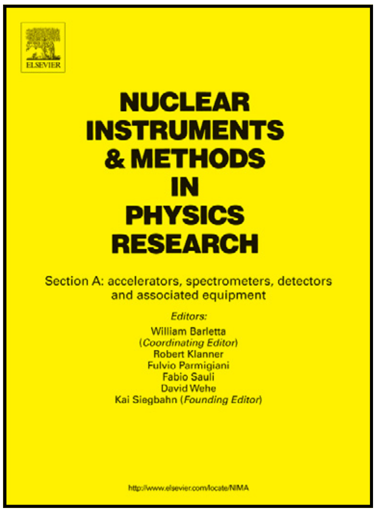

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Beam Studies of the Segmented Resistive WELL: a Potential Thin Sampling Element for Digital Hadron Calorimetry

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Abstract

Thick Gas Electron Multipliers (THGEMs) have the potential of constituting thin, robust sampling elements in Digital Hadron Calorimetry (DHCAL) at future colliders. We report on recent beam studies of new single- and double-THGEM-like structures: the multiplier is a Segmented Resistive WELL (SRWELL) - a single-faced THGEM in contact with a segmented resistive layer inductively coupled to readout pads. Several 10×10 cm^2 configurations with a total thickness of 5-6 mm (excluding electronics) with 1 cm^2 pads were investigated with muons and pions. The pads were coupled to a Scalable Readout System APV chip, APV-SRS [22]. Detection efficiencies in the 98% range were recorded with an average pad-multiplicity of ~1.1. The resistive anode resulted in efficient discharge damping, with potential drops of a few volts; the discharge probabilities were $\sim 10^{-7}$ for muons and $\sim 10^{-6}$ for pions, at rates of a few kHz/cm^2 and for detectors in the double-stage configuration. Further optimization work and research on larger detectors are underway.

Keywords: Micropattern gaseous detectors (MPGD), THGEM, SRWELL, Digital hadron calorimetry (DHCAL), Resistive electrode, SRS, ILC, CLIC

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1. Introduction

The Thick Gas Electron Multiplier (THGEM) [1] is a simple and robust electrode suitable for large area detectors, which can be economically produced by industrial Printed Circuit Board (PCB) methods. Its properties and potential applications are reviewed in [2,3]; recent progress can be found in [4-7]. One possible application of THGEM-based detectors is in Digital Hadronic Calorimeters (DHCAL), of the kind proposed for the ILC/CLIC-SiD experiment [8,9]. In this project, the calorimeter design dictates very narrow sampling elements, in the sub-centimeter range, with a lateral pixel size of 1×1 cm^2. Additional requirements are a high detection efficiency (>95%) and a minimum pad-multiplicity (number of pads activated per particle).

RPCs presently constitute the baseline technology for the SiD DHCAL, with 94% efficiency and a pad-multiplicity of 1.6 [10]; other solutions have been investigated, e.g. MICROMEGAS with 98% efficiency and a multiplicity of 1.1 [11], and Double-GEMs with 95% efficiency and a pad-multiplicity of 1.3 [12] (all results are for muons).

Recently, THGEM-based sampling elements were proposed: they were studied with muons and pions, primarily in single- and double-THGEM configurations with direct charge collection on readout pads, separated from the multiplier by a 2 mm induction gap [13]. The potential value of this concept for DHCAL was demonstrated, leaving room for further optimization, in terms of stability in hadronic beams, efficiency, multiplicity, and overall thickness.

We report here on the results of our latest beam study, conducted at the CERN SPS/H4 RD51 beam-line with 150 GeV/c muons and pions. Further substantial progress was made with a novel THGEM-like configuration, the Segmented Resistive WELL (SRWELL). More details can be found elsewhere [14].

2. Experimental setup and methodology

The SRWELL, first suggested in [13], is shown schematically in Figures 1 and 2; it is a THGEM that is copper-clad on its top side only, whose bottom is closed by a resistive anode. The anode consists of a 0.1 mm thick FR4 sheet patterned with a square grid of narrow copper lines, with the entire area coated with a resistive film (e.g. graphite mixed with epoxy [15]). Avalanche-induced signals are recorded inductively on a pad array located below the FR4 sheet. The grid lines on the resistive anode correspond to the inter-pad boundaries; they serve to prevent charge spreading across neighboring pads by allowing for rapid draining of the avalanche electrons diffusing across the resistive layer. The resistive layer itself (resistivity of ~10-20 MΩ/square) serves to significantly reduce the energy of occasional discharges. The closed-bottom geometry, also suggested in [16] and similar in its field shape to the WELL [17] and

C.A.T. (the French acronym for ”Compteur À Trou”) [18], reduces the total thickness of the detector; it also results in attaining a higher gain at a given applied voltage, compared to a standard THGEM with an induction gap [13]. The SRWELL has a segmented square hole-pattern with “blind” copper strips above the grid lines; these prevent more energetic discharges in the holes located above the metal grid.

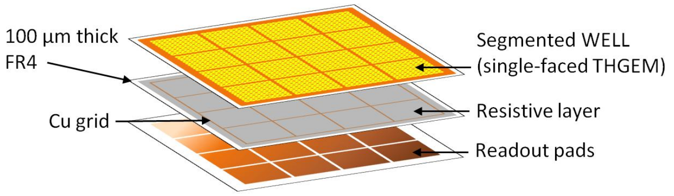

Figure 1: The three layers comprising the SRWELL. Bottom: readout pad array (here 4×4); middle: resistive layer on top of a copper grid (on FR4 sheet); top: segmented single-faced THGEM. The layers are assembled one on top of the other in direct contact (see Fig. 2).

Two basic detector configurations were investigated (Figure 2): one comprising a single-stage SRWELL, and the other a double-stage structure with a standard THGEM followed by an SRWELL. In both cases the electrodes were 10×10 cm^2 in size. Based on previous experience with neon-based gas mixtures, which allow for high-gain operation at relatively low voltages [4], the detectors were operated in Ne/5%CH$_4$ at 1 atm, with a typical flow of a few l/h; a minimally ionizing particle (MIP) passing through this gas mixture generates, on the average, ~60 electron-ion pairs per cm along its track [19].

In the single-stage detector the SRWELL was either 0.4 mm or 0.8 mm thick, with corresponding drift gaps of 5.5 mm and 5 mm, respectively. In the double-stage configuration, both the THGEM and the SRWELL were 0.4 mm thick; the transfer gap between them was 1.5 mm wide and the drift gap was 2.5 mm, 3 mm, or 4 mm in width. The total thickness of the detector from the resistive anode to the drift electrode was thus between 4.8 and 6.3 mm. The THGEM and the SRWELL electrodes were manufactured by Print Electronics Israel [20] by mechanical drilling of 0.5 mm holes in FR4 plates, Cu-clad on one or two sides, followed by chemical etching of 0.1 mm wide rims around each hole. In the double-stage detectors the THGEM had a hexagonal hole pattern with a pitch of 1 mm; the SRWELL’s square-shaped hole pattern had a pitch of 0.96 mm, with 0.86 mm wide “blind” strips above the grid lines (1.36 mm between the centers of the holes on the opposite sides of the strip). The resistive layers had a surface resistivity of 10-20 MΩ/square. The FR4 sheet serving as the base of the resistive anode was 0.1 mm thick. The grid patterned on the FR4 sheet had 0.1 mm wide copper lines, defining an array of 8×8 squares, 1 cm^2 each, matching the 8×8 readout pad array patterned here on a 3.2 mm thick FR4 plate located below the anode.

For the data acquisition the new CERN-RD51-SRS electronics (Scalable Readout System [21]) was used, with the 64-pad array read by a single SRS analog 128-channel APV25 chip [22]. External triggering and tracking were provided using the RD51 tracker/telescope setup [23], comprising three 10×10 cm^2 scintillators in coincidence with three MICROMEGAS tracking units, each equipped with two APV25 chips. The three tracker detectors and the investigated detector shared the same external trigger and front-end card (FEC), enabling event-by-event matching and track reconstruction. This permitted measuring both the global average values of the detection efficiency and of the pad-multiplicity, as well as their local, position-dependent values (e.g. their variations at the pad boundaries). The low-noise electronics enabled operating the detectors at relatively modest gas gains of ~2000-3000.

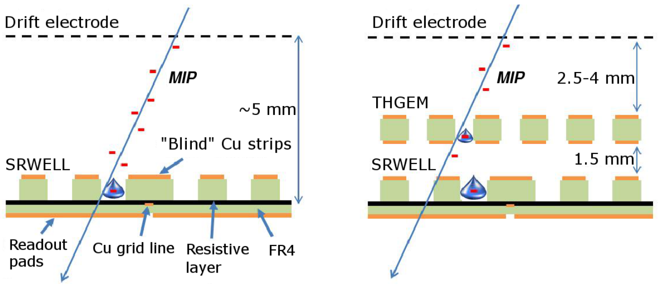

Figure 2: The two detector configurations investigated in this work. Left: single-stage SRWELL; Right: double-stage detector with a standard THGEM multiplier followed by an SRWELL.

The detector electrodes were biased individually through a CAEN SY2527 HV system. The voltage and the current of each HV channel were monitored and stored using the RD51 slow-control system [24], allowing for measuring the rate and the magnitude of occasional discharges (e.g. momentary voltage drops, accompanied by current pulses).

The detectors were investigated in a broad low-rate muon beam (10-20 Hz/cm^2), and in narrow pion beams of ~1 cm^2 area. The pion rates were varied between ~0.5 kHz/cm^2 to ~70 kHz/cm^2, with the majority of the data taken at rates of up to a few kHz/cm^2.

Average and local values of the detector efficiency and pad-multiplicity were studied using selected tracker events. Pads were considered as activated if their signal was above a pad-specific threshold (individually set according to the noise level of each pad). The detector efficiency was defined as the fraction of tracks where a corresponding cluster of pads was found with its calculated center of gravity not more than 10 mm away from the track projection on the detector. These same tracks were used to calculate the average pad-multiplicity by counting the number of pads activated per event. For more details see [14].

3. Results

The studies on single-stage detectors included two configurations: one with a 0.4 mm thick SRWELL and a 5.5 mm drift gap, and the other with a 0.8 mm thick SRWELL and a 5 mm drift gap. In a muon beam, the former reached 97% global efficiency at an average pad-multiplicity of 1.2, and the latter (0.8 mm thick SRWELL) displayed 98% global efficiency already at 1.1 multiplicity. The measured Landau pulse-height distributions were well above the noise level at gains of ~1500-2000. The discharge probabilities with muons were of the order of 10^{-6} for both configurations. However, with pions both configurations displayed a gain drop by a factor of ~2 at the above operating conditions, with a ~5-10 fold increase in the discharge probability; this resulted in lower detection efficiencies with pions for both cases. In both detector configurations, the observed discharges could be divided into two distinct groups: (a) a vast majority of micro-discharges, involving small voltage drops (~10-15 V) with a typical recovery time of ~2 seconds; (b) a small fraction of discharges involving large voltage drops (~100-200 V) with longer recovery times (a few seconds, depending on the size of the voltage drop). The 0.8 mm thick SRWELL appeared to be more stable than the 0.4 mm thick detector, but this requires further study and more precise quantification.

The studies of the double-stage detectors were done with 0.4 mm thick THGEM and SRWELL electrodes. The transfer gap was kept at 1.5 mm and the drift gap was varied between 2.5 mm and 4 mm. The efficiencies recorded with muons were similar to those obtained with the single-stage detectors, albeit shifted to slightly higher multiplicities. For example, the 4 mm drift, double-stage detector reached 97% global efficiency at an average multiplicity of 1.15; the 3 mm drift, double-stage detector reached 94% efficiency at a multiplicity of 1.2. The discharge probabilities with muons were extremely low, of the order of 10^{-7}, for the 4 mm drift double-stage detector. Figure 3 shows the global efficiency versus the average pad-multiplicity for the 0.8 mm thick single-stage SRWELL detector and for the double-stage THGEM/SRWELL detector with 4 mm drift. Measurement details are provided in [14].

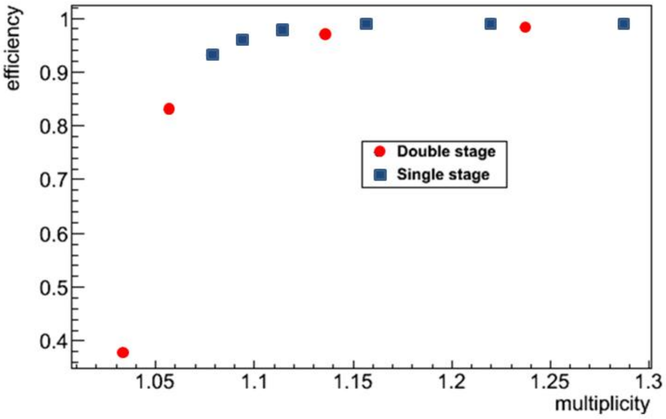

Figure 3: Global detection efficiency versus average pad-multiplicity for the 0.8 mm thick single-stage SRWELL detector with 5 mm drift gap, and for the double-stage THGEM/SRWELL detector with 4 mm drift gap and 1.5 mm transfer gap.

Unlike the results for the single-stage detectors, no gain drop was observed for the double-stage detectors when switching from muons to pions; Figure 4 compares the pulse-height distributions measured for both particle types with the double-stage detector having a 4 mm drift gap, under the same operation voltages. Although occasional discharges occurred with pions for this detector, their probability, at rates of a few kHz/cm^2, was of the order of 10^{-6}, and the observed voltage drops (on the SRWELL top) were all minute and limited to ~3 V, with a recovery time of ~1 second (no large discharges were observed). The efficiency for pions was similar to the one obtained with muons (~95% and above). A comparison between runs with and without these micro-discharges showed that their effect is negligible in terms of the detection efficiency. Moreover, the presence of micro-discharges had no effect on the data acquisition system, which operated stably even in high rate pion beams.

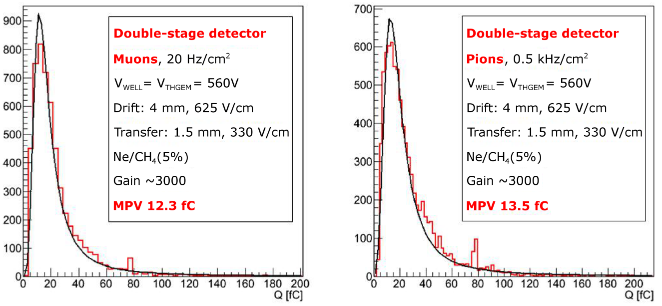

Figure 4: Pulse-height (Landau) distributions for muons (left) and pions (right) measured with the double-stage detector with 4 mm drift gap. The parameters and operation conditions are given in the figures. No gain drop was observed with pions in this double-stage configuration.

The ability to accurately match events between the tracker and the investigated detectors permitted studying the dependence of the local efficiency and of the pad-multiplicity on the track position relative to the pad boundary. The results are shown in Figure 5: essentially no drop in local efficiency occurred above the "blind" SRWELL strips in both configurations; the local increase in pad-multiplicity above the inter-pad boundary resulted from charge sharing between holes on the opposite sides of the copper strip (see Fig. 1).

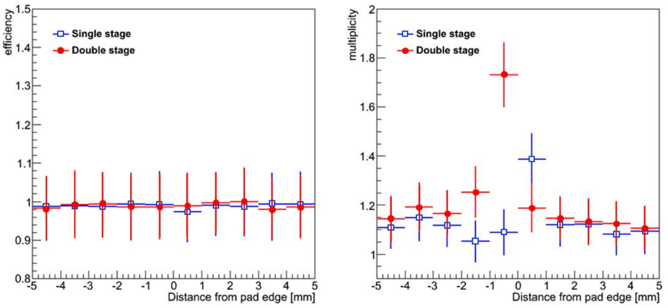

Figure 5: Local detection efficiency (left) and pad-multiplicity (right) as a function of the muon-hit distance from the pad boundary for the single-stage 0.8 mm SRWELL and the 4 mm drift double-stage detectors.

4. Summary and discussion

The beam tests described in this work were performed to investigate, for the first time, structures based on the Segmented Resistive WELL (SRWELL) concept. This new THGEM-variant has several key advantages which make it a promising candidate for Digital Hadronic Calorimetry: (1) By removing the "standard" induction gap, it allows for a significant reduction in thickness - a critical feature in applications such as the SiD experiment; the total thickness of the detector configurations studied in this test was 5-6 mm (excluding the readout electronics); (2) The resistive anode effectively quenches occasional discharges, whose magnitudes, in the double-stage configuration, are limited to ∼3 V with ∼1 s recovery time - with no effect on the detection efficiency or on the stability of the electronic readout system; (3) The copper grid underneath the resistive layer significantly reduces the cross-talk between neighboring pads, limiting the multiplicity to ∼1.1-1.15; the higher value is mostly due to particles inducing avalanches on more than one hole; (4) The detection efficiency for muons is exceptionally high: 98% at a multiplicity of 1.1 with the single-stage 0.8 mm SRWELL, and 97% at a multiplicity of 1.15 with the 4 mm drift double-stage THGEM/SRWELL. Finally - the SRWELL, like the standard THGEM, is a robust electrode which is essentially immune to spark damage. It can be readily and economically produced for large areas, using industrial methods. The combination of the above properties make the SRWELL-based detectors highly competitive compared to the other technologies considered for the SiD-DHCAL.

Single-stage detectors are obviously advantageous in terms of cost when considering large-area applications such as the DHCAL. While their efficiency and multiplicity figures for muons are very convincing, the pion-induced gain drop in the single-stage SRWELL - not observed for the double-stage detectors - is intriguing, and should be clarified (and mitigated) in additional laboratory tests.

The detector thickness limitation imposed by the SiD experiment calls for the use of extremely thin front-end electronics (a requirement which is, at present, not met by the SRS system). Two alternative readout systems may be suitable for this application: SLAC's KPiX board [25], already beam-tested with THGEM-based detectors [13], and the MICROROC chip developed by the LAL/Omega group and by LAPP [11], which was extensively tested with MICROMEGAS detectors. Investigations with THGEM-based detectors are already underway.

Optimization studies on SRWELL detectors (single- and double-stage), as well as work on larger detectors, are planned for the near future. One attractive option is the return to argon-based gas mixtures, implying 2-3 fold higher MIP-induced ionization electron numbers, though at the cost of higher operation potentials [26]. Modern low-noise electronics may allow for lower-gain operation, so this might be possible without problems.

5. Acknowledgements

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[1] R. Chechik, A. Breskin, C. Shalem, D. Mormann, Nucl. Instrum. Meth. A535 (2004), 303-8.
[2] A. Breskin et al., Nucl. Instrum. Meth. A 598 (2009) 107-11.
[3] A. Breskin et al., Nucl. Instrum. Meth. A 639 (2011) 117-20.
[4] M. Cortesi et al., 2009 JINST 4 P08001.
[5] C. D. R. Azevedo et al., 2010 JINST 5 P01002.
[6] V. Peskov, M. Cortesi, R. Chechik, A. Breskin, 2010 JINST 5 P11004.
[7] M. Alexeev et al., 2010 JINST 5 P03009.
[8] H. Aihara, P. Burrows, M. Oreglia (editors), SiD Letter of Intent 2009, arXiv:0911.0006v1.
[9] L. Linssen, A. Miyamoto, M. Stanitzki, H. Weerts (editors), Physics and Detectors at CLIC: CLIC Conceptual Design Report, arXiv:1202.5940.
[10] J. Repond, arXiv:1202.6653v2.
[11] C. Adloff et al., arXiv:1202.0624v1.
[12] J. Yu et al., arXiv:1110.4327v1.
[13] L. Arazi et al., 2012 JINST 7 C05011.
[14] S. Bressler at al., Beam studies of novel THGEM-based sampling elements for Digital Hadron Calorimetry, accepted for publication in JINST.
[15] G. Mikenberg, Nucl. Instrum. Meth. A265 (1988) 223-7.
[16] M. Alfonsi et al., Performance measurements on closed-geometry, GEM-like detectors, unpublished work
[17] R. Bellazzini et al., Nucl. Instrum. Meth. A423 (1999) 125-34.
[18] F. Bartol et al., J. Phys. III France 6 (1996) 337.
[19] F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09, 3 May 1977.
[20] www.print-e.co.il
[21] S. Martoiu, H. Muller, A. Tarazona and J. Toledo, 2013 JINST 8 C03015.
[22] M. Raymond et al., IEEE Nucl. Sci. Symp. Conf. Rec. 2 (2000) 9/113.
[23] K. Karakostas et al., Micromegas telescope for the RD51 Test Beams, XXVIII Workshop on Recent Advances in Particle Physics and Cosmology, March 26th, 2010.
[24] K. Karakostas et al., A Slow control system for RD51 test facilities, RD51 Note Number: 2011-011.
[25] D. Freytag et al., IEEE Nucl. Sci. Symp. Conf. Rec. (2008) 3447.
[26] C. Shalem, R. Chechik, A. Breskin and K. Michaeli, Nucl. Instrum. Meth. A558 (2006) 475-89.