PICOSEC Micromegas: Achievements in Precise Timing and Recent Advancements with Large Segmented Prototypes

HEP 2021 – 38th Conference on Recent Developments in High Energy Physics and Cosmology
19 June 2021 – Thessaloniki GREECE

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on behalf of the RD-51 PICOSEC collaboration
Outline

Introduction

• Motivation for the PICOSEC Micromegas detector project
• Detector description

Single anode PICOSEC prototype

• timing performance in laser and particle beams
• simulation and modeling

Multipad PICOSEC prototype: scaling up the detector

• issues related to the 1st multipad PICOSEC – performance in timing after corrections

Towards an optimized large PICOSEC detector

• the updated segmented PICOSEC design
• foreseen tests and actions

Concluding remarks
Introduction
Aim for ~ 20 ps timing in particle tracking

High Luminosity consequences:
High pile-up (up-to 200 events/BC) with large number of tracks
Harsher radiation environment

Requirements:
- Large surface coverage.
- Multi-pad readout for tracking.
- Resistance to aging effects.

Demand for precise timing detectors for physics (Time of Flight, Particle Identification)
Rising needs related to medical and industrial application

Available technology:
Solid state detectors
- Avalanche PhotoDiodes: ($\sigma_t \sim 20$ ps)
- Low Gain Avalanche Diodes ($\sigma_t \sim 30$ ps)
- HV/HR CMOS ($\sigma_t \sim 80$ ps)

$\Rightarrow$ Radiation hardness?
$\Rightarrow$ Cost

Gaseous detectors
- RPCs: ($\sigma_t \sim 30$ ps)

High rate limitation
- Micro-Pattern Gaseous Detectors ($\sigma_t \sim 1$ ns)

PID techniques: Alternatives to RICH methods,
J. Va'vra, NIMA 876, 185 – 193, 2017
https://doi.org/10.1016/j.nima.2017.02.075

Improve Micromegas performance by ~ 2 orders of magnitude
1st step: proof of concept
Next steps: increase area, position-sensitive, radiation hardness
A typical Micromegas

**Drift gap/Conversion region**
Ionizing particles create electrons, which drift towards readout plane.

**Amplification region**
Avalanches/amplification, charge movement induces signals.

Characteristic advantages of the technology:
Simplicity, Granularity, Homogeneity, Scalability, High rate capabilities, Radiation hardness, Low cost

**Timing properties/Limitations**
- Ionizations occur in different positions along the particle’s trajectory \( \rightarrow \sim \) ns time jitter for a 3-6 mm conversion region
- Diffusion effects
The Physics of Ionization offers the means for precise spatial measurements (high spatial resolution) but inhibits precise timing measurements.
Limitations: reminder

The Physics of Ionization offers the means for precise spatial measurements (high spatial resolution) but inhibits precise timing measurements.

What if we could tackle the ‘problem’ of the stochastic nature of the ionization by exploiting other physics phenomena?

Use prompt photons (Cherenkov radiation) to extract electrons from the proper material (Photoelectric effect).
The PICOSEC vs the typical MM

**Cherenkov radiator + Photocathode**

- Particle produce Cherenkov light
- Photo-electrons emerge from photocathode
- Electrons amplified by a two-stage Micromegas

**Signal components:** Fast <1ns (electron peak) & Slow ~100ns (ion-tail)

Small drift gap (~200 μm) + High E-field:

- Pre-amplification possible
- Limited direct ionization
- Reduced diffusion impact

**Cherenkov radiator/Photocathode:**

- Photo-electrons emerging the photocathode simultaneously (fixed distance from the mesh)
- Produce sufficient number of photo-electrons

**Result:** improved timing resolution
Single anode PICOSEC
The single anode PICOSEC prototypes

Tests with UV lamp / laser → quartz windows

Sensor:

- **Bulk Micromegas ø 1cm**
  - Amplification gap 50 μm
  - Capacity ~ 35 pF
- ‘Standard’ bulk Micromegas ø 1cm
  - Capacity ~ 8 pF
  - Amplification gap 64 / 128 / 192 μm
- Thin-mesh Bulk Micromegas (~5 μm)
  - High optical transparency
  - Amplification gap 128 μm

50 μm Kapton spacers

- Ensure homogeneous small drift gap & photocathode polarization

Photocathodes: \( \text{MgF}_2 \) crystal (3mm) +

- **CsI** (18nm) on **Cr** (5.5nm metallic substrate) for muon beam tests
- **Al** (8-10nm) for laser tests

COMPASS gas: (80% Ne + 10% CF\(_4\) + 10% C\(_2\)H\(_6\))

Pressure: 1 bar.
Laser tests setup: response to single p.e.

Signal from Laser runs (right is zoom in e-peak)

\[ T_{\text{e-peak}} = \text{Signal Arrival Time (SAT)} \]

* SAT of a sample of events = \( <T_{\text{e-peak}} > \)

* Time Resolution = \( \text{RMS}[T_{\text{e-peak}}] \)


Time the signal arrival with Constant Fraction Discrimination (CFD) on the fitted e-peak (CFD @ 20% of the e-peak amplitude)

Talk by I. Manthos, “Signal processing techniques for precise timing with novel gaseous detectors”
Laser tests: time resolution for single p.e.

Best time resolution for 1 photo-electron: \(76.0 \pm 0.4 \text{ ps}\) @ \(V_d/V_a = -425 \text{ V} / +450 \text{ V}\)

Improves strongly with higher drift field, less with anode field.

The Signal Arrival Time (SAT) depends on the e-peak charge:
- bigger pulses \(\Rightarrow\) smaller SAT
- higher drift field \(\Rightarrow\) smaller SAT

Shape of pulse is identical in all cases \(\Rightarrow\) timing with CFD method does not introduce dependence on pulse size.

Responsible for this “slewing” of SAT: physics of the detector.
Beam tests: muons @ CERN SPS

Beam tests with 150 GeV muons @ CERN SPS H4:

- **timing measurements**
- **photocathode quantum efficiency** (number of photoelectrons per muon)

3 beam periods per year (2016 - 2018)

**No beam for 2019/2020!**

alternatives:

- DESY, Frascati, PSI...
- Laboratory measurements: monochromators, UV lamps, cosmic bench

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**Time reference:** two MCP-PMTs (<5 ps resolution).

**Scintillators:** used to select tracks & to avoid showers.

**Tracking system:** 3 triple-GEMs (40 μm precision).

**Electronics:** CIVIDEIC preamp. + 2.5 GHz LeCroy scopes.
Beam tests: time resolution for MIPs

Same detector as for Laser tests:
- MgF2 radiator 3 mm thick
- 18 nm CsI on 5.5 nm Cr
- Bulk MicroMegas
- “COMPASS gas”

Optimum operation point: $V_{\text{drift}}/V_{\text{anode}}: -475\text{V}/+275\text{V}$

Best result: $24 \pm 0.3\text{ ps}$

$N_{\text{p.e.}} = 10.1 \pm 0.7$

Mean number of p.e. per muon produced in the CsI photocathode
**Modeling & simulation: thorough understanding of the detector**

Detailed Garfield++ simulations reveal the same behaviors as seen in single p.e. laser data! (slide 14)

**Phenomenological model describing stochastically the dynamics of the signal formation**

The model describes SAT and Resolution vs. avalanche length & vs. number of electrons in avalanche (i.e., e-peak charge)

Avalanche speed = 154 μm/ns

Electron speed = 134 μm/ns

Time spread of SAT defined by the avalanche length = avalanche size


Model driven optimization of the detector

- **Drift gap**: The majority of the tests was done with 200 µm gap. Reducing it is expected to improve avalanche size and stability. *Tests were performed in May 2019 at the fs laser for gaps of 120, 170, 195 and 245 µm*

- **Gas composition**: CF$_4$ is increasing drift velocity, however is decreasing the maximum gain. *Ne or He mixtures with only C$_2$H$_6$ as quencher* are expected to increase maximum gain

- **Gas pressure**: decreasing pressure is equivalent with decreasing the amplification gaps.

*First overview of the data from gap tests with the fs laser test of May 2019*

**Time resolution < 50 ps is observed for single photoelectrons!!!**
CsI photocathode: performance and limitations

Best time resolution with CsI, although it is sensitive to humidity, can be damaged from sparks and high ion backflow (>25% for high drift fields)

Ongoing R&D in two directions:

- Protection layers (LiF, MgF$_2$, ...)
- New detector design (e.g. double mesh Micromegas)

Investigate alternative photocathodes and/or combination of material/thickness (evaluate QE vs robustness):

- pure metallic (Cr, Al, ..)
- DLC (Diamond Like Carbon)
- B$_4$C (Boron Carbide)
First Multipad PICOSEC prototype
The first multipad PICOSEC

Similar detector configuration as for single pad:
- MgF2 radiator 3 mm thick,
- 18 nm CsI on 5 nm Cr
- Bulk MicroMegas
- “COMPASS gas”
- 200 µm drift gap

Optimum operation point: $V_{\text{drift}}/V_{\text{anode}} = -475V/+275V$
Individual pad response vs distance R

0 < R < 2mm: full Cherenkov cone (3mm) inside a single pad surface
2 mm < R < 4.33 mm
4.33 mm < R < 7.5mm: full Cherenkov cone (3mm) mostly outside a single pad

Time resolution for each individual pad worsens as R increases!
First multipad PICOSEC: unforeseen deformation

- Timing performance revealed anode deformation (confirmed later by an optical device measurement)
- Drift gap non-uniformity → spatial variation of the detector gain
- Direct impact on the timing performance between pads
- Corrections applied, restored a uniform timing response over all detector active area

A. Utrobicic

Global time resolution

Distribution of fully corrected arrival time measurements of all pad signals induced by MIPs passing within 2 mm from the respective pad center.

The solid line represent a double Gaussian fit to the data points with an RMS of $25.8 \pm 0.6 \text{ ps}$. 
Combined pads timing resolution (I)

MIPs producing Cherenkov ring **equally**
shared among neighboring pads!

- pad #4: $71.3\pm2.5$ ps
- pad #8: $68.0\pm2.5$ ps
- pad #7: $66.2\pm2.5$ ps
Combined pads timing resolution (II)

MIPs producing Cherenkov ring equally shared among neighboring pads!

pad #4: $71.3 \pm 2.5$ ps

pad #7: $66.5 \pm 2.5$ ps

pad #8: $68.0 \pm 2.5$ ps

SAT and time resolution dependence known via $\tau(Q_e^m)$ and $\sigma(Q_e^m)$

$$\chi^2 = \sum_{m=1,M} \frac{(T_{comb.} - \left[ T_{f-corr.}^m - \tau(Q_e^m) \right])^2}{\sigma^2(Q_e^m)}$$

$$\hat{T}_{comb.} = \frac{\sum_{m=1,M} \frac{(T_{f-corr.}^m - \tau(Q_e^m))^2}{\sigma^2(Q_e^m)}}{\sum_{m=1,M} \frac{1}{\sigma^2(Q_e^m)}}$$

...obtain an estimation of the MIP arrival time
Combined pads timing resolution (II)

MIPs producing Cherenkov ring **equally** shared among neighboring pads!

- Pad #4: 71.3±2.5 ps
- Pad #7: 66.5±2.5 ps
- Pad #8: 68.0±2.5 ps

RMS of 32.2 ± 0.5 ps
Combined pads timing resolution (III)

MIPs within a 1 mm radius around sampling points

Timing resolution along a ‘path’ from pad #11 towards pad#4

Cherenkov ring for a MIP passing at the edge of the 1mm sampling point

Best single pad timing performance

Timing performance of a multi-pad PICOSEC-Micromegas detector prototype

https://doi.org/10.1016/j.nima.2021.165076
The updated multipad PICOSEC detector
Towards large area coverage: modular design

Schematics/photos not to scale
New multipad PICOSEC: realization

New design:
- larger surface
- mosaic-type of 1 cm side pads
- thick, ceramic PCB for improved rigidity

Facts and Considerations
- larger area: demand to maintain a uniform pre-amplification gap (~10μm flatness of anode for a surface of several cm²)
- Segmented anode (total of 10 x 10 cm²)
- Mechanical tension due to stretched mesh (~14N/cm), stress caused by mounting the PCB to the detector housing

(Antonija Utrobicic, RD51 Collaboration Meeting, February 16, 2021)
Alternative method for a flat(er) anode

Micromegas made on a hybrid ceramic PCB, completely enclosed in the chamber. 100 channels prototype (10 × 10 cm²) ready @ CERN

The ATLAS New Small Wheel panel construction principle: bulk Micromegas on a thin PCB, backed on a Alu honeycomb, and glued on super flat surface (vacuum or marble table, with flatness <10 μm)

(Thomas Papaevangelou, IRFU - FCC meeting, January 2021)

Talk by I. Maniatis, “Construction and operation of large scale Micromegas detectors for the ATLAS Muon upgrade”
Test beam period allocated for July and October 2021

Availability: **Muons** (and **electrons** for limited time)

Objective: - validate the new 100 channel multipad detector and additional PICOSEC prototypes
- test robustness of DLC and $B_4C$ photocathodes candidates
- test of electronics (SAMPIC digitizer, Philippe Legou – CEA Saclay)
Conclusions
Summary I

✓ Coupling a Micromegas detector with a radiator/photocathode we have surpassed the physical constraints on precise timing with MPGDs, achieving:

\[ \sigma_t \sim 76 \text{ ps for single p.e. } \rightarrow \text{improved to } 44 \text{ ps (published)} \]

\[ \sigma_t \sim 24 \text{ ps for 150 GeV muons (published)} \text{ (3 mm MgF}_2\text{+5.5 nm Cr substrate+18 nm CsI photocathode), } <N_{\text{p.e.}}> \approx 11 \]

✓ Deep understanding of the PICOSEC detector: reproduce results with detailed simulation, apply the phenomenological model to explain the observed experimental behavior and use it to optimize parameters

✓ Confirmed Multipad PICOSEC timing precision (published) brings confidence for modular/large scale installation

✓ Critical role of tight mechanical tolerances on the depth of the drift/preamplification stage
Summary II

Status and scheduled actions:

- Commissioning and testing the new segmented PICOSEC (anode on a ceramic PCB)

- Test BLC & B$_4$C photocathodes on MIP beams to evaluate Q.E. and robustness

- Further optimization is expected to deliver improved precision per MIP
Contributions

The **RD51 – PICOSEC** Collaboration


**USTC** (China): J. Liu, B. Qi, X. Wang, Z. Zhang, Y. Zhou.


**NCSR** (Greece): G. Fanourakis.

**NTUA** (Greece): Y. Tsipolitis.

**LIP** (Portugal): M. Gallinaro.

**HIP** (Finland): F. García.

**IGFAE** (Spain): D. González-Díaz.

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\(^{(3)}\) Also at National Research Nuclear University MEPhI, Kashirskoe Highway 31, Moscow, Russia; and Department of Physics, Uluda University, 16059 Bursa, Turkey
Thank you!

It’s Saturday.
I plan on doing nothing and plenty of it.
References: publications


References: selected proceedings and talks

• S.E. Tzamarias, RD51 Open Lectures and Mini Week, 2017, (https://indico.cern.ch/event/676702/timetable/)


• The RD51 PICOSEC-Micromegas Collaboration, Letter Of Interest, SnowMass2021 IF5, August 2020


• A. Utrobicic, Assembly and gain uniformity measurements of a new large area PICOSEC detector, RD51 Collaboration Meeting, February 16, 2021

• Florian M. Brunbauer, Precise timing with gaseous detectors: towards a robust and tileable PICOSEC Micromegas detectors, EP R&D Seminar, May 3, 2021

few extras
Limitations: reminder

Using the drift velocity ($V$), we express the probability that the first electrons will reach the anode at $t$:

$$A_{1\text{rst}}^{n}(t) = n(V/L)e^{-nVt/L}$$

Setting typical values, i.e. $V=50\mu$m/\(\text{ns}\) and $n=10$ we conclude that:

**Typical Time Resolution ~6ns**

A typical MicroMegas cannot reach timing resolution at the level of tenths of ps

The probability that an e-ion pair has been produced at $Z=z$ is the same for any value of $Z$; $p=1/L$

Then, in case that $k$ pairs are produced, the probability that the $j$th pair has been produced at $Z=z$ is given by the binomial distribution

$$P(j) = \frac{k!}{j!(k-j)!} (1-x)^{k-j}x^{j-1}$$

where $x=z/L$ describes the probability that a pair is produced in the region $0-z$

The probability that the $j$th pair has been produced at $Z=z$ for any total number of e-ion pair

$$A_{j}^{n}(x) = \sum_{k=j}^{\infty} p^{n}q^{k-j}(x) = \frac{x^{j-1}}{(1-x)^{j-1}} e^{-nx}$$

The probability that the last pair (i.e. the closest to the edge 0) has been produced at $Z=z$ is given by ($j-1=0$)

$$A_{\text{last}}^{n}(x) = nxe^{-nx}$$

$$A_{\text{last}}^{n}(z) = ne^{-nz/L}$$
Detector alignment: estimating pad centers positions

The exact position of each participating pad is needed in order to calculate the combined time resolution

The part of the beam profile that illuminated the area covering all PICOSEC instrumented pads

Mean value of the electron-peak charge for pad #4

Mean value of the electron-peak charge for pad #7
Individual pad response vs distance $R$

19 hexagonal pads 5mm side

- ~ 25 ps resolution confirmed for the center of the pads
- SAT difference between outer vs inner area of the peripheral pads
- Gain non-uniformity $\rightarrow$ worse time resolution
- Drift gap distance differences due to the anode deformation
- Center of anode curvature located at pad #7

SAT for MIPs passing within $2 \text{ mm} < R < 4.33 \text{ mm}$ from pad center

- black points: raw SAT measurements
- red points: distributions after applying the flatness corrections

RMS $\sim$34ps

RMS $\sim$49ps
SAT and time resolution of a single pad ideally should obey the symmetry of points A-B regardless of θ.

SAT asymmetries reduces for θ approaching 90 deg (absolute value).
Gain non-uniformity investigation: spread of SAT

SAT and time resolution of a single pad ideally should obey the symmetry of points A-B regardless of Θ.

RMS values are approximately symmetric for all Θ.

Graph points correspond to tracks passing within 0.5mm around a spot.

solid lines represent empirical parametrizations
Gain non-uniformity: flatness corrections

Parametrize mean SAT values as a function of cylindrical coordinates. Apply a flatness correction to the arrival times of all signals of the specific peripheral pad.

\[ T_{j \text{ corr.}}^{k} = T_{SAT}^{k} (r, \Theta) - \Delta^{k} (r, \Theta) \]

After corrections the timing properties of the peripheral pads approach those of the central pad #7. Spread of SAT depends explicitly on e-peak charge regardless of the MIPs impact point.

SAT and time resolution after corrections, as compared to the central pad #7 (solid lines are fits of the central pad data).
Readout electronics I

Scheme during first test period (single cell and 1\textsuperscript{st} multipad PICOSEC prototype):

CIVIDEQ broadband amplifier, 2 GHz, 40 dB, (https://cividec.at/electronics-C2-HV.html)

LECROY WR8104 oscilloscope, operated at 1.0 GHz analogue bandwidth, sampling rate of 10 Gsamples/s, Waverunner 8000, Teledynelecroy, (http://cdn.teledynelecroy.com/files/pdf/waverunner8000-datasheet.pdf)

Costly and not convenient solution for multi-channel application.
Readout electronics II

“Home-made” preamp circuit (Philippe Legou – CEA) tested and proved compatible to PICOSEC timing requirements + ASIC

One card per channel

SAMPLIC considered as solution for digitisation with sampling rates ~8GS/s
Test bench for beam time (2021)

- CIVIDEC C2, Ortec 142 IH

- Oscilloscopes:
  - CERN (LeCroy WaveRunner 625Zi, R&S RTO 1044)
  - CERN-pool (LeCroy LECROY WR8104 oscilloscopes)

- UV led for single p.e spectrum (model:UVTOP240TO18BL)

- Gas: Compass Mixture (Ne:Ethane: CF4 - 80:10:10)

Timing
- MCP-PMT (available 11mm diameter)
- Large area

Triggering
- Scintillators (small area single MIP selection and large area)

Tracking
- Triple GEM detectors, XY readout
New multipad PICOSEC: first tests

Status
• assembly of the detector is finalized
• first HV test proved a stable operation
• gas tightness measurements performed to determine gas leak rates
• diode light tests done to measure the individual pad response and obtain gain mapping
New multipad PICOSEC: design requirements

PCB flatness within 10 μm over the active area
Material: hybrid ceramic instead of just FR4
Thickness: 4.85 mm instead of 3 mm
Potential applications
Scenario I: PICOSEC embedded in an EM calorimeter

- Relaxed photocathode – QE requirements (many secondary relativistic electron of the EM shower will produce many Cherenkov photons in the PICOSEC radiator)

- Metallic photocathode (e.g. Cr)
  - ~ 240 p.e. after just 2 rad.lengths for a 30 GeV electron shower (2 ps statistical, from simulation)
  - ~ 17 p.e. (20 ps) after 2 rad.lengths for a 5 GeV electron shower
  - ~ 33 p.e. (14 ps) after 5 rad.lengths for a 5 GeV electron shower
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Thin gap PICOSEC (119μm Drift gap) timing resolution of ~ 6.8 ps (for approx. 70 p.e.) it will improve all expected resolution values (x 0.7)
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- Potential applications in PID
  - e.g. tagging the production time and flavor of neutrino
    \[ K^+ \rightarrow \pi^0 e^+ \nu_e \] (ENUBET project)

Thin gap PICOSEC (119\,\mu m Drift gap)
- timing resolution of ~ 6.8 ps (for approx. 70 p.e.)
- it will improve all expected resolution values (x 0.7)
Scenario II: timing in Electron Ion Collider

- Barrel detectors
- TPC Readout
- Forward Detectors
- Timing Detectors

Scenario II: TOF for PID using PICOSEC

TOF PID at RHIC/EIC

Momentum reach of TOF PID reaches interesting levels if one can achieve ~ 20 ps

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Distance</th>
<th>Pion-Kaon Separation</th>
<th>Kaon-Proton Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_{tot}=100 ps</td>
<td>1m</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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<tr>
<td>σ_{tot}=10 ps</td>
<td>1m</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td>σ_{tot}=20 ps</td>
<td>0.85 m</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>σ_{tot}=20 ps</td>
<td>5m</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
</tbody>
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- t0 provided by the machine