µRWELL-PICOSEC: The Development of Fast Timing Resistive Micro-WELL Detector Technology.

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Outline

- ❖ Introduction and concept of picosecond timing Micro Pattern Gaseous Detectors (MPGDs)
- ❖ Development of µRWELL-PICOSEC detector @ JLab (LDRD FY22).
- ❖ Preliminary results: Impact µRWELL hole parameters on timing performance
- ❖ Ongoing R&D and approaches to address challenges of µRWELL-PICOSEC.

µRWELL-PICOSEC: Fast Timing µRWELL Detector

Background & Rationale:

- Develop precise and fast timing cost effective gaseous detectors for application in particle physics and medical instrumentation.
- Properties such as stability, radiation hardness, large area, segmented readout are highly desirable for such timing detectors.
- Proof of concept of precise timing detectors based on MPGDs has been established by the MM-PICOSEC collaboration with Micromegas
- Development of picosecond detector based on µRWELL technology has the potential to satisfy such requirements.

Applications in future particle physics (HEP and NP) experiments:

- Fast timing technology such as µRWELL-PICOSEC are attractive alternative PID technologies options such as Time-Of-Fight (TOF) detectors for charged particles or photosensors technologies for Cerenkov detectors.
- The technology could be deployed in future Electron Ion Collider (EIC) Detector II, ePIC upgrade or future experiments at Jefferson Lab
- Potential application in medical instrumentation such as for TOF-PET devices will be explored.

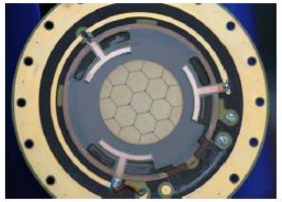
(MM-)PICOSEC Collaboration at CERN

MM-PICOSEC: Development of fast timing (picosecond resolution) MPGD using Micromegas amplification

- ❖ Large ongoing collaboration based at CERN with several major institutions from France, Greece, Poland, China … **and US (JLab)**
- ❖ Proof of principle picosecond timing with MPGD established with several MM-PICOSEC prototypes:
- ▪ Large-area (10 cm × 10 cm) and multi-channel (100 pads) prototype ➔ < 20 ps with MIPs and 70 ps with single photon (laser)
- ❖ PICOSEC-MM collaboration and RD51 collaboration ➔ strong connection (i.e., beam test campaign and GDD lab at CERN)
- ▪ Strong synergy between MM-PICOSEC & μRWELL-PICOSEC ➔ leverage on expertise & experience of MM-PICOSEC community

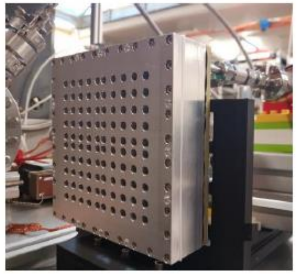
- 1-ch (ϕ1cm)
- Proof of concept
- Resistive and non-resistive prototypes.

- 7-ch (1cm)
- Signal sharing
- Resistive prototype



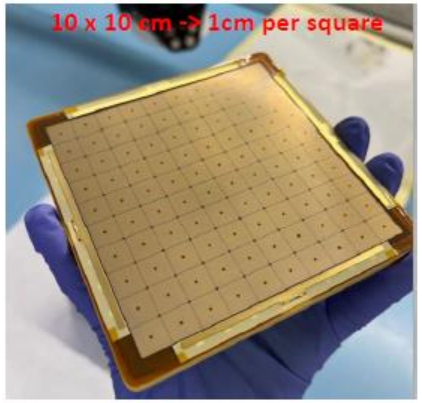
- 19-ch (ϕ3.6cm)
- Signal sharing.

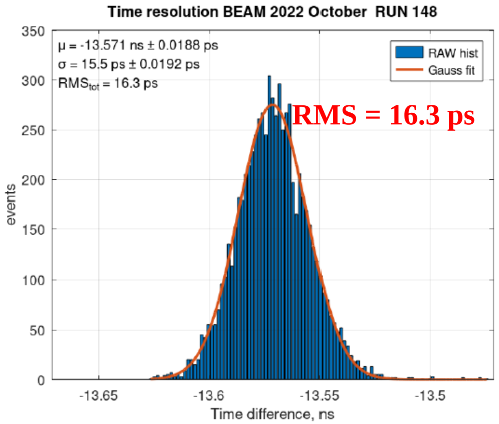
- 100-ch (10 cm x10 cm)
- Tileable
- Hybrid ceramic substrate MM
- MM decoupled from housing with spring-loaded pins



- 100 ch (10 cm x10 cm)
- MgF2 mechanically decoupled

- 100 ch (10 cm x10 cm)
- Sealed Ti housing
- Increased fill factor



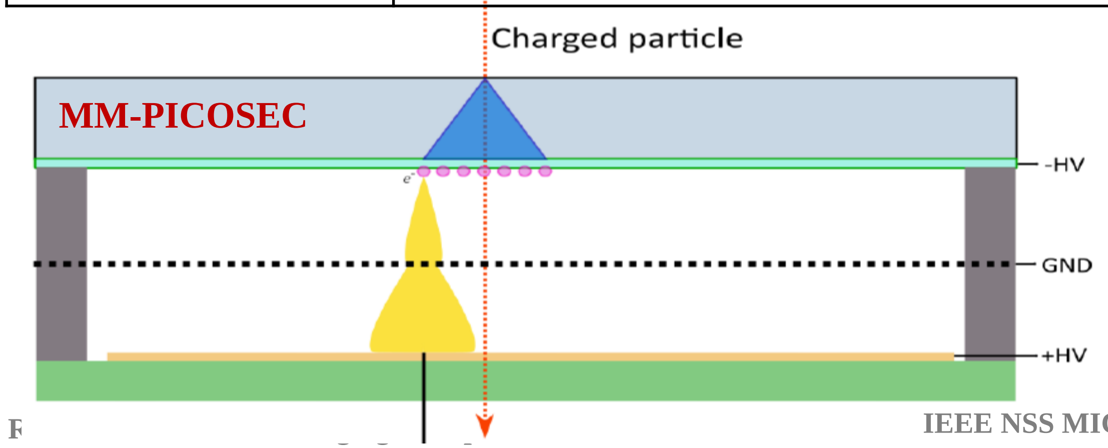


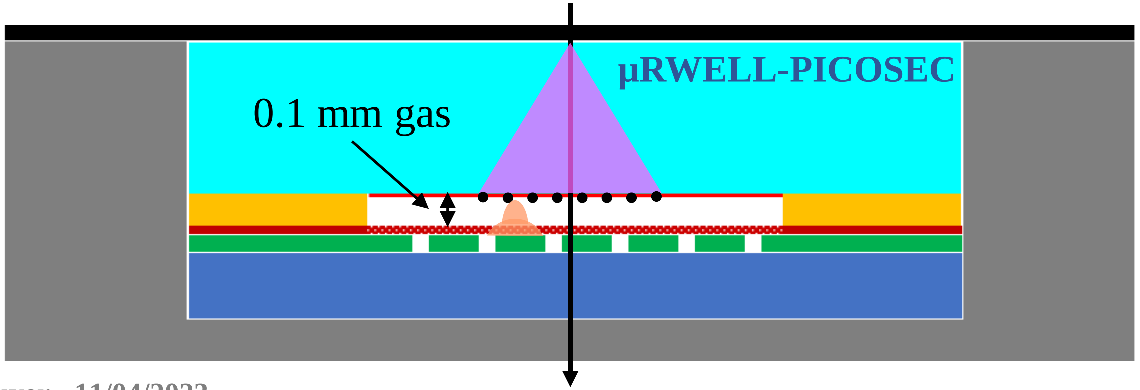
- Aune *et al.*, Nuclear Inst. and Methods in Physics Research, A 993 (2021) 165076, https://doi.org/10.1016/j.nima.2021.165076
- Bortfeldt *et al.*, Nuclear Inst. and Methods in Physics Research, A 903 (2018) 317–325, https://doi.org/10.1016/j.nima.2018.04.033
- A. Utrobicic *et al.*, 2023 JINST 18 C07012, https://doi.org/10.1088/1748-0221/18/07/C07012

µRWELL-PICOSEC or MM-PICOSEC

- µRWELL-PICOSEC and MM-PICOSEC belongs to the MPGD-based fast timing detector family
- Different amplification structure will allow different optimization of the technologies in term of operation stability and timing performance
- Parallel development of will mutually benefit the two technologies and offer options for applications

	MM-PICOSEC	**µRWELL-PICOSEC**	**Comments**
Radiator / photocathode	Both technologies share the same devices	Both technologies share the same devices	common R&D
Readout structure	Both technologies share the same devices	Both technologies share the same devices	common R&D
Amplification structure	mesh ➔ 128 µm gap ✓	Cu-clad Kapton foil ➔ 50 µm gap	large capacitance hurts µRWELL
Resistive vs. metallic	Both options available ✓	Only resistive ✓	Resistive ➔ HV stability
Segmentation MPGD	Segmentation of the mesh will be challenging	µRWELL Cu-electrode can be segmented ✓	Improve rate capabilities for resistive
Mechanical structure	Mesh gap uniformity ➔ challenging for large area	Gap uniformity ➔ no pillar, no stretching ✓	

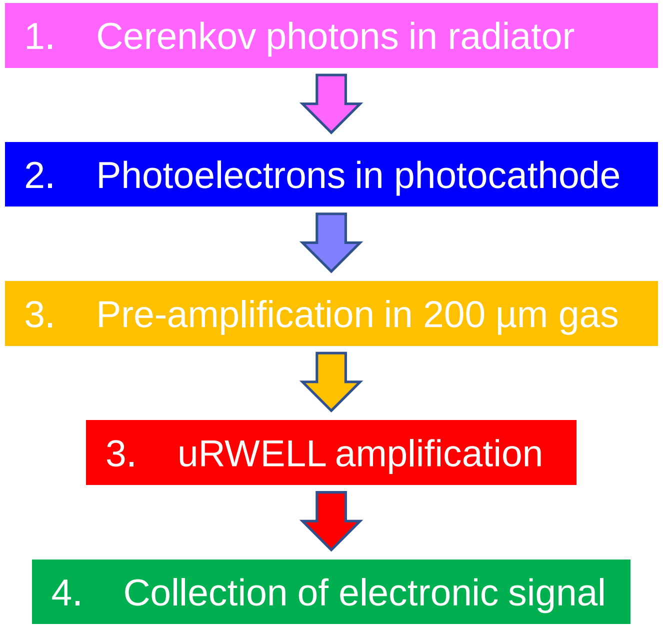


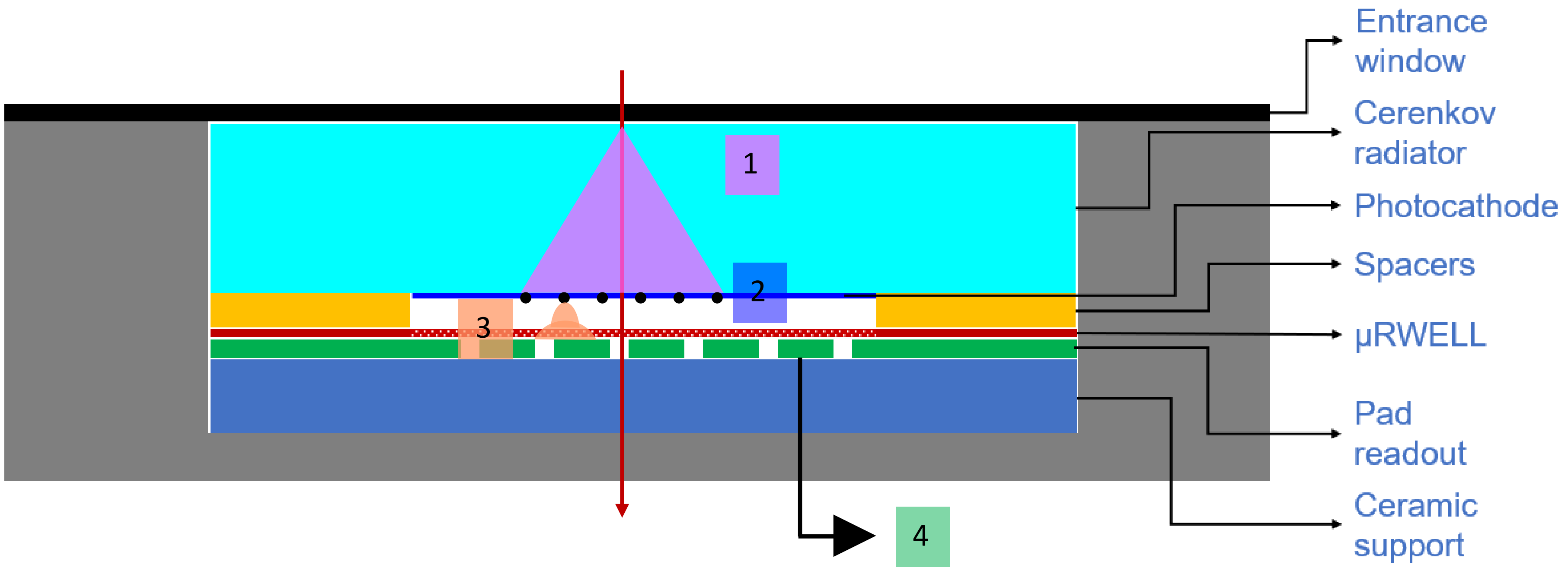


μRWELL-PICOSEC: Detector concept

Concept of μRWELL-PICOSEC: Develop fast timing gaseous detector using μRWELL amplification ➔ timing resolution of tens of ps

1. Cherenkov photons: relativistic charged particle creates Cerenkov photons ➔ prompt photons i.e., timing resolution.
2. Photoelectrons: convert the Cerenkov photons into electrons, all electrons created at the same z position ➔ timing resolution
3. Pre-amplification: First amplification of electrons 100 to 200 μm gas in high drift field region (~20 kV/cm)
4. Amplification : Final electron amplification in μRWELL gain structure ➔ high electric field (>40 kV/cm)
5. Electronic Signal: Arrival of the amplified electrons to the anode creates a signal.





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µRWELL-PICOSEC: Amplification structure

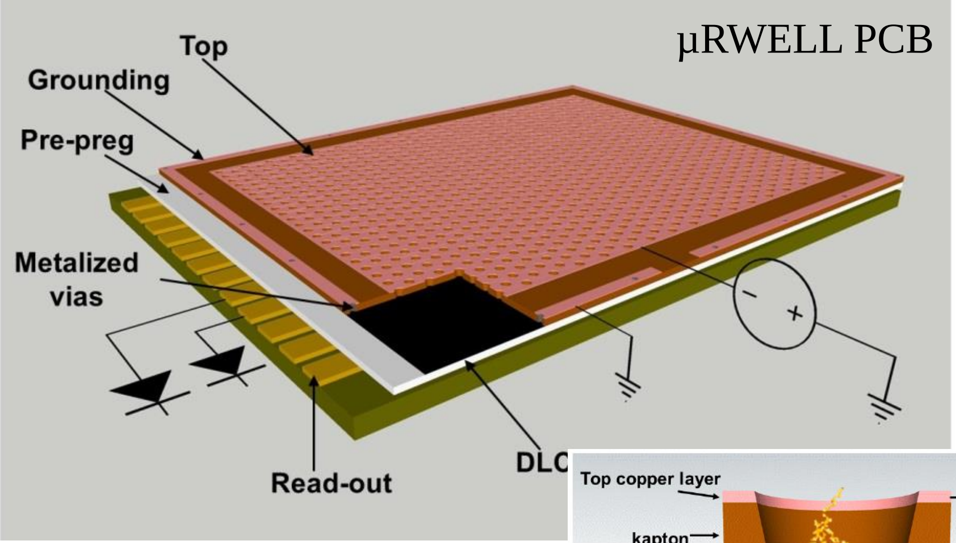
Design of µRWELL foil

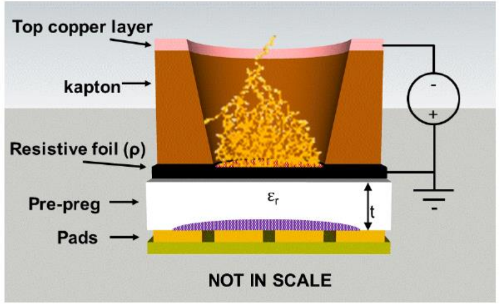
- ❖ Single layer amplification MPGD
  - Simple amplification structure using same material as GEM foil
  - Resistive technology ➔ intrinsically robust against spark
  - Large area capability
- ❖ Specially well suited for PICOSEC technology
  - µRWELL is a resistive MPGD ➔ improve detector stability
  - Segmented µRWELL (PEP) ➔ improve rate capability & timing

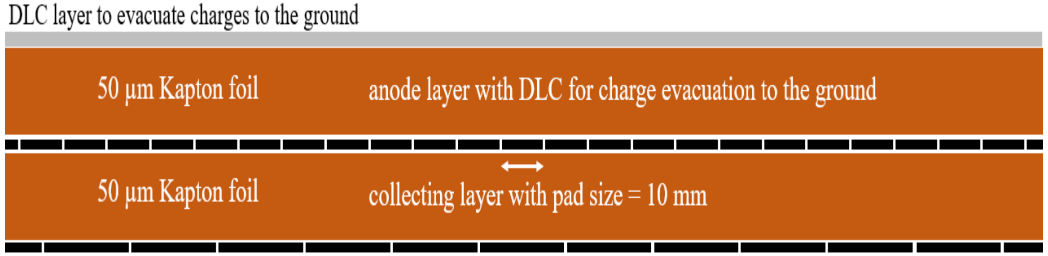
Integration of capacitive-sharing readout structures

- ❖ Capacitive-sharing pad readout will allow precise position information capability with limited readout channel number
- ❖ Combining segmented µRWELL and capacitive-sharing ➔ best of both world
  - Segmented µRWELL: excellent timing resolution
  - Capacitive-sharing readout: excellent position resolution

G. Bencivenni et al 2015 JINST 10 P02008







Concept capacitive-sharing pad readout

K. Gnanvo et al., NIM A, 1047 (2023) 167782

μRWELL-PICOSEC: Radiators and photocathodes

Photocathode:

Current technology: Cesium Iodide (CsI)

Pros:

- High quantum efficiency (QE) in vacuum ultraviolet (VUV) region which is most radiated by any radiator medium

Cons:

- Sensitivity to water ➔ performance rapidly deteriorates
- Ion bombardment (IBF) of CsI is challenging for high rate

We will investigate materials with similar level of QE:

Candidates are B4C, DLC and Nano diamond (ND)

- Goal is to achieve similar level of QE ➔ Extensive R&D
- Radiation hardness and unsensitivity to humid condition

Radiator:

Current technology: Magnesium Fluoride (MgF2)

Pros:

- Transparency in vacuum ultraviolet (VUV) region which is most radiated by any radiator medium

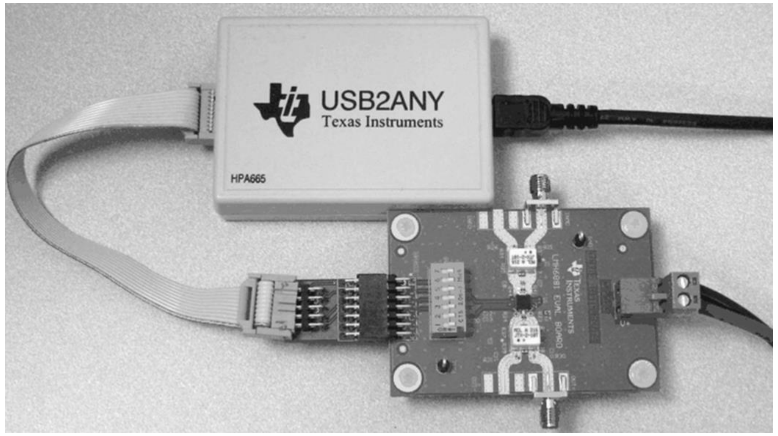
Cons:

- Low photon yield
- large Cerenkov angle sin (Θ_c) ➔ poor spatial information
- Smaller Θ_c material will results in even lower photon yield

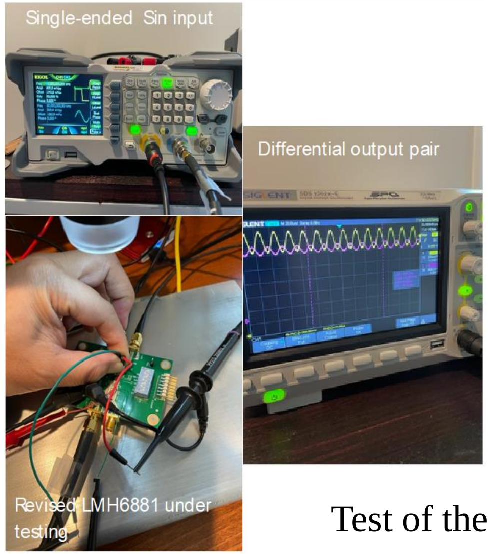
We will investigate radiator materials for higher photon yield capability

µRWELL-PICOSEC: Multi-channel readout and DAQ

Multi-channel Readout



LMH6881: Programmable differential amplifiers



Test of the LMH6881 evaluation board

Fast digitizer

CAEN FERS-5203: 64-ch Pico-TDC

- ❖ Provide 64 TDC channels :
- ❖ ~7 ps RMS timing resolution
- ❖ LVDS input differential signals
- ❖ 3.5 Gbits/s Optical ethernet bus

Lab test of single channel prototypes

Rohde & Schwarz, RTP164B:

- ❖ High performance oscilloscope:
- ❖ 2 × 16 GHz bandwidth channels for sub-ps resolution
- ❖ 40 GSamples/s & 16 bits measurement precision

Alternative options

- ❖ Multi channel digitizer SAMPIC (D. Breton, CEA Saclay)
- ❖ Multi-channel custom-made pre-amplifier (M. Kovacic, U. of Zagreb)

µRWELL-PICOSEC: Single-channel prototypes

Single-channel µRWELL-PICOSEC prototype

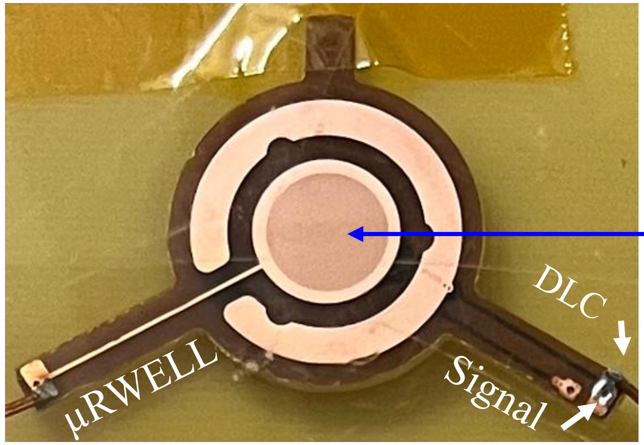
1 cm diameter active area / pad)

Two batches were produced for performance optimization

- Batch I: Standard µRWELL (pitch 140 um, holes diameters 70/50
- Batch II: Samples with different hole size, pitch, Kapton thickness

Tested in beam: RD51-PICOSEC July & August 2023 campaigns

- HV scan for optimal timing
- Test with different photocathodes (DLC and CsI)
- Different pre-amplification gaps (167 µm & 117 µm



µRWELL-PICOSEC prototype

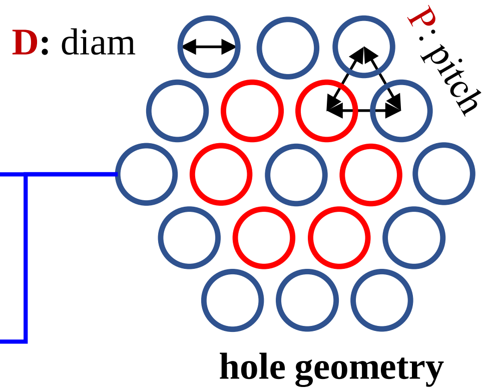
Nomenclature of the prototypes:

T150-P140-D70

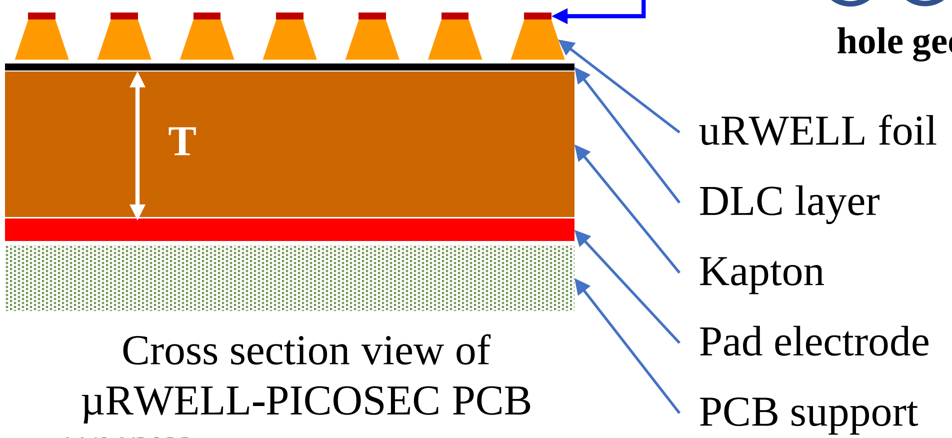
T = 150 µm ➔ Kapton thickness

P = 140 µm ➔ Hole pitch

D = 70 µm ➔ Hole Outer Diam.



batch	Prototype	T (µm)	P (µm)	D (µm)	d (µm)
I	T50-P140-D70	50	140	70	50
II	T150-P140-D70	150	140	70	50
II	T150-P140-D85	150	140	85	65
II	T150-P140-D70	150	120	70	50
II	T150-P140-D85	150	120	85	65



Cross section view of
µRWELL-PICOSEC PCB

µRWELL-PICOSEC: Single-channel prototypes

First µRWELL-PICOSEC prototype

Single-pad small prototype

- 1 cm diameter active area
- 3 mm thick radiator + CsI photocathode
- Sensor: 50 µm µRWELL on 50 µm Kapton
- Holes parameters: 140 µm / 70 µm / 50 µm

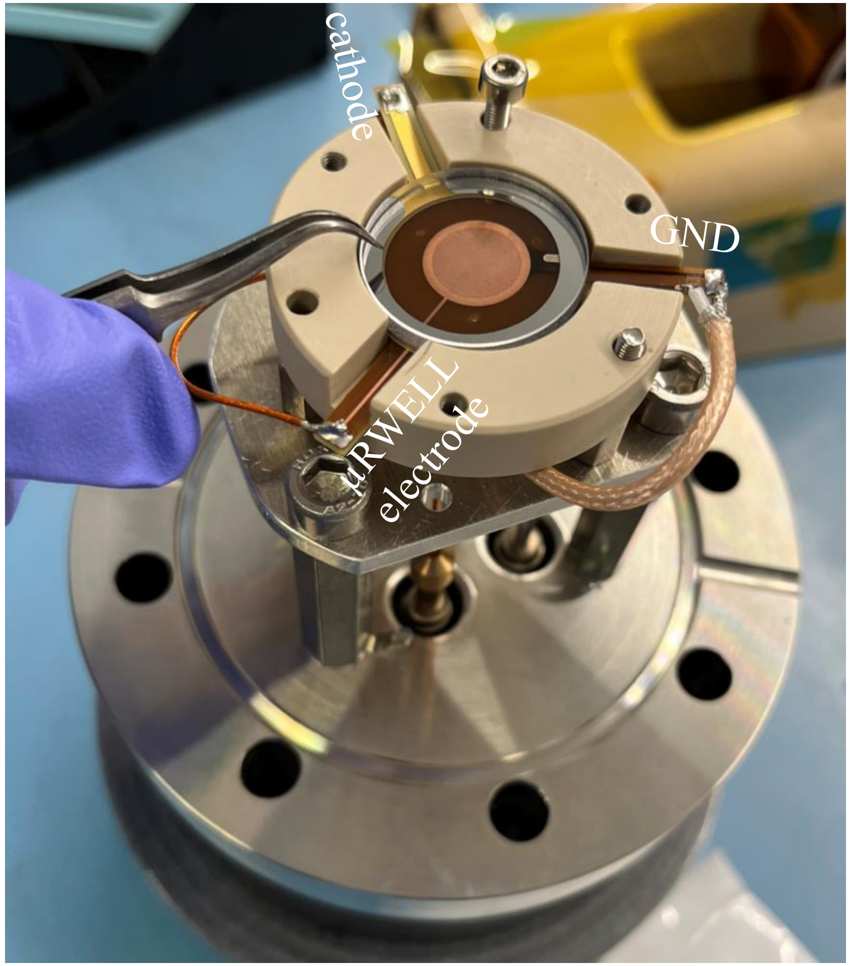
First tests with LED source (GDD lab, 12/2022)

- Poor timing compared to MM-PICOSEC
- Prototype very resilient against sparks

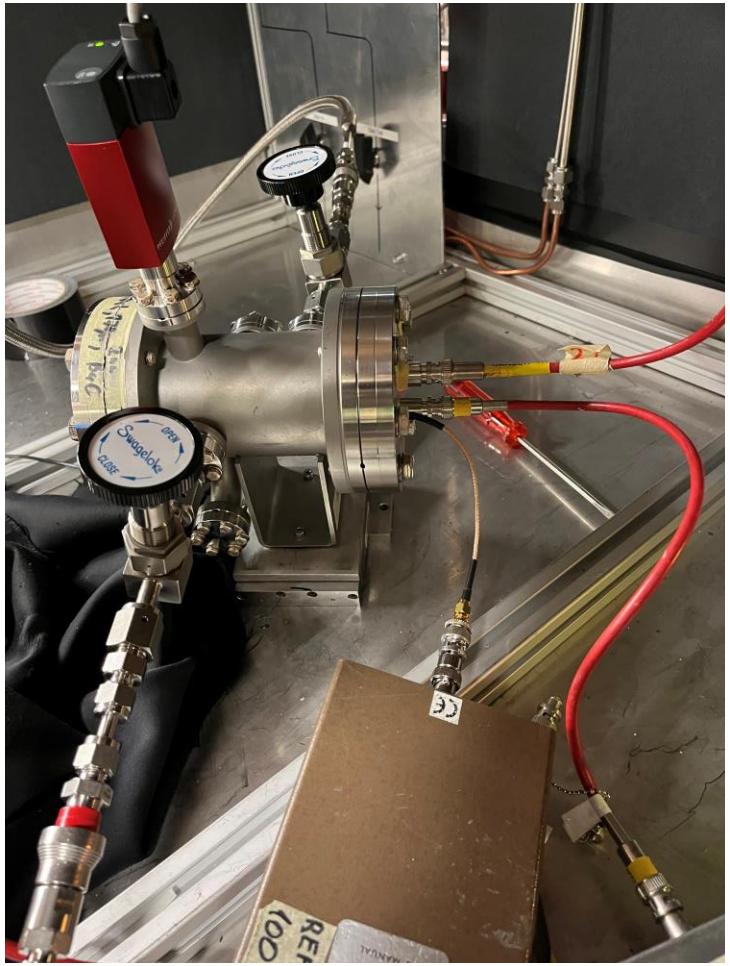
Lessons learned from preliminary tests

- Several parameters to be tweaked to improve resolution
- µRWELL hole parameters to be optimized
- Minimizing capacitance noise ➔ increase the gap between µRWELL device and pad layer
- Reduce or eliminate all external source of capacitance noise ➔ wire connection …

Single-pad µRWELL-PICOSEC prototype

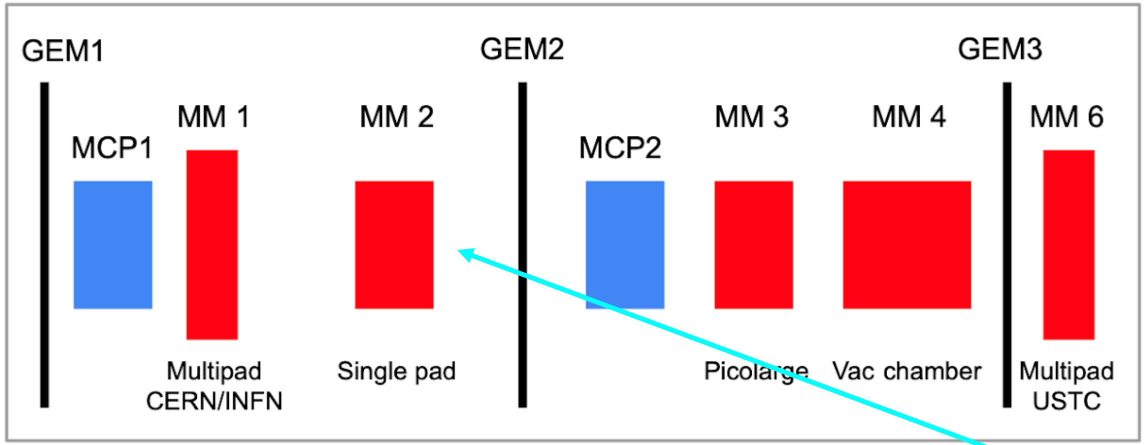


Prototype on test bench at CERN GDD Lab



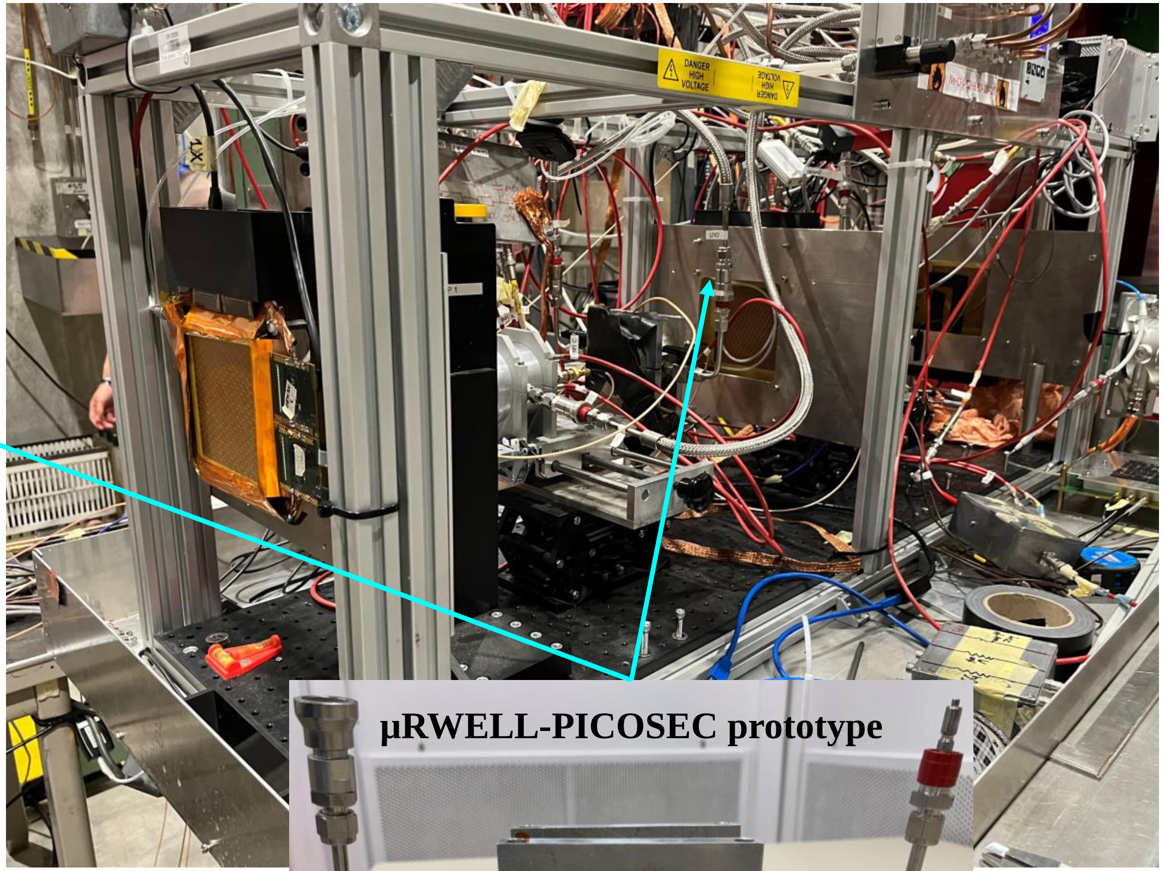
µRWELL-PICOSEC: CERN Test Beam (July & August 2023)

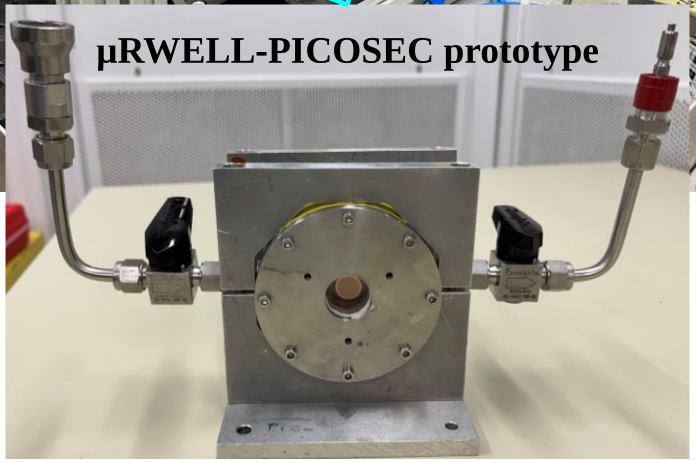
Beam



Picosec tracker

MM-PICOSEC Coll. Test beam setup @ CERN (July 2023)





- ❖ Participate in the PICOSEC Coll. 2 test beam campaigns @ CERN in July 2023 & Aug. –Sept. 2023
- ❖ Several single-channel µRWELL-PICOSEC prototypes with different parameters were tested
- ❖ HV scan on both the cathode (pre-amplification) and anode (µRWELL amplification)

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μRWELL-PICOSEC: Hole diameter comparison (07/2023)

July test beam (07/28): DLC photocathode

- ❖ Single-pad prototype Alu vessel housing with long wires connection to prototype ground ➔ degrades timing
- ❖ 4 prototypes with different μRWELL holes parameters
  - ▪ 2 × 140 μm pitch & outer / Inner diam 70 / 50 μm
  - ▪ 2 × 120 μm pitch & outer / Inner diam 85 / 65 μm
- ❖ Larger holes for same pitch ➔ better timing

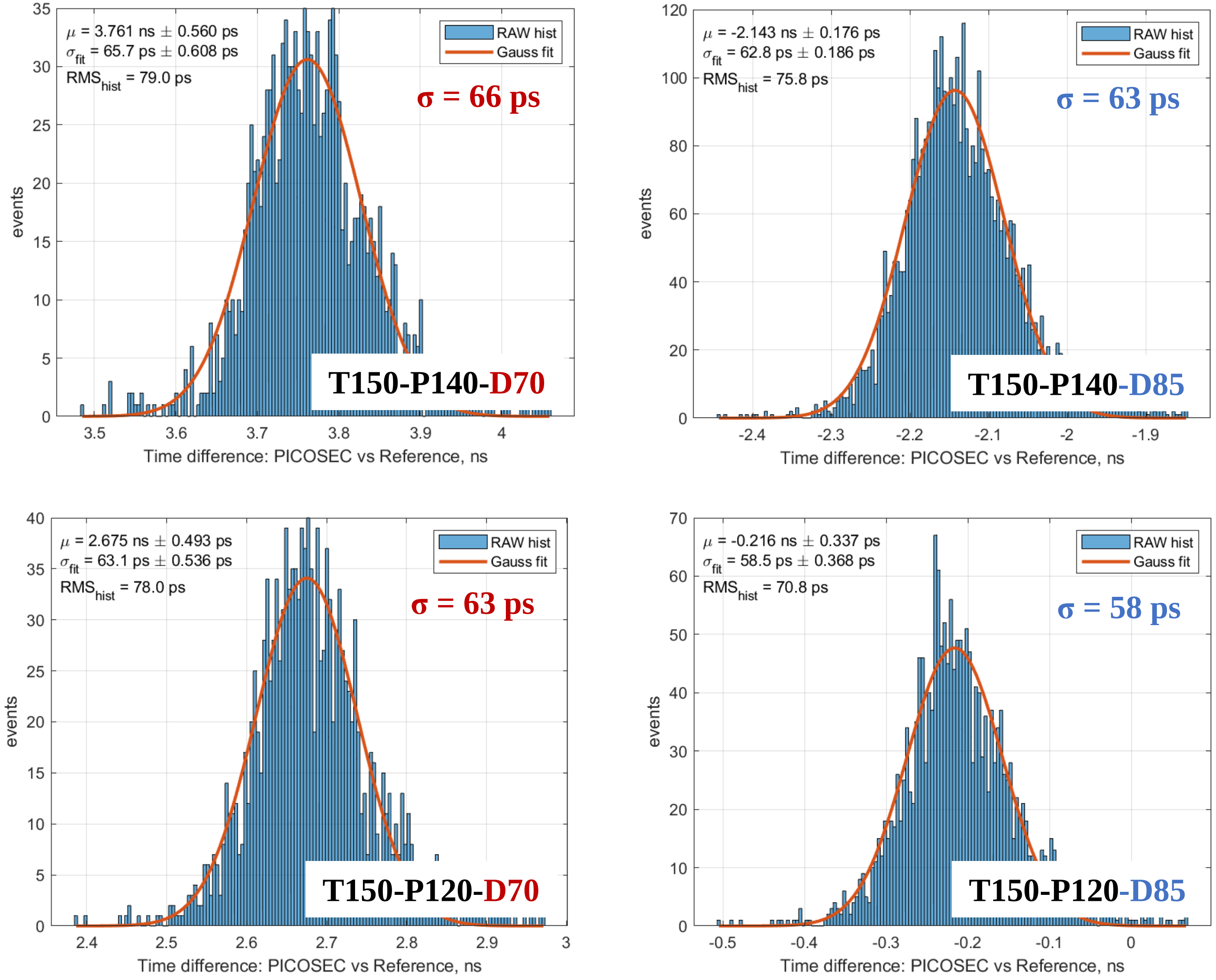
Hypothesis:

- ▪ Straighter field lines in pre-amplification gap to holes = shorter, uniform electron drift time
- ▪ Smaller Cu-to-hole area ratio ➔ smaller input capacitance seen by FE pre-amplifier

- ❖ smaller pitch ➔ better timing

Hypothesis: Same reason as above

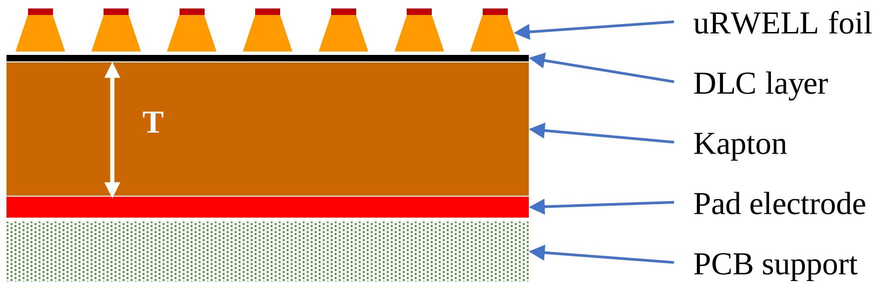
- ▪ More in next slides



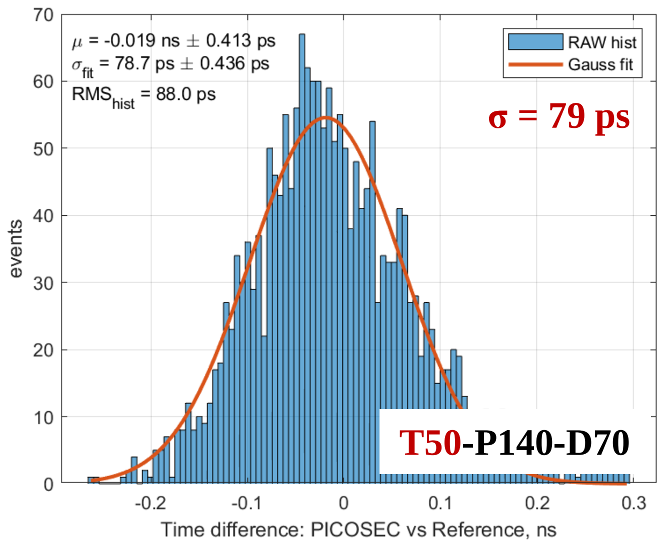
µRWELL-PICOSEC: Kapton thickness comparison (08/2023)

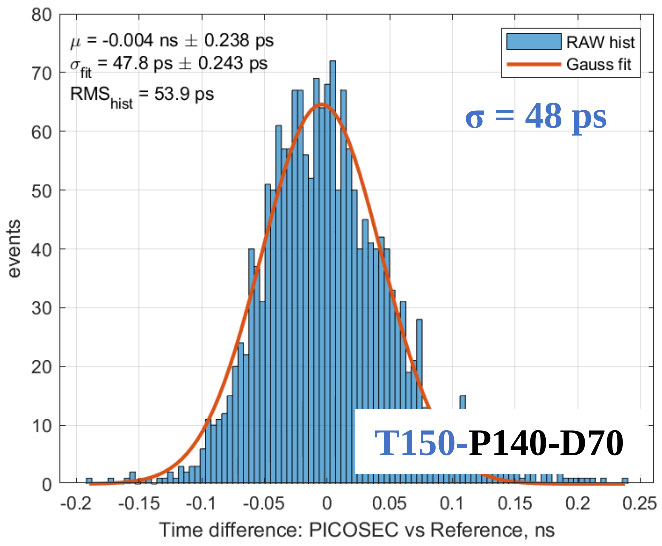
August test beam (08/28):

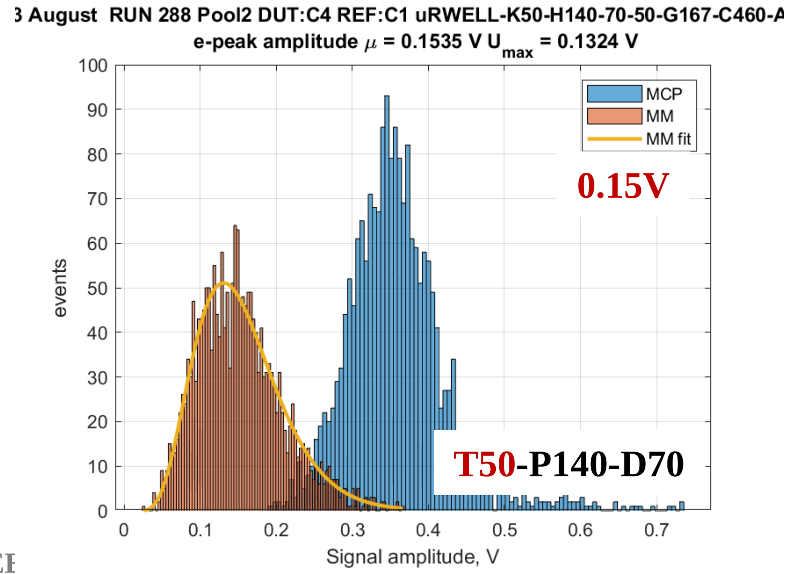
- ❖ With CsI photocathode.
- ❖ 2 prototypes with different µRWELL holes parameters
  - Kapton thickness 50 µm - P/OD/ID: 140/70/50
  - Kapton thickness 150 µm - P/OD/ID: 140/70/50
- ❖ Thicker Kapton ➔ better timing
- Smaller capacitance between the pad and the µRWELL layer

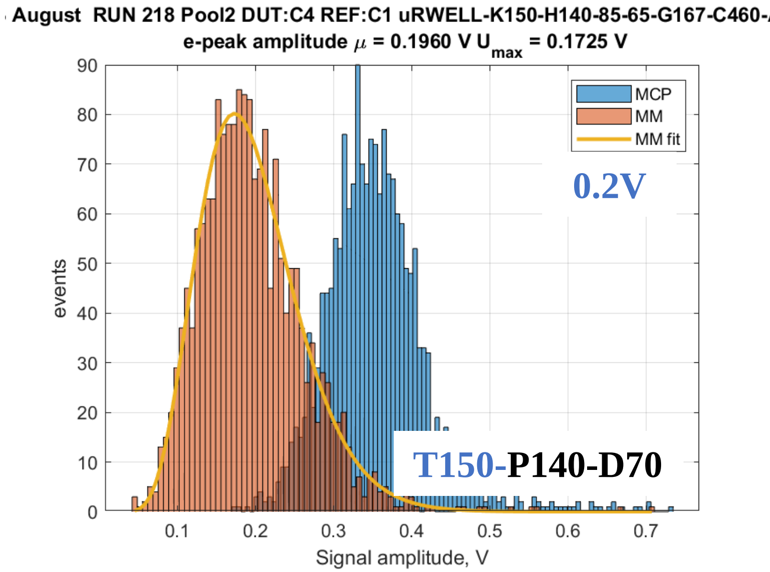


Cross section view of µRWELL-PICOSEC PCB









μRWELL-PICOSEC: Hole pitch comparison (08/2023)

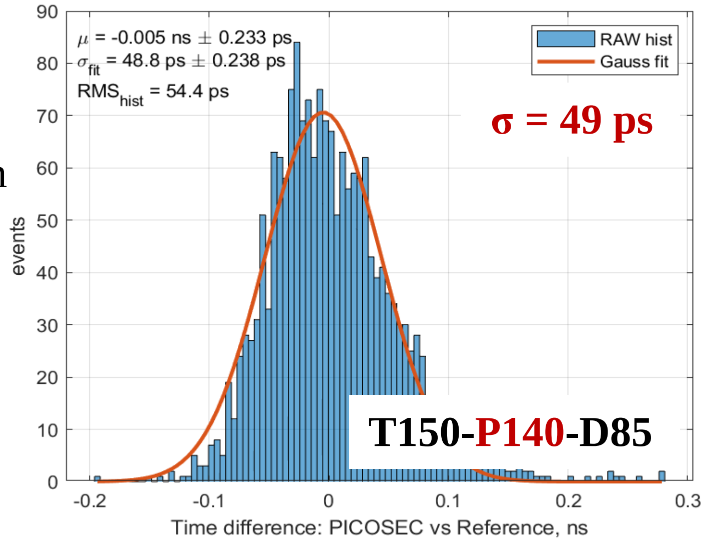
August test beam (08/28): CsI photocathode

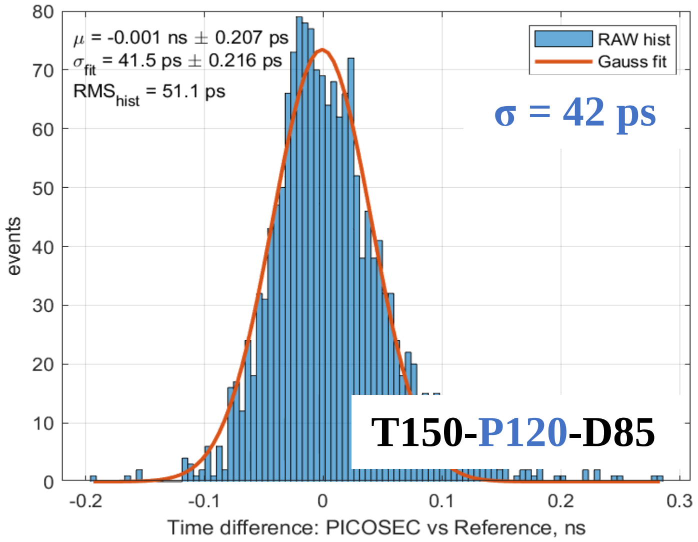
- 2 prototypes with different μRWELL holes parameters
  - 140 μm & 120 μm pitch, outer / Inner diam 85 / 65 μm
- smaller pitch ➔ better timing

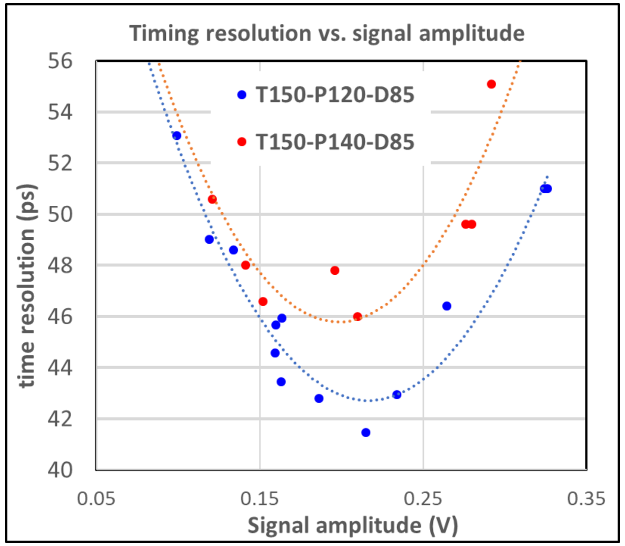
Hypothesis:

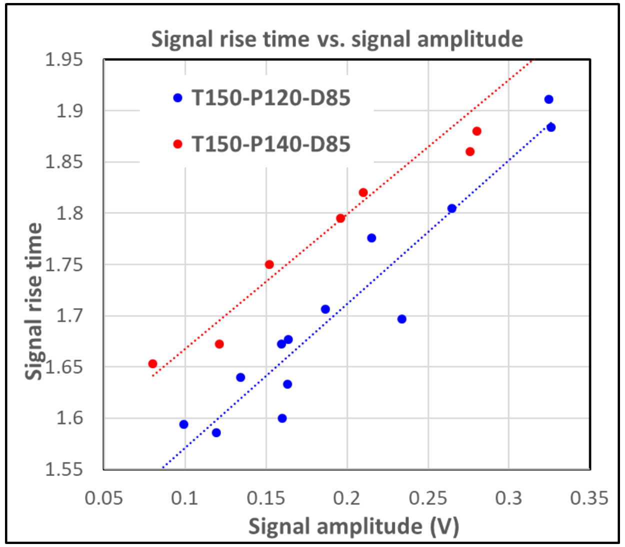
- Straighter field lines in pre-amplification gap
- Smaller Cu-to-hole ratio ➔ smaller input capacitance

- HV scan runs: Combination of μRWELL HV scan (amplification) and cathode HV scan (pre-amplification)
  - Signal amplitude of μRWELL-PICOSEC pad as variable
  - Timing has a minimum (optimal) at ~ 0.2 - 0.25 V ➔ explanation under investigation
  - Signal rise time: defined as the width of the distribution of the signal arrival time (SAT) w.r.t. MCP timing (ref) ➔ proportional to signal amplitude









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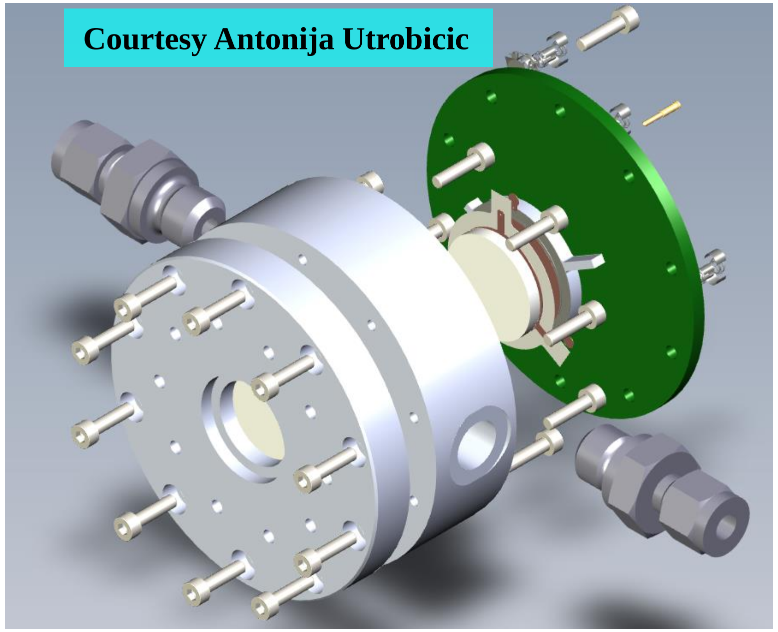
µRWELL-PICOSEC: Next steps ➔ Plans for 2024 test beam

Jefferson Lab

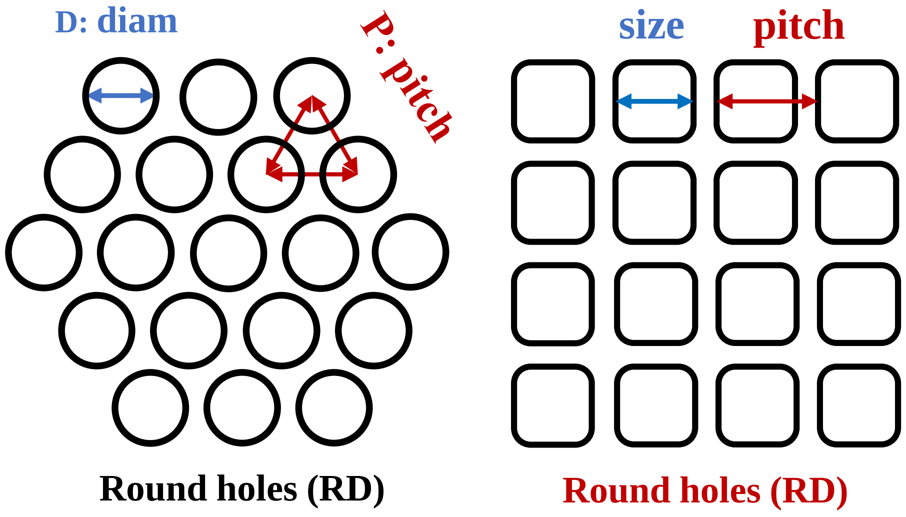
Vancouver 2023 IEEE NSS MIC RTSD

New housing for single-channel prototypes



- ❖ Minimize external source of noise (i.e grounding, cables pick-up antenna …)
- ❖ Makes it easier to quickly exchange prototypes (replacement of µRWELL-PCBs, photocathodes) during beam test

New holes geometries for µRWELL amplification

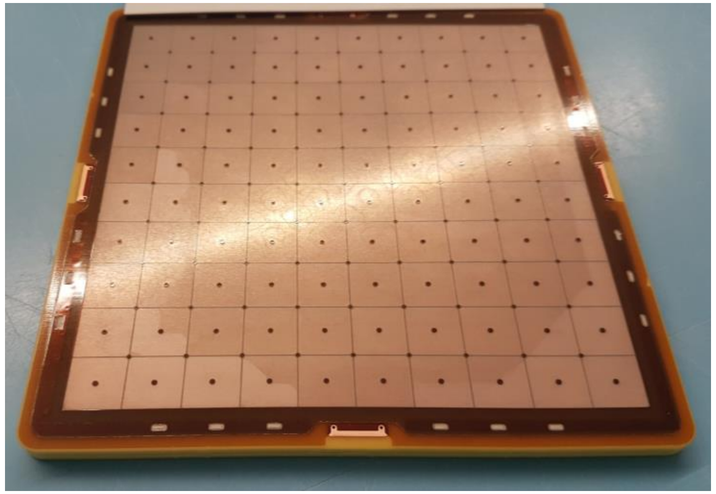


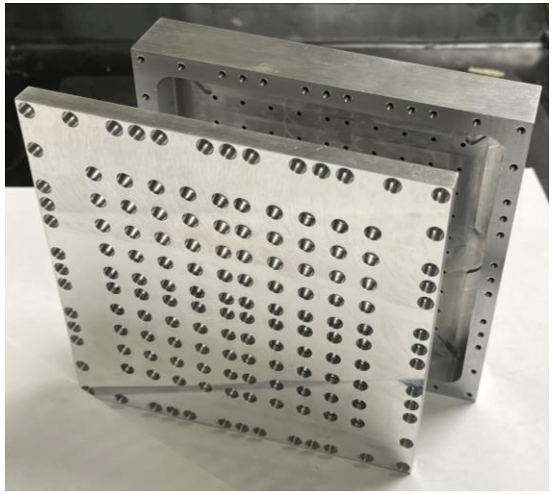
- ❖ Minimize external source of noise (i.e grounding, cables pick-up antenna …)
- ❖ Makes it easier to quickly exchange prototypes (replacement of

Prototype	Shape	P	D	d
SQ-T150-P120-D100	square	120	100	80
RD-T150-P120-D100	round	120	100	80
RD-T150-P100-D80	round	100	80	60
RD-T150-P80-D60	round	80	60	40

µRWELL-PICOSEC: Next steps ➔ Plans for 2024 test beam

Large 100-pad prototypes (Micromegas & µRWELL)



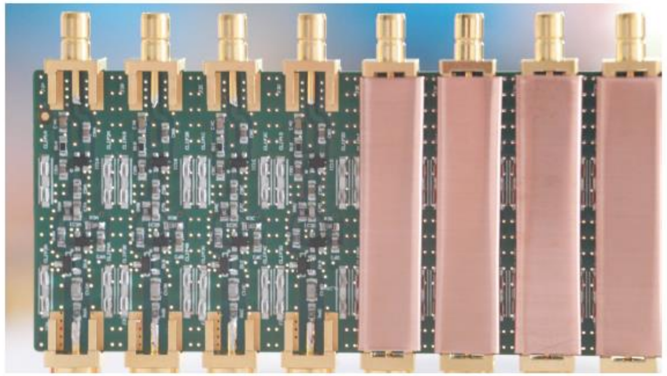


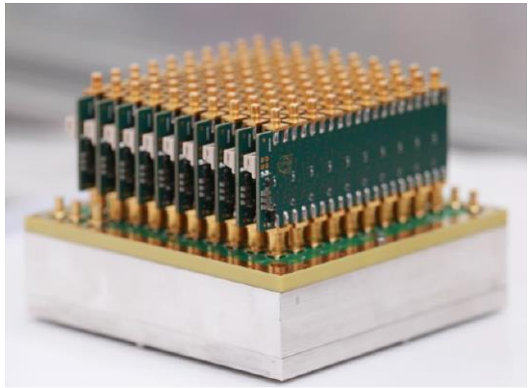
- 100-pad µRWELL-PICOSEC & MM-PICOSEC prototypes
- Parameters based on single-channel prototypes studies
- Mechanical housing fabricated in the JLab machine shop
- Same housing for MM-PICOSEC & µRWELL-PICOSEC
- Multi-channel readout PCB interface board under development
- MM-PICOSEC used as reference detector
- Large prototypes will be tested in beam at CERN in FY24

Multi channel digitizer SAMPIC (D. Breton, CEA Saclay)

https://indico.cern.ch/event/396441/contributions/1836629/attachments/794757/1089389/02_SAMPIC_Prague.pdf

Multi-channel custom-made pre-amplifier (M. Kovacic, U. of Zagreb)





Summary

- Fast timing MPGD detector with picosecond level timing resolution is a very promising and fast emerging field pioneered by the development of Micromegas-based MM-PICOSEC detector by the PICOSEC collaboration at CERN
- Fast timing MPGD can be option of choice for large area cost effective for Time of Flight (TOF) detector in HEP and NP field as well as in the field of medical instrumentation
- The resistive micro-Well µRWELL detector is an alternative technology ideally suited for PICOSEC technology and share synergy with the MM-PICOSEC
- Single-channel (1-cm diam.) µRWELL-PICOSEC prototypes have been developed and tested during two CERN RD51-PICOSEC test beam campaigns in summer 2023
- Preliminary from the prototypes show promising results with < 42 ps time resolution achieved with MIPs and with CsI photocathode and suggest that with a careful optimization of the µRWELL geometry, one can reach a timing resolution in the order of 20 ps.
- Large-area (10 cm × 10 cm) µRWELL-PICOSEC prototype with 100-pads readout and optimized µRWELL holes pattern is under fabrication for study in beam in 2024.

The research described in these slides was conducted under the Laboratory Directed Research and Development (LDRD) Program at Thomas Jefferson National Accelerator Facility for the U.S. Department of Energy

LDRD @ Jefferson Lab

Back-up

μRWELL-PICOSEC: The R&D effort at JLab

LDRD: Development of large-area picosecond timing detectors based on Resistive Micro Well for experiments at JLab and at the EIC

1. **Develop μrPICOSEC prototypes and demonstrate the proof of concept with the timing performance.**
   - Design μRWELL amplification / multi-channel readout to combine with Cerenkov radiator and photocathodes.
   - Optimize the mechanical structure for uniformity over large area (100 cm^2) and thin gap (100 - 200 μm) prototypes.
   - Full characterization of the prototype with laser source and in beam as well as test in high magnetic field.
   - Achieve the goal of a timing resolution better **than 50 ps** for charged particle with first prototype.
2. **Investigate alternative radiator and photocathode materials.**
   - Cesium Iodide (CsI) is unstable under humidity and susceptible to aging due to ion bombardment.
   - We will explore alternative and more robust photocathode materials with similarly high photoelectron yield.
   - Investigate ideas of focusing optic devices integrated with radiator for precise position measurement in addition to timing.
3. **Implement multi-channel fast electronics readout and DAQ system for μrPICOSEC detector.**
   - Lab bench precision measurement of the timing performances of μrPICOSEC prototypes.
   - Development of readout and DAQ system for 100-pads channels for μrPICOSEC prototypes.

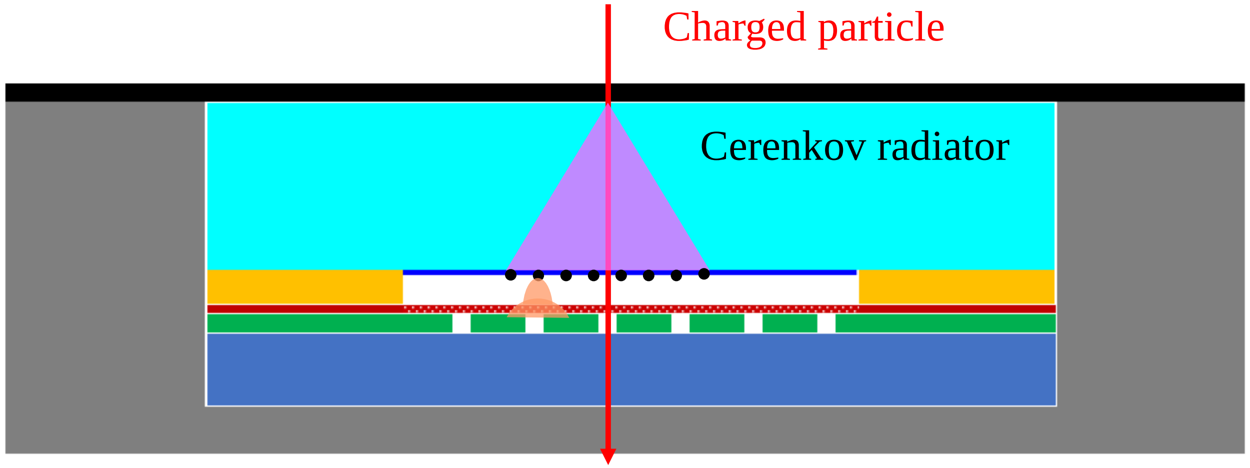
µRWELL-PICOSEC: Potential operation modes

Timing detector for relativistic charged particles:

- Cerenkov radiator crystal transparent in VUV region
- High quantum efficiency (QE) photocathode in VUV medium ~ 7 photoelectrons for 3 mm MgF2
- Goal for timing resolution (~25 ps)

Applications:

- Time of Flight detector
- T0 detector

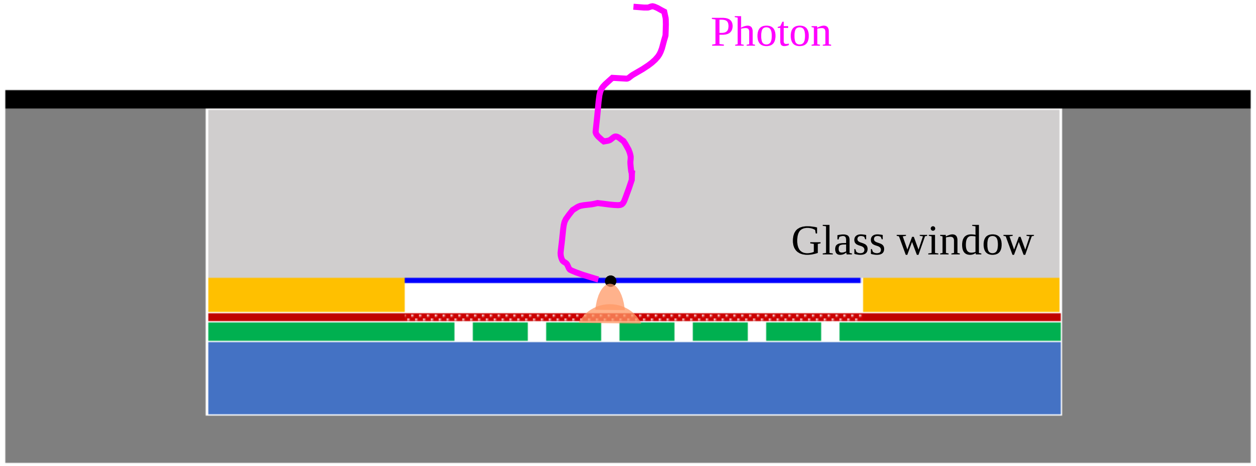


Single photon photodetector:

- High quantum efficiency (QE) photocathode in (VUV) medium which is most radiated by any radiator medium
- Window transparent to Cerenkov radiation
- High gain for single photon timing goal of ~50 - 70 ps

Applications:

- Photosensor for RICH detectors
- T0 tagger at neutrino detector (liquid Ar scintillator light)



μRWELL-PICOSEC: Alternative technologies

This R&D target

Time of Flight (TOF) detectors

	MRPCs	AC-LGAD	μrPICOSEC
Time resolution (ps)	20 – 70 ✓	20 ✓	25 ✓
Rate (MHz / cm^2)	0.05 ✗	N/A	> 1 ✓
Position resolution (mm)	~ 10 ✗	0.030 ✓ (claim)	< 1mm ✓
Performance in high B-field	Yes	Yes	Yes ✓
module size	20 × 20 cm^2 ✓	N/A	20 × 20 cm^2 ✓
Cost ($ M / m^2)	0.2 – 0.4 ✓	High ✗	0.2 – 0.4? ✓

This R&D target

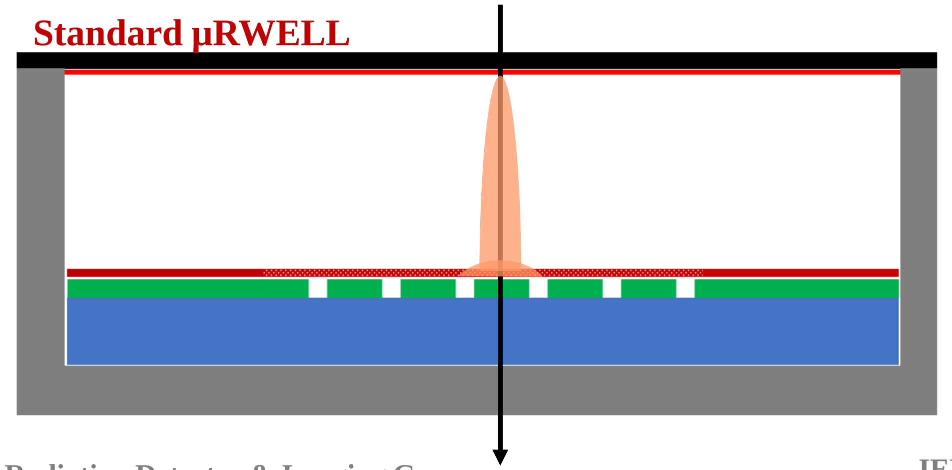
Photosensors for Cerenkov detectors

	SiPMs	MCP-PMTs	LAPPDs	μrPICOSEC
Time resolution (ps)	< 100	< 100	50 ✓	50 ✓
Position resolution (mm)	> 1 ✗	1 ✗	0.3 – 1 ✓	< 1 ✓
Performance in high B-field	Yes	Limited	Limited	Yes ✓
Radiation hardness	dark current ✗	N/A	N/A	Yes ✓
Cost ($ M / m^2)	0.8 – 1 ✗	> 1 ✗	0.8 – 1 ✗	0.2 – 0.4 ✓

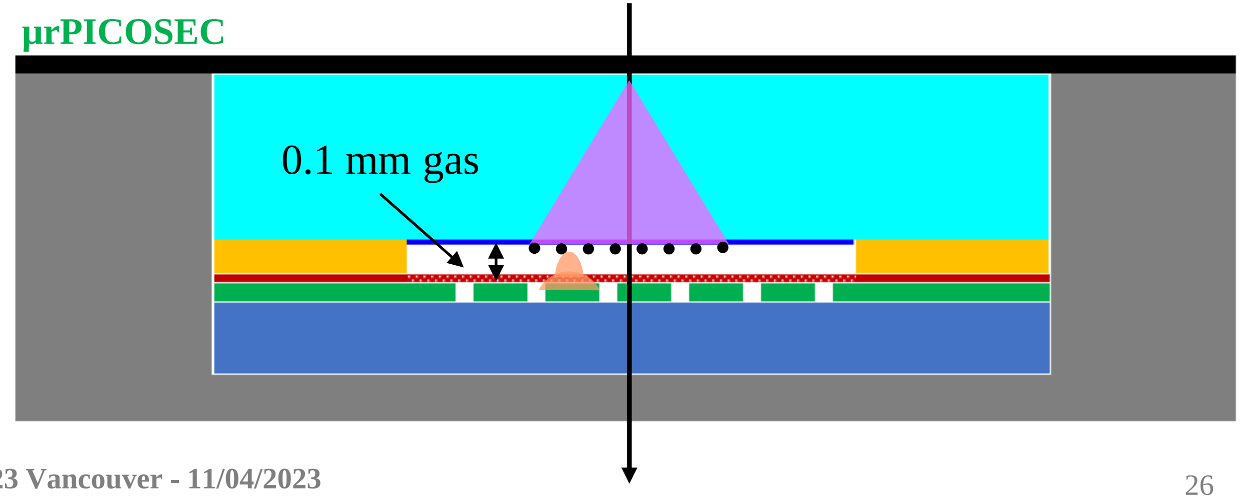
µRWELL-PICOSEC vs. standard µRWELL detector

	Standard µRWELL detector	µrPICOSEC: picosecond uRWELL detector
Primary electrons production	Ionization of gas molecule by charged particles, typically, 3 mm gas ➔ limitation for timing performance	Charged particles creates Cerenkov photons in radiator ➔ photons conversion in photocathode ➔ produced photoelectrons
Amplification mechanism	Primary charges drift to µRWELL amplification stage ➔ amplification with typical gain of 10^4	Photoelectrons are pre-amplified in high e-field in 100 to 200 um gas then a second amplification by µRWELL ➔ total gain can reach 10^7
Signal collection structures	Strips, pads, large capacitance, high rate	Pads, small capacitance critical for high S/N
Position resolution	~50 to 100 µm space point resolution	To be evaluated
Timing resolution	~ 4 ns with specific gas mixture	**Goal:** 25 ps for charged particle **Goal:** 50 to 100 ps for single photon detection
Area of application	**Tracking: large-area, low-cost, precision position**	**PID: Time of flight (TOF) & photosensors for Cerenkov detectors**

Standard µRWELL



µrPICOSEC



µRWELL vs. Micromegas: Drift Field Lines

MM-PICOSEC

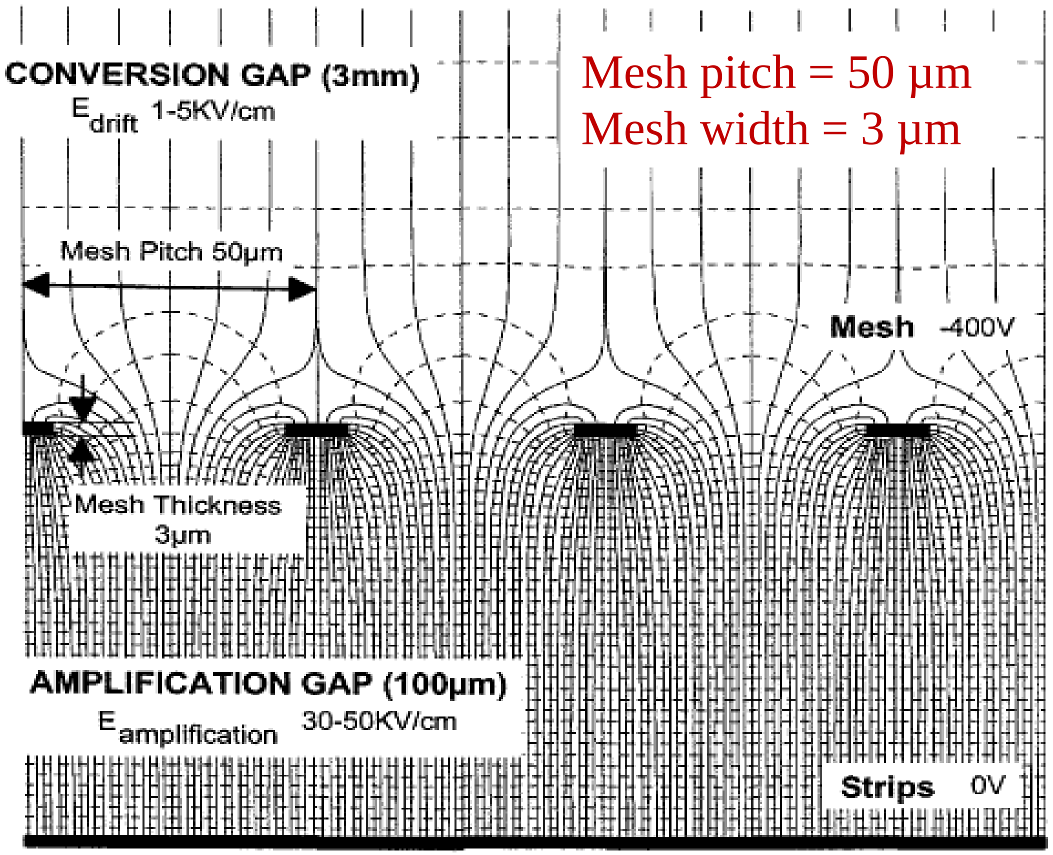
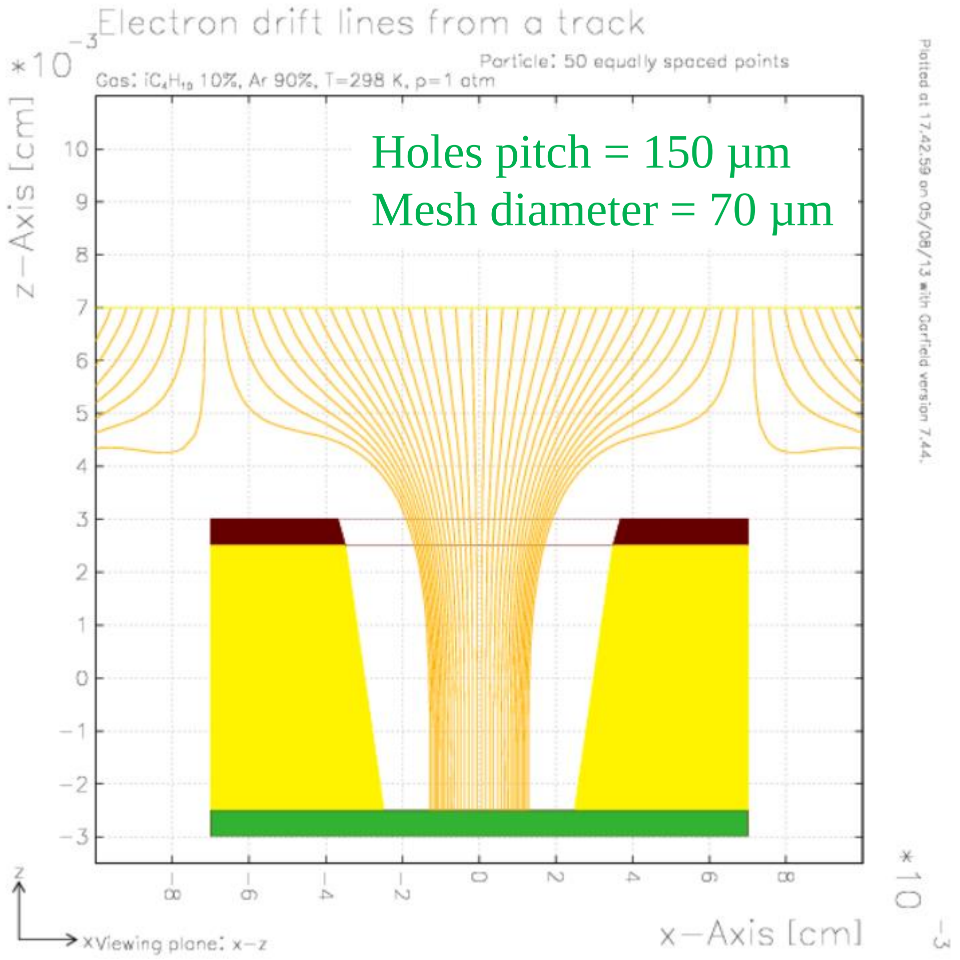


Fig. 1. Micromegas electric field map.

Mesh pitch = 50 µm
Mesh width = 3 µm

µRWELL-PICOSEC



Holes pitch = 150 µm
Mesh diameter = 70 µm

Gas mixture choices

Best time resolution for 1 p.e.

Gas mixture (Neon-Ethane-CF4)	U_{Amp} (V)	U_{Drift} (V)	echarge (pC)	amplitude (mV)	$\sigma_{tres.}$ (ps)
80-10-10	275	525	8.58 ± 0.13	166.3 ± 0.2	43.89 ± 1.00
89-2-9	255	445	1.69 ± 0.01	31.56 ± 0.44	112.15 ± 4.03
80-20-0	270	470	0.54 ± 0.01	21.61 ± 0.18	129.21 ± 6.03
85-15-0	310	395	0.74 ± 0.01	22.83 ± 0.21	113.48 ± 4.66
90-10-0	340	340	0.82 ± 0.01	20.72 ± 0.09	150.23 ± 3.17
95-5-0	230	375	1.13 ± 0.01	22.98 ± 0.16	181.09 ± 8.91

- Ethane+CF4 allows higher electric fields and thus better time resolution
- Improvement with Ethane: less gain but narrower signal at higher field
- Optimum mixture of only Neon-Ethane reached at 85-15

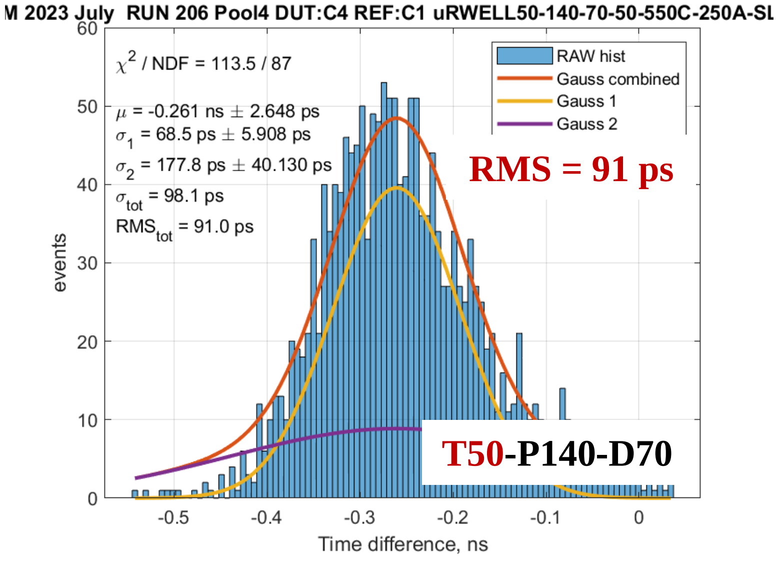
Lukas Sohl
RD51 miniweek 11/02/2020

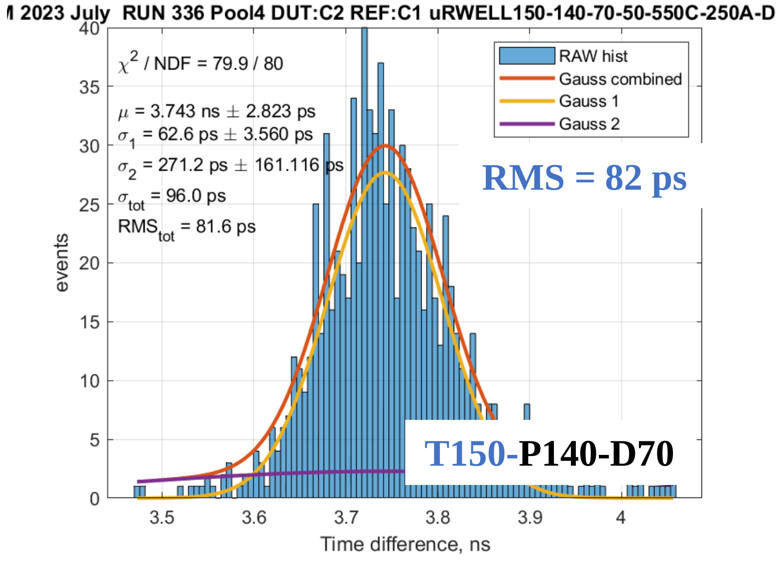
Lukas SOHL RD51 Miniweek 11.02.2020 - PICOSEC-Micromegas 11

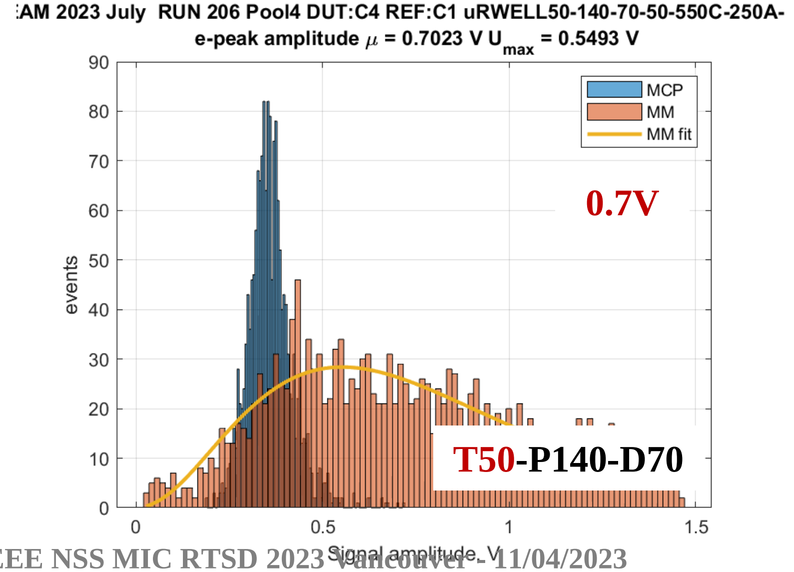
µRWELL-PICOSEC: Kapton thickness comparison (07/2023)

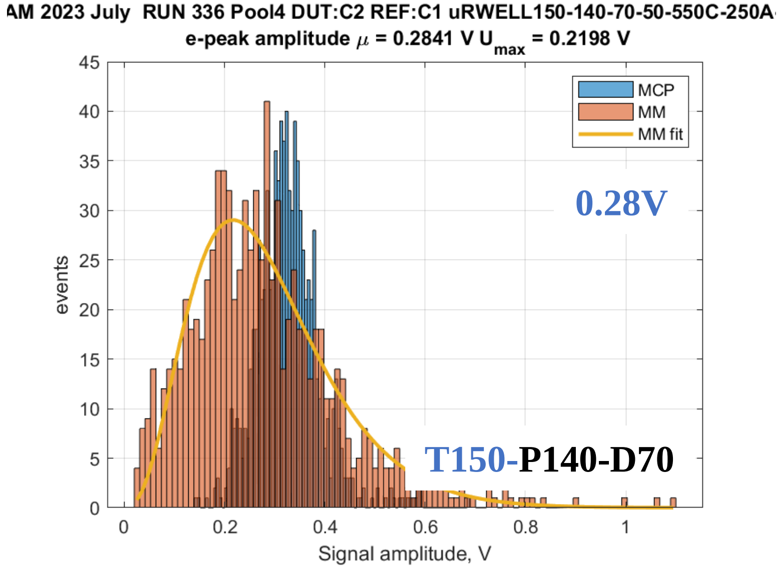
First µRWELL-PICOSEC prototype

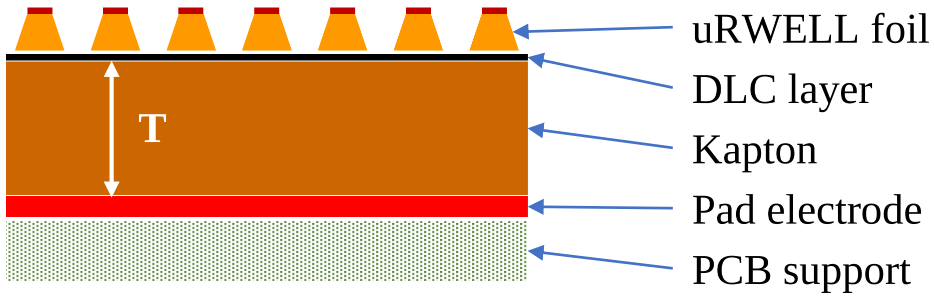
- Single-pad small prototype
  - 1 cm diameter active area
  - 3 mm thick radiator + **DLC photocathode**
  - Sensor: 50 µm µRWELL on 50 µm Kapton
  - Holes parameters: 140 µm / 70 µm / 50 µm
- First tests with LED source (GDD lab, 12/2022)
  - Poor timing compared to MM-PICOSEC











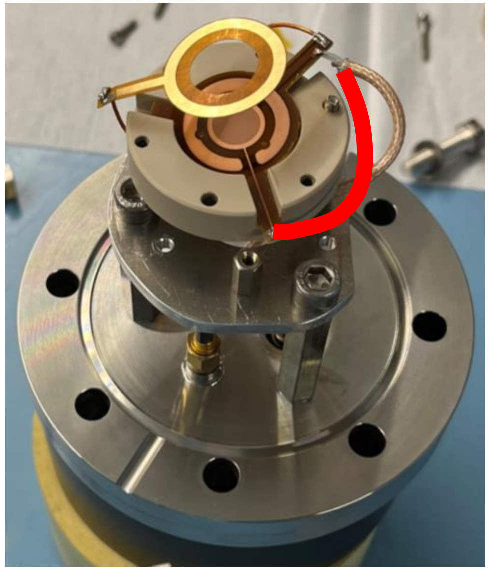
Cross section view of µRWELL-PICOSEC PCB

µRWELL-PICOSEC: External source of noise (08/2023)

µRWELL-PICOSEC prototype

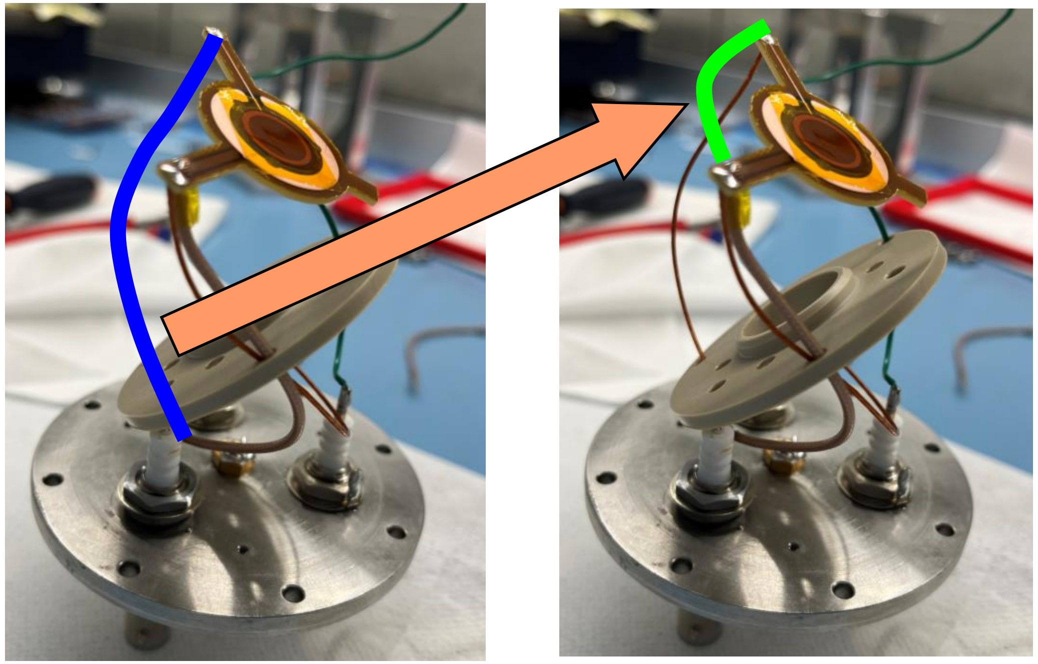
- Single-pad small prototype 1 cm diameter active area 3 mm thick radiator + CsI photocathode Sensor: 50 µm µRWELL on 50 µm Kapton
  - Holes parameters: 140 µm / 70 µm / 50 µm First tests with LED source (GDD lab, 12/2022)
  - Poor timing compared to MM-PICOSEC

Short wires in chamber 1



long wires in chamber 2

short wires in chamber 2



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