MEG II実験背景事象抑制に向けたDLC-RPC検出器の開発
―新型電極を用いた低レート環境下での性能評価―

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他MEG IIコラボレーション
(神戸大理、東大素セ[A]、 東大理[B])

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Outline

- Introduction
  - MEG II experiment
  - Radiative Decay Counter (RDC)
  - Resistive Plate Chamber with Diamond-Like Carbon (DLC-RPC) for upstream RDC
  - First Prototype of DLC-RPC
- Investigation of quenching problems in First Prototype
  - Operation test in low-rate
  - Quenching problems with conductive strips
- Summary and prospects

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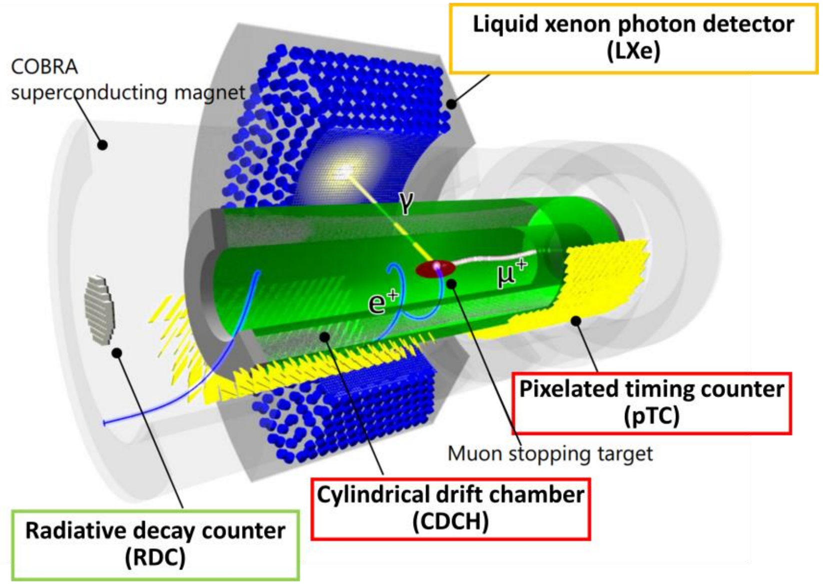
MEG II experiment

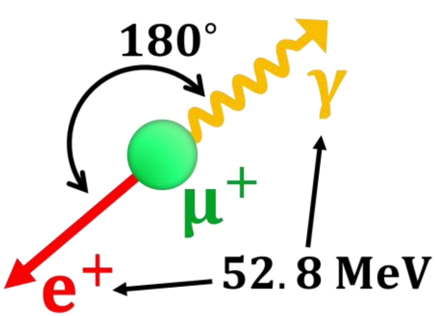
- MEG II searches $\mu^+ \to e^+\gamma$ decay
  - Charged lepton flavour violating decay
  - Clear evidence of new physics



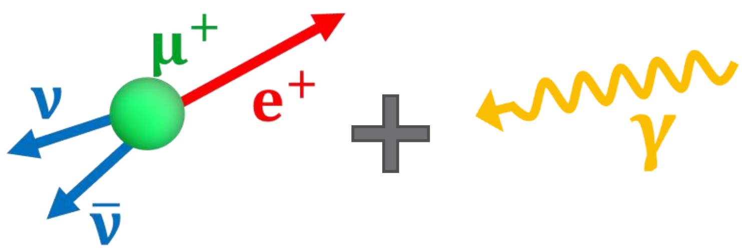
- The $\mu^+ \to e^+\gamma$ signal features
  - ✓ e^+ and γ have the same energy (52.8 MeV)
  - ✓ e^+ and γ emitted at the same time
  - ✓ e^+ and γ emitted in opposite directions

- Main background is accidental coincidence of BG-e^+ and BG-γ

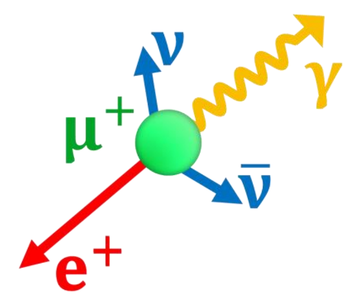
$\mu^+ \to e^+\gamma$ decay



Background event



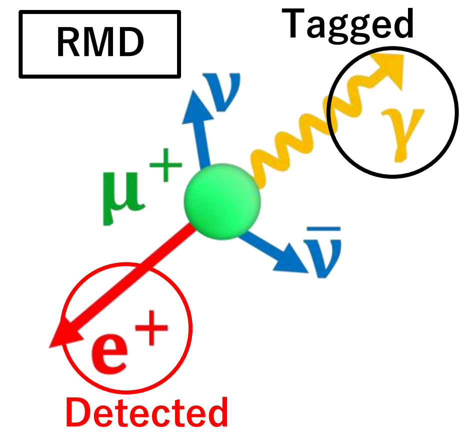
BG-γ source

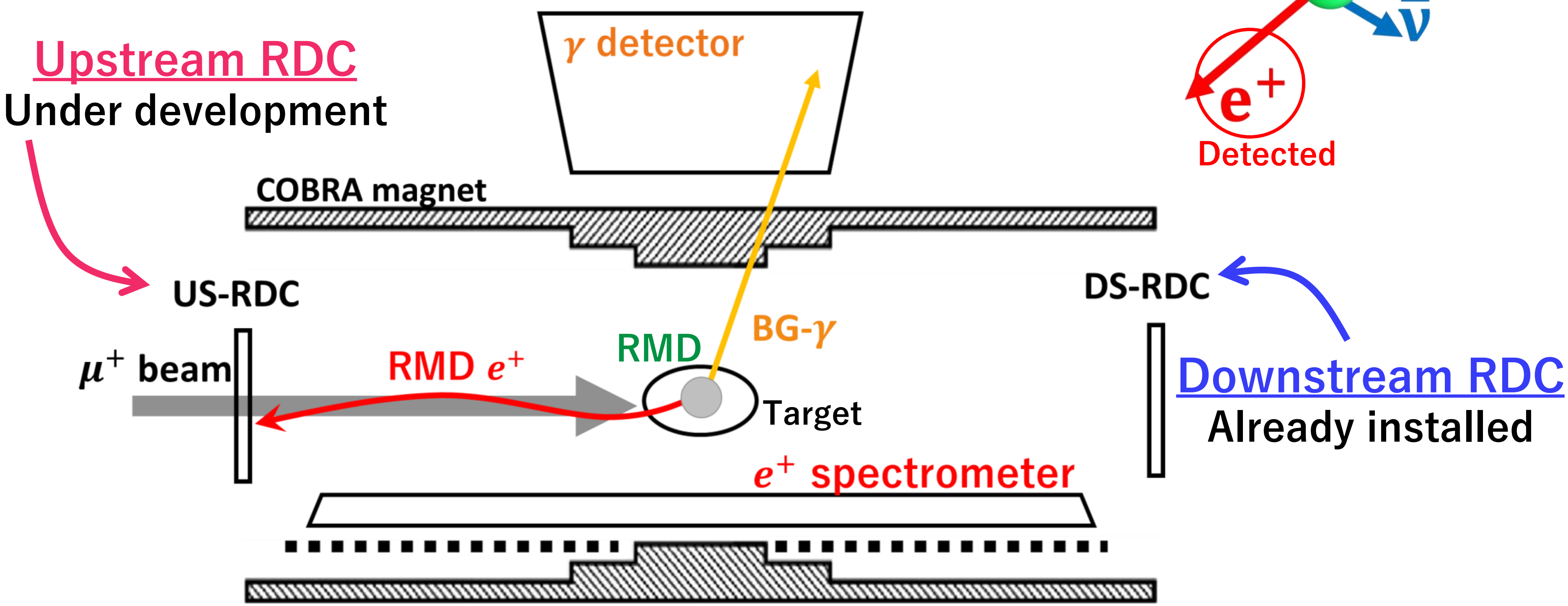


Radiative muon decay and annihilation in flight

Radiative Decay Counter (RDC)

- Detector for tagging BG-γ
- When BG-γ have signal-like energy (~ 52.8 MeV) most of e^+ have a low energy ($1-5$ MeV)
  - RMD e^+ distributed on the μ^+ beam axis

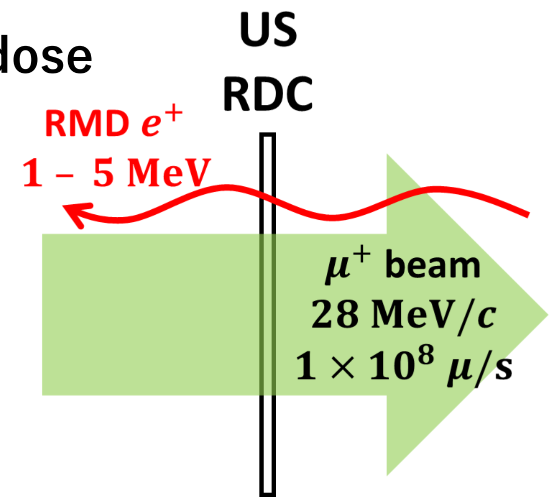




Requirements for upstream RDC (US-RDC)

- US-RDC needs to detect MIP e^+ from RMD in a low-momentum and high-intensity muon beam
  (28 MeV/c) $(1 \times 10^8\ \mu/s)$

1. Material budget: $< 0.1\%$ radiation length
2. Rate capability: $4\ \mathrm{MHz/cm^2}$ of muon beam
3. Radiation hardness: $\mathcal{O}(100)\ \mathrm{C/cm^2}$ irradiation dose for > 30 weeks operation
4. Efficiency: $> 90\%$ for MIP e^+
5. Timing resolution: < 1 ns
6. Detector size: 20 cm (diameter)

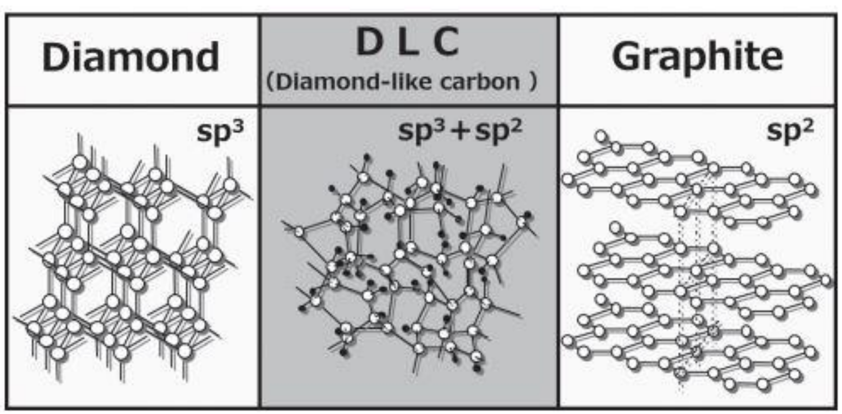


Development of Resistive Plate Chamber (RPC) with Diamond-Like Carbon (DLC) electrodes for US-RDC

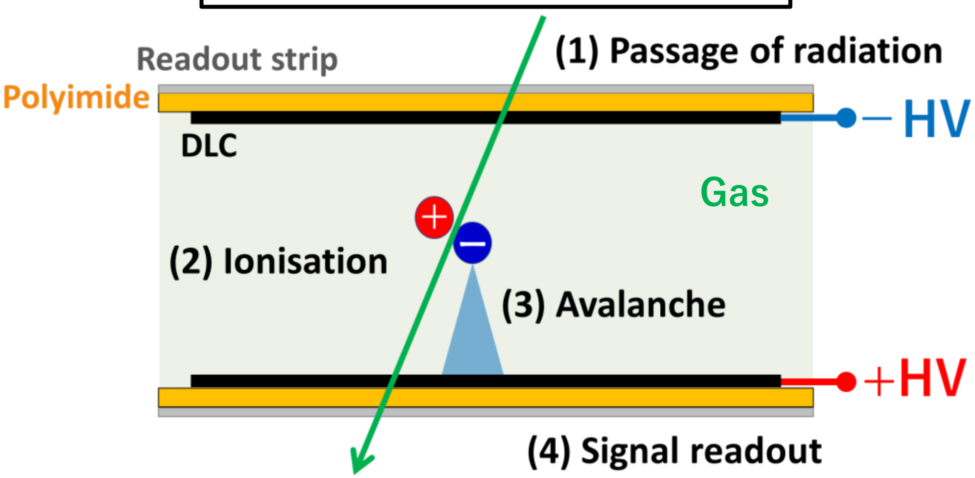
DLC-RPC

- DLC : high-resistance thin-film material
  - Small material budget by sputtering
  - Controllable resistivity by changing film thickness

- RPC : gas detector
  - Fast response (< 1 ns)
  - High detection efficiency (by multi layering)
    - Efficiency with n layers: $\epsilon_n = 1 - (1 - \epsilon_1)^n$

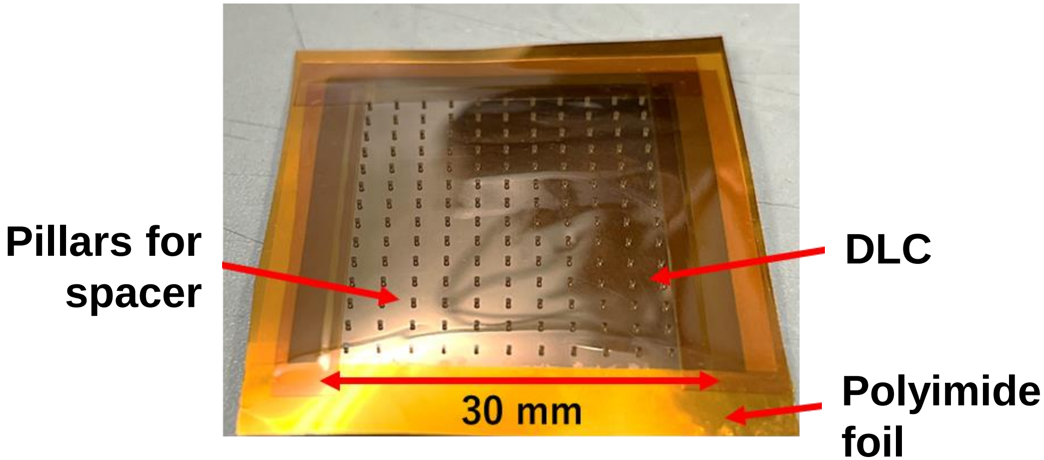


Principle of operation of DLC-RPC

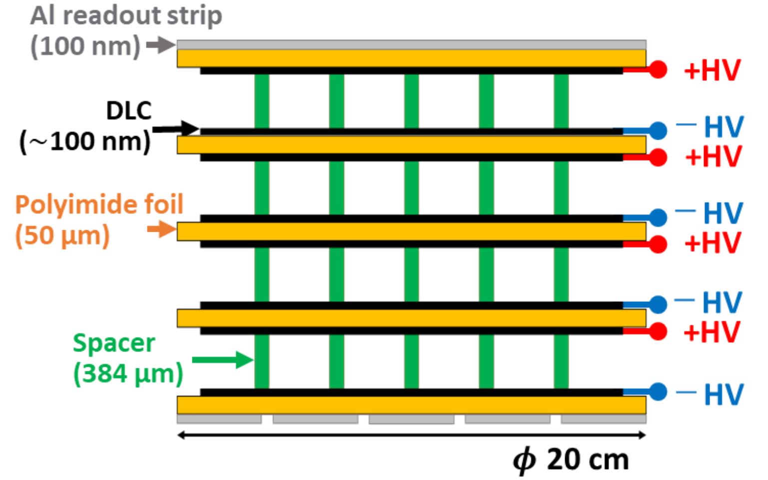


DLC-RPC for MEG II

Previous DLC-RPC electrode sample



Scheme of MEG II DLC-RPC structure

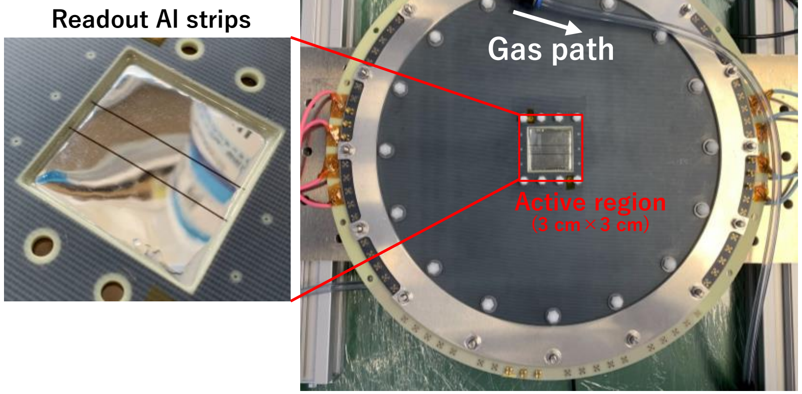


➢ Requirements for US-RDC and status of previous DLC-RPC

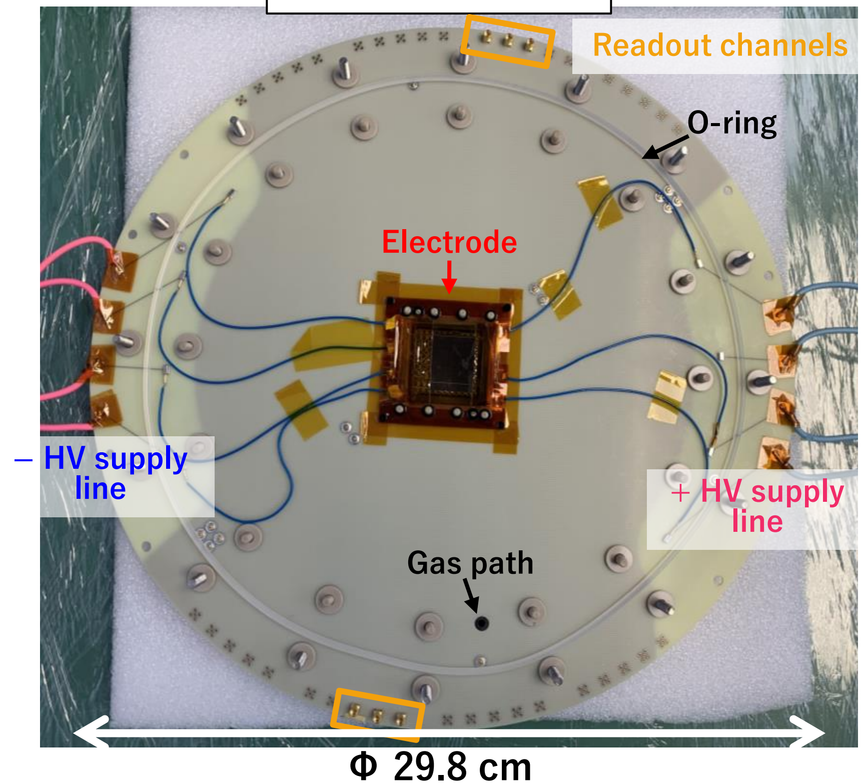
Contents	Requirements	Previous status
Material budget	$< 0.1\%\ X_0$	$\sim 0.095\%$
Rate capability	$4.0\ \mathrm{MHz/cm^2}$	$1\ \mathrm{MHz/cm^2}$
Radiation-hardness	$\mathcal{O}(100)\ \mathrm{C/cm^2}$	$\mathcal{O}(100)\ \mathrm{mC/cm^2}$
Detection efficiency	$> 90\%$	$> 40\%$ (with single-layer), $> 90\%$ (calculated)
Timing resolution	$1\ \mathrm{ns}$	$160\ \mathrm{ps}$
Detector size	$\phi\ 20\ \mathrm{cm}$	$3\ \mathrm{cm} \times 3\ \mathrm{cm}$ (active region)

First Prototype of DLC-RPC

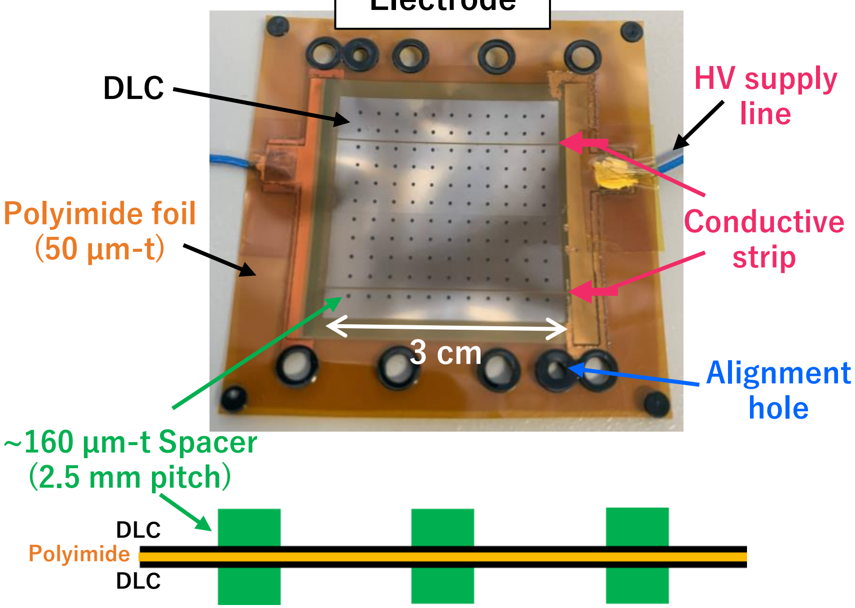
Outer overview



Internal overview

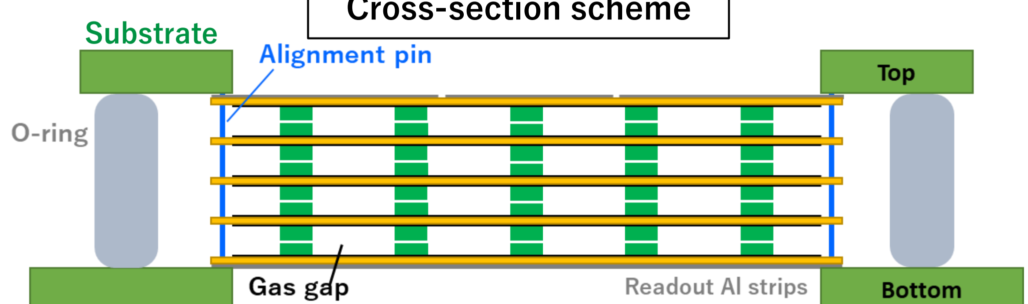


Electrode



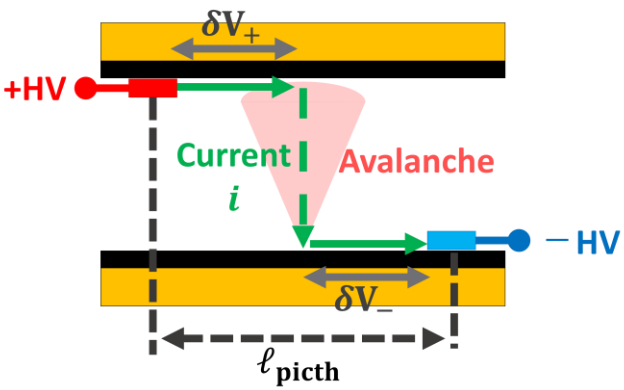
Form spacers on both side by manufacturing problems

Cross-section scheme



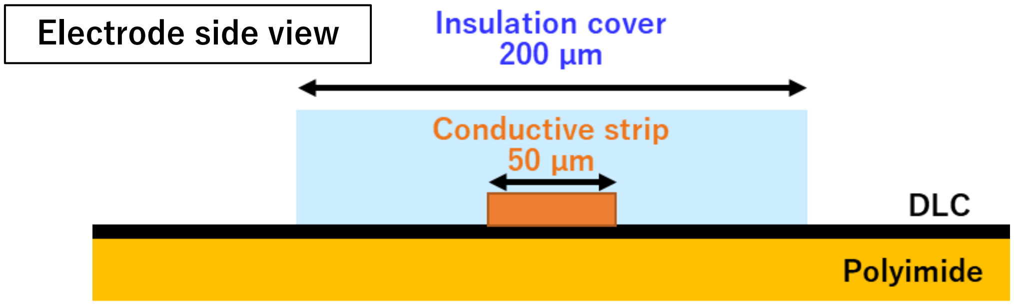
New electrode for high-rate capability

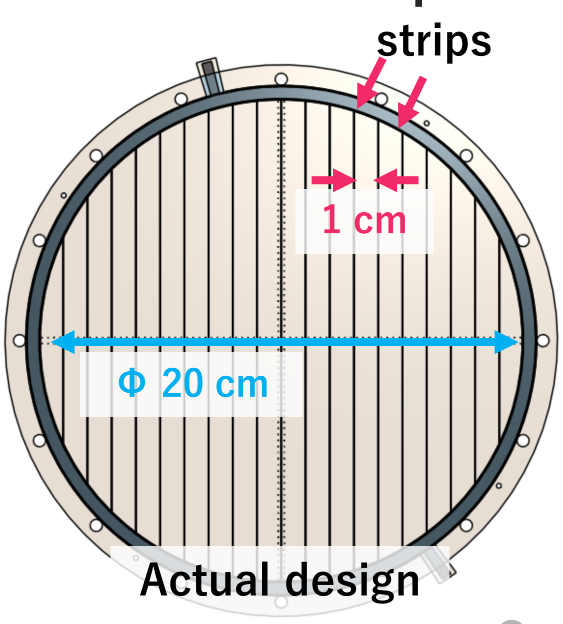
- Rate capability is determined by voltage drop
  - Surface resistivity
  - The distance between conductors
    - Implement of conductive strips



- Protection by insulation cover
  - Quench capacity is expected to be low near conductive strips
  - The insulation covers are inactive areas
    ➔ should be as small as possible

  Current design: ratio of inactive area: 2.1 %

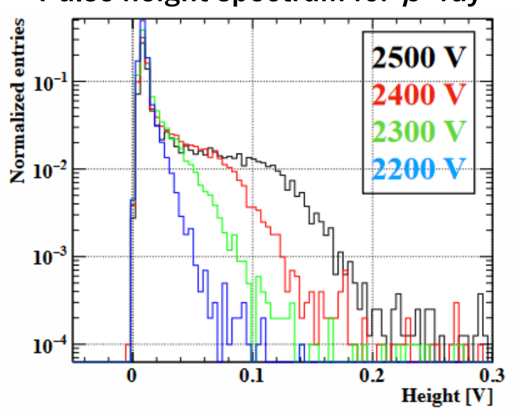




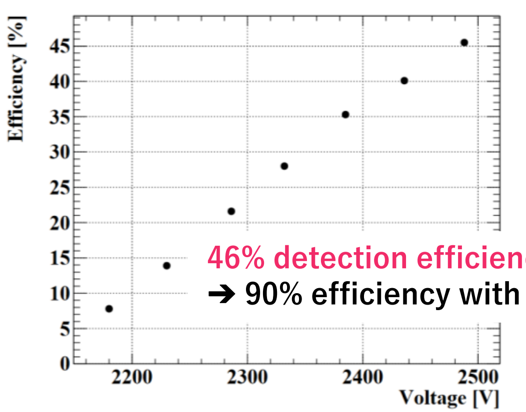
Performance of First Prototype

- **Reported in JPS autumn 2022** (6pA421-2)
  - Operation at positive pressure
  - Could be operated only in certain conditions

Pulse height spectrum for β-ray

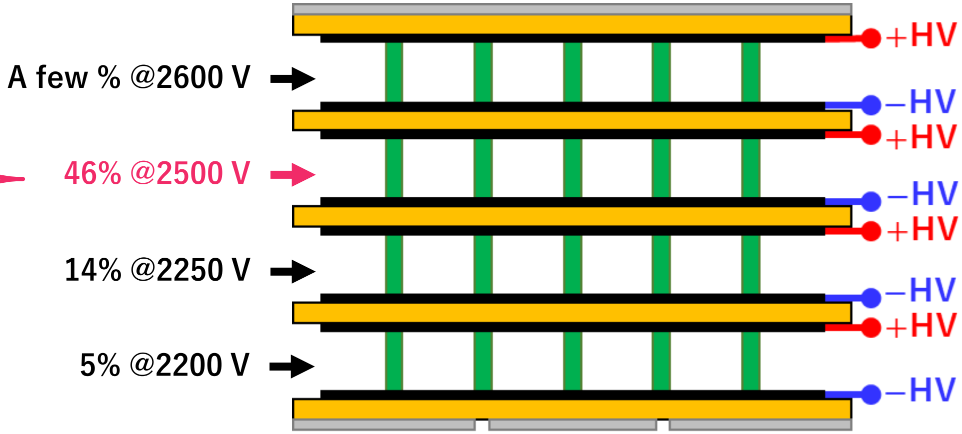


Efficiency vs. operation voltage

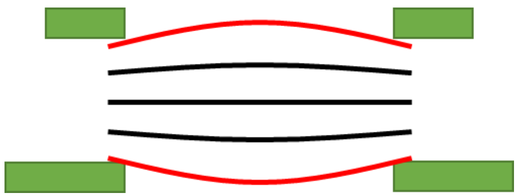


46% detection efficiency with single layer
➔ 90% efficiency with 4 layers $(1-(1-\epsilon_1)^4)$

Efficiency in each layer



Non-flatness by positive pressure



We need to do operation test at negative pressure

Today's talk

- Could not operate at negative pressure due to discharges
- The problems surfaced due to operation at negative pressure
  - ✓ Insufficient discharge quench capability
    - Unable to suppress the development of discharges
    - ➔ Details will be presented in this talk (23pT2-5)
  - Distortion of electric field
    - Causes excessive development of gas avalanche
    - ➔ Details will be presented by Weiyuan at next talk (23pT2-6)
- Estimation of the performance expected from actual detector
  - Considering the structure of the detector
  - Expected contribution to sensitivity
  - ➔ Details will be presented by Kensuke at the end of this series of talk (23pT2-7)

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  - **Quenching problems with conductive strips**
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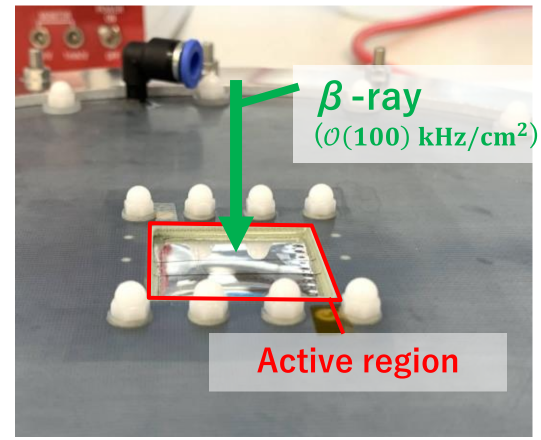
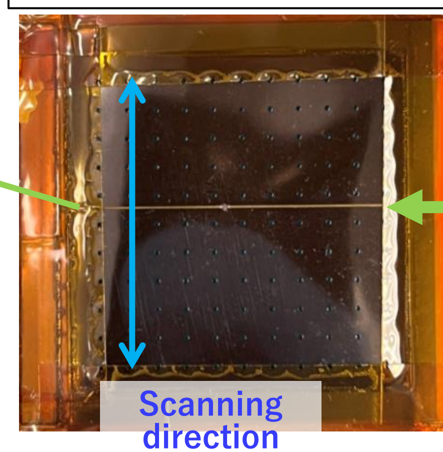
Operation test in low-rate

- **Insufficient quench capability near conductive strips**
- **DLC-RPC operation for β-ray irradiation**
  - Without β-ray irradiate :
    - Voltage can be supplied to ~ 2500 V
      ➔ expected working point
  - With β-ray irradiate :
    - Discharge at ~ 2100 V
  - Scanning of β-ray irradiation position :
    - Discharge when irradiated near the conductive strip



Scanning of irradiation position



Conductive strip

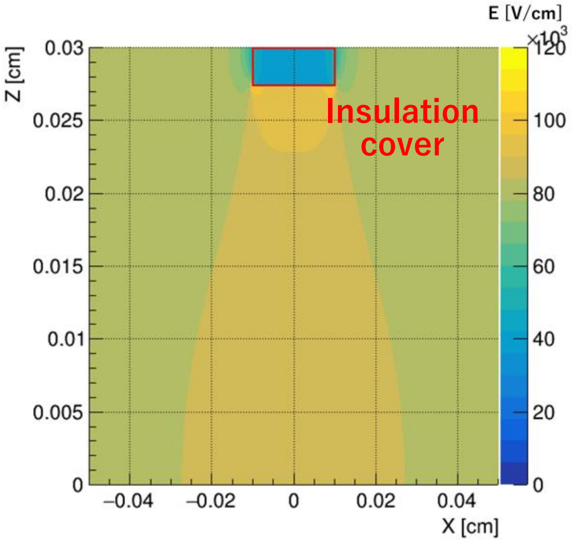
Quenching capability

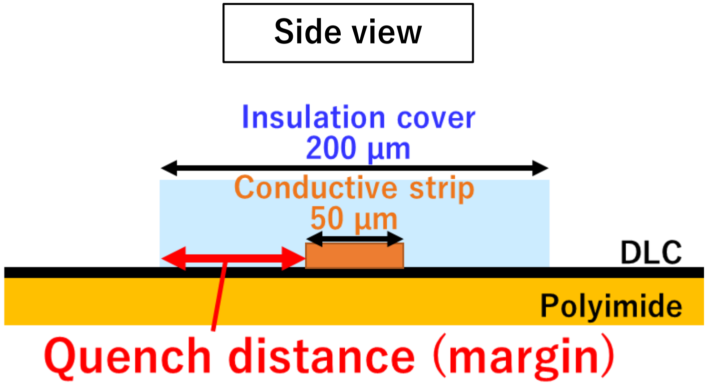
- DLC-RPC quenches discharge with resistive electrode
    - Weak quench capability near the conductor
      ➔ protected by insulation cover (200 µm width)

Current design values are insufficient
- Electric field over insulation covers is strong

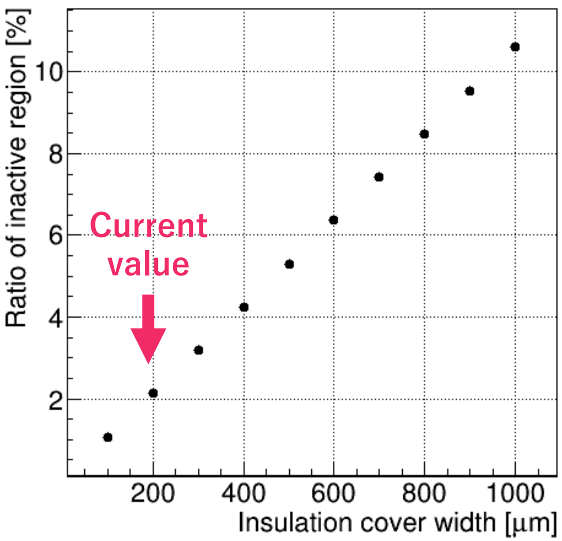
➔ Need to make enough distance to quench
- But need to consider the ratio of inactive region

Electric field near insulation cover



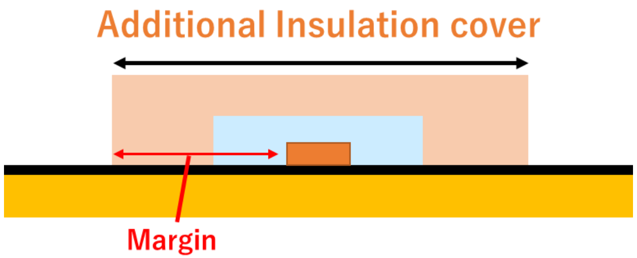


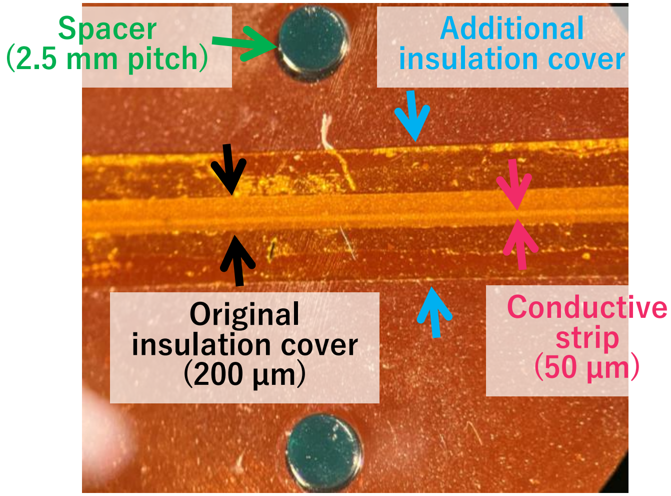
Ratio of inactive area



Test to add insulation cover

- Investigate optimum margins by adding insulation cover
  - ➔ But cannot be operated at working point due to discharges
- There are various problems other than problems with conductive strips
  - Low surface resistivity
  - Distortion of electric field
    - Details at next talk
  - ➔ Difficult to distinguish the causes
- Tests using previous electrodes that have been confirmed to work
  - Is the strip structure itself doing something wrong?

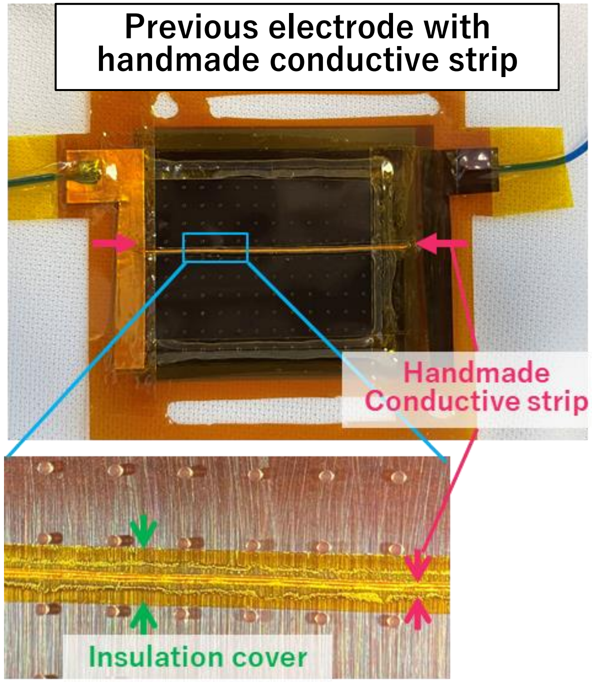




Test using prior electrodes

- **Previous electrodes**
  - No structural problems
  - Surface resistivity higher than First Prototype
    - Prior electrode : 60 – 70 MΩ/sq.
    - First Prototype : 10 – 20 MΩ/sq.

- **Handmade conductive strips on electrode**
  - Using copper tape
    - Width of margin: 500 – 750 µm
  - In First Prototype, using Cr+Cu sputtering



- **Confirmed the improvement of operating voltage due to adding margin**
  - Mechanical uncertainty cannot be eliminated because it is handmade
  - Different surface resistivity conditions

To be tested using samples with various strip widths

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Summary

- **DLC-RPC is under development for MEG II US-RDC**
  - The low-momentum and high-intensity muon beam passage
    ➔ Several stringent requirements are imposed

- **First Prototype cannot be operated due to some problems**
  - Insufficient quench capability to suppress discharge
  - Distortion of electric field
    - Details will be presented at next talk

- **Insufficient quench capability near the conductive strips**
  - Quench distance, distorted electric field over insulation cover
  - Investigated the optimal insulation cover width
    - **The improvement of operating voltage due to adding margin**
    - But it is currently difficult to isolate the problems

Prospects

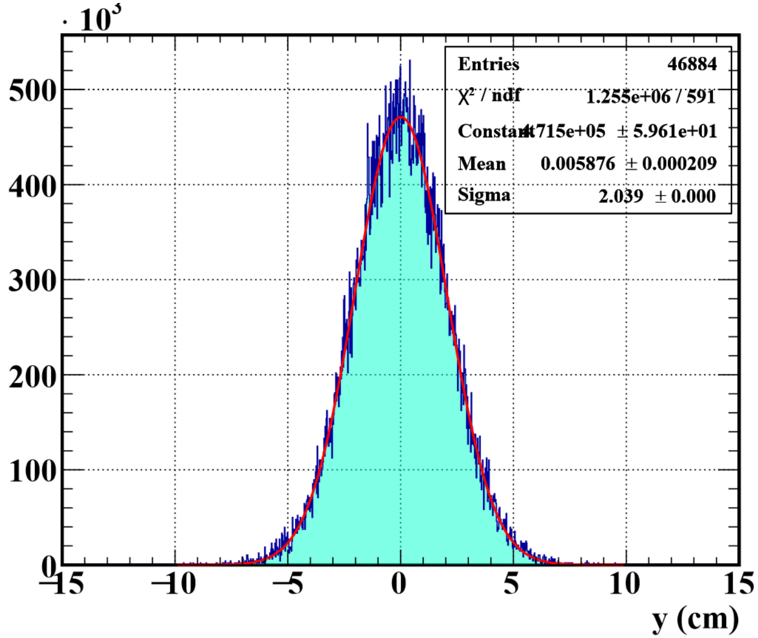
- **Optimisation of insulation cover widths on conductive strips for stable operation**
  - Production of electrode samples with different strip widths

- **DLC-RPC as US-RDC**
  - Estimation of the performance of DLC-RPC for different insulation cover width
    - Influence of the size of the insensitive area
    - Influence of insulation covers on muon beams

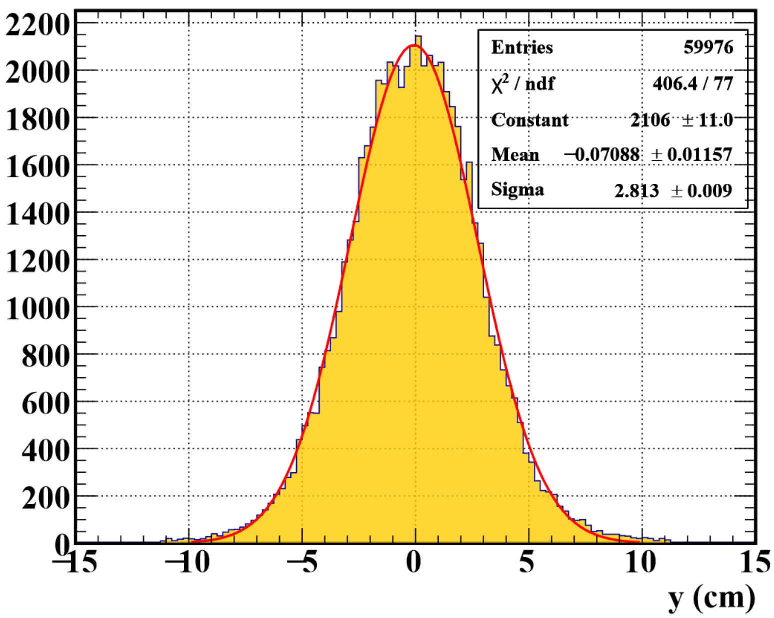
- **Improvements in other than quench capacity**
  - Investigation of the possibility of operating without increasing the width of the insulation cover
    - Suppression of electric field distortion to suppress of excess gas avalanche (see next talk)

Backup

Distribution of μ^+ beam and RMD e^+



μ^+ beam ($\sigma = 2.0$ cm)

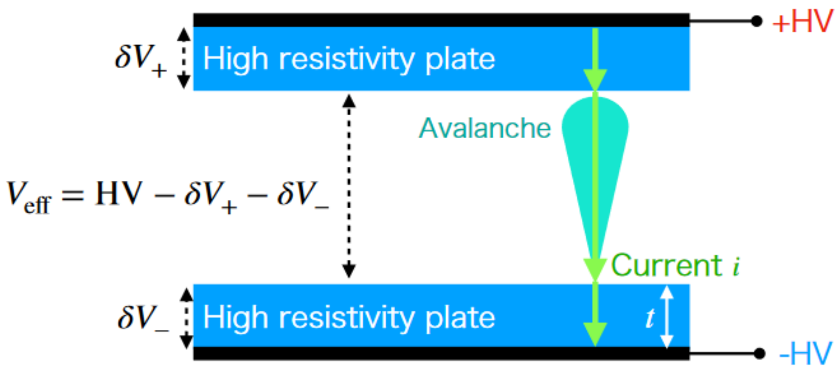


RMD e^+ ($\sigma = 2.8$ cm)

Rate capability of RPC

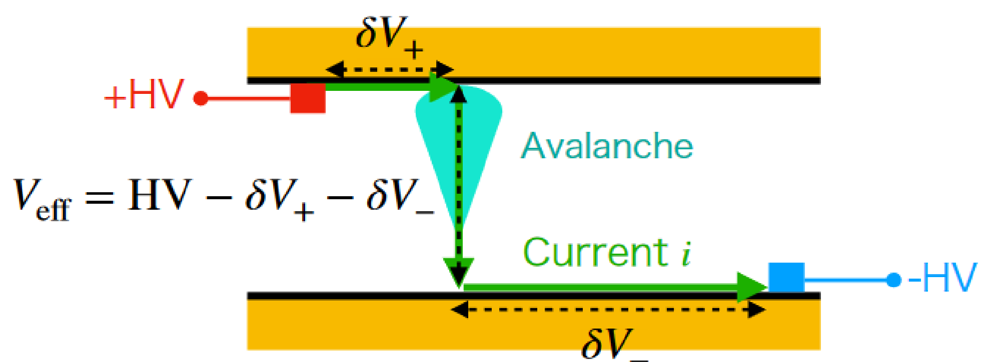
- 高レート環境では大電流が高抵抗電極に流れる
  - 電圧降下が生じ、実効的な印加電圧V_{eff}が減少
  - ガスゲインが小さくなり、検出器性能が悪化する

Conventional RPC



$$\delta V = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \cdot f(x,y) \cdot \rho_V \cdot t$$

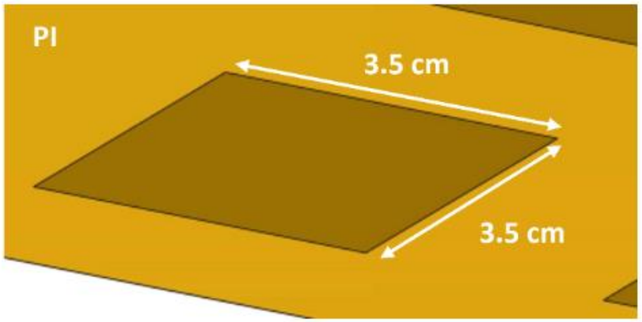
DLC-RPC



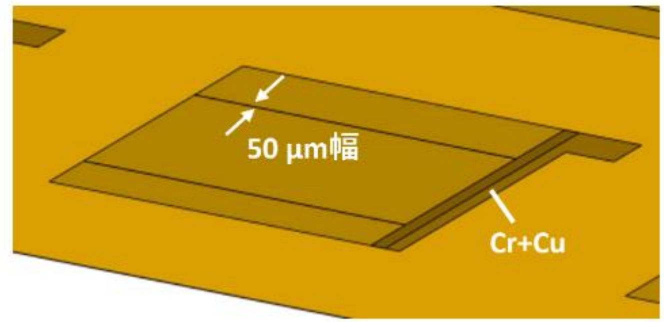
$$\nabla^2 \delta V(x,y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \cdot f(x,y) \cdot \rho_S$$

高電圧供給の構造が電流の流れる距離を決める
➔ 単純に大型化できない
➔ HV供給構造のセグメント化が必要

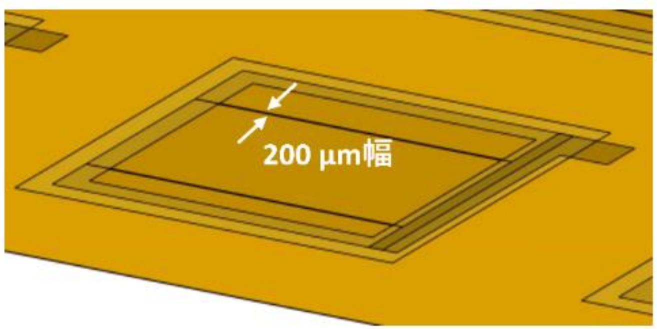
新型電極の製造工程



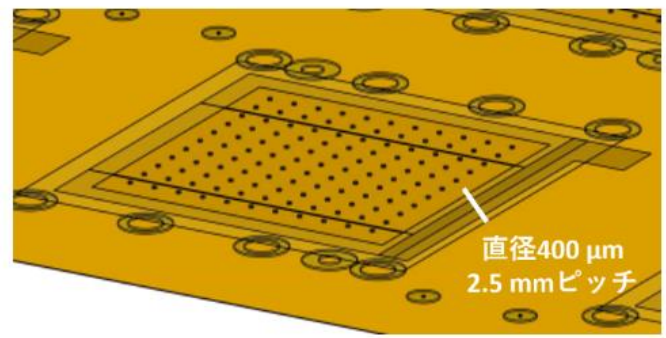
(a) ポリイミドフィルムに DLC をスパッタする



(b) DLC 上に Cr+Cu の導電パターンを形成する



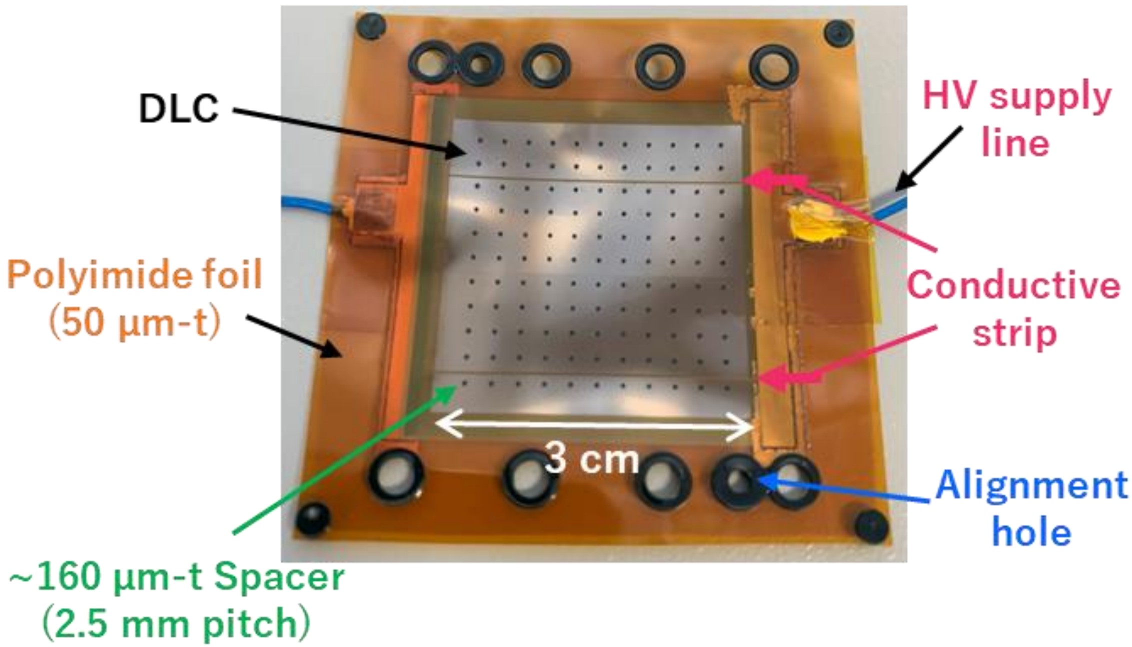
(c) 導電体に絶縁カバーを取り付ける

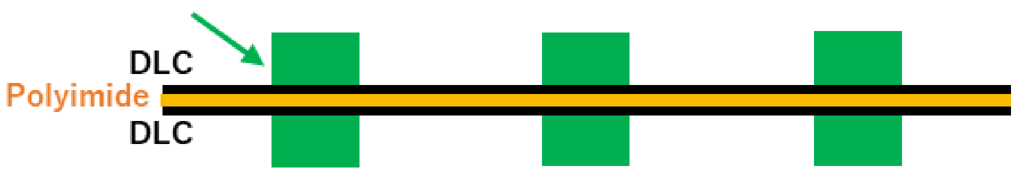


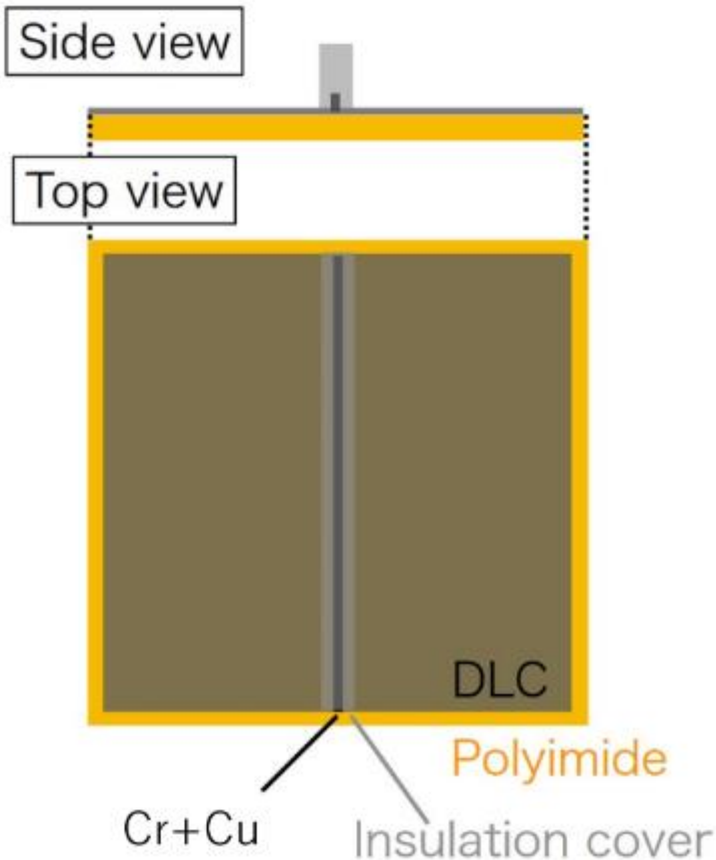
(d) DLC 上に直径 400 μm のピラーを 2.5 mm 間隔で形成する

図 6.1: 新型電極の製造工程

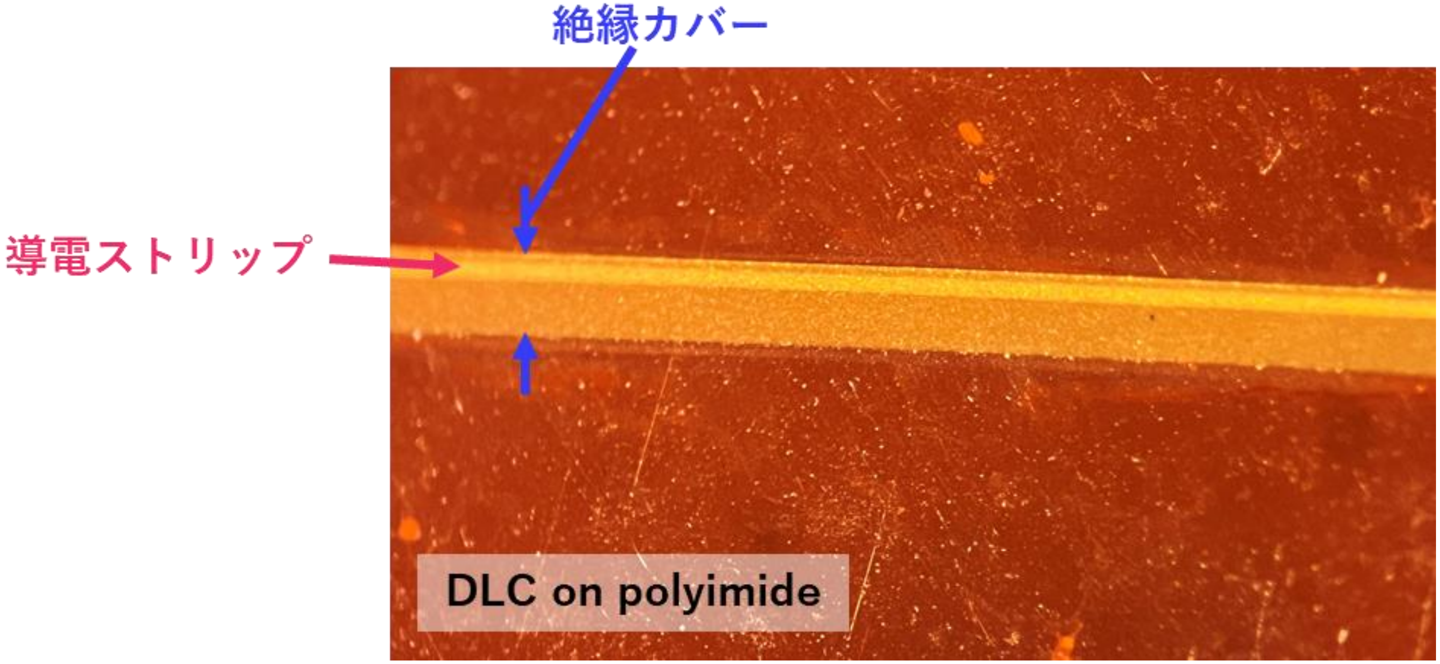
新型電極構造


DLC
HV supply line
Conductive strip
Polyimide foil (50 μm-t)
3 cm
Alignment hole
~160 μm-t Spacer (2.5 mm pitch)

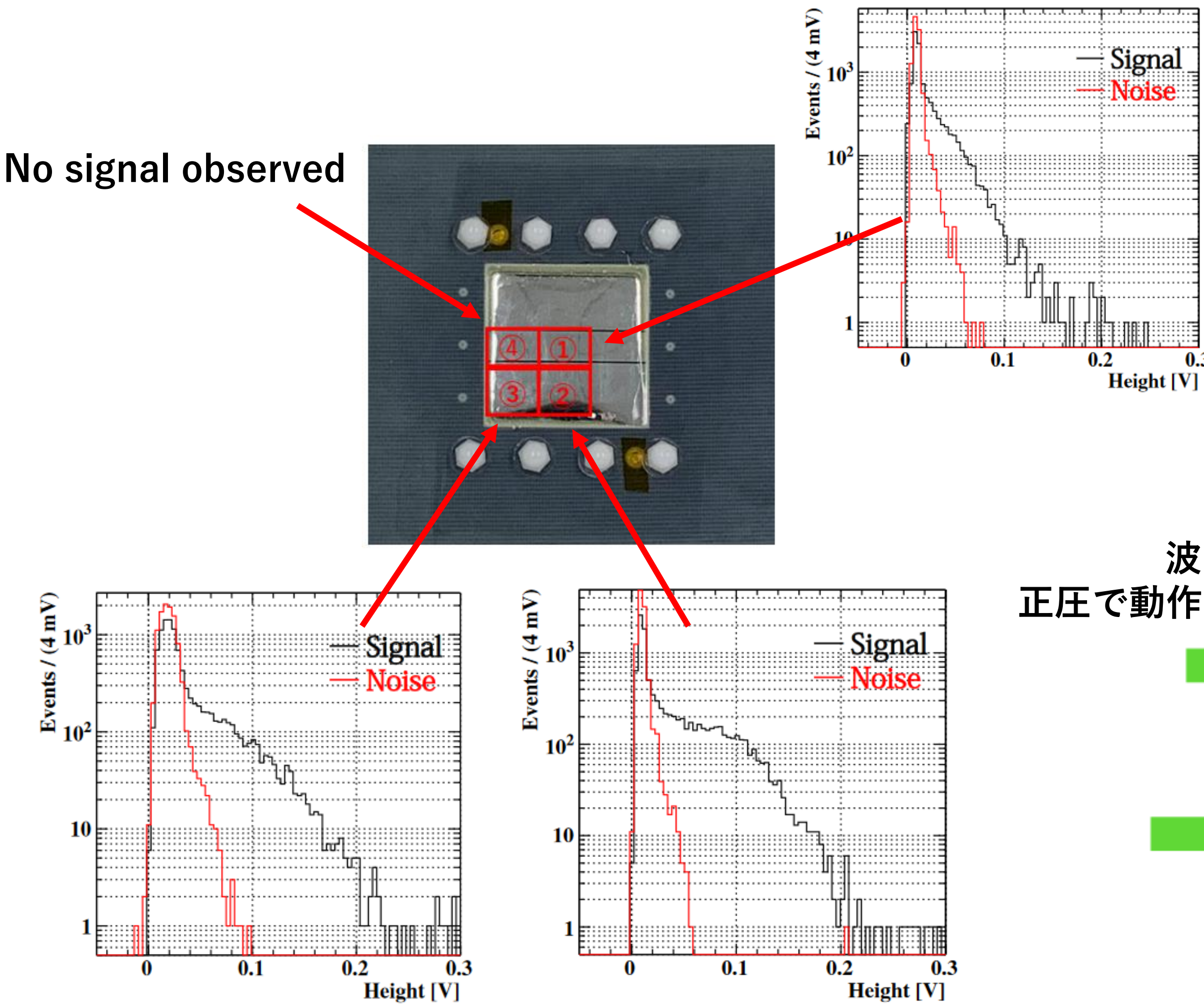

DLC
Polyimide
DLC


Side view
Top view
DLC
Polyimide
Cr+Cu
Insulation cover

導電ストリップと絶縁カバー



波高分布の読み出し位置依存性



波高分布の読み出し位置依存性は
正圧で動作させたことによる電極の非均一性が原因