High space resolution $\mu$-RWELL for high rate applications

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Abstract. The $\mu$-RWELL is a single-amplification stage resistive MPGD. The amplification element, realized on a polyimide foil micro-patterned with a high density blind-holes (wells), is embedded through a thin resistive film, in the readout PCB. The introduction of the resistive layer affects the charge spread on the readout electrodes and suppresses the transition from streamer to spark giving the possibility to achieve large gains ($>10^4$). As a drawback the capability to stand high particle fluxes is reduced. In order to get rid of such a limitation different resistive layouts with prompt current evacuation schemes have been designed. In this work we present the study of the performance of the high rate layouts done at PSI, together with the measurement of the space resolution for orthogonal and inclined tracks performed at CERN.

1. Introduction
The R&D on $\mu$-RWELL has a two main purposes: the improvement of the stability in harsh environment while simplifying the construction procedures for an easy technology transfer to industry. The $\mu$-RWELL, fig.1, is a resistive MPGD composed of two elements: the cathode, a simple FR4 PCB with a thin copper layer on one side, and the $\mu$-RWELL-PCB, the core of the detector.

The $\mu$-RWELL-PCB, realized as a multi-layer circuit by means of standard photo-lithography technology, is composed of a wells matrix patterned Apical$^{\circledR}$ foil acting as amplification element of the detector; a resistive layer, realized with a Diamond-Like-Carbon (DLC) film sputtered on the bottom side of the polyimide foil, as discharge limitation stage; a standard PCB,
Figure 1. Layout of the μ-RWELL. The drift gap is 6 mm.

Figure 2. Principle of operation of the μ-RWELL.

segmented as strip, pixel or pad electrodes, for readout purposes. Applying a suitable voltage between the copper layer and the DLC, the well acts as a multiplication channel for the ionization produced in the drift gas gap, fig. 2. The charge induced on the resistive film is spread with a time constant \[ \tau = \rho c = \rho \frac{\epsilon_0 \epsilon_r}{t} \]

being \( \rho \) the surface resistivity (in the following simply called resistivity), \( c \) the capacitance per unit area and \( t \) the distance between the resistive layer and the readout plane.

The discharge suppression mechanism is similar to the one of the RPCs, \[5, 6, 7\]: the streamer developed in the well, inducing a large current flowing through the resistive layer, generates a localized drop of the amplifying voltage with an effective quenching of the multiplication process in the gas. This mechanism suppressing the discharge amplitude allows to achieve large gains (>\(10^4\)) with a single amplification stage. As a drawback, the capability of the detector to stand high particle fluxes is reduced. Indeed a detector relying on a simple single-resistive layout suffers at high particle fluxes of a non-uniform response over its surface. This becomes evident as the size of the detector increases.

In this paper we discuss the layouts for high rate purposes and their performance in terms of efficiency and rate capability measured \[8\] at the \(\pi M1\) beam line of the PSI. In addition we present the results of a study of the space resolution for orthogonal and inclined tracks performed at the CERN H8-SpS beam facility.

2. The high rate layouts

The simplest scheme for the evacuation of the current in a μ-RWELL is based on a single resistive layer with a grounding line all around the active area, fig. 3 (simply called Single Resistive layout - SRL). For a large area device the path of the current to ground could therefore be large and strongly dependent on the incidence point of the particle. This problem can be overcome by introducing a high density grounding network on the resistive stage.

Two different layouts with fast grounding have been implemented: the Double-Resistive layout (DRL) with a 3-D grounding scheme and the Silver-Grid (SG) layout based on a single resistive layer with fast 2-D grounding.

2.1. The Double-Resistive layout

The DRL layout is sketched in fig. 4. The first DLC layer, sputtered on the back-plane of the amplification stage, is connected to a second DLC film by means of a matrix of conductive vias.
A further matrix of vias connects the second DLC stage to the underlying readout electrodes, providing the grounding of the whole resistive stage. The vias density is typically $\leq 1 \text{ cm}^{-2}$. In this way a sort of a 3D-current evacuation layout is implemented and the average resistive path to ground is minimized with respect to the SRL and the rate capability largely improved (as reported in the appendix of [8], the rate capability can improve up to a factor of $\sim 20$).

2.2. The Silver-Grid layout

The Silver-Grid, fig. 5, is a simplified layout based on a single resistive layer with a thin conductive grid deposited on the DLC. The conductive grid acts as a high density 2-D current evacuation scheme. The pitch of the grid together with the surface resistivity $\rho$ of the DLC (hereafter simply called resistivity) are two parameters of this layout. Since the presence of a conductive grid on the DLC can induce discharges over the DLC surface, a small dead zone in the amplification stage above the grid lines has been inserted.

In table 1 we report the characteristics of the resistive layouts described in this work. For completeness also the parameters of the SRL have been included. The $\Omega$ depends on the DLC resistivity and the geometrical parameters of the grounding scheme (i.e. pitch, dead zone, etc). Under the assumption of a uniform particle flow irradiating the basic cell of the detector, $\Omega$ represents the average resistance seen by the current on the DLC

$$\Omega = \frac{\rho}{2} \frac{(\text{pitch}/2 + \text{DOCA})}{w}$$
where DOCA (the *distance-of-closest-approach* before the occurrence of a discharge on the DLC surface) is the minimum distance between the grounding line and the closest well in the amplification element, and $\nu$ is the unitary *transverse-width* of the resistive path of the current on the DLC film \[8\].

As reported in the table, due to the presence of a dead zone, the SG layouts exhibit a geometrical acceptance lower than the other layouts. For the SG2++, exploiting the DLC+Cu technology (more details in \[9\]), that allows the photo-etching of very thin grid lines ($\approx 100$ $\mu$m width), the dead zone has been minimized down to 5% of the active area.

| Layout | $\rho$ (M$\Omega$/cm) | pitch (mm) | dead zone (mm) | geom. acc. (%) | $\Omega$ (M$\Omega$) |
|--------|----------------------|------------|----------------|---------------|------------------|
| SG1    | 70                   | 6          | 2              | 66            | 134              |
| SG2    | 65                   | 12         | 1.2            | 90            | 209              |
| SG2++  | 64                   | 12         | 0.6            | 95            | 200              |
| DRL    | 54                   | 6          | 0              | 100           | 270              |
| SRL    | 70                   | 100        | 0              | 100           | 1947             |

Table 1. Resistive and current evacuation geometrical parameters of the HR layouts compared with the low rate baseline option (SRL). All the detectors have an active area of 100×100 mm$^2$.

3. Performance of the HR-layouts

The performance of the the HR-Layouts has been measured at the $\pi$M1 of the PSI. Upstream and downstream the six $\mu$-RWELL prototypes\[1\], we have placed a couple of plastic scintillators, providing the DAQ trigger, together with two external GEM trackers, defining the particle beam with a spatial accuracy of the order of 100 $\mu$m. The GEM have been equipped with 650 $\mu$m pitch X-Y strips, while the $\mu$-RWELL readout boards have been segmented with $0.6 \times 0.8$ cm$^2$ pads. All gaseous detectors, operated with an Ar/CO$_2$/CF$_4$ (45/15/40) gas mixture, were read-out with APV25 front-end electronics \[10\]. The current drawn by the electrodes of both $\mu$-RWELLs and GEMs were monitored.

\[1\] One SG1, one SG2, two SG2++, one DRL and one SRL
3.1. Efficiency studies
In fig. 6 the efficiency of the HR-layouts is reported as a function of the detectors gain. The measurement has been performed with a 270 MeV/c $\pi^-$ beam with a $\sim 5 \times 5$ cm$^2$ average beam spot (FWHM$^2$).

![Efficiency as a function of the gas gain for the various HR layouts.](image)

Figure 6. Efficiency as a function of the gas gain for the various HR layouts.

At a gain of 5000, the DRL, without dead zone, shows an efficiency larger than 98%, while the SG1 and SG2 achieve a detection efficiency of 78% and 95% respectively, larger than their geometrical acceptance. The SG2++, with a minimized dead zone, tends to an almost full efficiency of about 97%.

We have investigated this effect, typical of detectors with GEM-like amplification stage [11, 12], reporting as example the efficiency and the charge profile for the SG1. In fig. 7 (top) we plot the efficiency and in fig. 7 (bottom) the charge as a function of the incidence point reconstructed by the GEM trackers. The geometrical structure of the detector layout is visible on both: an efficiency drop and an increase of the charge are present in correspondence of the dead zones. Actually the wells close to the dead zones collect also the primary ionization produced above the inefficient regions (focusing effect) resulting in a recovery of the detection efficiency; at the same time the amplification in these wells is increased probably due to the squeezing of the drift field lines. Moreover, as shown in fig. 8 increasing the HV applied to the amplification stage the efficiency in the dead zone improves, as observed in GEM detectors (KLOE-2 CGEM [13]).

3.2. Rate capability measurement
The result of the rate capability study is shown in fig. 9, where the normalized gain of the HR-layouts is reported as a function of the pion flux. The detectors have been operated at a gain of about 5000. The low rate measurements ($\leq$1 MHz/cm$^2$) have been performed with the $\pi^-$ beam, while the high intensity behaviour (>1 MHz/cm$^2$) has been studied with the $\pi^+$ beam.

The average beam spot was larger than the basic cell (pitch) of the HR layouts.

The $G_0$ is the initial gas gain, measured as the ratio between the current drawn by $\mu$-RWELL and the particle rate measured by GEM. The error bars with $\pi^-$ beam are larger with respect to $\pi^+$ because the currents drawn by GEM and $\mu$-RWELL detectors at low particle rate were close to the current offset of our instrument (few nA). Nevertheless the error bars for the low rate measurements are compatible with $G/G_0=1$. 

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Figure 7. Efficiency and charge profile for the SG1 layout measured at CERN. Visible its geometrical features: the 2 mm wide dead zones and the 6 mm grid pitch.

Figure 8. Zoom of the efficiency profile in the dead zone for different voltages for SG1. The ∆ is the difference between the inflection points of the two fitting Fermi-Dirac functions.

The particle rate has been estimated with the current drawn by the GEM, that owns a linear behaviour up to several tens of MHz/cm$^2$ [14]. The beam spot has been estimated with a 2-D gaussian fit of the hits reconstructed on the X-Y plane for each detector. The GEM have been operated at a gain of about 3500.

Figure 9. Normalized gas gain of the HR-layouts as a function of the $\pi^+/\pi^-$ flux at the $\pi$M1 facility of the PSI.

The gain drop observed at high particle fluxes is dominated by the Ohmic behaviour of the detectors due to the presence of the resistive film. The different behaviour of the HR layouts depends on their resistivity and current evacuation scheme. As shown in fig. 10, the rate capability decreases as Ω increases. In particular the HR-layouts corresponding to $\Omega \simeq 200$ MΩ stand particle fluxes up to 10 MHz/cm$^2$ with high detection efficiency.
3.3. Discharge studies

The radiation rate at PSI allows a dedicated study on the discharges occurrence and their amplitude. We have used for the test a 270 MeV/c $\pi^+$ beam with a proton contamination of 3.5%. The beam intensity has been set $\sim$90 MHz on a $\sim$5 cm$^2$ spot.

The currents drawn by all the electrodes have been recorded every second and then analyzed, removing from the analysis the values corresponding to the beam-off periods. The average current at a gain of 5000 has been of the order few µA.

A spark has been defined as the current spike exceeding 5σ the average current level due to the particle flux while its amplitude is the difference between the current peak and the reference current value. The spark probability per incident hadron is

$$P_{\text{spark}} = \frac{N_{\text{spark}}}{R \times \Delta t \times S}$$

where $R$ is the particle rate, $\Delta t$ is the irradiation time and $S$ is the spot area (FWHM$^2$).

As shown in fig. [11] the $P_{\text{spark}}$ for a $\mu$-RWELL (full circle) is slightly lower than the one measured for triple-GEM (full square). In the plot we have reported also measurements done in the 2004 in the framework of the R&D for LHCb (open square) [14] with triple-GEMs flushed with the same gas mixture. These points have been renormalized to the beam conditions of 2018 by re-scaling the gain of a factor 2.29, due to the different specific ionization and to the thickness of the drift gap, and the $P_{\text{spark}}$ of a factor 0.5 because of the different proton contamination.

In fig. [12] we report the distributions of the spark amplitude measured in one of the external trackers and in the six $\mu$-RWELLs. Taking into account the different gains (see the legend) this plot suggests that the spark amplitude for the $\mu$-RWELL is moderately lower than for triple-GEM.

During the irradiation test at PSI each detector has integrated a charge of the order 100 mC/cm$^2$ (in 42 hours) without showing any performance degradation. This result, confirmed by the exposure at GIF++ facility (180 mC/cm$^2$ in 250 days), should be compared with the expected 600 mC/cm$^2$ in 1 year of operation (10$^7$s) in the M2R1 HL-LHCb muon station.
Figure 11. Spark probability per incident particle averaged on the six μ-RWELL detectors compared with GEM.

Figure 12. Spark amplitude comparison among the GEM and the six μ-RWELL detectors. The μ-RWELL have been operated at higher gain than GEM.

4. Space resolution studies
For tracks orthogonal to the detector the space resolution is well determined with the Charge Centroid (CC) method, that use the charge weighted strip centroid to reconstruct the track position on the readout plane. For inclined tracks or in presence of a high magnetic field the CC method for MPGD fails, giving a broad spatial distribution on the anode strip plane. A valuable readout approach for MPGDs is the μ-TPC mode, introduced by the ATLAS MicroMegas group [15], that exploits the combined measurement of the time of arrival and the amplitude of the induced signals on the strip readout.

In fig. 13 we report the space resolution as a function of the track incidence angle performed at H8-SPS CERN with 150 GeV/c muon beam. The DRL detectors, equipped with a 400μm pitch 1-D strip readout, were operated with an Ar/CO₂/CF₄ (45/15/40) gas mixture at a gain of ≃8000 and a drift field \(E_d=0.5 \text{ kV/cm}\). The CC-mode (close circle) gives good results only for almost orthogonal tracks, while the μ-TPC mode (open square) improves the space resolution for particles with large incident angle. Combining the two analysis methods (close triangle) an overall spatial resolution ranging between 40÷60μm is achieved.

5. Conclusions
In this paper we have discussed different resistive layouts of μ-RWELL for high rate applications. The prototypes have been tested up to particle fluxes exceeding 20 MHz/cm² at the πM1 beam facility of the PSI.

A rate capability up to 10 MHz/cm² with a detection efficiency of the order of 98% are the performance achievable with the proposed HR-layouts. The SG2++ layout, based on DLC+Cu sputtered polyimide foils, can be manufactured with full Sequential-Build-Up technology, thus allowing an easy technology transfer of the device to the industry operating in the field of multi-layer PCB.

The detector, operated in combined CC/μ-TPC mode, exhibits an excellent space resolution (down to 40μm) over a wide range of track incidence angles.

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Figure 13. Space resolution of the µ-RWELL. The angles are measured with respect to the perpendicular to the detector plane.

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