µRWELL-PICOSEC: Development of Fast Timing Detector based µRWELL Technology

Kondo Gnanvo

JLab Radiation Detectors & Imaging Group (RD&I Group)

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Wenze Xi, Jack McKisson, Brian Kross
JLab - RD&I Group

Klaus Dehmelt , Wenglian Lee
Stony Brook University

Outline

- Introduction and concept of picosecond timing with Micro Pattern Gaseous Detectors (MPGDs)

- Development of µRWELL-PICOSEC detector within the JLab LDRD FY23 (LD2309).

- Preliminary results of first prototype.

- Ongoung R&D and approaches to address challenges and limitations of µRWELL-PICOSEC.

µRWELL-PICOSEC: Development of 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.

Application in Future Experiments at JLab and the EIC and beyond:

- **EIC detector I upgrade and future detector II:** Fast timing technology such as µRWELL-PICOSEC can be an attractive alternative options to AC-LGADs for TOF, LAPPDs for Cerenkov photosensors technologies currently under consideration.
- **Added value performance of µrPICOSEC: high-rate capability, stable in strong B-field, radiation hard, large-area, low-cost**
- High-luminosity / high energy upgrades at JLab: we anticipate demand for cutting edge technologies for high performance and cost effective PID detectors such as TOF and Cerenkov to satisfy the physic requirements of future experiments.
- Potential application in medical instrumentation i.e TOF-PET devices

µRWELL-PICOSEC compared to 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 ✓

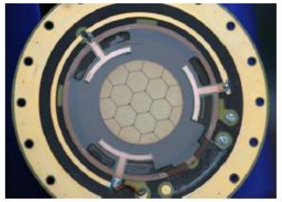
MM-PICOSEC Collaboration at CERN

PICOSEC-MM: 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 and SBU)**
- ❖ Proof of principle picosecond timing with MPGD established with several PICOSEC-MM prototypes:
  - ▪ Single-channel and small gap (100 µm) prototype ➔ 17 ps with MIPs
  - ▪ Large-area (10 cm × 10 cm) and multi-channel (100 pads) prototype ➔ 25 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)
  - ▪ The RD & I group at JLab is member of both RD51 and PICOSEC-MM
  - ▪ **Strong synergy between PICOSEC-MM & µrPICOSEC ➔ leverage on expertise & experience of PICOSEC-MM community**

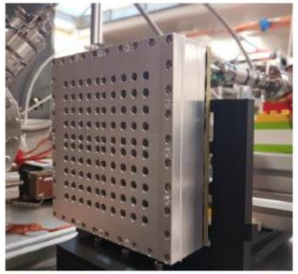
- 1-ch (ϕ1cm)
- Proof of concept
- Resistive and non-resistive prototypes.

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



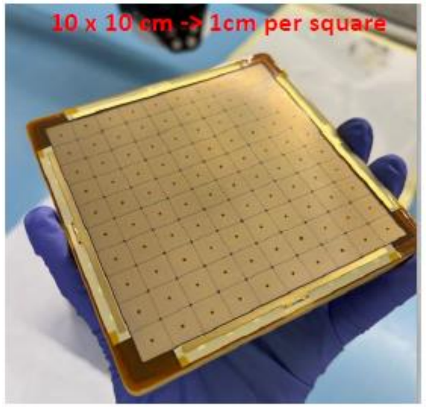
- 19-ch (ϕ3.6cm)
- Signal sharing.

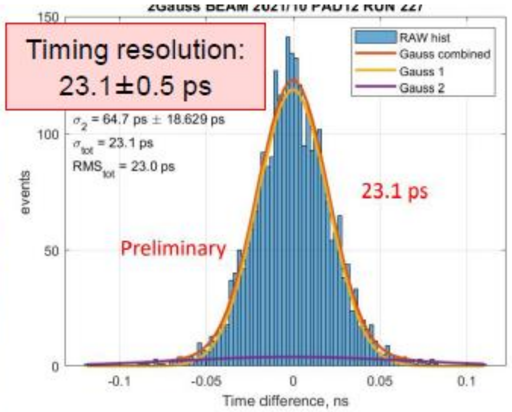
- 100-ch (10 cm x10 cm)
- Tileable
- Hybrid ceramic substrate MM
- MM decoupled from housing with spring-loaded pins



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

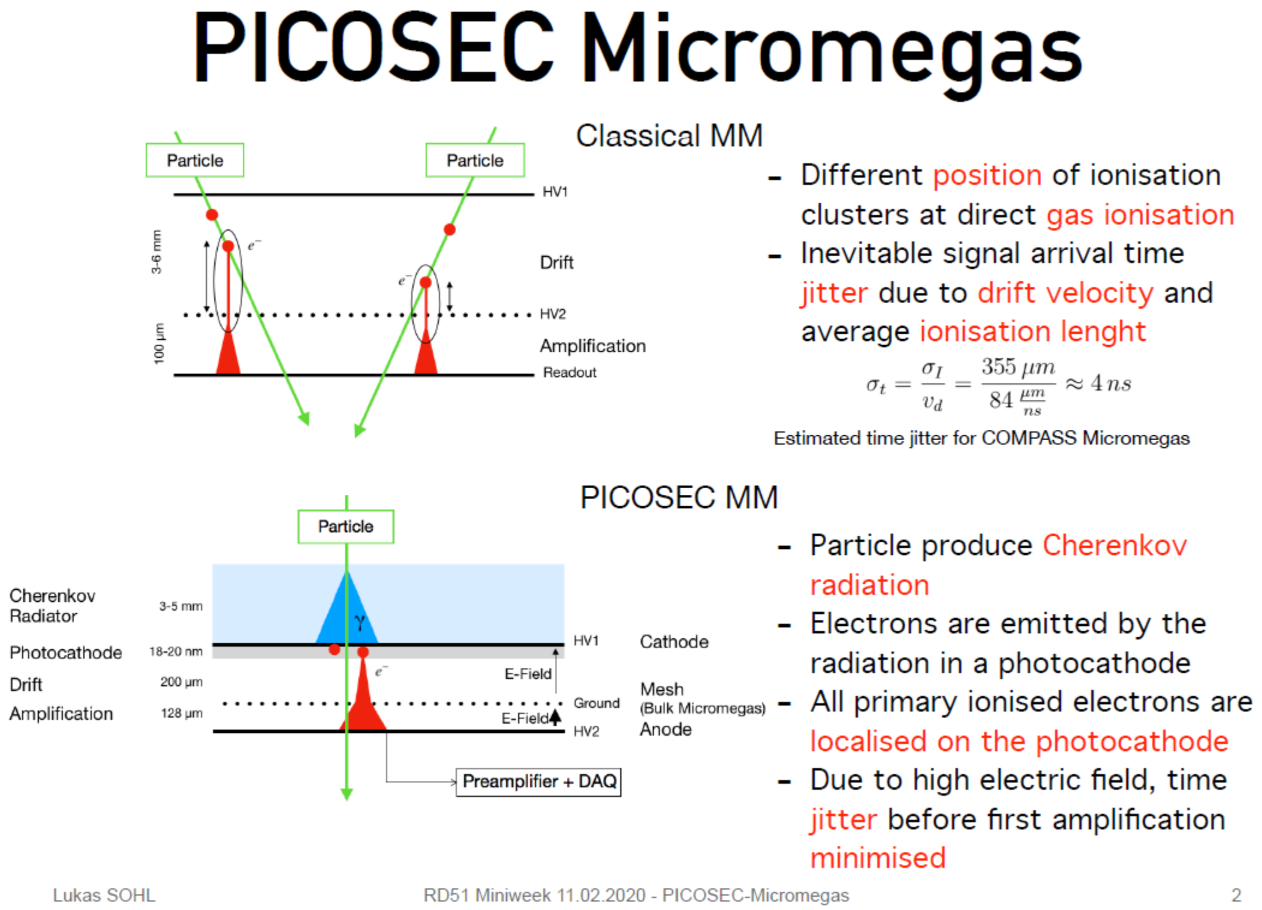
- 100 ch (10 cm x10 cm)
- Sealed Ti housing
- Increased fill factor





- 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

MM-PICOSEC Collaboration at CERN



PICOSEC Micromegas

Classical MM

- Different position of ionisation clusters at direct gas ionisation
- Inevitable signal arrival time jitter due to drift velocity and average ionisation lenght

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

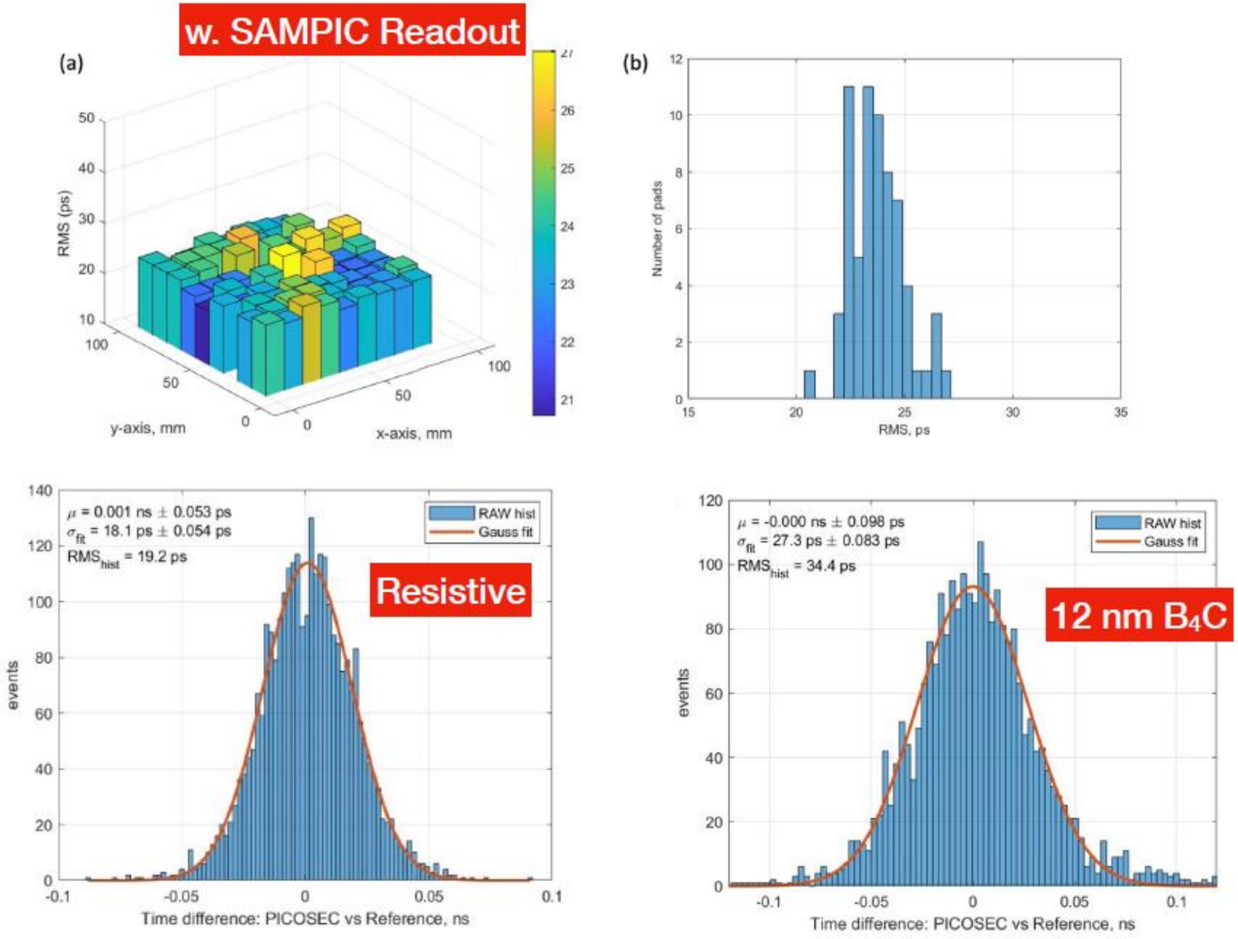
Estimated time jitter for COMPASS Micromegas

PICOSEC MM

- Particle 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

Lukas SOHL RD51 Miniweek 11.02.2020 - PICOSEC-Micromegas 2

Latest performance results of MM-PICOSEC

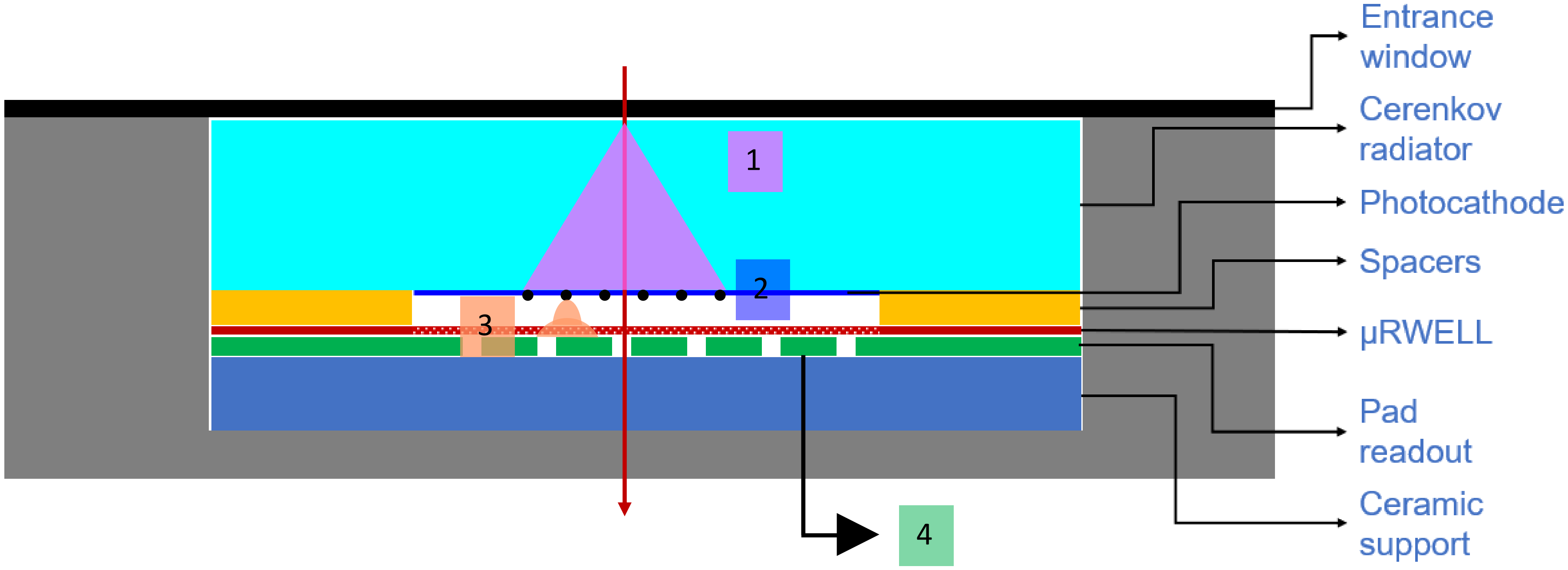


µRWELL-PICOSEC detector concept

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.

1. Cerenkov photons in radiator
2. Photoelectrons in photocathode
3. Pre-amplification in 200 µm gas
3. uRWELL amplification
4. Collection of electronic signal



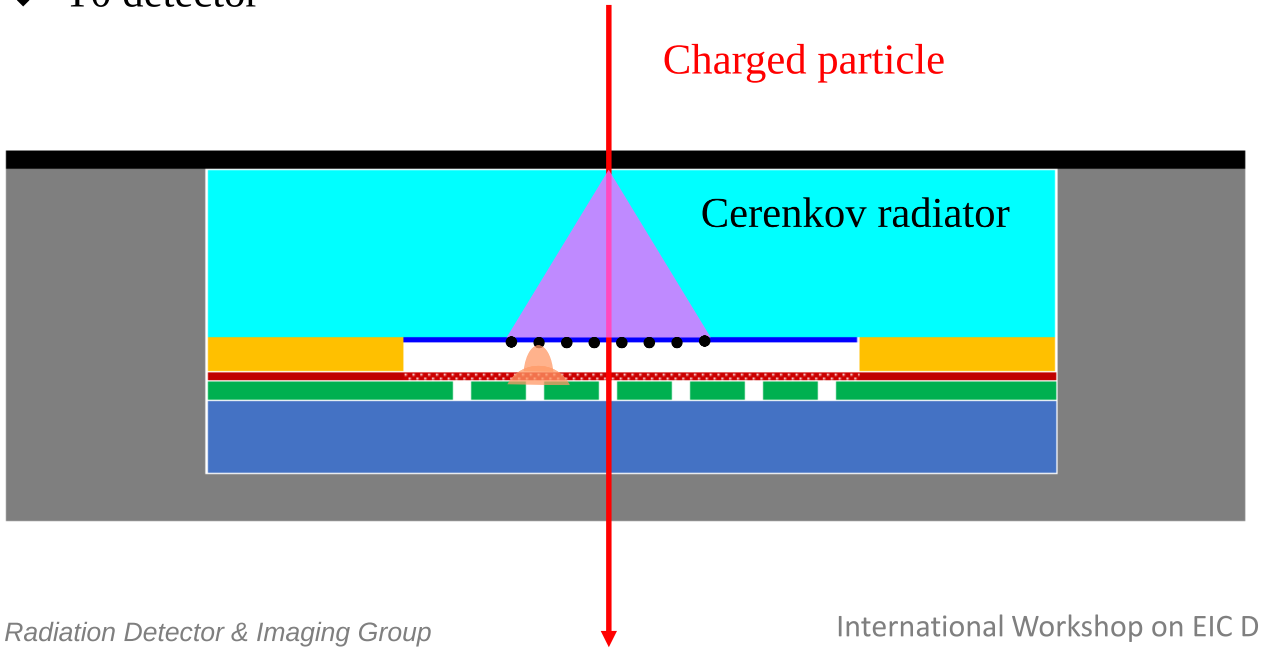
Dual operation modes for µRWELL-PICOSEC

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

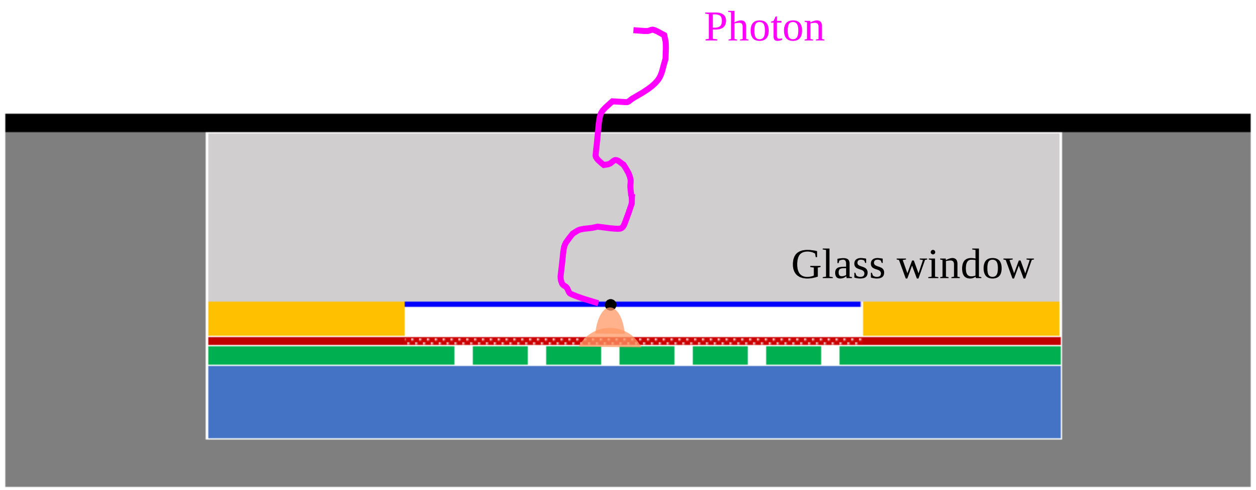


Single photon photodetector:

- ❖ 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 ps

Applications:

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

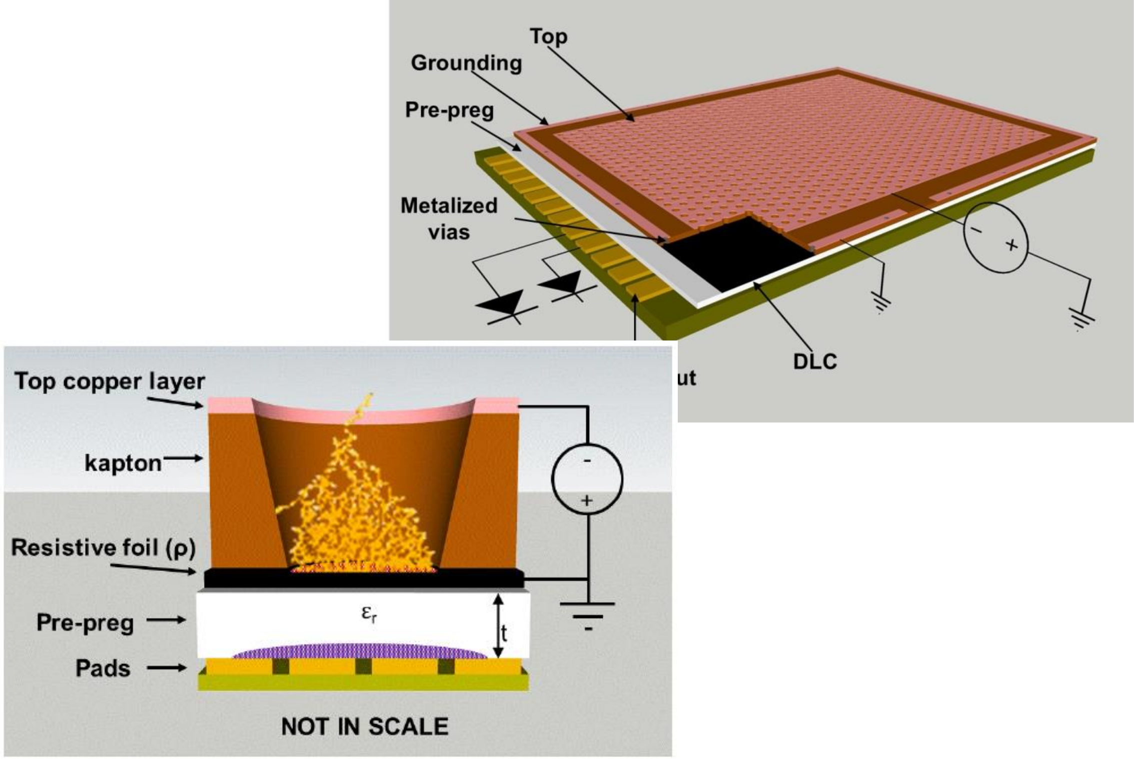


JLab LDRD FY23- LD2309: Development of µRWELL-PICOSEC detector

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.

LD2309: Amplification & readout of μRWELL-PICOSEC

μRWELL detector

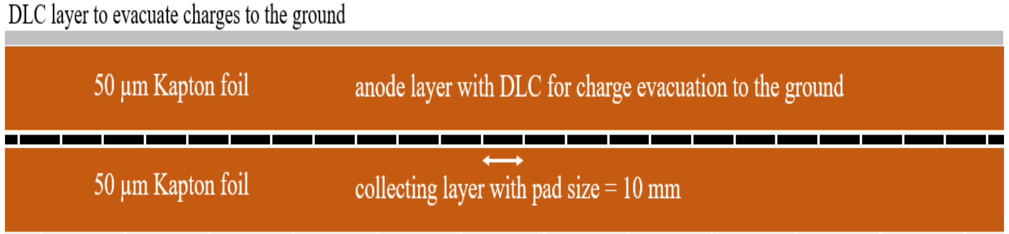


Design of μRWELL foil

- 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
  - Amplification gap 50 μm vs. to 128 μm for MM ➔ improve timing
  - 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



Concept capacitive-sharing pad readout

LD2309: Investigating radiators and photocathodes options

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 alternative 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

Evaporator facility at Stony Brook University (SBU):

- Radiator and photocathode materials studies performed at SBU
- SBU to provide an Ion-Beam Assisted Physical Vapor Deposition (IBA-PVD) apparatus in an Ultra-High Vacuum (UHV) vessel to for the studies:
- Needs to complement with cryogenic vacuum pumping device to improve the status of UHV to perform the for the proposed investigation

This R&D effort isled by Stony Brook Univ. colleagues

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 alternative radiator materials:

- For higher photon yield capability
- Explore focusing optic elements integrated into radiator material
  - combine high photon yield in a small area
  - Improve timing resolution and position resolution capability

3 mm MgF_2 + DLC of different thicknesses

https://indico.cern.ch/event/757322/contributions/3387110/attachments/1839691/3015624/MPGD2019_WangXu_f.pdf

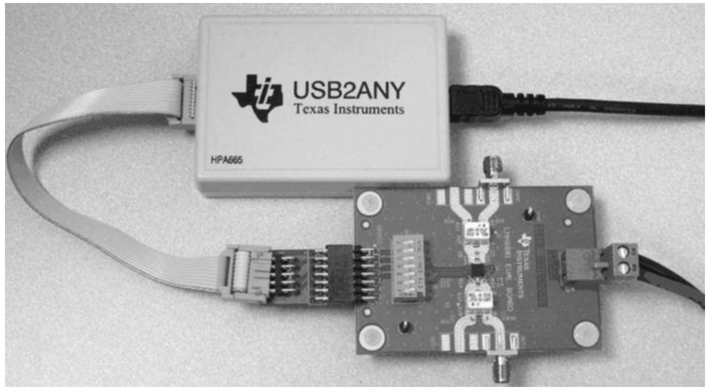
LD2309: Development of Readout and DAQ for uRWELL-PICOSEC

Testing:

High performance oscilloscope: Rohde & Schwarz, model RTP164B

- Provide 2 × 16 Ghz bandwidth channels for
- Sub-picosecond timing resolution with statistical analysis
- Measurement for differential SNR for detector output
- 40 Gsamples/s
- 16 bits measurement precision

Rohde & Schwarz, model RTP164B



LMH6881: Programmable differential amplifier

+

CAEN FERS-5203: 64-channel Pico-TDC

Data Acquisition System:

Provide 64 TDC channels with each channel:

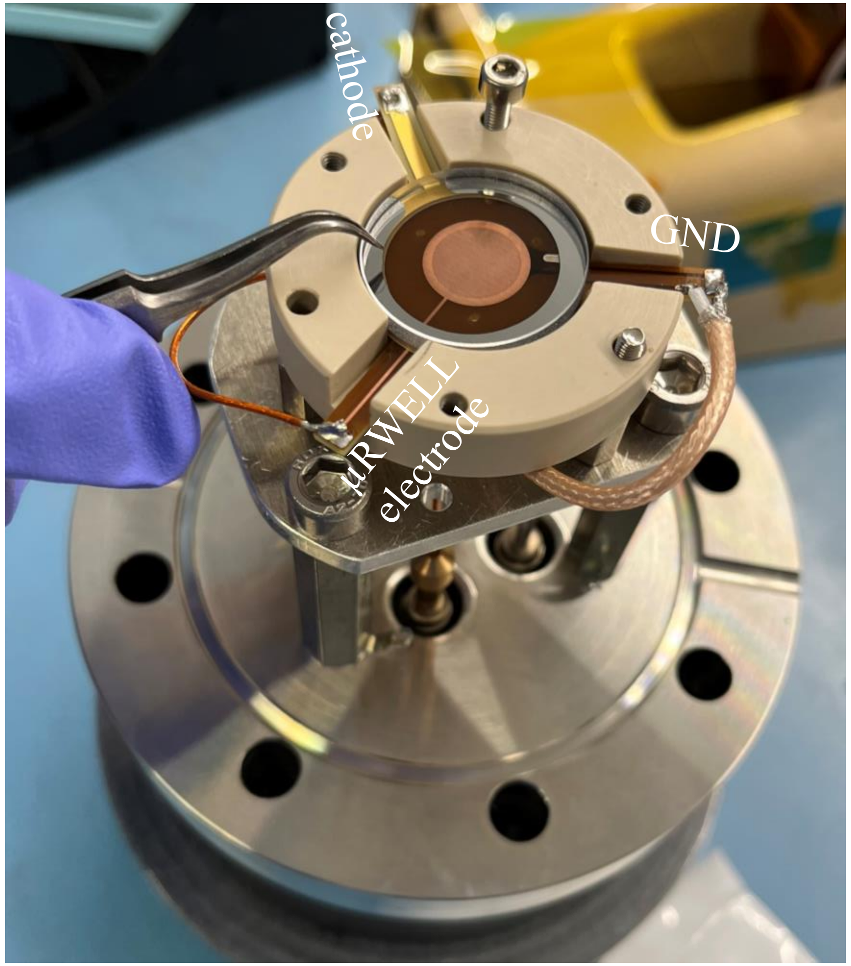
- ~7 ps RMS timing resolution
- LVDS input differential signals
- 3.5 Gbits/s Optical ethernet bus

LD2309 First prototype: Small single-channel uRWELL-PICOSEC

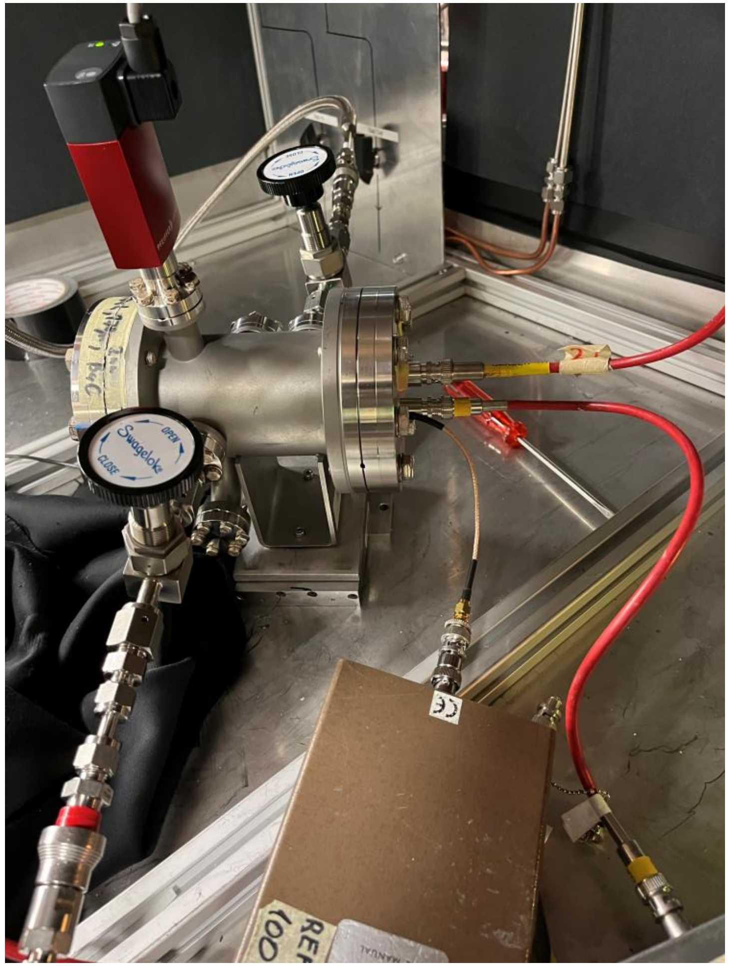
First µRWELL-PICOSEC prototype

- Single-pad small prototype
  - 3 cm diameter active area
  - 3 mm thick radiator + CsI photocathode
  - Sensor: 50 µm µRWELL + Kapton
  - µRWELL Holes: pitch / outer diameter-inner diameter 140 µm / 70 µm / 50 µm
- Preliminary tests with laser source (GDD lab, December 2022)
  - Demonstrate that the µRWELL works in picosecond mode
  - Prototype very resilient against sparks
  - Poor timing performance compared to Micromegas (MM-PICOSEC)
- Lessons learned from preliminary tests
  - Several parameters to be tweaked to improve resolution

Single-pad µRWELL-PICOSEC prototype



Prototype on test bench at CERN GDD Lab

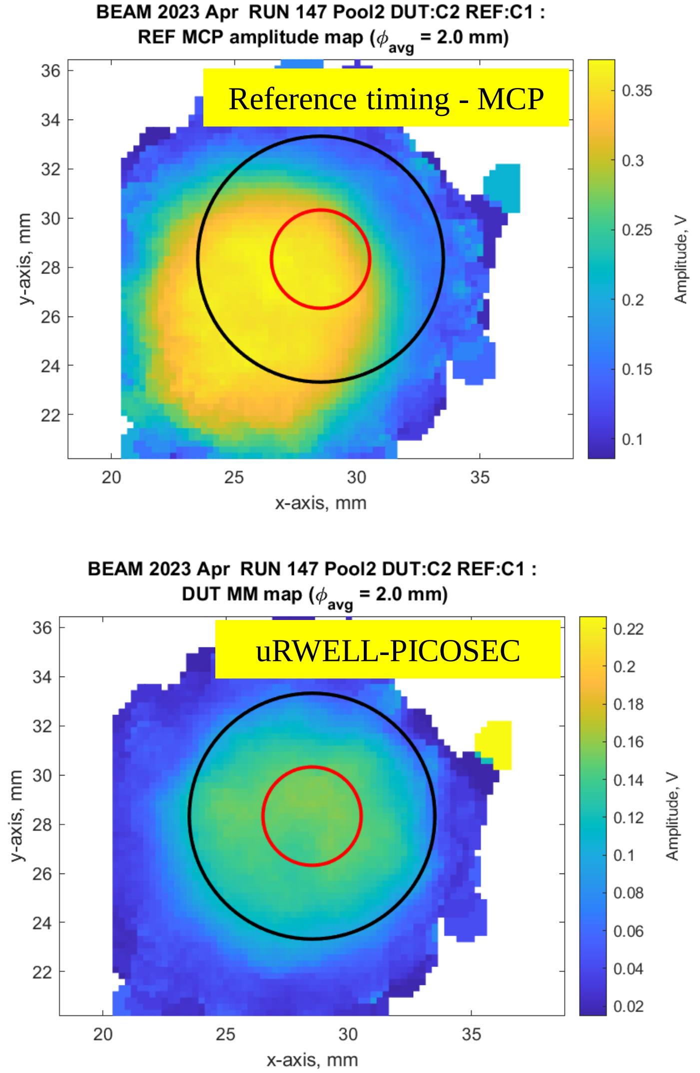


LD2309 First prototype: Test beam and preliminary results

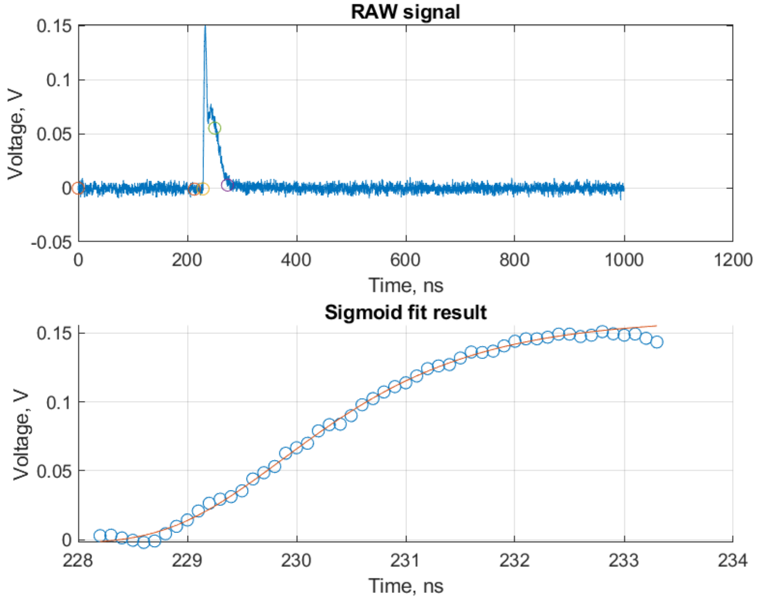
Prototype was tested again in beam at CERN (April 2023)

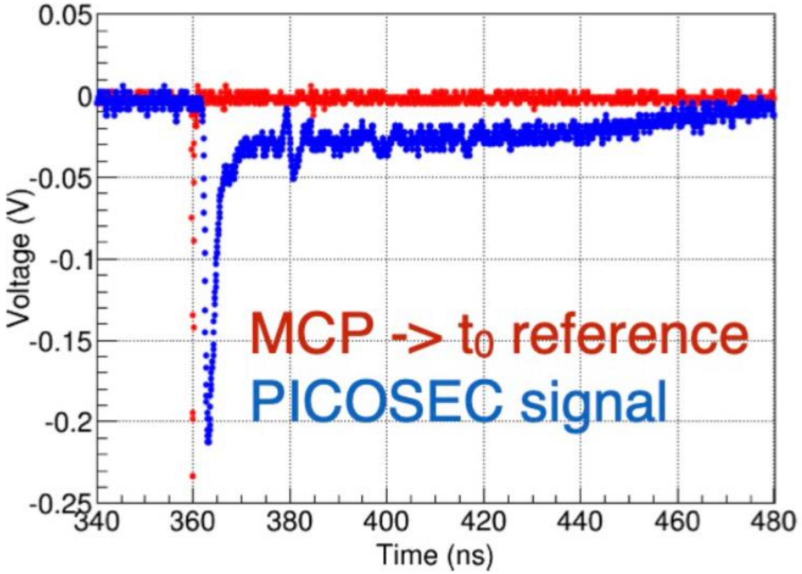
- ❖ More extensive tests in pion beam (RD51-PICOSEC coll. beam test (April 2023)
- ❖ HV scan to determine optimal anode HV vs. cathode HV combination
  - ▪ HV Anode (µRWELL) ➔ 160 V – 300 V
  - ▪ Cathode HV ➔ 380 V – 520 V
- ❖ Analysis of the data is ongoing

Signal amplitude XY map



Typical uRWELL-PICOSEC signal

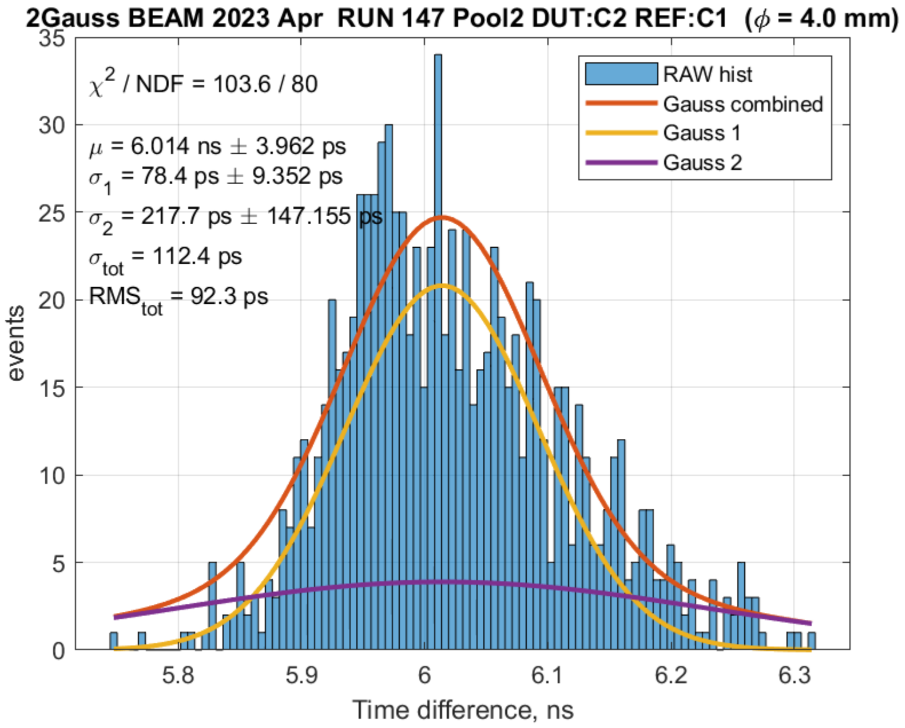




LD2309 First prototype: Preliminary timing performances

- HV scan (drift pre-amplification and μRWELL amplification)
- Best timing resolution with prototype: 84 ps for voltage setting Anode = 300 V and cathode 480 V
- **Preliminary** ➔ Analysis is ongoing

Timing resolution



Run number	Anode	Cathode	Time resolution	Ampl	Rise Time	Efficiency
147	300	380	92.3	150	2.61	63.4
153	270	430	101	272	2.54	87.2
154	270	420	89	183	2.47	85.6
155	270	410	90	133	2.48	79.7
150	250	450	98	254	2.48	87.8
151	250	440	91.5	177	2.42	86.7
152	250	430	84.5	134	2.43	79.4
159	200	500	92.5	222	2.36	77.9
165	200	480	83.8	136	2.32	74
162	200	460	96.5	73	2.31	44.4
158	160	520	92.8	130	2.26	75.6
161	160	480	136	36	2.01	28.2

LD2309 First prototype: First takes on preliminary test results

- 80 ps time resolution for the first prototype is very encouraging, **but** ~4 × higher than MM-PICOSEC and R&D goal

- Differences in amplification structure between Micromegas and µRWELL could help explain the

1. Amplification gap: Micromegas 128 um vs. µRWELL 50 um
2. Mesh area in Micromegas 20% vs. 80% in µRWELL

   ➔ Input capacitance from the amplification structure to the signal is significantly higher µRWELL .

3. Electric field lines in the pre-amplification drift region are different between Micromegas and µRWELL

   ➔ This also has a strong impact on the path of the electrons drift to the amplification devices, need to find the right electronic field balance between pre-amplification and amplification for an optimize timing

4. Recent beam test results with resistive Micromegas suggest that the resistivity of the DLC layer has to be tuned for optimal timing

LD2309 First prototype: New prototypes in beam test (July 2023 @ CERN)

- ❖ 4 new µRWELL-PICOSEC PCBs under fabrication to study the parameters for better timing performance
  1. Increase the gap between the µRWELL foil and the pick-up pad electrode from 50 µm to 150 µm
     ➔ reduce the capacitance noise effect
  2. Samples with different µRWELL hole parameters to study impact of electric field and geometric transparency
     - Standard configuration: pitch = 140 um / outer diam. = 70 um / inner diam. = 50 um ➔ 20% transparency
     - 3 new configurations: 140 um / 85 um / 65 um; 120 um / 70 um / 50 um and 120 um / 85 um / 65 um

     ➔ 50% transparency and more straight field lines
- ❖ All 4 new PCB samples will be assembled into µRWELL-PICOSEC prototypes and tested in beam in July 2023
  ➔ Direct comparison of performance with the standard gap and standard holes configuration
- ❖ **Next steps:**
  - ❖ Evaluate the effect of resistive layer (DLC) resistivity on timing resolution (Not be part of the current July 2023 test beam)
  - ❖ Develop large area (10 cm × 10 cm) 100-pad µRWELL-PICOSEC prototype and test performance in beam
  - ❖ Develop capacitive-sharing prototype to extract position information as well

Summary

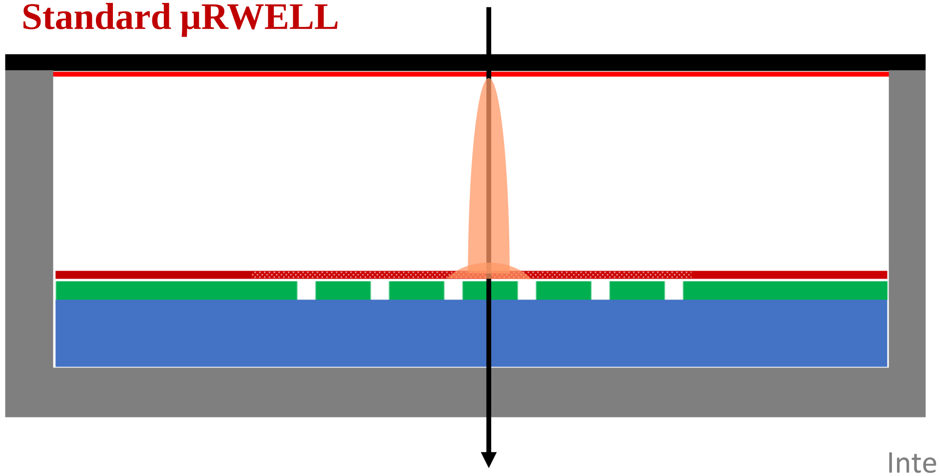
- Exciting ongoing R&D effort to develop gaseous based picosecond level fast timing detector using MPGDs technologies
- MPGD-PICOSEC detectors provide alternative options to Si-based fast timing detectors for TOF in Particle Physics and potential application in medical instrumentations
- CERN based MM-PICOSEC collaboration demonstrate < 20 ps level timing capabilities for high energy charged particle with large-area Micromegas detectors in combination with Cerenkov radiator and photocathode.
- µRWELL could also be used as alternative amplification structure for PICOSEC technologies
- Preliminary results on first µRWELL-PICOSEC prototype developed within the JLab LDRD program delivers ~ 80 ps timing performance ➔ Several ideas to improved further these performance by a factor ×4 are under investigation
- µRWELL-PICOSEC could be a technology suitable for TOF applications as well as photo-sensor options for EIC Detector II but sustained R&D effort is require to bring the technology to experiment-ready level in time for Detector II operation

Back-up

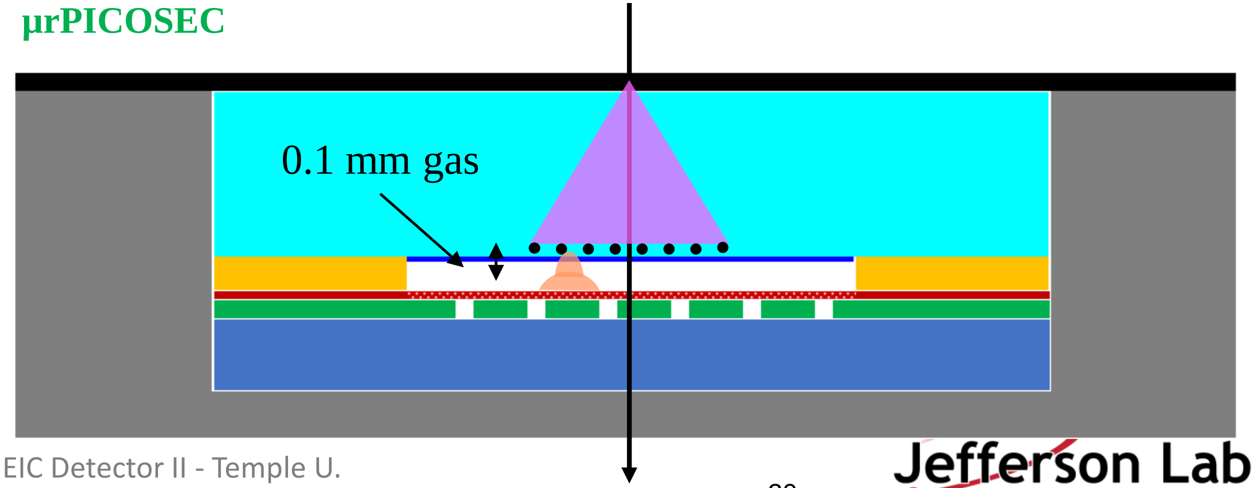
µrPICOSEC vs. standard µRWELL detector

	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 to 50 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

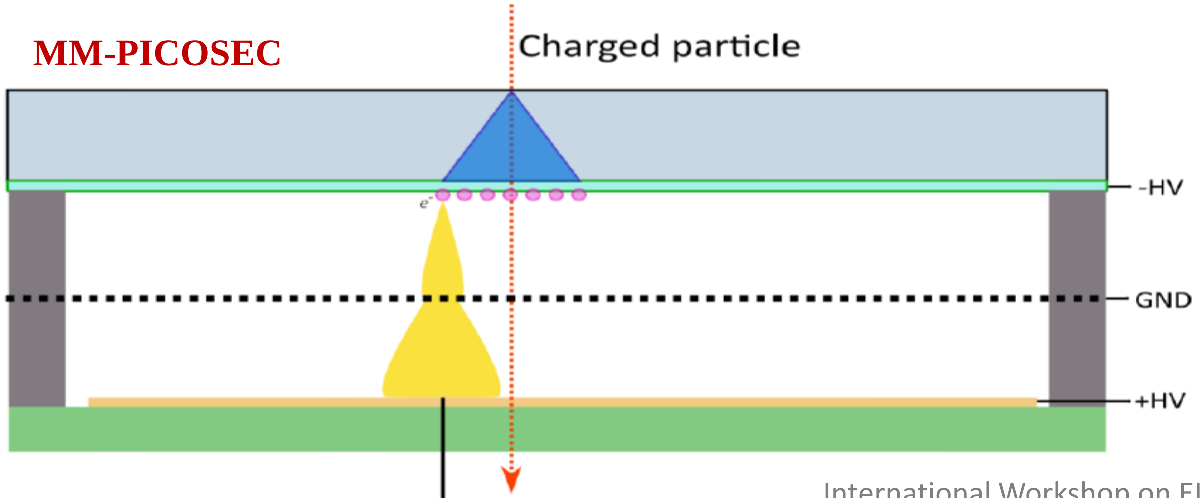


µRWELL-PICOSEC vs. MM-PICOSEC

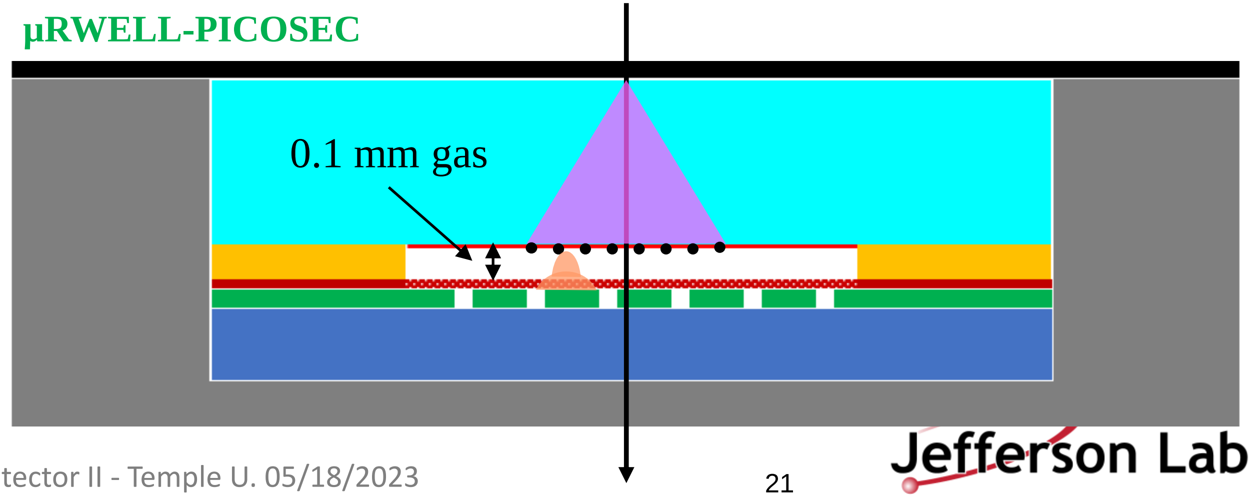
- µRWELL-PICOSEC and MM-PICOSEC belongs to the MPGD-based fast timing detector family
- Different amplification structure will allow different optimization of the technologies in term of operation stability and timing performance
- Parallel development of will mutually benefit the two technologies and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

	MM-PICOSEC	**µRWELL-PICOSEC**	**Comments**
Radiator / photocathode	Same technology can be share by both	Same material can be shared by both	No difference
Pad readout structure	Same technology can be share by both	Same technology can be shared by both	No difference
Amplification structure	Metallic mesh (micromegas) ➔ 128 µm gap (?)	Cu-clad Kapton foil ➔ 50 µm gap ✓ (?)	~~Thinner gap ➔ expect better timing performance with µrPICOSEC~~
Resistive / metallic	Both options available ✓	Only resistive	Resistive ➔ more stable Metallic ➔ better timing
Segmentation MPGD	Segmentation of the metallic mesh will be challenging	µRWELL Cu-electrode can be segmented (PEP) ✓	Signal from segmented uRWELL ➔ improved timing performance (?)

MM-PICOSEC



µRWELL-PICOSEC



µRWELL-PICOSEC vs. MM-PICOSEC: Drift Field Lines

MM-PICOSEC

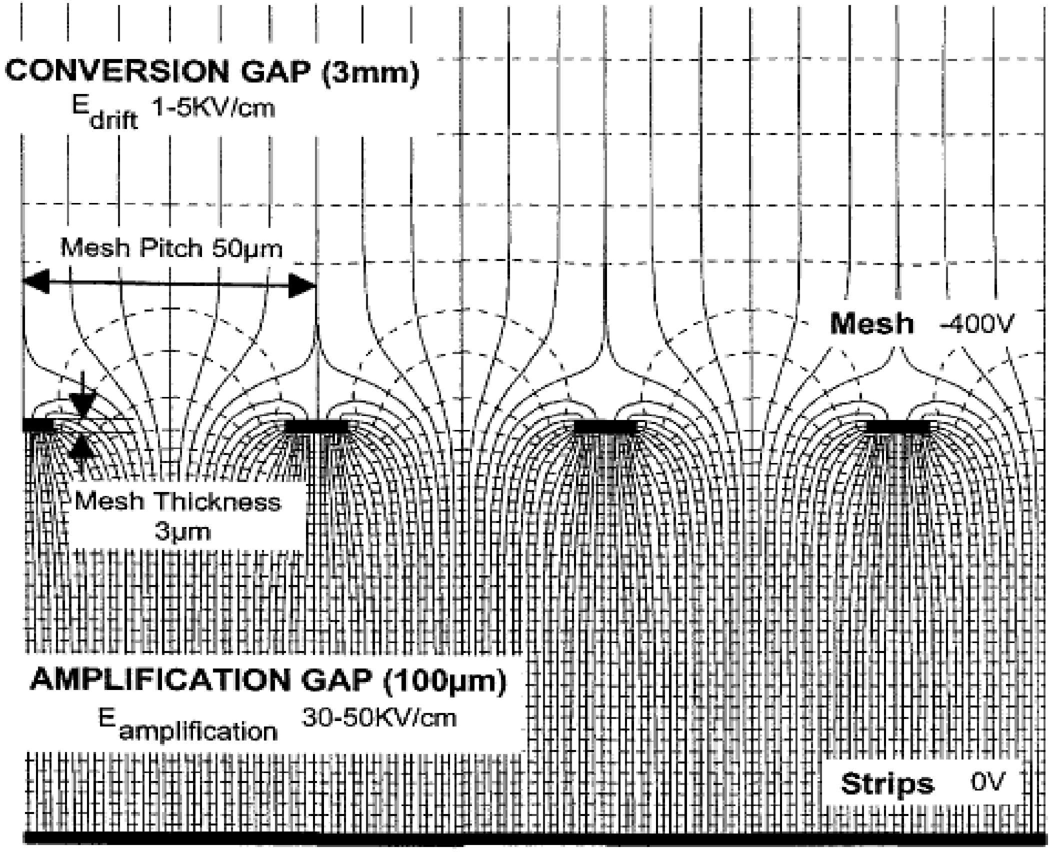
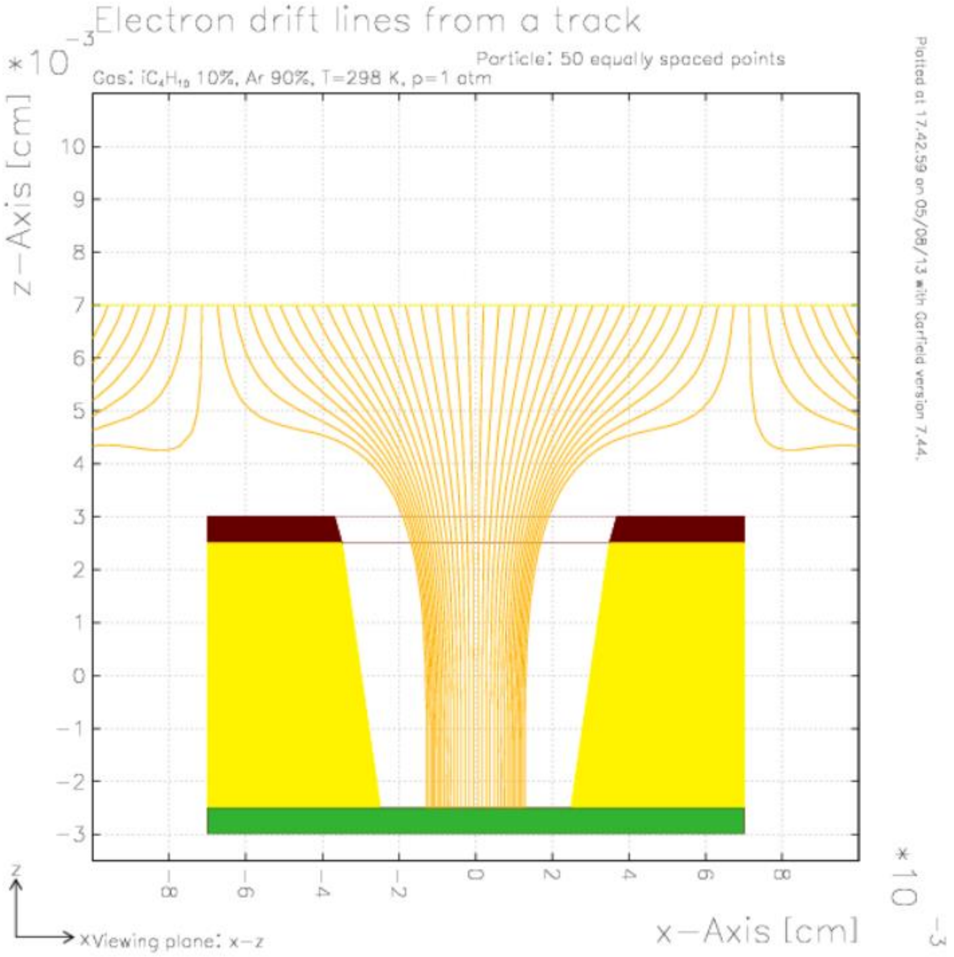


Fig. 1. Micromegas electric field map.

Mesh pitch = 50 µm

Mesh width = 3 µm

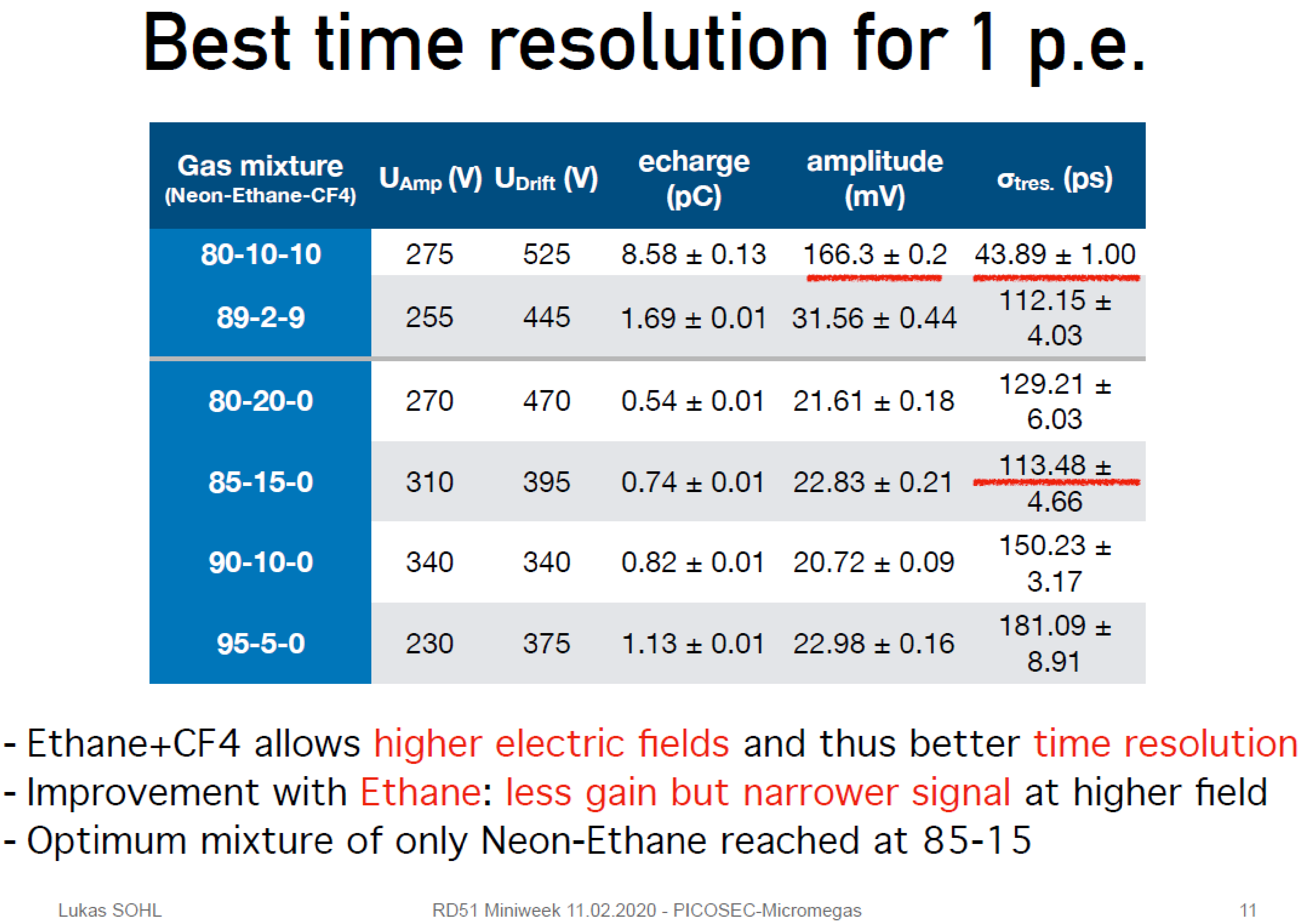
µRWELL-PICOSEC



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

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Lukas Sohl
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