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The G-RWELL for ePIC Endcap Tracking

E. Sidoretti,[a,*] **G. Bencivenni,**[b] **M. Bondì,**[c] **A. D'Angelo,**[a] **A. Fantini,**[a] **G. Felici,**[b] **M. Giovannetti,**[b] **S. Gramigna,**[a] **L. Lanza,**[a] **G. Morello,**[b] **M. Poli Lener**[b] **and L. Torlai**[a]

[a] *INFN and Univeristy of Roma Tor Vergata, Via della Ricerca Scientifica, 00133 Rome RM, Italy*
[b] *INFN Laboratori Nazionali di Frascati, Via Enrico Fermi 54 (già 40), 00044 Frascati, Italy*
[c] *INFN Sezione di Catania, Via Santa Sofia 64, 95125 Catania, Italy*

E-mail: elena.sidoretti@roma2.infn.it

Abstract: The ePIC detector will be the first detector at the upcoming Electron-Ion Collider (EIC) at Brookhaven National Lab. The design of the detector is optimized for the various physics goals of the EIC program, which include: investigating the origin of the nucleon spin, the three-dimensional structure of the nucleon, the study of saturation effects, and the study of hadronisation. This ambitious scientific program sets stringent requirements on the tracking system needed for the measurement of the scattered electron and charged particles produced in the collisions at the EIC.

The ePIC tracking system combines Silicon trackers with Micro Pattern Gaseous Detectors (MPGDs). The Endcap Trackers, one positioned in the leptonic region and the other in the hadronic region, are designed to cover the pseudo-rapidity region $|\eta| > 2$. Each consists of a pair of G-RWELL disks, a hybrid detector capable of very stable operation at gas gain larger than 2×10^4. This is accomplished through the coupling of a single GEM pre-amplification layer and a standard µ-RWELL. The R&D has been introduced in collaboration with the INFN-LNF group, which is studying its timing performance for the LHCb Phase II upgrade.

The performance requirements for the Encap Tracker include: spatial resolution of 150 µm, single layer efficiency of 96–97% (corresponding to 92–94% combined efficiency), time resolution of 10 ns, and material budget $\leq 1\%$ of X_0 per layer. The addition to the GEM pre-amplification is required for reaching the typical high gain necessary for satisfying such performance for angular tracks.

A recent test beam campaign was conducted in November 2024 at the PS-T10 East Area at CERN on $10 \times 10\,\text{cm}^2$ prototypes. The aim of the test was to evaluate the spatial resolution and detection efficiency under varying angles of incidence ensuring compatibility with ePIC's operational requirements. The G-RWELL technology ensured high stability at gains granting 96% efficiency and spatial resolution of 90 µm and 200 µm for perpendicular and inclined tracks, respectively.

Keywords: Gaseous detectors; Hybrid detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

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[*] Corresponding author.

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1 The Electron Ion Collider's ePIC detector

The Electron-Ion Collider (EIC) [1] will be built at Brookhaven National Laboratory, aiming to investigate gluon interactions at high densities, parton dynamics, the behavior of Quantum Chromodynamics (QCD) in the non-perturbative regime and the origin of mass and spin.

The collisions will be investigated by the ePIC detector, located in the Interaction Point 6 (IP6). Its many sub-detectors will form a central barrel region and two asymmetric endcaps to maximize angular coverage.

ePIC detector's tracking system will include various Micro-Pattern Gaseous Detectors (MPGD) and Silicon Detectors. The Tracking MPGDs adopt μ-RWELL [2], GEM [3], and MicroMegas [4] technologies. Two MPGD Endcap Trackers (ECT), each consisting of a pair of disks, cover the area and with pseudorapidity $|\eta| > 2$ and the entire azimuthal angle. Requirements for this subsystem include: a time resolution of 10 ns, a low material budget ($\approx 1\%$ X_0), a spatial resolution of 150 μm, and a single detector efficiency of 96-97%, which translates to a combined efficiency of 92-94%. To meet these performance criteria, the R&D moved towards an hybrid solution, the G-RWELL, which incorporates a GEM-based pre-amplification stage into the classic μ-RWELL design [5].

2 μ-RWELL and G-RWELL technologies

The simplest gaseous detector is composed of two electrodes, anode and cathode, enclosing a gas volume. When a charged particle passes through the detector, it ionizes the gas producing primary electron-ion couples. Thanks to an applied electric field, the electron drift towards the anode, the ions toward the cathode, and the signal produced is detected.

MPGDs are characterized by the use of micrometric structures as electrode, enabling high spatial resolution, rapid ion collection, and high-rate capability.

The μ-RWELL is a single-stage MPGD, combining amplification and signal readout on the anode. It is composed of a 50 μm thick polyimide (Kapton) foil, clad with a 10 μm copper layer on the top (gas-facing) side. A matrix of blind holes (WELLs) acts as amplification stage, having diameters of 70 μm and pitch of 140 μm, obtained using a photolithographic process. To provide spark protection, a thin resistive layer of Diamond-Like Carbon (DLC) with resistivity of 100 MΩ/□ is added, improving the detector's robustness. The signal is collected by pads or strips capacitively coupled to the DLC, and processed by front-end electronics. This configuration ensures fast signal formation and good position resolution, while maintaining protection from discharges even in high-rate operation. Using gas mixtures $\mathrm{Ar/CO_2}$ or $\mathrm{Ar/CO_2/CF_4}$, gains of up to 10^4 are achievable.

The μ-RWELL architecture is particularly suited for large-area tracking systems and muon detection in environments with high radiation flux, offering a compact, scalable, and cost-effective solution.

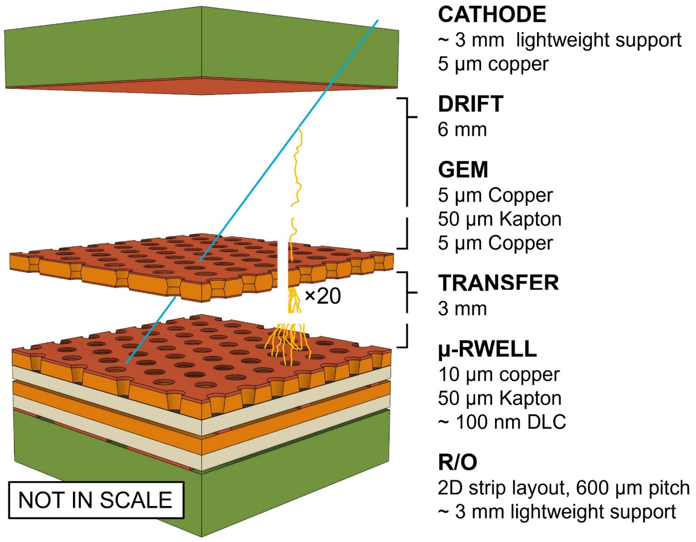

Figure 1. G-RWELL (not in scale).

The G-RWELL represents an evolution in MPGD technology, combining the features of a GEM and a μ-RWELL in a compact, hybrid architecture. This design takes advantage of both amplification techniques: the pre-amplification provided by the GEM foil and the compact discharge-protected readout structure of the μ-RWELL. A standard GEM foil is added above the μ-RWELL layer. The GEM is composed of a 50 μm thick Kapton foil, metal-clad on both sides, having a matrix of bi-conical holes, 70 μm in diameter with a 140 μm pitch. When a charged particle passes the detector, the primary electrons are first multiplied in the GEM holes, and then amplified in the μ-RWELL. By distributing the total gas gain across two amplification stages, the G-RWELL can operate each stage at a lower voltage, thus suppressing the occurrence of discharges and achieving stable gains well above 10^4. This makes the G-RWELL a highly attractive solution for tracking and triggering applications in modern high-energy physics experiments, particularly in environments with demanding high radiation and rate conditions.

For the ePIC MPGD Endcap Trackers, the design of the G-RWELL detector with a "COMPASS-like" 2D strip readout [6] with a 600 μm pitch is used. This configuration meets the required 150 μm spatial resolution even for inclined tracks. The drift gap is set to 6 mm to optimize the performance of the μTPC algorithm [7], with a transfer gap of 3 mm. Literature shows that with a 650 μm pitch and a 5 mm drift gap, spatial resolutions better than 150 μm are achievable for incident angles up to 30°, combining Charge Centroid and μTPC reconstruction techniques [8].

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3 Detector Under Test and test beam setup

In November 2024, a test beam was conducted at the PS-T10 beamline in the East Area of CERN, using 5 GeV/c muon beam. The purpose of the test was to characterize the performance of G-RWELL prototypes, with an active area of $10 \times 10\,\mathrm{cm}^2$, with respect to efficiency and spatial resolution with different angles of incidence of the beam. Two techniques were used for data analysis: the Charge Centroid method, and a µTPC (micro-Time Projection Chamber) algorithm, which is particularly effective at non-perpendicular incidence angles.

For data acquisition, the Scalable Readout System (SRS) [9] and APV25 front-end chips [10] were used, with the mmDAQ3 software [11]. Offline data analysis was performed using the Corryvreckan framework [12], a ROOT-based software developed for test beam studies.

The G-RWELL prototypes had a two dimensional "COMPASS-like" readout structure with 400 µm pitch. The strips were asymmetrical, with widths of 300 µm on the bottom layer and 60 µm on the top, optimizing charge sharing. Each detector had a 6 mm drift gap and a 3 mm transfer gap, and operated with a standard Ar:CO_2:CF_4 (45:15:40) gas mixture.

The experimental setup consisted of a tracking telescope composed of a µ-RWELL detector and a G-RWELL detector, positioned upstream and downstream. The two G-RWELL prototypes under test were mounted on a rotating support in a mirrored configuration, with their cathode sides facing each other. The trigger was provided by a system of three scintillators arranged to ensure precise timing.

4 Reconstruction algorithms and spatial resolution results

Two reconstruction algorithms were used for data analysis:

- The Charge Centroid method calculates the hit position by weighting the collected charge on adjacent strips. This technique works particularly well for tracks that are nearly perpendicular to the detector surface.

- The µTPC algorithm reconstructs the track in the gas gap by combining the time of arrival of the signals with the known drift velocity of the ionization electrons. The cluster position is then set as the intersection of the track with an arbitrary plane parallel to the readout plane. This method works best for inclined tracks.

Spatial resolution is then evaluated using the enemy technique. In this method, the residual is defined as the distance between the reconstructed cluster positions in two adjacent Detectors Under Test (DUTs). Systematic uncertainties due to the tracking system are minimized under the assumption that the two DUTs perform similarly.

The final resolution is given by:

$$\sigma = \frac{\sigma_{\mathrm{res}}}{\sqrt{2}} \quad \text{where} \quad \sigma_{\mathrm{res}} = \sqrt{\frac{V_1\sigma_1^2 + V_2\sigma_2^2}{V_1 + V_2}}\; V_1 = \sqrt{2\pi}A\sigma_1, \quad V_2 = \sqrt{2\pi}B\sigma_2 \tag{4.1}$$

Here, the residual distribution is fitted with a double Gaussian function, characterized by the combination of two gaussians: σ_1 and σ_2 as their standard deviations, and V_1 and V_2 as their integrals.

The resolution was calculated under voltage plateau conditions. At normal incidence (0°), the Charge Centroid method achieved a spatial resolution below 90 µm (figure 2). For tracks inclined 30°,

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the same method provided a resolution of approximately 370 µm, while the µTPC method achieved a resolution of 200 µm, demonstrating the advantages of a time-based reconstruction approach for inclined tracks.

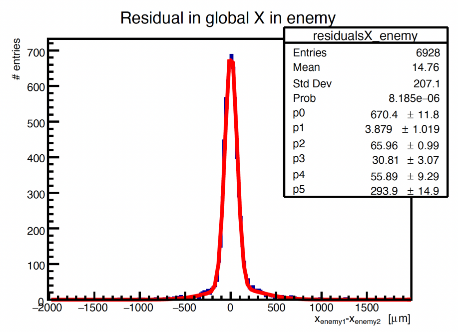

Figure 2. Resolution study at 0°: ΔV_{GEM} set to 350 V and ΔV_{WELL} to 550 V. $\sigma_1 = 68$ µm, $\sigma_2 = 297$ µm, $\sigma_{\mathrm{res}} = 125$ µm, $\sigma = 88$ µm.

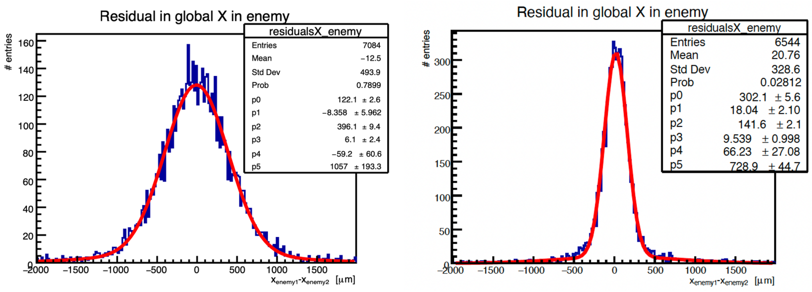

Figure 3. Resolution study at 30°: Left: Charge Centroid method, Right: µTPC method. ΔV_{GEM} set to 460 V and ΔV_{WELL} to 550 V. In µTPC mode: $\sigma_1 = 142$ µm, $\sigma_2 = 729$ µm, $\sigma_{\mathrm{res}} = 302$ µm, $\sigma = 213$ µm.

5 Efficiency results

For studying the DUT's efficiency, the voltage applied to the µ -RWELL layer was kept constant at 550 V, corresponding to a gas gain of approximately 1500, while the voltage across the GEM foil varied. The efficiency is defined as the number of reconstructed tracks for which a cluster was found on the projected track position over the number of tracks passing through the detector plane. The cluster was associated to the track if found in a spacial window, set to $\pm 10\sigma$.

At normal incidence, the Charge Centroid reconstruction method was used. The efficiency curve, shown in figure 4, has a plateau at approximately 96%, reached at a GEM voltage difference of $\Delta V_{\mathrm{GEM}} \simeq 300$ V. This corresponds to a total gas gain of about 5200.

For inclined tracks at an angle of 30°, the µTPC reconstruction algorithm was used. As illustrated in figure 5, the efficiency reaches a plateau around 96%, but at a higher GEM voltage of $\Delta V_{\mathrm{GEM}} \simeq 400$ V, corresponding to a total gain of approximately 15000. The higher voltage required is consequence of the increased spread of the ionization charge across multiple strips due to the track inclination, which reduces the charge collected by each individual strip and thus necessitates greater amplification.

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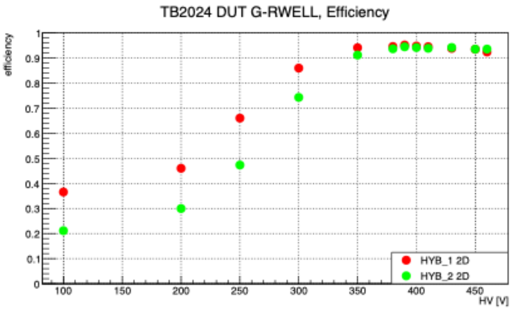

Figure 4. Efficiency study at 0°: the efficiency plateau (∼ 96%) is reached at $\Delta V_{\mathrm{GEM}} \sim 300$ V.

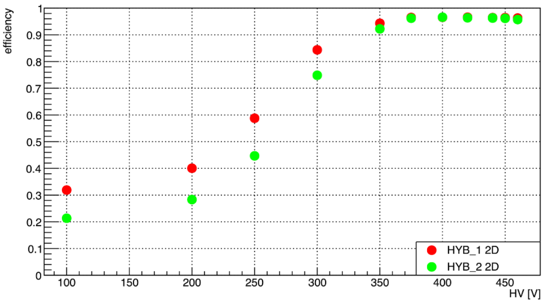

Figure 5. Efficiency study at 30°: the efficiency plateau (∼ 96%) is reached at $\Delta V_{\mathrm{GEM}} \sim 400$ V.

The detector maintained stable operation even at higher amplification settings, showing no signs of discharge or performance instability up to a total gain exceeding 35000.

Beyond tracking, the G-RWELL detector has also been tested for timing applications. In particular, time resolution studies conducted in collaboration with the LNF group for the LHCb muon system upgrade have reached a resolution of 3.8 ns [13], highlighting the detector's potential for fast-timing applications as well as high-resolution tracking.

6 Conclusions and outlook

Achieving the required 2D spatial resolution for the ePIC MPGD Endcap Trackers, particularly with inclined tracks, demands detector technologies capable of gas gains above 10^4. The G-RWELL meets this challenge, showing remarkable stability during operation up to gains of 10^5. Preliminary results show a spatial resolution of ∼ 90 µm for perpendicular tracks and ∼ 200 µm for inclined ones, and a time resolution of 3.8 ns, highlighting its strong potential for future high-rate, high-precision tracking applications in particle physics.

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