Status of the R&D on µ-RWELL

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Outline

- Detector architecture & principle of operation
- The low rate layout
- High rate layouts
- Space resolution studies
- Technology transfer
- Summary
Motivations

The R&D on µ-RWELL aims for a step-forward in terms of

- stability under irradiation (→ discharge mitigation)
- simplified construction/assembly
- technology transfer to industry (→ mass production)

a MUST for large scale applications in fundamental research at future colliders, for large area applications and for technology dissemination beyond HEP
The architecture

The μ-RWELL is a simple device composed of only two elements: the μ-RWELL_PCB & the cathode

The μ-RWELL_PCB is realized by coupling:
1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression w/surface resistivity ~ 50 ÷ 200 MΩ/☐
3. a standard readout PCB

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

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

$$C = \varepsilon_0 \times \varepsilon_r \times \frac{s_{pad}}{t} \approx 36 \, pF \times S (cm^2)$$
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.

1 - Large area bare DLC deposition is performed in Japan by the Be-Sputter (Kobe) The DLC uniformity on large foils, 1.2×0.6 m², is at level of ± 30%.

2 - Recent developments, at USTC – Hefei (PRC), brought to the manufacturing of DLC+Cu sputtered Apical® foils, where an additional layer of few microns of Cu above the DLC coating is deposited. This new technology open the way towards improved high rate μ-RWELL layouts.
The Low Rate Layout

Single Resistive Layer (SRL): a simple 2-D current evacuation scheme through a simple DLC film 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 incidence point, giving rise to detector response inhomogeneity → limited rate capability (~$5\div10$ kHz/cm$^2$ for a ~50x50cm$^2$ detector tile).
Towards high rate layouts

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

**Two layouts (but other ideas are under evaluation)** 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)** patterned on the resistive stage
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 further matrix of vias to the underlying readout electrodes. The pitch of the vias can be done with a density less than 1/cm². Realized with Sequential Build Up (SBU) technology.
The SG is a simplified HR layout based on the Single Resistive layer with a 2-D grounding by means a conductive strip lines grid patterned on the DLC layer. The conductive grid lines can be screen-printed or etched by photo-lithography (using the DLC+Cu deposition technology developed at USTC – Hefei), with a strip pitch of the order of 1/cm².

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.
The main application: LHCb

Detector requirements for HI-Lumi LHCb

- Rate ≥ 1 MHz/cm² on detector single gap
- Max input capacitance (double gap) ≤ 100 pF
- Efficiency (double gap) > 97% within a BX (25 ns)
- Pad cluster size < 1.2
- Long-term stability up to 1,6 C/cm² accumulated charge in 10 y of operation (M2R1 – with detector operated at G=4000)

Detector size

- **R1÷R2:** 288 detectors, size 30x25 to 74x31 cm², 45 m² det. - 65 m² DLC+Cu
- **R3:** 384 detectors, size 120x25 to 149x31 cm², 145m² det. - 207 m² DLC
- **R4:** 1536 detectors, size 120x25 to 149x31 cm², 582 m² det. - 831 m² DLC
Detector performance

Gain up to $\sim 10^4$

Rate capability (@ $G = 4000$) $\sim 10$ MHz/cm$^2$

Efficiency (SG2++ & DLR) $\sim 98$

$\sigma_t \sim 5$-6 ns (single gap)

Efficiency in 25 ns (single gap)

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Discharge studies

The µ-RWELL discharge probability measured at the PSI, and compared with the measurement done with GEM at the same time and in the 2004 (same gas mixture $\text{Ar:CO}_2:\text{CF}_4 = 45:15:40$).

The measurement has been done in 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 µ-RWELL comes out to be similar to the one measured for GEM. Moreover its discharge amplitude seems to be lower than the one measured for GEM.
The presence of the resistive layer affects also the charge spread on the readout strips and consequently the space resolution of the detector. With the charge centroid (CC) analysis (for orthogonal tracks) the track position is determined as a weighted average of fired strips.

The space resolution exhibits a minimum around 100 MΩ/□:
- at low resistivity the charge spread increases and then σ is worsening
- at high resistivity the charge spread is too small (cluster-size → 1 fired strip) then the CC method becomes no more effective (σ → pitch/√12)
Orthogonal vs inclined tracks

For inclined tracks and/or in presence of high B field, the CC method for MPGD gives a very broad charge spatial distribution on the anode-strip plane.

In the u-TPC mode (*), from the knowledge of the drift velocity 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 drift region is reconstructed.

(*) introduced for MMs by T. Alexopoulos (NIM A 617 (2010) 161)
The fit of the rise-time of the signal (with a Fermi-Dirac) gives the arrival time of drift electrons (corresponding to the inflection point of the fitting curve).

From the knowledge of the drift velocity, the track inside the drift gap is reconstructed.
Global Spatial Resolution

Ar:CO$_2$:CF$_4$ 45:15:40, Ed=0.5kV/cm, HV=600V, Gain $\sim 10^4$

Tuning the drift field an almost flat distribution over a wide incidence angle range is obtained with the $\mu$TPC mode. The smaller the drift field, the smaller the drift velocity, making easier for the FEE to discriminate between different clusters by their arrival times. The measurements were taken using APV25.
Status of the technology

• The whole R&D has been performed at the CERN PCB-Workshop (Rui de Oliveira)

• The detector is based on **Sequential Build Up (SBU) technology**, this means that the **Technology Transfer** to industry is **easy** → **cost effective mass production**

• All manufacturing process of the detector components are in our hands apart the **DLC** sputtering:
  - large area (bare) **DLC** foil sputtering at **Be-sputter in Japan**: 60×120 cm²
  - **R&D on DLC+Cu** sputtering (@ **USTC – Hefei – PRC**: 30×30 cm² → 30×120 cm²

**Things to do**

• Looking for **DLC/DLC+Cu production in Europe**
• **Validation test of DLC + aging studies**
The engineering and industrialization of the $\mu$-RWELL technology is one of the main goals of the project.

**Production tests of the SRL layout @ ELTOS:**
- $10 \times 10 \text{ cm}^2$ PCB – (PAD r/o)
- $10 \times 10 \text{ cm}^2$ PCB – (strip r/o)

**Large area tests @ ELTOS:**
- $1.2 \times 0.5 \text{ m}^2$ with strip r/o
- $1.9 \times 1.2 \text{ m}^2$ with strip r/o - (w/PCB splicing of tile w/size $40 \times 50 \text{ cm}^2$)
- $33 \times 33 \text{ cm}^2$ with strip r/o

Kapton etching done @ CERN
ELTOS performs the coupling of the DLC-foil with the readout PCB (only for the SRL layout). The max size of the μ-RWELL-PCB that can be produced by ELTOS is about 60x70 cm². Up to 8 PCBs of such size can be manufactured at the same time.

The manufacturing procedure is slightly different from the one used by Rui, but works fine.

Discussion in progress on a possible R&D on PI etching in ELTOS
Large area detectors

Very large area detectors can be realized by splicing detector tiles with small dead zone (< 1mm), as demonstrated with the large GE2/1 RWELL proto for CMS.

GE2/1 RWELL detector: ELTOS + CERN (Rui) manufacturing
DLC production in Europe

• Possible solution: installation of a magnetron sputtering machine at CERN (co-funded by CERN, LNF-INFN and possibly by other European Institutions ...)

• The machine should have the following features:
  
  • Chamber size: Φ800mm × 900mm
  • Max foil size with good DLC uniformity: ~ 50×200 cm²
  • Equipped w/automatic shutter, allowing the DLC and Cr/Cu coating in the same batch
Chung-Chuan Lai, Per-Olof Svensson, Linda Robinson
Detector Group - European Spallation Source ERIC - Linköping, Sweden

Experts in sputtering deposition (especially B4C)

Recently they showed interest in the R&D on DLC/DLC+Cu deposition

Max deposition size: 650×650 mm²
DLC & detector long-term stability, that for HR applications, must be verified up to 1-2 C/cm², are clearly mandatory.

- long term test of DLC foils (thin vs thick) under high current
- long term test of DLC foils under X-ray irradiation
- aging test of detectors with different radiation (gammas, X-ray, mip)
DLC stability tests

\[ R = \rho_s \times \ln \left( \frac{R_{\text{out}}}{R_{\text{in}}} \right) / 2\pi \]

- The DLC resistivity is measured/monitored with the usual annular probe
- Its long term stability (\(\Delta \rho < 10\%\)) tested under different conditions (with & without X-ray irradiation), simulating an integrated charge of the order 0,8 mC/cm\(^2\).
- The temperature dependence of the DLC resistivity has been also measured
Several irradiation tests have been performed with different radiation:

- **662 keV gammas (GIF++)**
- **5.9 keV X-Ray (LNF – lab)**
- **350 MeV/c pions/protons (PSI)**
Detector features

The μ-RWELL is a single-amplification stage resistive MPGD characterized by:

**Very simple design/assembly-procedure**
- only two components, the main one including readout & gas amplification stage
- no critical & time consuming assembly steps
  - no gluing
  - no stretching
  - easy handling
- suitable for large area with PCB splicing technique w/small dead zone
- the flexible version is a valuable and simplified option for cylindrical detectors

**Cost effective & mass-production technology**
- based on Sequential Build Up (SBU) technology, allowing an easy TT to industry operating in the field of multi-layer PCB

**Easy to operate**
- very simple voltage supply is required → only 2 independent HV channels or trivial passive divider
SUMMARY

The detector performance

- gas gain $\geq 10^4$
- rate capability $\geq 10$ MHz/cm$^2$ (w/HR layouts)
- space resolution $< 65\mu$m (over a large incidence angle of the tracks)
- time resolution $\sim 5.7$ ns

The experiments

- upgrade of the LHCb Muon apparatus
- EU project ATTRACT-URANIA as neutron detection
- EU project CREMLINplus as Cylindrical Inner Tracker at the SCTF

Future plans

- Production tests of the HR version of the detector at CERN
- Technology Transfer to industry (ELTOS)
- Import DLC technology in Europe
- Long term stability studies under irradiation

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References


• G. Bencivenni et al., *The μ-RWEL detector*, 2017 *JINST* **12** C06027


• G. Bencivenni et al., *The μ-RWELL layouts for high particle rate*, 2019 *JINST* **14** P05014

Charging up as observed @ G = 3000.
- The Gain drop is of the order of 15%.
- The measurement has been done on a 10x10 cm$^2$ active area irradiated with a thermal neutron flux of 750 Hz/cm$^2$ at the HOTNES neutron facility of the ENEA – Frascati.
- ~16 h monitoring
- ~1 h charging-up drop time
<table>
<thead>
<tr>
<th>#</th>
<th>Det</th>
<th>Layout</th>
<th>Active area [cm²]</th>
<th>DLC type</th>
<th>DLC resistivity [MΩ/□]</th>
<th>Gain</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Low Rate</td>
<td>5x5 Single PAD</td>
<td>Screen Printing &amp; Dot</td>
<td>100/100</td>
<td>8x10³</td>
<td>1</td>
<td>first detector 2009</td>
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<tr>
<td>1</td>
<td>Low Rate</td>
<td>5x5 STRIP</td>
<td>DLC JAP</td>
<td>880/N.A.</td>
<td>3x10⁴</td>
<td>1</td>
<td></td>
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<tr>
<td>1</td>
<td>Low Rate</td>
<td>5x5 STRIP</td>
<td>DLC JAP</td>
<td>80/N.A.</td>
<td>10⁴</td>
<td>1</td>
<td></td>
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<tr>
<td>1</td>
<td>Low Rate (CMS GE1-1)</td>
<td>1200x500 STRIP</td>
<td>DLC JAP</td>
<td>16 sectors: &lt;70&gt;</td>
<td>8x10³</td>
<td>Only 4 sectors working TB Nov. 2016 - GIF++</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Low Rate (CMS GE2-1)</td>
<td>600x470 STRIP</td>
<td>DLC JAP</td>
<td>N.A.</td>
<td>&gt; 5 x10³</td>
<td>1</td>
<td>Never Working</td>
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<td>#21</td>
<td>Low Rate</td>
<td>10x10 PAD/STRI P</td>
<td>DLC JAP</td>
<td>&lt;108&gt;/N.A.</td>
<td>&gt;8x10³</td>
<td>#2 detector in short: 1 is recovered, 1 is under HV recovery</td>
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<tr>
<td>Tot</td>
<td>24 Low Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

~10 ±12 % failure on LR layout

+ n. 32 LR 10×10 cm² to be built for uRANIA
+ n. 6 LR 33×33 cm²

<table>
<thead>
<tr>
<th>#</th>
<th>Det</th>
<th>Layout</th>
<th>Active area [cm²]</th>
<th>DLC type</th>
<th>DLC resistivity [MΩ/□]</th>
<th>Gain</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>High Rate Single Res. Layer (buried resistor/grid)</td>
<td>10x10 PAD/STRI P</td>
<td>DLC JAP</td>
<td>N.A./&lt;56&gt;</td>
<td>&gt;8x10³</td>
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<td></td>
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<td>High Rate Double Res. layers</td>
<td>10x10 PAD</td>
<td>2 DLCs JAP</td>
<td>N.A./&lt;54&gt;</td>
<td>&gt; 10⁴</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>High Rate Single Res. Layer (grid) - SG2++</td>
<td>10x10 PAD</td>
<td>DLC PRC/Cu</td>
<td>N.A./64</td>
<td>10⁴</td>
<td>Production 2018</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>High Rate Single Res. Layer (grid)- SG2++</td>
<td>10x10 PAD</td>
<td>DLC PRC/Cu</td>
<td>N.A./&lt;27&gt;</td>
<td>&gt;=4x10³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>High Rate Double Res. layers - SBU</td>
<td>10x10 2D-STRI P</td>
<td>DLC - PRC/Cu</td>
<td>N.A./N.A.</td>
<td>4x10³</td>
<td>TB PSI 2019 – Current instability under irradiation</td>
<td></td>
</tr>
<tr>
<td>Tot</td>
<td>17 High rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

~ 5 ±15 % failure on HR layout

+ n. 20 SG2 10 x 10 cm² under construction by Rui

small production test in order to check: quality, yield ...

+ some medium size SG2 (30×25 to 74×31 cm²)
Detector Gain

Gas gain of detectors as measured with a 270 MeV/c \( \pi^+ \) beam at PSI with particle fluxes ranging from ~320 kHz/cm² up to ~1.2 MHz/cm². Gas gain measured with X-rays (5.9 keV), for several gas mixtures.
• The spatial resolution can be evaluated avoiding trackers contribution with at least two µ-RWELL chambers in the same operating condition. The reasonable assumption is that they have the same spatial resolution.

• For a fixed incidence angle, the residuals were evaluated event by event as the difference of the coordinate of the two hits.

• Thus the resolution of the µ-RWELL is:

\[ \sigma_{\mu\text{RWELL}} = \frac{1}{\sqrt{2}} \sigma_{\text{residual}} \]

• Residuals distribution were studied both for CC reconstructions than for µTPC ones.
Cluster Size

H4 beam area (RD51) Muon beam momentum: 150 GeV/c
\( \mu \)-RWELL with 400 \( \mu \)m pitch strips readout by APV25 - drift gap 6 mm

Ar/CO2/CF4=45/14/40 @ G=5000

With a 3 mm drift gap as foreseen for LHCb, the CS should be smaller

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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 supplied voltage DV for foils with different surface resistivity.

\[ \rho > 60 \text{ M}\Omega/\square \implies \text{DOCA} < 250 \text{ \(\mu\)m} \]
Large area detectors

GE2/1 RWELL performance

Figure 1.17: First estimation of the efficiency for the top (top), and bottom (bottom) region of the M4-right tested.

Figure 1.18: Efficiency of the M4-right $\mu$-RWELL detector.
Milestones of the Project

- **2009** - first idea of the $\mu$-RWELL detector (Blind-GEM at that time) has been developed in parallel/collaboration with GDD and Rui.
- **2014/15** – start of the R&D on $\mu$-RWELL
- **2015/18** – R&D funded by Commissione Nazionale V – INFN in the framework of MPGD-NEXT program
- **2017/20** – TT to industry funded by Commissione Nazionale I – INFN in the framework of RD-FA program
- **2018/20** – R&D on advanced DLC deposition (DLC+Cu) by Common Project RD51 – CERN program
- **2019/20** – R&D on $\mu$-RWELL for thermal neutron detection funded by EU – ATTRACT in the framework of the URANIA project
- **2020/23** – R&D on Cylindrical $\mu$-RWELL funded by EU – CREMLIN-PLUS program
- **2019/20** – proposal for R&D + TT of micro-RWELL technology in the framework of AIDA++ (funded 2021/24)