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

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Why a new MPGD

The R&D on μ-RWELL is mainly motivated by the wish of

Improve stability under heavy irradiation

Simplify construction/assembly

Promote Technology Transfer to Industry
The micro-Resistive WELL

The \( \mu \)-RWELL is composed of only two elements: the \( \mu \)-RWELL_PCB and the cathode

The \( \mu \)-RWELL_PCB, the core of the detector, is realized by coupling:

1. a **WELL patterned Apical® foil** acting as amplification stage

2. a resistive layer for discharge suppression with **surface resistivity \( \sim 10 \div 100 \, \text{M}\Omega/\square \)** - with different current evacuation schemes:
   
   i. LR \( \ll 1 \, \text{MHz/cm}^2 \) - SHiP, CepC, STCF, EIC, HIEPA
   
   ii. HR \( \gg 1 \, \text{MHz/cm}^2 \) - LHCb-Muon upgrade & future colliders - CepC, Fcc-ee/hh

3. a standard readout PCB
The resistive layer: DLC sputtering

The Diamond Like Carbon (DLC) is sputtered on one side of a 50 µm thick Apical® foil using a pure graphite target, on the other side of the foil the usual 5 µm thick Cu layer, as for the base material used for GEM foil, is deposited.

The resistivity can be parametrized as function of the DLC thickness. The resistivity uniformity on large foils, 1.2×0.6 m², is at level of 30%.

Very recent developments, at USTC – Hefei (Dr. Zhou Yi), brought to the manufacturing of DLC+Cu sputtered Apical® foils, where an additional layer of few microns of Cu above the DLC coating has been deposited.

This technology open the way towards improved high rate μ-RWELL layouts manufacturing (slides > # 9).

Principle of operation

Applying a suitable voltage between the top Cu-layer and the DLC the “WELL” acts as a multiplication channel for the ionization produced in the conversion/drift gas gap.

The charge induced on the resistive foil is dispersed with a time constant, $\tau \sim \rho \times C$ [M.S. Dixit et al., NIMA 566 (2006) 281]:

- the DLC surface resistivity $\rightarrow \rho$
- the capacitance per unit area, which depends on the distance between the resistive foil and the pad/strip readout plane $\rightarrow t$
- the dielectric constant of the insulating medium $\rightarrow \varepsilon_r$

\[
C = \varepsilon_0 \times \varepsilon_r \times \frac{S}{t}
\]

- The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark, with a consequent reduction of the spark-amplitude
- As a drawback, the capability to stand high particle fluxes is reduced, but appropriate grounding schemes of the resistive layer solves this problem (see High Rate layouts)
Gas gain of detectors as measured with a 270 MeV/c $\pi^+$ beam at PSI with particle fluxes ranging from $\sim 320$ kHz/cm$^2$ up to $\sim 1.2$ MHz/cm$^2$. 

Gain up to $10^4$.
The Low Rate Layout

Single Resistive Layer (SRL): 2-D current evacuation scheme based on a single resistive layer with a conductive grounding all around the perimeter of the active area.

For large area detectors the path of the current towards the ground connection could be large and strongly dependent on the particle incident point giving rise to large detector response inhomogeneity.
High rate layouts (*)

To overcome the intrinsic limitation of the Single Resistive layout with edge grounding, the solution is to reduce as much as possible the paths towards the ground connection introducing a high density “grounding network” on the resistive stage of the detector.

Two layouts with a “dense” grounding network scheme have been designed and implemented:

- the Double Resistive layer (DRL) with a sort of 3-D grounding scheme
- the Single Resistive layout with a grounding grid (SG) deposited on the resistive stage

(*). G. Bencivenni et al., "The micro-RWELL layouts for high particle rate“, submitted to JINST
HR layouts: the double-resistive layer

Double Resistive Layer (DRL): 3-D current evacuation scheme based on two stacked resistive layers connected through a matrix of conductive vias and grounded through a second matrix of vias to the underlying readout electrodes. The pitch of the vias can be easily done with a density less than 1/cm².
A simplified HR scheme based on a Single Resistive layer with the implementation of a 2-D grounding based on conductive strip lines realized on the DLC layer. The conductive grid can be screen-printed or better etched by photo-lithography (if a Cu deposition is done above the DLC layer → USTC – Hefei R&D).

The conductive grid can induce instabilities due to discharges over the DLC surface, thus requiring for the introduction of a small dead zone on the amplification stage (\( \text{dead}_\text{zone} = 2 \times \text{DOCA} + \text{line}_\text{width} \)) DOCA is the Distance Of Closest Approach before discharge occurrence
## High rate layouts: relevant parameters

<table>
<thead>
<tr>
<th></th>
<th>SG1</th>
<th>SG2</th>
<th>SG2++</th>
<th>DRL</th>
<th>SRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid-pitch (mm)</td>
<td>6</td>
<td>12</td>
<td>12</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Dead zone (mm)</td>
<td>2</td>
<td>1.2</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Geometric acceptance (%)</td>
<td>66</td>
<td>90</td>
<td>95</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Conductive line width (mm)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DOCA</td>
<td>0.85</td>
<td>0.45</td>
<td>0.25</td>
<td>7</td>
<td>5.5</td>
</tr>
<tr>
<td>$\Omega_{eff}$ (MΩ)</td>
<td>134</td>
<td>209</td>
<td>200</td>
<td>270</td>
<td>1947</td>
</tr>
<tr>
<td>DLC resistivity $\rho$ (MΩ/□)</td>
<td>70</td>
<td>65</td>
<td>64</td>
<td>54</td>
<td>70</td>
</tr>
</tbody>
</table>

$\Omega_{eff} \simeq \frac{\rho}{2} \times \frac{pitch}{2 + DOCA}/w$

average resistance “seen” by a uniform particle flow irradiating the basic cell of the detector. $\Omega_{eff}$ summarizes the electrical and geometrical features of each current evacuation scheme.

basic cell
The gain drop is due to the Ohmic effect on the resistive layer: the current collected on the DLC drift towards the ground “through” an effective average resistance $\Omega_{eff}$, depending on the evacuation scheme geometry and the DLC surface resistivity.

The SG2++ exhibits a rate capability of 10 MHz/cm²

For the SRL, since the irradiation was not uniform, the measurement must be considered as an upper limit of its actual RC-90%.
The **DRL layout** reaches full tracking efficiency, **98%** (NO DEAD ZONE). The **SG1, SG2 and SG2++** show lower efficiency (**76% - 93% - 97%**) BUT higher than their **geometrical acceptance** (66% - 90% - 95% respectively), thanks to the efficient electron collection mechanism that reduce the effective dead zone.
Space resolution

Orthogonal tracks: Charge Centroid (CC) method. The track position is determined as a weighted average of fired strips.

\[
x = \frac{\sum q_i x_{\text{strip}}}{\sum q_i}
\]

Inclined tracks: \textbf{\(\mu\)-TPC mode, introduced for MMs by T. Alexopoulos et al. (NIM A 617 (2010) 161).} From the knowledge of the drift time and the measurement of the arrival time of electron clusters on the readout, each ionization cluster is projected inside the conversion gap and the track segment in the gas gap is reconstructed.
Space resolution

Thanks to the collaboration with BESIII-CGEM, G. Cibinetto, R. Farinelli (Ferrara) & L. Lavezzi (To)

Ar:CO$_2$:CF$_4$ 45:15:40 - HV=600V, Ed=1 kV/cm, Gain $\sim 10^4$

Combining the CC and the $\mu$-TPC mode with $E_d = 1$ kV/cm a spatial resolution ($40 \div 60$ $\mu$m) almost flat over a wide range of incidence angles is obtained (Analog FEE: APV25)
The $\mu$-RWELL discharge probability measured at the PSI, and compared with the measurement done with GEM at the same time and in the 2004 (\textit{same gas mixture} - $\text{Ar:CO}_2:CF_4$ 45:15:40).

The measurement has been done in \textit{current mode}, with an intense 270 MeV/c $\pi^+$ beam, with a proton contamination of the 3.5%.

A “discharge” has been defined as the current spike exceeding the steady current level correlated to the particle flux (~90 MHz on a ~5 cm$^2$ beam spot size).

The discharge probability for $\mu$-RWELL comes out to be slightly lower than the one measured for GEM.

Moreover its discharge amplitude seems to be lower than the one measured for GEM.
Ageing studies (on going)

GIF++ - Full area & Flux = 200 kHz/cm²

X-Ray gun - spot 50 cm² Flux(rx) = 700 kHz/cm²

TB PSI – beam spot 9 cm² – Flux = 10 MHz/cm²

GOAL:
Integrate a charge up to 6 C/cm²

Slice test of u-RWELLs
during RUN3 in the LHCb Muon APPARATUS under discussion
The engineering and industrialization of the µ-RWELL technology is one of the main targets of the project.

Production Tests for the SRL @ ELTOS already started:
- 10x10 cm² PCB – (PAD r/o)
- 10x10 cm² PCB – (strip r/o)

Production Tests @ ELTOS, large area detectors (w/CMS):
- 1.2x0.5m² with strip r/o
- 1.9x1.2m² with strip r/o - (w/PCB splicing)

The etching of the kapton still done by Rui @ CERN
For the SG2++ TT straightforward

Prototypes proposed for CMS phase-2 muon upgrade
The μ-RWELL is a single-amplification stage, spark-protected resistive MPGD based on a breakthrough technology suitable for very large area planar tracking devices.

- Gain up to $10^4$
- Low-rate and high-rate layouts developed to attend different requirements
- Good efficiency obtained (~97%) with HR-layout SG2++
- Rate capability up to 10 MHz/cm²
- Time resolution down to 5.7 ns
- Space resolution down to 40 μm in a large range of incidence angles of the tracks, with the combination of CC and μ-TPC algorithms
- Discharge studies to be continued with very promising results
- Ageing studies in progress in two setups with different accelerating factors. No sensitive effect on the detector operation
- The Technological Transfer is in progress, with the purpose to make the device cost-effective

THE PROJECT μ-RANIA (μ-RWELL Advanced Neutron Imaging Apparatus), HAS BEEN SELECTED FOR FUNDING BY ATTRACT EU COLLABORATIVE
SPARES SLIDES
HR layouts performance: the efficiency

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.

Increasing the HV applied to the amplification stage the efficiency in the dead zone improves, as observed in GEM detectors (KLOE-2 CGEM)
Main detector features

The $\mu$-RWELL is a single-amplification stage, intrinsically spark protected MPGD characterized by:

**Very simple design/assembly-procedure:**

- only two components
- no critical & time consuming assembly steps:
  - no gluing
  - no stretching ($\rightarrow$ no stiff & large frames needed)
  - easy handling
- suitable for large area with **PCB splicing technique** w/small dead zone

**Cost effective & mass-production technology:**

- based on full **Sequential Build Up (SBU) technology** thus allowing an easy TT to industry operating in the field of multi-layer PCB

**Easy to operate:**

- very simple voltage supply is required $\rightarrow$ only 2 independent HV channels
  - (3-GEM detector $\rightarrow$ 7 HV floating/channels)
The CMS-M4 single resistive layer: H4 test beam (July 2017)

Cutting events not inside the M4-right active area

<table>
<thead>
<tr>
<th>TOP</th>
<th>Run 3838</th>
<th>Run 3829</th>
<th>Run 3816</th>
<th>Run 3821</th>
<th>Run 3819</th>
<th>Run 3818</th>
<th>Run 3827</th>
<th>Run 3836</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>98.3 ± 0.2</td>
<td>97.7 ± 0.2</td>
<td>98.4 ± 0.2</td>
<td>99.1 ± 0.1</td>
<td>98.7 ± 0.1</td>
<td>99.9 ± 0.1</td>
<td>98.9 ± 0.1</td>
<td>99.2 ± 0.1</td>
</tr>
<tr>
<td>BOTTOM</td>
<td>Run 3827</td>
<td>Run 3826</td>
<td>Run 3825</td>
<td>Run 3828</td>
<td>Run 3829</td>
<td>Run 3830</td>
<td>Run 3831</td>
<td>Run 3832</td>
</tr>
<tr>
<td>Efficiency</td>
<td>98.5 ± 0.2</td>
<td>96.7 ± 0.2</td>
<td>98.4 ± 0.1</td>
<td>98.9 ± 0.1</td>
<td>98.7 ± 0.1</td>
<td>98.5 ± 0.1</td>
<td>98.9 ± 0.1</td>
<td>99.1 ± 0.1</td>
</tr>
</tbody>
</table>

Average over all surface: \( \varepsilon = 98.5\% \)

Thanks to L. Borgonovi, L. Benussi, P. Giacomelli
The Low Rate Layout: manufacturing procedure

1. Copper layer 5 μm
   Kapton layer 50 μm
   DLC layer: 0.1-0.2 μm (10-100 MΩ/□)

2. DLC-coated kapton base material
   Insulating medium
   PCB (1.6 mm)

3. DLC-coated base material after copper and kapton chemical etching (WELL amplification stage)
Single Resistive Layer, edge grounding, 2D evac.
Current (d=10 cm)

Double Resistive Layer, 3D grounding (d’=1 cm)

Ω \text{ is the resistance seen by the current generated by a point-like radiation incident the center of the detector cell, } r \ll d

\[ \Omega_{\text{SRL}} \sim \rho_s \times \frac{d}{2\pi r} \]

\[ \Omega_{\text{DRL}} \sim \rho'_s \times \frac{3d'}{2\pi r} \]

If \( \rho_s = \rho'_s \rightarrow \)

\[ \frac{\Omega_{\text{DRL}}}{\Omega_{\text{SRL}}} = \frac{\rho (d' + d'/2)}{\rho \frac{d}{2}} = \frac{1.5}{5} = 0.3 \]

The rate capability depends on the inverse of \( \Omega \rightarrow \) for the DRL it can be expected a 3 times larger than SRL

(* Morello’s model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)
Space resolution vs DLC resistivity

With the charge centroid analysis (for orthogonal tracks) the track position is determined as a weighted average of fired strips.

\[
x_{hit} = \frac{\sum x_i \cdot q_i}{Q_{TOT}}
\]

The space resolution exhibits a minimum around 100 MΩ/□:

- at low resistivity the charge spread increases and then \( \sigma \) is worsening
- at high resistivity the charge spread is too small (Cluster-size \( \rightarrow 1 \) fired strip) then the Charge Centroid method becomes no more effective (\( \sigma \rightarrow \text{pitch/}\sqrt{12} \))
Each hit is projected inside the conversion gap, where the x position is given by each strip and the \( z = v_d t \). The drift velocity is provided by the Magboltz libraries.

The arrival time of the ionization clusters is obtained with a fit of the charge sampled every 25 ns (as seen by the APV25) from each FEE channel associated to the strip.

For each event we obtain a set of projected hits that once fitted provide a track segment

A fast time reference (\( t_0 \)) must be provided to define the intercept of the track-segment on the z-axis inside the gas gap
Conductive Grid: optimization

In order to reduce the dead area, we studied the Distance Of Closest Approach (DOCA) without discharges between two tips connected to an HV power supply. We recorded the minimum distance before a discharge on the DLC occurred vs the ΔV supplied for foils with different surface resistivity.

\[ \rho > 60 \text{ M}\Omega/\square \Rightarrow \text{DOCA} < 250 \mu m \]
Comparing different HR Layouts

Under the assumption of uniform irradiation, we can define an \textit{average effective resistance} (\(\Omega_{\text{eff}}\)) to ground as follows:

\[
\Omega = \frac{1}{\int_{DOCA}^{pitch/2} \delta x} \times \rho \times \int_{DOCA}^{pitch/2} x \delta x
\]

\[
\Omega = \frac{\rho}{2} \times (pitch/2 + DOCA)/w
\]

Where:
- \textit{pitch/2} is half of the distance between two grounding-grid lines
- \(\rho\) is the surface resistivity of the DLC layer
- \textit{DOCA} is the distance between the last (or first) amplification hole and the center of the grounding-grid line
### μ-RWELL vs GEM & MM

<table>
<thead>
<tr>
<th></th>
<th>μ-RWELL</th>
<th>GEM</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td># electrodes/components</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td># amplification stage</td>
<td>1 (*)</td>
<td>3</td>
<td>1 (*)</td>
</tr>
<tr>
<td>PCB splicing for large area</td>
<td>YES</td>
<td>NO</td>
<td>YES but not for mesh</td>
</tr>
<tr>
<td>Cleaning</td>
<td>easy</td>
<td>Very easy</td>
<td>YES-but not easy</td>
</tr>
<tr>
<td>Assembly</td>
<td>very easy</td>
<td>complex</td>
<td>simplest than GEM</td>
</tr>
<tr>
<td>Stretching</td>
<td>NO</td>
<td>YESx3</td>
<td>YES (mesh)</td>
</tr>
<tr>
<td>HV</td>
<td>2 chs - easy</td>
<td>7 floating chs</td>
<td>2 chs - easy</td>
</tr>
<tr>
<td>Technology Transfer → cost-effective mass production</td>
<td>easy</td>
<td>Not easy</td>
<td>YES-but not for mesh</td>
</tr>
<tr>
<td>Discharge protection</td>
<td>high</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>Rate capability</td>
<td>Medium/high</td>
<td>Very high</td>
<td>Medium/high</td>
</tr>
</tbody>
</table>

(*) amplification stage resistively coupled with readout

M. Poli Lener, MPDG 2019 - La Rochelle, 10/05/2019
OUTLINE

- Detector architecture & principle of operation
- From Single-Resistive layout to High Rate layouts: design & performance
- Time and Spatial resolution studies
- Technology Transfer to industry
- Summary
Time Performance (*)

Efficiency in 25 ns

Ar/CO2/CF4=45/14/40

Time already deconvoluted from the FEE contribution (25 ns/√12)

The saturation at 5.7 ns is dominated by the FEE (measurement with VFAT2)

Measurements done with GEM by LHCb group gave $\sigma_t = 4.5$ ns with VTX chip, constant fraction discriminator\(^1\).


\(^1\) G. Bencivenni et al, “Performance of a triple-GEM detector for high rate charged particle triggering”, NIM A494 (2002) 156