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Performance of resistive MPGDs for hadron calorimeter at a Muon Collider experiment

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ABSTRACT. A multi-TeV muon collider represents a powerful tool to explore the Standard Model with unprecedented precision, as a possible successor of the High-Luminosity LHC. The Muon Collider aims for precise Higgs boson coupling measurements and searches for new physics at the TeV scale, requiring accurate event reconstruction and particle identification. The Particle Flow Algorithm (PFA), which integrates data from various subsystems, is well-suited for this task. However, one major challenge for the Muon Collider is mitigating the muon beam-induced background, which affects the detector performance. Therefore, the implementation of a PFA at the Muon Collider calls for the use of precise, robust and radiation-hard detector technologies.

This contribution presents the studies for the development of a hadronic calorimeter for the Muon Collider using resistive Micro Pattern Gas Detectors (MPGD). This MPGD-based calorimeter is ideal for PFA thanks to the high-granular readout capabilities ($O(\text{cm}^2)$) and is particularly suitable for the Muon Collider background conditions, thanks to its radiation-hard technology and high rate

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capabilities (up to 10 MHz/cm²). Furthermore, resistive MPGDs offer excellent spatial resolution, operational stability, and uniformity. The results of the characterization studies performed with muon beam at the CERN SPS on three MPGD technologies, resistive MicroMegas, μ -RWELL, and RPWELL, are presented. Additionally, preliminary results for an HCAL prototype consisting of eight layers ($\sim 1 \lambda_I$) of alternating stainless steel and MPGD detectors tested with pion beams of energy ranging up to 10 GeV are shown.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEAS, InGrid, etc); Calorimeters

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1 Introduction

Among the possibilities for future accelerators after the High Luminosity phase of the LHC, the International Muon Collider Collaboration (IMCC) [1] has proposed a muon collider [2] as a possible machine with high discovery potential. Indeed, a muon collider uniquely combines the precision of e^+e^- colliders with the energy reach of pp colliders, offering unprecedented opportunities to explore and characterize new physics. One of the main drawbacks is related to the background induced by the muon decays. This is a driving factor in the layout of the experiment and the choice of detector technologies. For instance, high granularity and precise timing are essential features for the detectors to effectively discriminate signal events from the background. Specifically, for the hadronic calorimeter the readout element size should range between 1×1 and 3×3 cm² to facilitate the use of a Particle Flow (PF) reconstruction algorithm. These requirements are essential to achieve an HCAL energy resolution better than $60\%/\sqrt{E}$, thus enabling a jet energy resolution of 3% for jets above 100 GeV, which is crucial for distinguishing hadronic decays of W and Z bosons [3]. Additionally, the time resolution per cluster is required to be on the order of a few ns.

In this context, a sampling calorimeter read out by Micro-Pattern Gaseous Detectors (MPGDs) is proposed. MPGDs not only meet the above-mentioned requirements but also offer higher rate capabilities and better spatial resolution compared to other gaseous detectors, such as RPCs.

This study considers three MPGD technologies as potential candidates for the active layer of the hadronic calorimeter: resistive MicroMegas [4], micro resistive WELL (μ -RWELL) [5], and Resistive Plate WELL (RPWELL) [6]. Some preliminary performance results obtained on the prototypes are presented in the following sections.

2 Performance of MPGD prototypes

Twelve detectors have been built employing the latest developments on the high-rate layout: four resistive MicroMegas with the Double-DLC (Diamond-Like Carbon) scheme [4], seven μ -RWELL based on the high-rate layout [7], and one RPWELL [6]. All the detectors share a common scheme for the readout board, consisting of 1×1 cm² pads, covering a total active area of $\sim 20 \times 20$ cm². These prototypes have been tested in a muon beam at the SPS facility at CERN, to assess their performance in terms of efficiency, spatial resolution, and uniformity. The detectors were operated with their respective operational gas mixtures, the Ar/CO₂/iC₄H₁₀ (93/5/2) for the Micromegas and RPWELL, and the Ar/CO₂/CF₄ (45/15/40) for the μ -RWELLS. A common readout system based on the APV25

hybrids [8] and the Scalable Readout System [9] was used for the entire setup. Figure 1 shows a diagram of the experimental setup, which also included two Micromegas with a double layer of strips, with a pitch of $250\ \mu\text{m}$, for muon track reconstruction, and two plastic scintillators (S1 and S2 in the sketch), for triggering data acquisition.

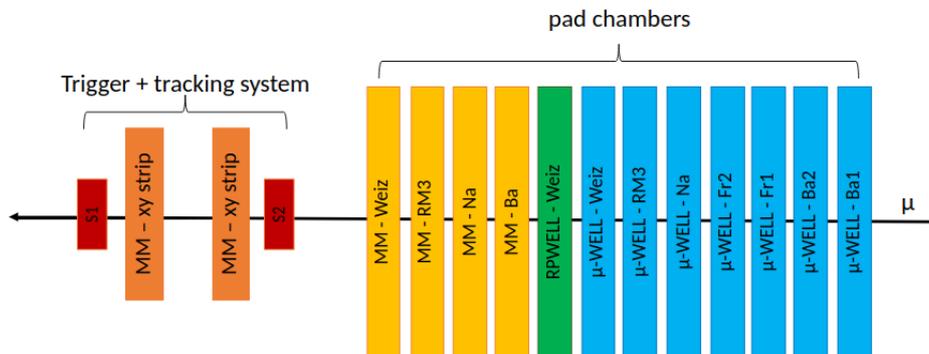


Figure 1. The sketch illustrates the setup under test at the SPS facility.

Since a high probability of cross-talk between pads has been observed on the detectors under test, due to the copper lines connecting the pads to the electronics connectors, an algorithm based on the assumption that no more than four pads can form a cluster, given the pad dimension, is applied for the detectors under test. The position of the clusters is then assigned using the weighted charge method.

The position residual distributions are obtained as the difference between the intersect of the track propagated on the detector plane and the position of the closest cluster on the same detector. The sigma of these distributions is close to $\sim 3\ \text{mm}$, in agreement with the spatial resolution achievable with a digital readout with this readout granularity, given that 90% of the clusters have cluster size equal to 1.

The efficiency of the detectors is measured as the ratio between the number of events in which a cluster matches a track over the total number of tracks. A cluster matches a track if its position falls within 3σ of the residual distribution. The efficiency measurement is performed at a fixed value of the drift field (0.5 kV/cm for Micromegas and RPWELL, 1.8 kV/cm for μ -RWELLS) varying the amplification field in the range between approximately 35–50 kV/cm for the MicroMegas, in the range between 80 and 120 kV/cm for the μ -RWELLS and between 25–30 kV/cm for the RPWELL. The efficiency reaches a plateau higher than 95% for the Micromegas and RPWELL, around 75% for the μ -RWELLS. First, the presence of dead areas caused by the so-called Patterning-Etching-Plating (PEP) lines, required to ground the DLC layer, leads to an efficiency drop of approximately 10%. Second, the applied drift field during these measurements was set to 1.8 kV/cm, which is not the optimal value for maximizing efficiency [5]. To further investigate this effect, the efficiency of one μ -RWELL detector was also measured in a later test beam varying drift fields and with a different readout electronics. In these measurements, the efficiency reached a plateau of $\sim 90\%$ for drift fields in the range of 4–6 kV/cm and an amplification field of 100 kV/cm. Further studies are ongoing to better understand both of these effects.

The response uniformity is evaluated from the distribution of the most probable charges of clusters matched to tracks across the detector area. For each detector, this distribution is fitted with a Gaussian, and the ratio of the standard deviation to the mean from the fit provides an estimate of the response uniformity, expressed as the charge spread relative to the mean. It is measured over the entire active

area of each detector, using a fixed field configuration that corresponds to a gain of approximately 10^3 . Both MicroMegas and μ -RWELLS exhibit good response uniformity of the order of 15%; however, a pattern in the uniformity maps was observed for some of the μ -RWELLS and further investigations on the origin of this effect are ongoing. The RPWELL prototype shows a response uniformity of $\sim 23\%$.

3 Performance of calorimeter prototype with pions

Eight of these detectors, 3 MicroMegas and 5 μ -RWELLS, have been used as active layers to build a small-size ($\sim 1 \lambda_I$) calorimeter prototype, alternated with 2 cm thick iron slabs as absorbers.¹ The calorimeter was tested with negative pion beams of energies up to 11 GeV in the CERN East Area. The data analysis has been performed to emulate a digital readout: all the pads in the entire calorimeter with an induced charge higher than the threshold are counted per each showering pion event and for each energy value. The threshold is set to 80 ADC counts² to exclude noisy pads and corresponds to approximately 2.5 fC. The showering events are selected based on the number of firing pads per active layer, in order to reject MIP-like events or showers starting late in the calorimeter by requiring at least 4 firing pads per layer starting from the third layer; a Geant4 [10] simulation also supports the data analysis and is used for comparison. The data to Monte Carlo comparison shows good agreement between the distribution of the total number of hits, as shown for a pion beam energy of 6 GeV on the left of figure 2. The right of the same figure shows the mean value of the number of hits distributions as a function of the pion beam energy. The mean number of hits increases with the pion energy, even if a loss of linearity in the response function can be observed at higher energies given to the non-full shower containment.

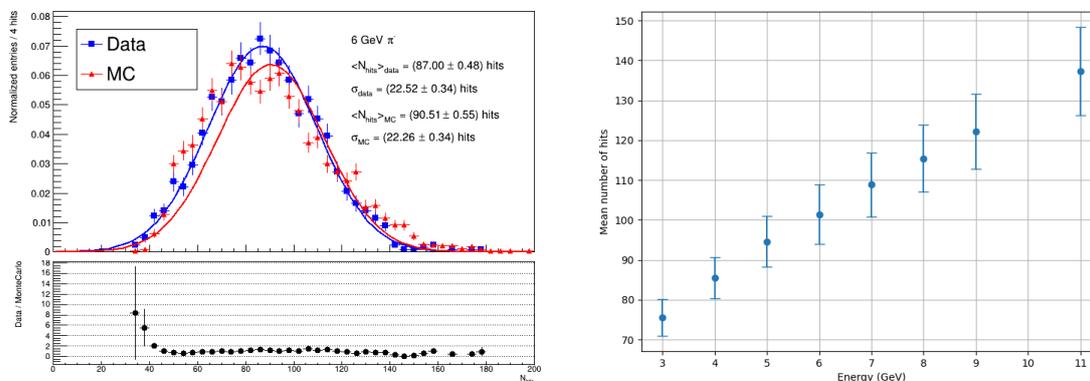


Figure 2. On the left, the distribution of the number of hits for a pion beam energy of 6 GeV, for the data collected in 2023 test beam. The blue data set is the experimental data; the red ones are the simulated data. On the right, the mean number of hits as a function of the pion beam energy. The error bars are the standard deviation of the distribution of the number of hits, for the 2024 test beam. The difference between the number of hits at 6 GeV for the two datasets is due to the fact that in 2024 the first two layers were fully working and the setup counted fewer dead channels in the electronics.

¹The first two layers of the absorbers are 4 cm thick, to increase the fraction of pions showering earlier in the calorimeter, thus increasing their containment.

²1 ADC count corresponds to 200 e^- .

4 Conclusions and outlook

The results summarized in this study show that the three considered technologies exhibit good efficiency, spatial resolution, and uniformity. Further studies are ongoing to understand the uniformity issues found on some of the μ -RWELL. Moreover, the timing performance of these detectors has to be studied as well, both as single layers and within the more complicated structure of the calorimeter.

Finally, the results on the MPGD-based calorimeter show a good agreement between the experimental data and Monte Carlo in the digital readout approach in terms of the total number of hits. The response function shows good linearity for a range of energies that allows a good fraction of shower containment. The analysis has to be improved by implementing a better event selection and a refined algorithm for pad counting to limit the cross-talk effect. Four new prototypes with an active area of $50 \times 50 \text{ cm}^2$ are currently under construction and will be included in the calorimeter. The new version of the calorimeter will extend up to $\sim 2 \lambda_1$ and will be tested in future test beam campaigns.

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