Recent Advances with RPWELL detectors: Physics and potential applications

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The Resistive-Plate WELL (RPWELL): a robust single-element detector

- Single-sided THGEM
- Coupled to segmented readout through material of high bulk resistivity \((10^9 \text{ – } 10^{12} \, \Omega \text{ cm})\)
- Combining MPGD and RPC concepts

**Features:**

**Discharge-free operation** (Gain \(10^4 \text{ – } 10^7\))

- With Ne- and Ar-based gas mixtures
- Broad dynamic range: MIPs (\(\mu, \pi\)); x-rays, UV-photons
- Low avg. pad multiplicity at High efficiency
- Up to 50x50 cm\(^2\) RPWELL prototypes tested
- Gain stabilization mechanisms studied
- Moderate counting rates (\(~10^4 \text{ Hz/cm}^2\))
- Sub-mm localization resolution (\(\sigma \approx 280 \, \mu\text{m}\))

2013 JINST 8 P11004
2016 JINST 11 P01005
2016 JINST 11 P09013
*NIM A 845 (2017) 262 -265*
2017 JINST 12 P10017
2017 JINST 12 P09036
arXiv:1904.05545v1
Motivation

Applications requiring **cost-effective large-area detectors with moderate spatial resolution.**

Single-stage **sampling elements** for (Semi) Digital Hadronic Calorimeter – *(S)*DHCAL - Up to 50x50 cm² RPWELL prototypes *(Talk by Dan Shaked Renous).* [arXiv:1904.05545v1](https://arxiv.org/abs/1904.05545v1)

Single- & double-stage **RPWELL-based detectors** - potential candidates for **UV-photon detection @ Room Temperature (RT)**
With high dynamic range and detection efficiency

**Cryogenic RPWELL-based detectors** at LXe & LAr Temperatures *(T) →*
- UV-photon detection in noble-liquid detectors with **Cryogenic Gaseous Photomultipliers (GPM);** neutrino physics, Dark Matter & other rare-event searches, fast-neutron and Gamma-imaging.
- **Charge multipliers in dual-phase noble-gas detectors:** investigating possible operation at higher stable gain relative to LEM (Large Electron Multipliers).
- **Immediate challenge → Resistive materials** of $\rho = 10^9 – 10^{12} \Omega\text{-cm}_\text{bulk}$ resistivity @ LXe & LAr T.
Single-stage sampling elements for (Semi) Digital Hadronic Calorimeter – (S)DHCAL

Physics requirements:
- High detection efficiency
- Low pad multiplicity
- Moderate rate capability
- Stability over wide dynamic range

Reached DHCAL requirements with RPWELL
- 98% efficiency
- Multiplicity 1.2
- No efficiency loss up to $10^4$ Hz/cm$^2$
- Stable operation in high intensity pion beam – No discharge over $10^8$ events
- Total thickness ~ 5 mm w/o electronics
- Use of Argon gas – Low cost, high # of PEs, low diffusion

Meet DHCAL requirement for a single sampling element

JINST (2016) P09013 ; JINST (2016) P01005
Double-stage RPWELL-based detectors -- potential candidates for UV-photon detection @ RT
RPWELL–based 2-stage UV-photon detector (RT)

MOTIVATION: enhanced Polya distributions ➜ increase efficiency for single photons (e.g. in RICH)

RT UV photon detection with MPGD for RICH
Recent example: COMPASS RICH-1

J. Agarwala et al., NIM A (2019),
https://doi.org/10.1016/j.nima.2019.01.058
(Micromegas +THGEM based)

Get Signal pulse-height distribution with peaked Polya distribution

⇒ Better signal-to-noise ratio (compared to an exponential distribution)
⇒ Increased single photon detection efficiency

\[ P(N_e) = \frac{(1+\theta)^{N_e}}{\Gamma(1+\theta)} \left( \frac{N_e}{\bar{N}_e} \right)^\theta \exp \left[ -(1+\theta) \frac{N_e}{\bar{N}_e} \right] \]

where \( \bar{N}_e \) is the mean gain and \( \theta \) the Polya parameter which gives the relative gain variance \( f \):

\[ f = \left( \frac{\sigma_{N_e}}{\bar{N}_e} \right)^2 = \frac{1}{1+\theta} \]

Byrne J, NIM A 74 (1969) 291-296
RPWELL–based 2-stage UV-photon detector (RT)

- Double Stage RPWELL – high dynamic range of gain
- Clear Polya distribution, improves with higher gain
- Stable operation up to high gain

Detector parameters:
- 5 mm Drift Gap; 2 mm Transfer gap
- 0.6 mm thick CsI-coated Double-sided THGEM
- 0.4 mm thick Single-sided THGEM
- 0.4 mm thick Semitrion as RP
- Source: Hg Lamp
- Gas: Ne/5%CH₄

Single Electron Spectrum Evolution, $\Delta V_{RP} = 500 – 775$V

- Gas: Ne/CH₄ 95/5
- $\Delta V_{THGEM} = 700$ V
- Drift Field = 0 V/cm
- Transfer Field = 500 V/cm

Counts

0 5 10 15 20
Electrons

$9.4 \times 10^4$ $4.2 \times 10^5$ $1.0 \times 10^6$ $3.4 \times 10^6$

$5.5 \times 10^6$
Efficiency estimated numerically - from the fitted spectrum

Electronics threshold $\sim 10^4$ electrons $\rightarrow$ Detecting single electrons ($\theta \sim 0.2$) with $> 90\%$ efficiency

The spectra were fitted with $P(N_e, \theta)$

The spectra were fitted with $P(N_e, \theta)$

- $\theta$ parameter vs $Gain$, Efficiency($e$) & $% (CH_4)$ in Ne
  - Observation: Increase in CH$_4$ $\rightarrow$ lower $\theta$ at same gain
  - Preliminary - Stable UV detection ($\varepsilon>90\%$) under 6 keV X-ray background.
  - Ongoing measurements: lower gains, Ar-mixtures & background rate dependence

Observed Gas Mixture dependence
Cryogenic-RPWELL

In collaboration with:

Carlos Pecharromán (Instituto de Ciencia de Materiales de Madrid, ICMM)
Miguel Morales (University of Santiago de Compostela, USC) and
Diego Gonzalez Diaz (University of Santiago de Compostela, USC)

Thanks!
## Challenges for low-T operation: Resistive-plate materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Volume Resistivity ($\rho$)@ RT</th>
<th>Resistivity as f(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semitron ESD 225 (Acetal based)</td>
<td>Quadrant Plastics USA</td>
<td>1.5x10^9 Ω-cm</td>
<td>Quenches discharges completely at RT. $\rho$ increases exponentially with decreasing T. Investigated with small RPWELL prototypes</td>
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<tr>
<td>Low Resistivity Silicate (LRS) Glass</td>
<td>Prof. Wang Yi; Tsinghua University, China</td>
<td>2x10^{10} Ω-cm</td>
<td>Quenches discharges completely at RT. $\rho$ increases exponentially with decreasing T. Investigated @ RT with up to 50x50 cm$^2$ RPWELL</td>
</tr>
<tr>
<td>Ferrite Ceramics</td>
<td>C Pecharromán, M Morales et al, ICMM/CSIC, Spain</td>
<td>~10$^5$ - 10$^7$ Ω-cm</td>
<td>$\rho$ increases exponentially with decreasing T but tunable. Investigated in RPWELL down to 150K</td>
</tr>
</tbody>
</table>

Other Resistive materials tested → **Fail to quench Discharges @ RT and/or low T**:

1. Tivar EC (UHMW-PE) & Tivar ESD (UHMW-PE) -> Prof. Jerry Vavra, SLAC, $\rho \sim 10^6 - 10^7$ Ω-cm, constant as f(T); $\rho$ too low - fails to quench discharges.
2. (PTFE + 1.5% Carbon) -> 3M, USA, $\rho \sim 10^7 - 10^8$ Ω-cm (function of Carbon content); constant as f(T); $\rho$ too low - fails to quench discharges.
3. Araldite + Graphite (Graphite % from 15-30 %) -> Fabricated @WIS, $\rho \sim 10^8 - 10^{14}$ Ω-cm. Fails to quench discharges.
4. Si-based Ceramics -> Prof. Lothar Naumann, HZDR, Germany, $\rho \sim 10^8$ Ω-cm. $\rho$ too low @ RT increases exponentially with decreasing T, unsuitable @low T.
The Resistive Plate - Fe Ceramics

- Resistive materials range $\rho \sim 10^9 - 10^{12}$ $\Omega \cdot$cm 
  (LXe & LAr T’s)

- Semitron & LRS Glass (suitable @ RT)
  $\rho > 10^{14}$ $\Omega \cdot$cm around 200K.

- Fe-Ceramics - robust ceramic composites with tunable electrical properties 
  (C Pecharrromán, M Morales et al; 2013 JINST 8 P01022)

- Sample S24: $\rho \sim 10^{11}$ $\Omega \cdot$cm @ LXe Temp 
  (measured in controlled conditions).

- Preliminary $\rho$ measurements down to LAr T.
  Promising results with ZN80

- Dedicated experiments ongoing @ USC, Spain and WIS to understand the behavior.
First Fe-Ceramic RPWELL @ LXe T

- First proof of discharge-free RPWELL detector operation at 163K !!

- Fe-Ceramic RPWELL tested in Ne/5%CH₄ at RT & low T in LN₂ + ethanol bath down to 160 K (ρ~ 10¹¹ Ω-cm)

- Detector investigated with X-rays & single UV-photons (RPWELL without/with CsI photocathode)

Fe Ceramic RPWELL compared to THWELL (same THGEM, but with standard Cu anode)
Single-stage Cryo-RPWELL – first results @ 163K

Discharge-free RPWELL operation up to $\sim 10^4$ gain with X-rays, and $\sim 10^5$ with single UV-photons (without CsI) @ 163K
Cryo-RPWELL Results @ 163K – Discharge behavior

Discharge behavior at 163K:

RPWELL → **Discharge-free operation** upto $10^4$ gain. ~5nA discharges @ gain > $10^4$. THWELL → ~200nA discharges! Onset of discharges around $10^3$ gain (850V). Unstable @ $10^4$ gain. Regular discharges
2-stage THGEM+ Cryo-RPWELL – first results @ 163K

Detector parameters:
- 5 mm Drift gap; 2 mm Transfer gap
- 0.6 mm thick CsI-coated Double-sided THGEM
- 0.4 thick Single-sided THGEM
- 2.1 mm thick Fe ceramic as RP
- Source: H₂ discharge lamp

2-stage THGEM + Cryo-RPWELL (Ne/5%CH₄) →
Gain >10⁵ with X-rays @ RT and 163K
Gain >10⁶ with single UV photons @ RT and
Gain ~10⁶ @ 163K
2-stage THGEM+ Cryo-RPWELL — first results @ 163K

Gain ~ 1.2e5;
\(\Delta V_{RP} = 875\text{V} \)
\(\Delta V_{TH} = 800\text{V} \)

FWHM ~ 14%

Ne/5%CH\(_4\)  
163K

Pulse height spectra of double-stage detector with X-rays; T = 163K

Clear Polya distributions obtained @ T = 163K with the double-stage detector with Single UV-photons

\(\Delta V_{RP} = 750\text{V} \)
\(\Delta V_{TH} = 900\text{V} \)
Gain ~ 2.5e6
Single UV photons, 163K, w/o CsI
Cryo-RPWELL based noble liquid detectors -- Investigating possible enhancement of maximum achievable stable detector gain in ultrapure Ar vapor
Cryo-RPWELL charge multipliers in dual-phase noble-gas detectors

Dedicated LAr cryostat @ WIS – WISArD
(Weizmann Institute Argon detector)

Breakdown of Fe-Ceramic RPWELL vs THWELL (Fe-Ceramic -> $\rho \sim 10^6$-$10^7$ Ω-cm @ RT):

- **200-300K** – No difference in breakdown voltages -> Fe-Ceramic $\rho$ inadequate to quench discharges!

- **$T < 200K$** -- $\rho \sim 10^9$ Ω-cm $\Rightarrow$ Effect of RP clearly seen. **Higher RPWELL Breakdown Voltages.**
Summary & Outlook

- **Resistive material – main challenge → Fe-Ceramics suitable at 163K.** Promising results for LAr (~87K).
  
  *Ongoing:* Detailed investigations @ USC and WIS

- **UV detectors @ RT → 2-stage CsI-THGEM + RPWELL.**
  
  Clear Polya distributions in Ne/5%CH₄.
  
  Single-photon detection efficiency >90%.
  
  ➔ potential candidate for UV-photon detection.
  
  *Ongoing:* efficiency vs background, Single-stage RPWELL, other gases & quenchers (Ar, CF4, etc).

- **Cryogenic RPWELL @ 163K → Single-stage RPWELL (Ne/5%CH₄)**
  
  Gain ~10⁴ with X-rays, and ~10⁵ with single UV-photons.
  
  Discharge quenching at 163K: RPWELL ~5nA vs THWELL ~200nA!

- **RPWELL-based Cryogenic Gaseous Photomultipliers (GPM) @ 163K → 2-stage THGEM + RPWELL (Ne/5%CH₄)**
  
  Gain >10⁵ with x-rays and ~10⁶ with single UV photons. Clear Polya distributions.
  
  *Ongoing:* 2-stage CsI-THGEM + RPWELL; 10cm diameter cryo-GPM; Photon Detection Efficiency.

- **Cryo-RPWELL charge multipliers in dual-phase Ar detectors →**
  
  Preliminary studies highlight role of RP at low T
  
  *Ongoing:* Tuning resistivity to LAr-T; gain with single-stage RPWELL in dual-phase Ar.
Thanks!!