PICOSEC Micromegas precise-timing gaseous detectors and studies on robust photocathodes

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ON BEHALF OF THE CERN EP-DT-DD GDD GROUP
AND OF THE PICOSEC MICROMEGAS COLLABORATION

DETECTOR SEMINAR - SPECIAL SESSION
(EP-RD, AIDAINNOVA POSTER AWARDS), 12 JULY 2024

GDD
Gas Detectors Development Group

EP R&D

PICOSEC Micromegas

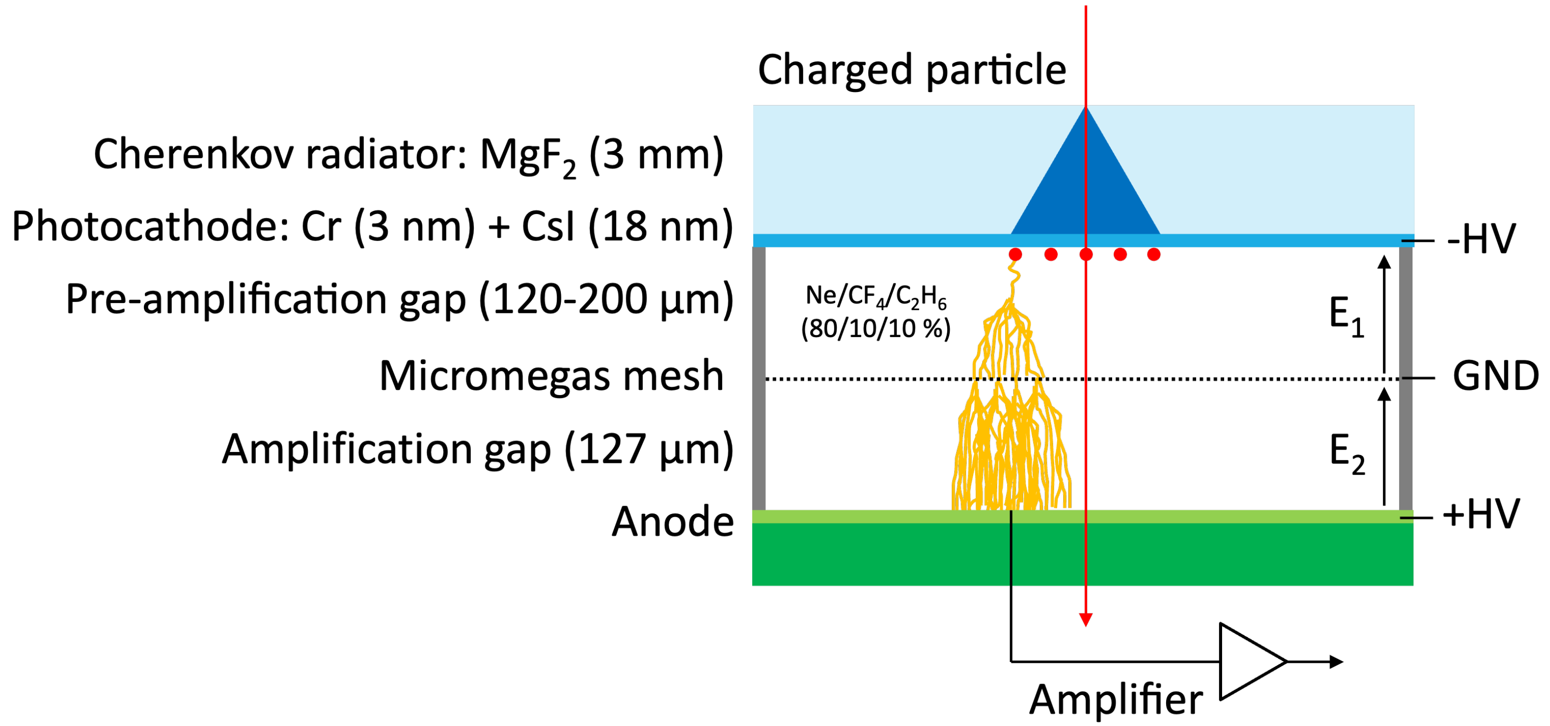
université PARIS-SACLAY

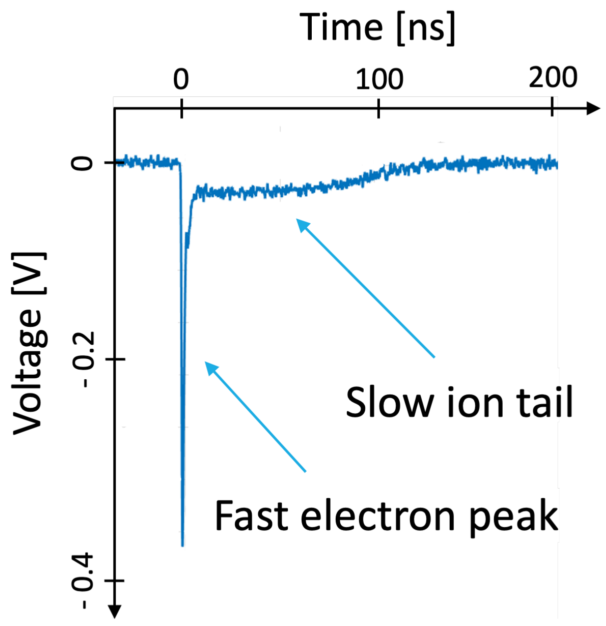
École Doctorale PHENIICS Doctoral School

PICOSEC Micromegas

Detector concept

- **PICOSEC Micromegas:** a gaseous detector aiming at achieving **a time resolution of tens of picoseconds** for MIPs





- First single-pad prototypes with a time resolution below σ = 25 ps → Now we want to adapt the concept for applications

PICOSEC Micromegas

Developments towards applicable detector

- <u>**Objective:** Robust tileable multi-channel detector modules for large-area coverage</u>

- **Detector optimisation:**

  gaps thickness, fields settings, operating gas

- **Stability and robustness:**

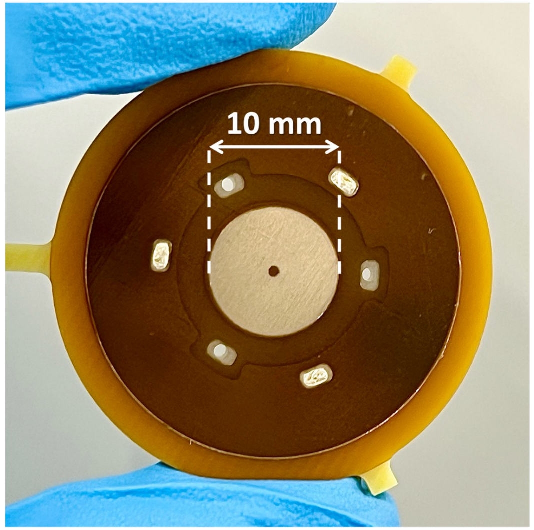
  resistive Micromegas, robust photocathodes

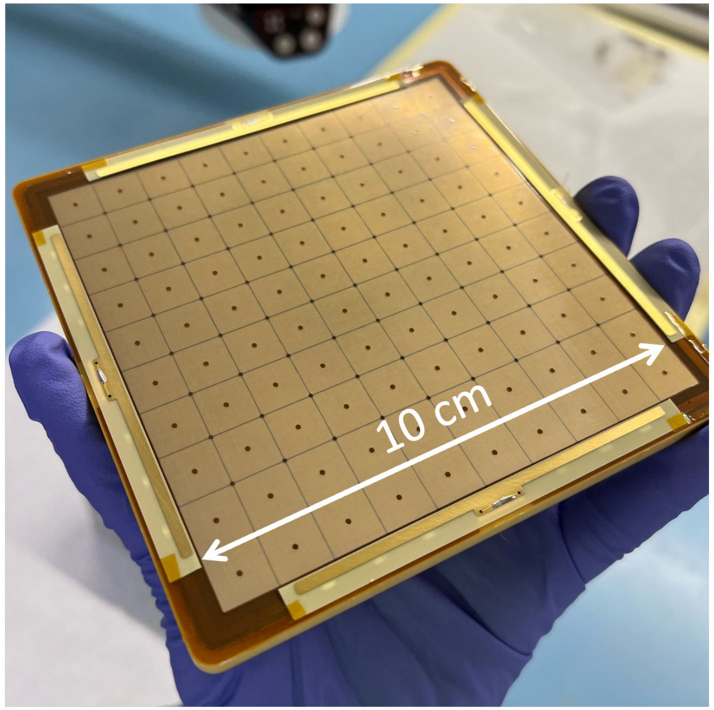
- **Large area coverage:**

  100-channel prototypes, tileable modules

- **Scalable electronics:**

  scalable amplifiers, multi-channel digitisers





PICOSEC Micromegas

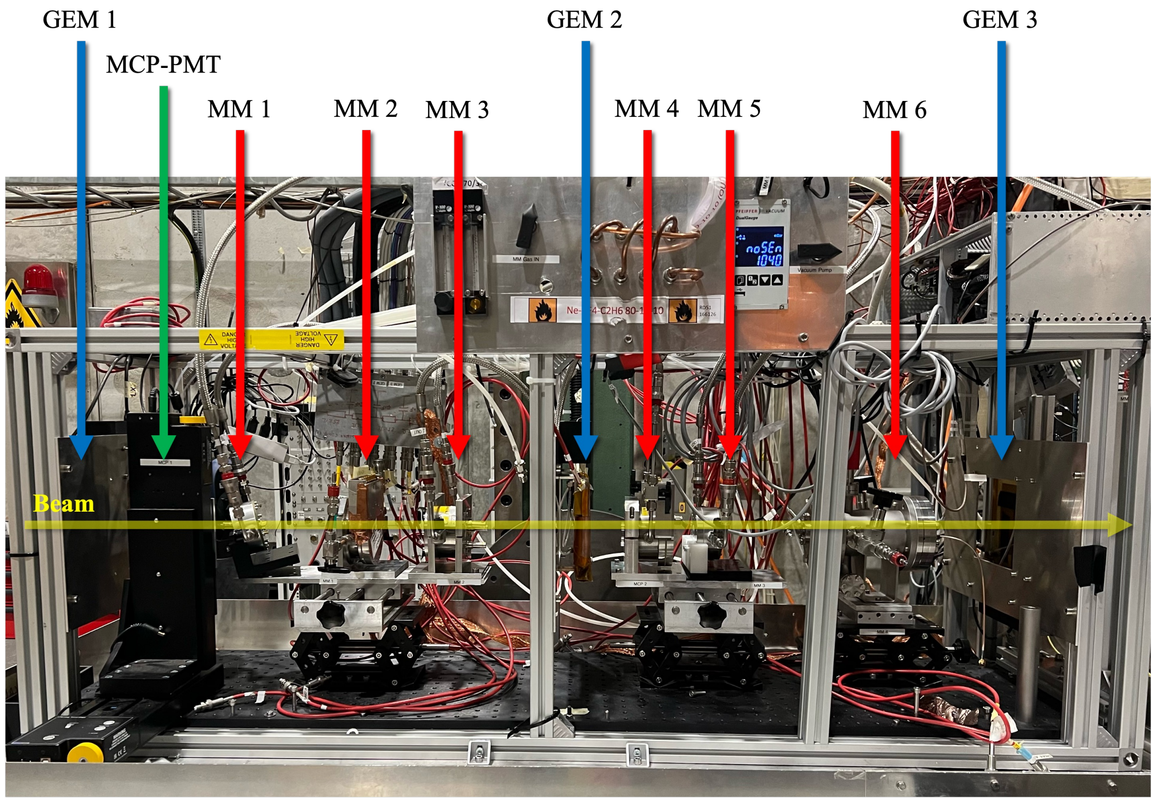
Detector characterisation with particle beams

- **Intensive R&D activities:** From **simulations** and **design**, through **production** and **assembly** to **measurements** and **analysis**

- **Objective of the test beam campaigns:** to measure the time resolution of the detectors assembled in various configurations

- **Beam type:** CERN SPS H4 beam line, 150 GeV/c muons (also pions and electrons)

- **Experimental setup:** tracking/timing/triggering telescope
  → Three triple-GEM detectors for precise particle tracking
  → MCP-PMT for timing reference and DAQ trigger
  → PICOSEC Micromegas (MM) detectors under test
  → MCP-PMT and PICOSEC signals read out by oscilloscopes

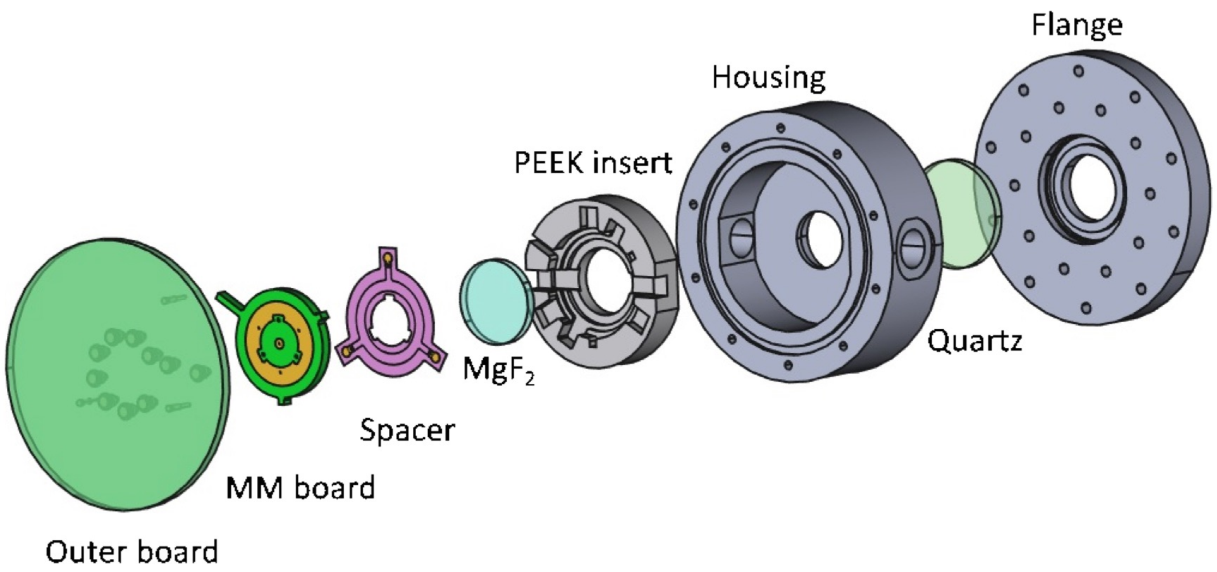


PICOSEC Micromegas

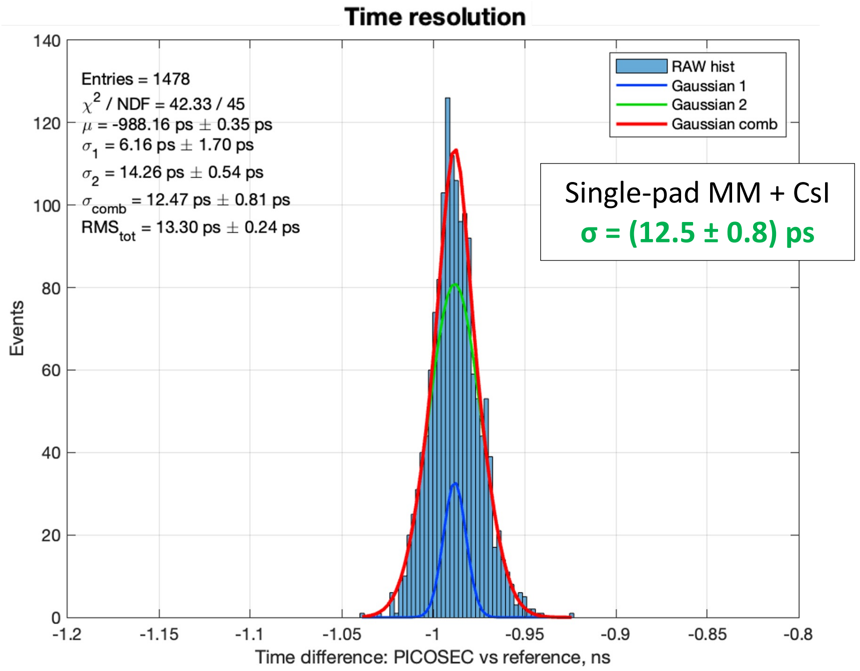
Single-pad prototype performance

New record! ☺

- Optimisation studies on a single-pad prototype to
  → enhance HV stability
  → reduce noise
  → achieve a uniform timing response
  → all while using a simplified assembly procedure



- Single-pad detector with 10 mm dia. active area equipped with a CsI photocathode + custom developed RF amplifiers showed an **improved time resolution of σ = 12.5 ± 0.8 ps**



A. Utrobičić et al., arXiv:2406.05657

Resistive Micromegas

Advantages and requirements

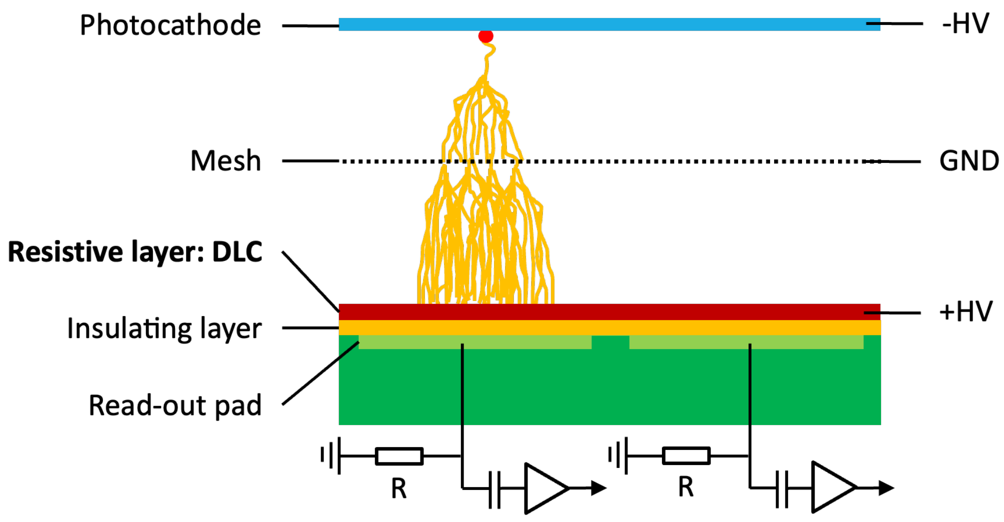
- **Advantages of resistive Micromegas:**

  + protection against violent discharges

  + ensuring stable operation under intense particle beams

  + possibly better position reconstruction by charge spreading

- **Objective:** profit from the advantages of the resistive Micromegas while maintaining a good time resolution



Requirements for the surface resistivity selection:

low enough to:

→ minimise voltage drop during high-rate beam conditions

high enough to:

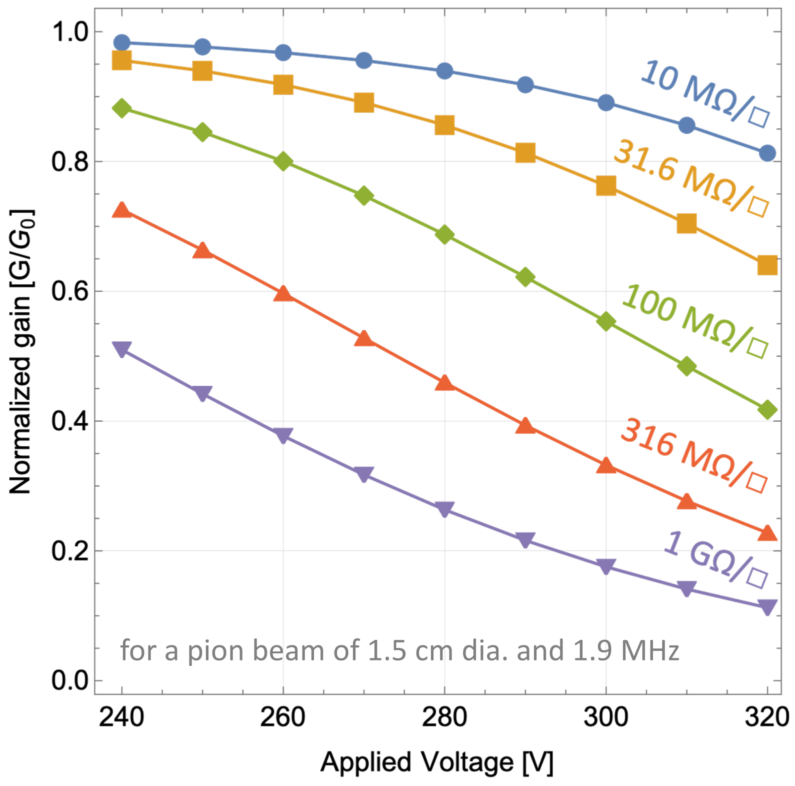
→ guarantee stable operation

→ prevent any negative impact on the signal's leading edge

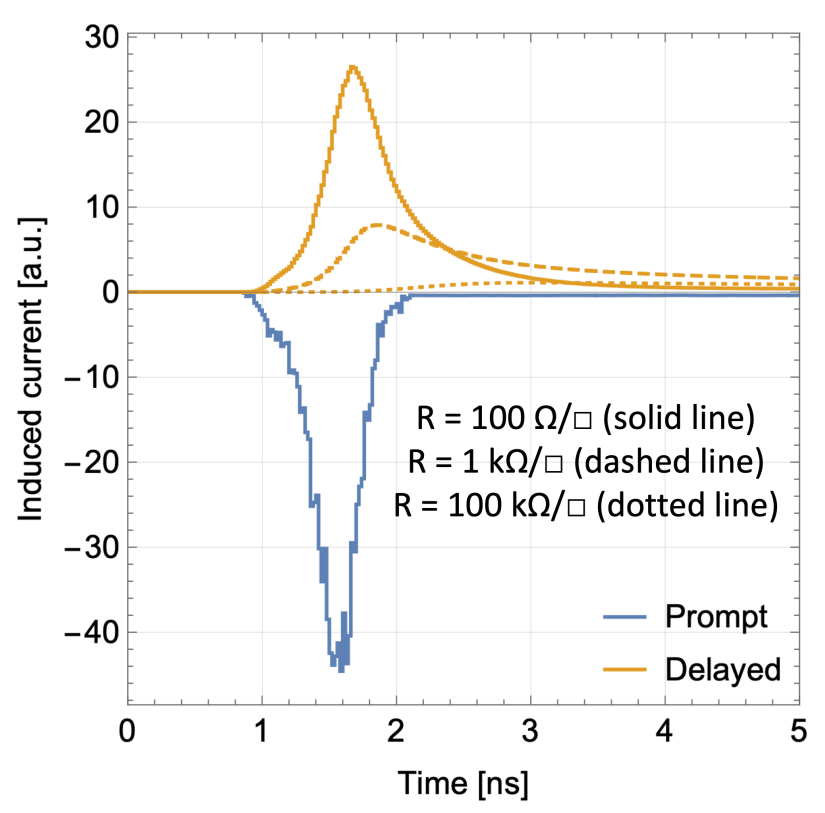
Resistive Micromegas

Rate capability and dependence on the rising edge of the signal

- **Simulated gain drop for different resistivities**



- **Simulated shape of the induced signal**



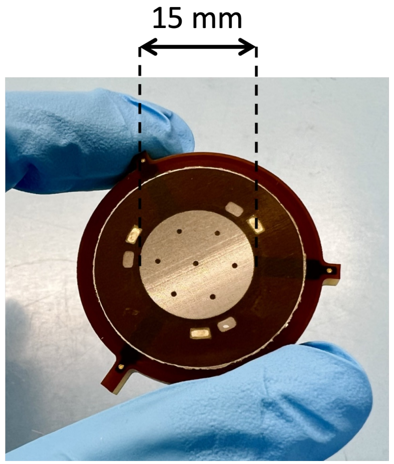
- To ensure robustness, the nominal **surface resistivity of 20 MΩ/□** was selected for future PICOSEC prototypes

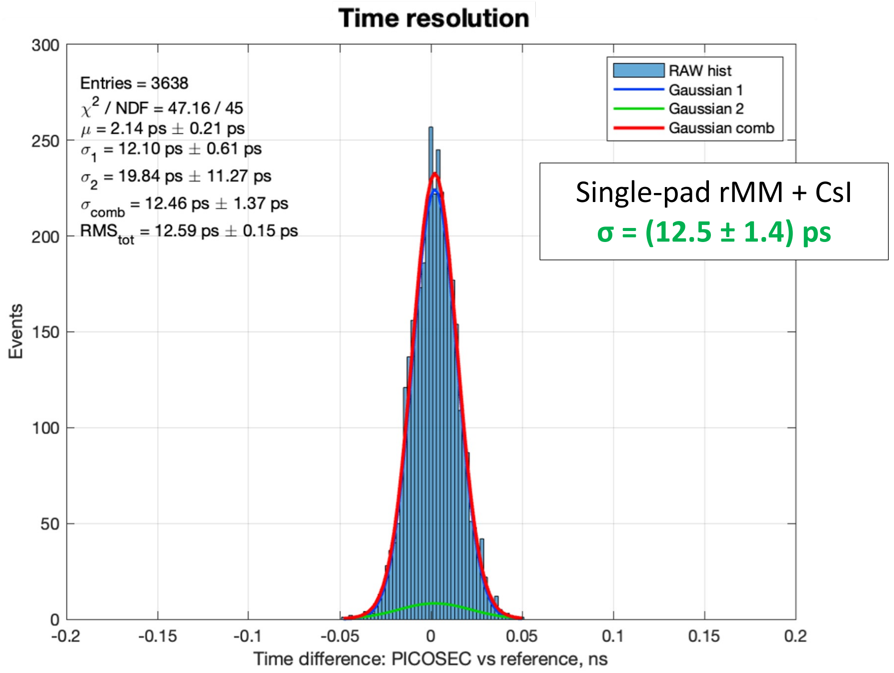
D. Janssens, PhD dissertation

Resistive Micromegas

Single-pad prototype performance

- The single-pad detectors were manufactured following the procedure used for metallic prototypes with an **additional step involving a thin DLC layer of 20 MΩ/□ surface resistivity**
- Two different active areas: 10 mm and 15 mm dia.
- Detector of with 10 mm dia. active area equipped with a CsI photocathode obtained equivalent precision to a non-resistive prototype, **exhibiting an excellent time resolution of σ = 12.5 ± 1.4 ps**
- Detector with 15 mm dia. active area - time resolution of σ = 13.7 ± 2.2 ps

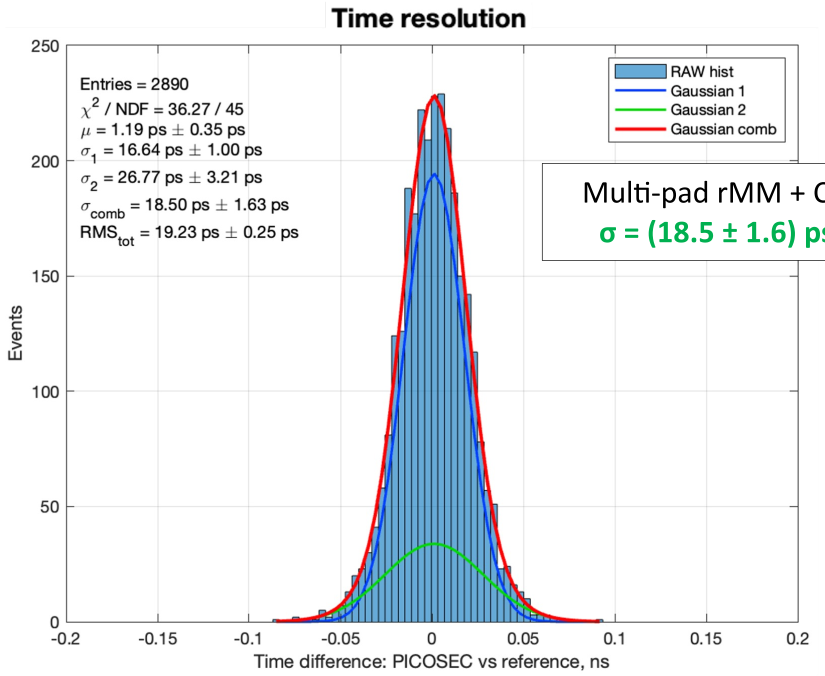




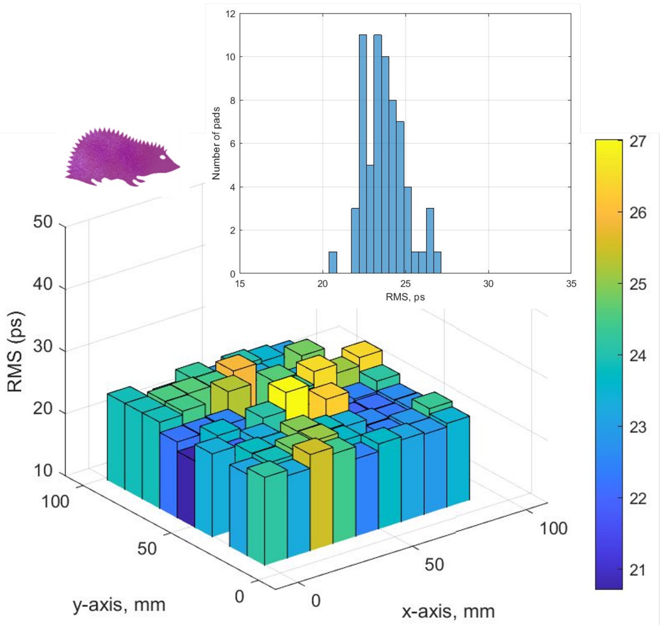
Resistive Micromegas

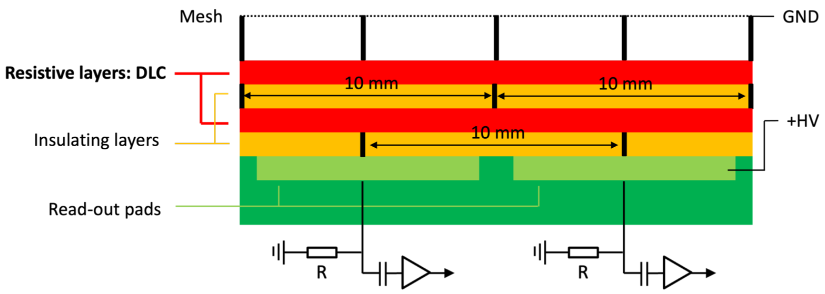
100-channel prototype performance

- 100-channel detector with 10×10 cm^2 resistive MM **20 MΩ/□** yielded a **time resolution of below σ = 20 ps** for an individual pads
- SAMPIC readout: narrow time resolution distribution RMS ≈ 23.7 ps + **tool to study the response of multi-channel detector**
- <u>Next step</u>: production of a high-rate 10×10 cm^2 MM with double-layer DLC for charge evacuation and evaluation of rate capability



Multi-pad rMM + CsI
σ = (18.5 ± 1.6) ps





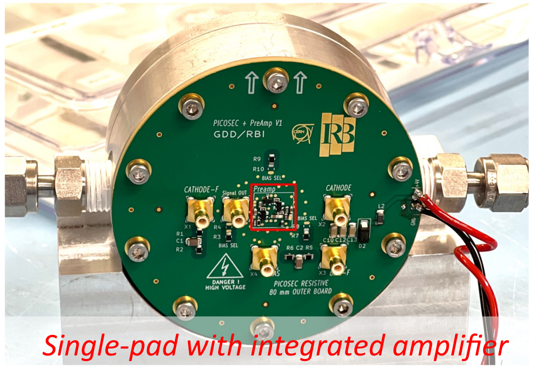
Scalable electronics

Integrated preamplifiers and FastIC readout and

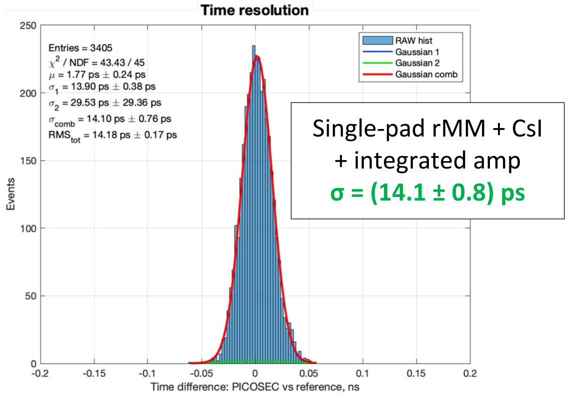
- **Integrated amplifiers:**
  - → electronics directly integrated on outer PCB to optimize signal routing and compactness
  - → single-pad prototype achieved comparable time resolution
  - → <u>next step</u>: amplifiers integrated on the 100-channel detector

- **FastIC ASIC readout:**
  - → fixed threshold timing and timewalk correction with energy information from energy pulses provided by FastIC
  - → achieved time resolution of σ = 50 ps for an individual pad
  - → multi-channel readout ongoing

- Evaluation of alternative TDCs and ASICs

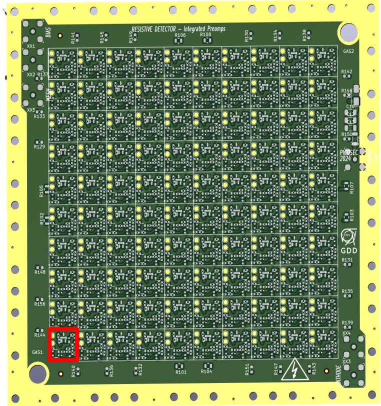


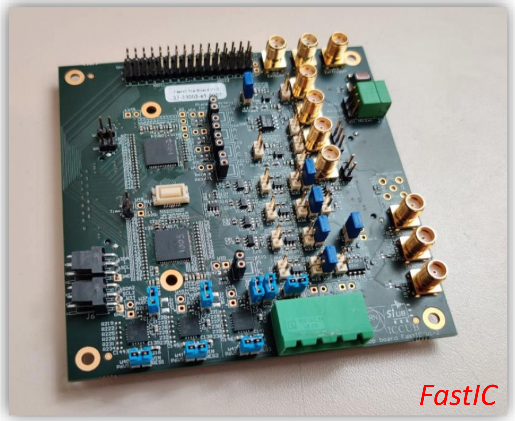
Single-pad with integrated amplifier



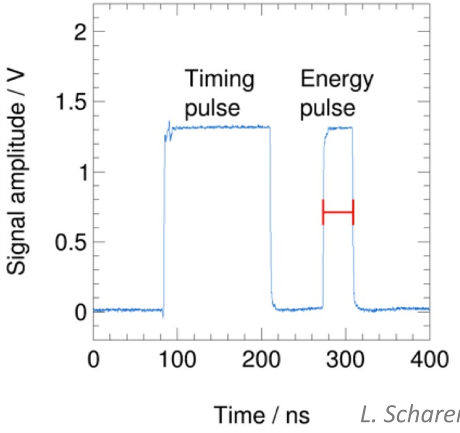
100-channel with amplifier cards

→





FastIC



L. Scharenberg, <u>link</u>

Robust photocathodes

CsI photocathode and the alternatives

- **First single-pad prototype:** CsI photocathode

  + high QE compared to other materials

  - can be damaged by ion back flow, discharges

  - sensitive to humidity (assembly)

- Need to search for **alternative materials**:

  → Diamond-Like Carbon (DLC)

  → Boron Carbide (B_4C)

  → Nanodiamonds

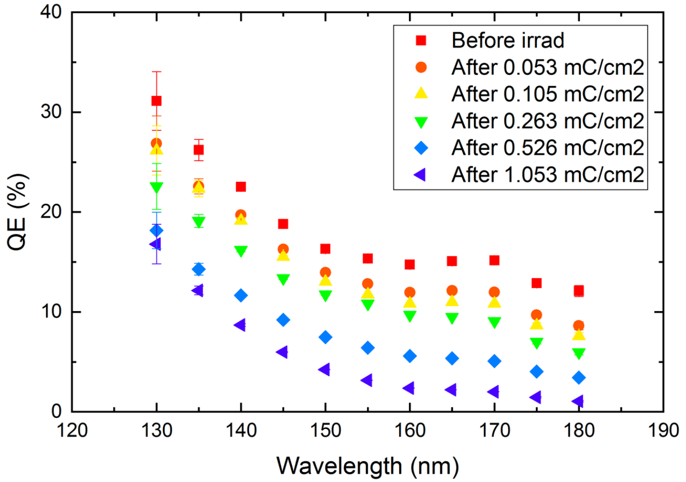
  → Carbon nano-structures

- **ASSET** – Photocathode characterisation setup

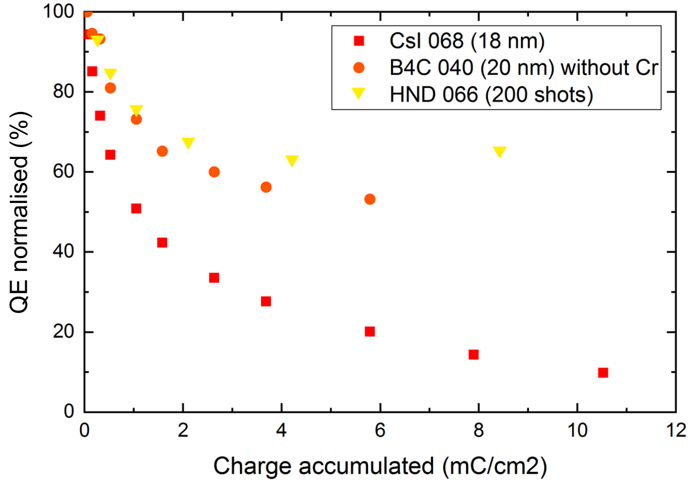
  M. Lisowska, MSc thesis

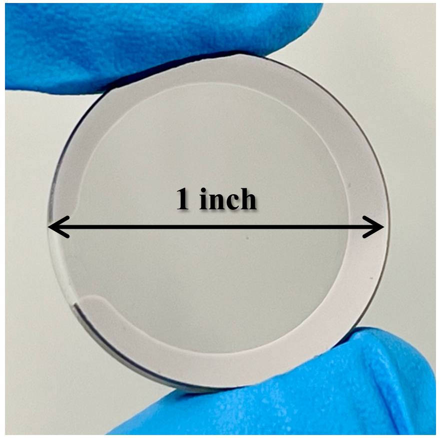
QE AND AGEING STUDIES PERFORMED USING UV LIGHT

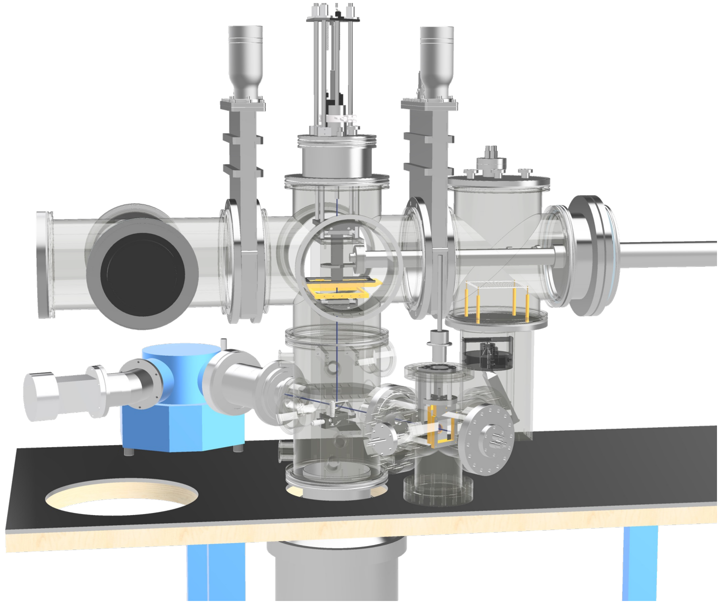
Ageing studies - CsI



Ageing studies – Comparison



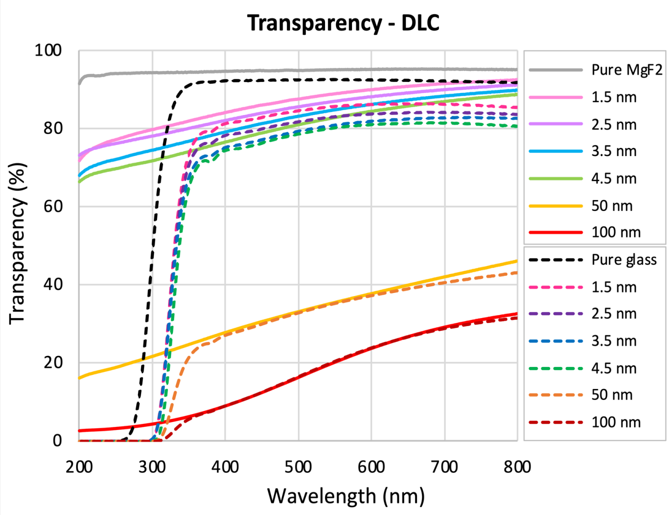


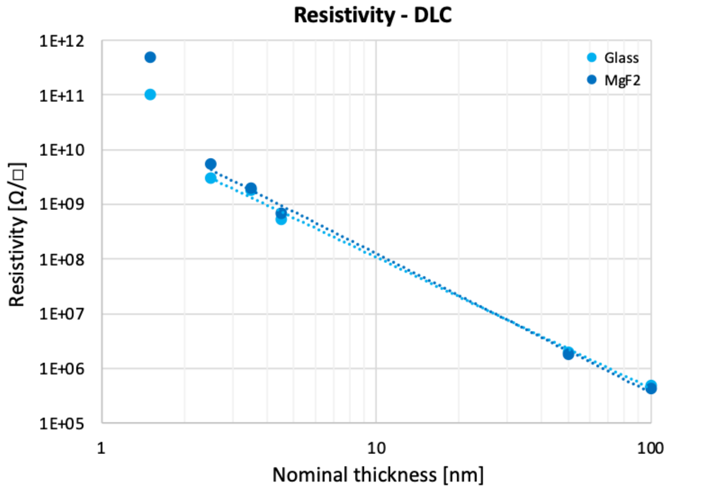


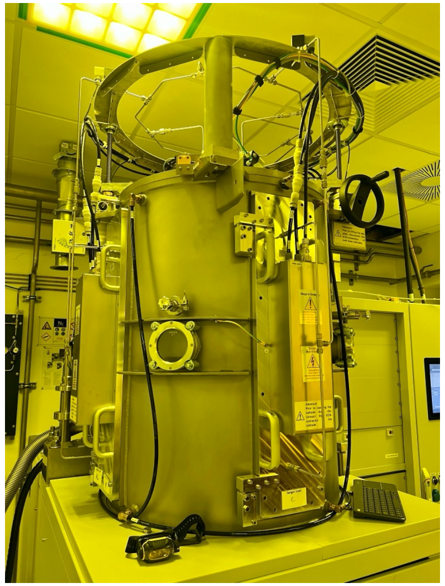
Robust photocathodes

Diamond-Like Carbon

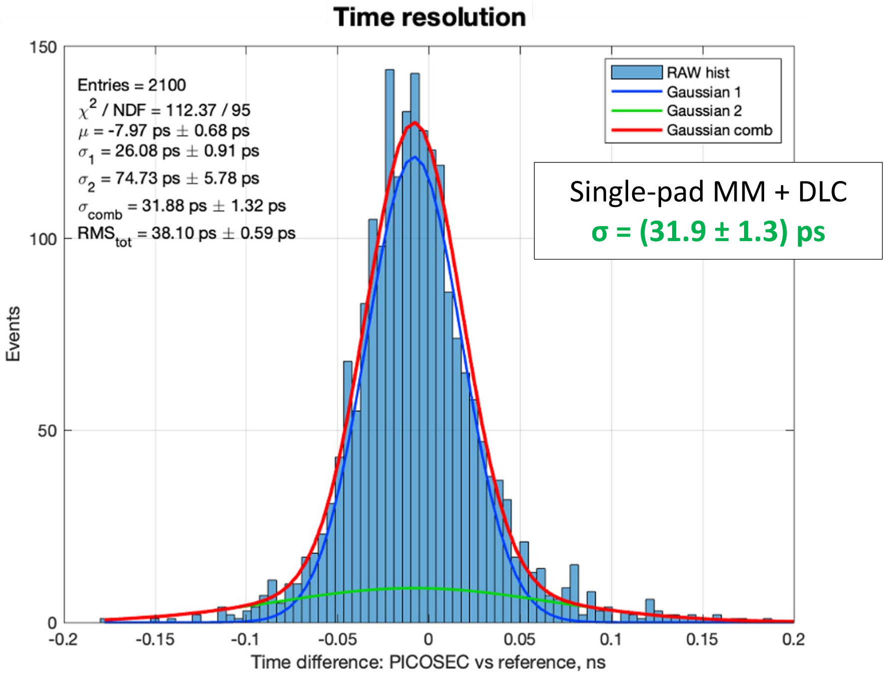
- **First depositions of DLC photocathodes** with layer thicknesses ranging from 1.5 nm to 4.5 nm carried out at the **CERN MPT workshop using a magnetron sputtering technique**
- Transparency and surface resistivity measurements
- The best results achieved with a **1.5 nm DLC**, yielding **a time resolution of σ ≈ 32 ps**
- **B_4C photocathodes**: time resolution σ ≈ 34.5 ps
- <u>Next step</u>: evaluation of a 10×10 cm^2 robust photocathode, incorporating a conductive interlayer







Pulsed DC magnetron vacuum deposition machine



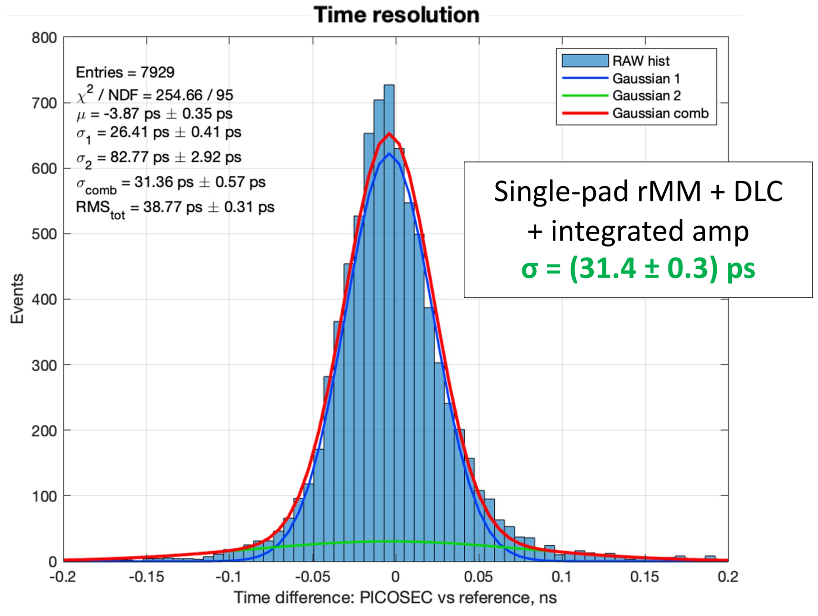
Towards applicable detector

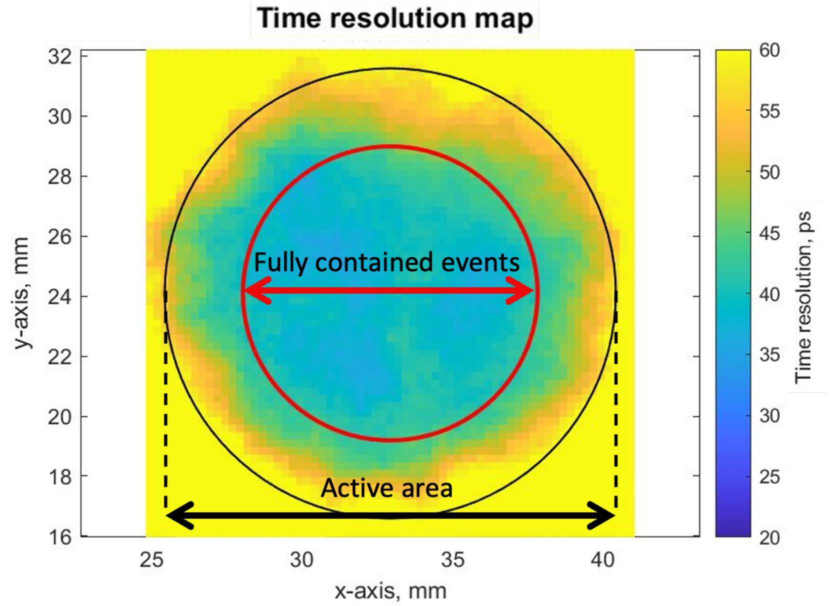
Stable and robust prototype

- First measurement combining a single-pad 15 mm dia. **resistive Micromegas, a DLC photocathode and an integrated preamplifier** showcased **great performance and excellent timing properties**

- The detector achieved a **time resolution of σ ≈ 31.4 ps** within a 9 mm dia. circle centered around the pad, capturing exclusively fully contained events

- The device displayed a uniform time response across this region, with an RMS ≈ 38.8 ps

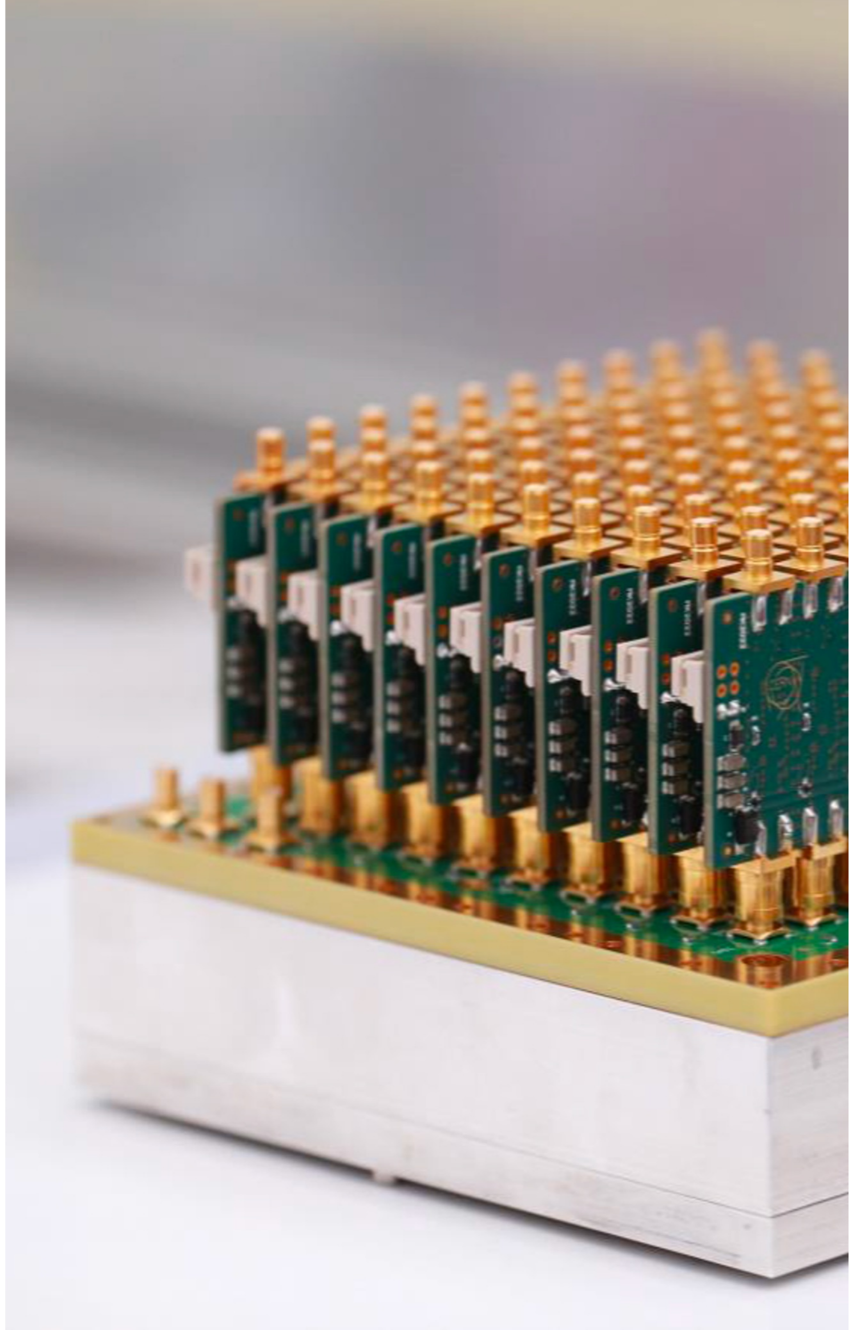




Summary

Intensive R&D activities to characterise the **timing response of the PICOSEC MM** prototypes

- **Detector optimisation** → Improvement of the **single-pad detector's time resolution to σ ≈ 12.5 ps** by introducing a new design
- **Resistive Micromegas** → Single-pad detector **with 20 MΩ/□ surface resistivity** obtained equivalent precision to a non-resistive prototype, **exhibiting an excellent time resolution of σ ≈ 12.5 ps**
- **Robust photocathodes** → Single-pad prototype with a time resolution **σ ≈ 32 ps for DLC photocathodes** and σ ≈ 34,5 ps for B_4C photocathodes
- **Large area coverage** → 100-channel PICOSEC MM detectors with a **time resolution σ < 18 ps for a metallic prototype** and **σ < 20 ps for a resistive** for individual pads
- **Evaluation of waveform TDC and timing ASICs** → **Readout of multi-channel detectors**



Precise timing with PICOSEC Micromegas

Other ongoing activities within the PICOSEC Collaboration

- **Stability:** fine mesh Micromegas
- **Rate-capability:** double-layer DLC MM for vertical charge evacuation
- **Improving the spatial resolution:** charge spreading with resistive PICOSEC MM
- **Robust photocathodes:** studies on B_4C, DLC, Nanodiamonds
- **Alternative electronics:** integrated preamplifiers; FastIC ASICs; SAMPIC TDC
- **Operating gas**: exploring alternative gas mixtures
- **Material budget:** alternative ways to preserve detector's planarity; sealed detectors
- **Scaling up to larger area:** tiling 10x10 cm^2 modules, development of larger prototypes

Conclusions

- Efforts dedicated to detector developments enhance the feasibility of the PICOSEC concept for experiments requiring precise timing
- **Detectors with sub-ns time resolution: Tileable multi-channel detector modules for large area coverage fulfilling the requirement of the robustness with "relaxed" timing properties**

PICOSEC Micromegas Collaboration

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PICOSEC Micromegas

Thank you for your attention!

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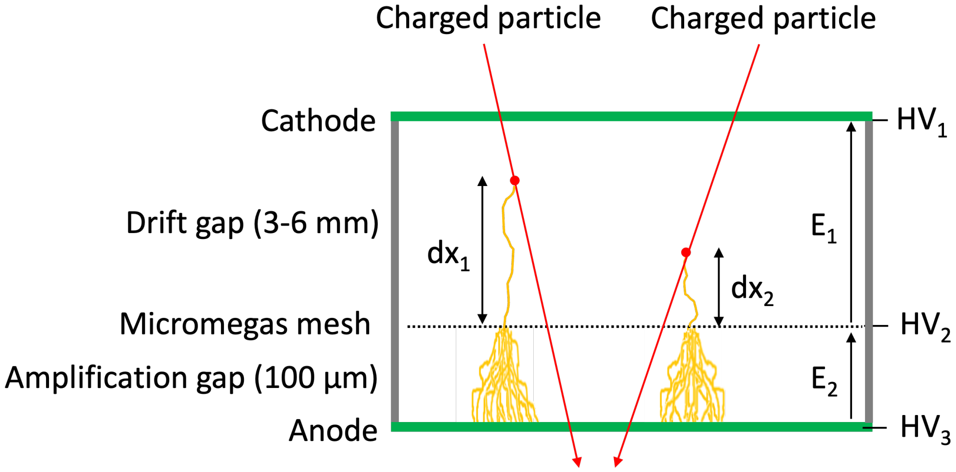
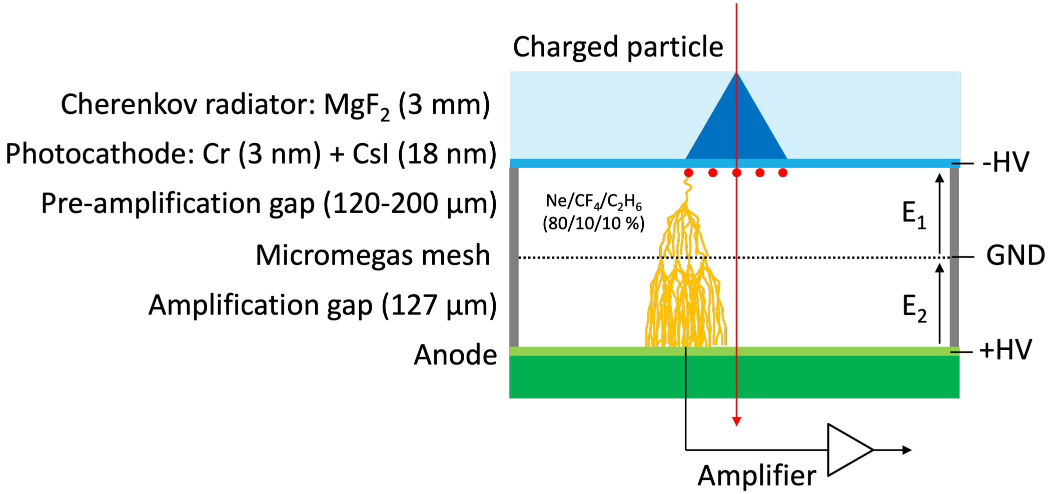
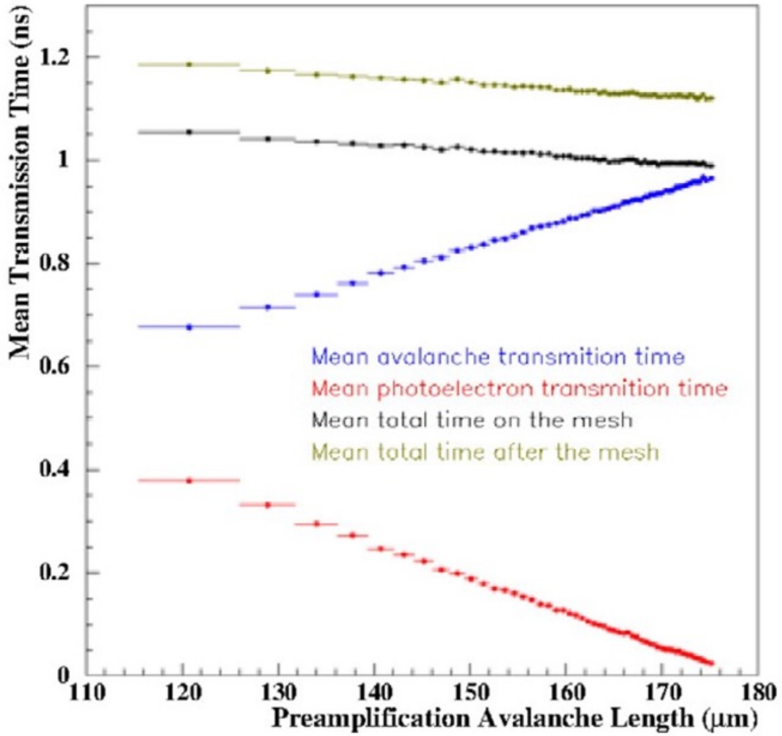
Back up slides

Convencional vs PICOSEC Micromegas

Signal arrival time jitter



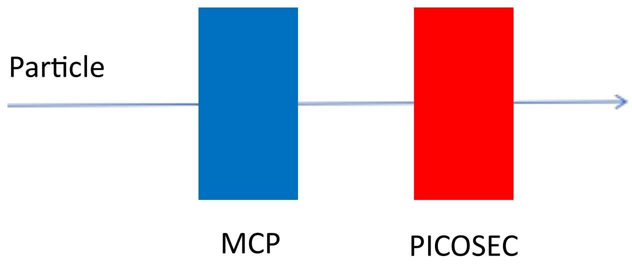


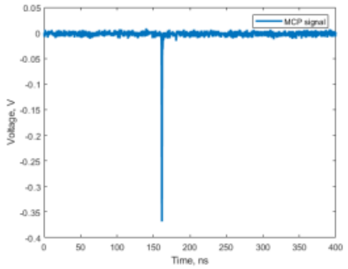


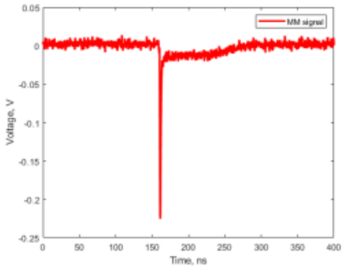
PICOSEC Micromegas

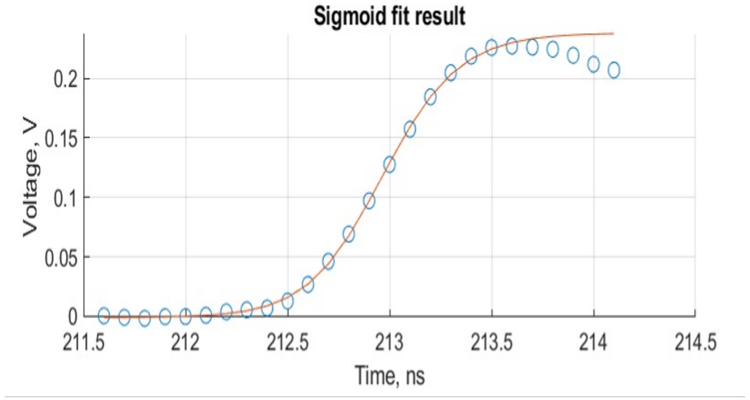
Signal analysis

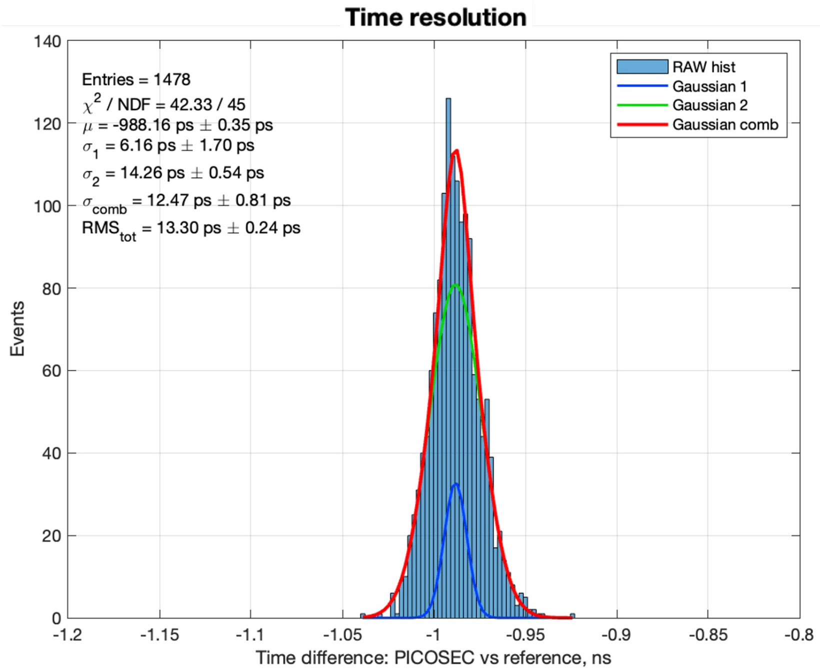
- Quantifying the PICOSEC detector’s time resolution requires a reference device with a superior timing precision
- Leading edge of the signal fitted using a sigmoid function - timestamps determined at 20% of the signal amplitude (CFD method)
- SAT: difference between the timestamps of PICOSEC and the MCP-PMT
- <u>Time resolution:</u> standard deviation of the SAT distribution











Resistive Micromegas

Other resistive detectors under test

Exploring different resistivity values, detector geometries layer architectures

- **7-pad resistive prototypes with hexagonal pads of 1 cm dia.**

  → different resistivity values: 200 kΩ/□, 10 MΩ/□

  → different layer architectures: resistive vs capacitive sharing

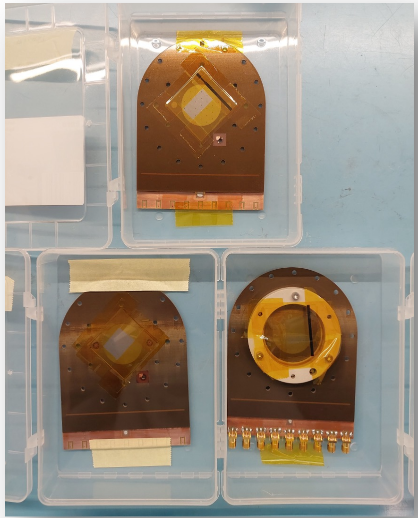
  → evaluation of time resolution, rate capability, signal sharing, special resolution, amplitude and timing uniformity

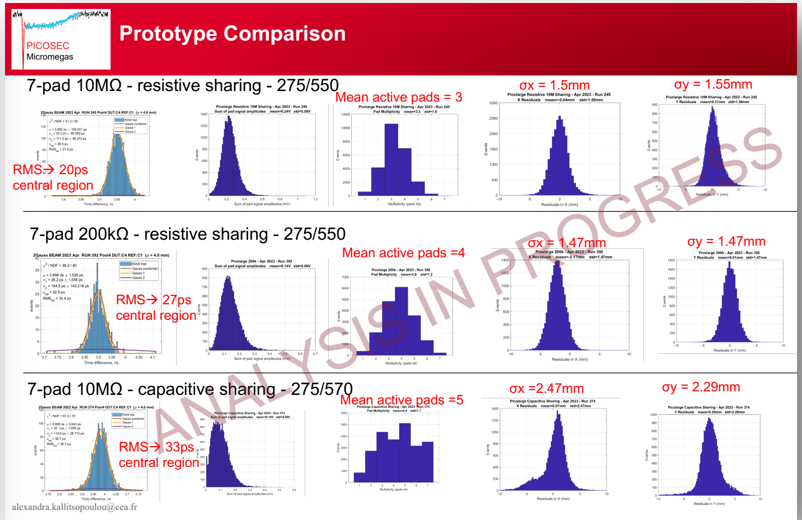
- **Single-pad µRWELL prototypes**

  → multiple detector geometries with different capacitances and varying pitch

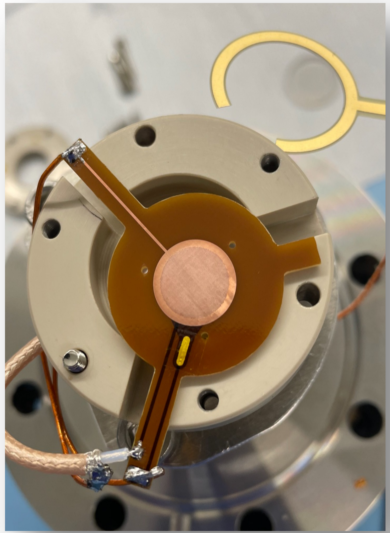
  → high gain and stable operation achieved

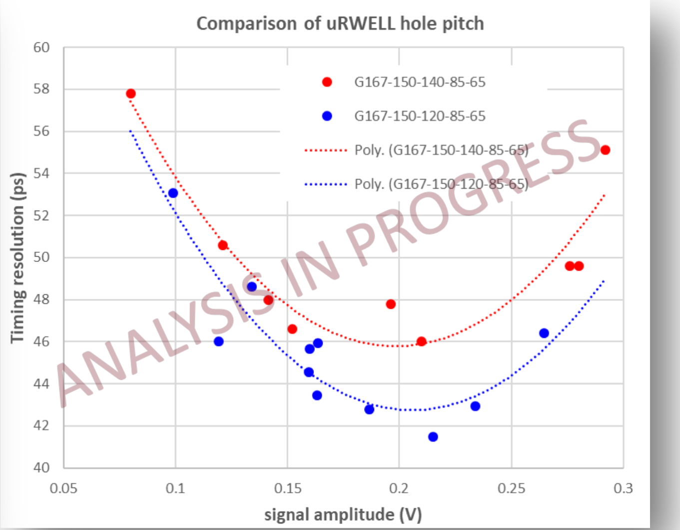
  → slower rising time of e-peak observed compared to MM





Details: A. Kallitsopoulou, CEA Saclay, RD51 CM June 2023: link

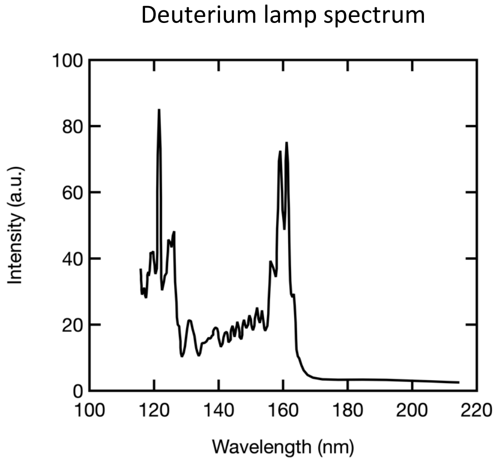


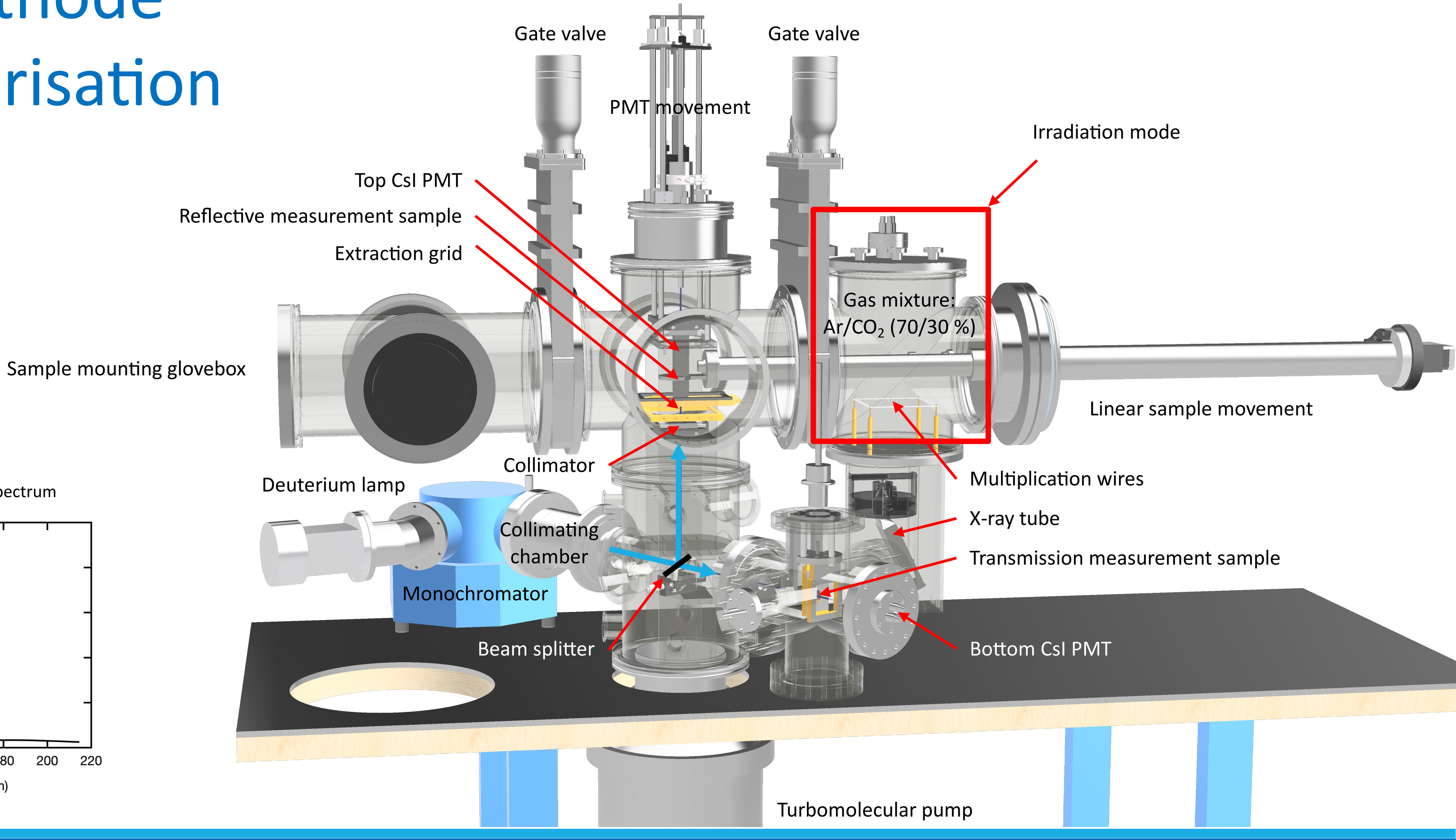


Details: K. Gnanvo, JLab, IEEE meeting: link

Photocathode characterisation

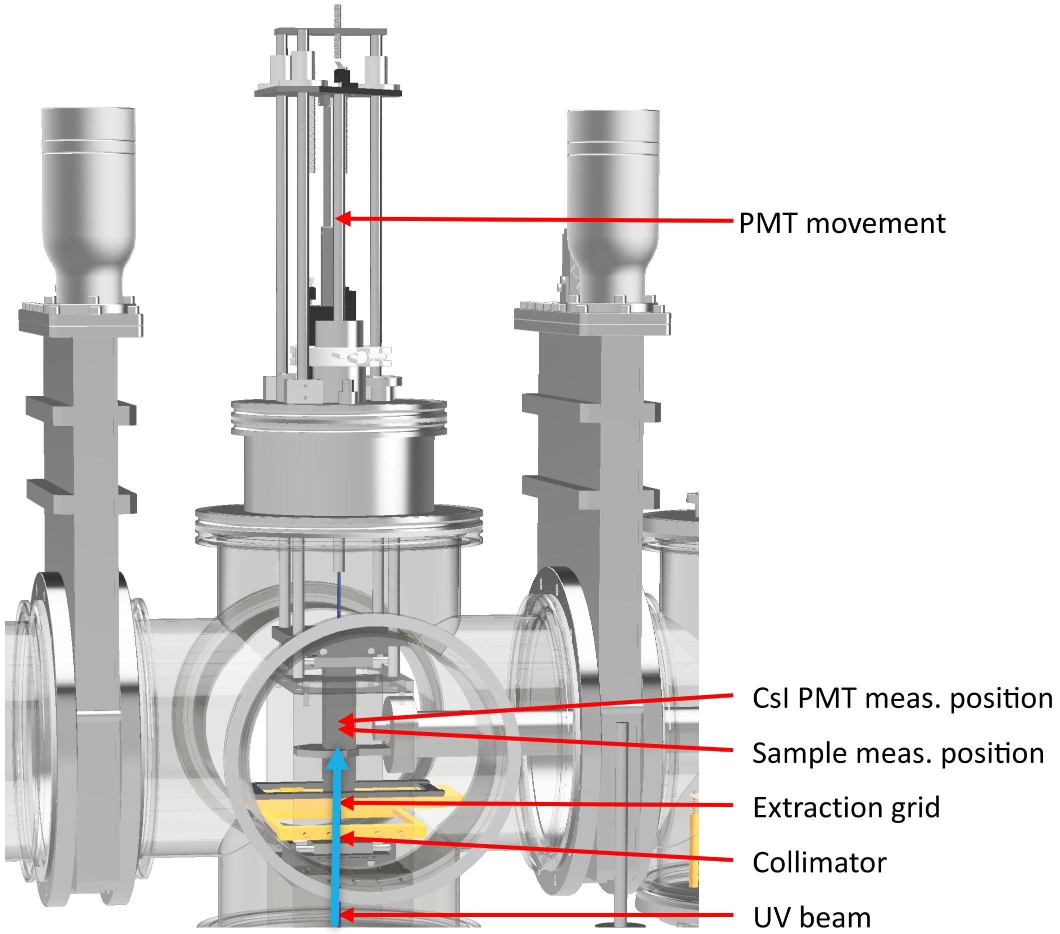
Setup overview





Photocathode characterisation

QE measurements - Reflective mode

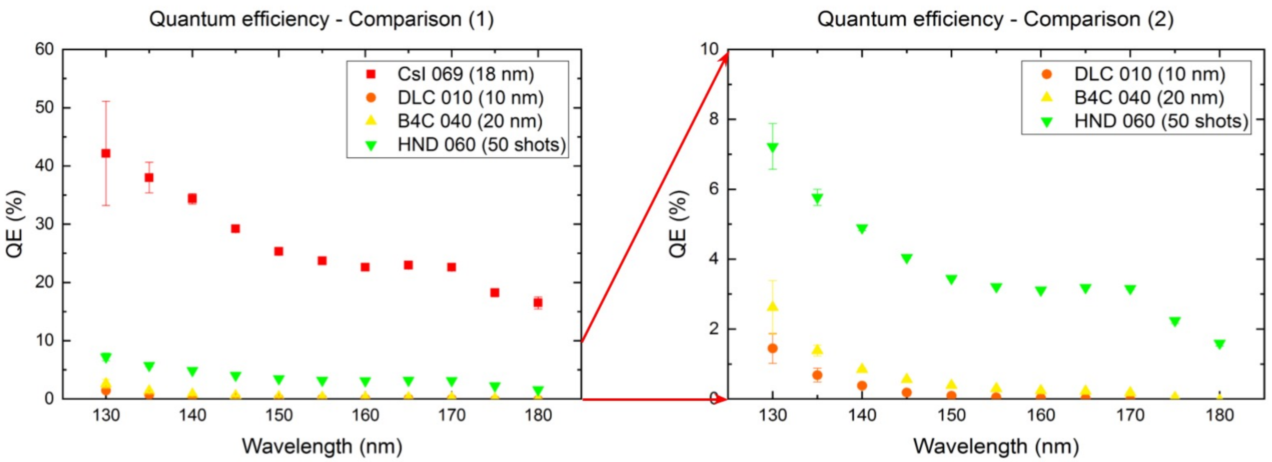


Samples: cesium iodide (CsI), diamond-like carbon (DLC), boron carbide (B_4C) and hydrogenated nanodiamonds (HND)

$$QE = \frac{Electrons_{sample}}{Photons_{PMT}}$$

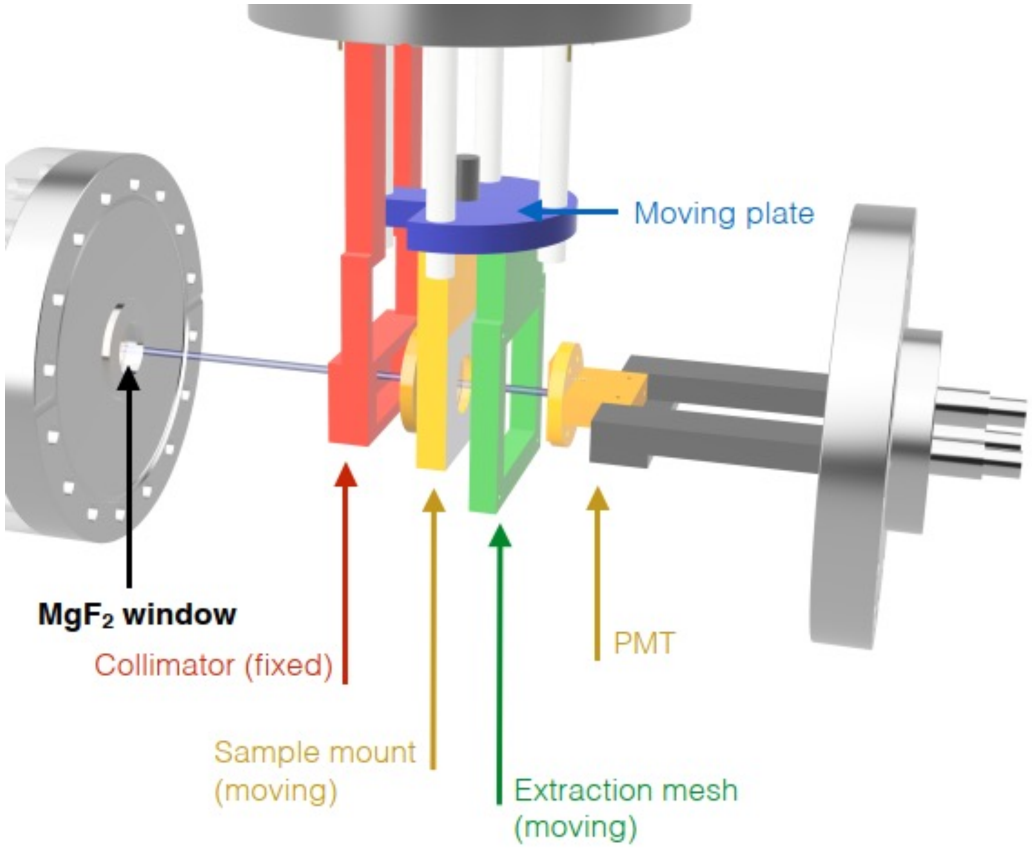
$Electrons_{sample}$ - electrons extracted from the sample

$Photons_{PMT}$ - photons that arrived to the sample



Photocathode characterisation

QE measurements - Transmission mode

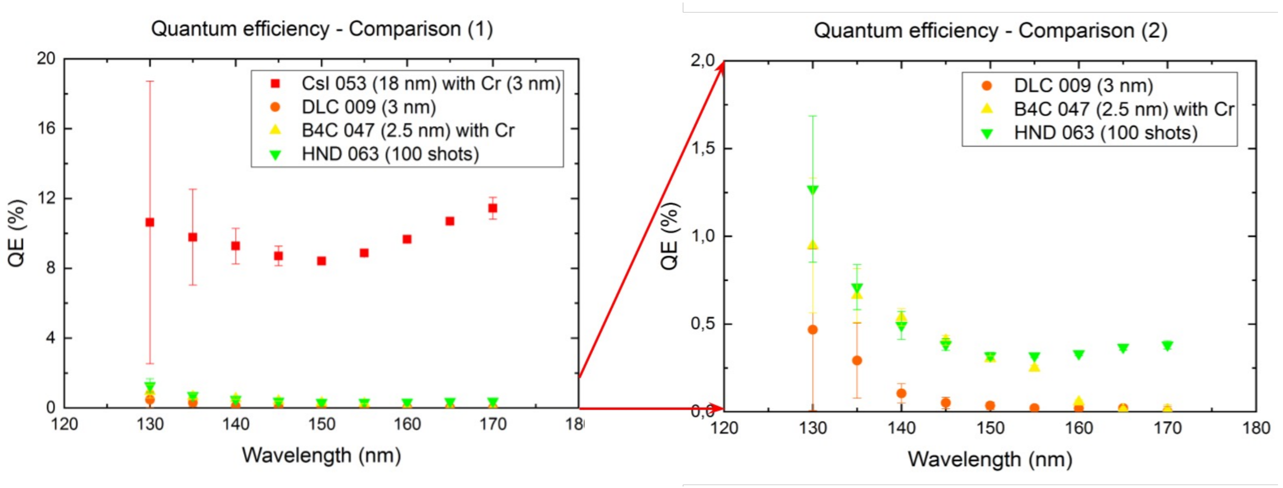


$$\text{Transparency} = \frac{\text{PMT current: sample in}}{\text{PMT current: sample out}}$$

$$\text{QE} = \frac{Electrons_{sample}}{Photons_{PMT}}$$

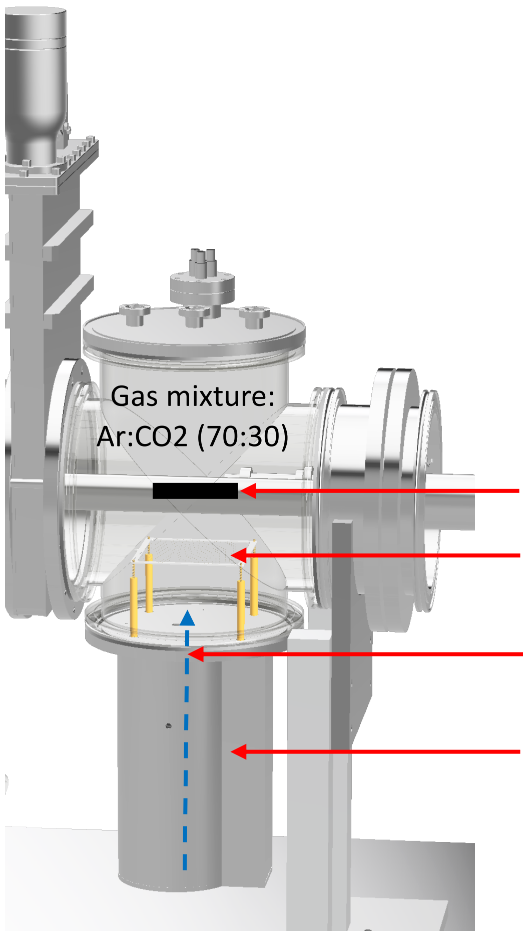
$Electrons_{sample}$ - electrons extracted from the sample

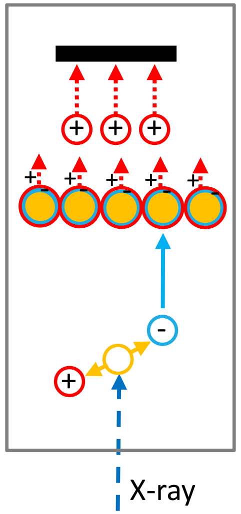
$Photons_{PMT}$ - photons that arrived to the sample



Photocathode characterisation

Ageing studies – Irradiation mode

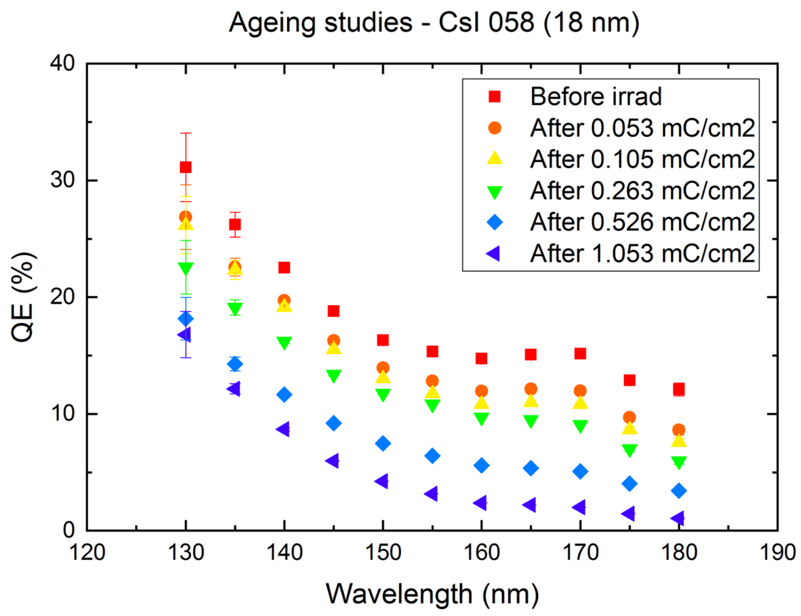


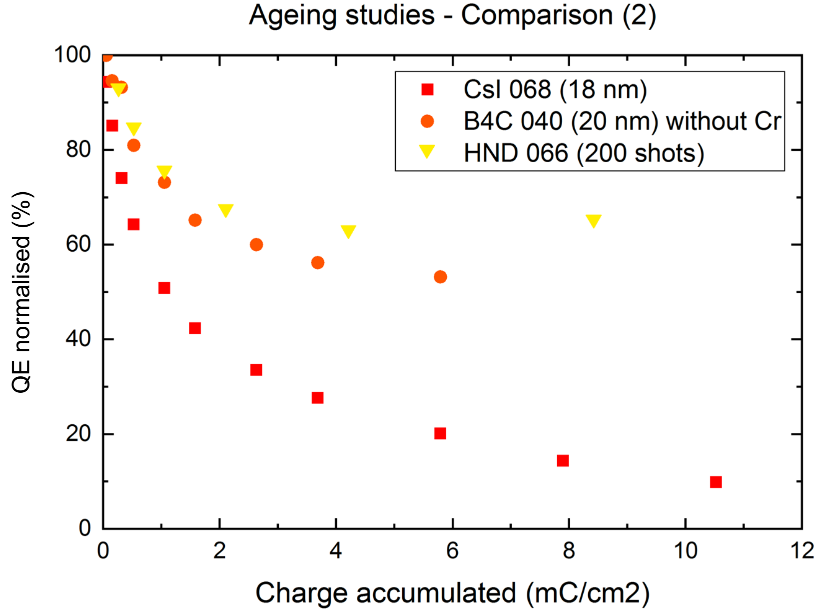


3. Irradiated sample (grounded):
Attraction of ions from avalanche
Accumulation of charge

2. Multiplication wires (positive HV):
Attraction of primary electrons
Avalanche multiplication
Production of electrons and ions

1. X-ray beam in a gas chamber:
Ionization of particles
Creation of primary charge

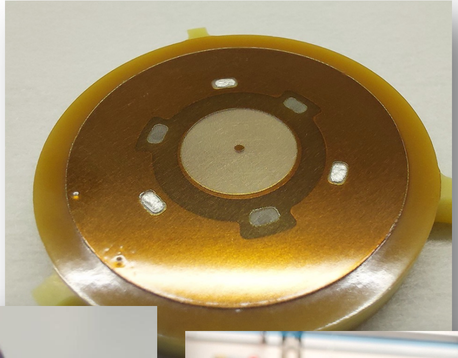


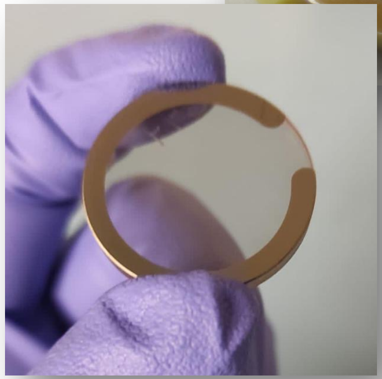


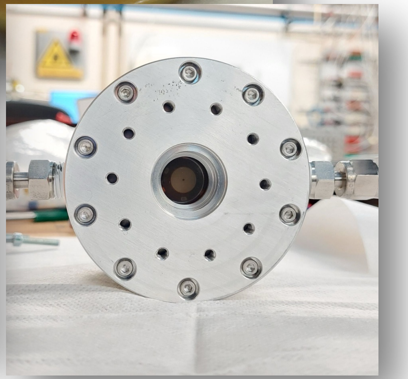
Robust photocathodes

RD51 and DRD1 test beam campaign measurements

Improvement of the measurement and analysis procedures

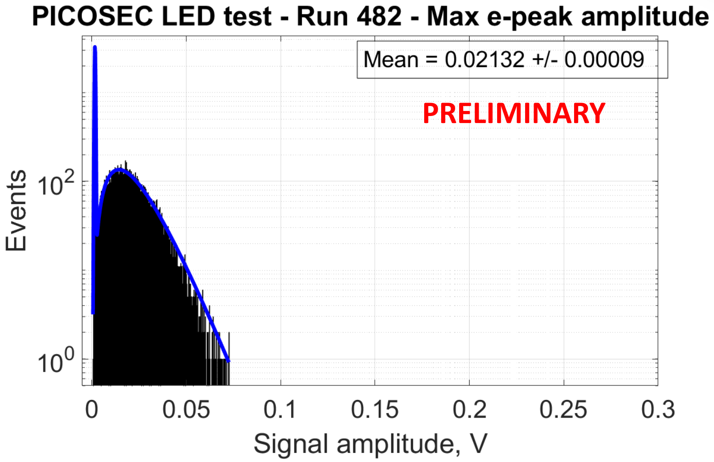


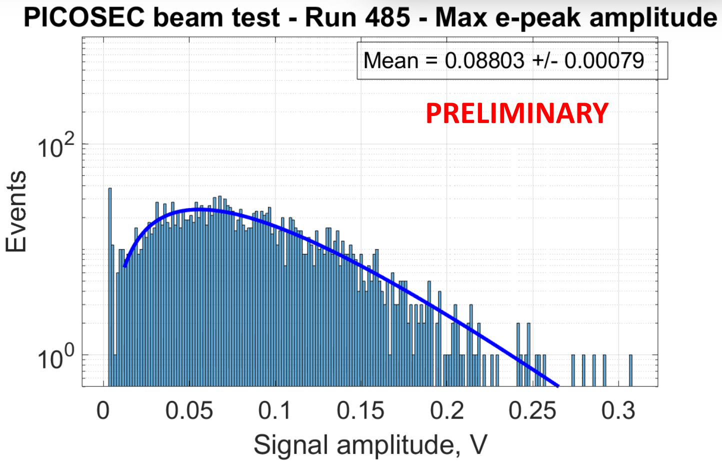




- **Measurements**:
  1. Transparency measurement with ASSET
  2. Single PhotoElectron measurement with LED
  3. Beam measurement @ CERN SPS H4 beam line, 150 GeV/c muons
  4. Timing measurement @ CERN SPS H4 beam line, 150 GeV/c muons

- **Number of PhotoElectron analysis procedure*:**
  1. Find maximum amplitude for each waveform
  2. Plot a histogram of all maximum amplitudes
  3. Fit with Gauss for noise and Polya for signal and calculate the mean value of Polya
  4. Divide MIP mean amplitude by SPE mean amplitude to obtain NPE for each photocathode





*PE analysis thanks to help of S. Tzamarias, F. Brunbauer, D. Janssens, **M. Robert and C. Volpato (CERN Summer Students 2022 and 2023, reports: link and link)**

Robust photocathodes

Time resolution

New promising results of robust photocathodes from 2023 test beams

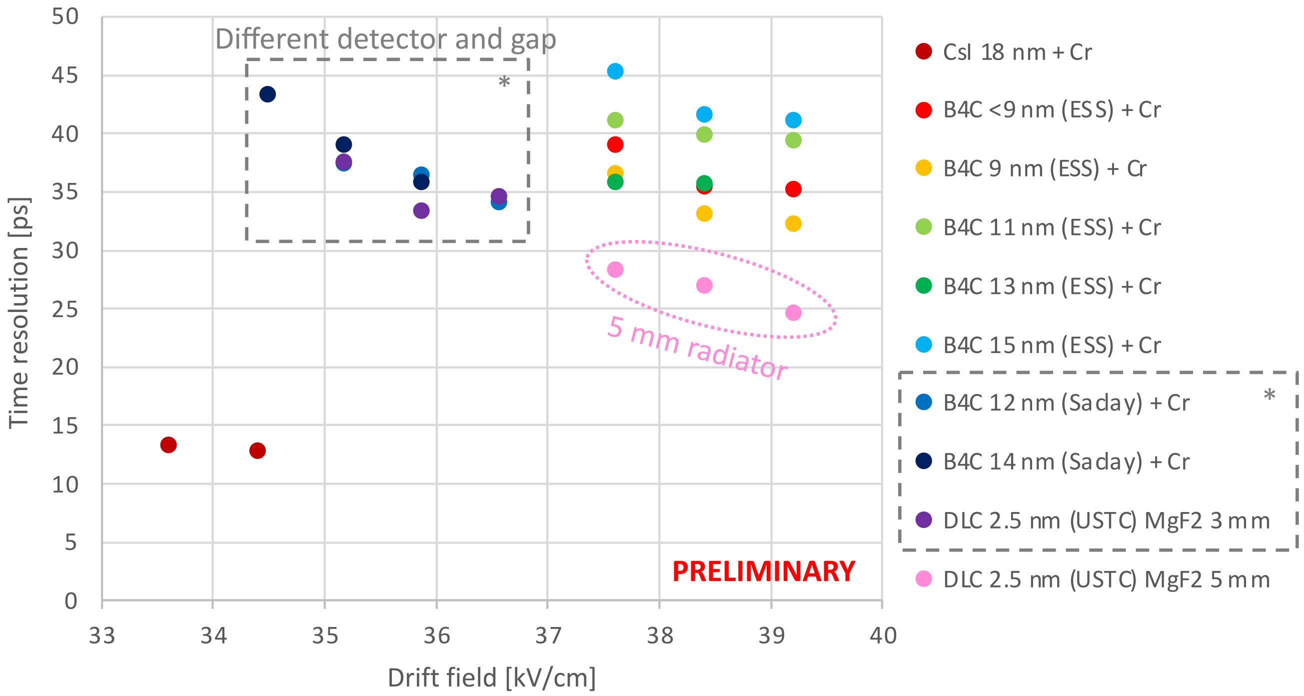
- **Prototype**: Single pad non-resistive MM, pre-amplification gap 126/145 µm*
- **Photocathodes**: CsI, DLC, B_4C of different thicknesses from different collaborators**
- **Time resolution** after MCP subtracted:

$$\sigma_{PICO} = \sqrt{\sigma_{combined}^2 - \sigma_{MCP}^2},$$

where MCP double split $\sigma_{MCP} \approx 7.67$ ps

- **Photocathodes** measured in combination with a **new detector with optimized design** were able to **reach higher drift fields** resulting in **better time resolution**

(results at 39.2 kV/cm taken for the further analysis)



*Samples measured in a new detector with 126 µm gap SEALED in August, except for 3 measured with Saclay detector with 145 µm gap FLUSHING in July (marked with a star)

**Depositions: CsI at CERN, DLC at USTC, B_4C at CEA Saclay and ESS

PICOSEC Micromegas

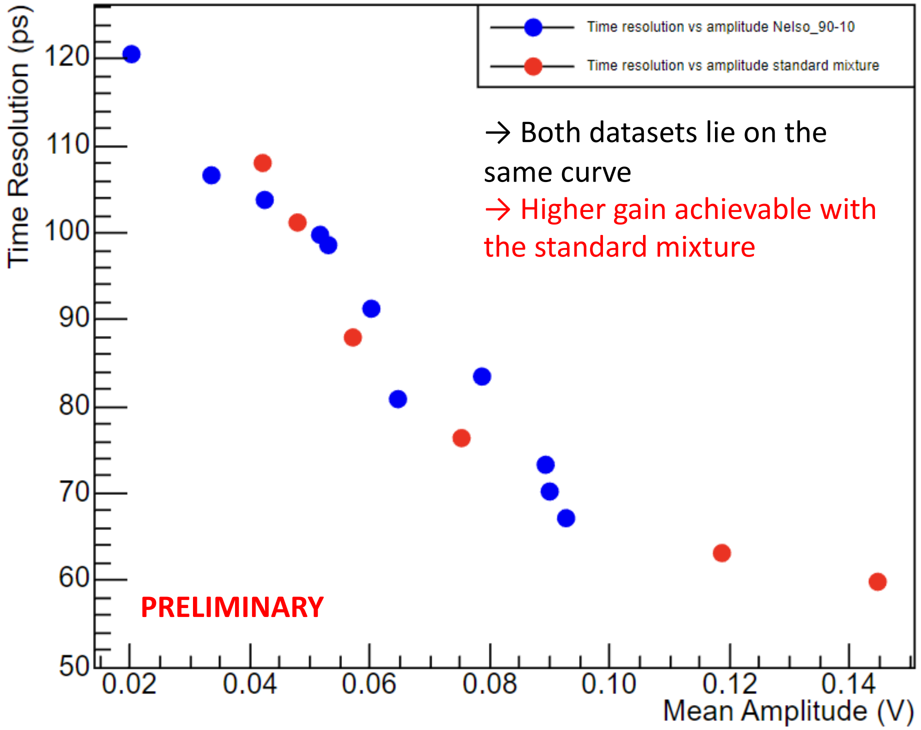
Alternative gas mixture studies

Studies on alternative gas mixtures

- **PICOSEC standard gas mixture:** $Ne:CF_4:C_2H_6$ (80:10:10) → high gain, quenching, drift velocity, but expensive, **not eco-friendly**, flammable
- **Alternative gas mixture:** $Ne:iC_4H_{10}$ → CF_4 dropped, iC_4H_{10} as a replacement of C_2H_6 → low GWP (0.2 instead of 740), good quenching

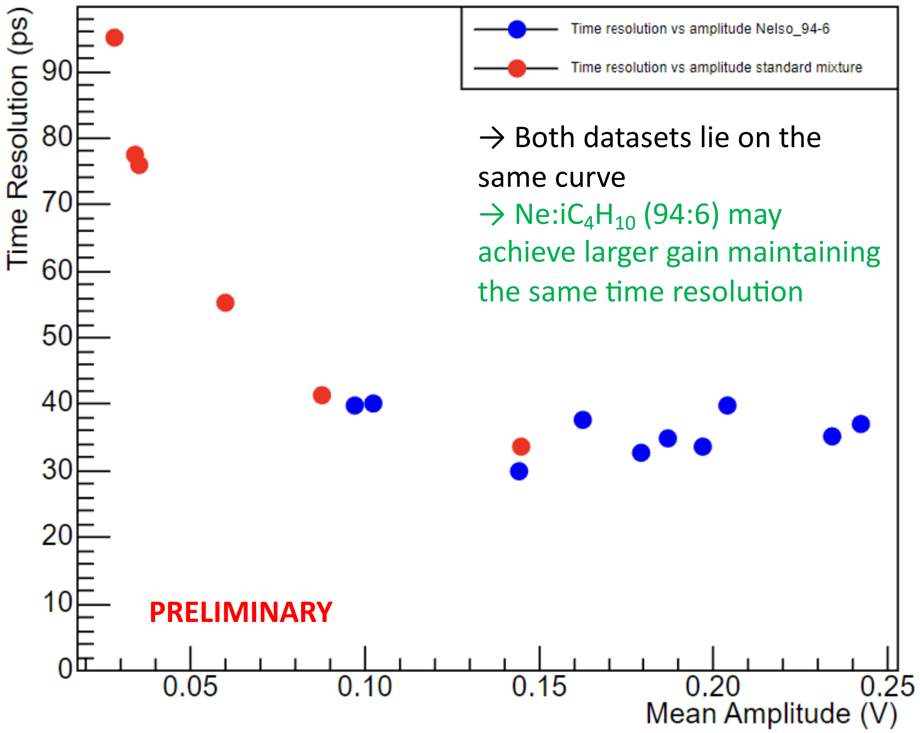
$Ne:iC_4H_{10}$ (90:10)

Pavia Chamber – 120 µm drift gap – rMM 380 kΩ/□ – B_4C 7 nm



$Ne:iC_4H_{10}$ (94:6)

CERN Chamber – 160 µm drift gap – rMM 82 MΩ/□ – CsI 18 nm



Promising results with $Ne:iC_4H_{10}$, further studies on the alternative gas mixtures to be performed

Ar-based gas mixtures:
→ $Ar:CO_2$ (93:7)
→ $Ar:CO_2:iC_4H_{10}$ (93:5:2)
also tested but showed unstable operation

Details: D. Fiorina, INFN Pavia, FAST2023: link

Integration

Sealed detectors

- **Advantages of sealed detectors:**

  + clean, hermetically closed devices with high gas quality

  + high ratio of active area to the size of the device

- **Current status:**

  → one 10 x 10 cm^2 titanium housing ready to assembly

  → large area robust photocathode (DLC, B_4C) required

  → gas connectors (pinch-off tubes) ready to assembly

  → when all components ready – electron beam welding

  → last step – filling the detector with gas mixture