Update on μ-RWELL technology

G. Bencivenni¹
R. De Oliveira², G. Felici¹, M. Gatta¹, M. Giovanetti¹, G. Morello¹, A. Ochi³, M. Poli Lener¹, Y.Zhou⁴

1. Laboratori Nazionali di Frascati – INFN, Frascati - Italy
2. CERN, Meyrin - CH
3. Kobe University, Kobe - Japan
4. USTC, Hefei - PRC
OUTLINE

- Detector architecture & principle of operation
- Low rate layout: the single-resistive layer
  - performance & Technology Transfer to industry
- High rate layouts: design & performance at PSI
- Cylindrical IT based on μ-RWELL technology
- Summary
The µ-RWELL: the detector architecture

The µ-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 kapton foil acting as amplification stage
2. a resistive layer (*) for discharge suppression w/surface resistivity ~ 50-100 M$\Omega$/☐ - with different current evacuation schemes:
   i. LR, < 100 kHz/cm$^2$ - SHiP, CepC, STCF, EIC, HIEPA
   ii. HR, >1 MHz/cm$^2$ - LHCb-Muon upgrade & future colliders - CepC, Fcc-ee/hh
3. a standard readout PCB

(*) DLC = Diamond Like Carbon high mechanical & chemical resistant
Principle of operation

Applying a suitable voltage between the top copper 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, $\tau = \rho C$, determined by [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 $\Rightarrow \varepsilon_r$

- The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark.
- 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 scheme).
The Low Rate Layout

single resistive layer w/edge (2-D) grounding scheme

1. Copper layer 5 µm
   Kapton layer 50 µm
   DLC layer: 0.1-0.2 µm (10-200 MΩ/☐)

2. DLC-coated kapton base material
   Insulating medium (50-100 µm)
   PCB (1.6 mm)

3. DLC-coated base material after copper and kapton chemical etching (WELL amplification stage)

Joint Workshop of future tau-charm factory, Orsay - Dec. 6th 2018
Detector Gain

Single Resistive Layer prototypes with different resistivity have been tested with X-Rays (5.9 keV), with several gas mixtures, and characterized by measuring the gas gain in current mode.

Recent prototypes showed Gain $>10^4$ in $\text{Ar}/\text{CO}_2/\text{CF}_4 = 45/15/40$.
Space resolution vs DLC resistivity

Charge Centroid analysis (for orthogonal tracks) uses the charge to weigh the position of the fired strips. The track position is determined as a weighted average of fired strips.

The space resolution exhibits a minimum around \(100 \, \text{M}\Omega/\square\)

- 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 (\(\sigma \rightarrow \text{pitch}/\sqrt{12}\)
Space resolution vs inclined tracks: μ-TPC mode

For inclined tracks and/or in presence of high B field, the charge centroid method gives a very broad spatial distribution on the anode-strip plane. In the u-TPC mode each ionization cluster is projected inside the conversion gap, then, from the knowledge of the drift time of primary electrons, the track segment in the gas gap can be reconstructed.

The method has been introduced for MMs by T. Alexopoulos (NIM A 617 (2010) 161):

• the information of the **arrival time of primary electrons** can be extracted from the **time sampling** of the APV signal

• 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
Space resolution vs inclined tracks: μ-TCP mode

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

Ar:CO₂:CF₄ 45:15:40 - HV=600V, Ed=1kV/cm, Gain ~10⁴

The combination of the CC and the μ-TPC mode with $E_d = 1$ kV/cm

The combined spatial resolution is almost flat over a wide range of incidence angles

The combination of the CC and the μ-TPC mode with $E_d = 1$ kV/cm

The combined spatial resolution is almost flat over a wide range of incidence angles
The engineering and industrialization of the μ-RWELL technology is one of the main objective of the project. TT to industry can open the way towards cost-effective mass production. Manufacturing process of the single resistive layer has been extensively tested at the ELTOS SpA (http://www.eltos.it)

Production Tests @ ELTOS:
- 10x10 cm² PCB – (PAD r/o)
- 10x10 cm² PCB – (strip r/o)
- 1.2x0.5m² (strip r/o)
- 1.9x1.2m² (strip r/o)

Etching of the kapton done by Rui @ CERN
Kapton etching test @TECHTRA (Poland) planned for the near future.
High rate layouts
High rate layout: the double-resistive layer

The idea is to reduce the path of the current on the DLC implementing a matrix of conductive vias connecting two stacked DLC layers. A second matrix of vias connects the second resistive layer to ground through the readout electrodes (3-D grounding scheme).

The pitch of the vias is typically of the order 1/cm² (or less).

**WARNING:** The engineering/industrialization of the double-resistive layer seems to be difficult due to the manufacturing of the conductive vias on kapton foil.
New ideas for the HR layout

Simplified HR schemes are based on the Single Resistive layout with surface grounding by conductive strip lines realized on the DLC layer. The conductive grid can be screen-printed as well as etched (if a Cu deposition is done on top of the DLC layer).

<table>
<thead>
<tr>
<th>High Rate layout</th>
<th>Resistivity [MΩ/□]</th>
<th>Dead Area over grid</th>
<th>Grid Pitch</th>
<th>Geometrical acceptance [%]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG1</td>
<td>70</td>
<td>2 mm</td>
<td>6 mm</td>
<td>66</td>
<td>conductive grid</td>
</tr>
<tr>
<td>SG2</td>
<td>65</td>
<td>1,2 mm</td>
<td>12 mm</td>
<td>90</td>
<td>conductive grid</td>
</tr>
<tr>
<td>SG2++ (*)</td>
<td>64</td>
<td>0,6 mm</td>
<td>12 mm</td>
<td>95</td>
<td>conductive grid</td>
</tr>
</tbody>
</table>

(*) the base material of the SG2++, DLC+Cu polyimide foil, has been produced by Zhou Yi – USTC, Hefei (PRC).

The conductive grid on the bottom of the amplification stage can induce instabilities due to discharges over the DLC surface, thus requiring for the introduction of a small dead zone (2xDOCA) on the amplification stage.
As expected the **DL prototype** reaches **full tracking efficiency** – 98% (NO DEAD ZONE). The SG1, SG2 and SG2++ show lower efficiency (76% -94% - 97%) BUT higher than their geometrical acceptance (66% - 90% - 95% respectively), thanks to the **efficient electron collection mechanism** that reduce the effective dead zone.
Rate Capability for HR Layout

Gain=5000, beam spot up to 7 cm² FWHM

The gain drop is due to the **Ohmic effect** on the resistive layer: the currents collected on the DLC drift towards the ground facing an effective average resistance $\Omega$, depending on the evacuation scheme geometry (i.e. effective pitch) and the DLC surface resistivity.
Lower the effective average resistance ($\Omega$) higher the rate capability

(under the assumption of uniform irradiation)

$$\Omega = \frac{\rho}{2} \times \left( \text{pitch}/2 + \text{DOCA} \right)$$
Cylindrical μ-RWELL

The Cylindrical MPGD concept, introduced the first time with GEMs (KLOE & BESIII), can be applied also to μ-RWELL (C-RWELL), with several advantages wrt CGEMs:

- lower material budget, down to 1-1.2% $X_0$ for n. 4 C-RWELL layers (tbc with 2% $X_0$ for KLOE2-CGEM)

- more simple construction/assembly and cheaper: less cylindrical electrodes (2 instead of 5), less toolings are required (2 molds instead of 5)

- the concepts of “openable detector”, “floating-amplification”, “reversed conical hole shape” (increasing the gain), can be easily implemented for the μ-RWELL making the C-RWELL more reliable & performing than CGEM (great advantages for detector debug & fixing – when needed, while the spark suppression mechanism of the μ-RWELL make the operation of the detector more safe)

- μ-RWELL operated in micro-TPC mode exhibits a spatial resolution down to 40-60 μm over a wide track incidence angular range (0-45°)
The μ-RWELL is a breakthrough technology suitable for large area planar tracking devices as well as ultra-light high space resolution Cylindrical Inner Trackers:

The detector has been extensively characterized

- gas gain $\geq 10^4$
- rate capability $> 1 \text{ MHz/cm}^2$ (w/HR layouts)
- space resolution $< 60\mu\text{m}$ (over a large incidence angle of tracks)
- time resolution $\sim 5.7$ ns

The technology is ready for TT to industry

- low rate version is already partially built outside CERN at ELTOS, while test at TECHTRA is going to be started
- the R&D on new high rate layouts is almost completed & for TT to Industry

Exploiting the μ-RWELL technology for Cylindrical IT seems to have many advantages with respect to what has been done till now with standard GEM technology
SPARES SLIDES
Maximum Gain under heavy irradiation

![Graph showing gain vs. voltage](image-url)
Increasing the Gain of a factor of 2 (I)

Gain for different hole shapes

FTM (140/50/70) vs $\mu$-RWELL (140/70/50)

(a) Ratio of $G_{FTM}/G_{\mu$-RWELL}$

(b) $\Delta G = (G_{FTM} - G_{\mu$-RWELL})/G_{\mu$-RWELL}$

Figure: Gain ratio for different hole shapes ($70/50 = \mu$-RWELL; 60/50; 50/50; 50/60; 50/70 = FTM) in Ar:CO$_2$ 70:30 (left) and the percentual difference of the gain $\Delta G$ (%) (right).

(Dashed= no Penning, Full= Penning included)
Increasing the Gain of a factor of 2 (II)

E field: hole shape $\mu$-RWELL vs FTM

(a) Electric Field calculated for different well geometries

(b) Ratio Inverted / Normal geometry

Figure: Electric Field calculated for different well geometries, starting with the Standard geometry with a top diameter of 70 $\mu$m and bottom diameter of 50 $\mu$m, reducing first the top diameter to 50 $\mu$m with a step of 10 $\mu$m, then changing the bottom diameter to 70 $\mu$m, arriving at the Inverted geometry with 50 $\mu$m top diameter and 70 $\mu$m bottom diameter (left). Ratio of the Inverted and Simulation Studies for the fast-timing module (FTM)
Towards High Rate grounding schemes

single resistive layer, edge grounding, 2D evac. current

double resistive layer, 3D grounding (1cm)d'
d' top layer

d (50cm)

d

cast

cast

cast

cast

cast

cast

cast

cast

cast

(* point-like irradiation, $r \ll d$

$\Omega$ is the resistance seen by the current generated by a radiation incident the center of the detector cell

$\Omega \sim \rho_s \times d/2\pi r$

$\Omega' \sim \rho'_s \times 3d'/'2\pi r$

$\Omega / \Omega' \sim (\rho_s / \rho'_s) \times d/3d'$

If $\rho_s = \rho'_s \rightarrow \Omega / \Omega' \sim \rho_s/\rho'_s \times d/3d' = 50/3 = 16.7$

(*) Morello's model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)

Joint Workshop of future tau-charm factory, Orsay - Dec. 6th 2018
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.

\[
\rho \sim 60-80 \text{ MΩ/□} \Rightarrow \text{DOCA} < 300 \mu\text{m}
\]

\[\text{DOCA} = 300 \mu\text{m}\]
Different chambers with different dimensions and resistive schemes exhibit a very similar behavior although realized in different sites (large detector realized @ ELTOS).
The saturation at 5.7 ns is dominated by the FEE (measurement with VFAT2).
Comparing different HR Layouts

Under the assumption of uniform irradiation, we can define an average effective resistance ($\Omega$) to ground as follows:

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

$$\Omega = \frac{\rho}{2} \times (\text{pitch}/2 + DOCA)$$

Where:
- $\text{pitch}/2$ is half of the distance between two grounding-grid lines
- $\rho$ is the surface resistivity of the DLC layer
- DOCA is the distance between the last (or first) amplification hole and the center of the grounding-grid line
## HR proto parameters

<table>
<thead>
<tr>
<th></th>
<th>SG1</th>
<th>SG2</th>
<th>SG2++</th>
<th>DL</th>
<th>LR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grid-pitch</strong></td>
<td>6 mm</td>
<td>12 mm</td>
<td>12 mm</td>
<td>6 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td><strong>Dead zone</strong></td>
<td>2 mm</td>
<td>1.1</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Conductive line width</strong></td>
<td>300 um</td>
<td>300 um</td>
<td>100 um</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Doca (distance of close approach) between edges active area &amp; conductive line</strong></td>
<td>0.85 mm</td>
<td>0.45 mm</td>
<td>0.25 mm</td>
<td>7 mm (path between vias on the 2nd layer)</td>
<td>5.5 mm</td>
</tr>
<tr>
<td><strong>Effective average resistance to ground</strong></td>
<td>134 MΩ</td>
<td>209 MΩ</td>
<td>200 MΩ</td>
<td>640 MΩ</td>
<td>1947 MΩ</td>
</tr>
<tr>
<td><strong>Nominal resistivity</strong></td>
<td>70 MΩ/□</td>
<td>65 MΩ/□</td>
<td>64 MΩ/□</td>
<td>75 MΩ/□</td>
<td>70 MΩ/□</td>
</tr>
</tbody>
</table>
Preliminary study: $\mu$-RWELL vs GEM

- discharges for $\mu$-RWELL are of the order of few tens of nA (<100 nA @ high gain)
- for GEM discharges the order of 1\(\mu\)A are observed at high gas gain
The ageing effects on DLC is under study at the GIF++ by irradiating different \( \mu \)-RWELL prototypes operated at a gain of \( \sim 4000 \). On the most irradiated detector (\( \sim 200 \text{ kHz/cm}^2 \text{ m.ip. equivalent} \)) a charge of about 180 mC/cm\(^2\) has been integrated (in about 240 days up-time of the source). No effects have been observed till now. Detectors will be opened by the end of the 2018.