Development of ultra-low mass and high-rate capable RPC based on Diamond-Like Carbon electrodes for MEG II experiment

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XVI Workshop of Resistive Plate Chambers and Related Detectors (RPC2022)

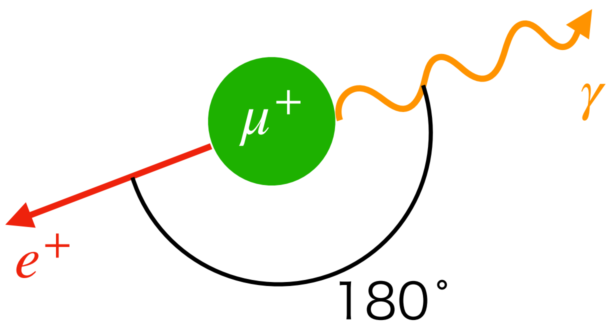
Outline

- Introduction
  - MEG II experiment
  - DLC-RPC
- High-rate performance test with our 1st prototype detector
- Improved prototype test
- Summary and prospects

MEG II signal and background

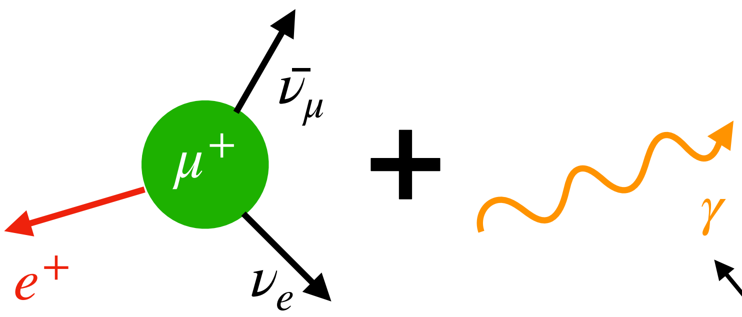
- MEG II searches for $\mu \to e\gamma$ decay, one of charged lepton flavour violation (cLFV) channels
- Dominant background is accidental coincidence of BG-e^+ and BG-γ

Signal



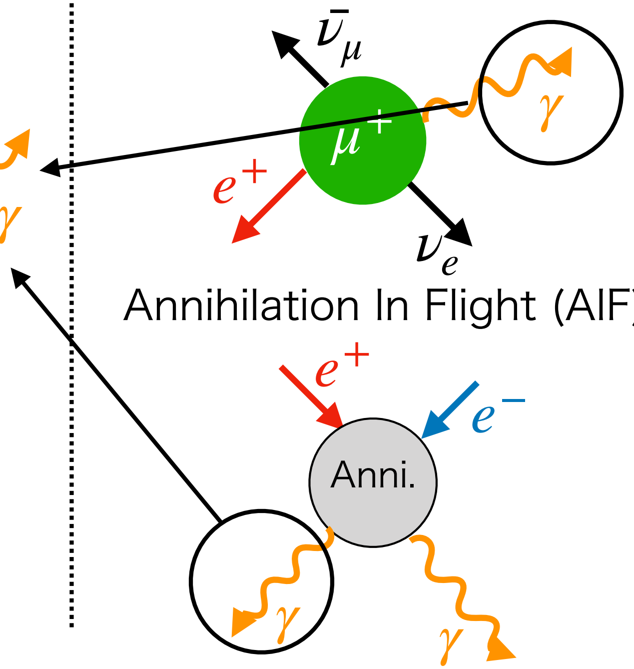
- The same energy of 52.8 MeV
- Opposite direction
- The same timing

Accidental BG



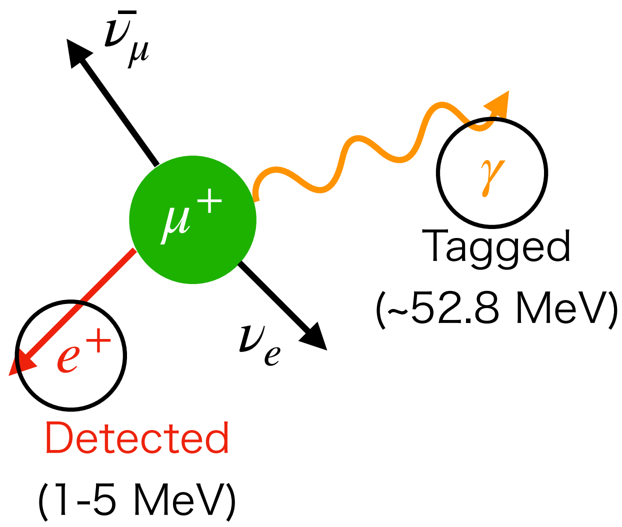
Signal-like accidental coincidence of e^+ and γ with ~52.8 MeV

Radiative Muon Decay (**RMD**)

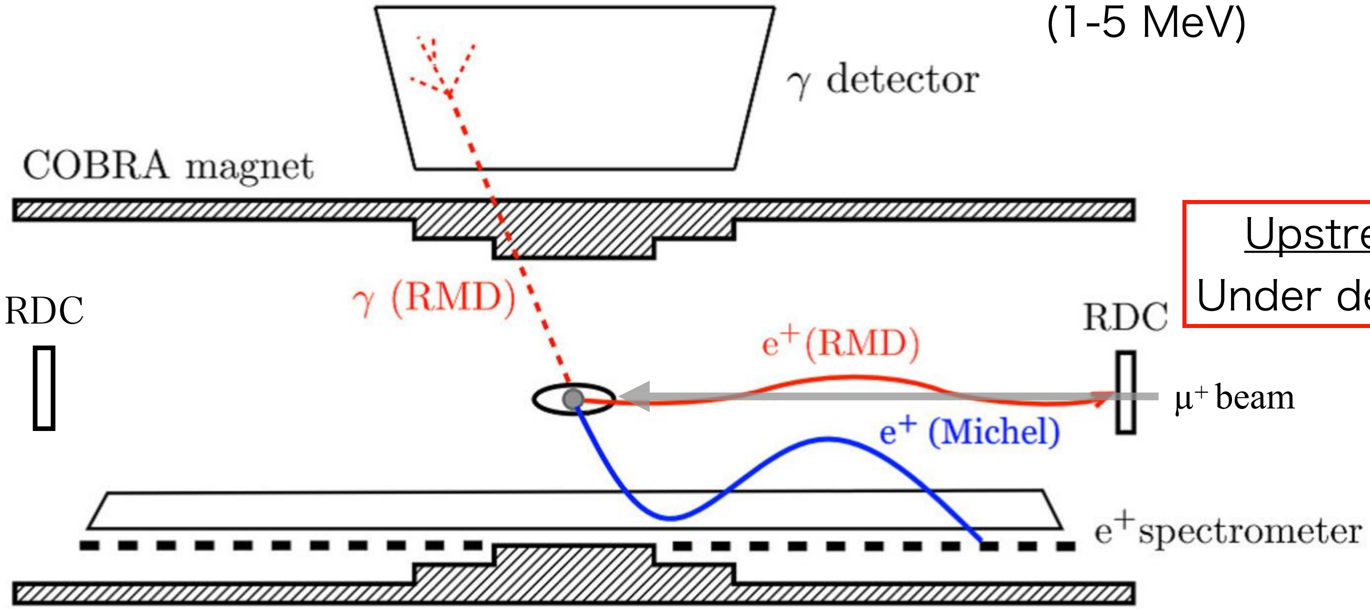


Radiative Decay Counter

- Radiative Decay Counter (RDC) detects RMD e^+ with 1-5 MeV to tag BG-γ
  - RMD γ tagged by time difference between γ in γ detector and e^+ in RDC
  - Low-energy e^+ fly around beam axis due to magnet



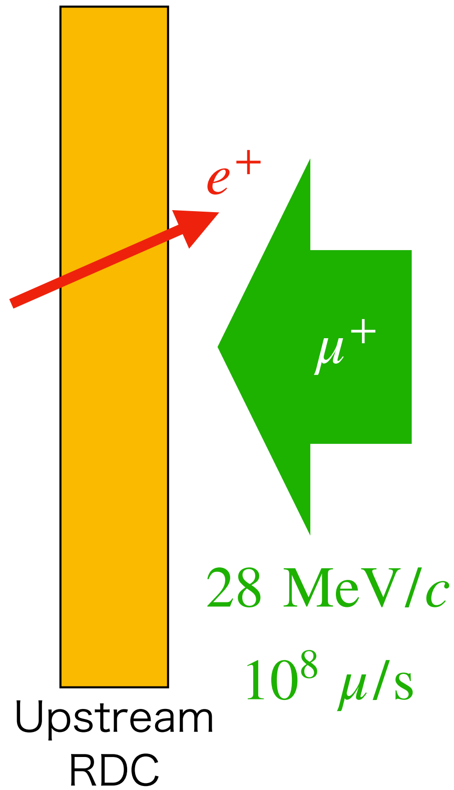
Downstream RDC
Already developed and installed



Upstream RDC
Under development

Requirements for upstream RDC

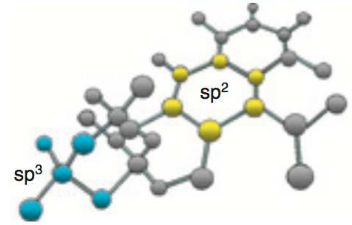
1. <0.1% X_0 material budget
   - μ beam with 28 MeV/c must pass through the detector
2. Rate capability for 10^8 μ/s (4 MHz/cm^2 at centre)
3. Radiation hardness for >60 weeks operation
4. 90% efficiency for RMD e^+ with 1-5 MeV
5. 1 ns timing resolution
6. 20 cm diameter detector size



Ultra-low mass and high-rate capable RPC with Diamond-Like Carbon electrodes for upstream RDC

DLC-RPC (1)

Diamond-Like Carbon



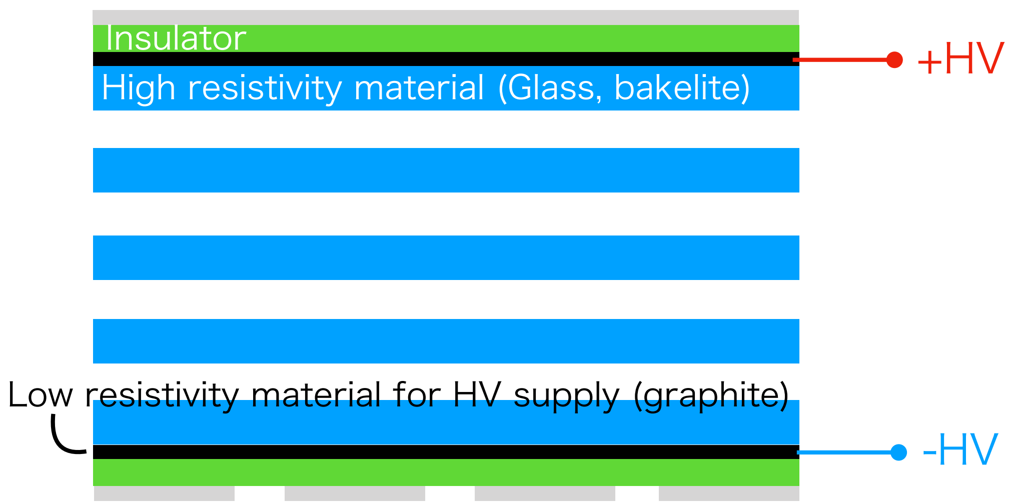
- RPC with DLC electrodes (DLC-RPC)
  - DLC sputtered on 50 μm-thick polyimide (PI) foil

➡ **Material budget can be suppressed**

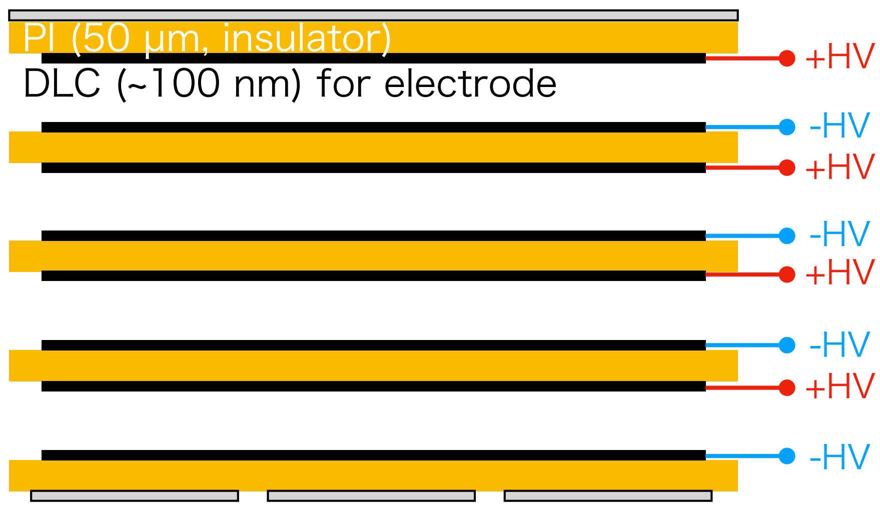
  - Electrodes decoupled by PI

➡ **HV applied for each layer independently**

(Conventional) bulk RPC

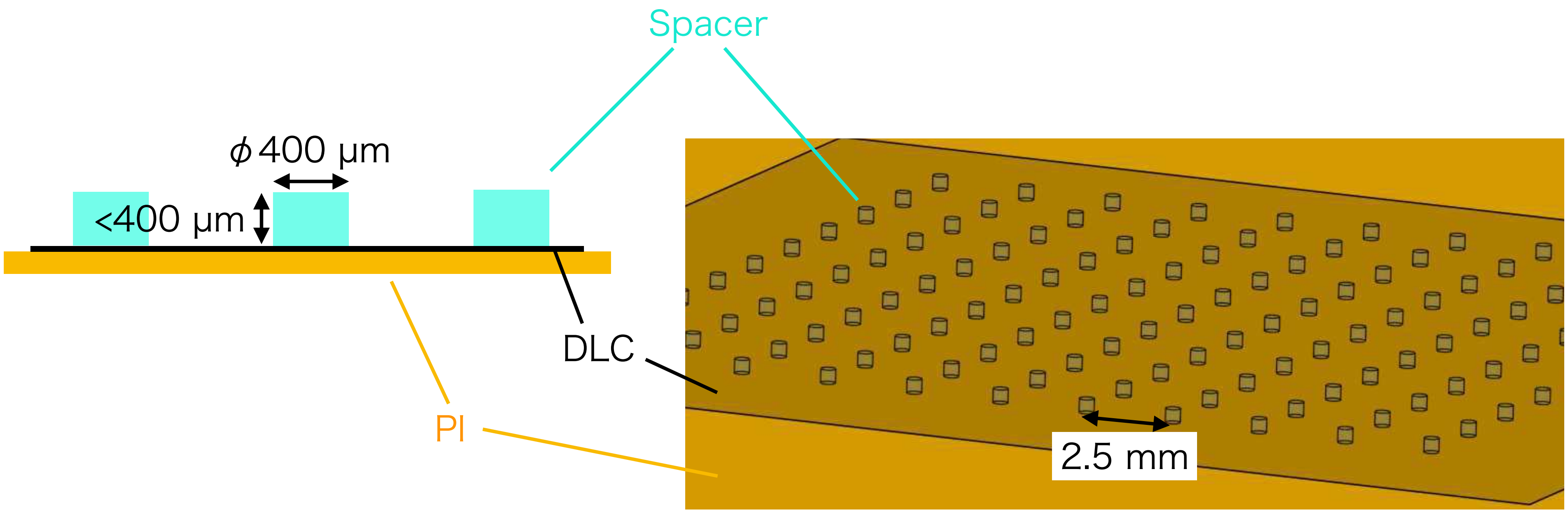


DLC-RPC



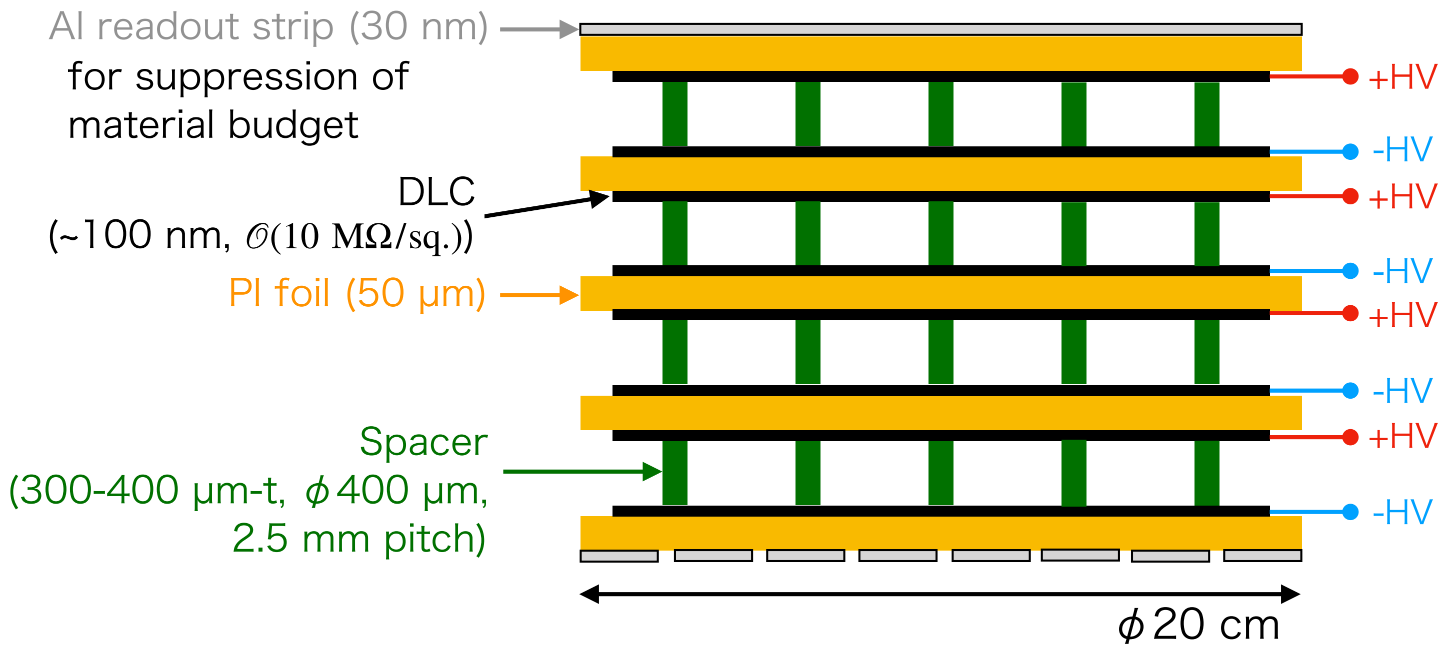
DLC-RPC (2)

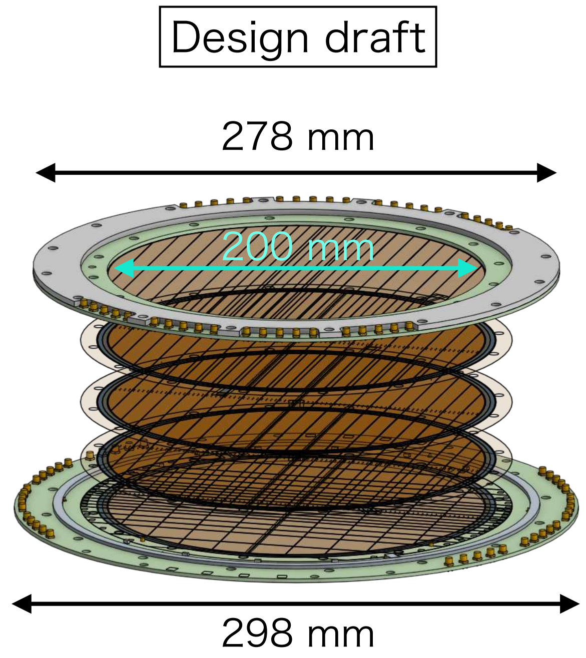
- Spacers formed using photolithographic technology
  - Should be careful to make flat thin film



DLC-RPC for MEG II

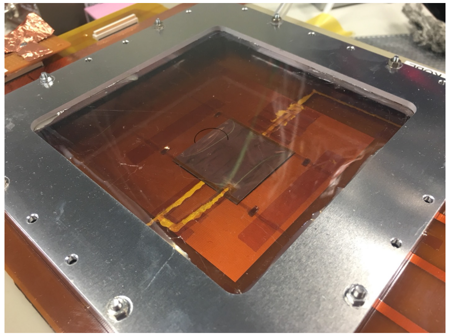
- Electrodes stacked for higher detection efficiency
  - Efficiency with n layers: $\epsilon_n = 1 - (1 - \epsilon_1)^n$
- **4 layers** limited by material budget
  - 50 µm-thick PI foil: 0.018% X_0
- $\epsilon_1 > 40\,\%$ for 90% detection efficiency with 4 layers
  - **>300 µm gap thickness** needed



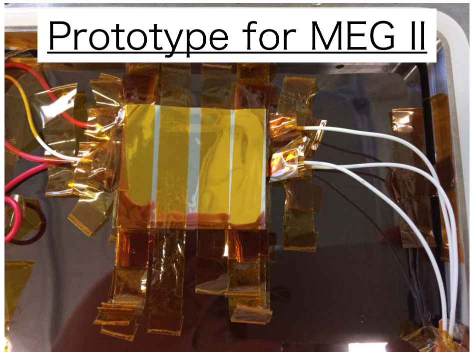


R&D history

R&D for fast timing RPC

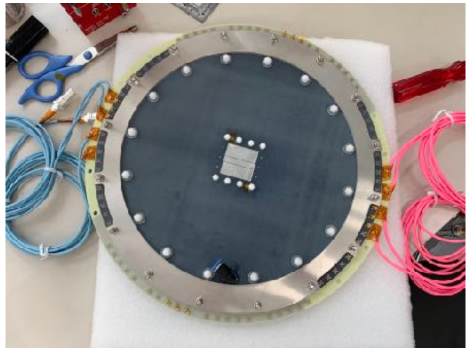


Prototype for MEG II



μ^+ beam test at PSI

Improved detector R&D



Aim to install in MEG II

2016 2017 2018 2019 2020 2021 2022 2023

New RPC idea by A. Ochi

Adopted for Grant-in-Aid for Challenging Research

Report at CLFV2019 by A. Oya

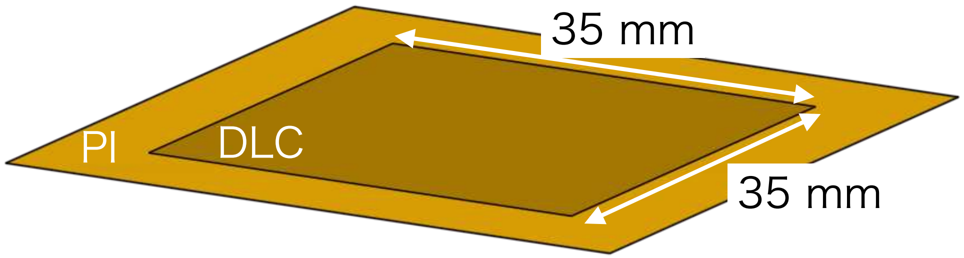
Report at TIPP2021 by A. Oya

Report at RPC2022

Outline

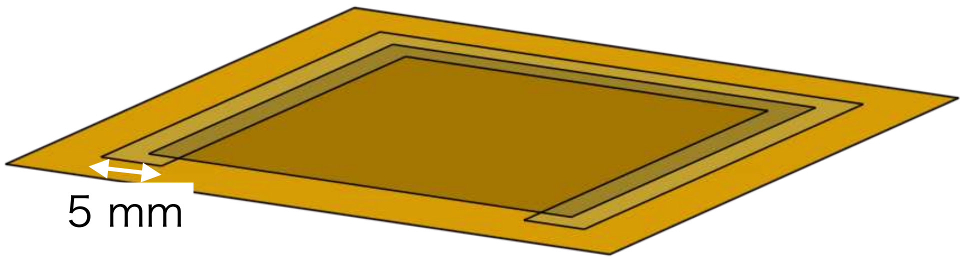
- Introduction
- High-rate performance test with our 1st prototype detector
  - 1st prototype detector
  - High rate performance
- Improved prototype test
- Summary and prospects

Electrode production



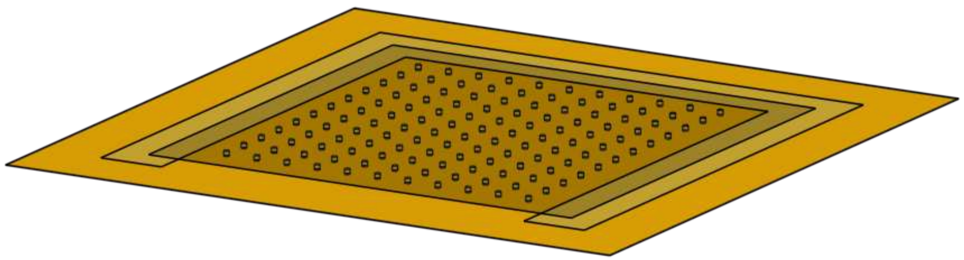
1 - DLC sputtered on Kapton foil

- DLC thickness ~ 800 Å



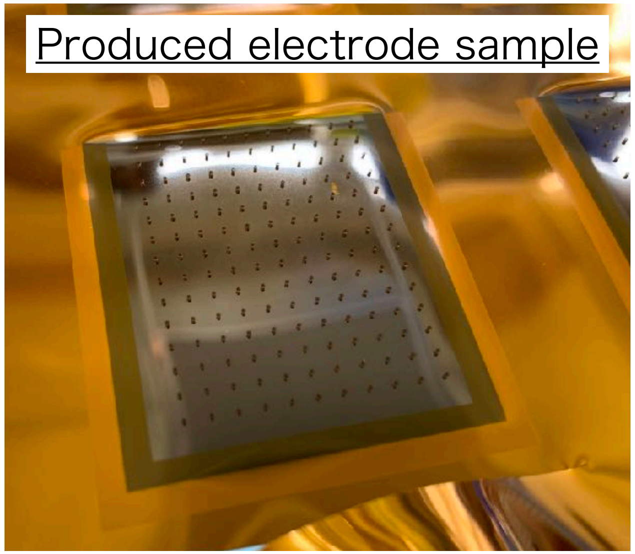
2 - Insulation cover deposited

- 25 μm-thick photo-resist
- Deposited on DLC boundary

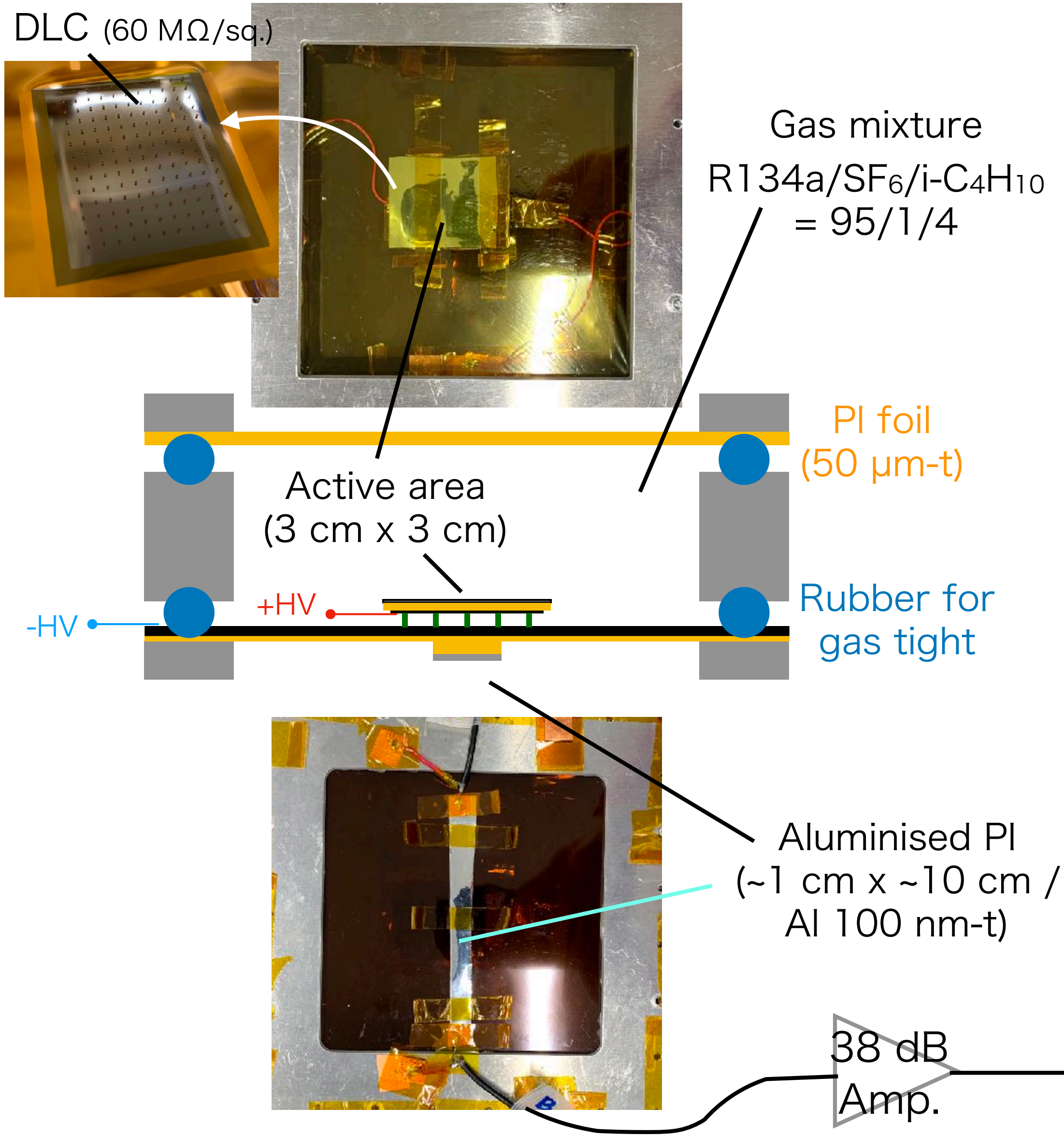


3 - Spacers formed

- 384 μm-thick photo-resist
- 2.5 mm pitch



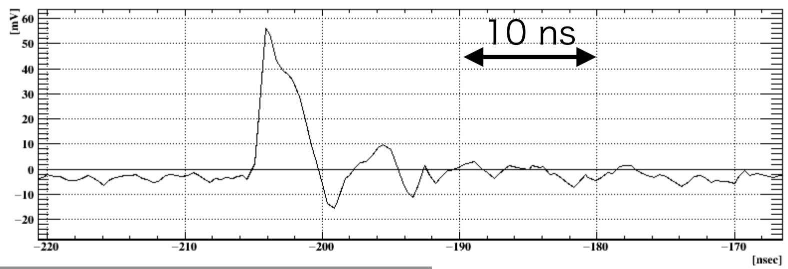
1st prototype detector



Performance overview

at $\mathcal{O}(1 - 10\ \mathrm{kHz/cm^2})$

- Successful operation with ultra-low mass design (<0.1% X_0)
  - Detect low-momentum μ^+ (28 MeV/c) penetrating detector
- 60% MIP efficiency achieved with single layer
- 85% MIP efficiency achieved with multi layers
  - Due to non-flatness of electrode
- 170 ps timing resolution

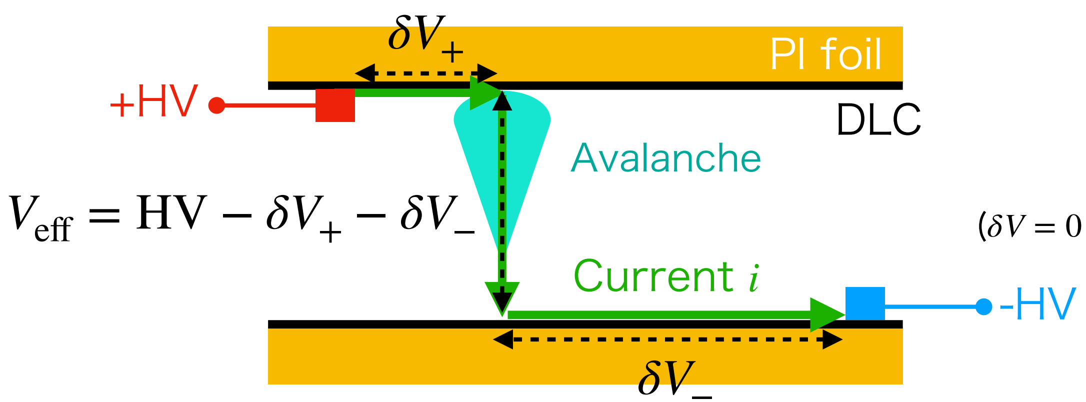


High rate capability of DLC-RPC

- Large current on resistive electrodes at high rate

➡ Voltage drop δV reduces effective applied HV V_{eff}

➡ Gas gain reduction



$$\nabla^2 \delta V(x, y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \cdot f(x, y) \cdot \rho_S$$

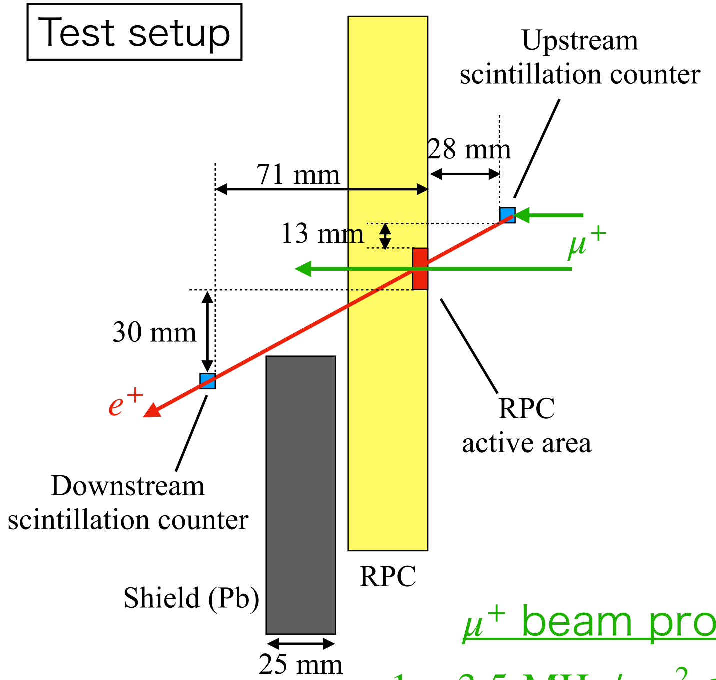
- $\nabla^2 \delta V(x, y)$: Voltage drop ($\delta V = 0$ at HV supply electrode)
- $Q_{\mathrm{mean}}(V_{\mathrm{eff}})$: Avalanche charge
- $f(x, y)$: Hit rate
- ρ_S: Sheet resistivity

- $\delta V \propto$ (current flow distance)^2
- $\delta V \propto$ sheet resistivity

High-rate performance test

- MIP e^+ detection in low-momentum μ^+ beam
  - μ^+ beam at piE5 at Paul Scherrer Institut

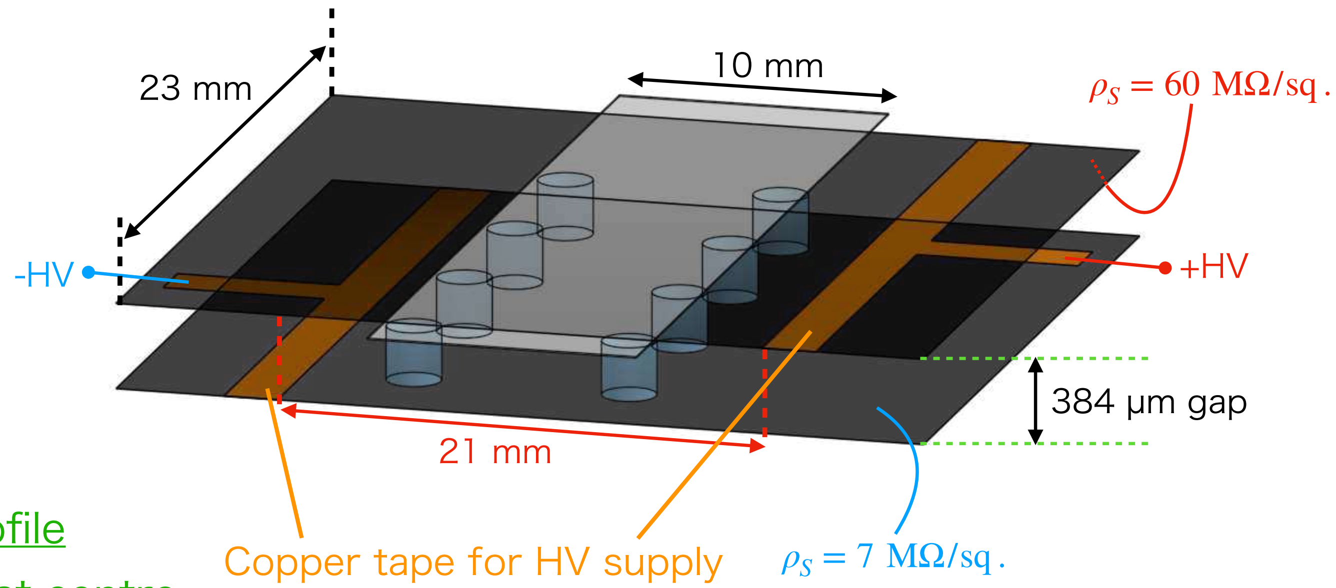
Test setup



μ^+ beam profile

- $1 - 3.5\ \mathrm{MHz/cm^2}$ at centre
- $\sigma_x = 13$ mm, $\sigma_y = 23$ mm

Detector setup

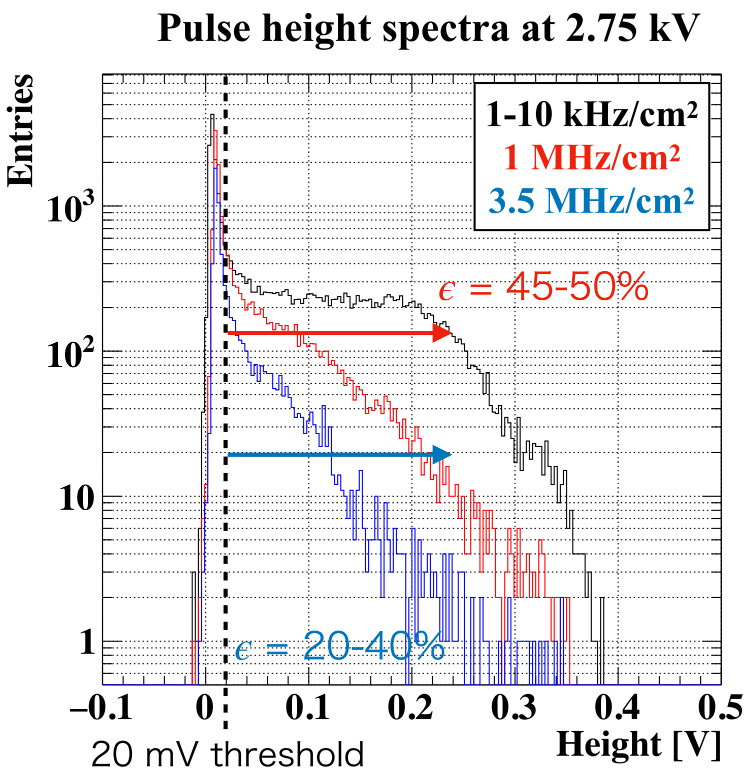


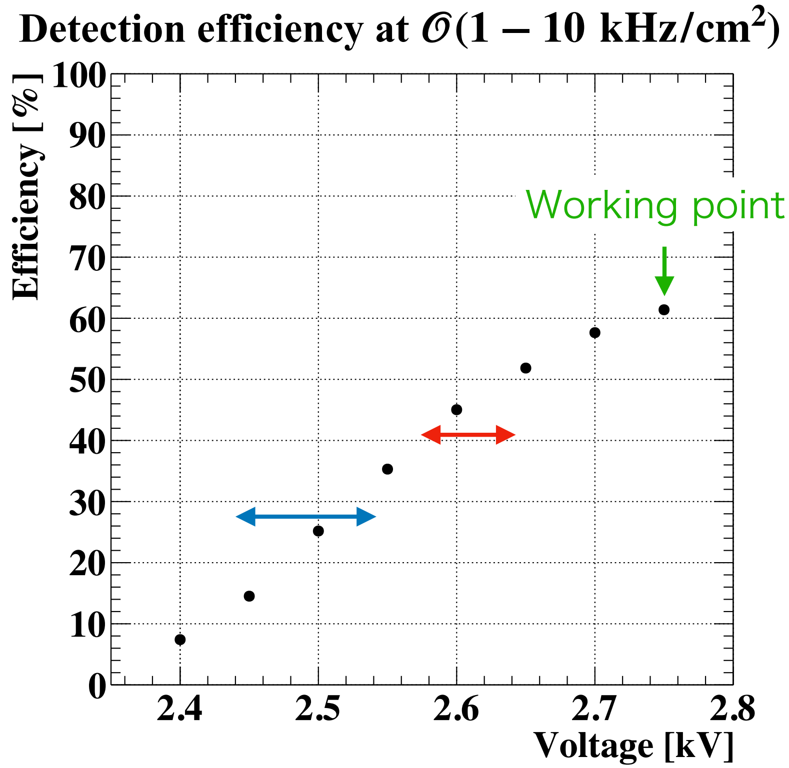
Performance at high rate

Detection efficiency:
- 45-50% at 1 MHz/cm²
- 20-40% at 3.5 MHz/cm²

Calculated voltage drop:
- 110-170 V at 1 MHz/cm²
- 210-310 V at 3.5 MHz/cm²

➡ 1 MHz/cm² rate capability

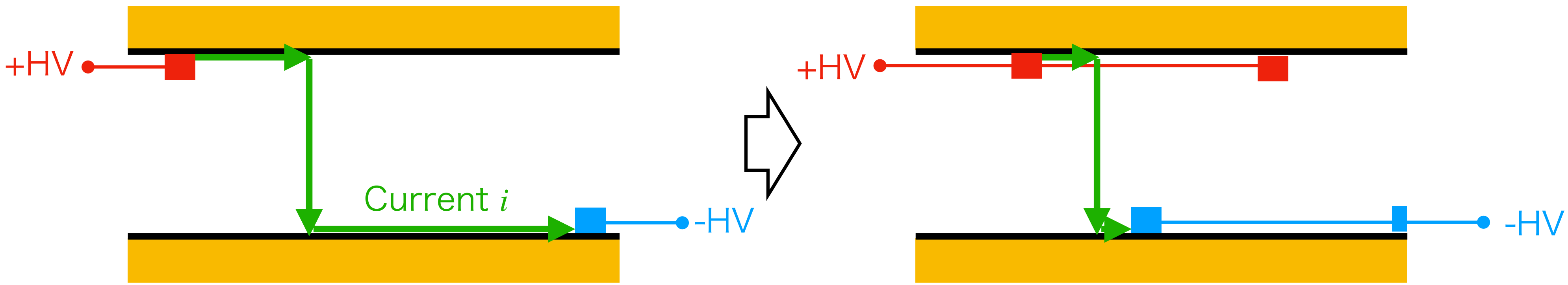




Electrode to be improved

- Voltage drop should be suppressed for higher rate capability
  - **HV supply segmented for short current flow** (1 cm pitch)
    - **Voltage drop ∝ (current flow distance)²**
    - Need also for scalability
  - **Resistivity should be low** (10 MΩ/sq.)
    - Voltage drop ∝ (sheet resistivity)
    - Not too low for stable operation

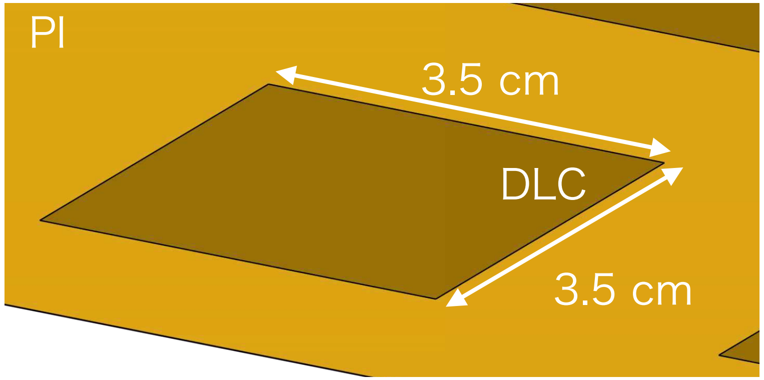
➡ **Voltage drop will be 60-80 V at 4 MHz/cm²**



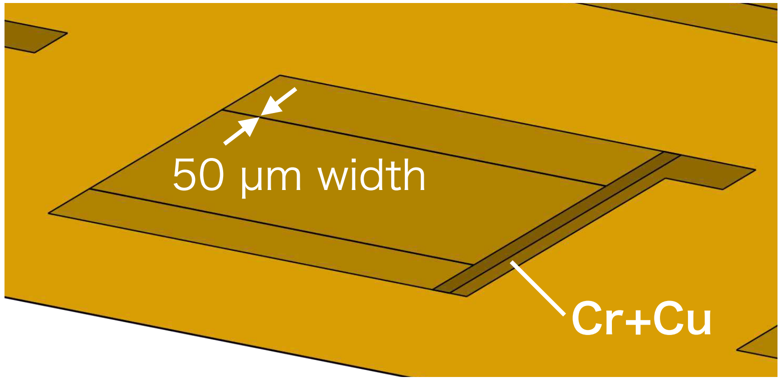
Outline

- Introduction
- High-rate performance test with our 1st prototype detector
- Improved prototype test
  - Develop improved electrode
  - Performance test at $\mathcal{O}(10\ \mathrm{kHz/cm^2})$
- Summary and prospects

Electrode production

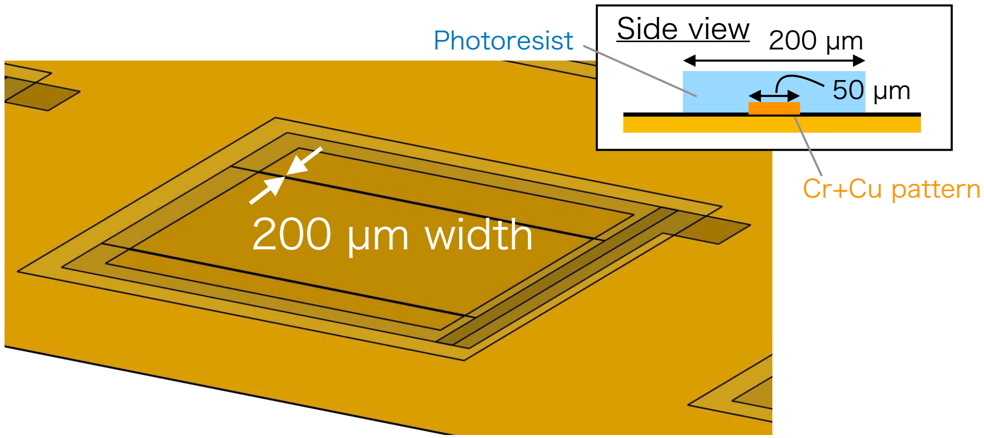


1 - DLC sputtered on Kapton foil



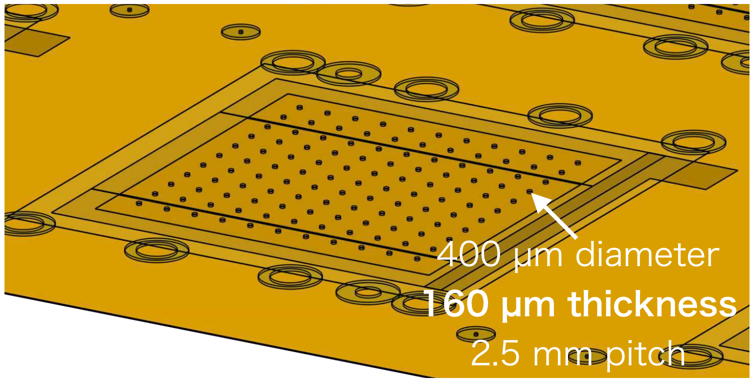
2 - Conductive pattern implemented

- Cr can be well-connected onto DLC



3 - Insulation cover deposited

- 25 µm-thick photo-resist
- Deposited on conductive pattern and DLC boundary



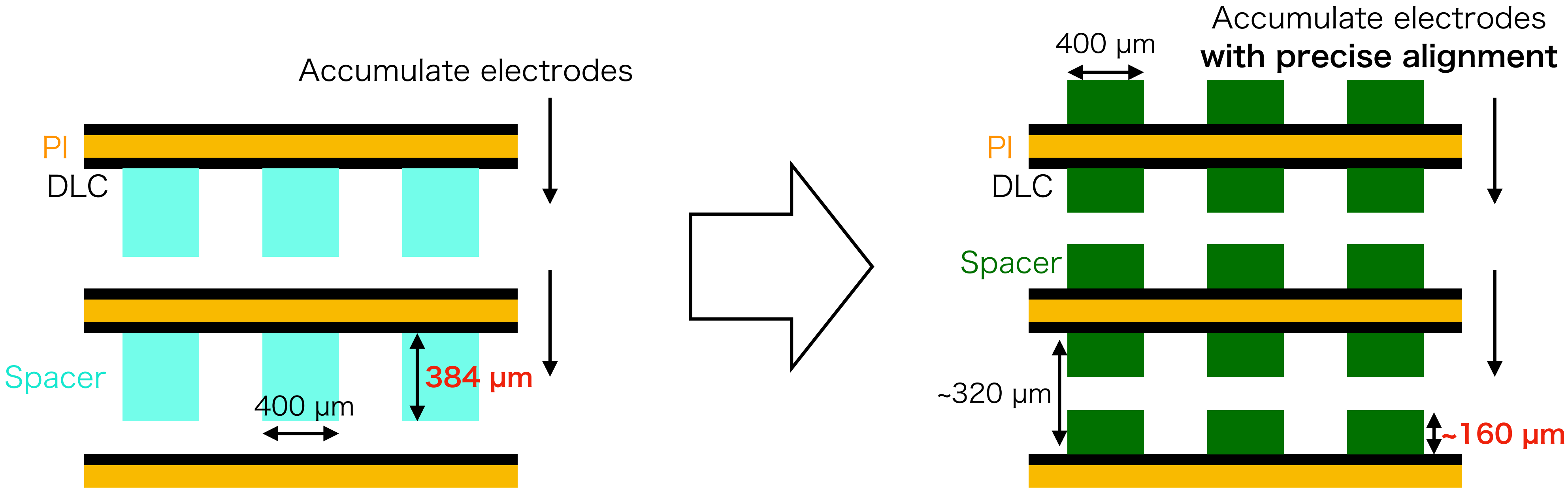
4 - Spacers formed

- ~160 µm-thick photo-resist
- Doubly accumulated for >300 µm gap thickness

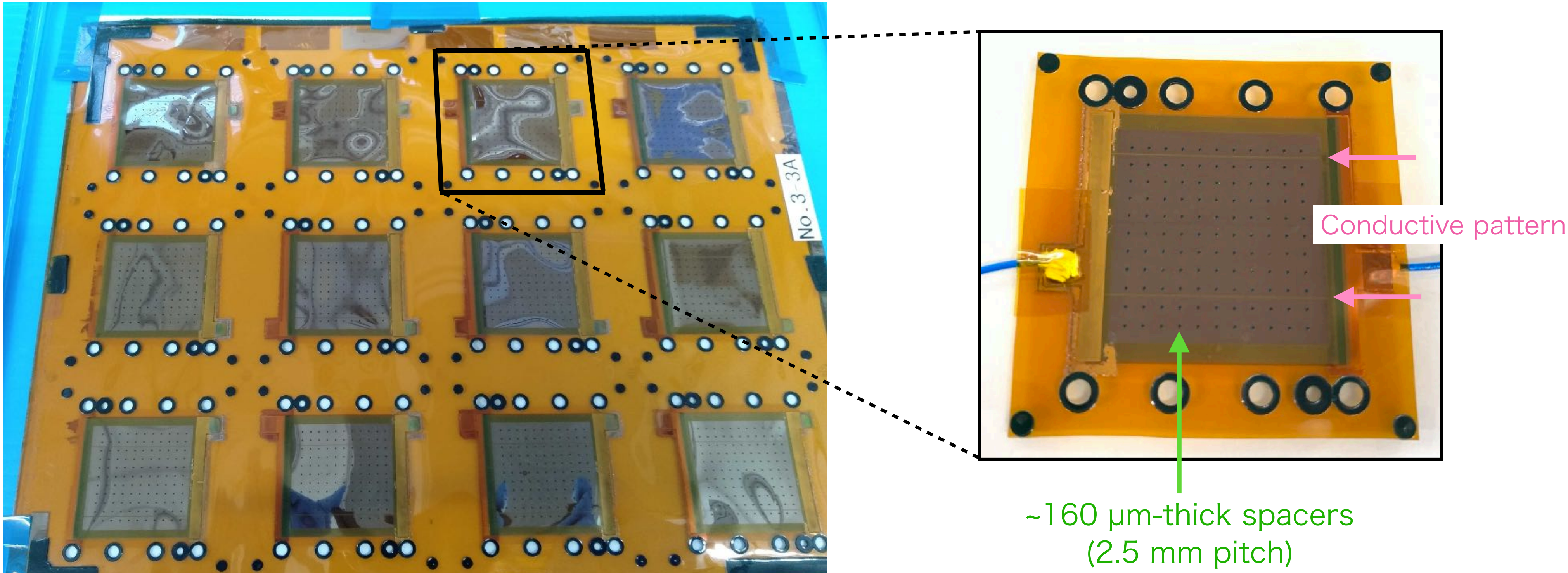
Spacer formation

- Previous spacer material production cancellation

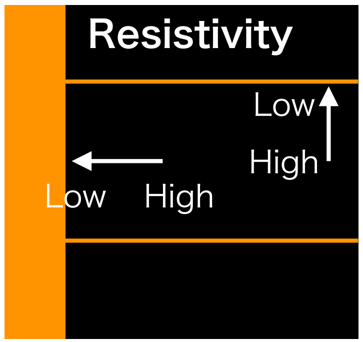
➡ New spacer material used
  - >300 μm-thick spacers cannot be formed ⟷ 300 μm gap thickness needed for enough efficiency
- Strategies for enough gap thickness
  - **Form ~200 μm-thick spacers**
  - **Doubly accumulate spacers with precise alignment**



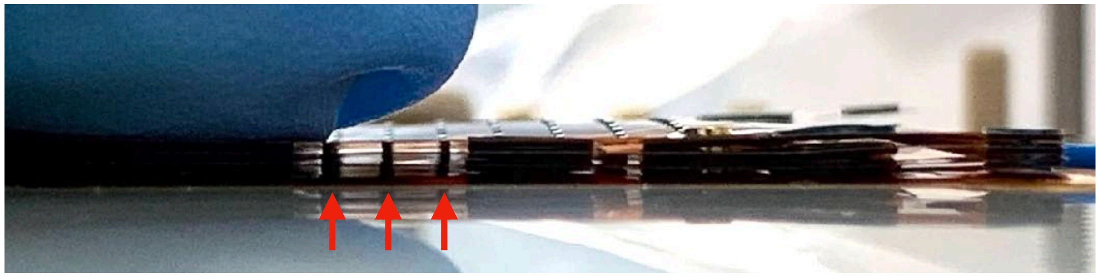
Produced electrode



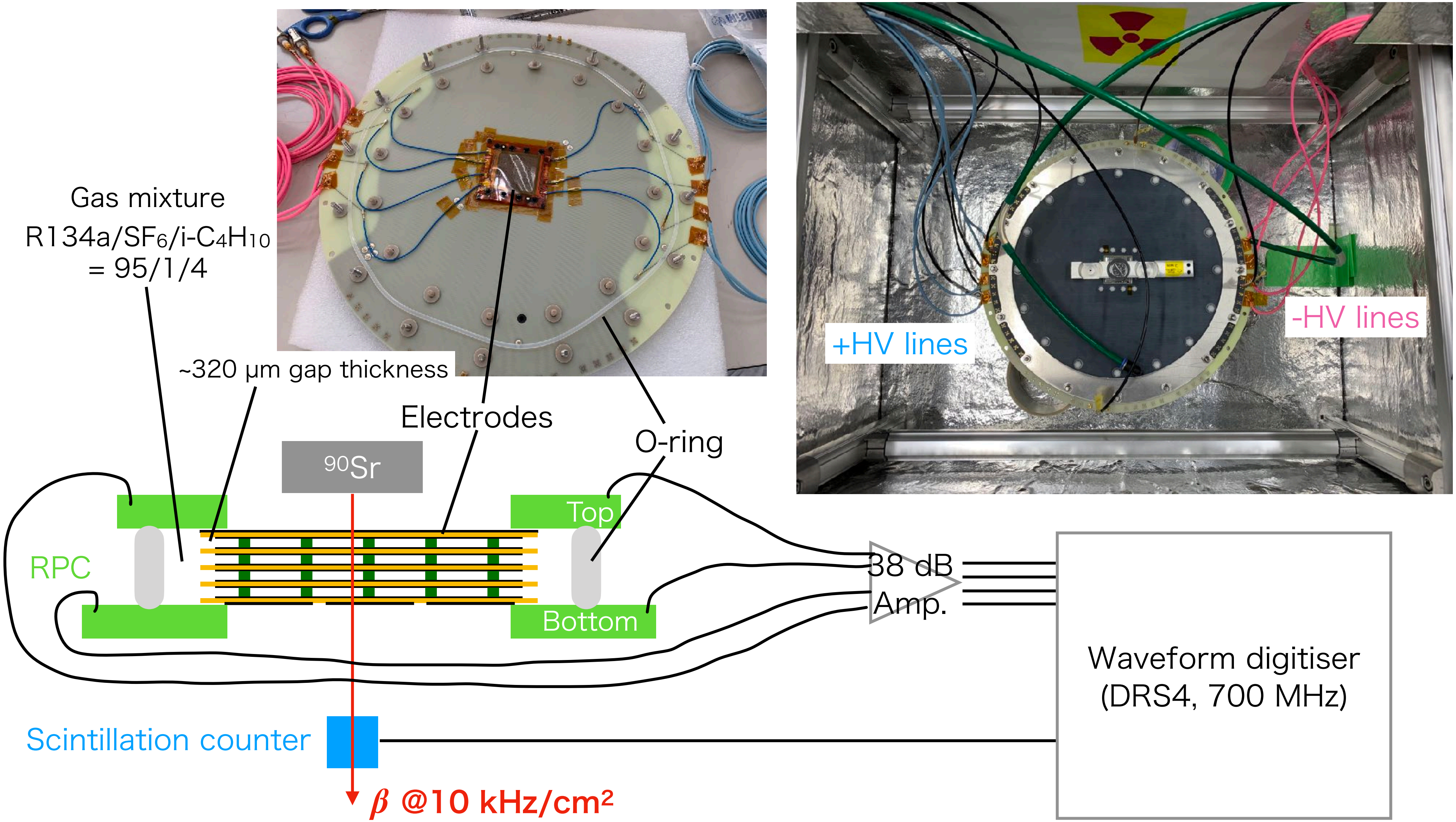
Good connection between Cr & DLC



Good alignment



Test setup

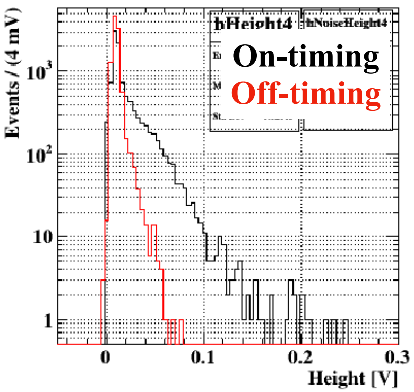

Gas mixture
R134a/SF6/i-C4H10
= 95/1/4
~320 μm gap thickness
Electrodes
O-ring
+HV lines
-HV lines
90Sr
Top
Bottom
RPC
38 dB
Amp.
Waveform digitiser
(DRS4, 700 MHz)
Scintillation counter
β @10 kHz/cm²

Gap thickness non-uniformity

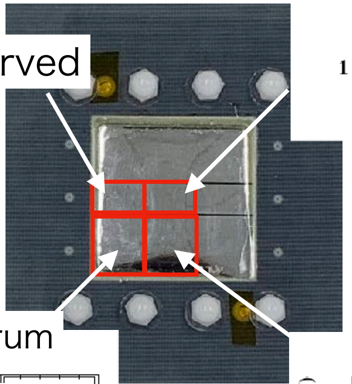
Non-uniformity in a layer

Detector response depends on β incident position

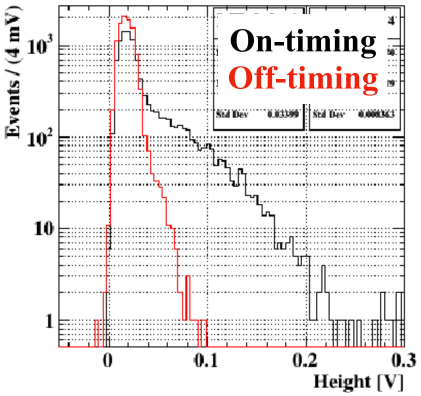
Height spectrum



No signal observed

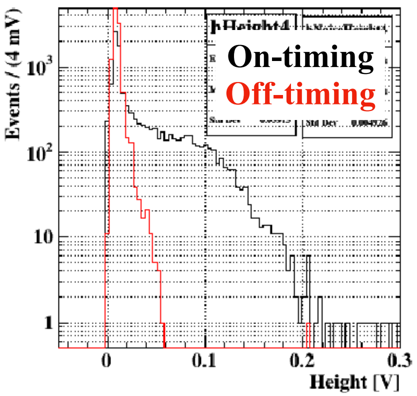


Height spectrum

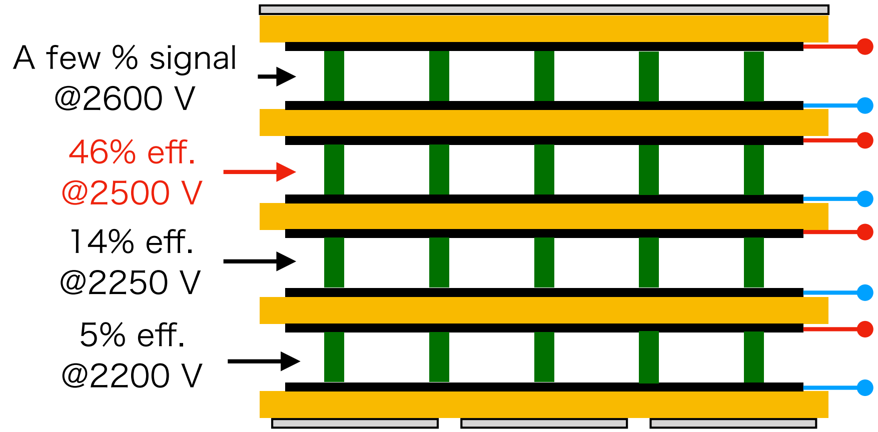


Large noise in this strip

Height spectrum

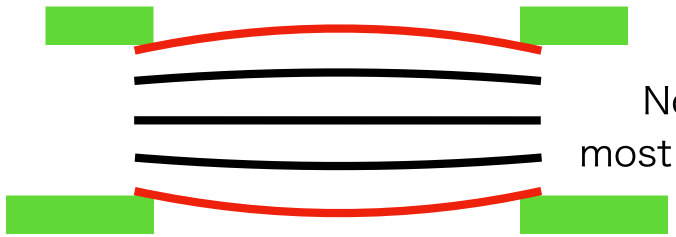


Non-uniformity among different layers



Different gap thickness among different layers

Expected cause

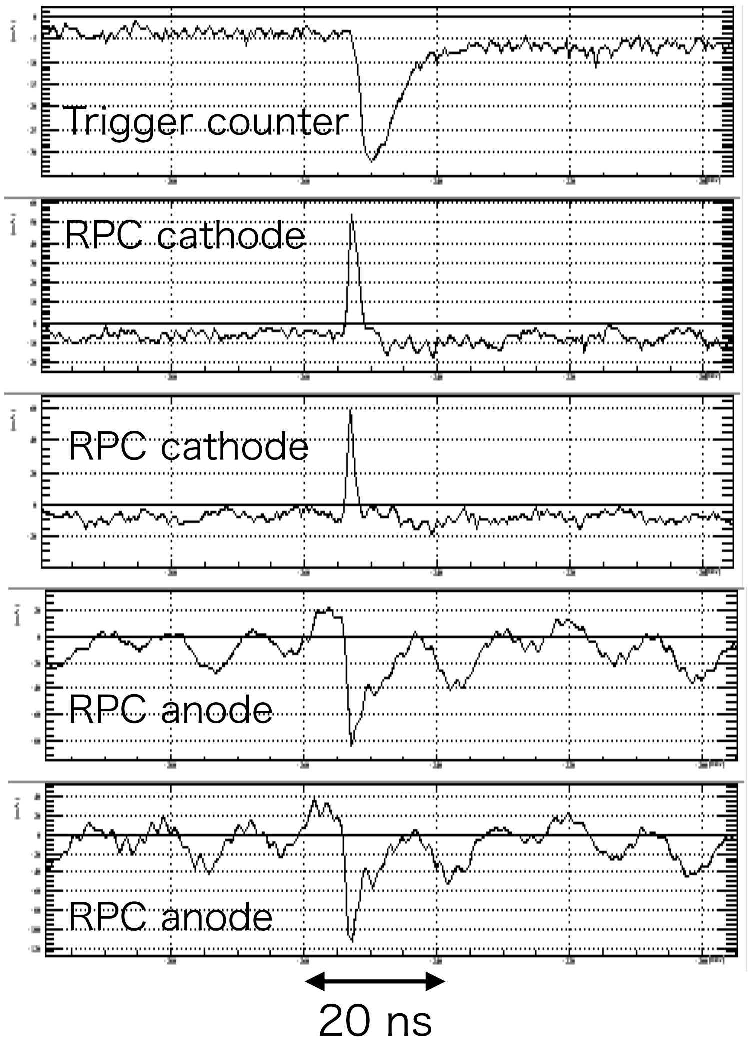


Non-flatness of most outer electrodes

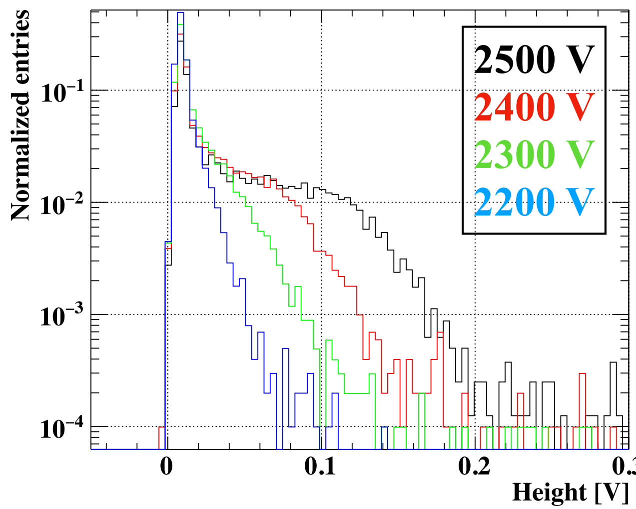
To be controlled by negative pressure in gas gap

Performance with single layer

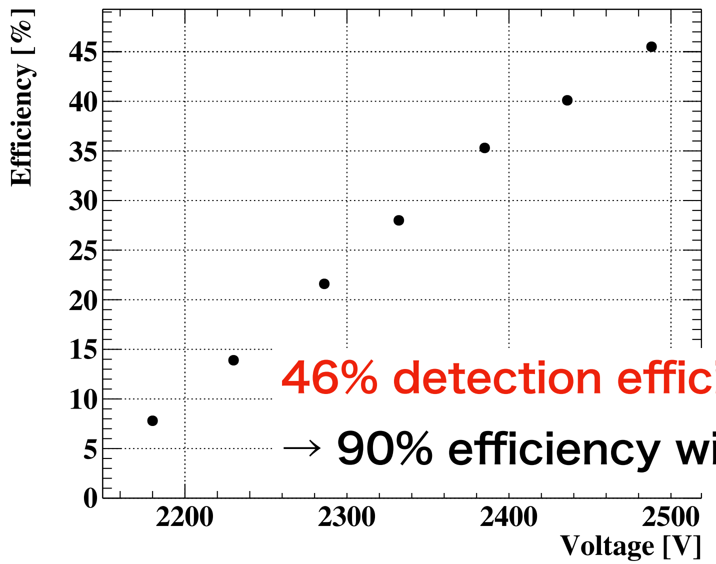
Event display



Pulse height spectra



Efficiency vs voltage



46% detection efficiency with single layer

→ 90% efficiency with 4 layers $(1-(1-\epsilon_1)^4)$

Outline

- Introduction
- High-rate performance test with our 1st prototype detector
- Improved prototype test
- Summary and prospects

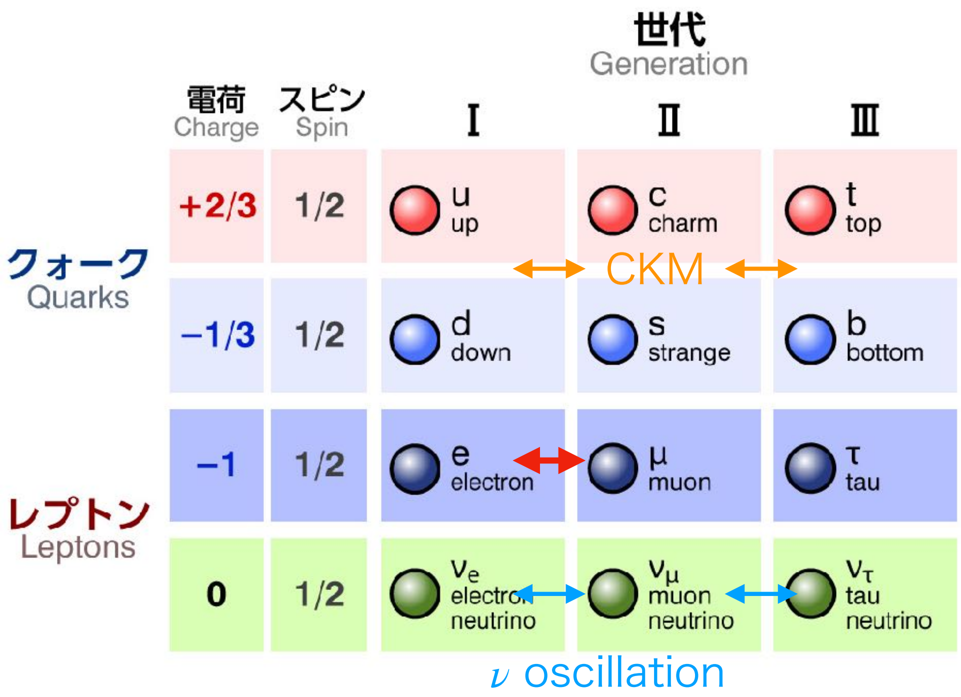
Summary & prospects

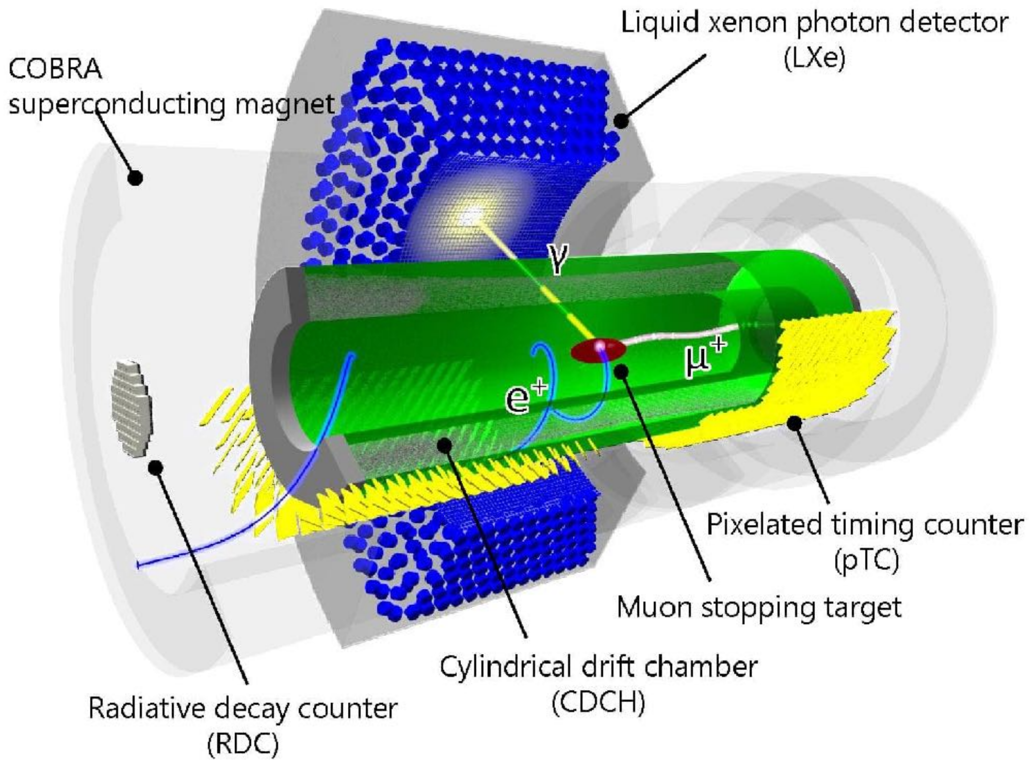
- Ultra-low mass and high-rate capable RPC with DLC electrodes is under development
  - For BG tagging in MEG II experiment
- 1 MHz/cm^2 rate capability achieved with 1st prototype detector
  - 45-50% detection efficiency with single layer even with 110-170 V drop
- Improved prototype detector produced and tested
  - Cr+Cu pattern formed on DLC for HV supply segmentation
  - 46% detection efficiency achieved with single layer at 10 kHz/cm^2
  - Gap thickness to be controlled
- Performance to be evaluated with μ^+ beam at 4 MHz/cm^2

Backup

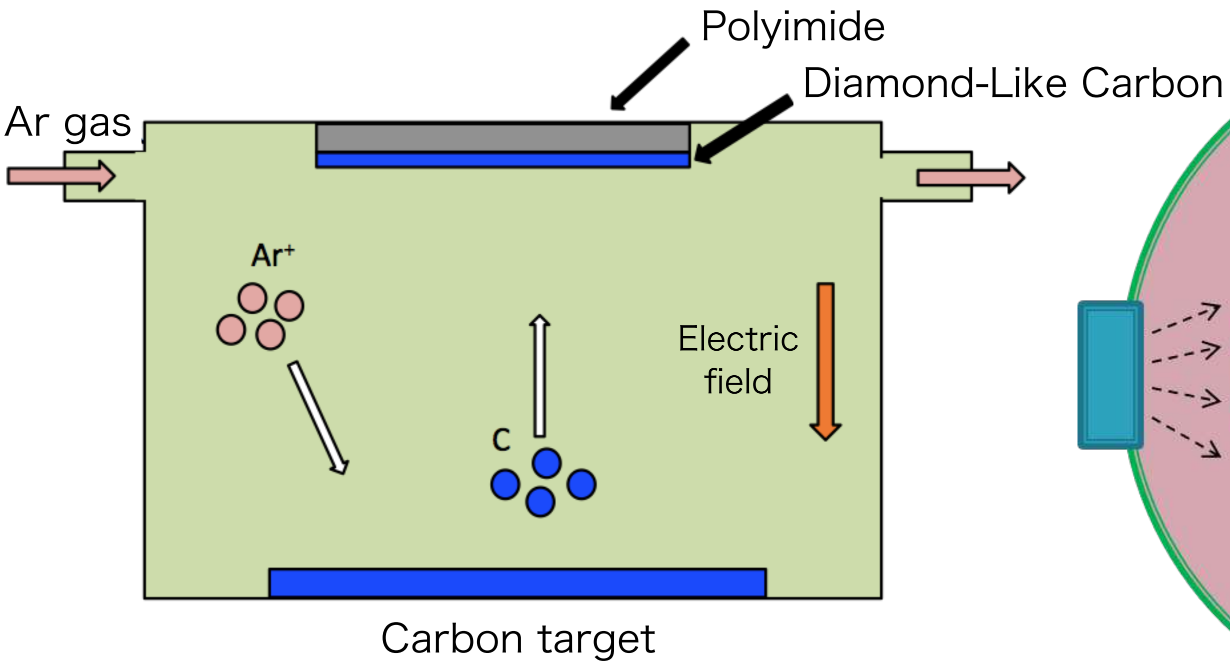
MEG II experiment

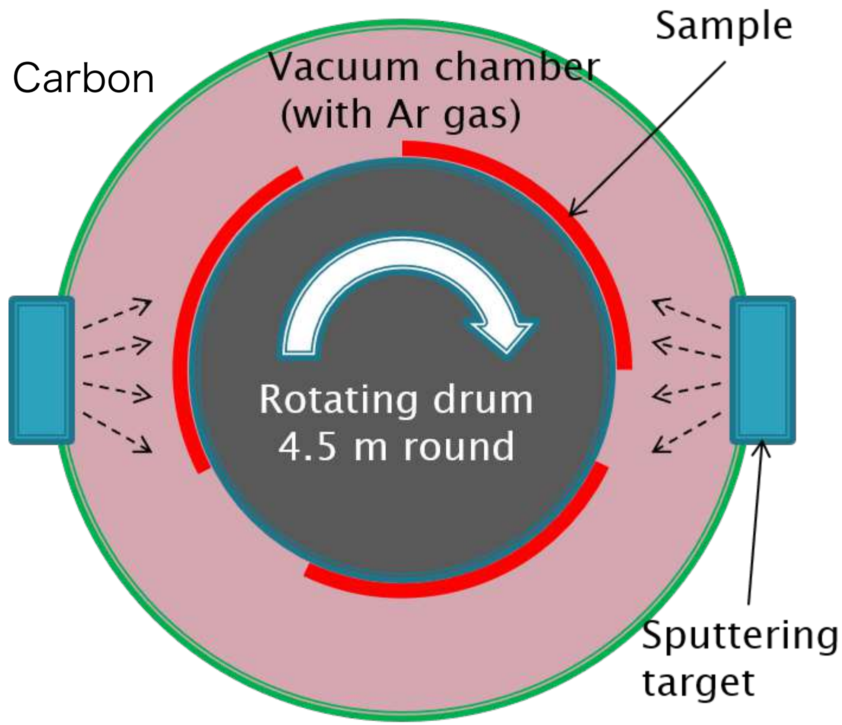
- MEG II searches for $\mu^+ \to e^+\gamma$ decay with the sensitivity of 6×10^{-14}
  - SM + ν osc: $\mathscr{B}(\mu^+ \to e^+\gamma) \sim 10^{-54}$
  - BSM (SUSY-GUT, SUSY-seesaw): $\mathscr{B}(\mu^+ \to e^+\gamma) \sim 10^{-11} - 10^{-15}$





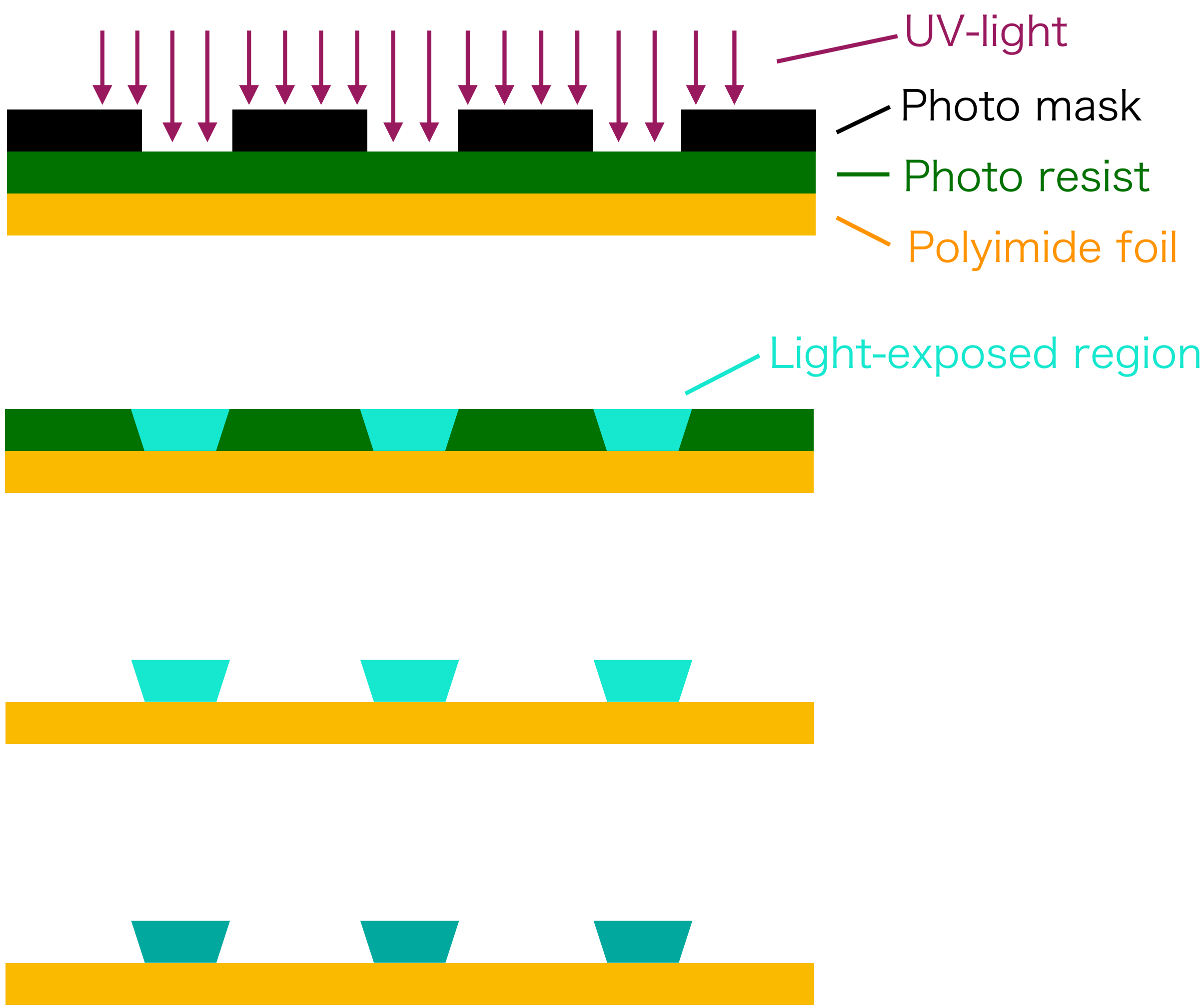
DLC sputtering





Spacer formation

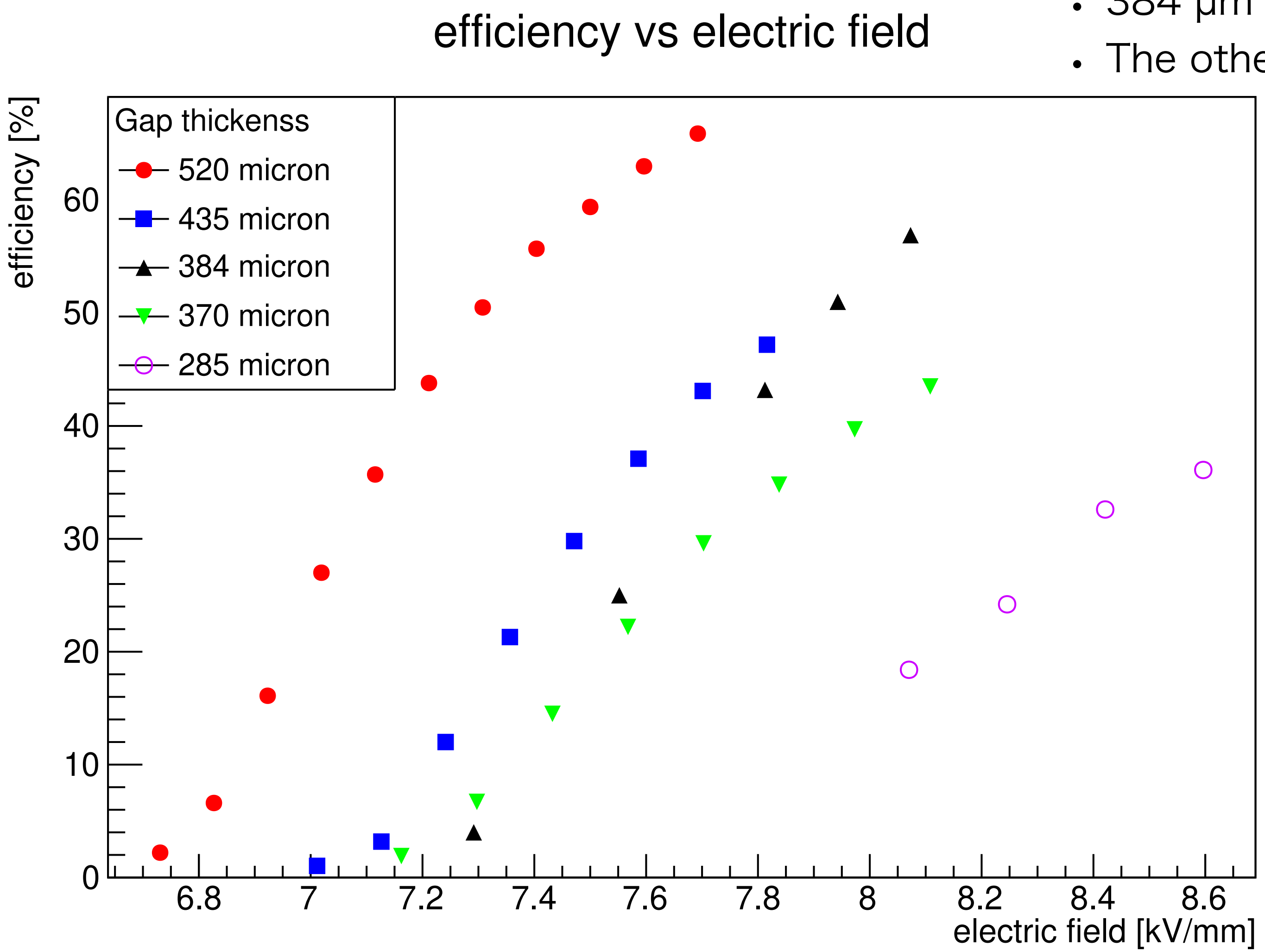
1. UV-light exposed
2. Development
3. Pillars formed
4. Baking



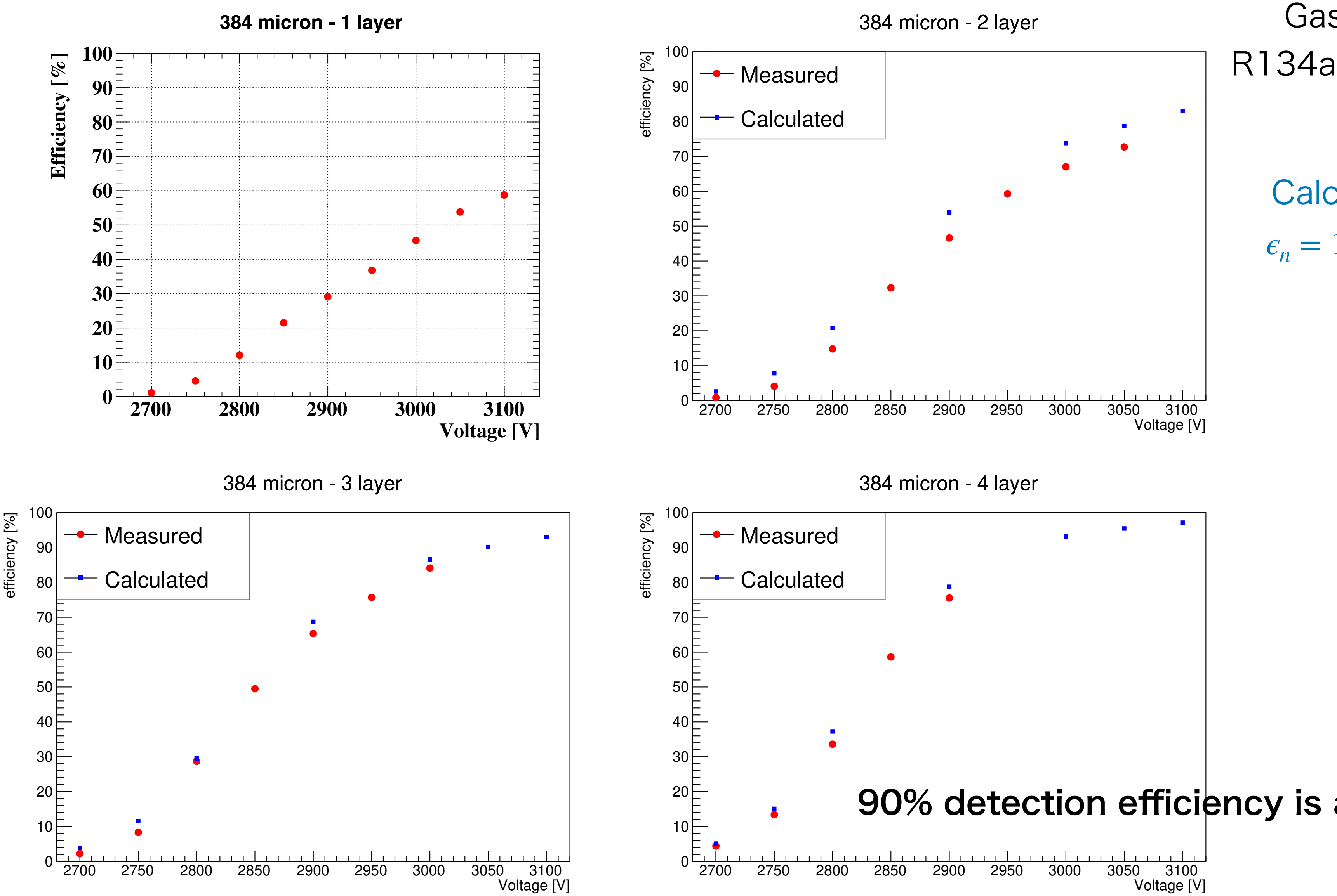
Efficiency vs gap thickness

Spacers:

- 384 μm - photolithographic pillars
- The others - fishing line



Efficiency improved by stacking



Gas mixture
R134a/SF_6 = 93/7

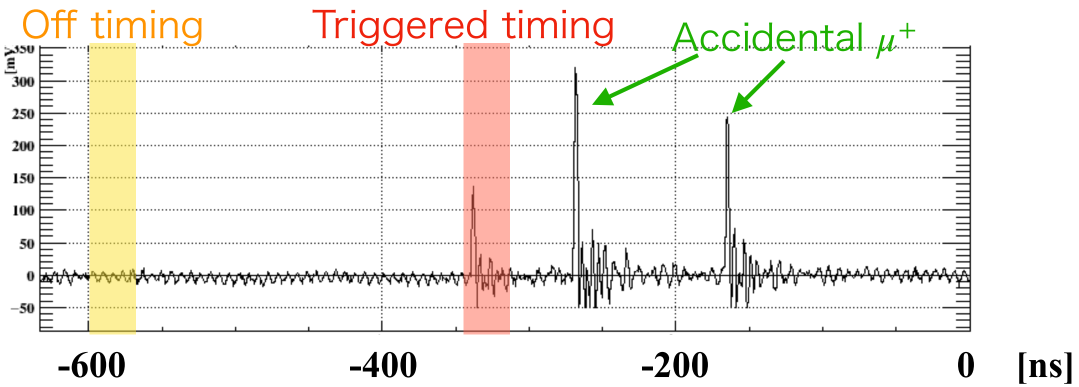
Calculated by
$\epsilon_n = 1 - (1 - \epsilon_1)^n$

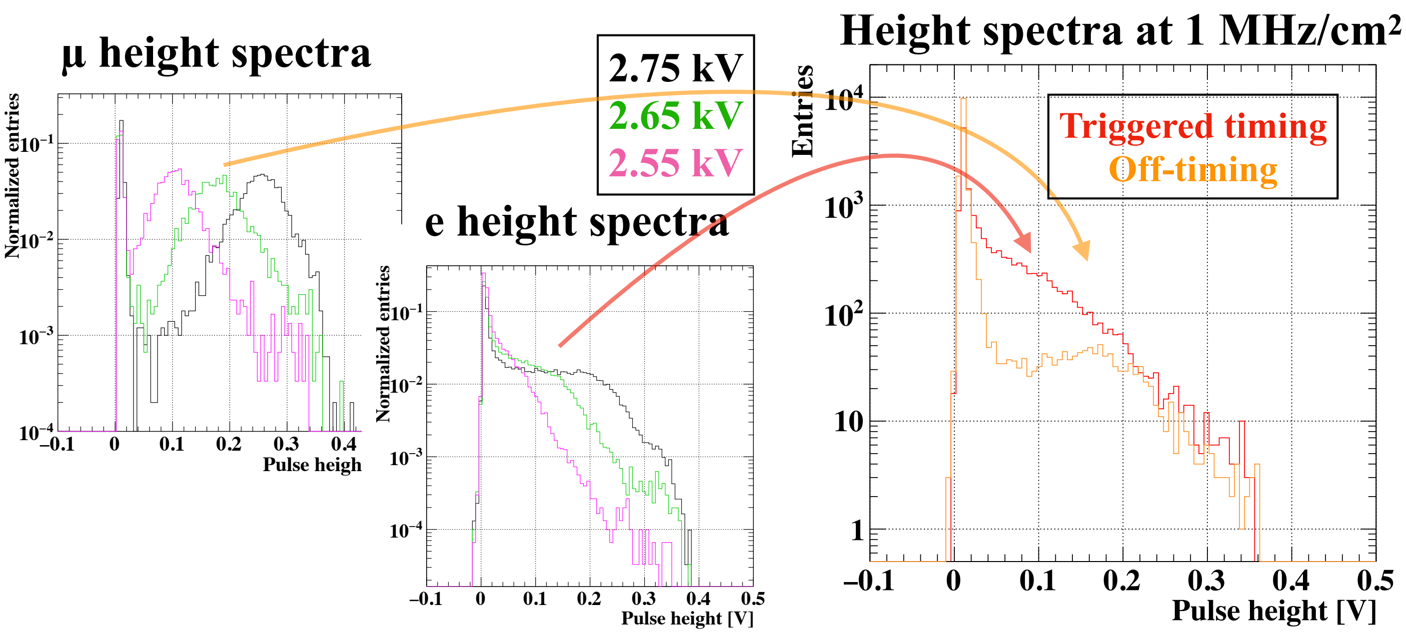
90% detection efficiency is achievable

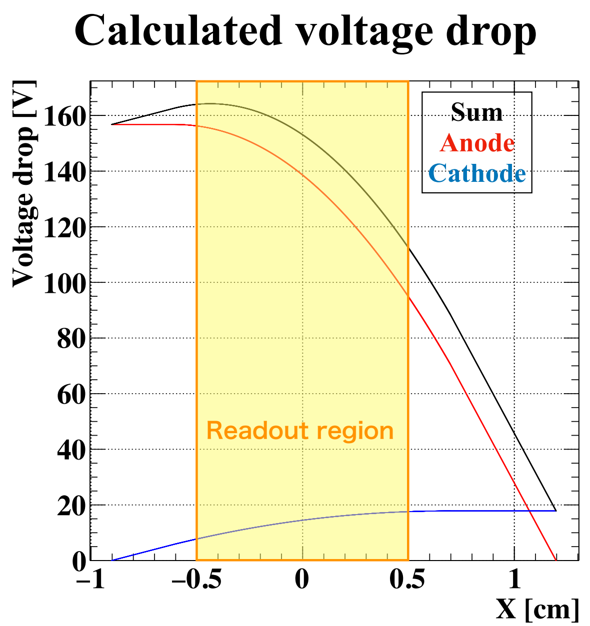
Voltage drop evaluation

Observe voltage drop of 110-170 V

Details are shown in
A. Oya, et al, "Development of high rate capable and ultra-low mass Resistive Plate Chamber with Diamond-Like Carbon", TIPP2021



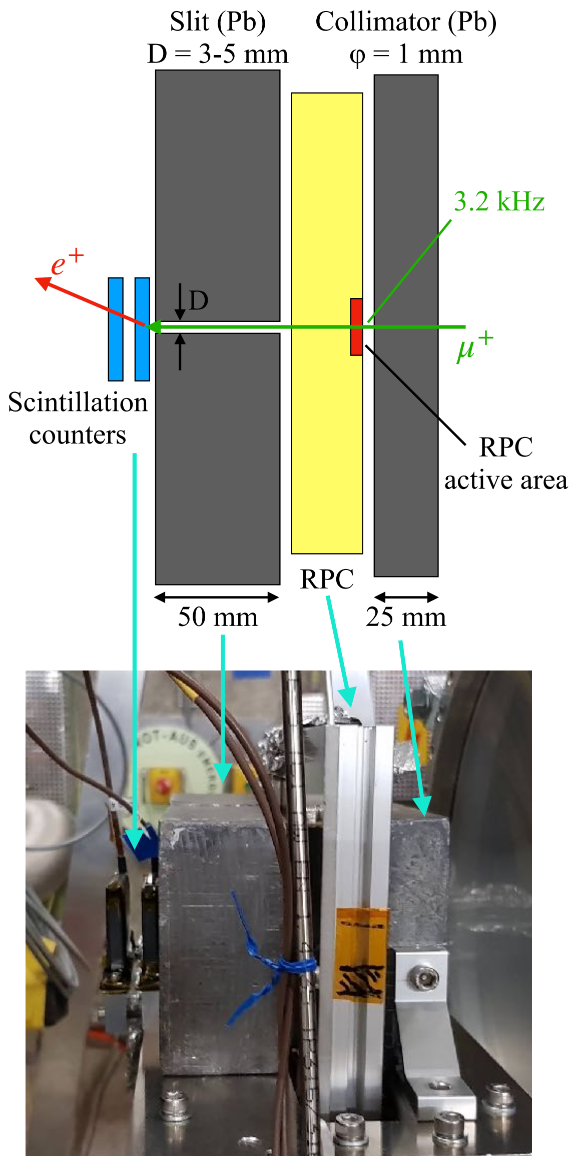


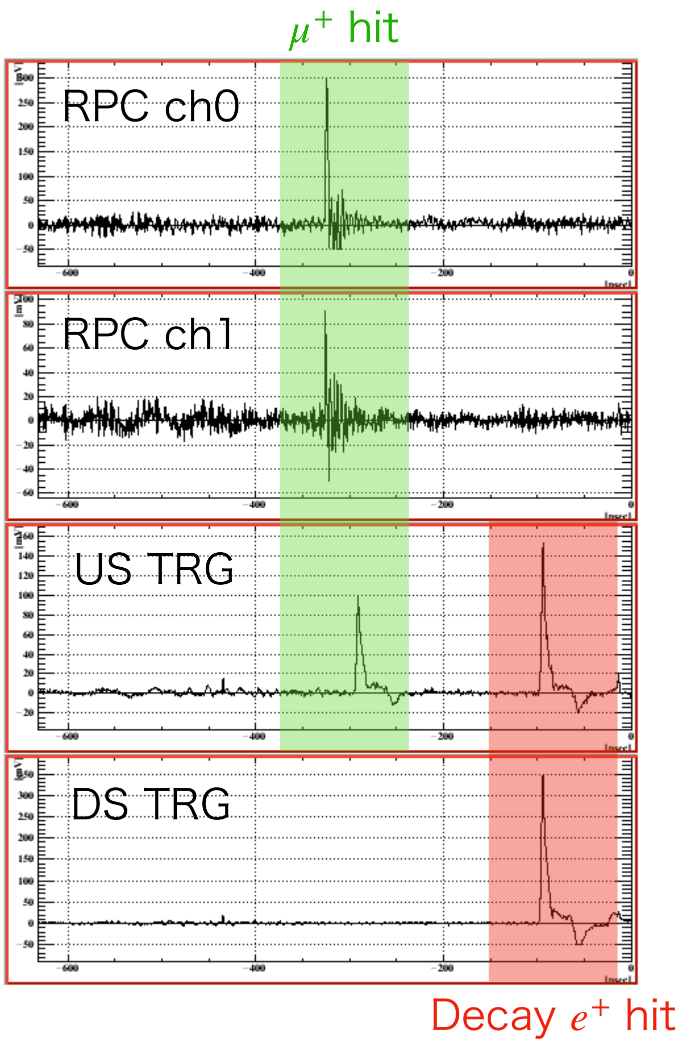


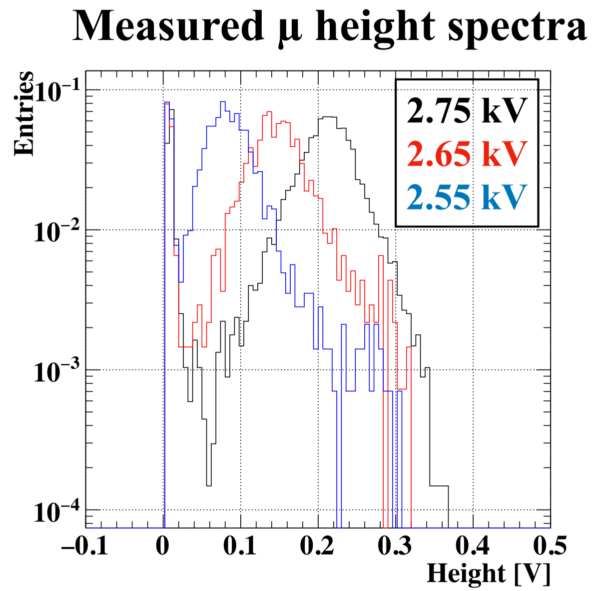
$$\nabla^2 \delta V(x,y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \cdot f(x,y) \cdot \rho_S$$

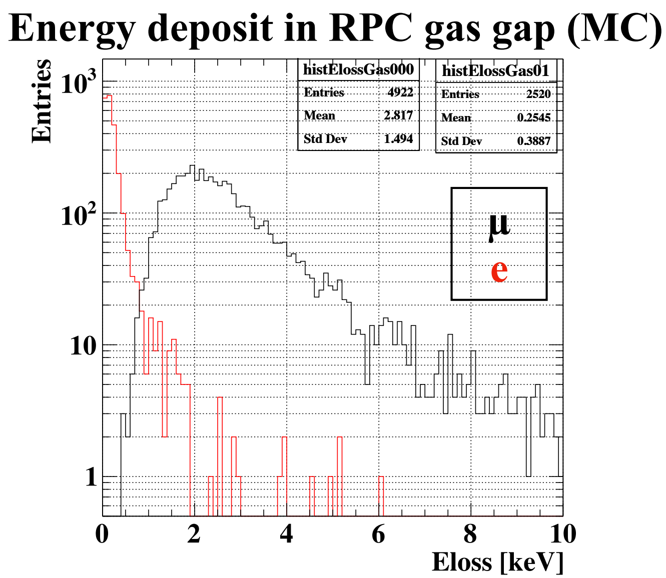
- $Q_{\mathrm{mean}} = 2.3$ pC
- $\rho_S = 60$ MΩ/sq for anode
- $\rho_S = 7$ MΩ/sq for cathode

Response to low-momentum μ^+

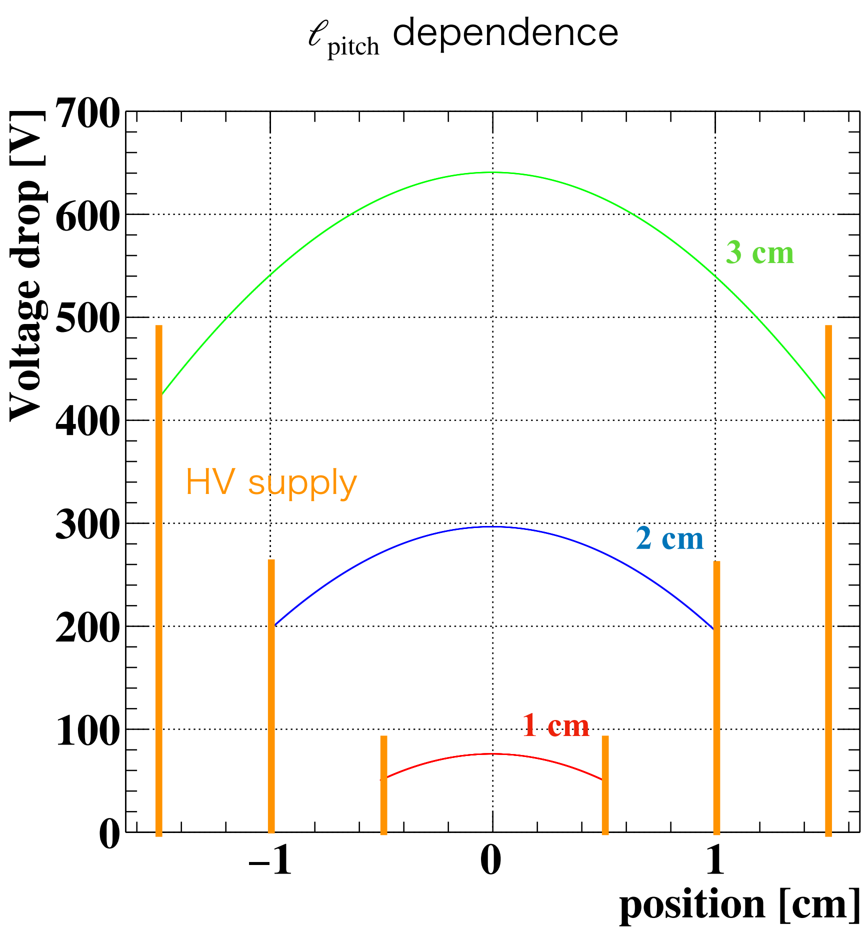


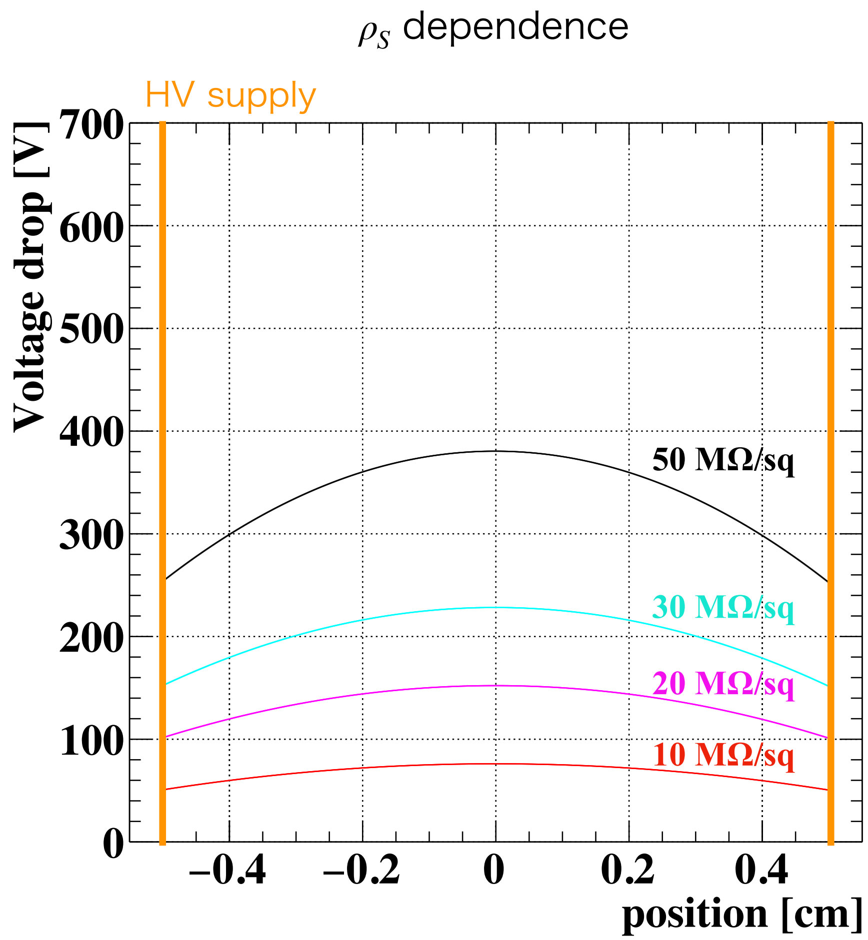






Voltage drop estimation

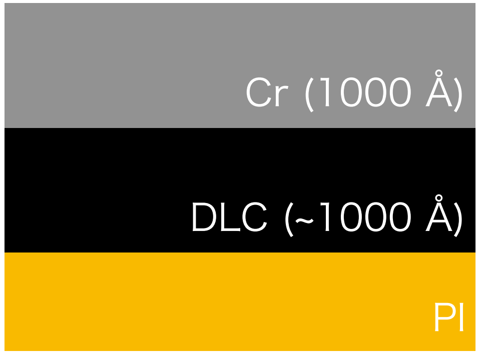




Conductive pattern structure

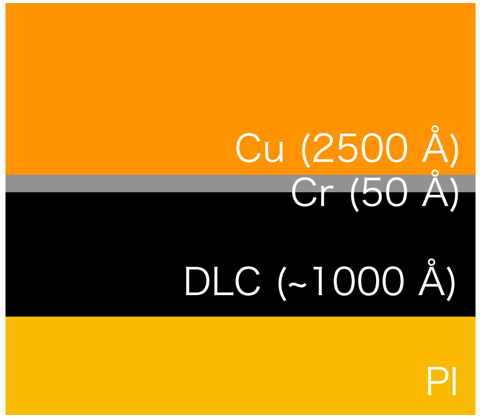
- Not trivial for metal to deposit on DLC
- **Cr can be well-connected**

1st trial

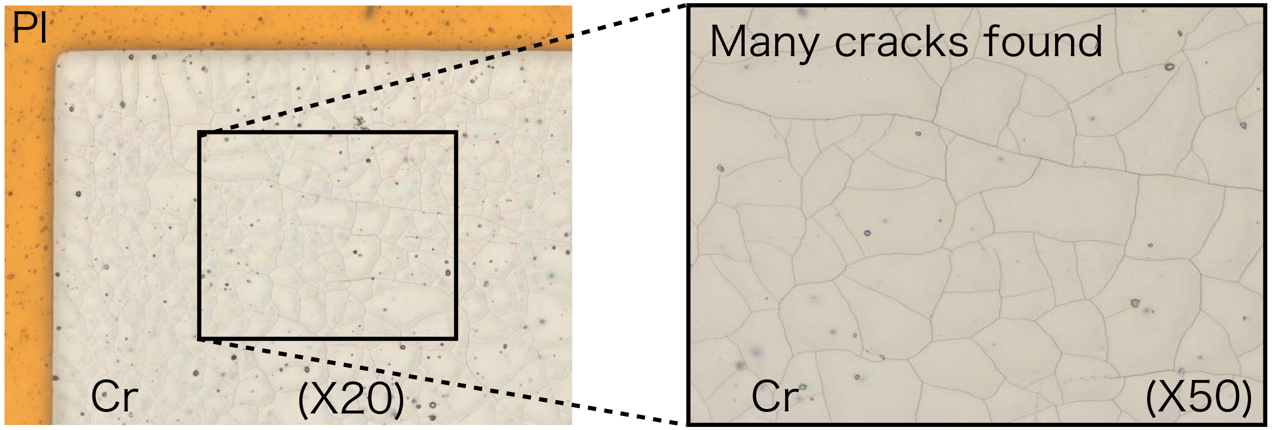


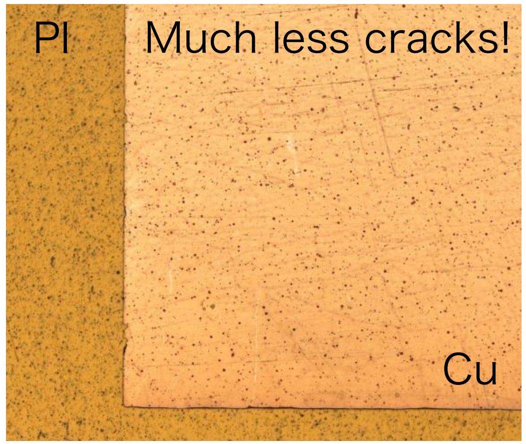
- Crack and removal of Cr
- Cr surface oxidised

Current structure



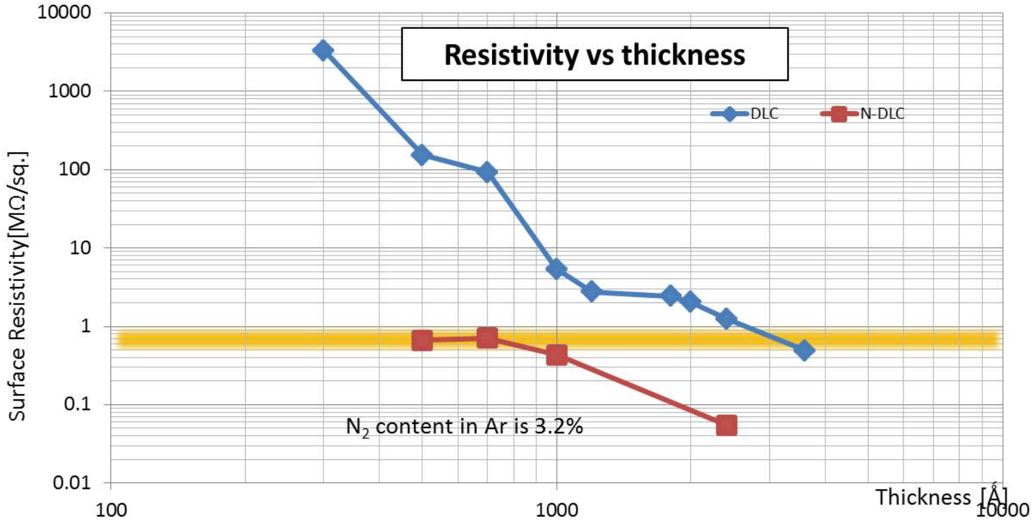
- **No problem found**





Resistivity control

DLC thickness



Ochi, A. et al. "Carbon sputtering technology for MPGD detectors", PoS TIPP2014 (2014) 351

Resistivity reduction by annealing