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The μ-RWELL for future HEP challenges

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ABSTRACT

The challenges posed by the forthcoming High-Energy Physics experiments require advanced particle detection technologies that are industrially scalable. The μ-RWELL, a single-amplification stage resistive MPGD utilizing sequential build-up (SBU) technology, addresses these needs. This paper reviews the main characteristics of the detector, the design of high-rate layouts, and their testing at INFN-LNF. It provides a detailed description of the detector construction processes at ELTOS and the CERN MPT Workshop. The findings highlight the industrial feasibility of detector construction, offering benefits in production time and cost. A significant focus is on the production of large DLC foils, which are essential for the detector's amplification stage. This was facilitated by the acquisition of a DC-magnetron sputtering machine through a CERN-INFN collaboration. Detailed test results using an X-ray gun at LNF and particle beams at the CERN North Area clearly show that the detector achieves a gas gain of 10^4 and a rate capability greater than 1 MHz/cm^2, while the efficiency of the optimized high-rate layout is about 98%. Preliminary outcomes from the 2023 co-production pilot test show a production yield larger than 90%. This successful technology transfer marks a step towards building larger detectors for future HEP challenges.

1. Introduction

The μ-RWELL [1] is a resistive MPGD composed of two PCBs: a PCB acting as the cathode, defining the gas detector gap, and the μ-RWELL_PCB that couples in a unique structure the electron amplification and the readout stages, as shown in Fig. 1. A 50 μm thick polyimide (Apical®) foil, copper-clad on the top side and sputtered with DLC [2] on the bottom side, is coupled to a standard PCB readout board, through a 50 μm thick pre-preg foil. The thickness of the DLC layer (typically in the range 10 ÷ 100 nm) is adjusted according to the desired surface resistivity value (typically in the range 50÷100 MΩ/square) to provide discharge suppression as well as current evacuation. A chemical etching process of the polyimide foil is performed on the top surface of the overall structure to create a GEM-like matrix of truncated cones with 70 μm (50 μm) top (bottom) diameter and 140 μm pitch. This pattern constitutes the amplification stage. The high voltage applied between the copper and the resistive DLC layers produces the required electric field within the WELLs that is necessary to develop charge amplification. The signal is capacitively induced on the strips/pads on the readout board [3]. The introduction of the resistive layer allows achieving large gas gains up to 10^4 with a single amplification stage, while partially reducing the capability to stand high particle fluxes [4]. The μ-RWELL technology, based on sequential build-up (SBU) technology, has been proposed for the phase-II upgrade of the innermost regions of the muon detection system of the LHCb experiment at the High Luminosity LHC (HL-LHC). The main requirements for the detectors in the LHCb muon upgrade include the capability to withstand high particle fluxes, up to 1 MHz/cm^2, and achieving a high efficiency of greater than 98% within a 25 ns time window. In addition this endeavor will involve the production of approximately 600 detectors with an active area ranging from 250 × 300 mm^2 up to 300 × 650 mm^2. In this context, we engaged in a technology transfer (TT) of specific manufacturing steps of the detector to ELTOS SpA, an Italian company specialized in PCB manufacturing. The ELTOS has a large experience in the construction of MPGDs, including technologies such as Thick GEM (THGEM) [5] and MicroMegas [6]. The involvement of private industries in this R&D opens the way for the extensive adoption of μ-RWELL technology across

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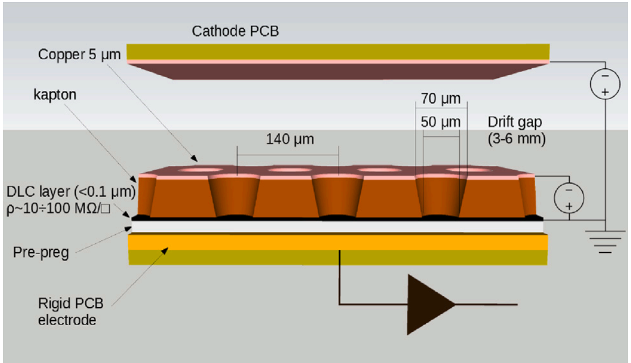

Fig. 1. Sketch of the µ-RWELL.

various fields of application, ranging from HEP to industrial, medical, and homeland security domains. Within the LHCb project, our R&D activities have been divided into two main streams:

- Optimizing detectors for high-rate environments
- Facilitating technology transfer to industry to meet the demands of large-scale construction efforts

2. High-rate layouts

To overcome the intrinsic rate limitations of the baseline µ-RWELL layout, which is based on a single resistive layer (SRL) with the grounding of the DLC film performed via two conductive lines placed at its edge, it is essential to implement a high-density grounding network for the resistive stage (DLC). This is accomplished by segmenting the DLC with conductive grid of micro-strips or matrix of dots with a typical pitch of 1 cm, effectively tiling the active area with a set of smaller SRLs. After several R&Ds on high-rate layouts [4] with different pros and cons, a new µ-RWELL scheme called PEP (Patterning-Etching-Plating) has been introduced. This layout is based on a single DLC layer, in which the grounding network of the resistive stage is patterned by etching from the top copper layer through the Kapton foil down to the DLC. In this layout, an automatic alignment between the grounding elements and the amplification stage pattern is obtained. The layout is easily scalable to large sizes and is easily engineered, as it is based on Sequential Build Up (SBU) technology. Two different PEP layouts have been developed in the last two years: the PEP-groove Fig. 2, in which the DLC grounding element is a grid of conductive micro-strips, and the PEP-dot Fig. 3, in which the DLC grounding is realized with a matrix of conductive dots connecting the DLC with the underlying readout pads (similar to plated blind vias). In both layouts the PEP-grounding element has a pitch of 9 mm. However, since the groove is much larger than the dot, the geometric acceptance of the two layouts is significantly different: ~85% for the PEP-groove, ~97% for the PEP-dot. In Fig. 4 the microscopic images of the two PEP layouts are shown, while their metallographic cross-sections are presented in Fig. 5. A preliminary characterization of the µ-RWELL prototypes was conducted at a high-intensity 5.9 keV X-ray gun facility. Common measurements include the gas gain and rate capability. The gas gain curves for the two PEP layouts are shown in Fig. 6, demonstrating that a gas gain on the order of 10^4 has been achieved for both layouts. The normalized gas gain curves as a function of the X-ray flux for various irradiation spots are presented in Figs. 7 and 8 for the PEP-groove and PEP-dot layouts, respectively. These measurements have been performed at a gas gain of 4000, with detectors operated with the Ar:CO_2:CF_4 = 45:15:40 gas mixture. Since the irradiated area is larger than the DLC grounding pitch (~ 0.9 cm for both layouts), the gain drop is, as expected, almost independent of the spot size. The rate capability,

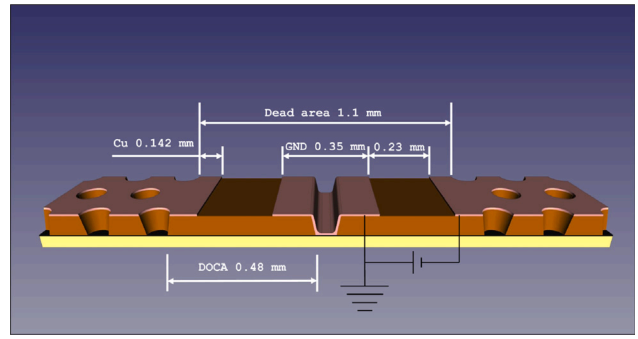

Fig. 2. Sketch of the PEP-groove layout with the nominal dimensions.

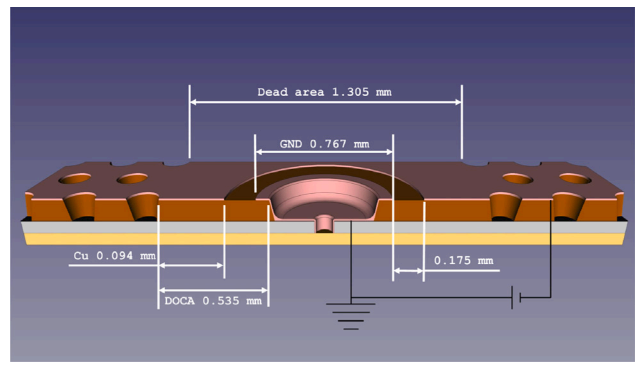

Fig. 3. Sketch of the PEP-dot layout with the nominal dimensions.

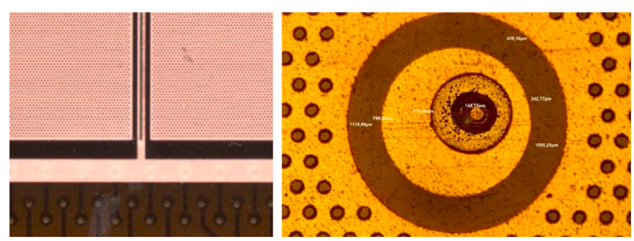

Fig. 4. Microscopic images of the PEP-groove layout (left) and the PEP-dot layout (right).

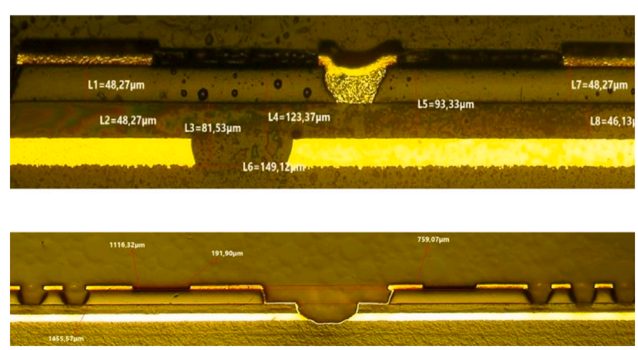

Fig. 5. Metallographic cross-section of the PEP-Groove layout (top) and the PEP-Dot layout (bottom).

defined as the rate corresponding to a gain drop of 10%, is on the order of several MHz/cm^2.

The characterization of the two PEP layouts has been completed through a dedicated beam test at the CERN North Area with a pion/muon beam of about 150 GeV/c. The test setup has included an external

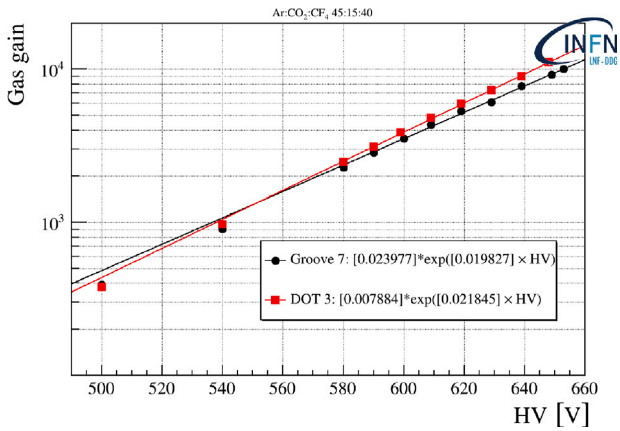

Fig. 6. Gas gain curves for the PEP-groove and PEP-dot layouts. A maximum gas gain of 10^4 is achievable for both layouts.

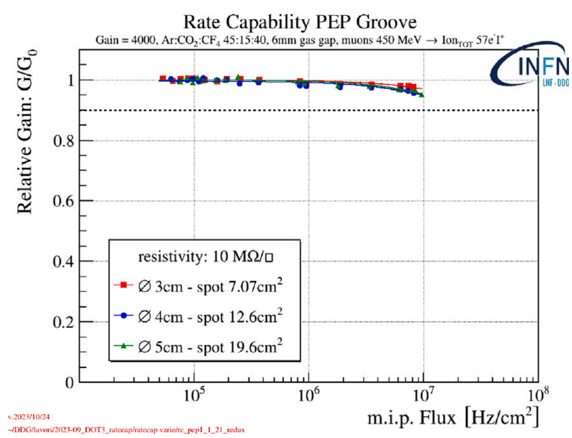

Fig. 7. Rate capability for the PEP-groove layout, measured with X-ray with different spot size. A rate capability on the order of several MHz/cm^2 has been achieved.

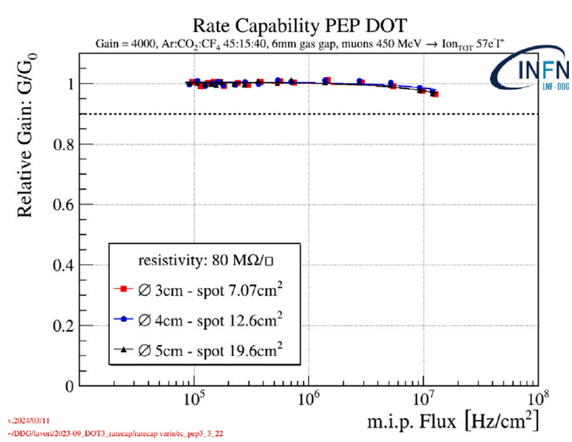

Fig. 8. Rate capability for the PEP-dot layout, measured with X-ray with different spot size.A rate capability on the order of several MHz/cm^2 has been achieved.

2D tracking system, for the evaluation of the efficiency. A detailed investigation of the DLC-grounding area, which introduces a dead zone, has been carried out. By irradiating the detectors with a muon beam spot size of approximately 3 × 3 cm^2 (FWHM), we assessed the impact of the dead zone around the grounding elements of the DLC on the detection efficiency. As it is evident from Fig. 9, showing the XY map efficiency of the two layouts, the PEP-dot significantly reduces the dead zone. In Fig. 10, the overall efficiency as a function of the HV applied to the amplification stage for both PEP layouts, at a drift field of 3.5 kV/cm, demonstrates that the PEP-dot layout achieves an average efficiency of approximately 98%, whereas the PEP-groove layout struggles to exceed an efficiency of about 80%.

3. Detector manufacturing

The manufacturing process of the μ-RWELL can be divided in the following tasks:

1. Detector design
2. DLC sputtering on the backplane of the Apical®
3. Production of PCB readout (pad/strip patterned)
4. DLC patterning
5. DLC foil gluing on PCB
6. Creation of the PEP structure
7. Amplification stage patterning by Apical® etching
8. Electrical cleaning in dry atmosphere

Supervised by our group, ELTOS and CERN have jointly produced several 100 × 100 mm^2 μ-RWELL prototypes with 9 × 9 mm^2 pad readout based on the PEP-DOT layout.

3.1. Detector design

The initial step in detector production involves the electronic CAD design of the μ-RWELL_PCB and the cathode, managed by the LNF electronic design service (SEA), Fig. 11.

3.2. DLC sputtering

The manufacturing process of the detector begins with producing the core component of the amplification stage. This involves using a 50 μm thick Apical® foil, coated with a 5 μm thick copper film on one side, and a thin DLC layer on the other. The DLC sputtering on Apical®, initially performed by Be-sputter Company in Japan, has been successfully transferred to CERN using the CERN-INFN DLC (C.I.D.) sputtering machine, operational since early 2023. Fig. 12 shows details of this machine, which can handle flexible substrates up to 1.7 m×0.6 m and rigid substrates up to 0.2 m×0.6 m.

Fig. 13 presents the DLC resistivity plot along the z-direction of the drum, with two curves for different sputtering configurations using a 2% Acetylene-Argon gas mixture.

3.3. DLC patterning

DLC patterning is required before coupling the DLC foil to the PCB. The DLC material must be removed from all areas except the detector's active area, which corresponds to the portion of the PCB with the readout electrodes (currently, only pad PCB is considered). Figs. 14 and 15 show the main steps of the DLC patterning process.

3.4. Gluing the DLC foil on the PCB

The final operation at ELTOS involves the gluing of the DLC to the readout PCB using a thin sheet of prepreg (typically in the range 28÷50 μm). This process is performed in a press, with a cycle lasting approximately 8 h at a temperature of 210 °C and a pressure of 180 N/cm^2. Fig. 16 shows the preparation sequence for the DLC/prepreg/readout PCB sandwich. The sandwich is inserted between layers of anti-stick sheets (Pacothane) and anti-conformant sheets (Pacoflex). Fig. 17 show the details of the stacking inside the press. Once manufacturing at ELTOS is complete, the μ-RWELL PCB is shipped to CERN for finalization. At the CERN MPT Workshop, the following photolithographic processes are conducted (the Apical® etching process is patented):

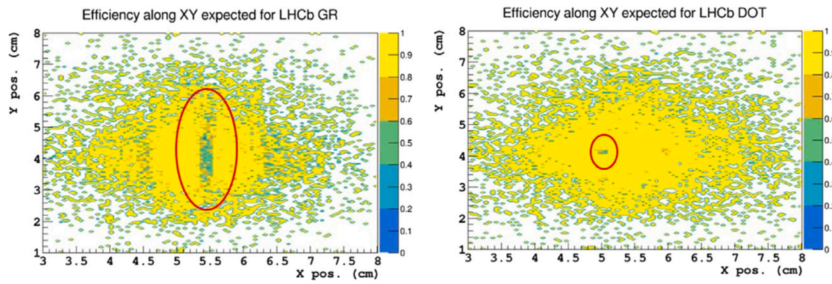

Fig. 9. X-Y map efficiency for the two PEP layouts: the red circles indicate the grounding zone of the detectors, where a corresponding efficiency drop is observed.

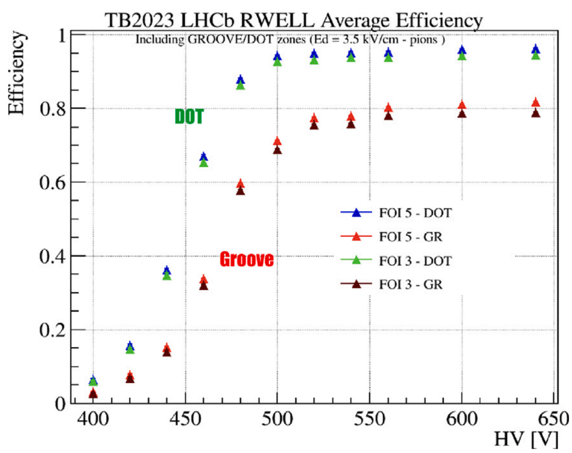

Fig. 10. Average efficiency as function of the HV applied to the amplification stage of the PEP-dot (green point) and the PEP-groove layout (red point). The impact of the large dead zone corresponding to the groove on the efficiency of the PEP-groove layout is evident.

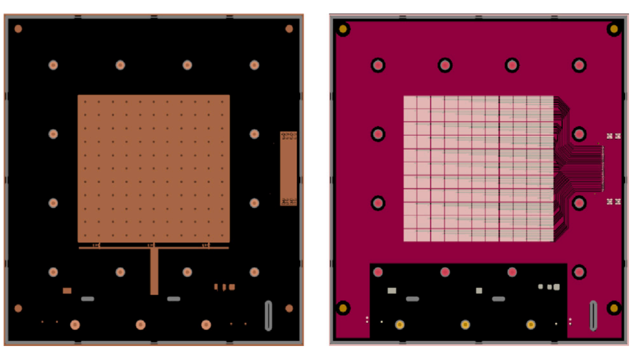

Fig. 11. Top (left) and bottom (right) drawings of the 100 × 100 mm^2 PEP-DOT layout with (9 × 9 mm^2) readout pad.

Fig. 12. The magnetron sputtering facility C.I.D., installed at the CERN MPT Workshop. C.I.D. is used to prepare the base material for the amplification stage of the detector by sputtering DLC on Apical® foils.

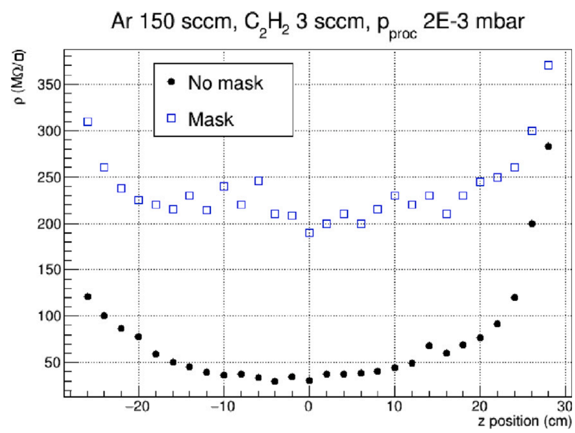

Fig. 13. DLC resistivity of two different samples in different sputtering configurations.

Fig. 14. DLC foil lamination with phot-resist film (left); UV exposure of the photo-resist by means of a Laser Direct Imaging (LDI) UV machine (center); DLC foil after photo-resist developing (right).

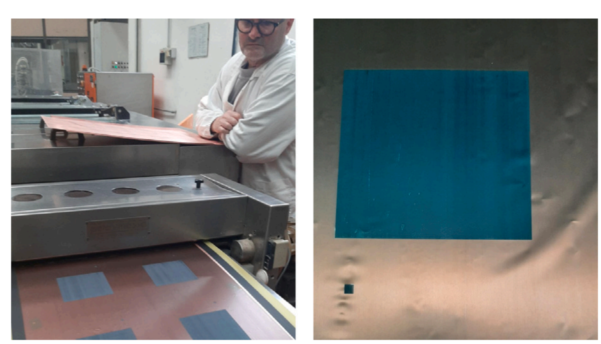

Fig. 15. The DLC foil at the end of the patterning process, ready to be glued onto the readout PCB.

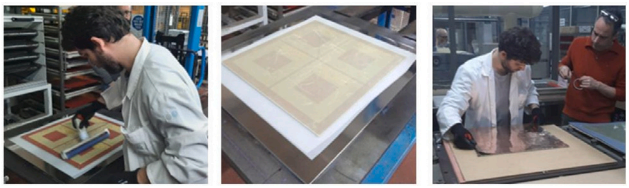

Fig. 16. The main steps for the preparation of the μ-RWELL_PCB.

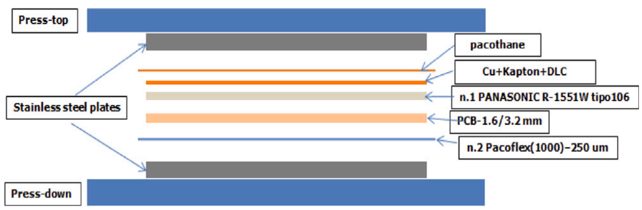

Fig. 17. Details of the stacking inside the press.

1. The DLC grounding network is created using the PEP technique (sec. 3), requiring masking of the rest of the PCB.
2. The WELL pattern on the copper layer is created, by masking the PEP DLC grounding network.
3. The Apical® undergoes chemical etching using the copper hole pattern as a mask, creating amplification wells.

The detector manufacturing is completed with the electrical hot cleaning, involving a gradual voltage increase up to 680 V in a dry atmosphere at 90 °C for at least 24 h. Good detectors exhibit a residual dark current of a few nA.

Upon completion, the detector undergoes characterization at the LNF-DDG laboratory using a high-intensity X-ray gun to measure the gas gain curve and rate capability.

3.5. Conclusions

Future high-energy physics experiments require detectors that are simple, reliable, and easily manufacturable by industry. The μ-RWELL detector, based on SBU technology, meets these criteria. Within the AIDAInnova project, we transferred a significant portion of the detector construction to ELTOS SpA, an Italian company specializing in PCB manufacturing.

This paper discusses the design of the high-rate layouts of the μ-RWELL, their testing procedures, and construction processes conducted at INFN-LNF, ELTOS, and the CERN MPT Workshop. The performance evaluations were conducted using X-ray and high momentum pion/muon beams at CERN. All these tests show that the detector achieves a gas gain of 10^4 and a rate capability greater than 1 MHz/cm^2, while the efficiency of the optimized high-rate layout is about 98%.

The successful co-production of 16 prototypes (100 × 100 mm^2 active area), with a production yield greater than 90%, demonstrated the feasibility of industrial production. This suggests potential for significant reductions in both production time and cost.

Additionally, the development of large DLC foils marks a significant technological advancement. This was facilitated by the acquisition of a DC-magnetron sputtering machine, a joint effort between CERN and INFN.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: G. BENCIVENNI reports financial support was provided by European Union. If there are other authors they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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