Progress on the PICOSEC-Micromegas Detector Development: towards a precise timing, radiation hard, large-scale particle detector with segmented readout

Kostas KORDAS on behalf of the RD51 PICOSEC-Micromegas Collaboration
Outline

• PICOSEC MicroMegas: a detector with precise timing:
  – Single-channel prototype in Laser and Particle beams

• A well-understood detector:
  – reproduce observed behaviour with detailed simulations and a phenomenological model

• Towards a practical detector: robustness
  – resistive anodes & robust photocathodes

• Towards a large-scale detector: multi-channel
  – response of multi-channel PICOSEC prototype
**Motivation**

Precise timing needs → *picosec domain*

A Review:

- E.g., in the High Luminosity LHC, ~140 “pile-up” proton-proton interactions (“vertices”) in the same pp bunch-crossing

**140 pp interactions / bunch-crossing**

(Gaussian $\sigma \sim 45\text{mm}$):

**crowded along beam-axis**

- Using the time-dimension → separates vertices:

**needed precision ~ order 30ps**
1. A precise-timing detector

Detector concept and the proof with results of single-channel prototypes
PICOSEC detector concept

- Classic MicroMegas
  Giomataris Y. et al., NIMA 376 (1996) 29

- **Multiple electrons produced at different points along particle’s path in the ~3-6mm drift region** → **Time jitter order few ns**

- With Cherenkov radiator + photocathode → **synchronous photo-electrons (p.e) enter MicroMegas**

- Small drift gap & high field → **avalanches start as early as possible** with minimal time jitter → **Timing resolution a few tens of ps**

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**PICOSEC single-channel Prototype**

Single pad prototypes
(1 cm diameter active area)

- Bulk MicroMegas readout (6 pillars)
- 4 kapton rings spacers → 200 μm drift
- Radiator + photocathode.

* Cherenkov Radiator:
  MgF$_2$ 3mm thick → 3mm Cherenkov cone

* Photocathode: 18nm CsI (with 5.5 nm Cr)

* COMPASS gas (80% Ne + 10% CF$_4$ + 10% C$_2$H$_6$)
  Pressure: 1 bar.

* Drift gap = 200 μm
* Amplification gap = 128 μm
* Mesh thickness = 36 μm (centered at 128 μm above anode)

Results from Laser and Beam tests presented next are from this detector
Since 2016, different prototypes studied (bulk, thin mesh etc. MM, multipad MM, different gas, anode schemes, photocathodes)
1a.
Response to single photoelectrons
Laser beam: response to single electron (1)

- **Pulsed laser** at IRAMIS facility (CEA Saclay)
- **Wavelength**: 267-288 nm
- **Repetition rate**: up to 500 kHz
- **Intensity**: attenuated to get single photoelectron directly on photocathode
- **Read out with CIVIDEC preamp**
- **Digitized waveform by 2.5GHz LeCroy osciloscope @ 20GSamples/s = 1 sample/50ps.**

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

- **Two-component signal:**
  - **Electron peak ("e-peak")** → fast (~0.5ns)
  - **Ion tail** (~100ns)

**Typical single p.e signal**
Laser beam: response to single electron (2)

- t0 reference: fast photodiode (~10 ps resolution)
- Detector response at different field settings
  - Timing resolution $76.0 \pm 0.4$ ps achieved @ drift/anode: -425V / +450 V
    - improves strongly with higher drift field, less with anode field

$T_{e-peak} = \text{Signal Arrival Time (SAT)}$
- SAT of a sample of events $= \langle T_{e-peak} \rangle$
- Time Resolution $= \text{RMS}[T_{e-peak}]$

$T_{e-peak}$ Time (ns)

→ Time the signal arrival with Constant Fraction Discrimination (CFD) on the fitted noise-subtracted e-peak

( CFD @ 20% of the e-peak amplitude)

Laser beam: response to single electron (3)

- t0 reference: fast photodiode (~10 ps resolution)
- Detector response at different field settings
  - Timing resolution $76.0 \pm 0.4$ ps achieved @ drift/anode: -425V / +450 V
    - improves strongly with higher drift field, less with anode field

Time Resolution depends mostly on e-peak charge:

"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector", J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325
Laser beam: response to single electron (4)

- t0 reference: fast photodiode (~10 ps resolution)
- Detector response at different field settings
- Timing resolution $76.0 \pm 0.4$ ps achieved @
  drift/anode: -425V / +450 V
  - improves strongly with higher drift field, less with anode field

The Signal Arrival Time (SAT) depends non-trivially 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 the SAT: physics of the detector

$T_{e\text{-peak}}$ = Signal Arrival Time (SAT)
* SAT of a sample of events $\Rightarrow T_{e\text{-peak}}$
* Time Resolution $= \text{RMS}[T_{e\text{-peak}}]$

The Signal Arrival Time (SAT) depends non-trivially on the e-peak charge:

- bigger pulses $\rightarrow$ smaller SAT
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* Shape of pulse is identical in all cases
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* Responsible for this “slewing” of the SAT: physics of the detector
1b. Response to Minimum Ionizing Particles (MIPs)
Testing with Particle Beams @ CERN SPS H4

- **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**: CIVIDEC preamp. + 2.5 GHz LeCroy scopes.

Last run Oct. 2018: The latest for the next 2 years at CERN
Time resolution for MIPs

- Same detector as for Laser tests (MgF$_2$ radiator, CsI photocathode, Bulk MicroMegas, COMPASS gas)
- **Best time resolution: 24ps $\pm 0.3$ ps**

@ Drift/Anode: -475V/+275V

Number of photoelectrons per MIP

Noise component

Signal for single photoelectron (p.e) from UV-lamp tests: “Polya” (Gamma distribution)

Signal of MIPs: the Red histogram represents the convolution of Poison and single p.e response (Polya)

Estimated Mean number of photoelectrons per muon produced in the CsI photocathode = 10.4 ± 0.4

2. A well understood detector
detailed simulations and modeling
Detailed simulation with “trimmed” Garfield++

Black: Averaged PICOSEC waveforms in a certain e-peak charge region
Red: e-peak Simulation Prediction (Garfield++ and Electronics Response) derived from single p.e data (our “impulse response”)

All behaviours seen in single p.e. laser data are also seen in these detailed Garfield++ simulations. e.g., see below:

The Signal Arrival Time (SAT) depends non-trivially on the e-peak size:

* bigger pulses → smaller SAT
* higher drift field → smaller SAT

* Time resolution depends mostly on e-peak charge
Detailed simulations: under the hood

Microscopic equivalent to e-peak’s SAT = Mean Time (T) of all electron arrival times on the mesh
* <SAT> linear with <T>
* RMS(SAT) linear with RMS(T)

Gives e-peak pulse
**Detailed simulations: under the hood**

Microscopic equivalent to e-peak’s SAT = Mean Time (T) of all electron arrival times on the mesh

- \(<\text{SAT}\)> linear with \(<T>\)
- \(\text{RMS(SAT)}\) linear with \(\text{RMS(T)}\)

Gives e-peak pulse

Avalanche runs with higher drift velocity than pre-ionization electron

So, SAT slewing seen in single p.e data is explained:

- SAT reduces with avalanche length
- Long avalanches → big e-peak charge
- SAT reduces with e-peak charge
Understood in terms of phenomenological model

- Known in literature that quenchers in the gas-mix increase drift velocity →

**Model:** assume a time-gain per inelastic interaction compared to an elastic interaction

The model describes SAT and Resolution

a) vs. avalanche length &

b) vs. number of electrons in avalanche (i.e., vs. e-peak charge)

→ Before and after the mesh

Not only averages and RMS, but full distributions, vs. values of operational parameters (e.g., drift voltage) arXiv:1901.10779v1 [physics.ins-det]
3. Towards a robust detector

#1 robust anode
#2 robust photocathode
Best resolution was at voltages which give high currents on anode: robust anode

Readout beneath resistive layer: picks up signal from above
Resistive strip grounded

Copper Layer to HV via resistor; Readout “floating”

Developed in the MAMA project

Resistive readouts operate stably at high gain in neutron fluxes of $10^6$ Hz/cm$^2$.

T. Alexopoulos et al., NIMA 640 (2011) 110-118.

Non resistive ← MAMA results → With resistive strip
~ no discharges

Current

Irradiation time →

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Beam results with protected anodes

- Values not far from the Picosec bulk readout.
  - Resistive strips: 41 ps (10 MΩ/□), 35 ps (300 kΩ/□).
  - Floating strips: 28 ps (25 MΩ).
Best resolution was at voltages which give high ion backflow? Robust photocathode

- Ion back flow damages CsI photocathode

Robust photocathodes needed.
Investigating Photocathodes

- For each photocathode material the working point with the best time resolution has to be determined.
  - The time resolution, quantum efficiency and efficiency are compared.
  - Reference single photon measurements and tracking data are necessary.

And they have to be robust.

Most promising performance results for non-CsI are from Diamond-Like Carbon (DLC), which also seems robust:
- atmospheric conditions for a few months
- irradiated with pions, in a resistive MM prototype → minimal reduction of Npe/MIP

Different Materials tested like:
- Metallic Photocathodes
- CsI with protection layer
- Nano Diamond Seeding
- Diamond secondary emitter
- Diamond-like Carbon

3mm MgF$_2$ + DLC of different thicknesses:
Promising: Diamond Like Carbon (DLC) photocathodes

- 2.5 nm DLC time resolution up to 34 ps observed
- Results repeatable in independent samples and measurements
- Additional tests with heating treatment under N2 and H2
- Additional aging tests under pions
- Samples survived rough transport from China

<table>
<thead>
<tr>
<th>Thickness of DLC film (nm)</th>
<th>Npe/per muon</th>
<th>Detection efficiency for muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>2.5</td>
<td>3.7</td>
<td>97%</td>
</tr>
<tr>
<td>5</td>
<td>3.4</td>
<td>94%</td>
</tr>
<tr>
<td>7.5</td>
<td>2.2</td>
<td>70%</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
<td>68%</td>
</tr>
<tr>
<td>5 nm Cr + 18 nm CsI</td>
<td>7.4</td>
<td>100%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A/D Voltage</th>
<th>Time Res. (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250/550</td>
<td>37</td>
</tr>
<tr>
<td>250/575</td>
<td>34</td>
</tr>
<tr>
<td>275/525</td>
<td>38</td>
</tr>
<tr>
<td>275/550</td>
<td>34</td>
</tr>
<tr>
<td>300/500</td>
<td>39</td>
</tr>
<tr>
<td>300/525</td>
<td>34</td>
</tr>
</tbody>
</table>
4. Towards a large scale detector

Results from a multi-channel prototype
Multi-pad MicroMegas

- Like the MgF$_2$/CsI/bulkMM/COMPAS gas single-pad PICOSEC which achieved 24ps per MIP

Hexagonal pads 5mm side
Readout 4 pads → 2 oscilloscopes
(*** for multi-channel: have to move to chip solutions. Tried SAMPIC, no results yet)
Multi-pad: individual pad response vs. R

- Like the MgF$_2$/CsI/bulkMM/COMPAS gas single-pad PICOSEC which achieved 24ps per MIP

Study response vs. R: distance of track impact from pad center

0 < R < 2 mm:
- full Cherenkov cone (3mm) inside pad

4.33 < R < 7.5 mm:
- Cherenkov cone (3mm) mostly outside pad

Hexagonal pads 5mm side

e-peak charge should have all info about where is Cherenkov cone compared to pad. Indeed, universal curves vs. e-peak charge:

0. < R < 2. mm
- 2. < R < 4.33 mm
- 4.33 < R < 7.5 mm

After corrections

PRELIMINARY

<20ps for large e-peaks
Multi-pad: Same resolution as single-pad

At center of each pad (0<R<2mm):

a time resolution of 25ps for all pads

E.g.:

\[ \sigma_{\text{tot}} = 25\text{ps} \]

\[ \Delta T = \text{Time after all corrections (ns)} \]
Multi-pad: pad responses for any impact point

These are not the easiest regions

For tracks falling around a “three-pads” region:

Each individual pad: resolution worsens moving outwards

200μm inter-pad space

Pilars of ~650μm diameter

ΔT = Time after all corrections (ns)

μ = -2 ps
σ = 86 ps

μ = 1.5 ps
σ = 81 ps

P R E M I N A R Y

ΔT = Time after all corrections (ns)

μ = -2.5 ps
σ = 70 ps

P R E M I N A R Y

μ = -2 ps
σ = 86 ps

P R E M I N A R Y

μ = 1.5 ps
σ = 81 ps

P R E M I N A R Y

μ = -2.5 ps
σ = 70 ps
**Multi-pad: Combining pads**

For tracks falling around a “three-pads” region:

Combining pads event-by-event → Excellent time resolution

Each individual pad: resolution worsens moving outwards

Similar results all across the area covered by the 4 pads

**Excellent Properties of pull**

**Combining pads event-by-event**

\[ \Delta T = \text{Time after all corrections (ns)} \]

\[ \mu = -2.0 \text{ ps} \]
\[ \sigma = 31 \text{ ps} \]

\[ \mu = 1.5 \text{ ps} \]
\[ \sigma = 81 \text{ ps} \]

\[ \mu = -2.5 \text{ ps} \]
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\[ \mu = -2 \text{ ps} \]
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\[ \sigma = 81 \text{ ps} \]

\[ \Delta T / \sigma \]

\[ \tau \]
Conclusions

● PICOSEC MicroMegas: a detector with precise timing:
  - Single-channel prototype in Laser and Particle beams
  - 76ps for single photoelectrons, 24ps resolution for timing MIPs

● A well-understood detector:
  - reproduce observed behaviour with detailed simulations and a phenomenological
    model: valuable tool for parameter-space exploration

● Towards a practical detector: robustness
  - resistive anodes & robust photocathodes: promising progress

● Towards a large-scale detector: multi-channel
  - response of multi-channel PICOSEC prototype: similar precision as the single-
    channel prototype, for any impact point of a MIP
Thank you
RD51 PICOSEC-MicroMegas Collaboration

- **CERN (Switzerland):** J. Bortfeldt, F. Brunbauer, C. David, J. Frachi, M. Lupberger, H. Müller, E. Oliveri, F. Resnati, L. Ropelewski, T. Schneider, P. Thuiner, M. van Stenis, R. Veenhof\(^2\), S. White\(^3\).
- **USTC (China):** J. Liu, B. Qi, X. Wang, Z. Zhang, Y. Zhou.
- **AUTH (Greece):** K. Kordas, I. Maniatis, I. Manthos, V. Niaouris, K. Paraschou, D. Sampsonidis, S.E. Tzamarias.
- **NCSR (Greece):** G. Fanourakis.
- **NTUA (Greece):** Y. Tsipolitis.
- **LIP (Portugal):** M. Gallinaro.
- **HIP (Finland):** F. García.
- **IGFAE (Spain):** D. González-Díaz.

\(^1\) Now at Synchrotron Soleil, 91192 Gif-sur-Yvette, France
\(^2\) Also MEPhI & Uludag University.
\(^3\) Also University of Virginia.
Progress on the PICOSEC-Micromegas Detector Development: towards a precise timing, radiation hard, large-scale particle detector with segmented readout

Kostas KORDAS on behalf of the RD51-PICOSEC Collaboration
MCP-PMT: Hamamatsu R3809U-50

Multi-Channel Photomultiplier
With 3.3mm MgF₂ Cherenkov radiator in front
Operated at 2800V
Understood in terms of phenomenological model

- Known in literature that quenchers in the gas-mix increase drift velocity →

**Model:** assume a time-gain per inelastic interaction compared to elastic interactions

Electron population on the mesh

Electron population on the mesh

Total on the mesh

Electron population on the mesh

Time spread (ns)

Avalanche

Photoelectron

Time (ns)

arXiv:1901.10779v1 [physics.ins-det]
Understood in terms of phenomenological model

- Known in literature that quenchers in the gas-mix increase drift velocity →

**Model:** assume a time-gain per inelastic interaction compared to elastic interaction

Describe SAT and Resolution

a) vs. avalanche length &

b) vs. number of electrons in avalanche

(i.e., vs. e-peak charge)

→ Before and after the mesh

Not only averages and RMS, but full distributions, vs. values of operational parameters (e.g., drift voltage) arXiv:1901.10779v1 [physics.ins-det]
Best resolution was at voltages which give high ion backflow? **robust photocathode**

- Ion back flow damages CsI photocathode

Robust photocathodes needed.

**Different materials tested:**
- Metallic
- CsI with protection layer
- Nano Diamond Seeding
- Diamond secondary emitter
- Diamond-Like Carbon, etc

**Tested in terms of:**
- timing resolution
- N(p.e)/muon
- Efficiency to detect muons
Multi-pad MicroMegas

- Like the MgF$_2$/CsI/bulkMM/COMPAS gas single-pad PICOSEC which achieved 24ps per MIP

Sudy response vs. R: distance of track impact from pad center

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

Correct arrivals times inside each pad, to have same behaviour vs. R, for all azimuthal directions

e-peak charge should have all info about where is Cherenkov cone compared to pad. Indeed:

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

After corrections

<20ps for large e-peaks

Hexagonal pads 4.33 mm side
Readout 4 pads

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Multi-pad MicroMegas

- Like the MgF₂/CsI/bulkMM single-pad PICOSEC which achieved 24ps per MIP
Multi-pad PICOSEC: Combining multiple pads

\[ \chi^2 = \sum_{i = 1,4} \left( \frac{t_i - \{ \langle \text{SAT} \rangle(R_i, \theta_i) - \langle \text{SAT} \rangle(R_i, 90^\circ) \} - \{ \text{SL}(Q) \}- i}{\text{Re}\, s(Q)} \right)^2 \]
Multi-pad: Tracks are selected within a circle of 1.5 mm radius

\[ \mu = 1.6 \pm 2 \text{ps} \]
\[ \sigma = 25 \pm 1.5 \text{ ps} \]

\[ \mu = 0 \pm 2 \text{ps} \]
\[ \sigma = 31 \pm 1.5 \text{ ps} \]

\[ \mu = 2 \pm 2 \text{ps} \]
\[ \sigma = 31 \pm 1.5 \text{ ps} \]

\[ \mu = 5 \pm 2 \text{ps} \]
\[ \sigma = 25 \pm 1.5 \text{ ps} \]
Multi-pad: Tracks are selected within a circle of 1.5 mm radius.

\[
\begin{align*}
\mu &= 1.6 \pm 2 \text{ ps} \\
\sigma &= 25 \pm 1.5 \text{ ps}
\end{align*}
\]

\[
\begin{align*}
\mu &= -2 \pm 2 \text{ ps} \\
\sigma &= 29 \pm 1.5 \text{ ps}
\end{align*}
\]

\[
\begin{align*}
\mu &= -4 \pm 2 \text{ ps} \\
\sigma &= 32 \pm 1.5 \text{ ps}
\end{align*}
\]

\[
\begin{align*}
\mu &= -1.5 \pm 2 \text{ ps} \\
\sigma &= 33 \pm 1.5 \text{ ps}
\end{align*}
\]

PRELIMINARY
Multi-pad: Tracks are selected within a circle of 1.5 mm radius

\[ \mu = 1.6 \pm 2 \text{ps} \]
\[ \sigma = 25 \pm 1.5 \text{ ps} \]

\[ \mu = 3 \pm 2 \text{ps} \]
\[ \sigma = 32 \pm 1.5 \text{ ps} \]

\[ \mu = 1 \pm 2 \text{ps} \]
\[ \sigma = 33 \pm 1.5 \text{ ps} \]

\[ \mu = 4 \pm 2 \text{ps} \]
\[ \sigma = 31 \pm 1.5 \text{ ps} \]