DRD1.pdf`.

7. K. Gnanvo at al., *Performance of a resistive micro-well detector with capacitive-sharing strip anode readout*, Nucl. Instr. & Meth. **A 1047** (2023) 167782.

8. S. Martoiu et al.*Development of the scalable readout system for micro-pattern gas detectors and other applications*, 2013 JINST 8 C03015.

9. M. Raymond et al.,*The APV25 0.25 /spl mu/m CMOS readout chip for the CMS tracker*, 2000 IEEE Nuclear Science Symposium. Conference Record (Cat. No.00CH37149).

10. A. Amoroso et al., *The CGEM-IT readout chain*, 2021 JINST P08065.