

PICOSEC Micromegas Precise-timing Detectors: Development towards Large-Area and Integration

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ABSTRACT: PICOSEC Micromegas (MM) is a precise timing gaseous detector based on a Cherenkov radiator coupled with a semi-transparent photocathode and an MM amplifying structure. The detector concept was successfully demonstrated through a single-channel prototype, achieving sub-25 ps time resolution with Minimum Ionizing Particles (MIPs). A series of studies followed, aimed at developing robust, large-area, and scalable detectors with high time resolution, complemented by specialized fast-response readout electronics. This work presents recent advancements towards large-area resistive PICOSEC MM, including $10 \times 10 \text{ cm}^2$ area prototypes and a $20 \times 20 \text{ cm}^2$ prototype, which features the jointing of four photocathodes. The time resolution of these detector prototypes was tested during the test beam, achieved a timing performance of around 25 ps for individual pads in MIPs. Meanwhile, customized electronics have been developed dedicated to the high-precision time measurement of the large-area PICOSEC MM. The performance of the entire system was evaluated during the test beam, demonstrating its capability for large-area integration. These advancements highlight the potential of PICOSEC MM to meet the stringent requirements of future particle physics experiments.

KEYWORDS: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MI-57 CROPIC, MICROMEAS, InGrid, etc); Timing detectors; Cherenkov detectors

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1 Introduction

Precise-timing detection techniques are in high demand for future particle physics experiments. PICOSEC Micromegas (MM) is a precise timing gaseous detector based on a Cherenkov radiator coupled to a semi-transparent photocathode and a Micromegas amplifying structure [1]. A single-channel prototype has been successfully manufactured for proof of concept and achieved sub-25 ps time resolution with Minimum Ionizing Particles (MIPs), followed by ongoing developments toward detector optimization and large-area coverage. Recent advancements include a new single-channel structural design which achieved an improving timing performance of 12.5 ps [2], the development of robust photocathodes and resistive Micromegas, the exploration of alternative gas mixtures [3], and the extension of μ RWELL technology to the PICOSEC concept [4]. Expanding the detection area is crucial for the application in future particle physics experiments. While several approaches to multi-channel prototypes have been extensively explored and developed [5, 6], large-area prototypes still face challenges related to robustness, uniformity, and the limitations imposed by the maximum size of the photocathode. In this paper, we present approaches to large-area expansion while ensuring robustness. The large-area resistive prototypes were designed and fabricated, and a series of tests were conducted with the prototypes to validate their performance. In addition, customized electronics systems dedicated to facilitating the fast signal processing of large-area PICOSEC MM were developed. The performance of the entire system has been tested through the beam test campaign.

2 Development of Multi-channel PICOSEC Micromegas Prototypes

Based on the PICOSEC concept, multi-channel PICOSEC MM with an effective area of $10 \times 10 \text{ cm}^2$ PICOSEC MM was designed, produced, and tested, achieving a time resolution of 25 ps in beam tests [6]. Extensive research has been conducted on the resistivity of Micromegas, and a $10 \times 10 \text{ cm}^2$ area resistive PICOSEC MM was developed by adding a resistive diamond-like carbon (DLC) layer on the Micromegas. Additionally, a double DLC layer was developed to further

enhance charge evacuation and evaluate rate capability. Other approaches, such as the PICOSEC detector concept based on the μ RWELL structure, have also been explored for the $10 \times 10 \text{ cm}^2$ area.

To enable the expansion to larger areas while ensuring robustness, a scalable detector scheme was proposed. A $10 \times 10 \text{ cm}^2$ PICOSEC MM prototype incorporating 100 channels of $9.7 \times 9.7 \text{ mm}^2$ pads was designed and manufactured. It consists of a gas frame with a quartz window, a whole $104 \text{ mm} \times 104 \text{ mm} \times 3 \text{ mm}$ MgF_2 as Cherenkov radiator, an MM printed circuit board (PCB), and an outer PCB to extract signals, as shown in figure 1 (a). A thermal bonding method was applied to fabricate the resistive Micromegas [7] with a resistivity of approximately $50 \text{ M}\Omega/\text{sq}$. The amplification gap of the Micromegas is approximately $100 \mu\text{m}$, while the pre-amplification (PA) gap defined by the spacers are around $170 \mu\text{m}$. The MM board was adhesively bonded to a ceramic board to ensure its flatness and maintain detector uniformity. Based on a similar design, a $20 \times 20 \text{ cm}^2$ prototype design was then developed, allowing the assembly of four crystals to extend the detector to an even larger area. Figure 1 (b) illustrates the design concept for assembling the four $10 \times 10 \text{ cm}^2$ MgF_2 crystals in the detector frame. The four crystals were placed directly on the frame using cylindrical pins for alignment. The spacers used here are approximately $190 \mu\text{m}$, serving to define the PA gap. Kapton films were inserted underneath the crystals to compensate for thickness variations. The Micromegas was designed as a single unit, which utilized the thermal bonding method for fabrication and was reinforced with a ceramic plate. This design and manufacturing approach ensures the scalability of the detector for larger areas while maintaining stability.

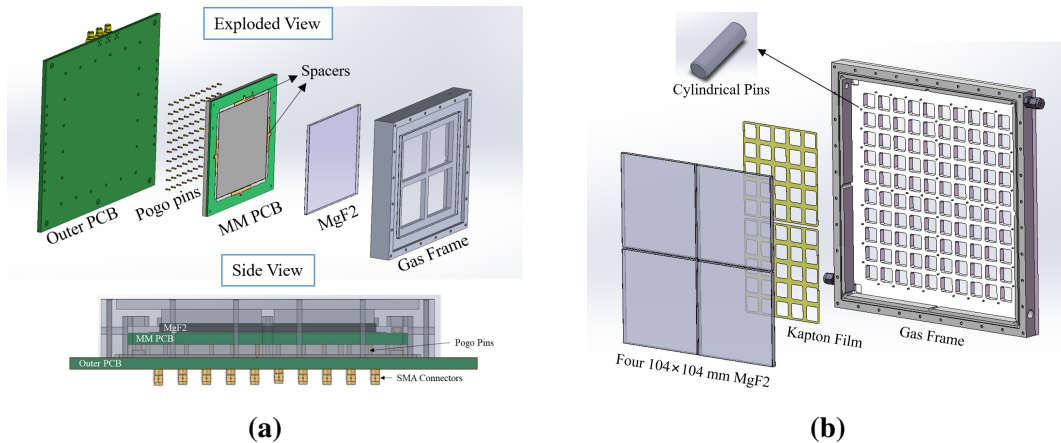


Figure 1. (a) Scheme of the $10 \times 10 \text{ cm}^2$ PICOSEC MM layout. (b) Schematic diagram of the four crystals assembly in the $20 \times 20 \text{ cm}^2$ PICOSEC MM.

3 Performance of the Large-area Prototypes

A series of tests were conducted on the large-area PICOSEC MM prototypes to evaluate their performance in laboratory conditions and test beam. The gain uniformity of the detector was tested with the single photoelectron spectrum, and the uniformity map is presented in figure 2 (a) and figure 2 (b), respectively. The gain uniformity of the $10 \times 10 \text{ cm}^2$ PICOSEC MM prototype was measured to be 29.6%, indicating a notable improvement following efforts to enhance the MM

board’s planarity. Still, the slight deformation of the MM board remains the primary contributor to the residual non-uniformity, exhibiting a trend of smaller in the center and larger at the edges. For the $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype, a subset of channels were measured to assess the overall uniformity of the detector, which was found to be approximately 32.3%. In addition to the board deformation, the tilt of the four crystals also emerged as a factor affecting uniformity, as evident from the trends observed in the figures.

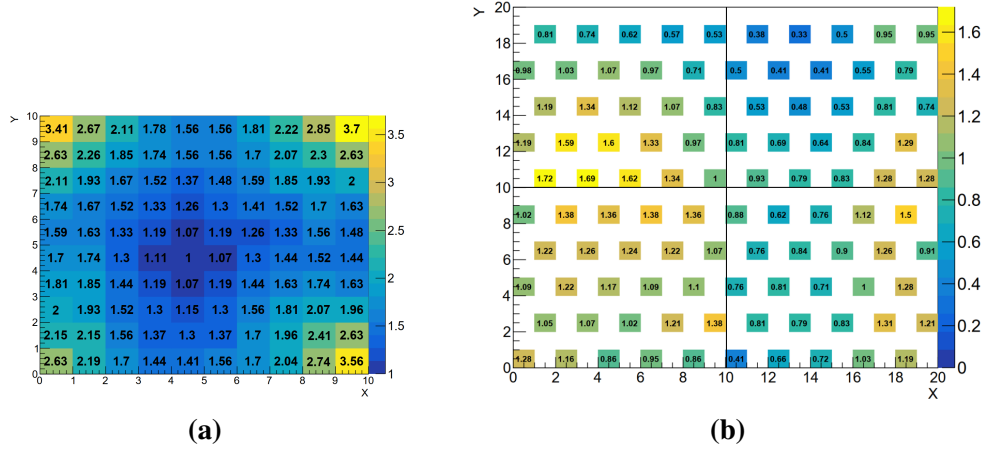


Figure 2. Gain uniformity map of (a) the $10 \times 10 \text{ cm}^2$ PICOSEC MM and (b) the $20 \times 20 \text{ cm}^2$ PICOSEC MM. The values on the channels represent the gain normalized to that of the channel in the middle. The uniformity is determined by the ratio of the standard deviation to the mean value of each channel.

The time resolution of the prototypes was tested at the CERN SPS H4 beam line with 150 GeV/c muon beams, with the experimental setup detailed in [8]. Figure 3 (a) shows the time resolution of the $10 \times 10 \text{ cm}^2$ PICOSEC MM prototype as a function of the PA gap voltage with different photocathodes. The Cesium Iodide (CsI) photocathode, despite its relatively high yield of approximately ten photoelectrons (PEs) per Minimum Ionizing Particle (MIP), is susceptible to aging. In contrast, with the robustness characteristic, the DLC photocathode yields about three PEs per MIP [9]. With a CsI photocathode, the prototype achieved its optimal time resolution of 20.38 ps at the pad’s central area, with PA and amplification voltages set to 520 V and 240 V, respectively. When equipped with a DLC photocathode, the prototype also achieved a time resolution of less than 30 ps, showing its excellent timing performance. Similar tests were conducted with the $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype to evaluate its time resolution. Figure 3 (b) shows the time resolution of the prototype with different photocathodes tested across two different channels, both of which exhibit relatively higher gain. The detector equipped with a CsI photocathode achieved its optimal time resolution of 25 ps at the pad’s center, with a PA voltage of 510 V and an amplification voltage of 210 V. This performance is comparable to that of the previous prototype, with the slightly degraded time resolution likely attributed to the thicker PA gap in this detector.

4 Readout Electronics Development

Customized readout electronics dedicated to high-precision time measurement for multi-channel PICOSEC were designed and tested. An electronic prototype consisting of an RF amplification

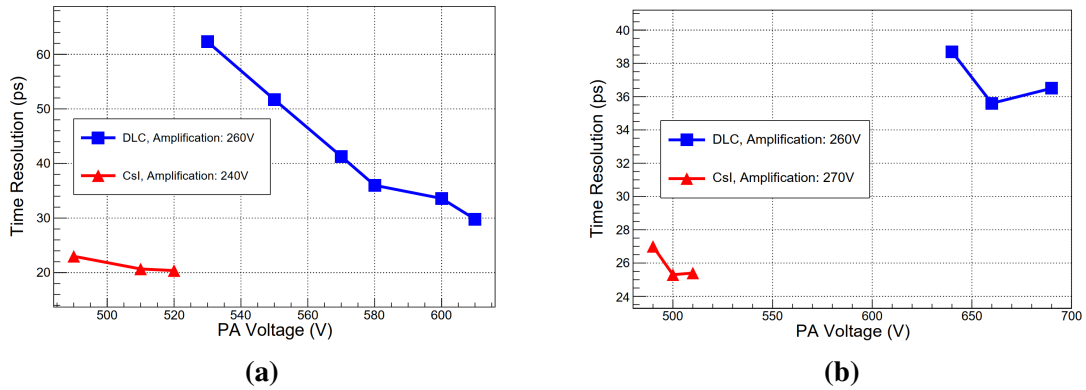
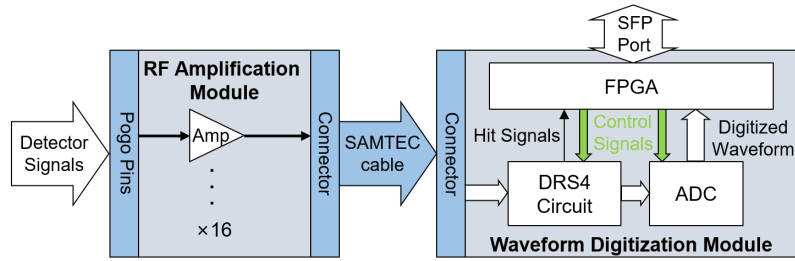


Figure 3. Time resolution results of (a) the $10 \times 10 \text{ cm}^2$ PICOSEC MM prototype and (b) the $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype versus PA voltage with two different photocathodes: CsI and DLC.

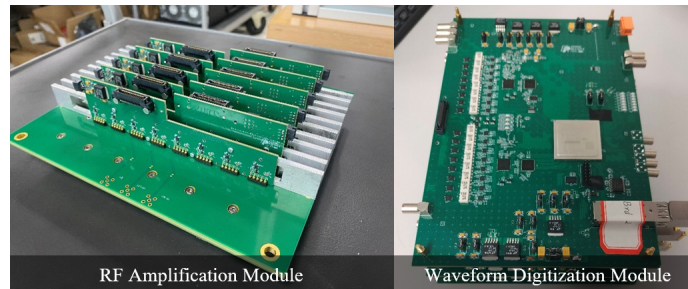
module (RF-AM) and a Waveform Digitization Module (WDM) was designed, as illustrated in figure 4. The RF amplifiers, featuring 16 channels, are mechanically mounted on the Outer PCB of the PICOSEC MM to read out signals from either a $10 \times 10 \text{ cm}^2$ or a $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype. Fast signals from the detectors are input via pogo pins to the RF-AM and then transmitted to the WDM through SAMTEC cables. After being sampled by the DRS4 chip and digitized by the Analog-to-Digital Converter (ADC), the signals are processed by the FPGA and subsequently uploaded to a PC via an SFP interface. During the aforementioned muon test beam, the entire system was tested in conjunction with the large-area PICOSEC MM prototypes. The performance of the RF-AM was individually tested while sampled by an oscilloscope to compare with a commercial amplifier Cividec¹. The RF-AM demonstrated superior time resolution compared to the Cividec amplifier, due to its higher signal-to-noise ratio. Subsequently, the entire electronics was tested with the $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype equipped with a CsI photocathode, with the time resolution results presented in figure 5. The system possesses the ability to achieve an overall time resolution below 30 ps, which includes the combined time jitter contributions from the RF-AM, WDM, and the PICOSEC MM. These results highlight the system’s high precision, integration, and reliability, making it well-suited for large-scale, multi-channel PICOSEC MM applications.

Other fast-timing response electronics approaches were developed and extensively tested in conjunction with the PICOSEC MM. For example, a readout chain incorporating an RF Pulse Amplifier with a SAMPIC-based digitizer was employed [10, 11]. In the test beam, this electronic setup was implemented to read out multiple channels of a $10 \times 10 \text{ cm}^2$ PICOSEC MM [12], showing a good ability to analyze the uniformity of its signal response. More recently, an integrated readout circuit specially designed to process fast signals based on the Application-Specific Integrated Circuit (ASIC), namely FastIC (Fast Integrated Circuit), was developed. The FastIC is an 8-channel front-end ASIC, making it a suitable approach for multi-channel readout of the PICOSEC MM. Its capability to process fast signals from the PICOSEC MM was validated in beam tests, where a time resolution of approximately 50 ps was achieved. Multi-channel readout of the PICOSEC MM using FastIC was subsequently tested, demonstrating its potential as a valuable option for the integrated

¹C2-HV Broadband amplifier (2 GHz, 40 dB), <https://cividec.at/electronics-C2-HV.html>



(a)



(b)

Figure 4. (a) Structure of the prototype readout electronics. (b) Photograph of the prototype readout electronics.

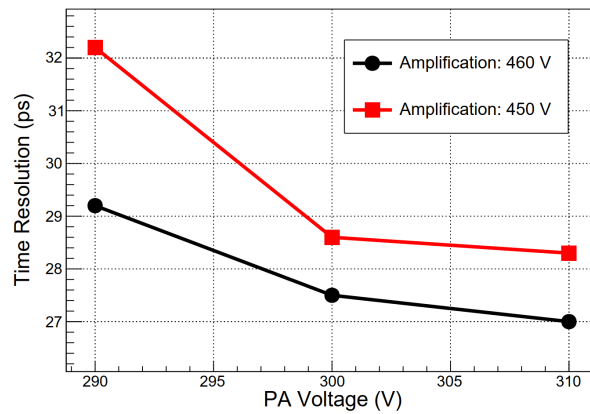


Figure 5. Time resolution results of $20 \times 20 \text{ cm}^2$ PICOSEC MM prototype in conjunction test with the readout electronics, equipped with a CsI photocathode. The results are shown for different amplification voltages and plotted as a function of PA voltage, with the optimal time resolution reaching below 30 ps.

readout of PICOSEC MM.

5 Conclusion

PICOSEC MM is undergoing continuous development aimed at detector optimization and large-area coverage. Several approaches to the $10 \times 10 \text{ cm}^2$ resistive PICOSEC MM structure were developed, and a $20 \times 20 \text{ cm}^2$ resistive PICOSEC MM was developed to expand the coverage by integrating four photocathodes. Beam tests with various photocathodes showed that the $10 \times 10 \text{ cm}^2$ resistive PICOSEC MM achieved a time resolution of around 20 ps, while the $20 \times 20 \text{ cm}^2$ PICOSEC MM reached a time resolution of 25 ps with a CsI photocathode, demonstrating excellent timing performance. Customized readout electronics dedicated to the multi-channel PICOSEC MM, including a readout chain of an RF-AM and WDM, were developed and thoroughly tested. The electronic system, when coupled with the large-area PICOSEC MM prototypes, achieved an overall time resolution below 30 ps during beam tests. This demonstrates that the PICOSEC MM and the entire system possesses the capability for high time precision and large-area integration, showcasing the potential for its application in future experiments with complex environments.

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