Current status of PICOSEC Micromegas precise timing 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

RD51 COLLABORATION MEETING, 05 DECEMBER 2023

GDD
Gas Detectors Development Group

CERN EP R&D PICOSEC Micromegas

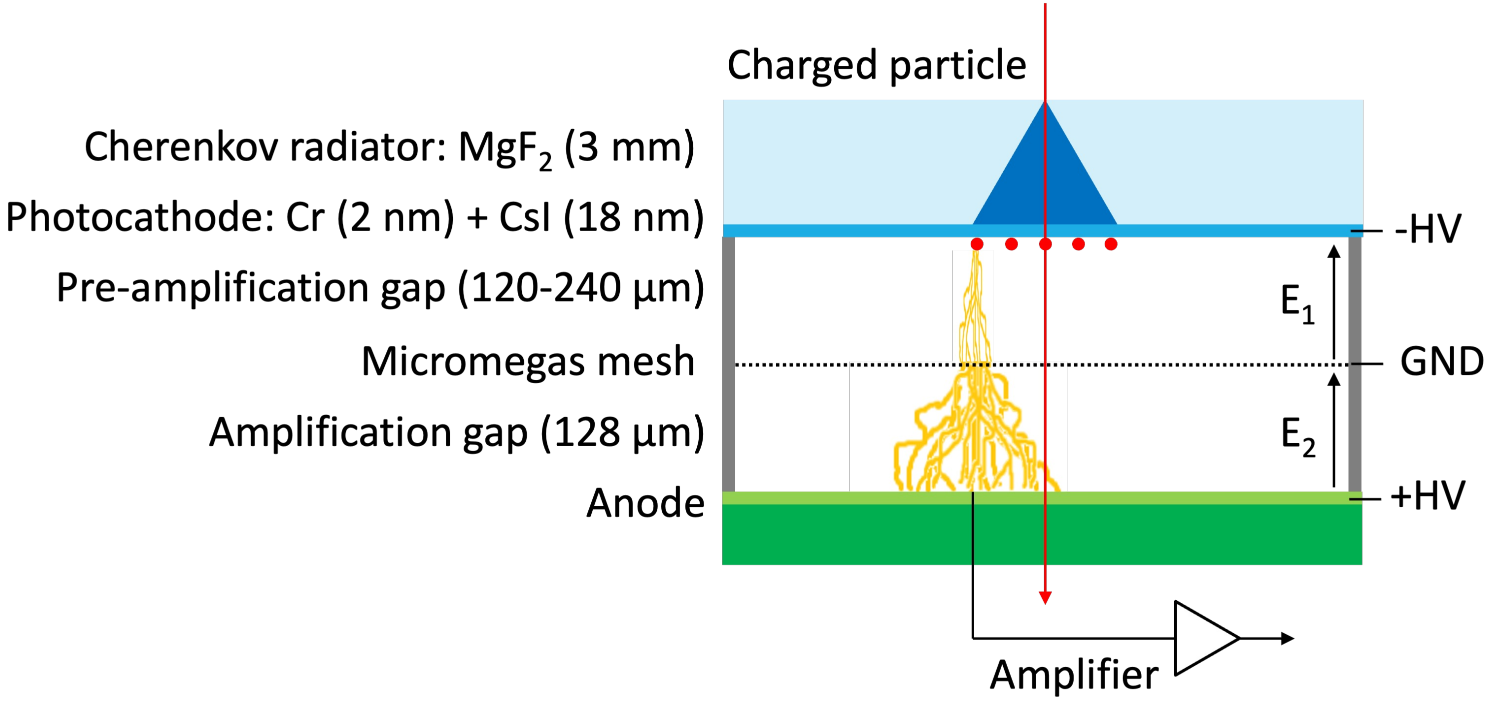
université PARIS-SACLAY

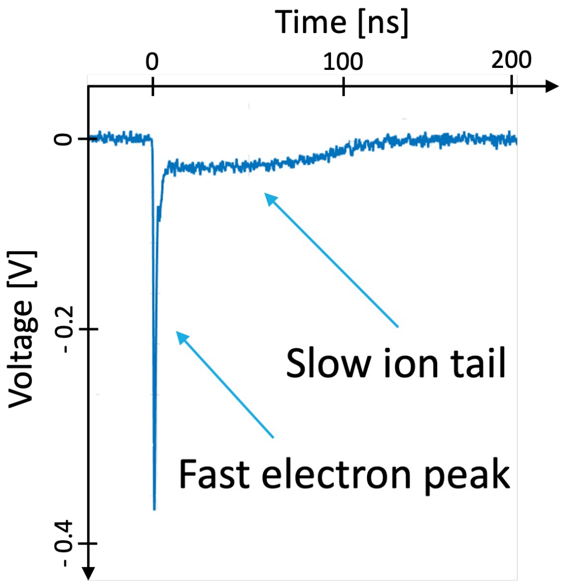
École Doctorale PHENIICS Doctoral School

PICOSEC Micromegas

Detector concept

- **PICOSEC Micromegas collaboration:** gaseous detector that aims at reaching a time resolution of **tens of picoseconds**





- First single-pad prototype with σ < 25 ps → Now we want to make the concept appropriate to physics applications

PICOSEC Micromegas

Developments towards applicable detector

- **Objective:** Robust tileable multi-channel detector modules for large area coverage

- **Detector optimisation:**

  gaps thickness, fields settings, operating gas

- **Robustness:**

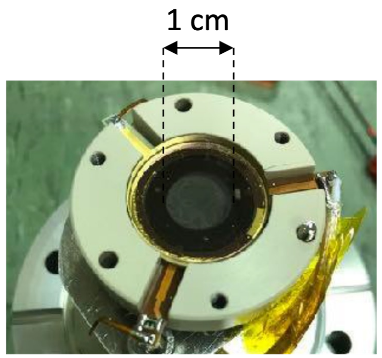
  resistive Micromegas, **robust photocathodes**

- **Large area coverage:**

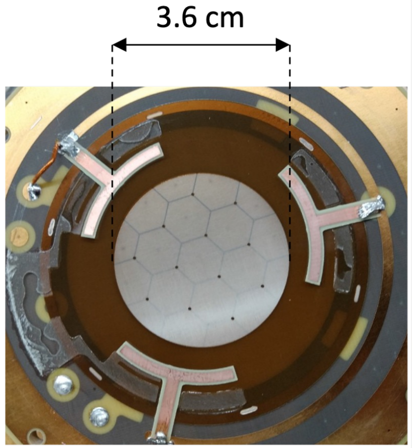
  100-channel prototypes, tileable modules

- **Electronics:**

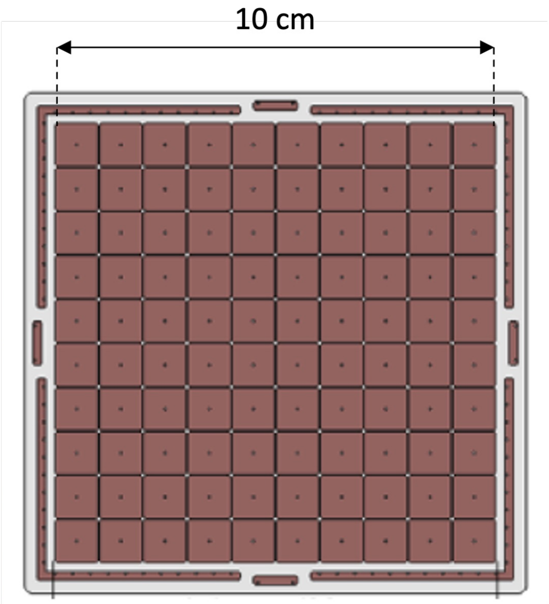
  scalable amplifiers, multi-channel digitiser, FastIC ASIC



Single pad (2016)
⌀1 cm



Multi pad (2017)
⬡ 1 cm

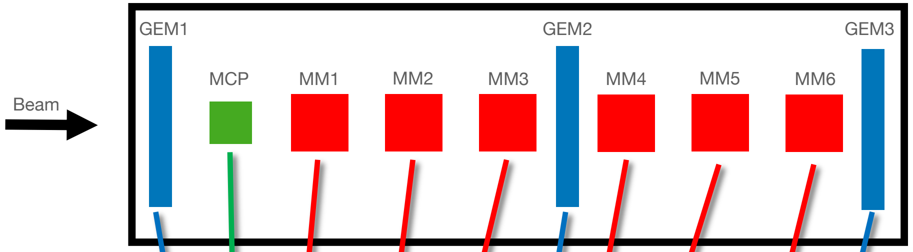


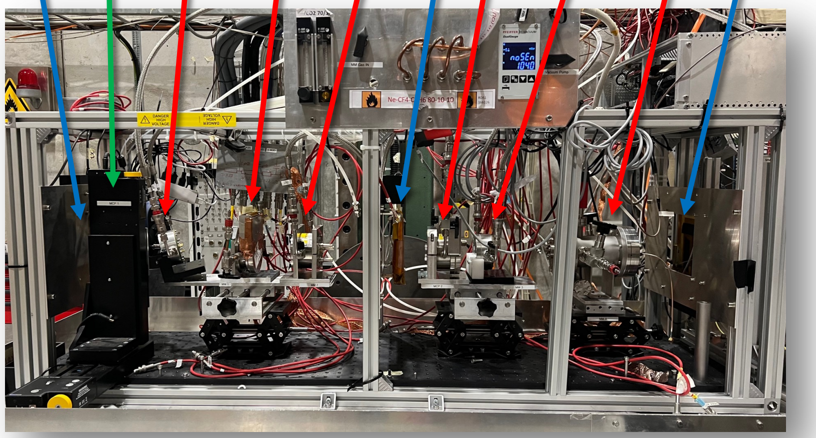
10x10 module
□ 1 cm

PICOSEC Micromegas

RD51 test beam campaign measurements

- **Intensive R&D activities:** From **simulations** and **design**, through **production** and **assembly** to **measurements** (lab, test beam campaigns) and **analysis**



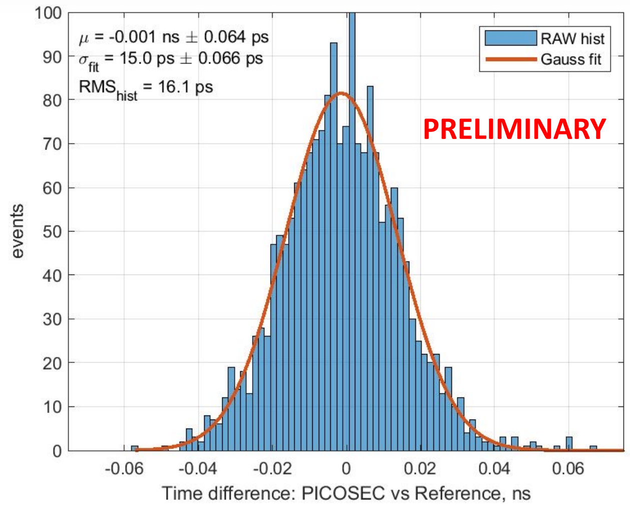


- **Beam type:** CERN SPS H4 beam line, 150 GeV/c muons (also pions and electrons)
- **Experimental setup:**

  → tracking/timing/triggering telescope: GEMs + MCP PMT

  → PICOSEC Micromegas (MM) detectors

  → gas mixture: $Ne:CF_4:C_2H_6$ (80:10:10)



- **Time resolution –** std of signal arrival time distribution. **Highlights from last years**:

  → Excellent timing performance of the single-channel proof of concept transferred to the **100-channel prototype giving uniform time resolution < 18 ps** for all measured pads

  New record! → Improvement of the **single-pad detector's time resolution to 15 ps** by design optimisation

Details in the following presentation by A. Utrobičić: link

PICOSEC Micromegas

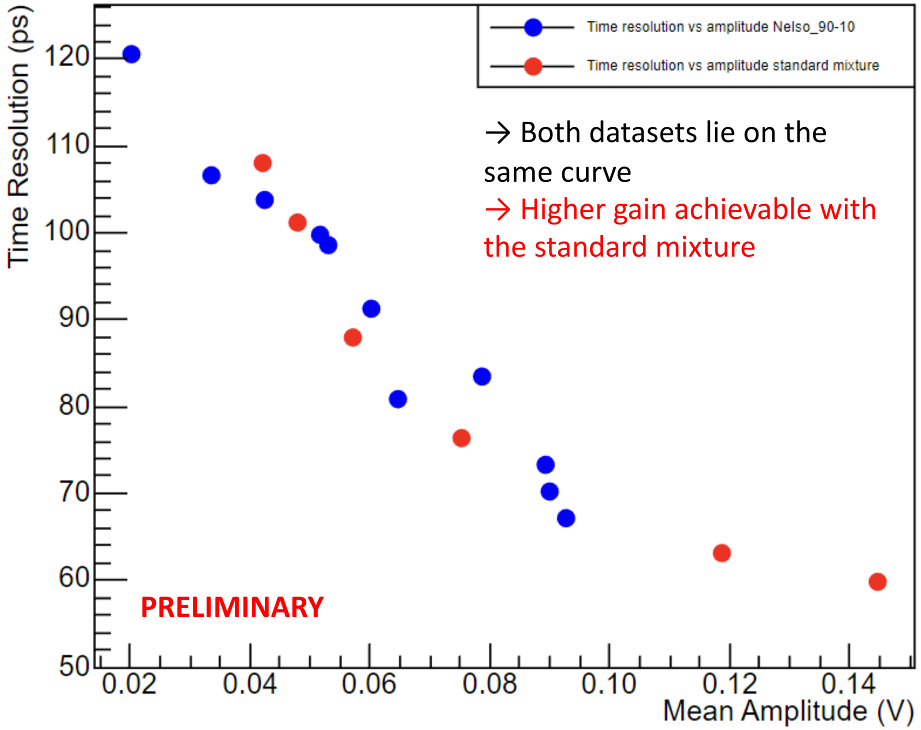
Alternative gas mixture studies

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)

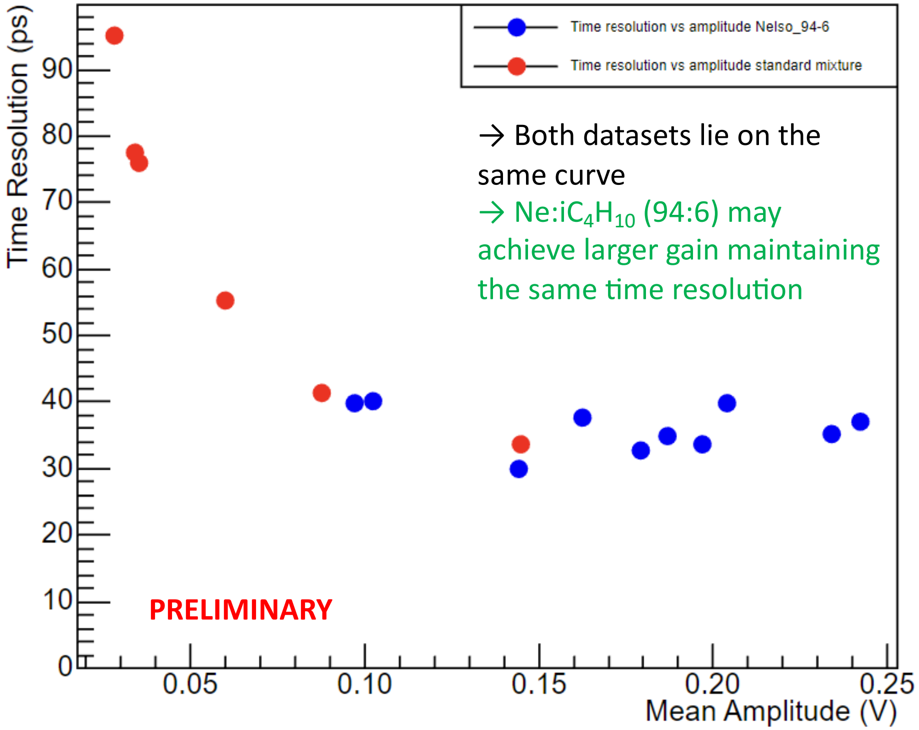
Pavia Chamber – 120 µm drift gap – rMM 380 kΩ/□ – B_4C 7 nm



→ Both datasets lie on the same curve
→ Higher gain achievable with the standard mixture

Ne:iC_4H_{10} (94:6)

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



→ Both datasets lie on the same curve
→ Ne:iC_4H_{10} (94:6) may achieve larger gain maintaining the same time resolution

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

Resistive Micromegas

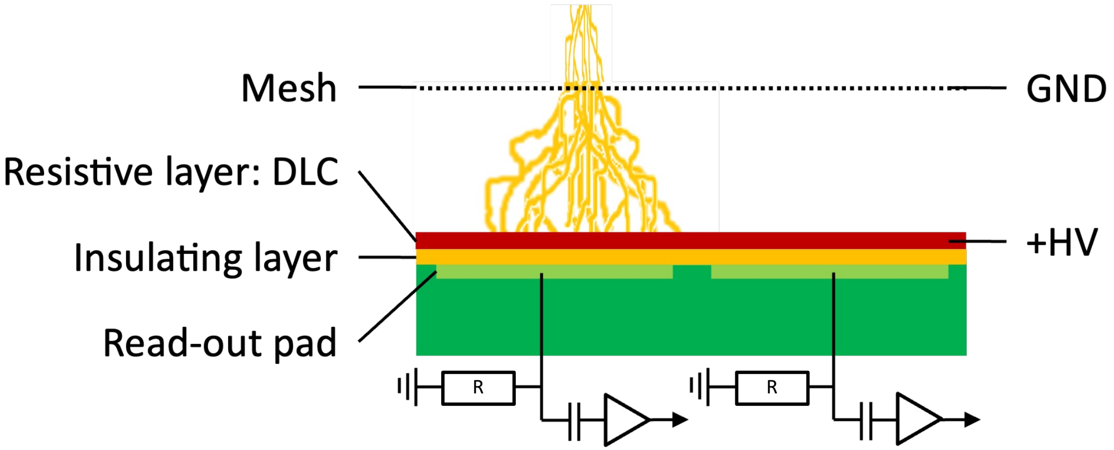
Advantages and requirements

- **Advantages of resistive Micromegas:**

  + protecting detectors from highly ionizing events

  + ensuring stable operation under intense particle beams

  + achieving better position reconstruction by signal sharing



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

Requirements for choosing the resistivity:

low enough to:

→ minimise the voltage drop during high-rate beam

→ improve the position reconstruction

high enough to:

→ ensure stable operation

→ not affect the rising edge of the signal

Resistive Micromegas

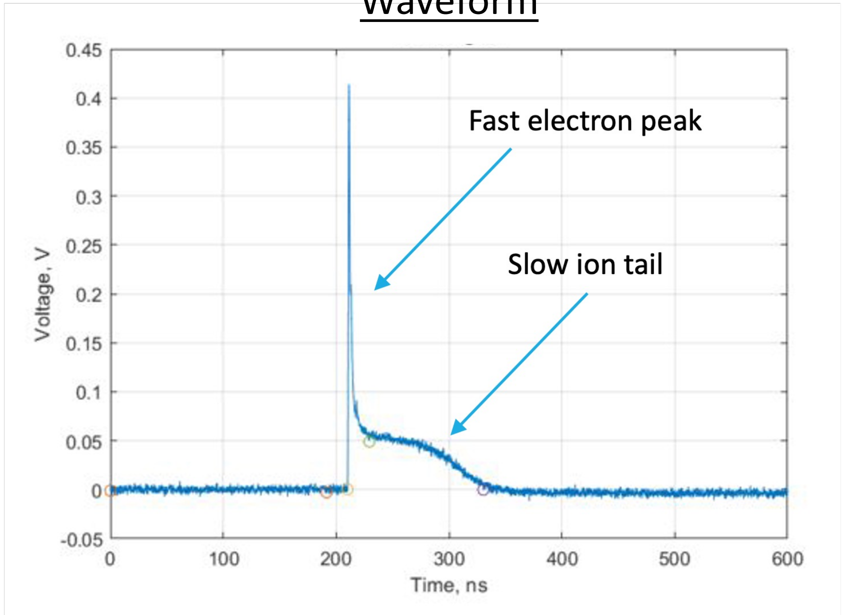
100-channel detector with a 10x10 cm^2 area resistive MM

Promising results with 10 x 10 cm^2 resistive MM

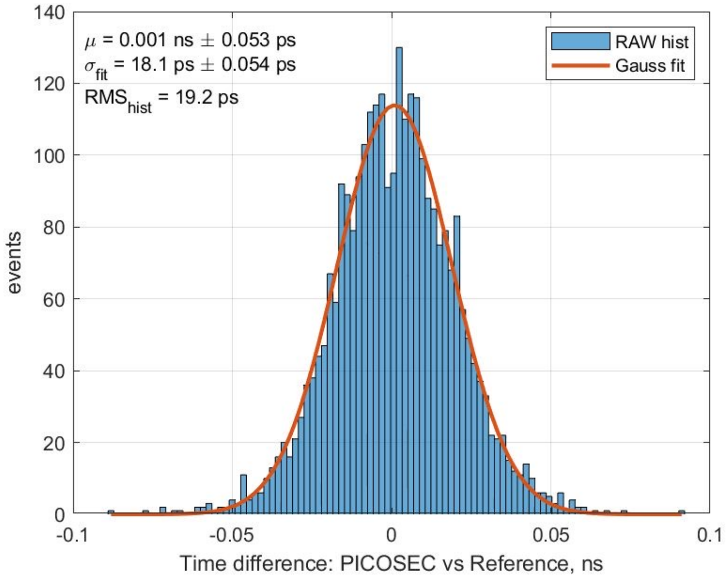
Plan: multi-layer DLC MM to study charge evacuation to evaluate the rate capability

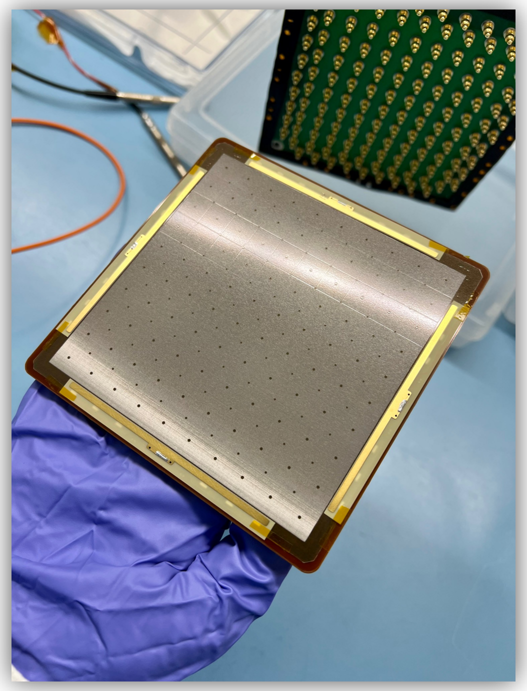
- Simulations* of rate capability and signal rising edge dependence to select the resistivity for a prototype
- Production of a 100-channel detector with a 10 x 10 cm^2 area **resistive MM** with anode surface resistivity of **20 MΩ/□**
- Multipad with a CsI photocathode and RF pulse amplifiers measured with an oscilloscope:

Waveform



Time resolution





- Results for 10 x 10 cm^2 resistive MM 20 MΩ/□ showed a time resolution below 20 ps for an individual pad!

Details: M. Lisowska, MPGD2022: link; JINST: link

*All simulations by D. Janssens

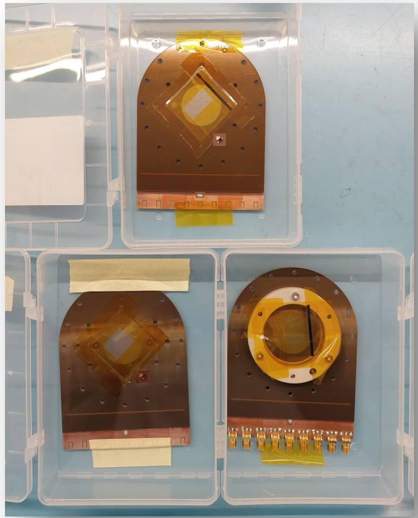
Resistive Micromegas

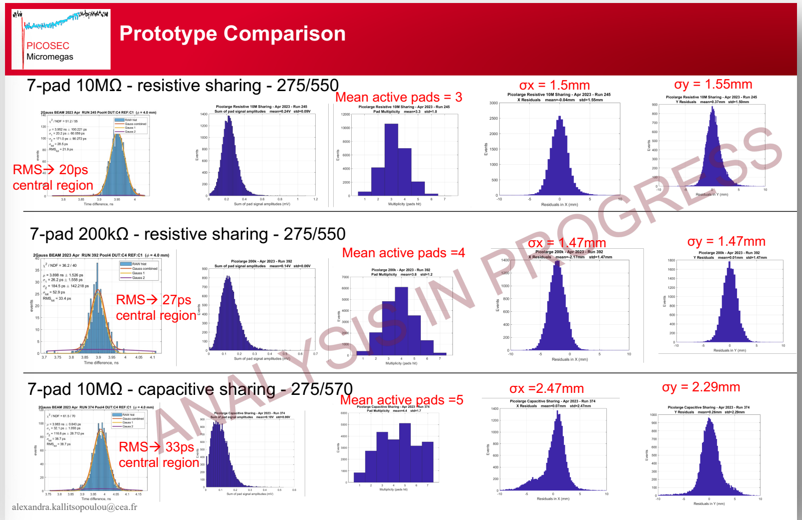
Other resistive detectors under test

Exploring different resistivity values, detector geometries layer architectures

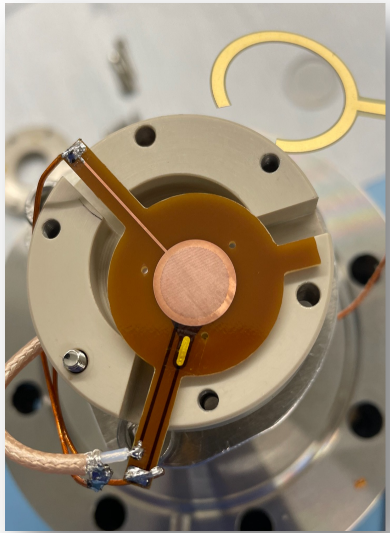
- **7-pad resistive prototypes with hexagonal pads of 1 cm dia.**
  → different resistivity values: 200 kΩ/□, 10 MΩ/□
  → different layer architectures: resistive vs capacitive sharing
  → evaluation of time resolution, rate capability, signal sharing, special resolution, amplitude and timing uniformity

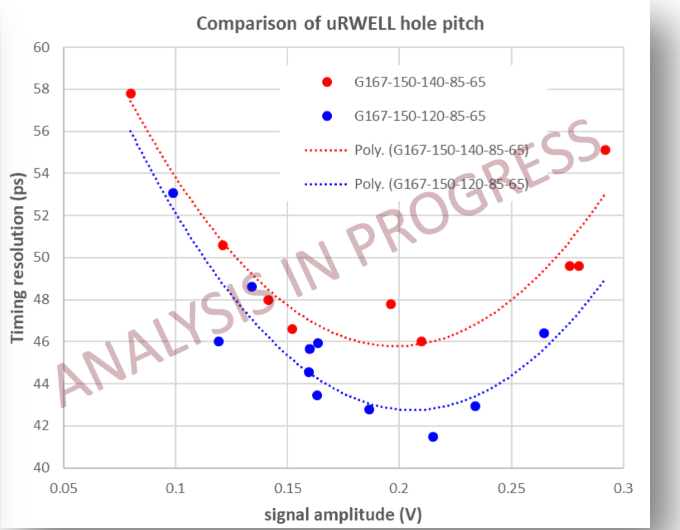
- **Single-pad µRWELL prototypes**
  → multiple detector geometries with different capacitances and varying pitch
  → high gain and stable operation achieved
  → slower rising time of e-peak observed compared to MM





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





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

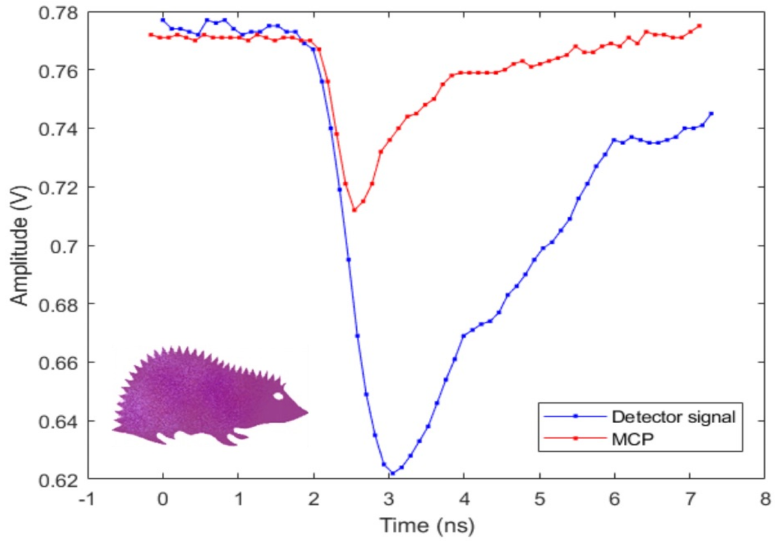
Readout of a multi-channel detector

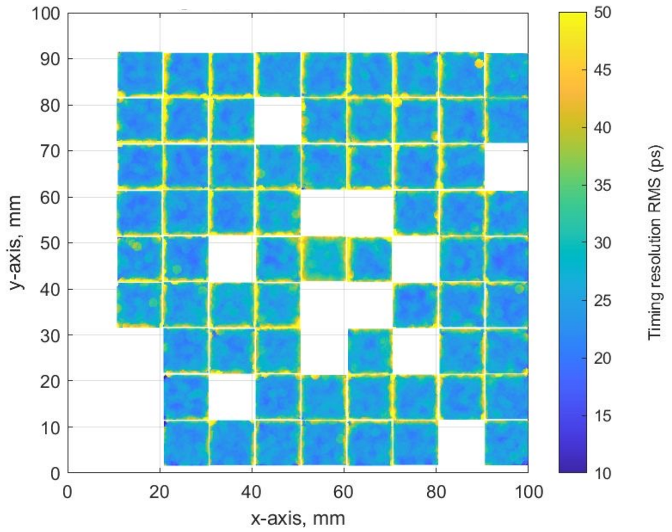
Scalable electronics: custom-made amplifiers and SAMPIC digitiser

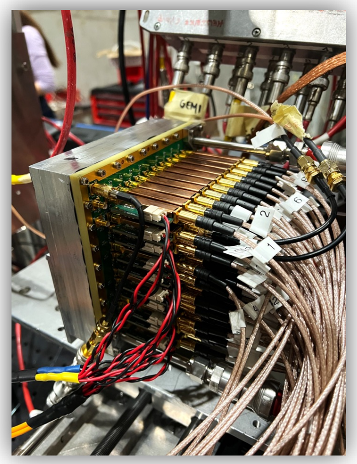
Different readout approach: FastIC ASIC
- details by L. Scharenberg on Wed: link

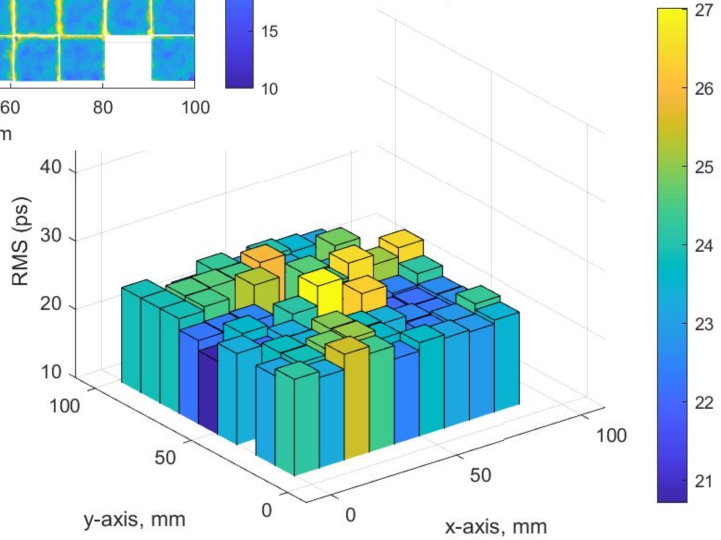
- Readout of a 10x10 cm^2 area 100-channel PICOSEC detector

Waveform from SAMPIC

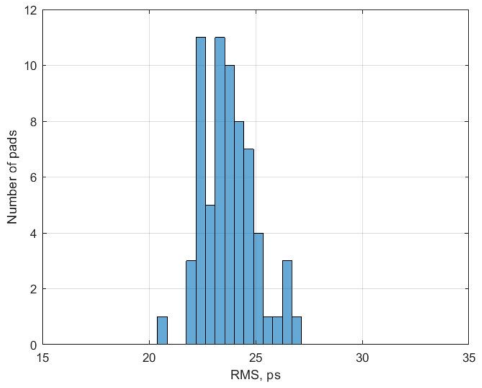








Time resolution



- Uniform time resolution within the pads
- Narrow distribution of the time resolution across the area
- **Tool to study the response of 100-channel PICOSEC detector**

Details: M. Lisowska, MPGD2022: link; JINST: link

Robust photocathodes

CsI photocathode and the alternatives

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

  + high quantum efficiency in comparison to other materials

  - can be damaged by ion back flow, discharges

  - sensitive to humidity (assembly)

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

  → Diamond Like Carbon (DLC)

  → Boron Carbide (B_4C)

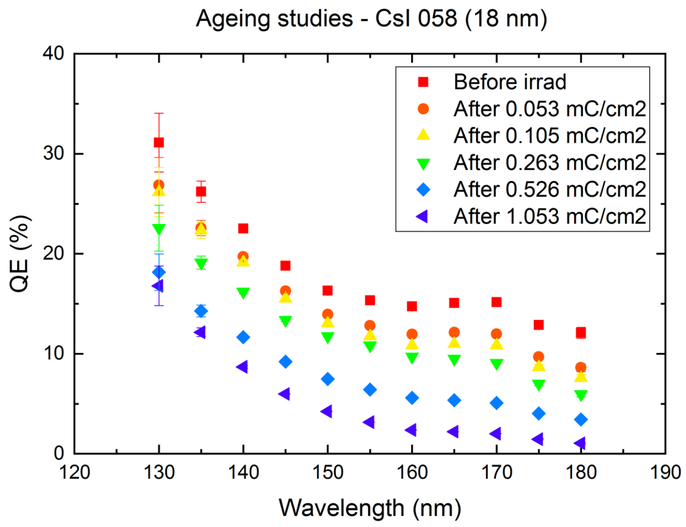
  → Nanodiamonds

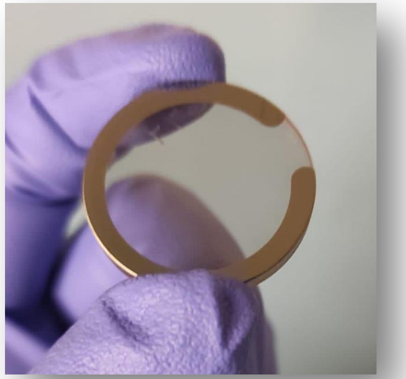
  → Carbon nano-structures

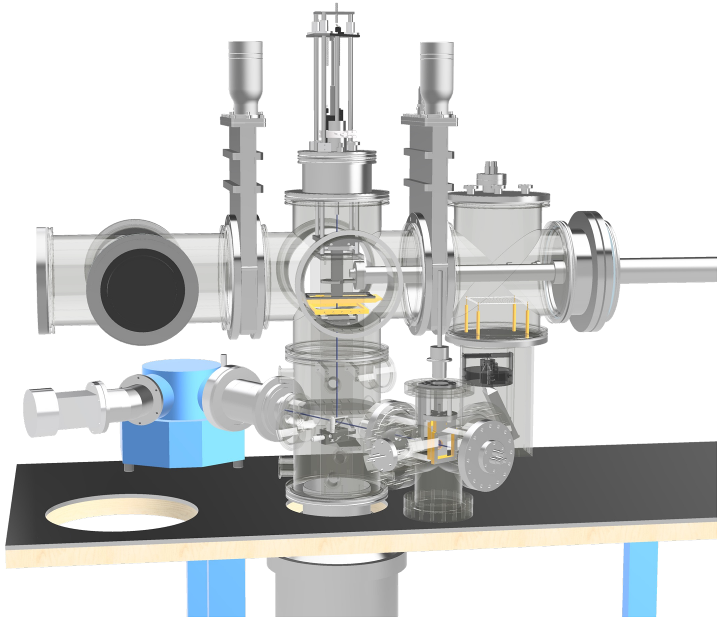
- **ASSET** – Photocathode characterisation setup

  Details: M. Lisowska, RD51 MW 2020, link

QE AND AGEING STUDIES PERFORMED USING UV LIGHT





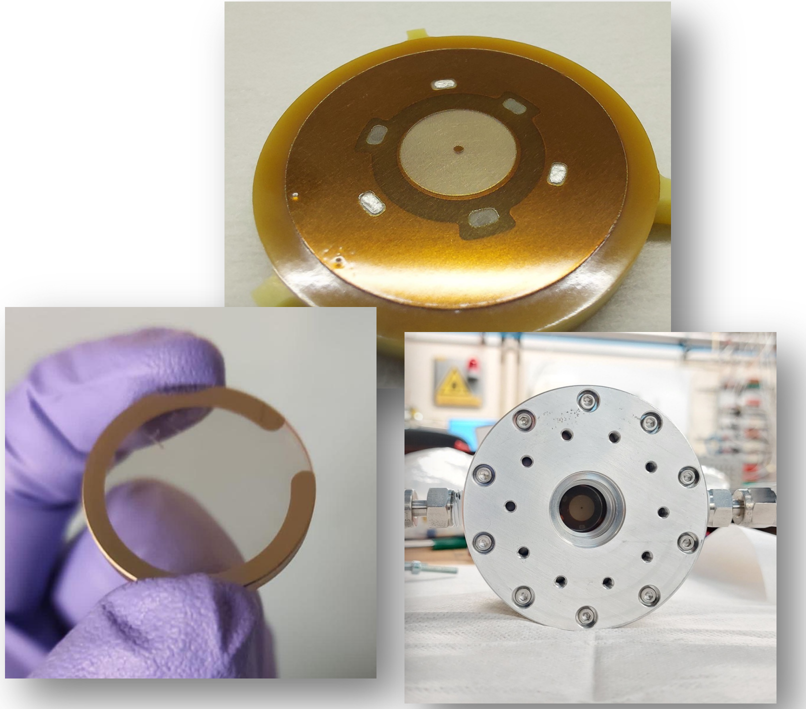


Robust photocathodes

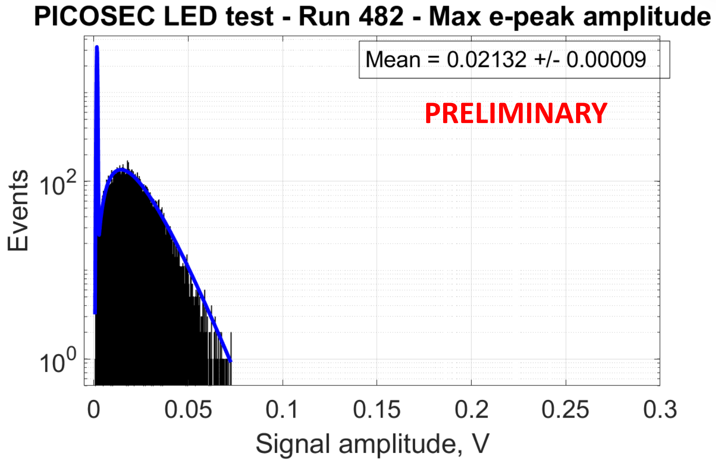
RD51 test beam campaign measurements

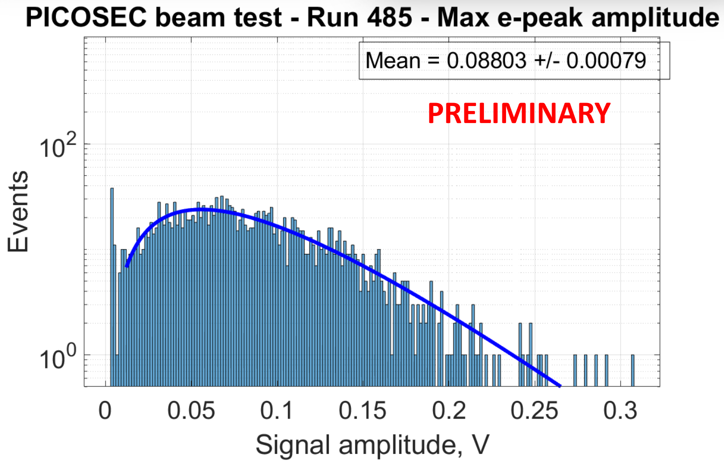
- **Measurements**:
  1. Transparency measurement with ASSET
  2. Single PhotoElectron measurement with LED
  3. Beam measurement @ CERN SPS H4 beam line, 150 GeV/c muons
  4. Timing measurement @ CERN SPS H4 beam line, 150 GeV/c muons

Improvement of the measurement and analysis procedures



- **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 125/145 μm*
- **Photocathodes**: CsI, DLC, B_4C of different thicknesses from different collaborators**

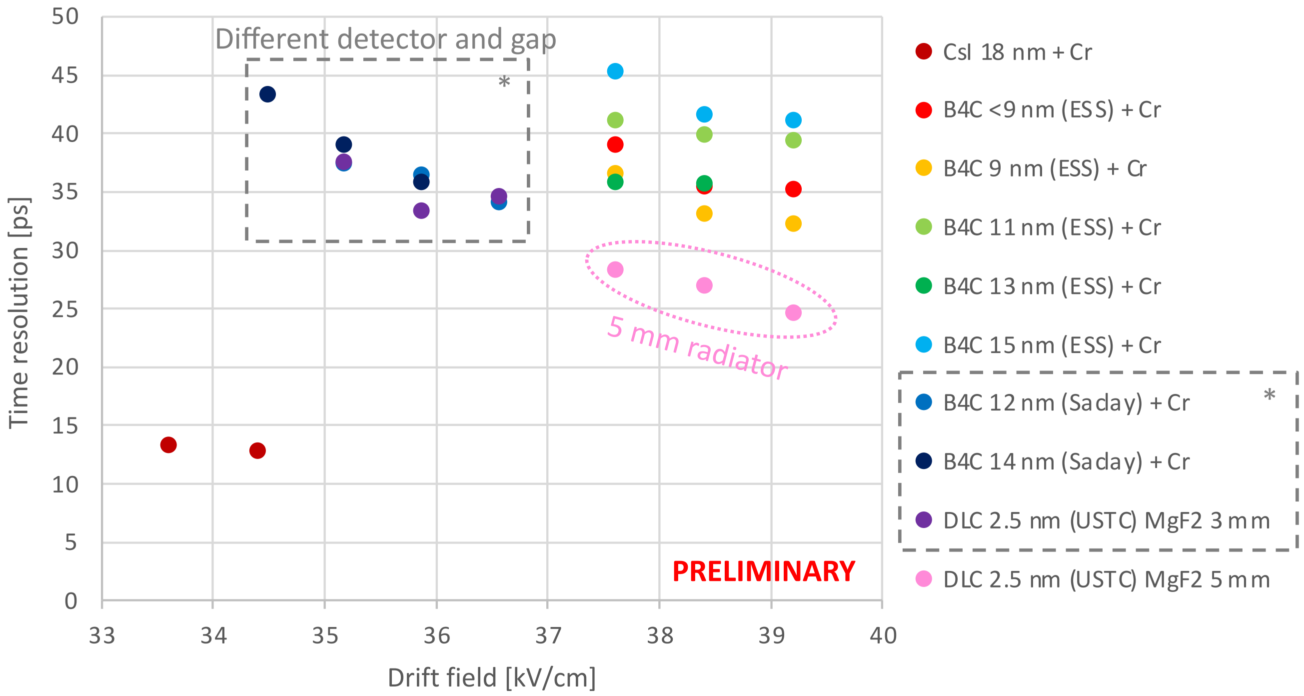
- **Time resolution** after MCP subtracted:

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

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

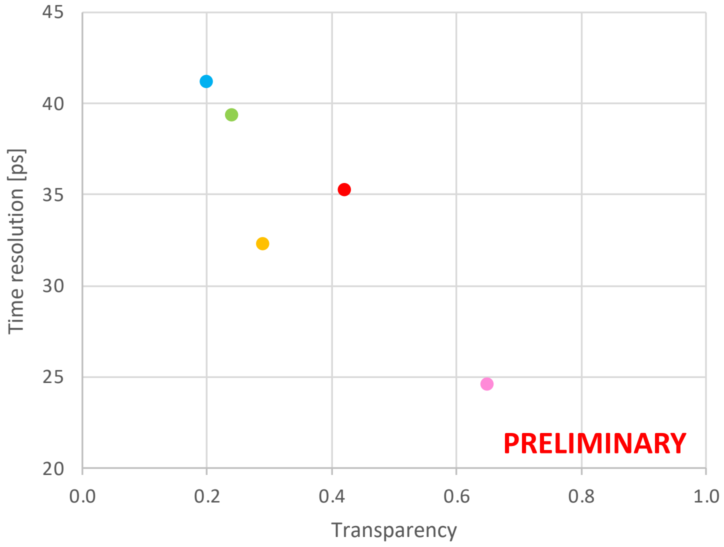
**Depositions: CsI at CERN, DLC at USTC, B_4C at CEA Saclay and ESS

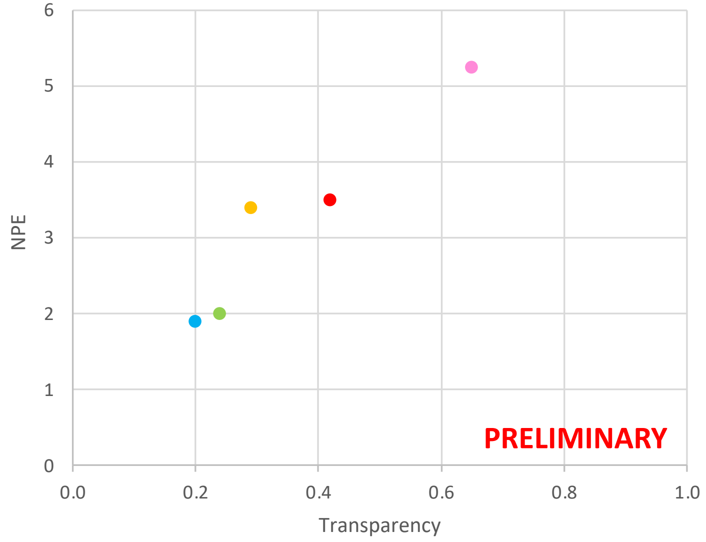
Robust photocathodes

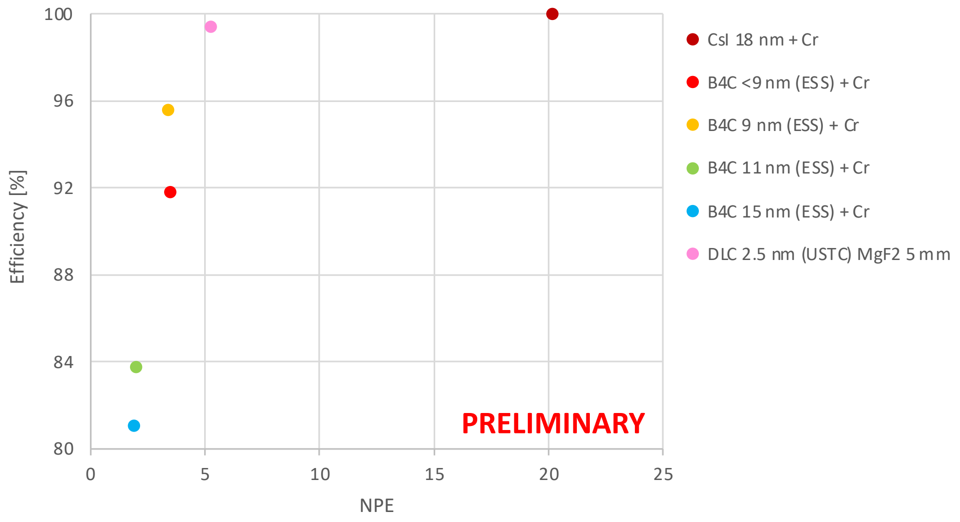
Time resolution, NPE and efficiency

New promising results of robust photocathodes from 2023 test beams

- **Prototype**: Single pad non-resistive MM, pre-amplification gap 125 µm
- **Photocathodes**: CsI, DLC, B_4C of different thicknesses from different collaborators**
- **Time resolution** defined as standard deviation of signal arrival time distribution
- **Number of PhotoElectrons** referred to ~20 p.e. / MIP measured with 3 mm MgF_2 radiator + 3 nm Cr layer + 18 nm CsI photocathode
- **Efficiency** of converting photons into electrons measured with a muon beam in the center of the detector (4 mm dia.)







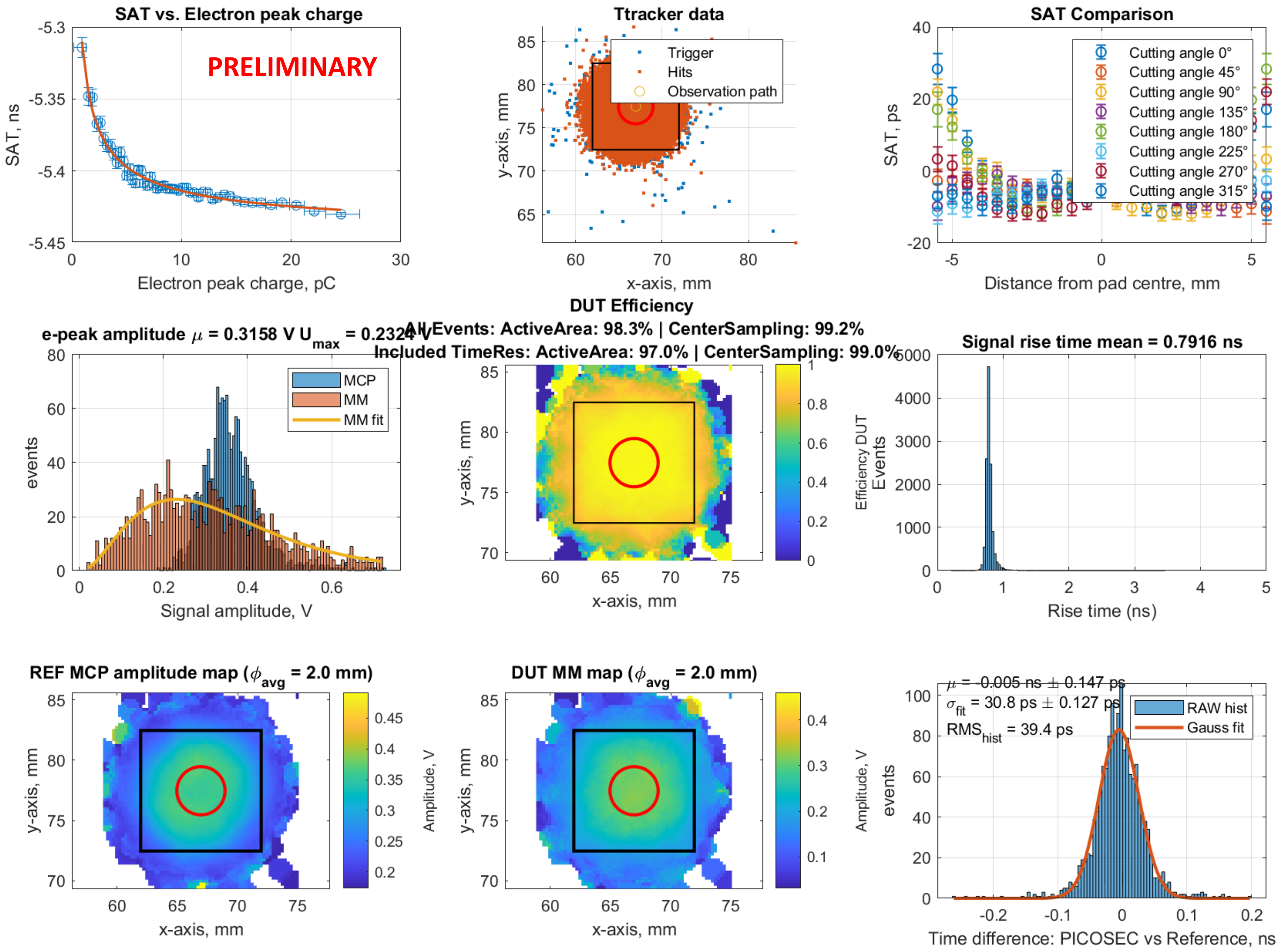
**Depositions: CsI at CERN, DLC at USTC, B_4C at CEA Saclay and ESS

Robust photocathodes

10 x 10 cm^2 DLC photocathode

First measurements with 10 x 10 cm^2 DLC 2.5 nm photocathode on 5 mm MgF_2

- Measurements of the 100ch Multipad: non-resistive MM, pre-amp gap 180 µm, 10 x 10 cm^2 area 5 mm thick MgF_2 with 2.5 nm thick DLC photocathode
- Time resolution of the 100ch MM with DLC photocathode **σ ∽30 ps an individual pad**
- Response of full area of 100ch Multipad measured with custom-made amplifiers and SAMPIC digitiser → analysis in progress



DLC photocathodes

First DLC photocathode deposition at the CERN MPT workshop

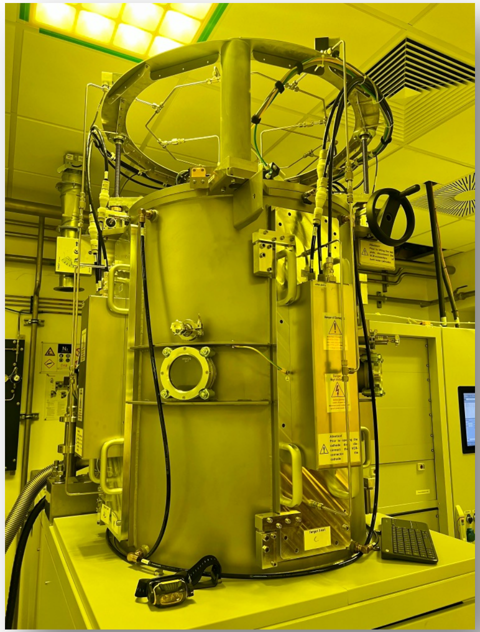
Possibility to deposit DLC photocathodes at CERN MPT workshop

- **Pulsed DC magnetron vacuum deposition machine at CERN MPT workshop:**

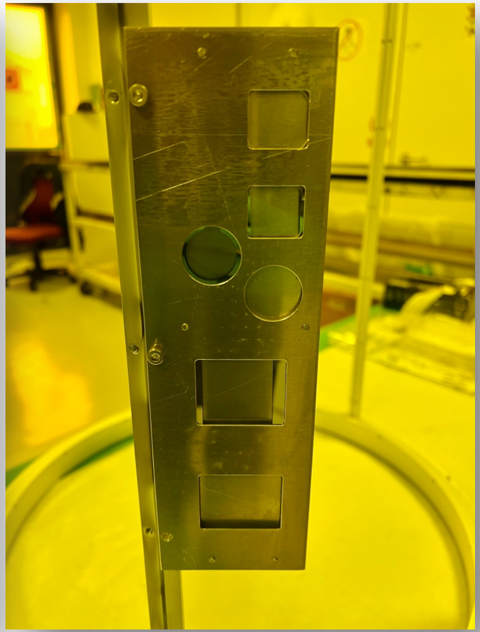
  → can be used for the **deposition of the robust photocathodes for PICOSEC** including DLC and B_4C

  → November 2023: first deposition of DLC on MgF_2 and glass samples

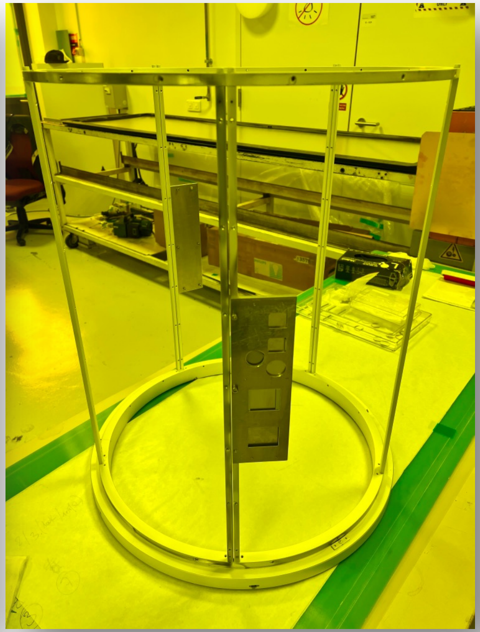
  → "thickness vs resistivity vs coating time" dependance still needs to be understood



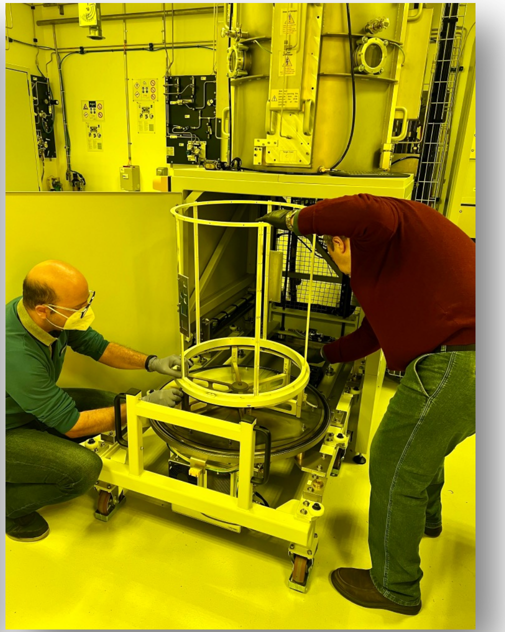
Pulsed DC magnetron vacuum deposition machine



Samples inside the holder with different sizes and masks



Holders with samples attached to the drum



Loading the drum into the chamber

Huge thanks to Serge, Rui, Gianfranco, Givi, Miranda and Thomas for the opportunity to do the deposition as well as all the help during the procedure!

Details on the machine: MPGD School 2023, R. de Oliveira: link

Details on the DLC coatings on Thursday by Gianfranco Morello: link

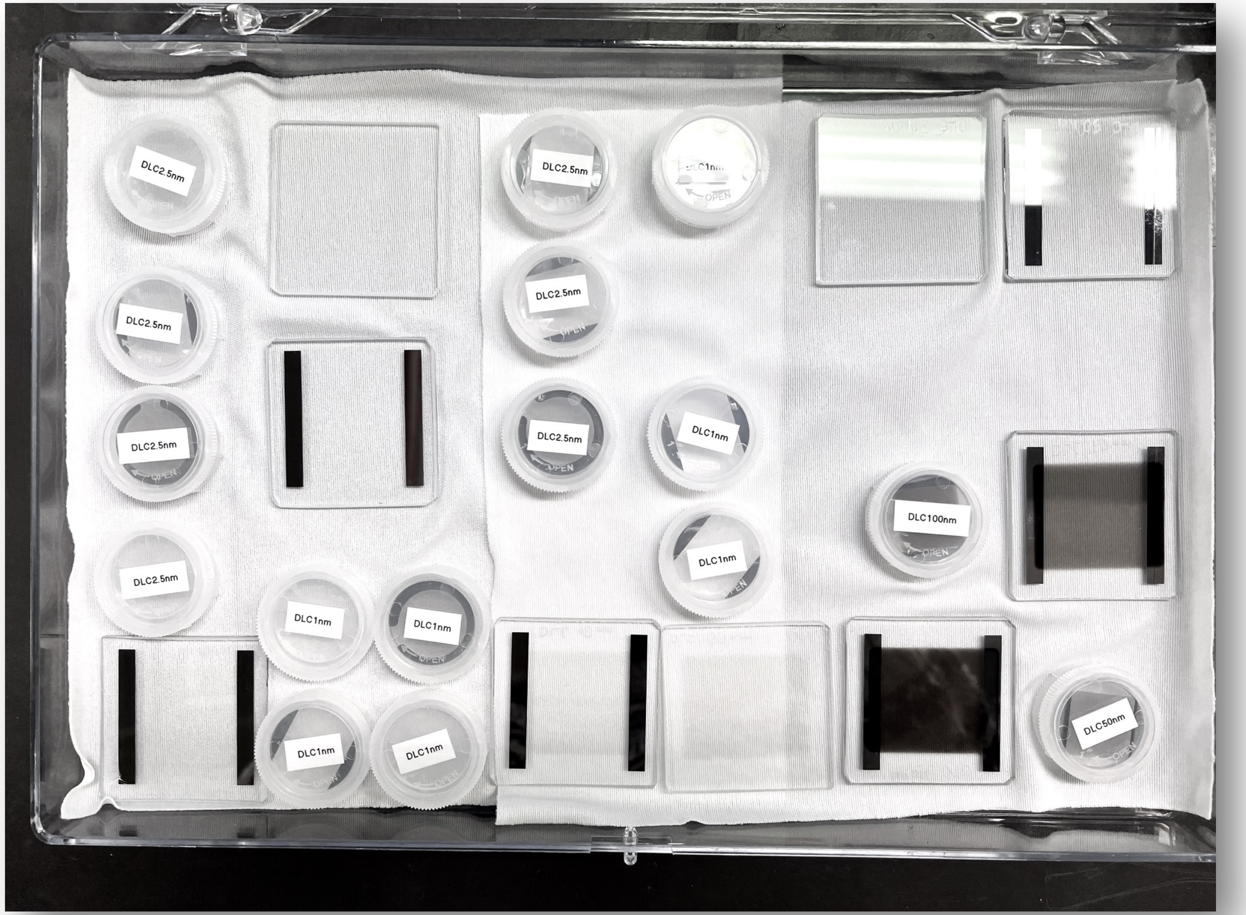
DLC photocathodes

List of the measurements

Successful deposition of DLC of different layer thickness

- **Successful deposition of DLC** of different layer thickness:
  1 nm, 2.5 nm, 50 nm, 100 nm, on MgF_2 and glass samples

- **Measurements to be performed:**
  → **Thickness** with a profilometer at Thin Film workshop
  (resolution ~5 nm, not enough for thin layers,
  AFM needed to measure thin layers)
  → **Transparency:** MgF_2 samples in VUV in ASSET, glass
  samples in visible light
  → **Quantum efficiency** in ASSET in transmission and
  reflective modes
  → **Resistivity** with Keithley by applying voltage between
  2 conductive strips deposited on the sides of the samples



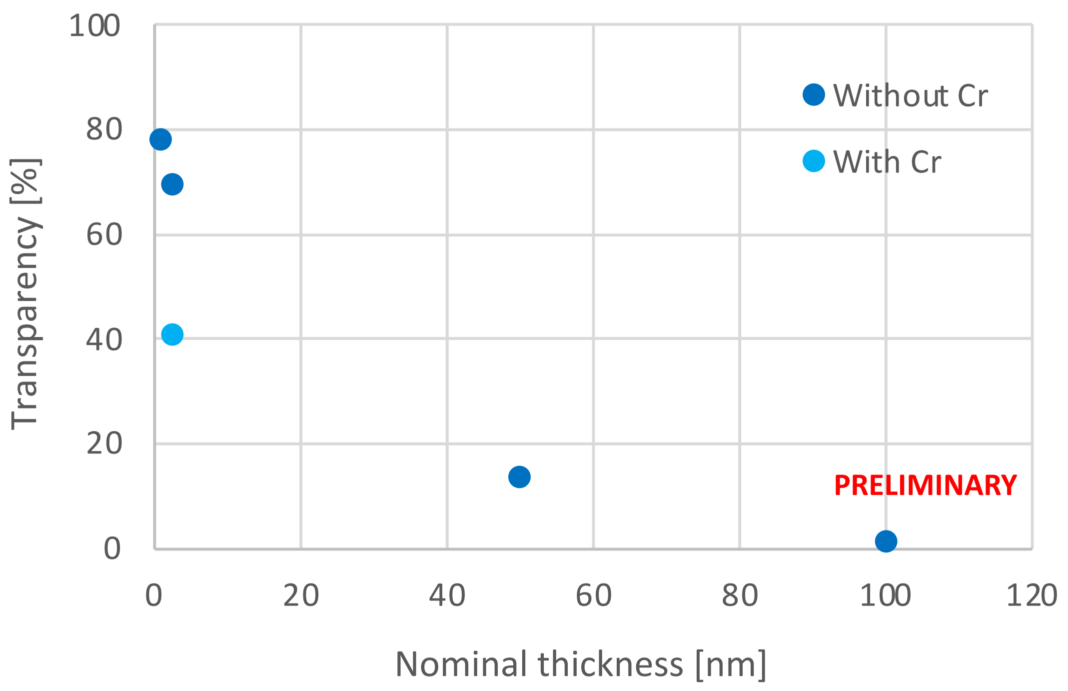
DLC photocathodes

Transparency

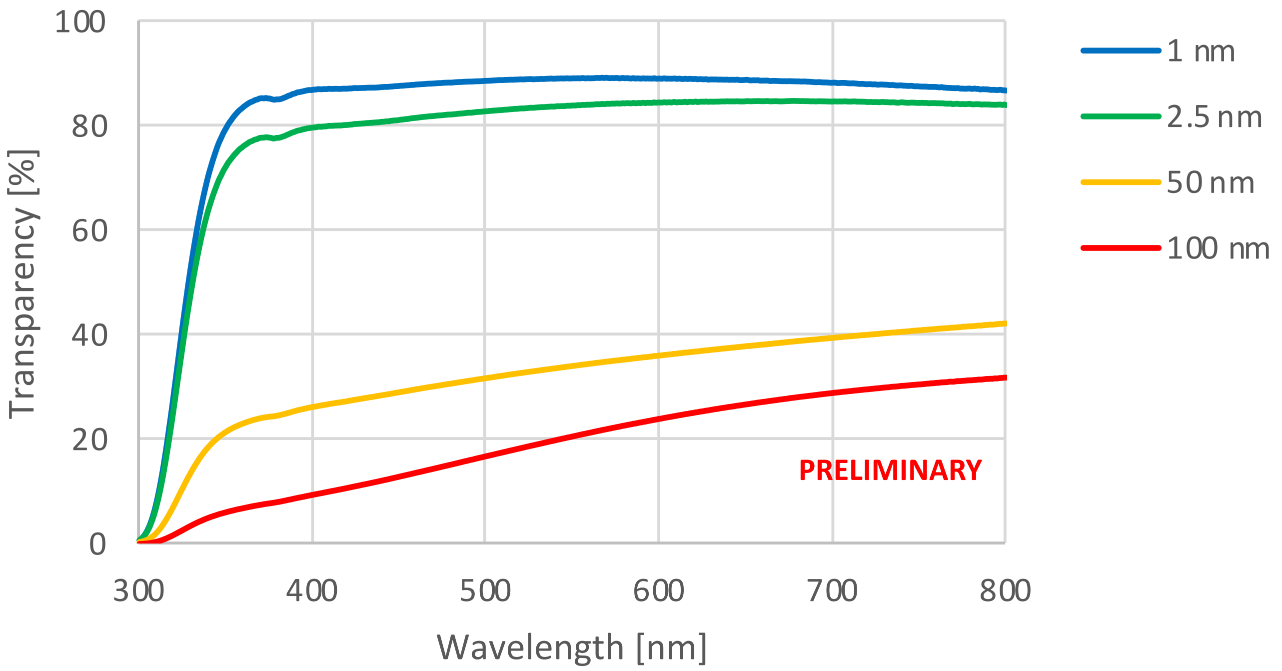
Characterisation of new DLC photocathodes

- **Transparency was measured in 2 different ways:**

→ MgF_2 samples in VUV in ASSET (trans @ 180 nm)



→ glass samples in visible light in spectrophotometer



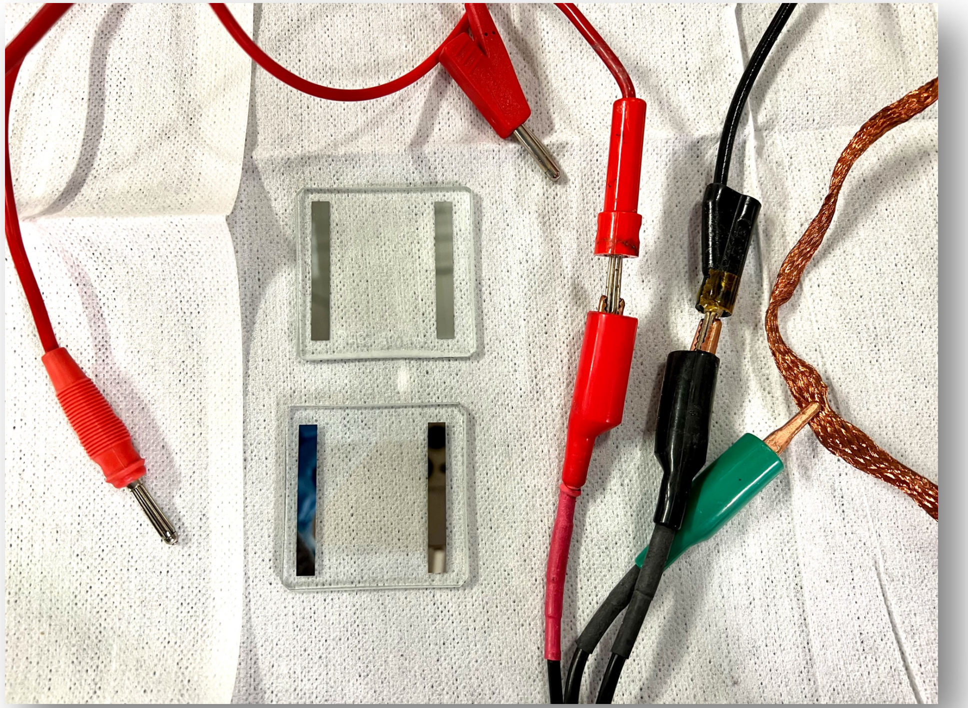
Transparency of MgF_2 samples and pure glass to be measured

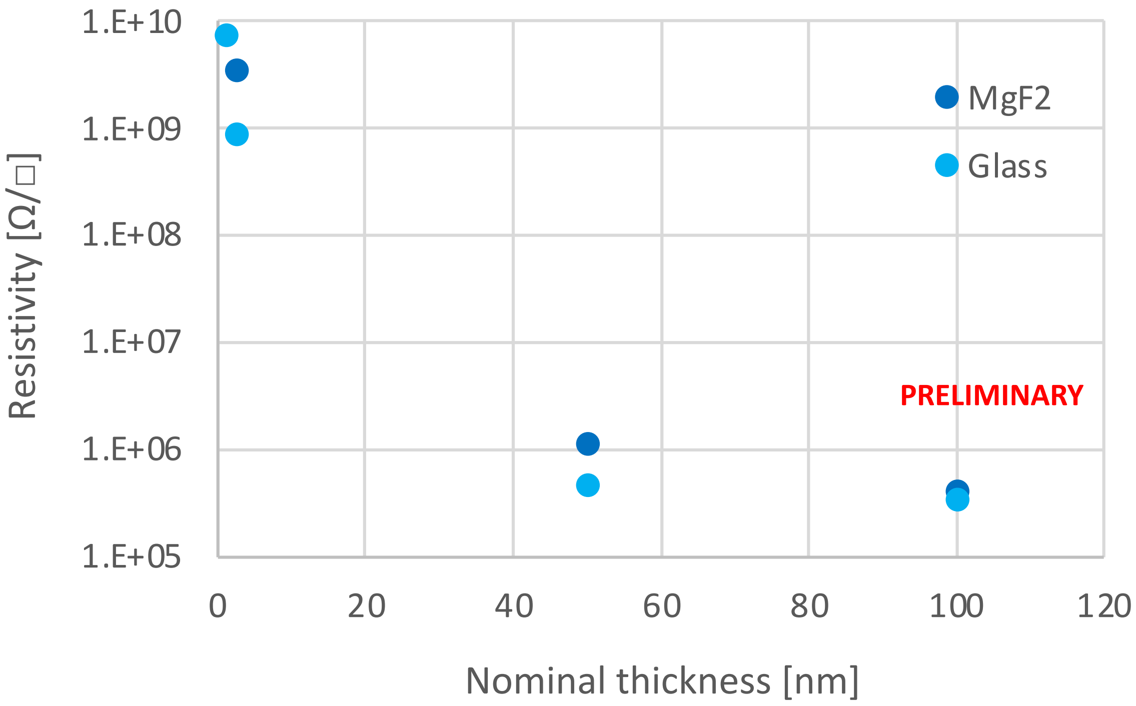
DLC photocathodes

Resistivity

Characterisation of new DLC photocathodes

- **Resistivity** was measured with Keithley by applying voltage between 2 conductive strips deposited on the sides of the samples





- Resistivity of DLC layer on the MgF_2 substrate is higher than on the glass substrate → DLC layer on the MgF_2 samples is thinner than on the glass samples → MgF_2 crystals have lower adhesion

Summary

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

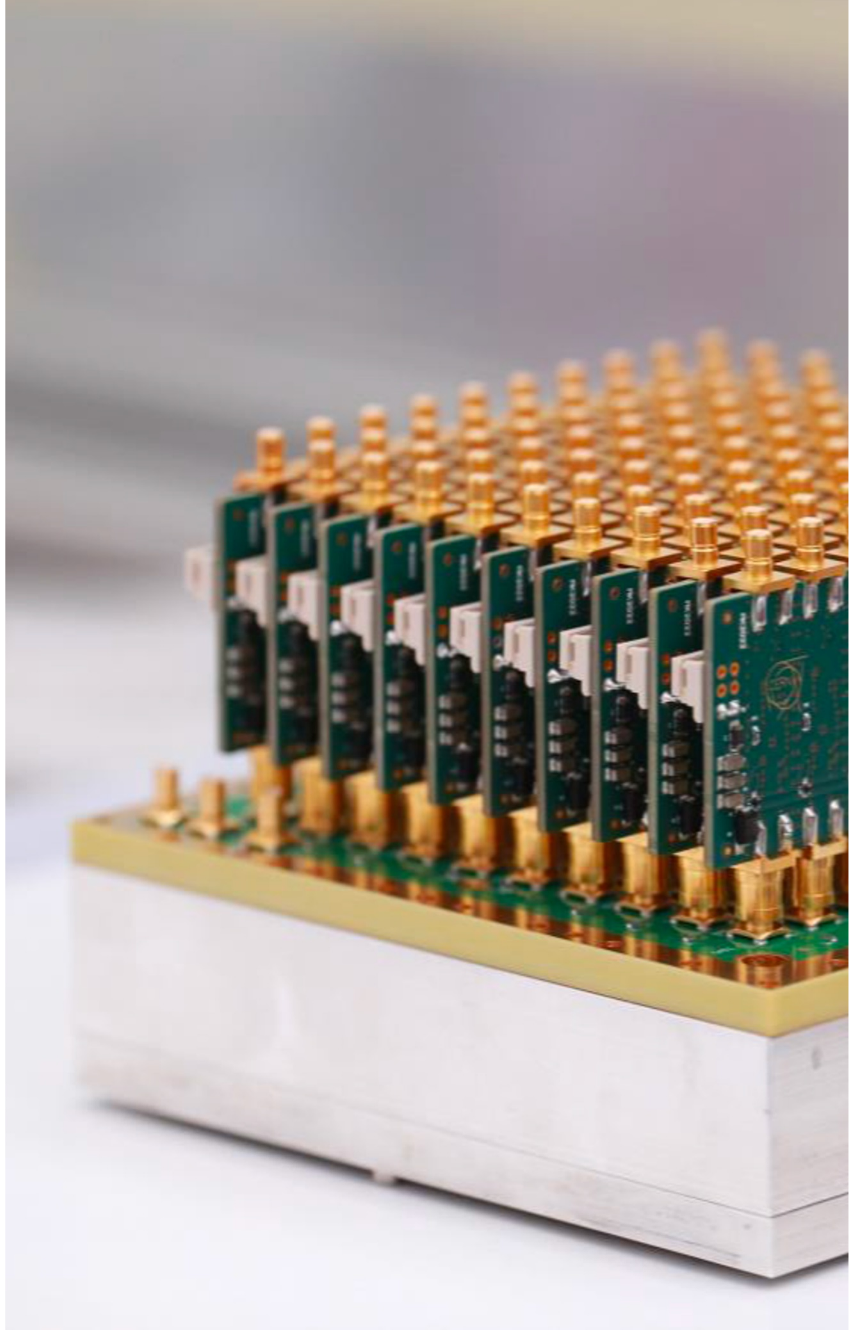
- **Detector optimisation** → Improvement of the **single-pad detector's time resolution to 15 ps** by introducing a new design

- **Large area coverage** → Excellent performance of the **100-channel PICOSEC MM prototype** with a **time resolution < 18 ps** for an individual pad

- **Resistive Micromegas** → Preliminary results of a 10x10 cm^2 **resistive MM 20 MΩ/□** showed a **time resolution < 20 ps** for an individual pad

- **Robust photocathodes** → Single-pad prototype with a time resolution **σ < 25 ps for DLC photocathode** and **σ < 35 ps for B_4C photocathode**; time resolution of the 100-channel MM with **10x10 cm^2 area DLC photocathode σ ∽30 ps** for an individual pad

- **Complete readout chain** → **Successful readout of multiple channels**



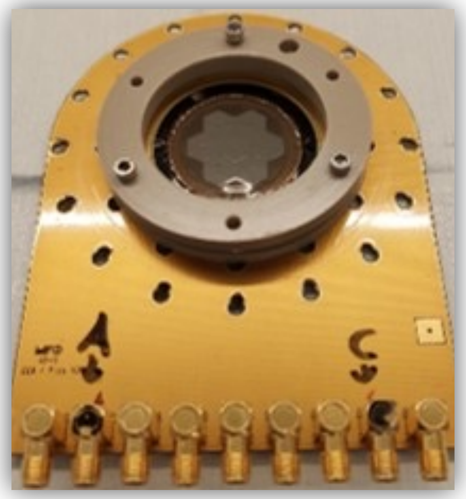
PICOSEC Micromegas

Future prospect

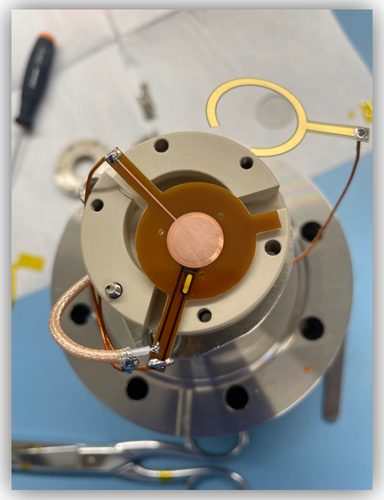
- **Resistive detectors:** **Multi-layer DLC MM** to study charge evacuation;
  Prototypes with different resistivities (200 kΩ/□, 10 MΩ/□, …) (A. Kallitsopoulou, CEA Saclay, RD51 CM June 2023: link); µRWELL PICOSEC (K. Gnanvo, JLab, IEEE meeting: link)
- **Improving the spatial resolution:** Signal sharing with resistive PICOSEC MM
- **Stability:** **Multi-layer DLC MM**; High-rate capability studies (D. Fiorina, Pavia, RD51 MW, link)
- **Robust photocathodes:** Studies on **B_4C, DLC, Nanodiamonds** (R. Rai, Trieste, Ageing, link)
- **Alternative electronics:** **FastIC ASICs** (L. Scharenberg, link); TDC; threshold-based readout
- **Operating gas**: Exploring alternative gas mixtures (D. Fiorina, M. Brunoldi, INFN Pavia)
- **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

- **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**

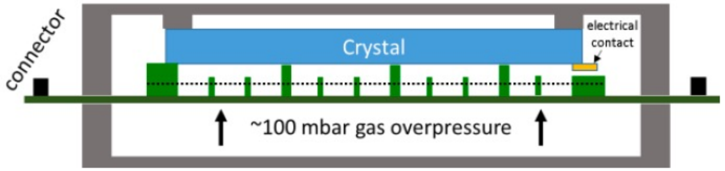
PicoLarge 7-pad resistive detector



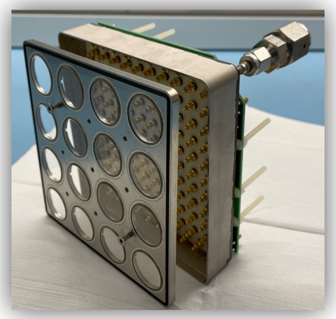
µRWELL PICOSEC



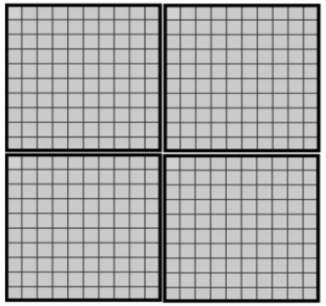
Thin MM PCB with longer pillars



Sealed detector



Tiling: 4 x 10x10 cm^2



PICOSEC Micromegas Collaboration

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Thank you for your attention!

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Back up slides

Classical vs PICOSEC Micromegas

Signal arrival time jitter

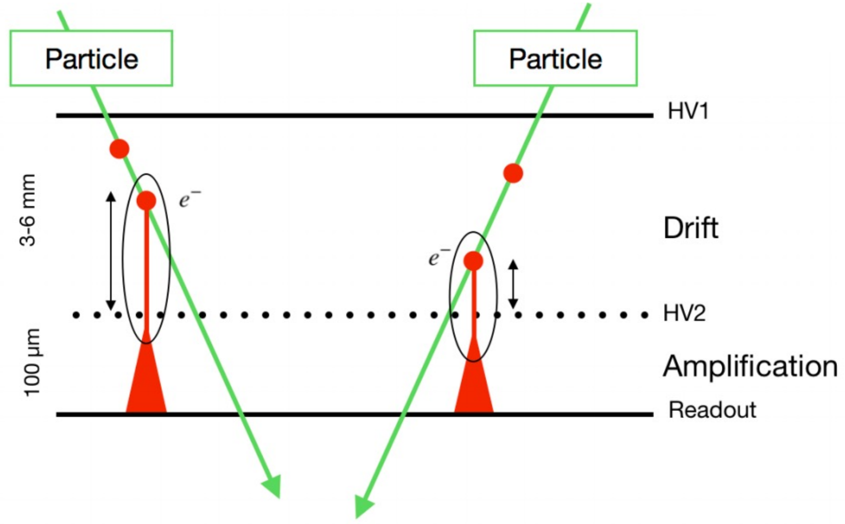
- **Classical Micromegas:**

  → different position of ionisation clusters at direct gas ionisation

  → signal arrival time jitter due to drift velocity and average ionisation length

$$\sigma_t = \frac{\sigma_I}{v_d} = \frac{355\,\mu m}{84\,\frac{\mu m}{ns}} \approx 4\,ns$$

Estimated time jitter for COMPASS Micromegas



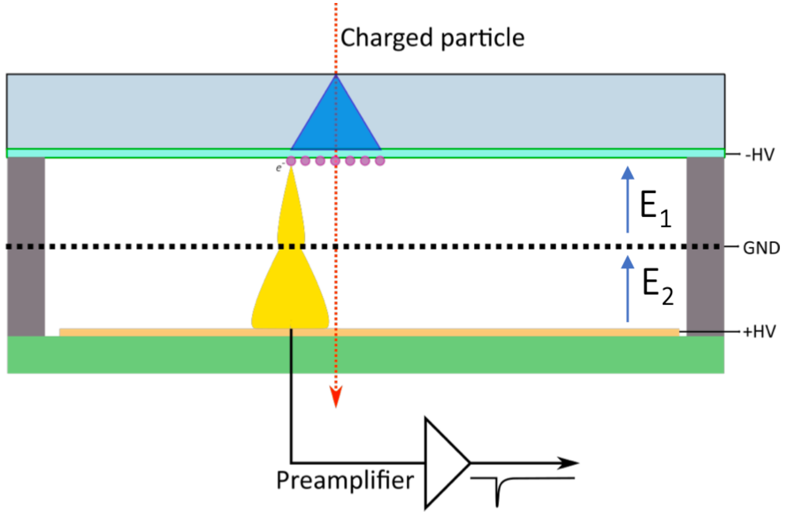
- **PICOSEC Micromegas:**

  → particles produce Cherenkov radiation

  → electrons are emitted by the radiation in a photocathode

  → all primary ionised electrons are localised on the photocathode

  → due to high electric field, time jitter before first amplification minimised



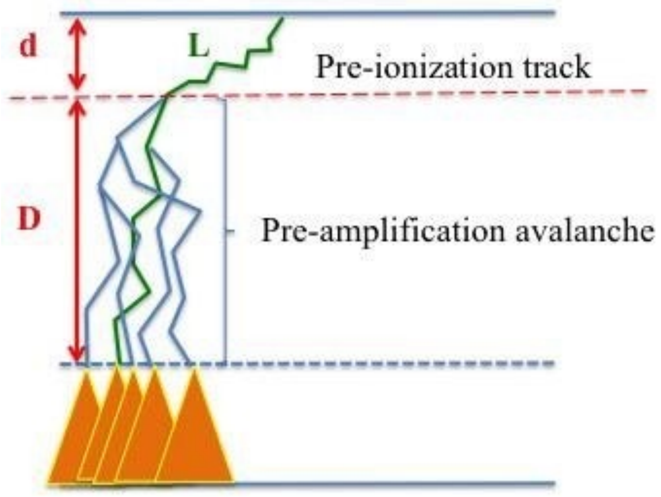
L. Sohl, RD51 MW 2020, link

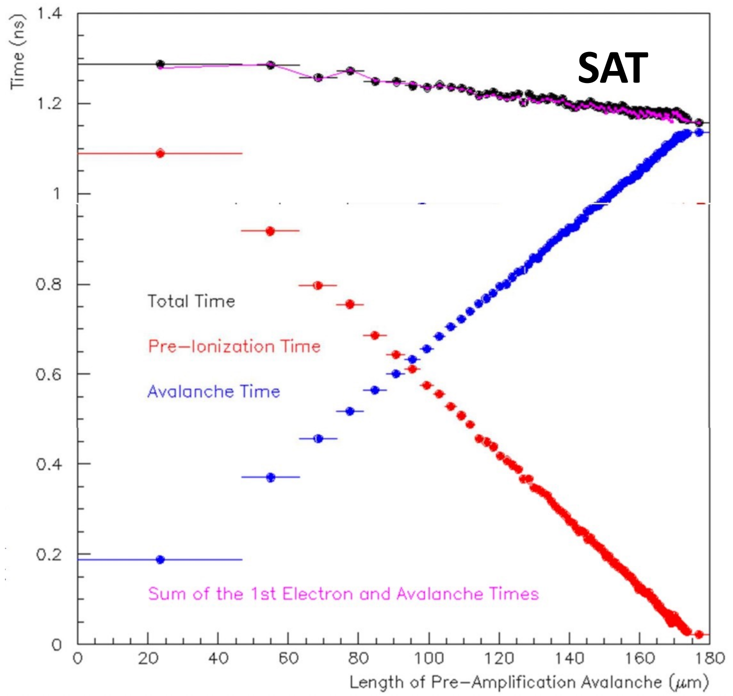
PICOSEC Micromegas

Signal arrival time

- **Signal arrival time (SAT) = <$T_{e\text{-}peak}$>**
  → SAT depends on e-peak charge
  → SAT can be reduced by higher drift field and bigger pulses

- **Location of first ionisation determines length of avalanche**
  → longer avalanches result in bigger e-peak charge
  → bigger e-peak charge reduces SAT



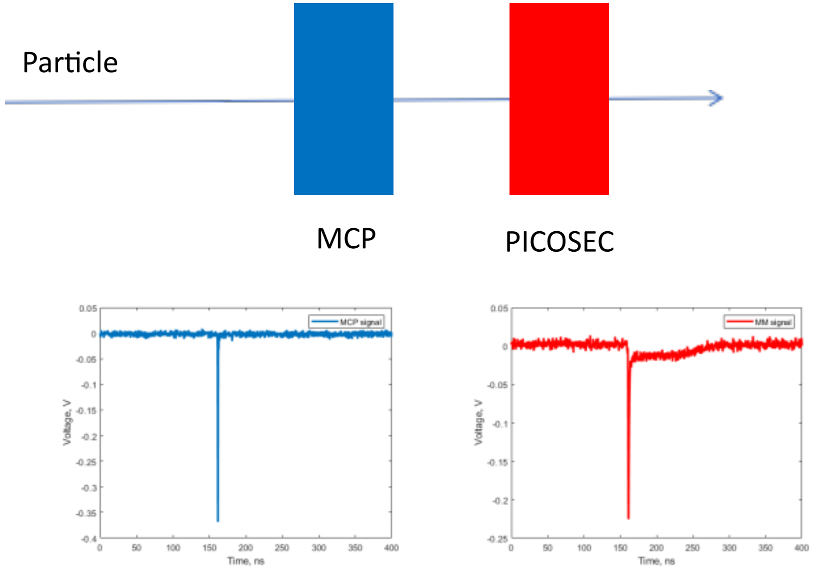


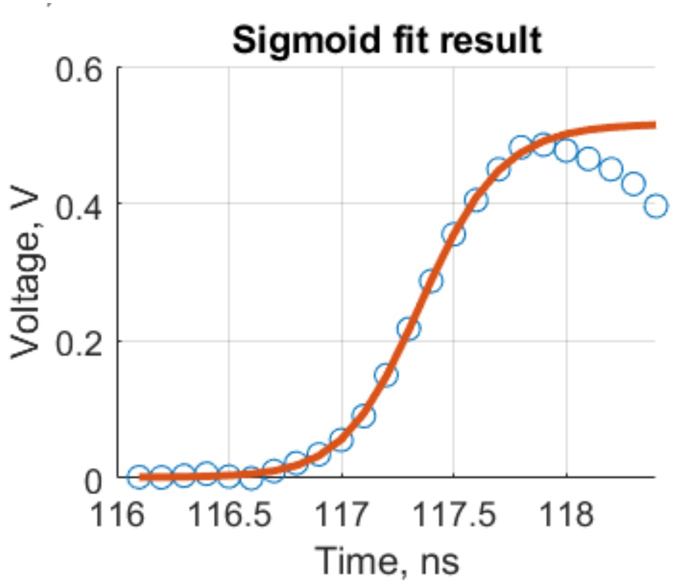
K. Kordas, VCI 2019 conference, link

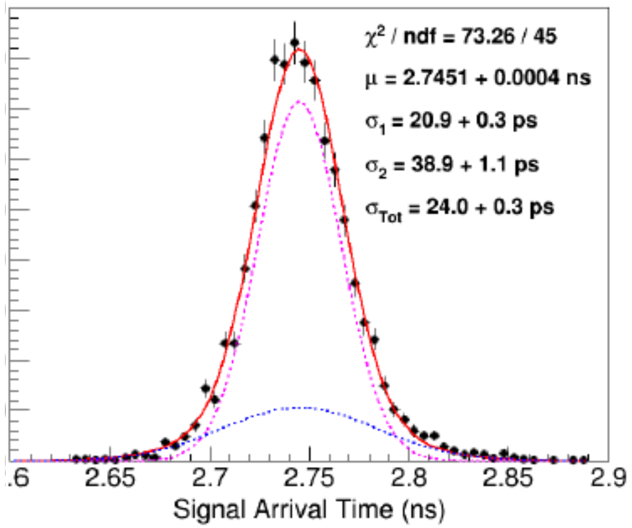
PICOSEC Micromegas

Timing properties

- Reference device with better timing precision than the PICOSEC is needed to quantify the timing precision of PICOSEC.
- Sigmoid function is fitted to the leading edge of the electron peak. Position of the signal is calculated at 20% Constant Fraction (CF).
- Signal arrival time (SAT): the difference between PICOSEC and reference detector timing marks.
- Time resolution of the detector is defined as standard deviation of SAT distribution.







A. Utrobičić, VCI 2022 conference, link

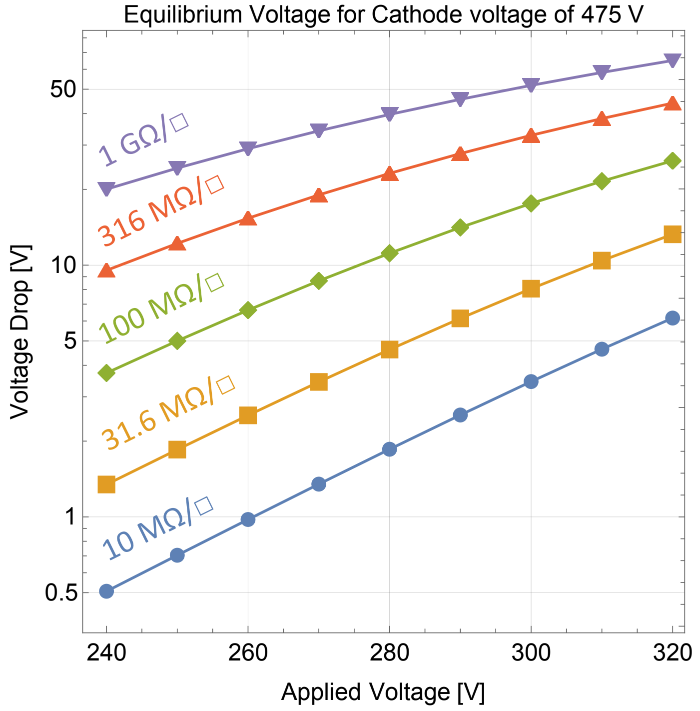
Resistive Micromegas

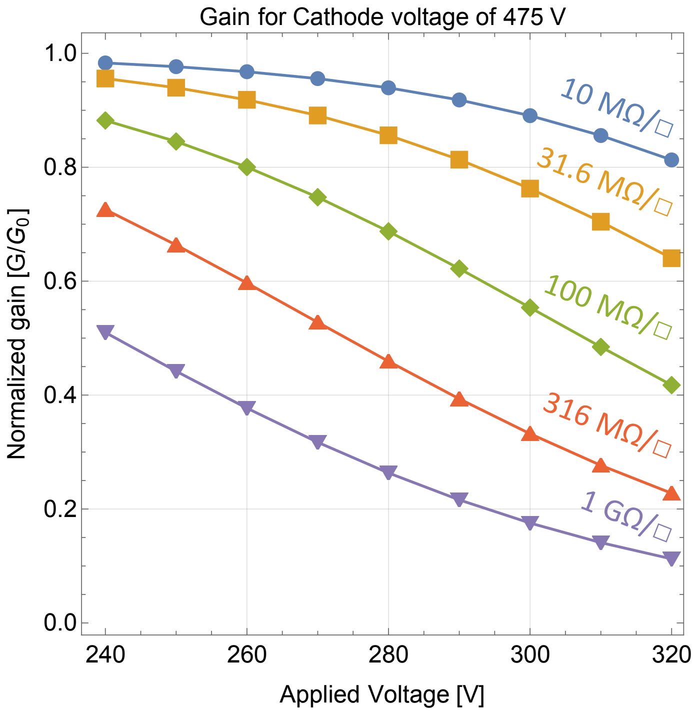
SIMULATIONS

Rate capability

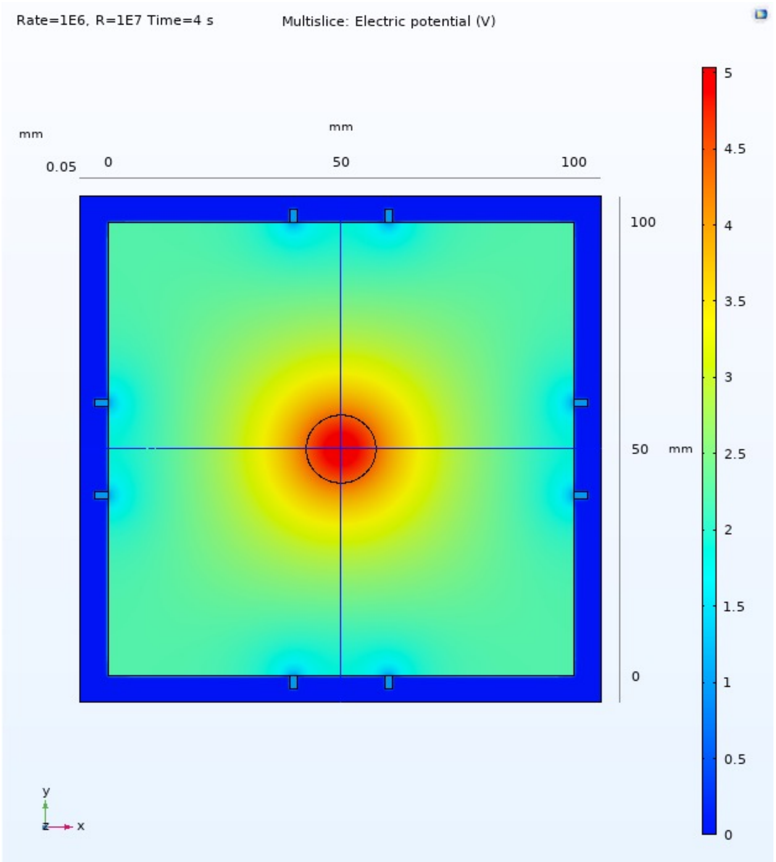
for a pion beam of 1.5 cm dia. and 1.9 MHz

Simulated voltage and gain drop vs applied voltage for different resistivities





Simulated voltage drop across the area



The minimum resistivity that ensures a detector's stable operation is 10 MΩ/□

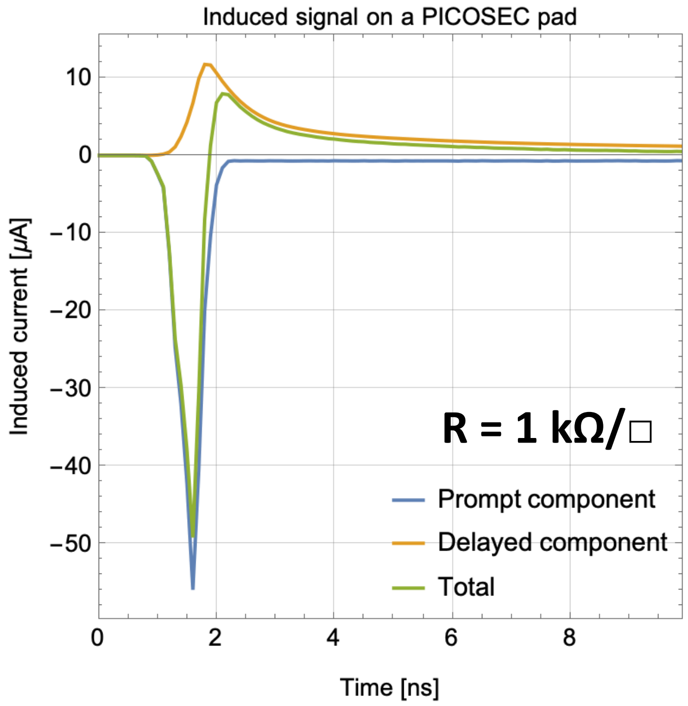
All simulations by D. Janssens

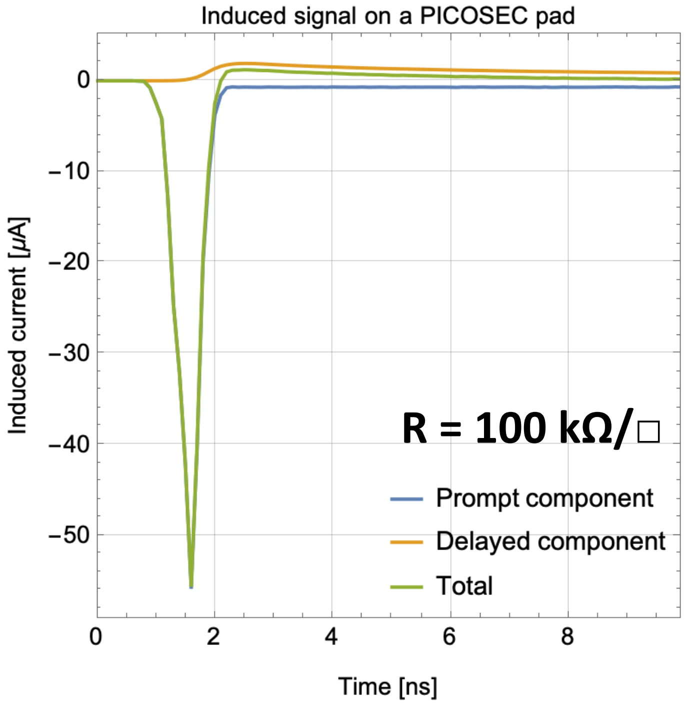
Resistive Micromegas

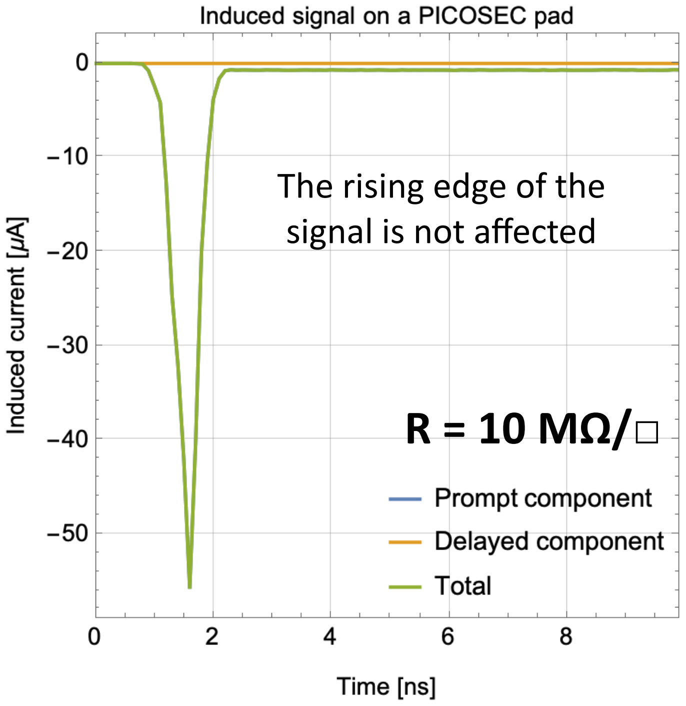
SIMULATIONS

Dependence on the rising edge of the signal

Simulated shape of the induced signal for different resistivities







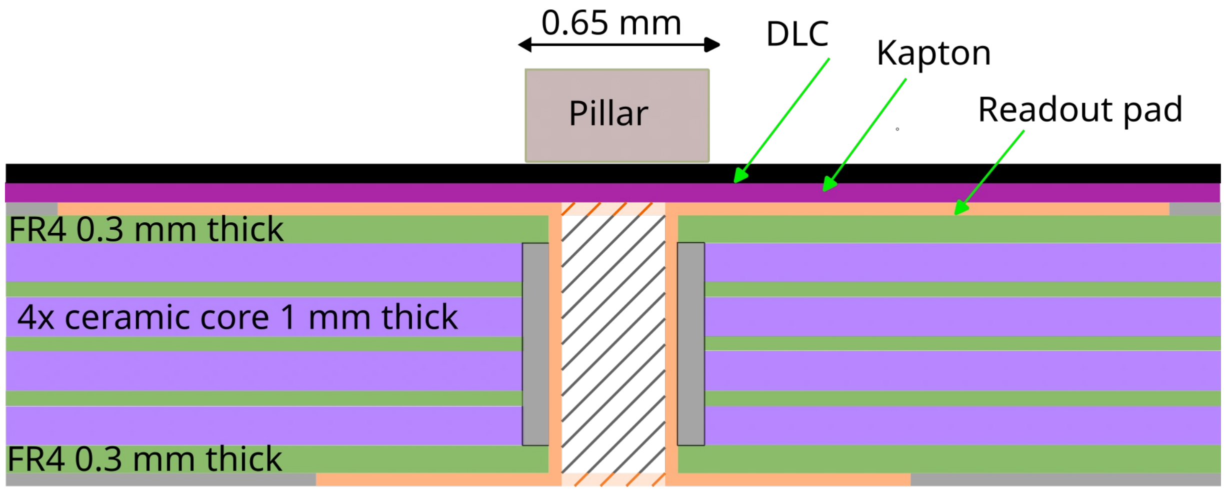
Resistivity chosen for the 10x10 cm^2 area PICOSEC MM detector: **20 MΩ/□**

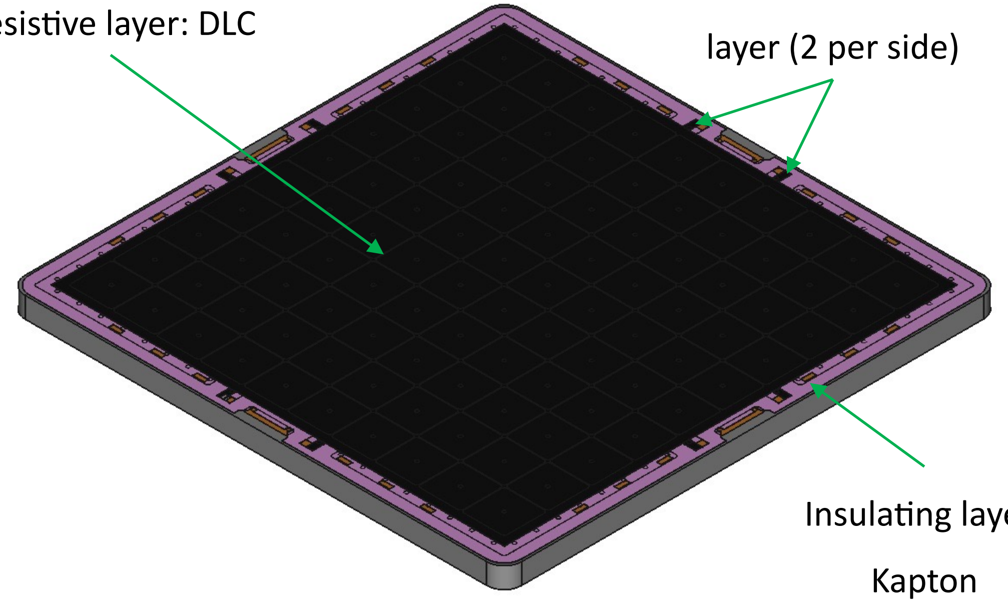
All simulations by D. Janssens

Resistive Micromegas

Simulations and production of a 100-channel resistive PICOSEC MM detector

- Simulations* of rate capability and signal rising edge dependence to select the resistivity for a PICOSEC prototype
- Production of a 100-channel detector with a 10x10 cm^2 area **resistive MM** with anode surface resistivity of **20 MΩ/□**
- Production procedure as for a non-resistive multipad** with an additional production step to add a resistive layer

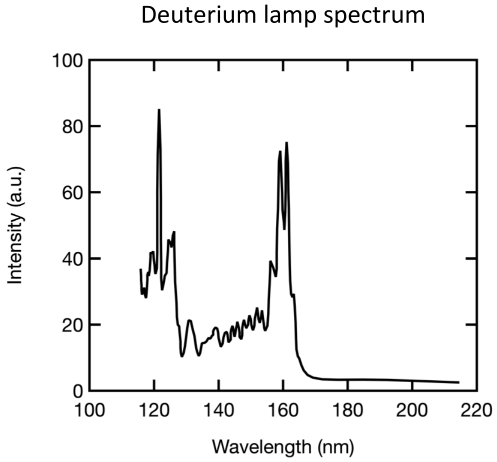


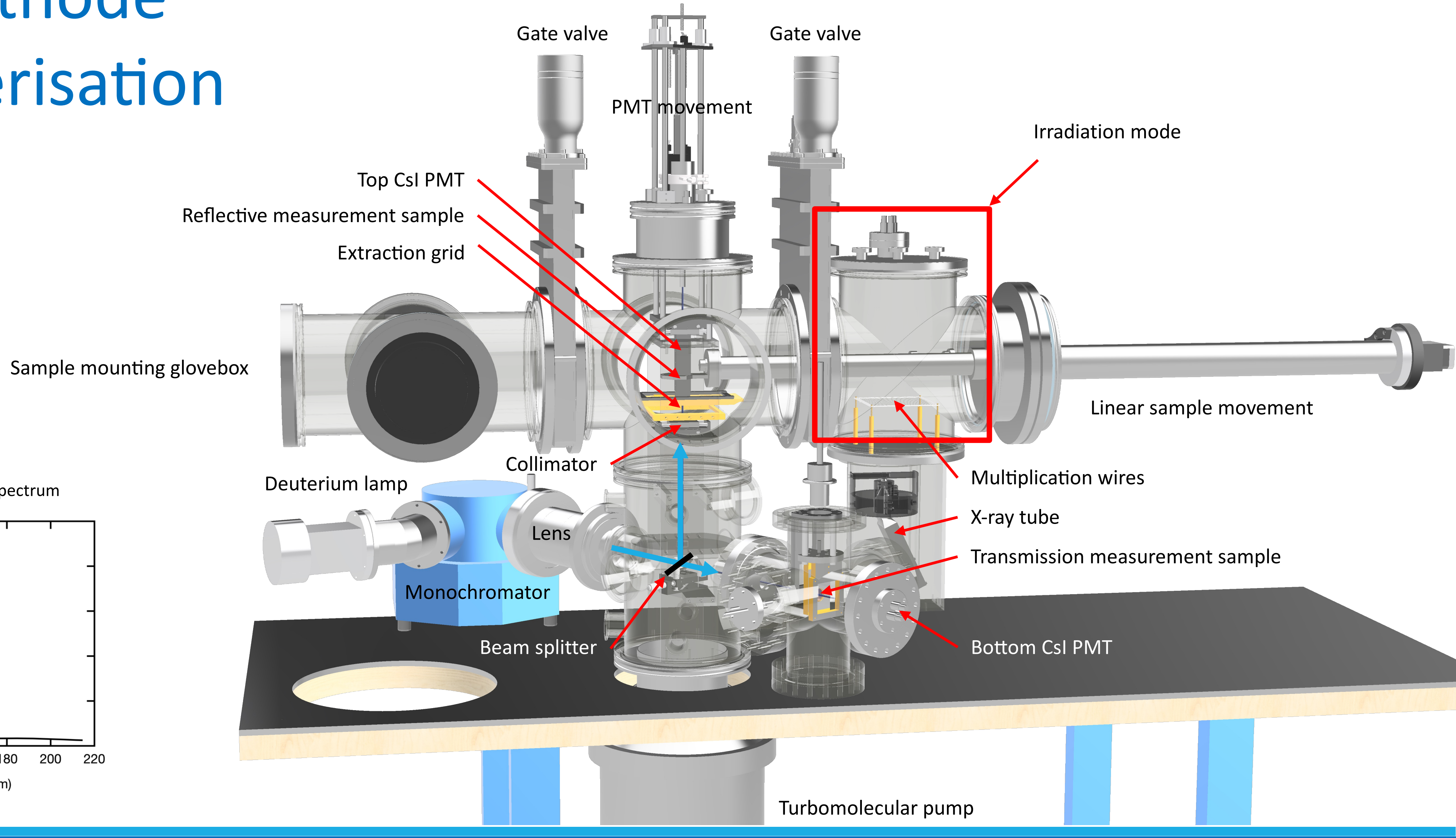


*All simulations by D. Janssens | **Details: A. Utrobičić, Multipad design and production

Photocathode characterisation

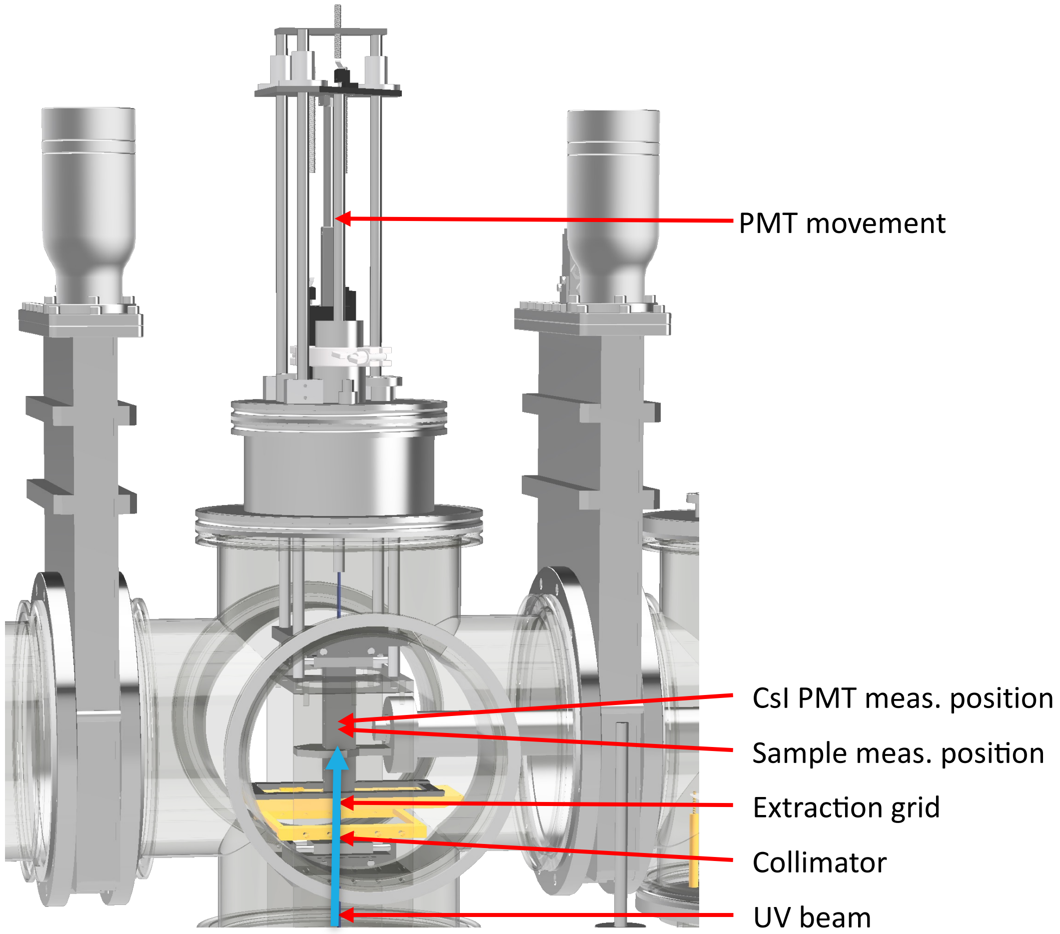
Setup overview





Photocathode characterisation

QE measurements - Reflective mode

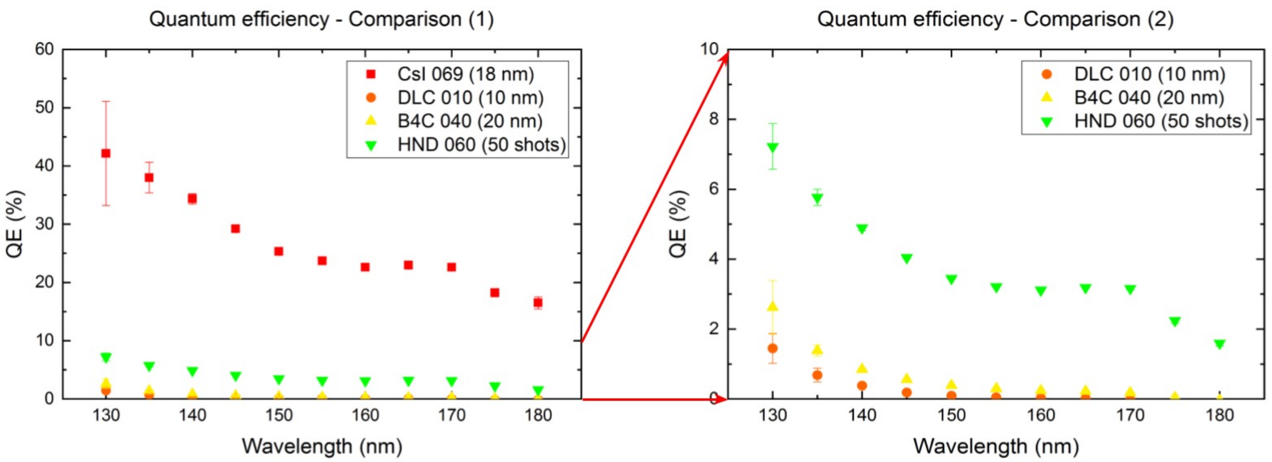


Samples: cesium iodide (CsI), diamond-like carbon (DLC), boron carbide (B_4C) and hydrogenated nanodiamonds (HND)

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

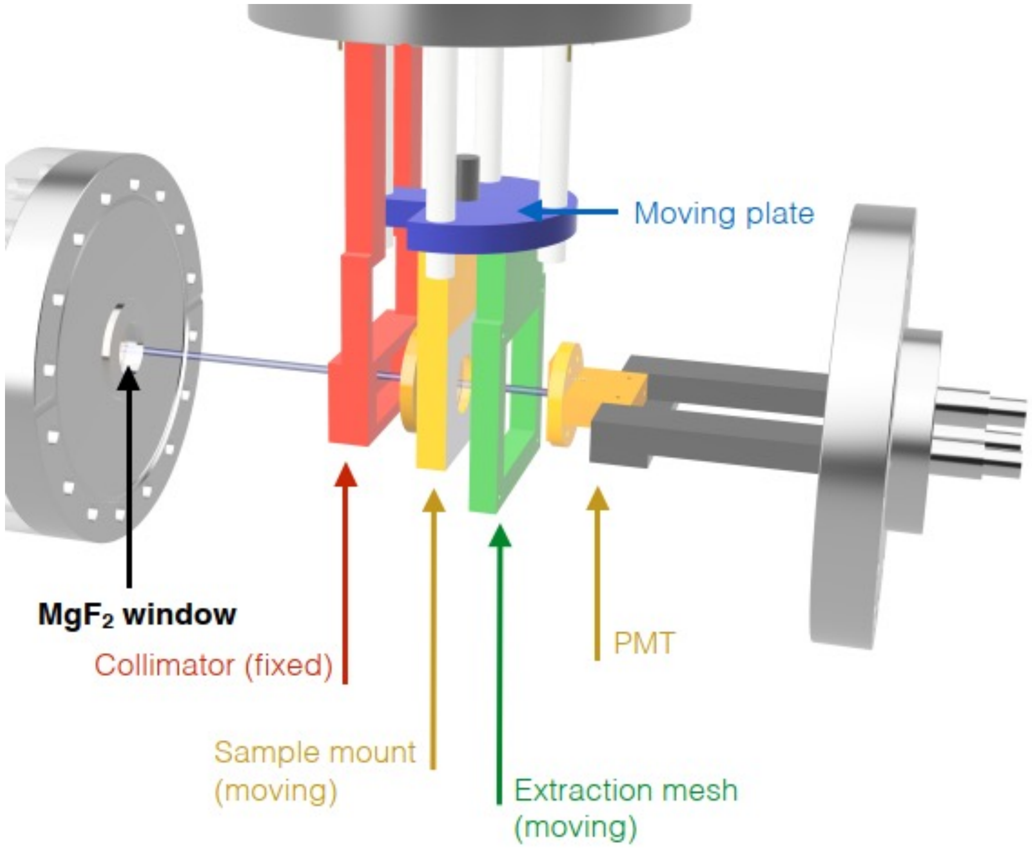
$Electrons_{sample}$ - electrons extracted from the sample

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



Photocathode characterisation

QE measurements - Transmission mode

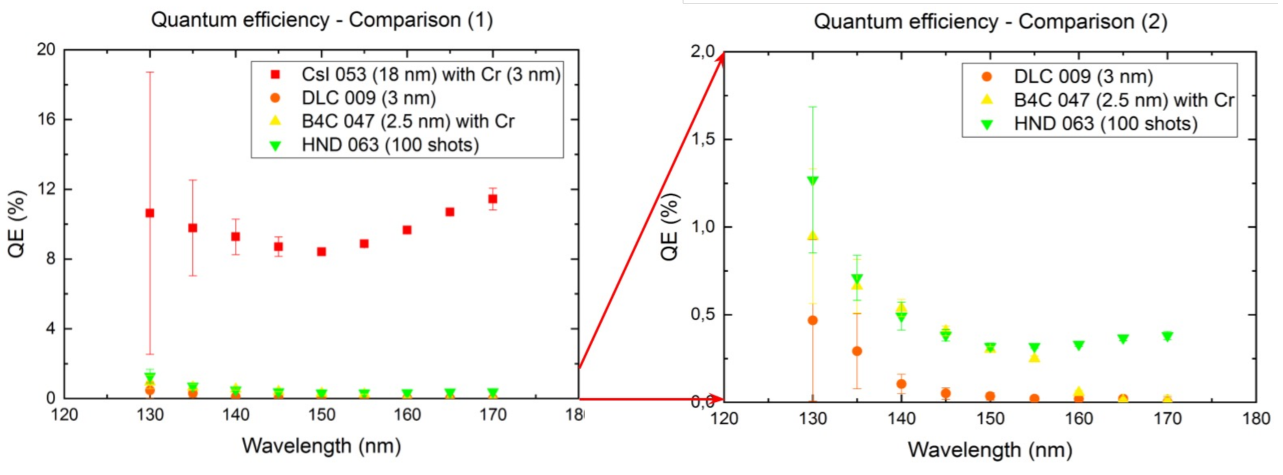


$$\text{Transparency} = \frac{\text{PMT current: sample in}}{\text{PMT current: sample out}}$$

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

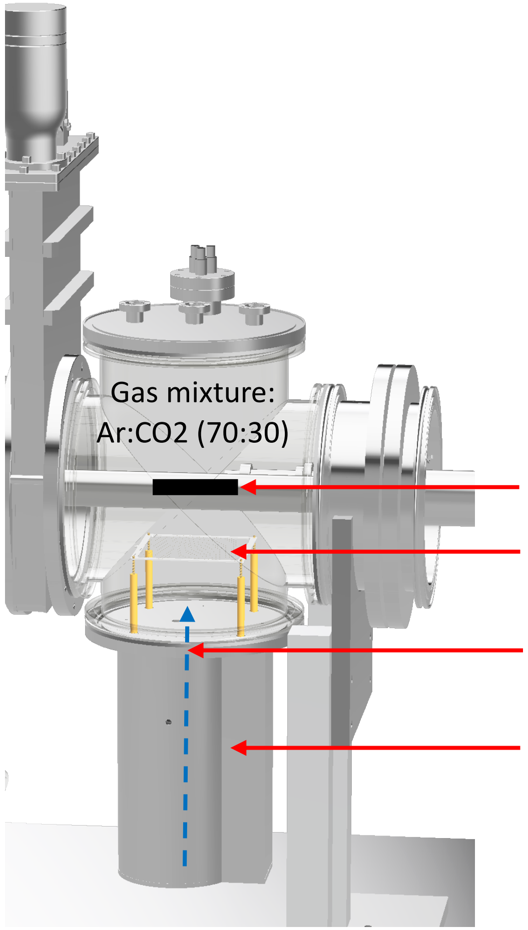
$Electrons_{sample}$ - electrons extracted from the sample

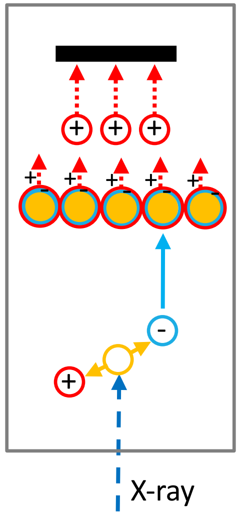
$Photons_{PMT}$ - photons that arrived to the sample



Photocathode characterisation

Ageing studies – Irradiation mode

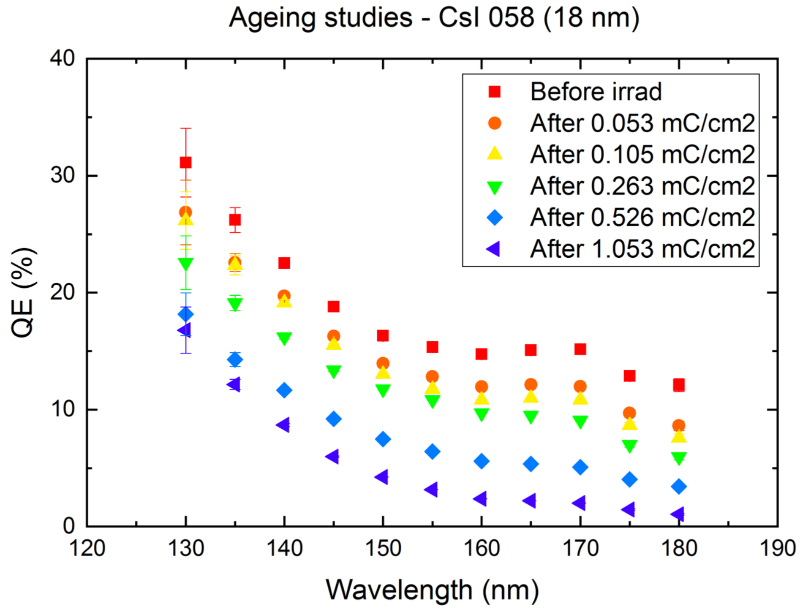


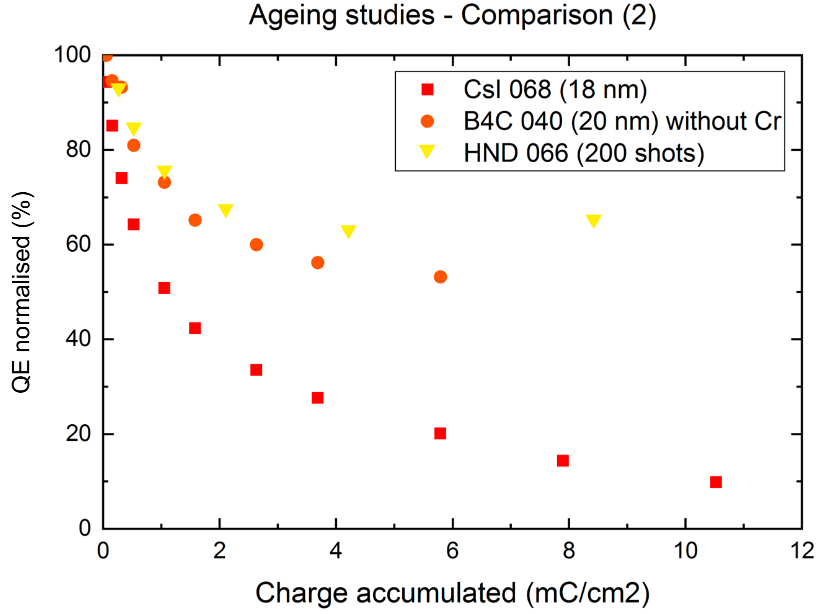


3. Irradiated sample (grounded):
Attraction of ions from avalanche
Accumulation of charge

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





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