Fast and precise timing with resistive µRWELL-PICOSEC detector technology

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Outline

- **Motivation**
- **Detection concept of μRWELL-PICOSEC**
- **Test beam setup**
- **Preliminary results from Test beam-2024**

  (New housing & design of single channel μRWELL-PICOSEC prototype)

  (Large-area (10 cm × 10 cm) μRWELL-PICOSEC prototype with 100-pads readout)
- **Summary**

Motivation: µRWELL-PICOSEC Technology

- **Develop fast, precise, and cost-effective gaseous detectors for particle physics and medical applications with properties like stability, radiation hardness, large area coverage, and segmented readout capabilities.**

- **The MM-PICOSEC collaboration has proven the concept using Micromegas technology, and picosecond detectors based on µRWELL technology show great potential.**

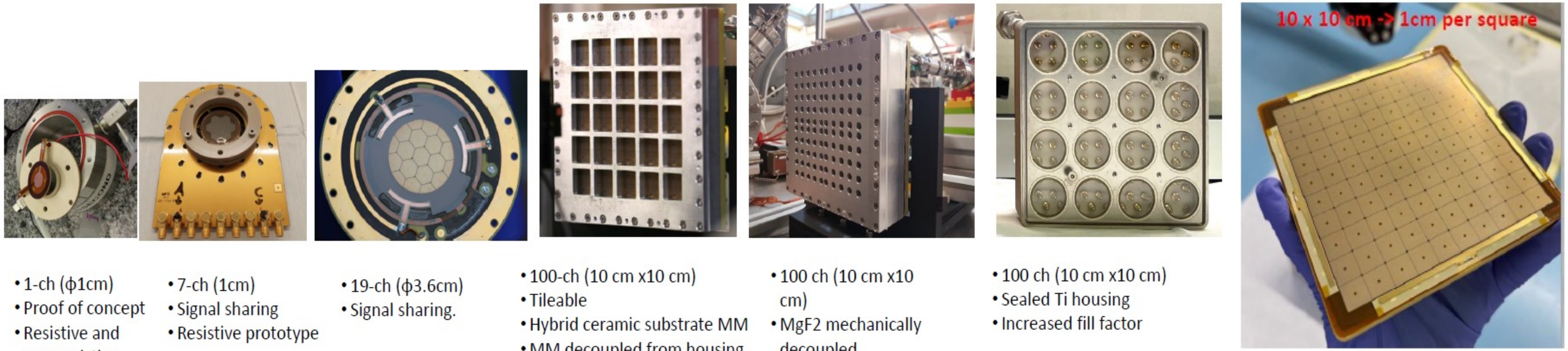
- **µRWELL-PICOSEC technology offers promising alternatives for PID systems, TOF detectors for charged particles, and Cerenkov photosensor technologies.**

Applications include future projects like the Electron Ion Collider (EIC) Detector II, the ePIC upgrade, future experiments at Jefferson Lab, and medical instrumentation such as TOF-PET devices.

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)



- 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

Design of μRWELL-PICOSEC

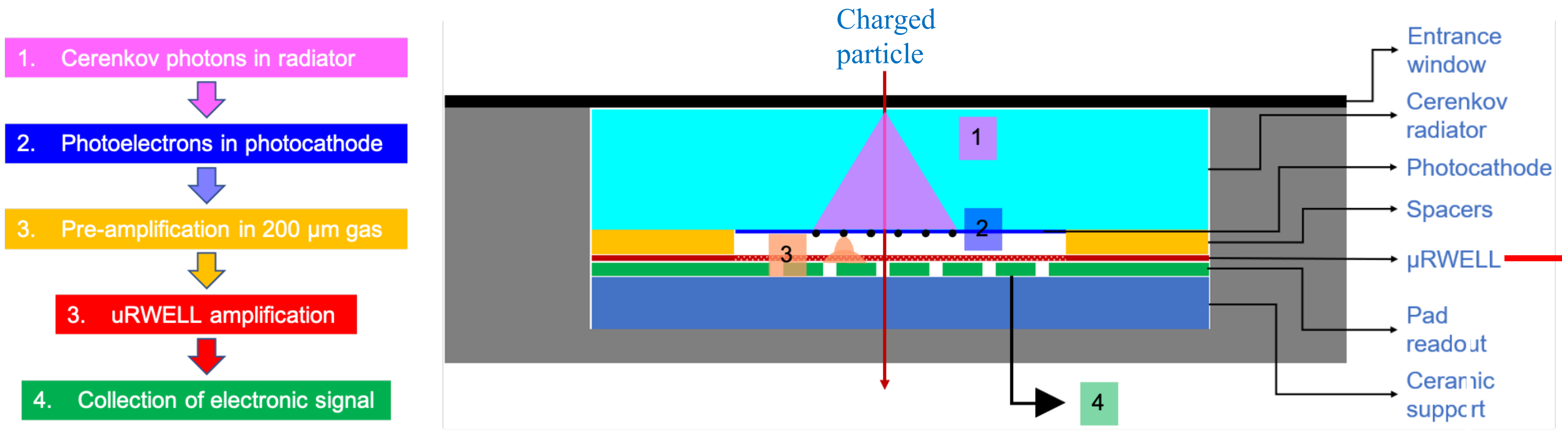
1. Cherenkov photons: relativistic charged particle creates Cerenkov photons➔prompt photons i.e., timing resolution.

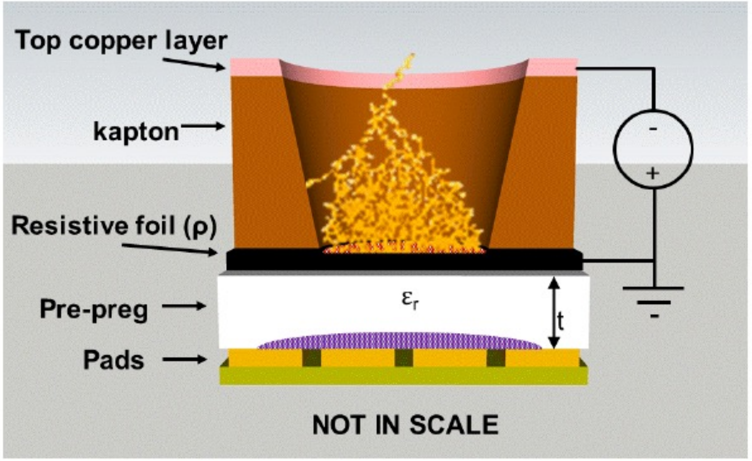
2. Photoelectrons: convert the Cerenkov photons into photoelectrons, all electrons created at the same z position➔timing resolution

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.



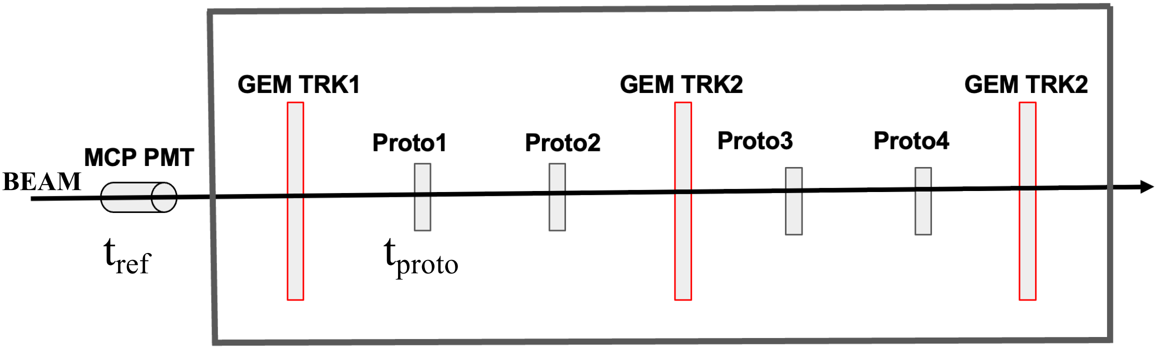


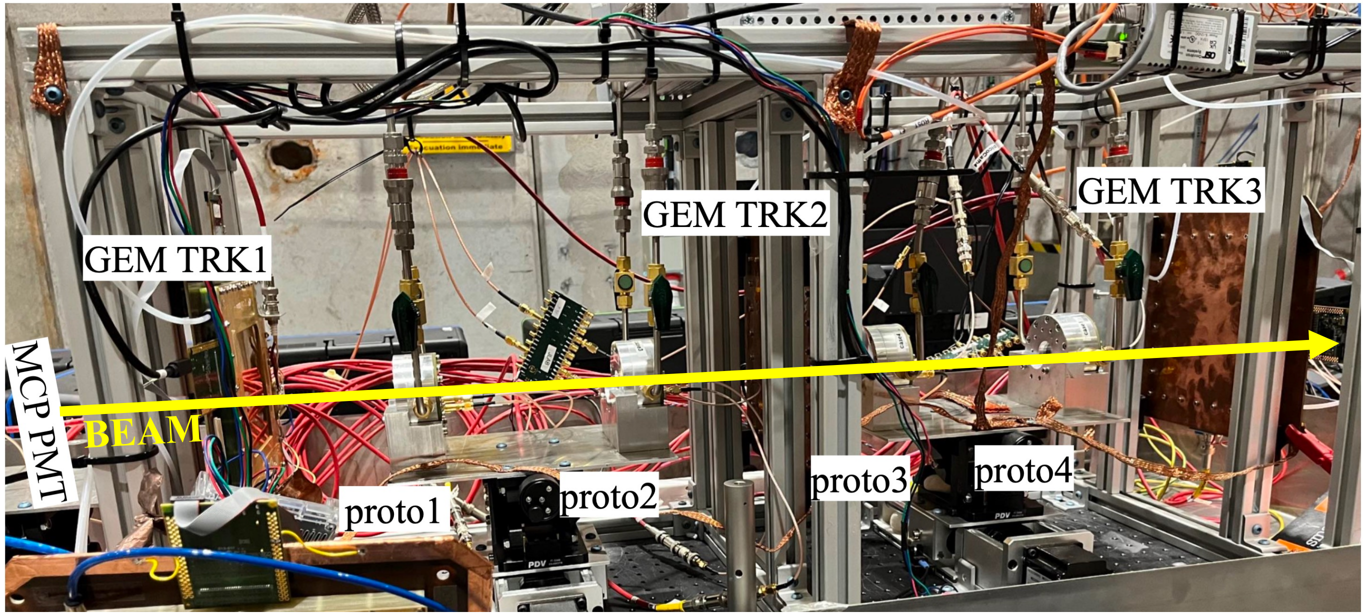
μRWELL PCB

Gas mixture Neon : C_2H_6 : CF_4 = 80 : 10 :10 (at ambient pressure)

Test beam experimental setup of single channel µRWELL-PICOSEC

This single-channel µRWELL-PICOSEC prototype was tested during the DRD1 test beam campaigns at CERN with 150 GeV/c muons.





JLab µRWELL-PICOSEC Telescope used in April and July 2024 test beam at CERN

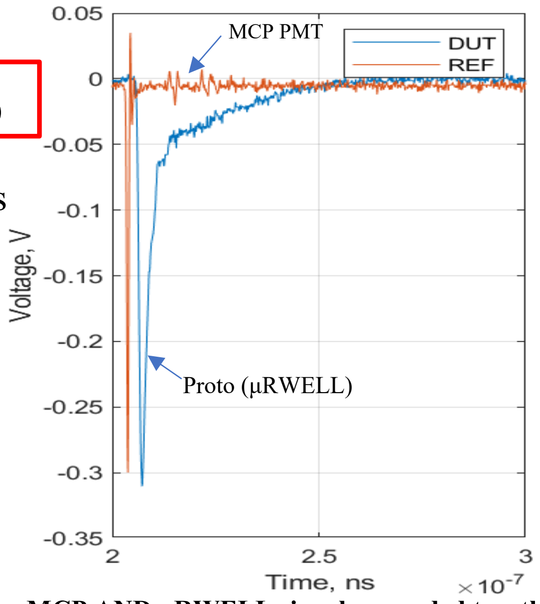
Time difference= $(t_{proto} - t_{ref}) - t_0$

t_0 = Time resolution of MCP PMT~10ps

t_{ref} = Time stamp of MCP PMT

t_{proto} = Time stamp of µRWELL

→ **Constant Function (CF) analysis**



MCP AND µRWELL signals recorded together with 150 GeV/c muons.

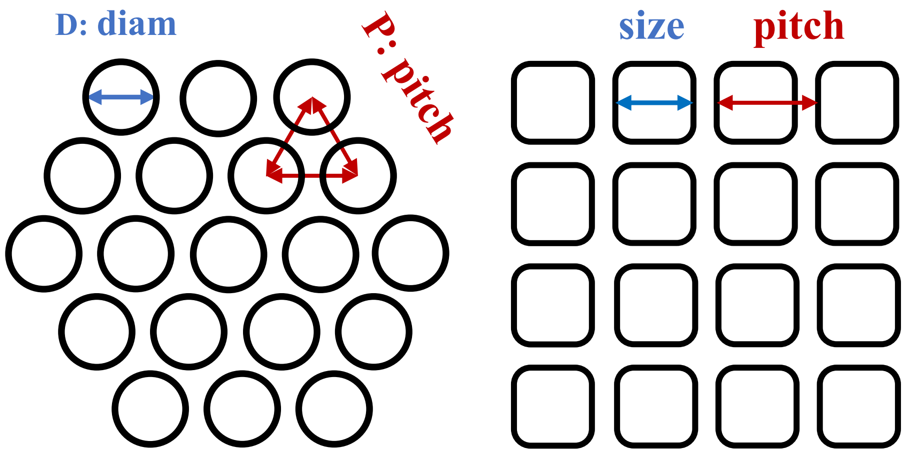
Tracking data → 3 triple GEM TRKs + APV25-SRS

Timing reference and trigger → MCP-PMT

Preamplifier → fast preamplifier CIVIDEC

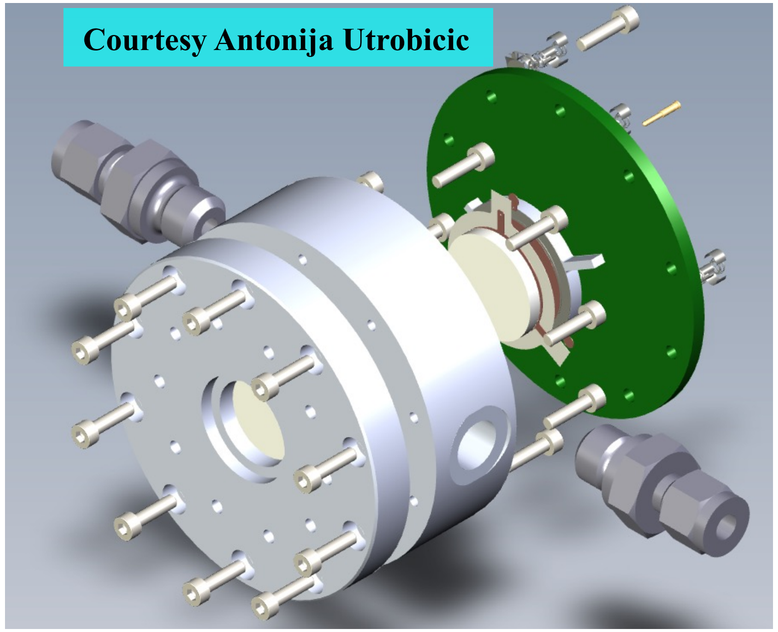
New mechanical housing and design of single channel µRWELL-PICOSEC (Test beam 2024)

New hole geometries



Round holes (RD)   Square holes (RD)

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

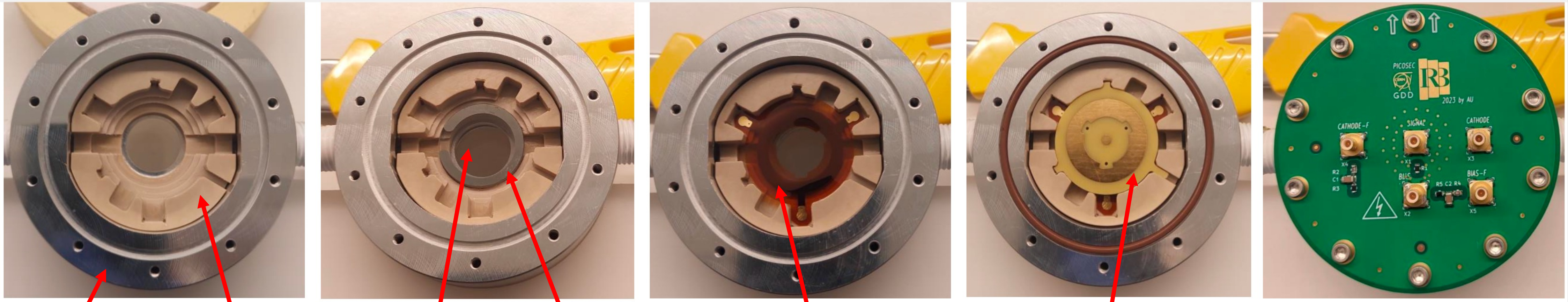


New mechanical housing

- 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 mechanical housing of single channel µRWELL-PICOSEC (Test beam 2024)

Courtesy Antonija Utrobicic



Al chamber

PEEK insert

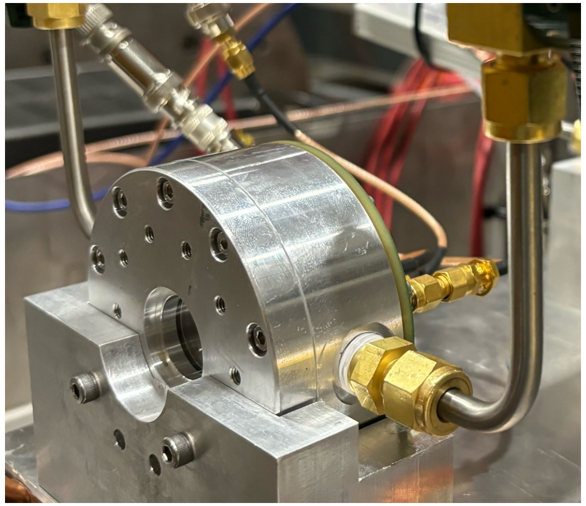
3mm MgF_2 crystal

18nm CsI/DLC photocathode

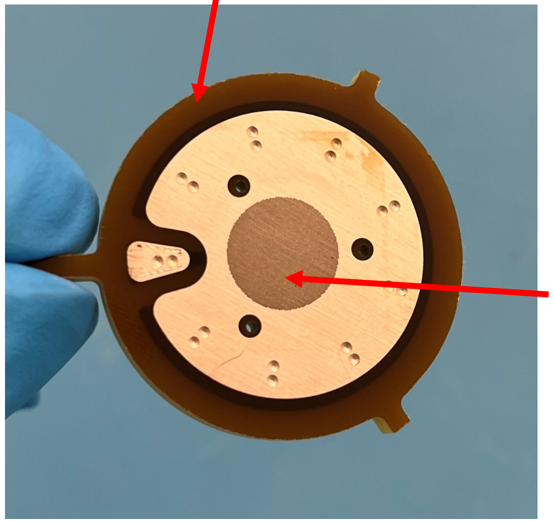
spacer

µRWELL PCB

Outer board



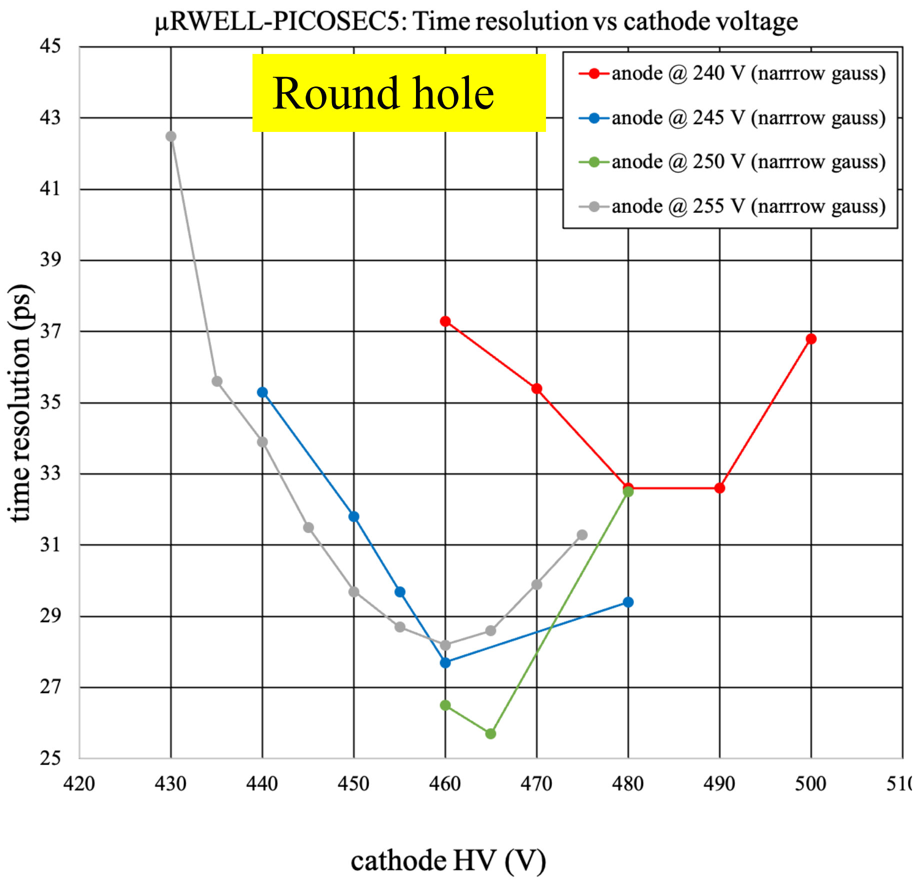
µRWELL prototype in the Alu housing

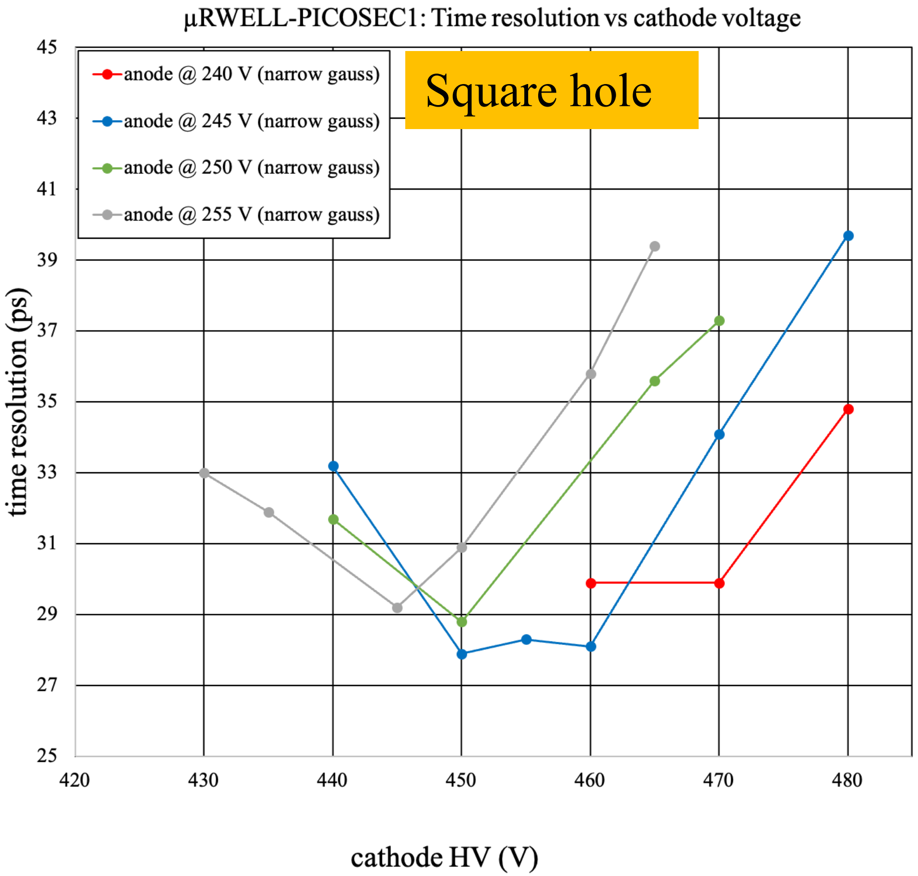


1cm diameter active area

Analysis results of the single channel µRWELL-PICOSEC prototypes having CsI photocathode

Comparison of time resolution based on the hole shape

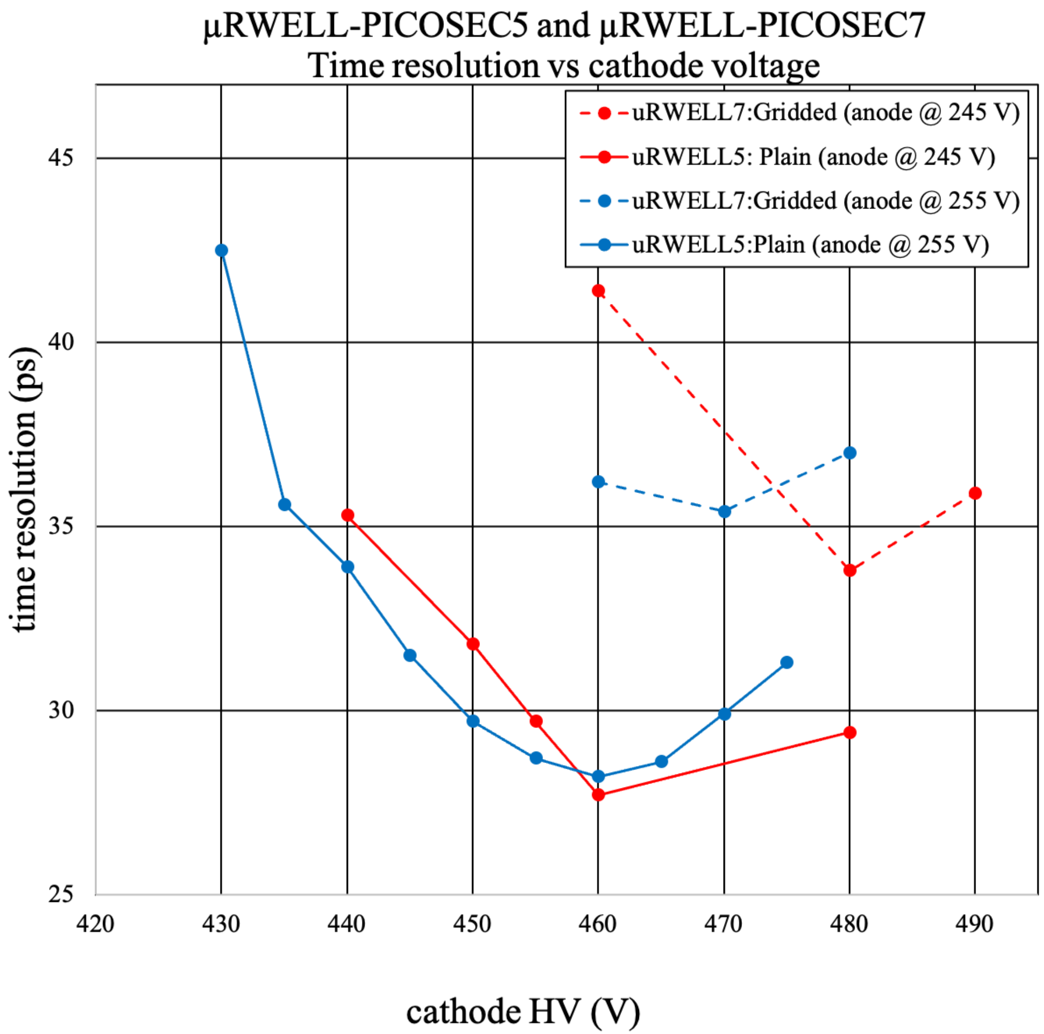


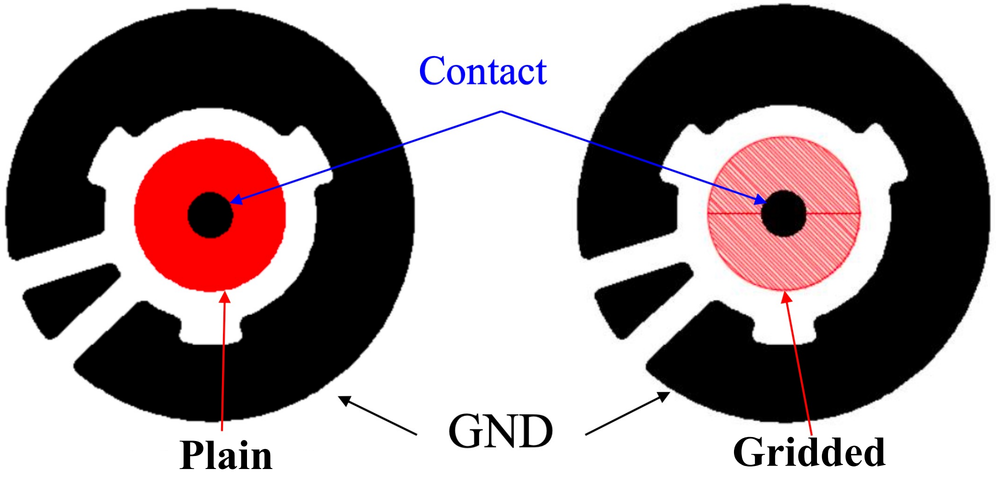


Parameters	µRWELL5	µRWELL7
Pitch (µm)	120	120
Hole(o) (µm)	100	100
Hole(i) (µm)	80	80
Hole shape	Round	Square
Readout	Plain	Plain
Spacer (µm)	170	170
Photocathode	CsI	CsI

The prototype featuring a round hole geometry demonstrates improved timing resolution compared to the prototype with a square hole geometry

Comparison of time resolution based on the readout scheme

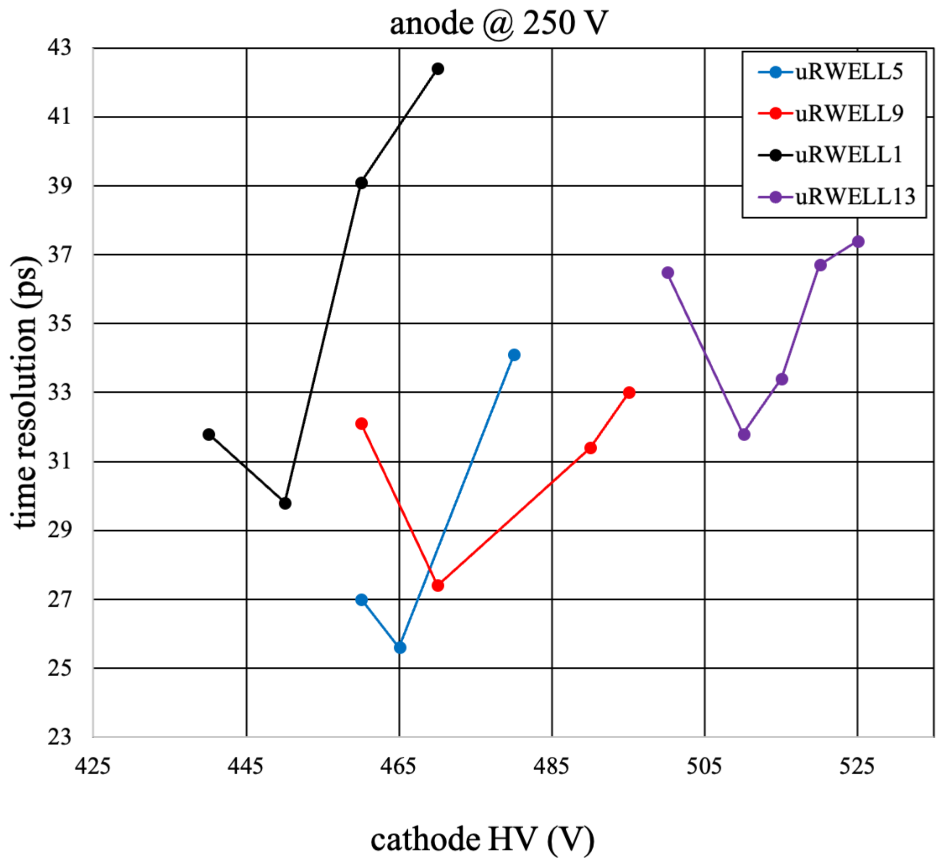




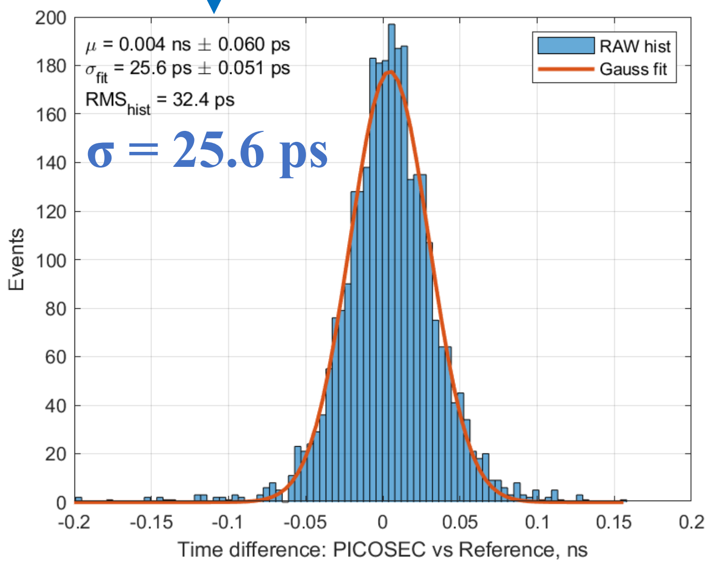
Parameters	µRWELL5	µRWELL7
Pitch (µm)	120	120
Hole(o) (µm)	100	100
Hole(i) (µm)	80	80
Hole shape	Round	Round
Readout	Plain	Gridded
Spacer (µm)	170	170
Photocathode	CsI	CsI

Prototype featuring a plain readout demonstrates improved timing resolution compared to the prototype with a grided readout scheme.

Timing characteristics in Single-Channel Prototypes with constant Anode Voltage



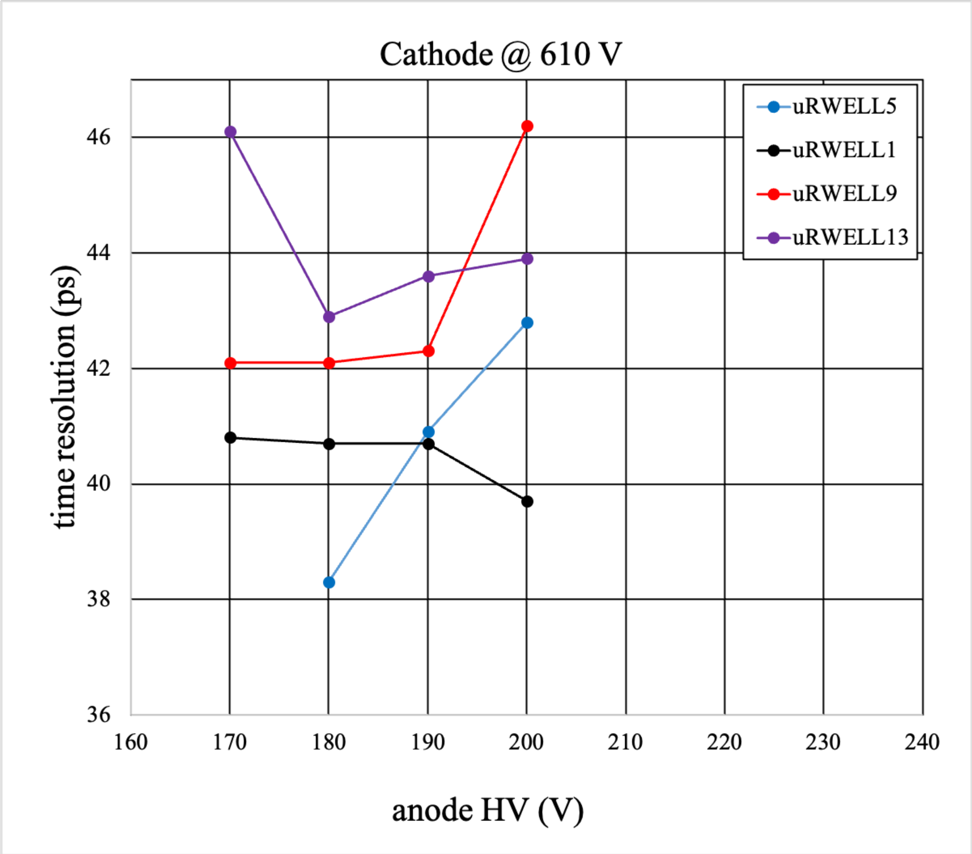
Parameters	µRWELL5	µRWELL1	µRWELL9	µRWELL13
Pitch (µm)	120	120	100	80
Hole(o) (µm)	100	100	80	60
Hole(i) (µm)	80	80	60	40
Hole shape	Round	Square	Round	Square
Readout	Plain	Plain	Plain	Plain
Spacer (µm)	170	170	170	170
Photocathode	CsI	CsI	CsI	CsI



The prototype with higher pitch, larger hole diameters, round shape hole exhibits superior timing performance compared to those with lower pitch, smaller diameters, square shape hole.

Analysis results of the single channel µRWELL PICOSEC prototypes having DLC photocathode

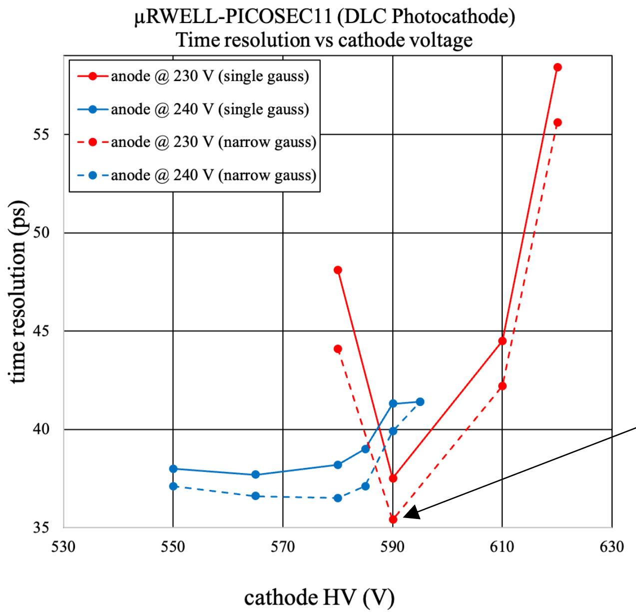
Timing characteristics in Single-Channel Prototypes with constant Anode Voltage

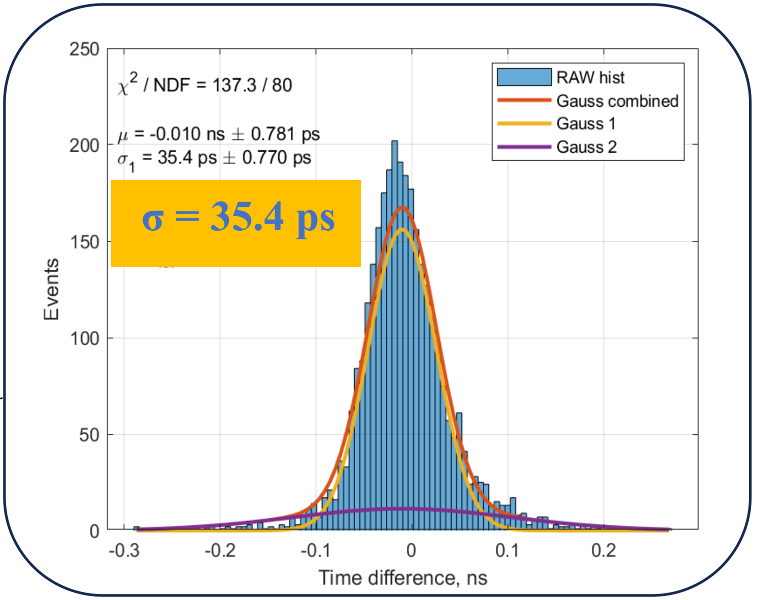


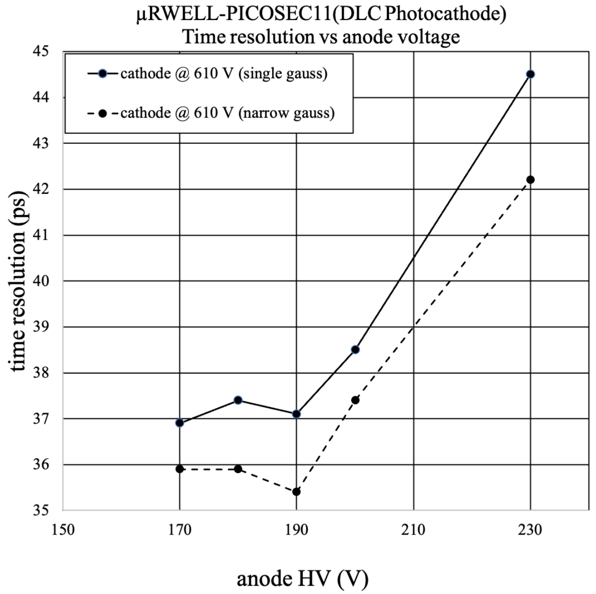
Parameters	µRWELL5	µRWELL1	µRWELL9	µRWELL13
Pitch (µm)	120	120	100	80
Hole(o) (µm)	100	100	80	60
Hole(i) (µm)	80	80	60	40
Hole shape	Round	Square	Round	Square
Readout	Plain	Plain	Plain	Plain
Spacer (µm)	170	170	170	170
Photocathode	DLC	DLC	DLC	DLC

The prototype with higher pitch, larger hole diameters, round shape hole exhibits superior timing performance compared to those with lower pitch, smaller diameters, square shape hole.

Best timing performance with prototype having DLC photocathode



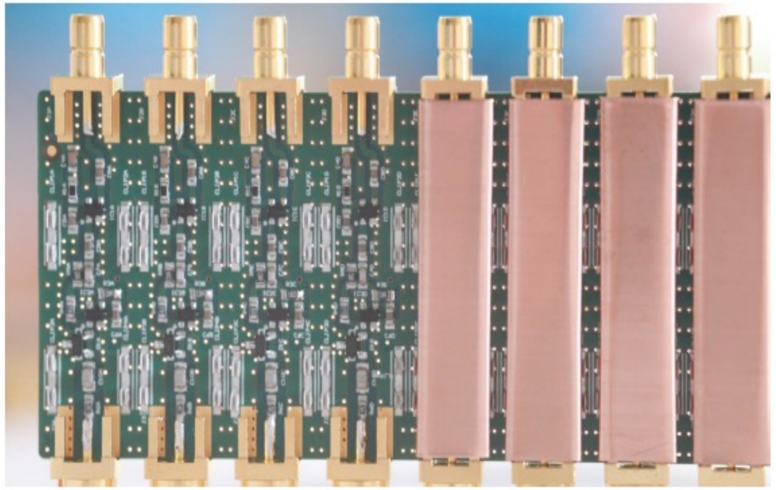




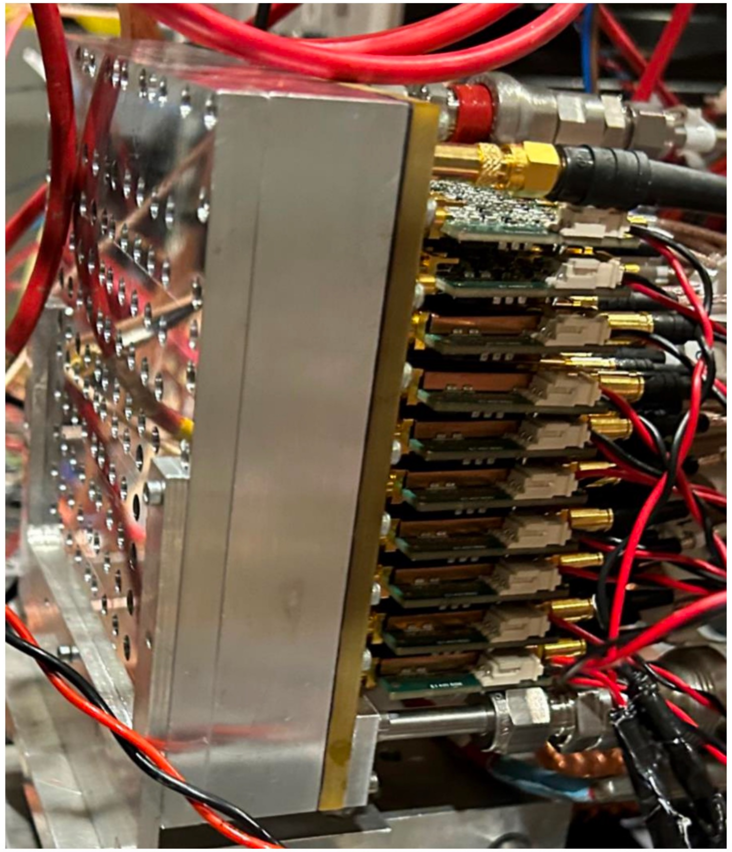
Parameters	µRWELL11
Pitch (µm)	100
Hole(o) (µm)	80
Hole(i) (µm)	60
Hole shape	Gridded
Readout	Plain
Spacer (µm)	170
Photocathode	DLC

µRWELL-PICOSEC: Multi-channel readout and DAQ

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



10 channel fast preamp card



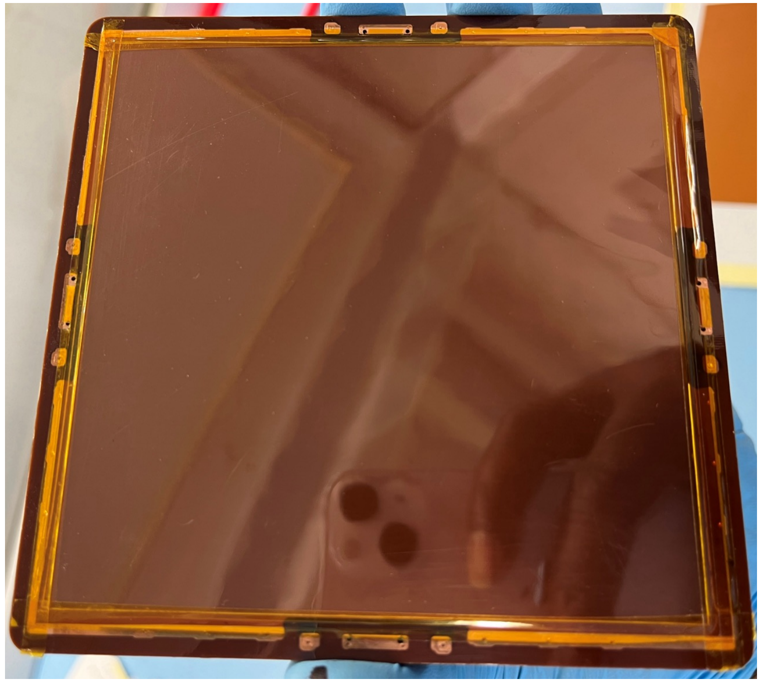
10 x 10 channel fast preamp cards mounted on large prototype

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

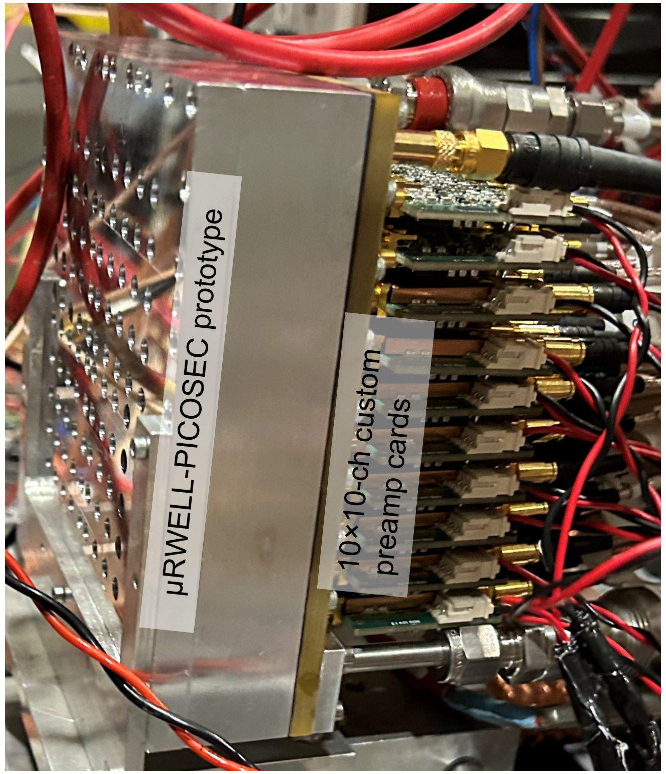
Crate with 64-channel SAMPIC digitizer card

Large (10 cm × 10 cm) µRWELL-PICOSEC Prototype (100-pads readout)

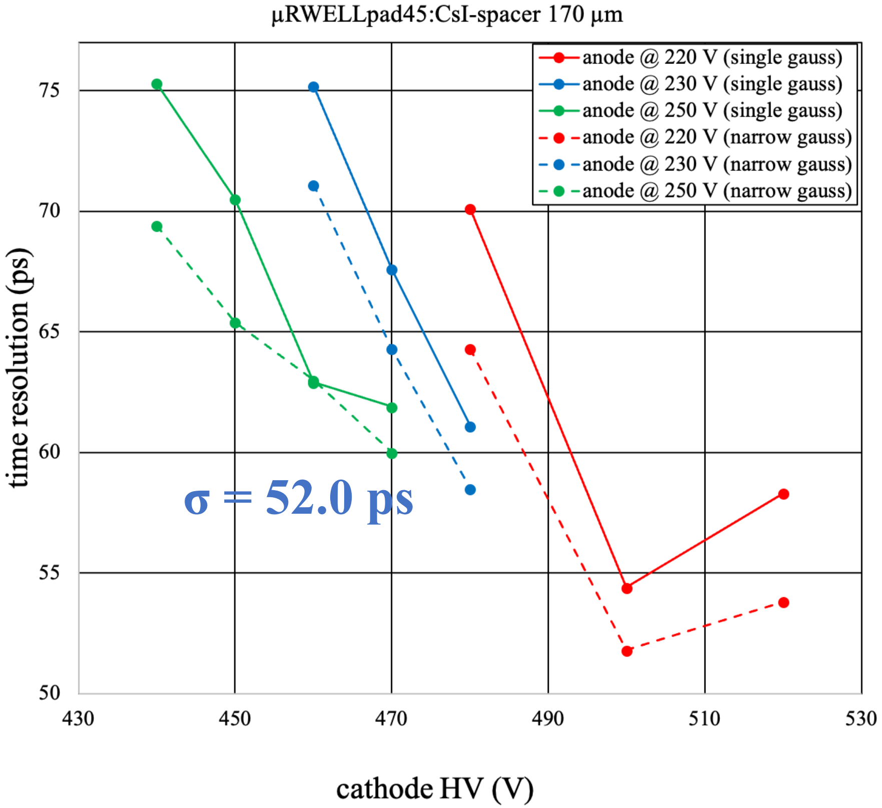
- µRWELL-PICOSEC with **120** µm pitch, **100** µm outer diameter and **80** µm inner diameter assembled and fully instrumented with fast electronics readout
- Readout: custom fast preamplifiers coupled with the SAMPIC digitizer for multi channel readout and DAQ system
- Prototype was successfully tested in H4 beam at CERN in July 2024 with CsI photocathode
- preliminary test beam results on individual pads give time resolution ~50 ps ➔ partially due to drift gap non uniformity and poor photocathode quality
- Full analysis of the test beam data is ongoing



100-pads µRWELL-PICOSEC PCB



Large µRWELL-PICOSEC in beam at CERN with 100-ch fast electronic readout & DAQ



Time resolution vs. cathode HV scan

Summary

- Timing resolution measured for several single channel µRWELL-PICOSEC prototypes with different hole shapes, size, pitch and readout using CERN test beam.
- The higher pitch, larger hole diameter and round shaped hole prototypes performed the best
- Timing performance best for prototypes with plain readout vs grid readout.
- ~25 ps timing resolution achieved with µRWELL-PICOSEC prototype:
  - ➢ round shaped hole
  - ➢ 120 µm pitch
  - ➢ 100 µm OD, 80 µm as ID
  - ➢ 170 µm preamplification gap
  - ➢ CsI photocathode
- ~35 ps timing resolution achieved with µRWELL-PICOSEC prototype:
  - ➢ round shaped hole
  - ➢ 100 µm pitch,
  - ➢ 80 µm as OD, 60 µm as ID,
  - ➢ 170 µm preamplification gap
  - ➢ DLC photocathode
- ~50 ps timing resolution measured on the individual pads of large 10x10 µRWELL PICOSEC prototype. Full analysis is ongoing.

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LDRD @ Jefferson Lab

Questions?

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2) Also MEPhI & Uludag University.
3) Also University of Virginia.
4) Now at University of Birmingham

Jefferson Lab

JSA

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Backup

Timing Analysis

uRWELL PICOSEC signal
- fast electron-peak (electrons) → **Timing Analysis**
- Slow component (ion drift)

Electron peak: the difference between the highest point of the waveform and the baseline

For the timing measurement, a **Constant Fraction** (CF) method based on a sigmoid function is used to minimize the contribution of the noise

A sigmoid function is fit to the leading edge of the electron-peak:

$$V(t) = \frac{P_0}{1 + \exp\left(-P_2 \times (t - P_1)\right)} + P_3$$

where P_0 and P_3 respectively the maximum and the minimum values, P_1 is the inflection time (i.e. where the slope changes derivative), and P_2 quantifies the speed of the sigmoid change (i.e. is correlated to the signal risetime).

The time corresponding to a 20% CF is calculated as follows:

$$t_z = P_1 - \frac{1}{P_2} \log\left[\frac{P_0}{0.2 \times V_{\max} - P_3} - 1\right]$$

Now above time is calculated for both uRWELL and MCP PMT and then difference of them gives time resolution.

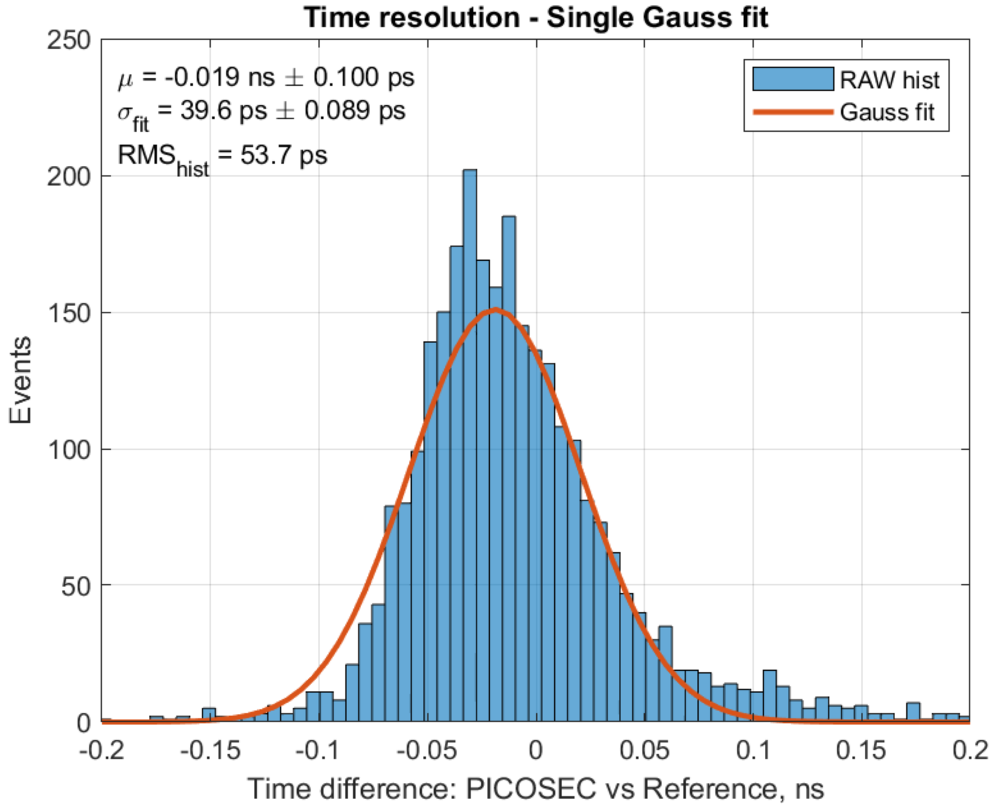
Cuts used to obtained final time difference distribution:
1. Time window cut applied to select events within pm300 ps of the median time difference of all triggered events.
2. Min and maximum signal amplitude cut
3. Geometrical cut: central pad only (to avoid partial loss of photoelectrons outside center pad region)

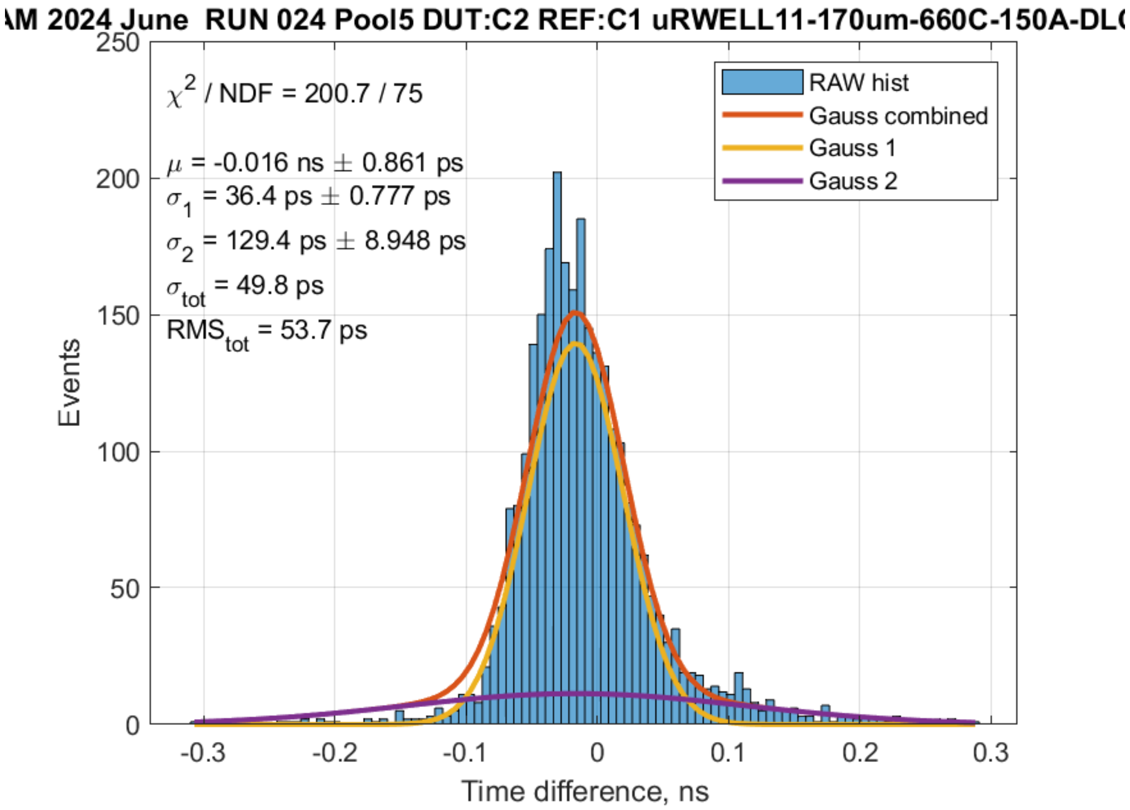
J. Bortfeldt, F. Brunbauer, C. David, D. Desforge, et al. NIM A 903 (2018) 317–325. doi:https://doi.org/10.1016/j.nima.2018.04.033.

Micromegas-PICOSEC vs µRWELL-PICOSEC

	MM-PICOSEC	µRWELL-PICOSEC
Radiator / photocathode	Both technologies share the same devices	Both technologies share the same devices
Readout structure	Both technologies share the same devices	Both technologies share the same devices
Amplification structure	mesh ➔ 128 µm gap	Cu-clad Kapton foil ➔ 50 µm gap
Resistive vs. metallic	Both options available	Only resistive
Segmentation MPGD	Segmentation of the mesh will be challenging	µRWELL Cu-electrode can be segmented

Single and narrow gaussian fitting





μRWELL-PICOSEC: Amplification structure

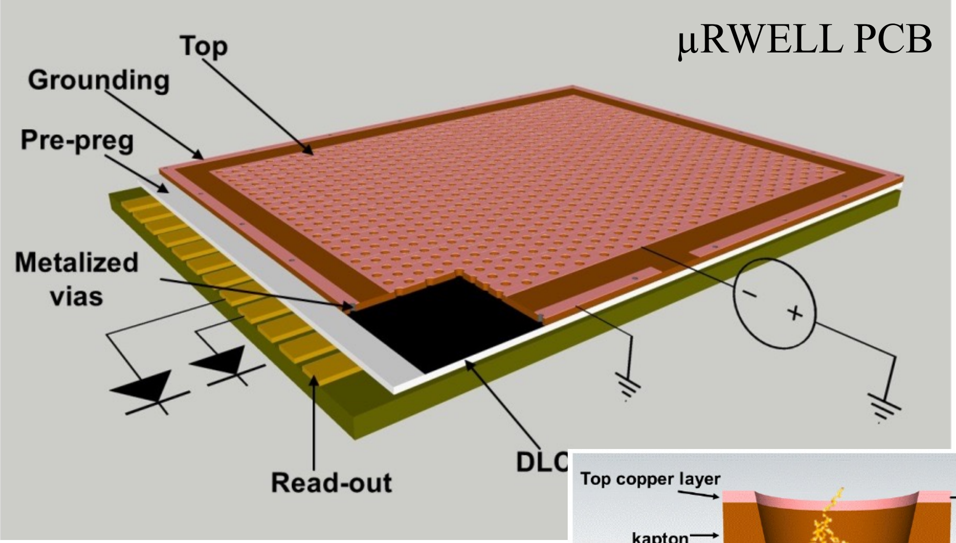
Design of μRWELL foil

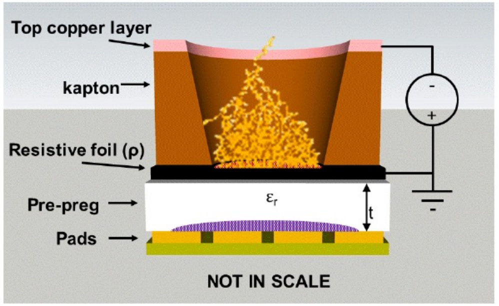
- Single layer amplification MPGD
  - Simple amplification structure using same material as GEM foil
  - Resistive technology ➔ intrinsically robust against spark
  - Large area capability
- Specially well suited for PICOSEC technology
  - μRWELL is a resistive MPGD ➔ improve detector stability backup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

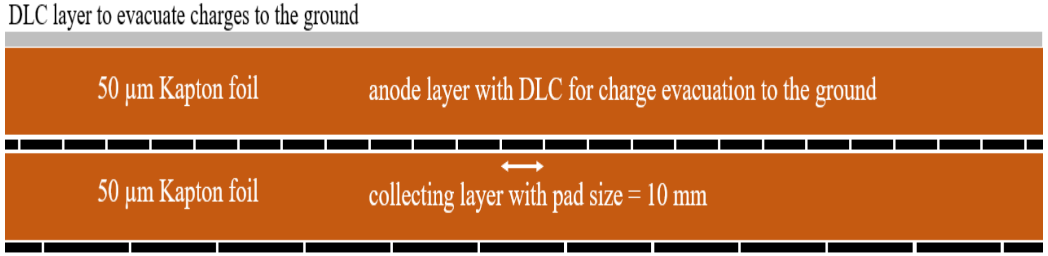
Integration of capacitive-sharing readout structures

- 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



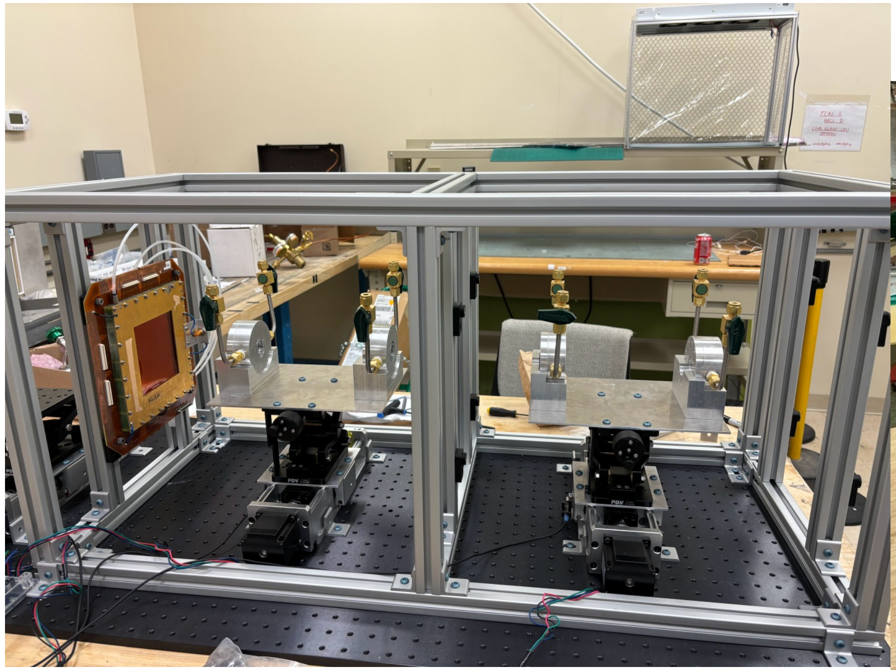


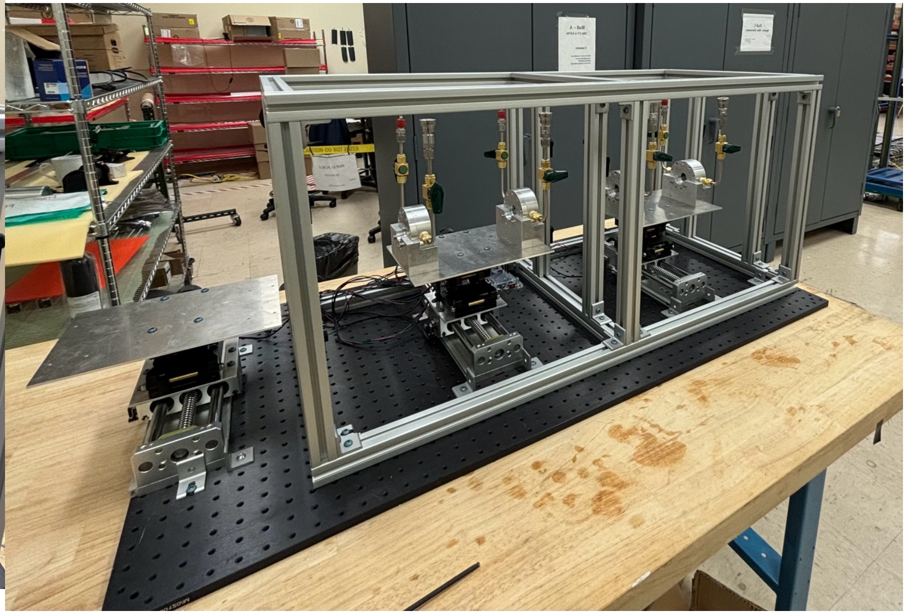


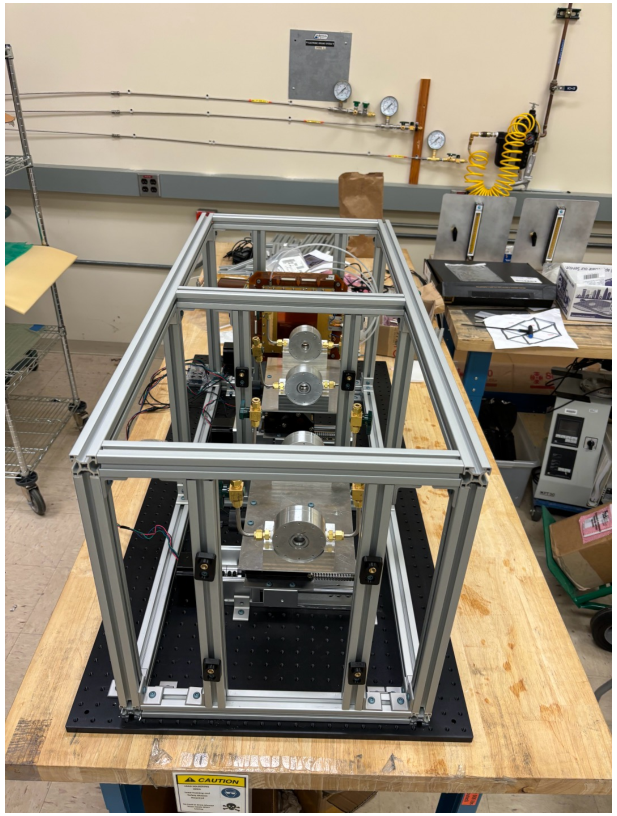
Concept capacitive-sharing pad readout

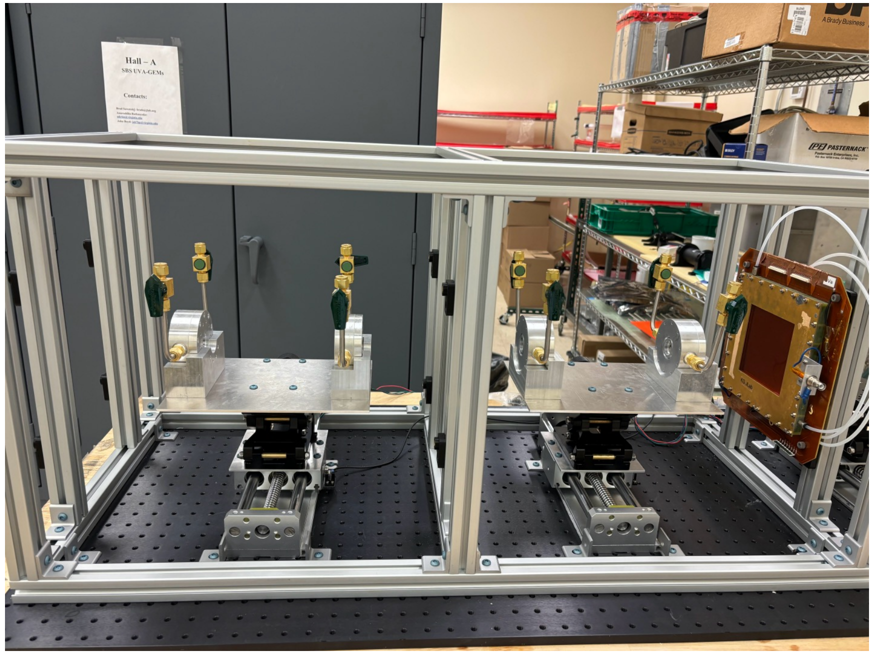
K. Gnanvo et al., NIM A, 1047 (2023) 167782

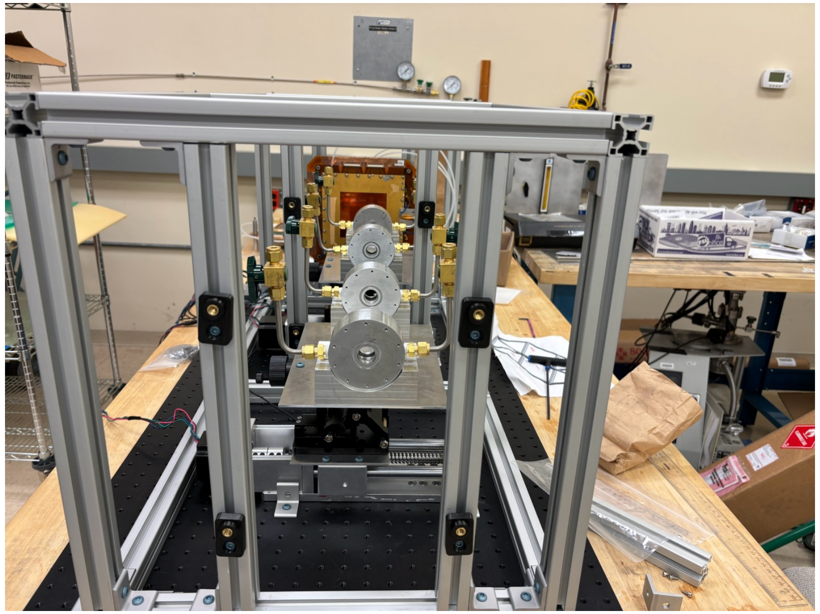
Assembly of µRWELL-PICOSEC telescope at JLab











We have tested the following combinations of single channel μRWELL-PICOSEC protypes:

1. uRWELL7 (CsI batch 2), Round P:120 H(o):100 H(i):80, Spacer: 170 um, Readout: Grided
uRWELL5 (CsI batch 4), Round P:120 H(o):100 H(i):80, Spacer: 170 um, Readout: Plain

2. uRWELL9 (CsI batch 2), Round P:100 H(o):80 H(i):60, Spacer 170 um, Readout: Plain
uRWELL11 (CsI batch 4), Round P:100 H(o):80 H(i):60, Spacer 170 um, Readout: Grided

3. uRWELL1 (CsI batch 4), Square P:120 H(o):100 H(i):80, Spacer 170 um, Readout: Plain
uRWELL3 (CsI batch 4), Square P:120 H(o):100 H(i):80, Spacer 170 um, Readout: Grided

4. uRWELL5 (CsI batch 4), Round P:120 H(o):100 H(i):80, **Spacer 120 um**, Readout: Plain
uRWELL9 (CsI batch 4), Round P:100 H(o):80 H(i):60, **Spacer 120 um**, Readout: Plain

5. uRWELL13 (CsI batch 4), Square P:80 H(o):60 H(i):40, Spacer 170 um, Readout: Plain
uRWELL9 (CsI batch 4), Round P:100 H(o):80 H(i):60, **Spacer 120 um**, Readout: Plain

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)

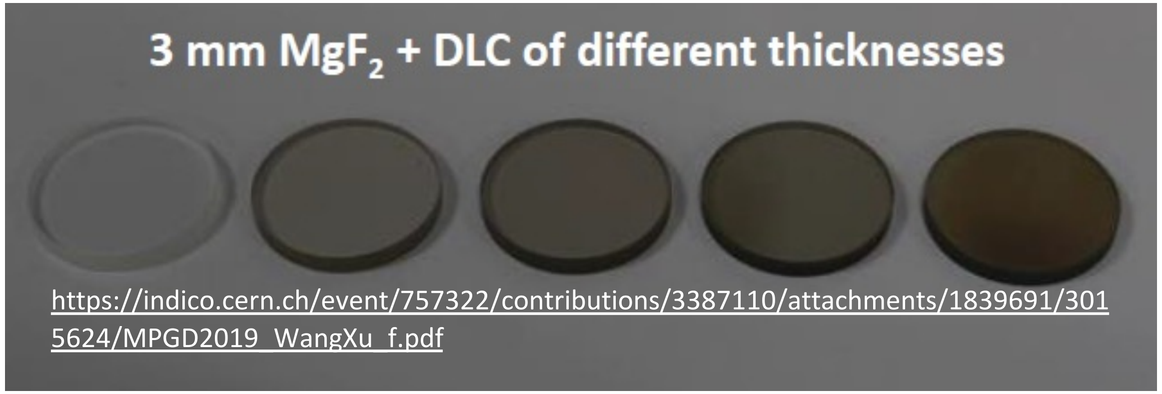
Pros:

- 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

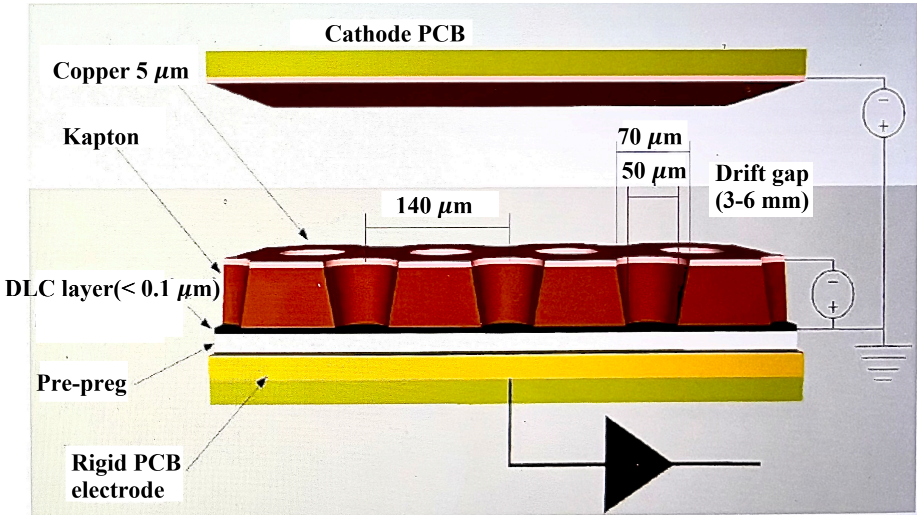
We will investigate radiator materials for higher photon yield capability



μRWELL: Layout

Courtesy: Giovanni Bencivenni

The uRWELL is a resistive Micro Pattern Gas Detector (MPGD) that incorporates a gas electron multiplier (GEM)-derived amplification stage.



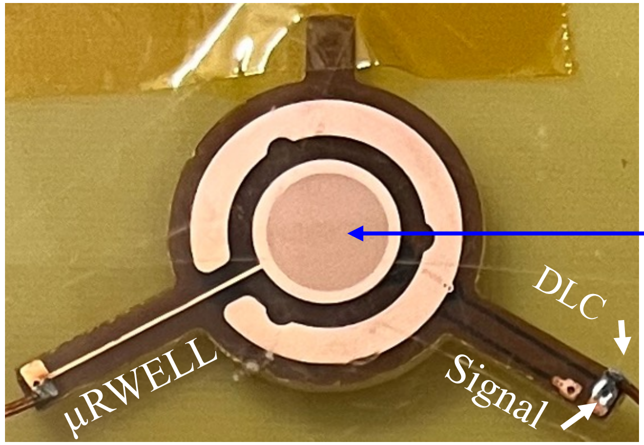
Two primary components:

- ✓ **Cathode PCB**
- ✓ **uRWELL PCB**: features a WELL-patterned Kapton foil with an overlying copper layer serving as the amplification stage.

This assembly exhibits a resistivity of approximately 50÷100 MΩ/□, along with a standard readout PCB that utilizes pad/strip segmentation for signal extraction.

- Fused silica window, MgF_2 as crystal
- Gas mixture of Neon: $C_2H_6 : CF_4 = 80: 10:10$

Single channel μRWELL protoypes (Test beam-2023)



μRWELL-PICOSEC prototype

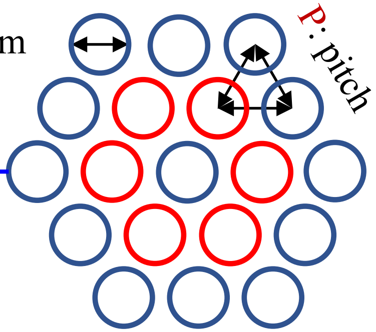
Nomenclature of the prototypes:

T150-P140-D70

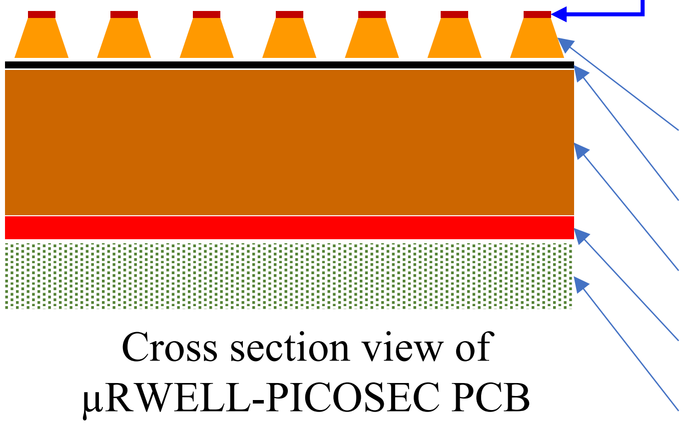
T = 150 μm ➔ Kapton thickness

P = 140 μm ➔ Hole pitch

D = 70 μm ➔ Hole Outer Diam.

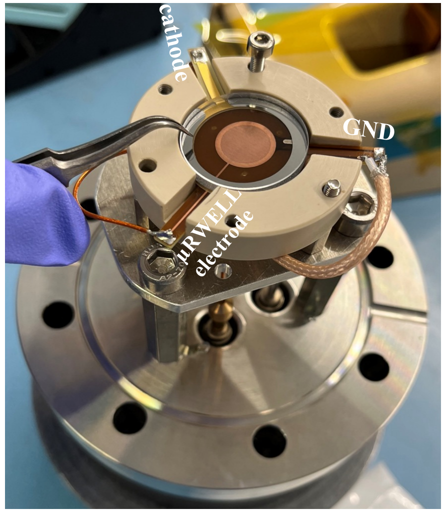


hole geometry

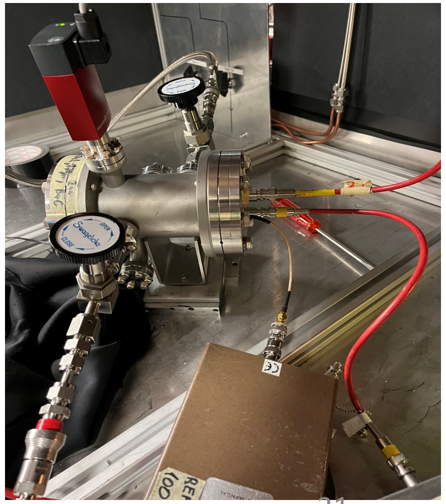


Cross section view of μRWELL-PICOSEC PCB

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



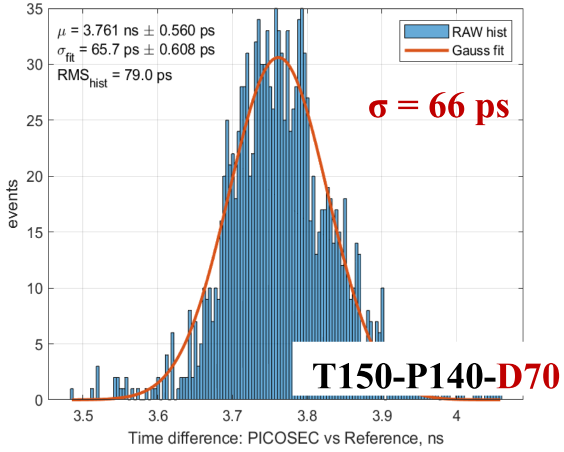
Single-pad μRWELL-PICOSEC prototype

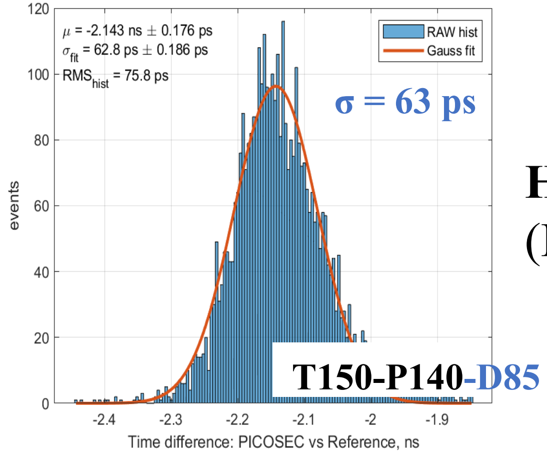


Prototype on test bench at CERN GDD Lab

Jefferson Lab

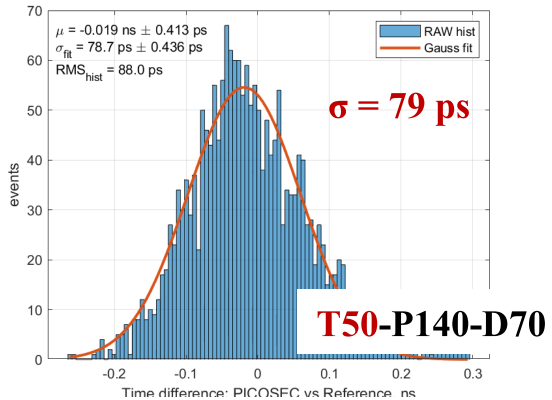
Preliminary results (Test beam-2023)

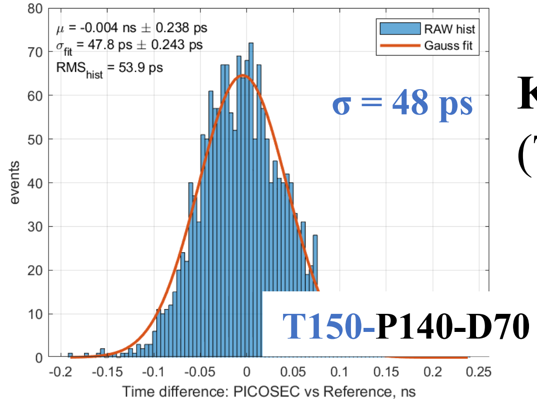




Hole diameter comparison

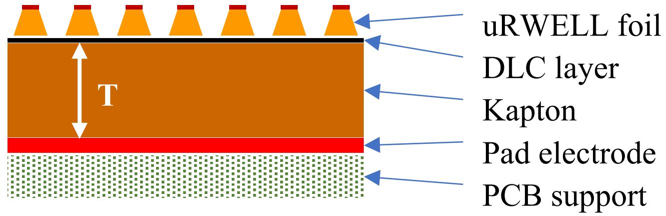
(Larger holes for same pitch ➔ better timing)



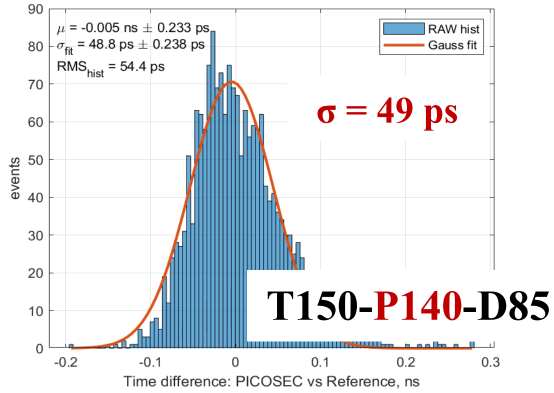


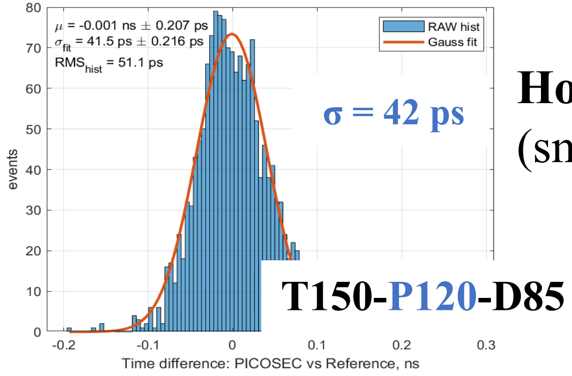
Kapton thickness comparison

(Thicker Kapton ➔ better timing)



Cross section view of μRWELL-PICOSEC PCB

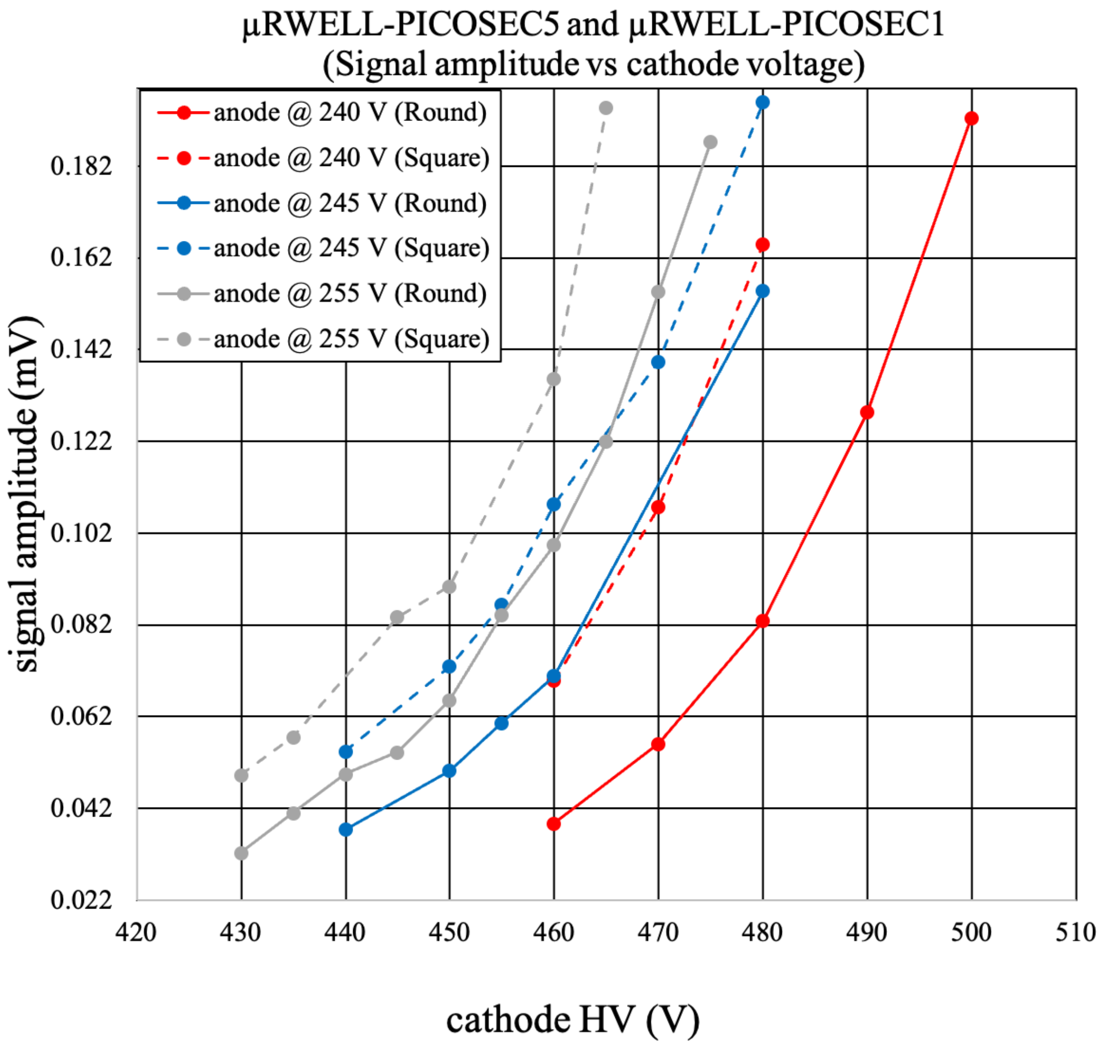


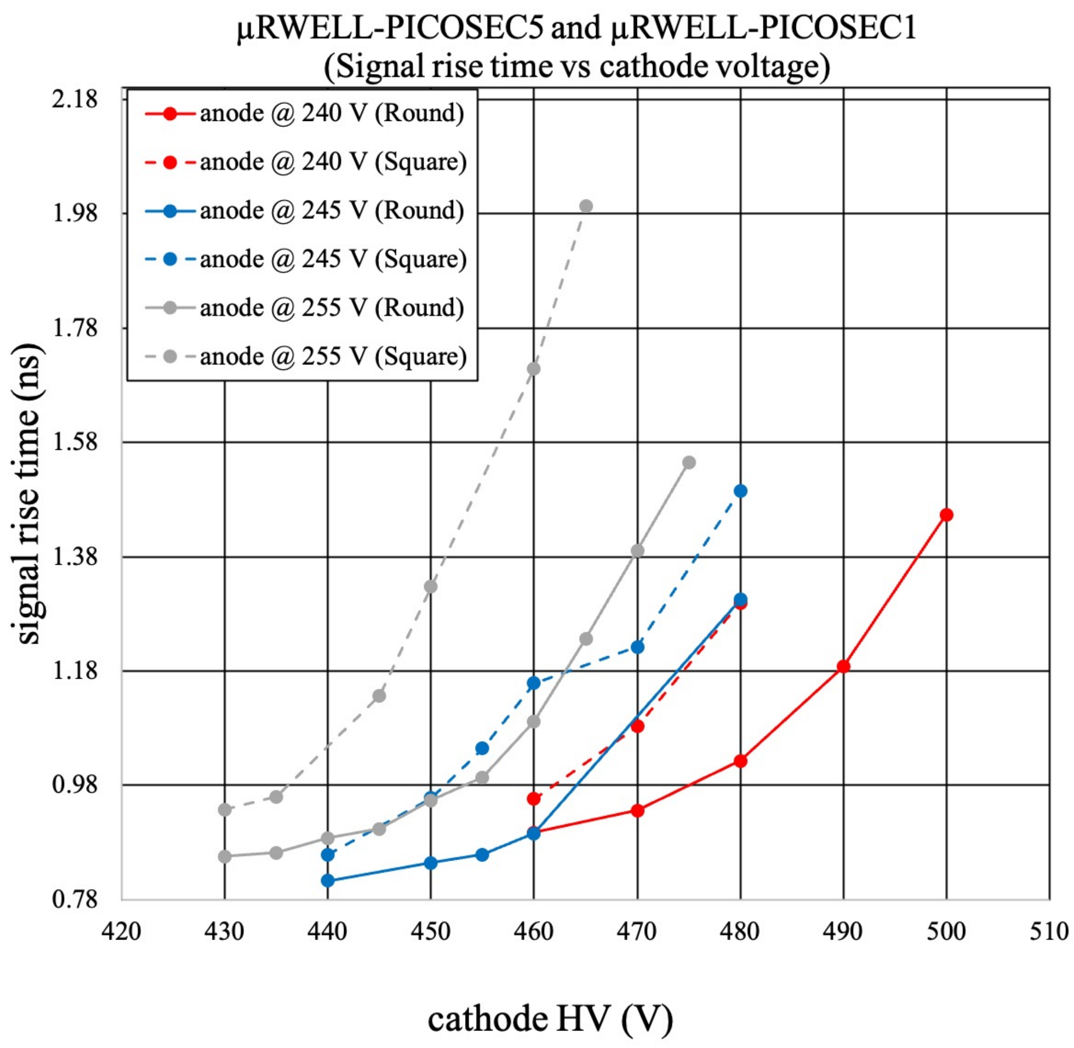


Hole pitch comparison

(smaller pitch ➔ better timing)

Signal Characteristics Influenced by Hole Shape



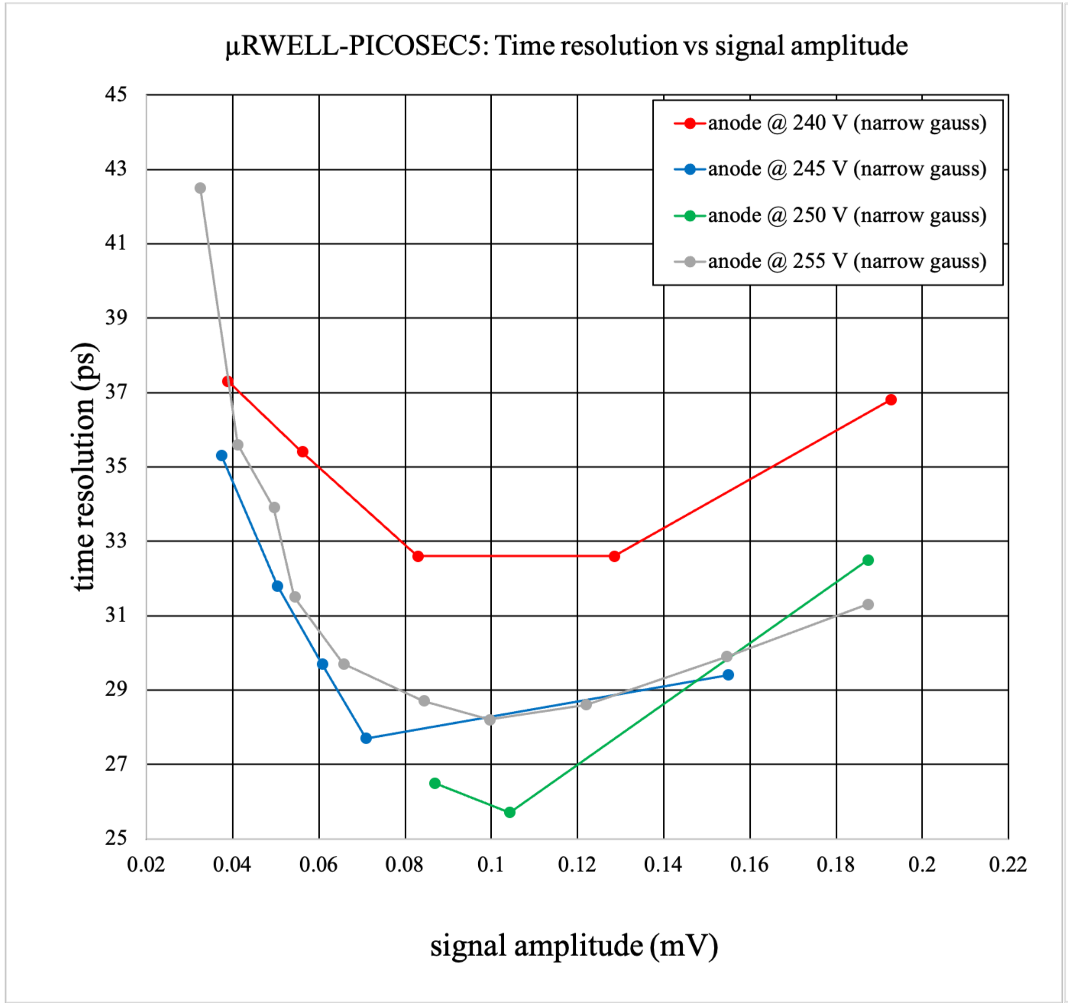


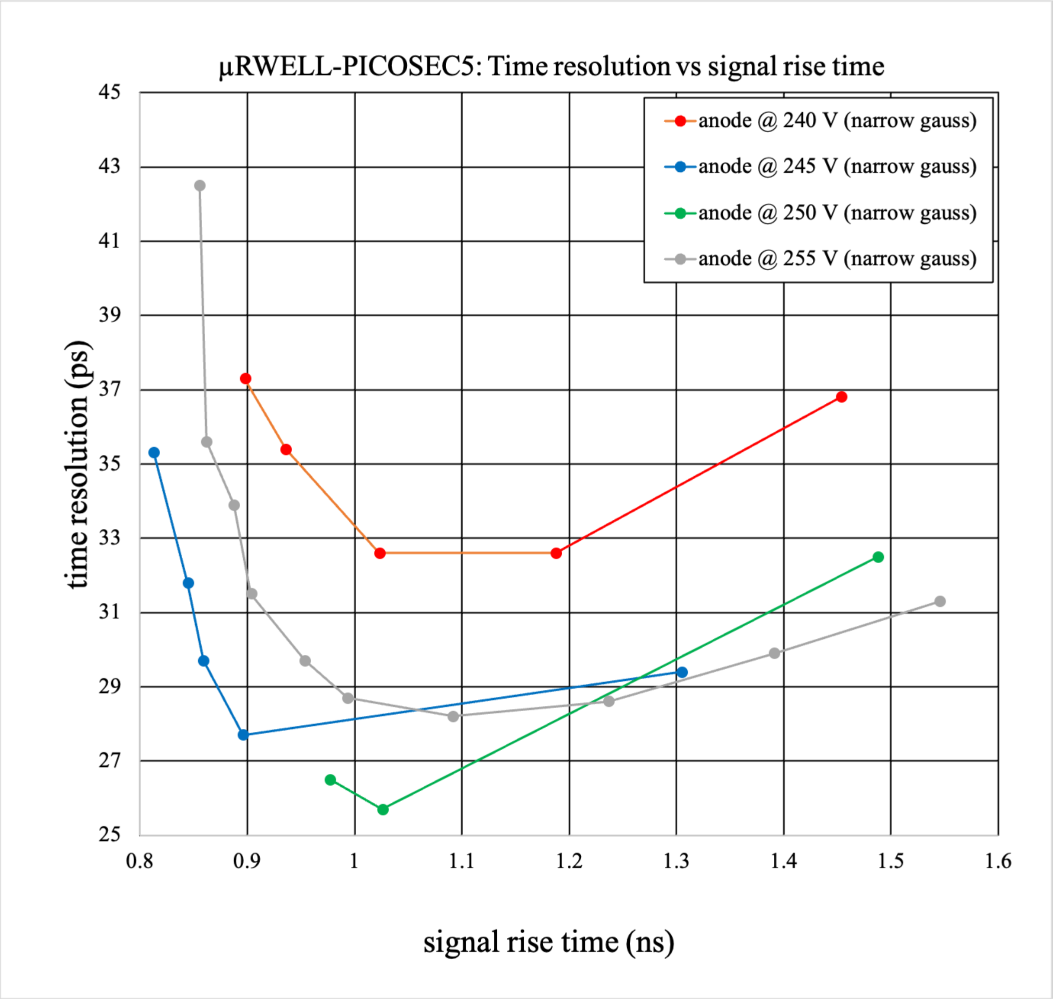
uRWELL-PICOSEC5**: Pitch** (µm): 120, **Hole(o)** (µm): 100, **Hole(i)** (µm): 80, **Hole shape: Round**, **Readout:** Plain, **Spacer** (µm): 170, **Photocathode:** CsI
uRWELL-PICOSEC1**: Pitch** (µm): 120, **Hole(o)** (µm): 100, **Hole(i)** (µm): 80, **Hole shape: Square**, **Readout:** Plain, **Spacer** (µm): 170, **Photocathode:** CsI

Jefferson Lab

prototype with round hole geometry demonstrated lower signal amplitude and rise time, alongside improved timing resolution compared to the square hole geometry. These results suggest that the shape of the holes significantly affects overall signal performance.

Correlation of Time Resolution with Signal Amplitude and Signal Rise Time

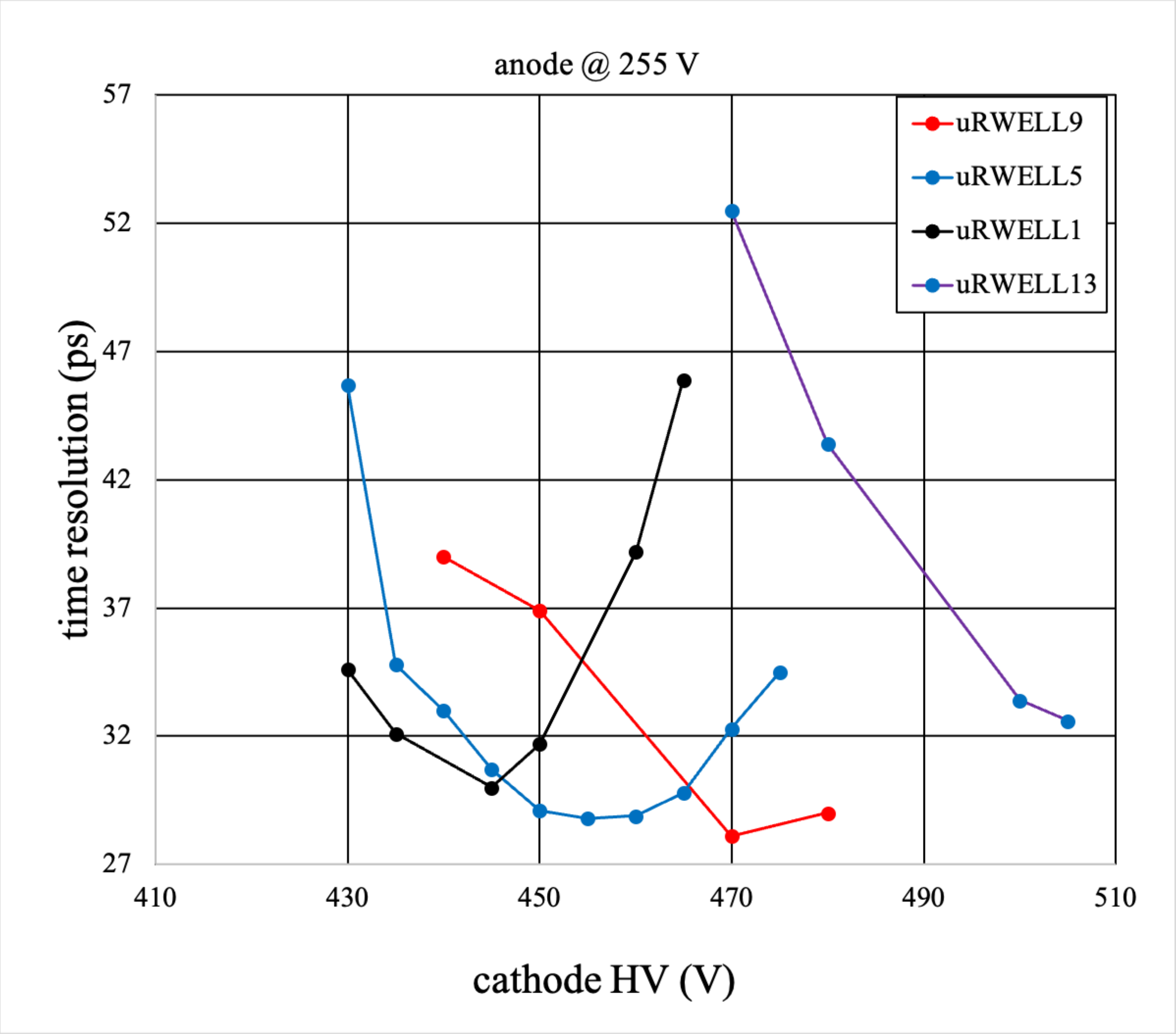




uRWELL-PICOSEC5**: Pitch** (µm): 120, **Hole(o)** (µm): 100, **Hole(i)** (µm): 80, **Hole shape:** Round, **Readout:** Plain, **Spacer** (µm): 170, **Photocathode:** CsI

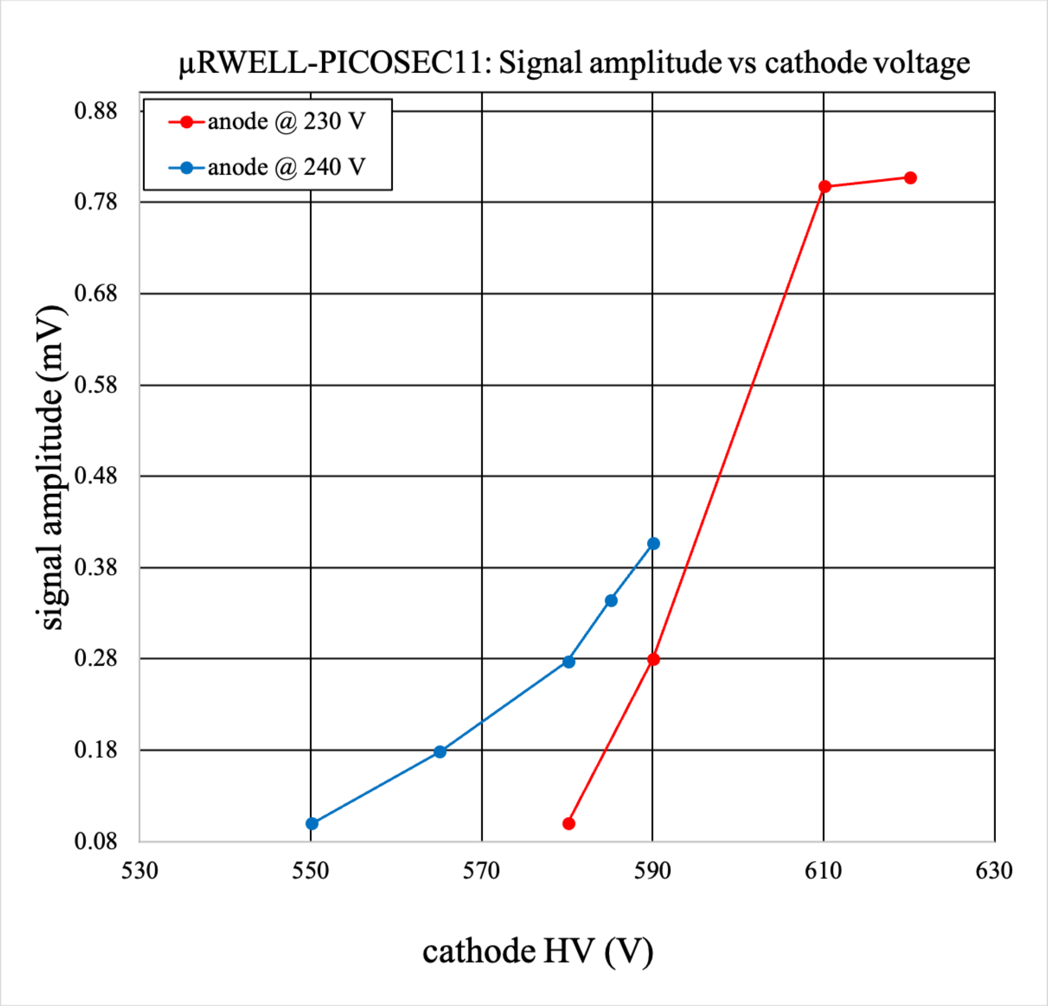
The magnitude of time resolution decreases as signal rise time and signal amplitude increases, reaches a minimum point, and then begins to increase again with further increases in rise time as well as signal amplitude.

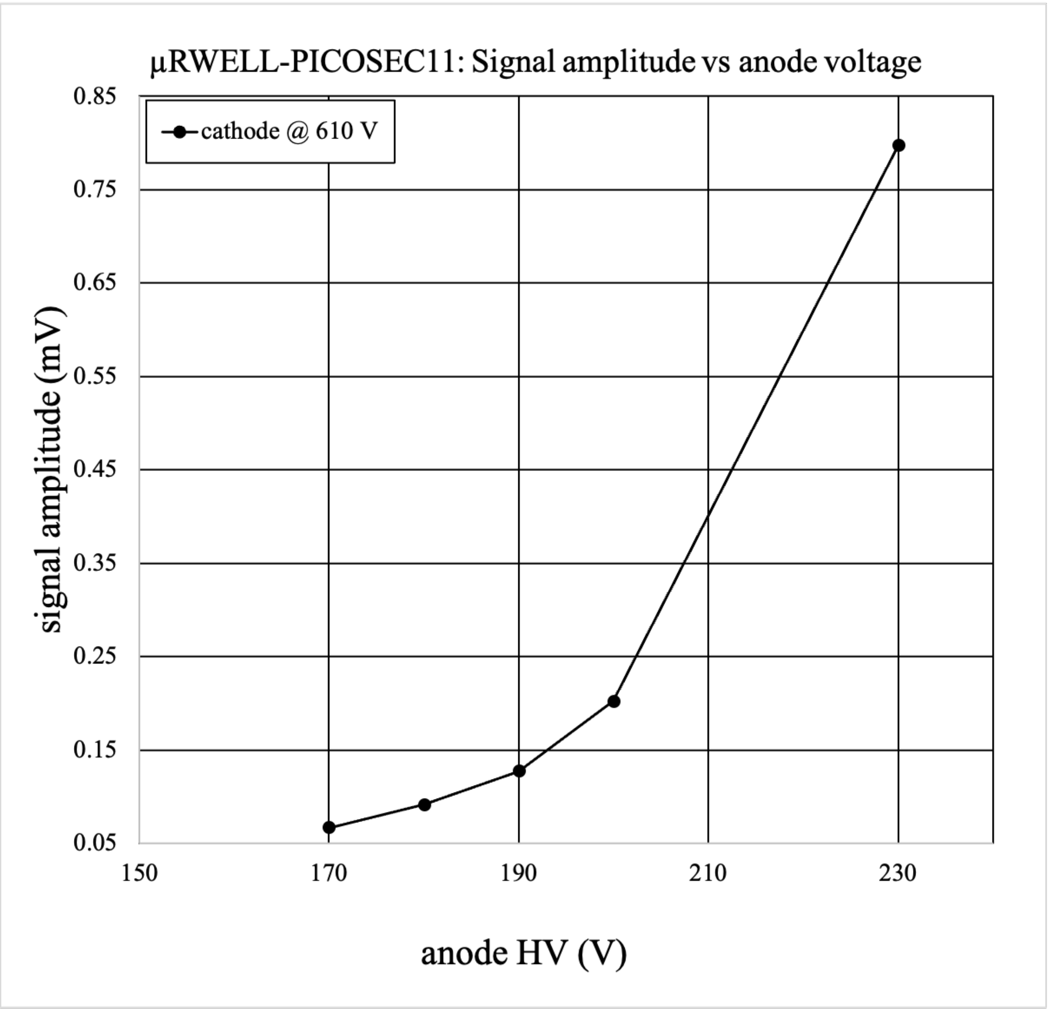
Timing characteristics in Single-Channel Prototypes with constant Anode Voltage



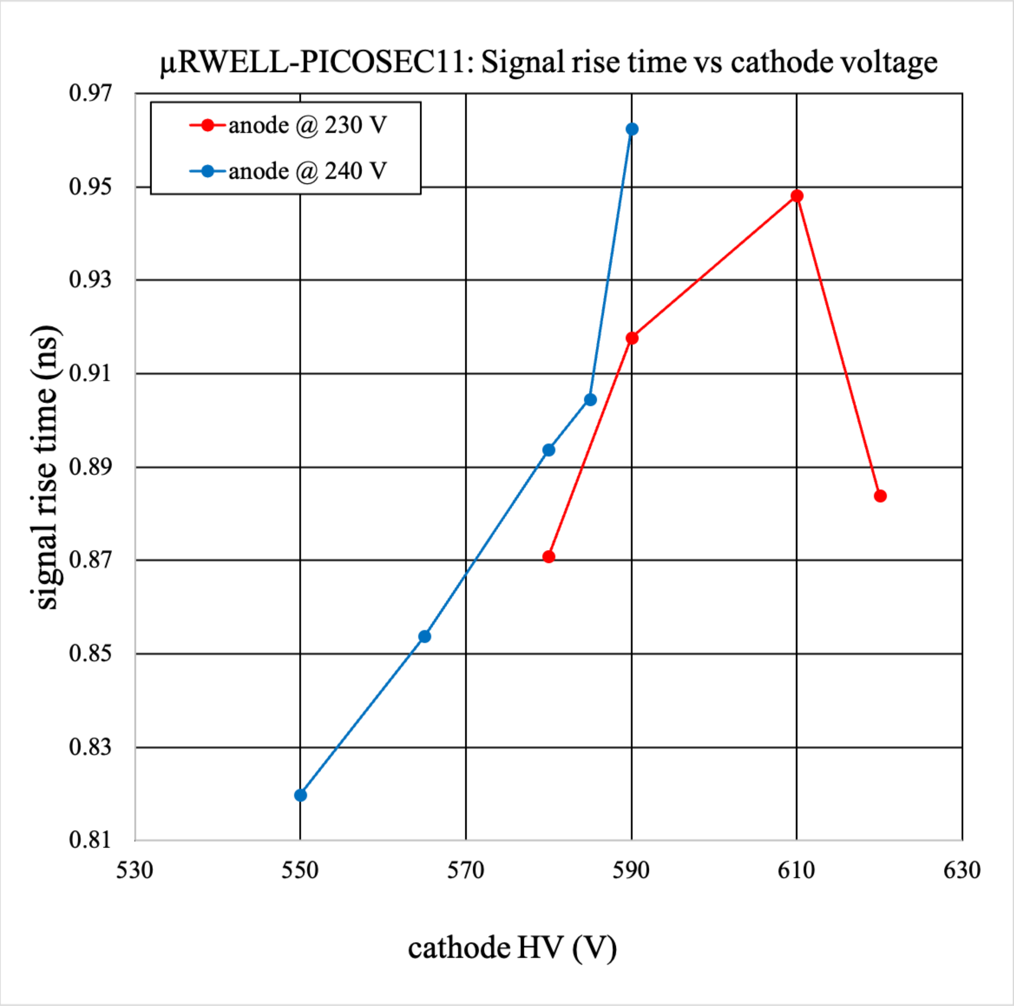
	uRWELL5	uRWELL1	uRWELL9	uRWELL13
Pitch (µm)	120	120	100	80
Hole(o) (µm)	100	100	80	60
Hole(i) (µm)	80	80	60	40
Hole shape	Round	Square	Round	Square
Readout	Plain	Plain	Plain	Plain
Spacer (µm)	170	170	170	170
Photocathode	CsI	CsI	CsI	CsI

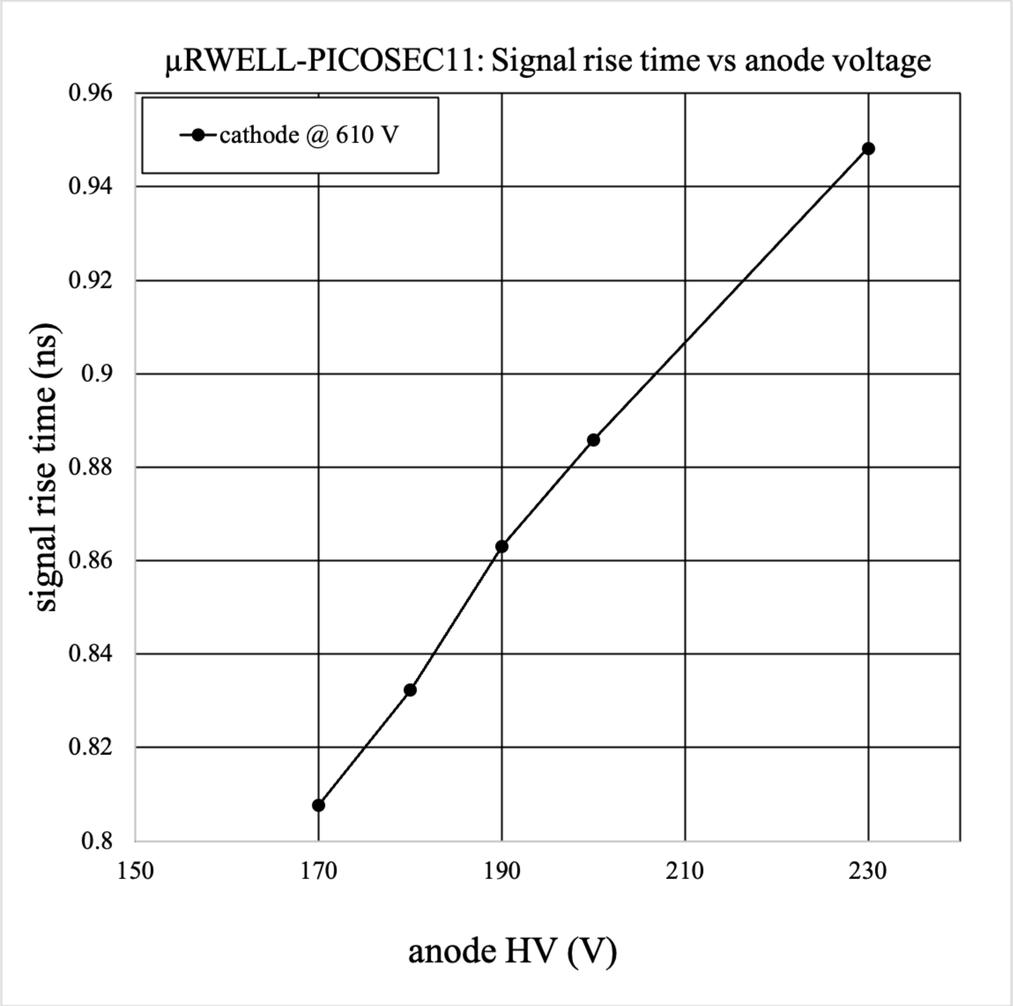
The prototype with higher pitch, larger hole diameters, round shape hole exhibits superior timing performance compared to those with lower pitch, smaller diameters, square shape hole.





uRWELL-PICOSEC11**: Pitch** (µm): 100, **Hole(o)** (µm): 80, **Hole(i)** (µm): 60, **Hole shape**: Round, **Readout:** Gridded, **Spacer** (µm): 170, **Photocathode:** DLC





uRWELL-PICOSEC11**: Pitch** (μm): 100, **Hole(o)** (μm): 80, **Hole(i)** (μm): 60, **Hole shape**: Round, **Readout:** Gridded, **Spacer** (μm): 170, **Photocathode:** DLC