MEG II実験に向けた高レート耐性DLC-RPCの導電体近傍における放電の研究

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他 MEG IIコラボレーション
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連続講演

- 高橋 真斗（神戸大理）
  「MEG II実験に向けた高レート耐性DLC-RPCの導電体近傍における放電の研究」
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- 鈴木 大夢（神戸大理）
  「MEG II実験背景事象抑制のためのDLC-RPCの長期安定性の評価」
  18aWA203-7

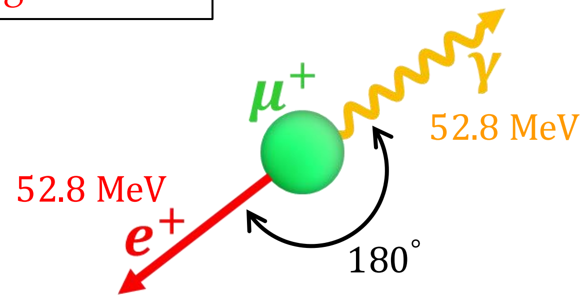
Outline

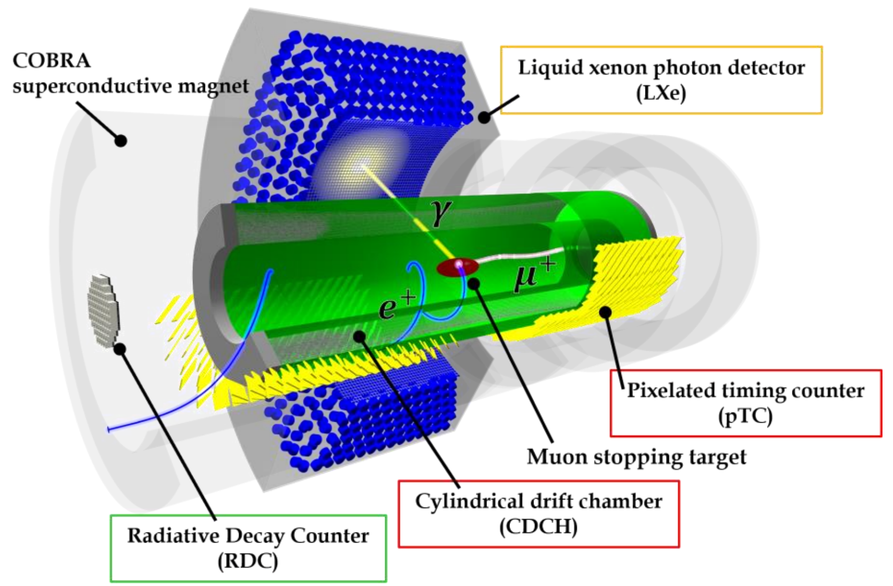
- Introductions
  - MEG II experiment
  - DLC-RPC for background suppression
- Conductive strips for high-rate capability
  - To improve the rate capability of the DLC-RPC
  - Problems in first prototype with conductive strips
- Operation test with various protective covers
  - Performance for β-ray
  - Current spikes at higher voltage
  - Cover width dependence
- Summary and prospects

MEG II experiment

- MEG II searches for $\mu \rightarrow e\gamma$ decay at Paul Scherrer Institut
  - Charged lepton flavor violating process

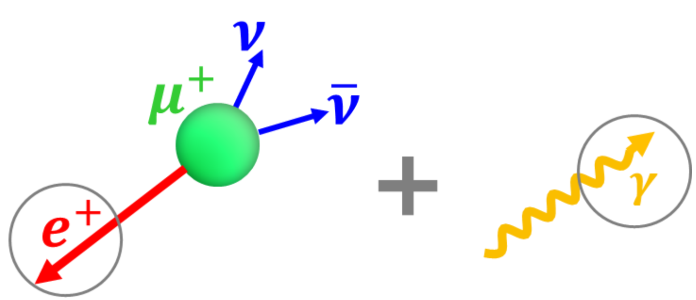
Signal events





Main Background

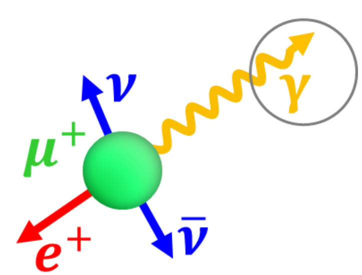
Accidental coincidence between BG-e^+ and BG-γ



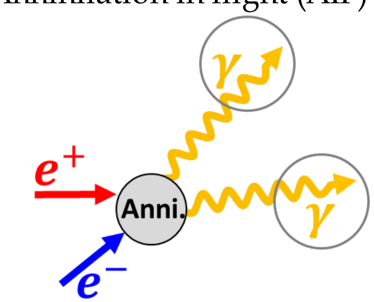
BG-e^+ from Michel decay

BG-γ source

Radiative muon decay (RMD)

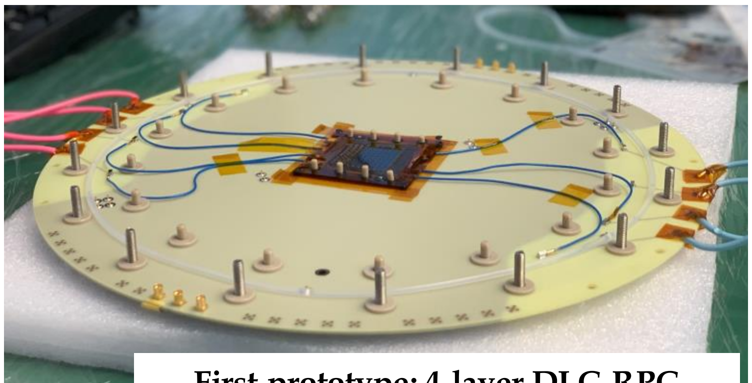


Annihilation in flight (AIF)

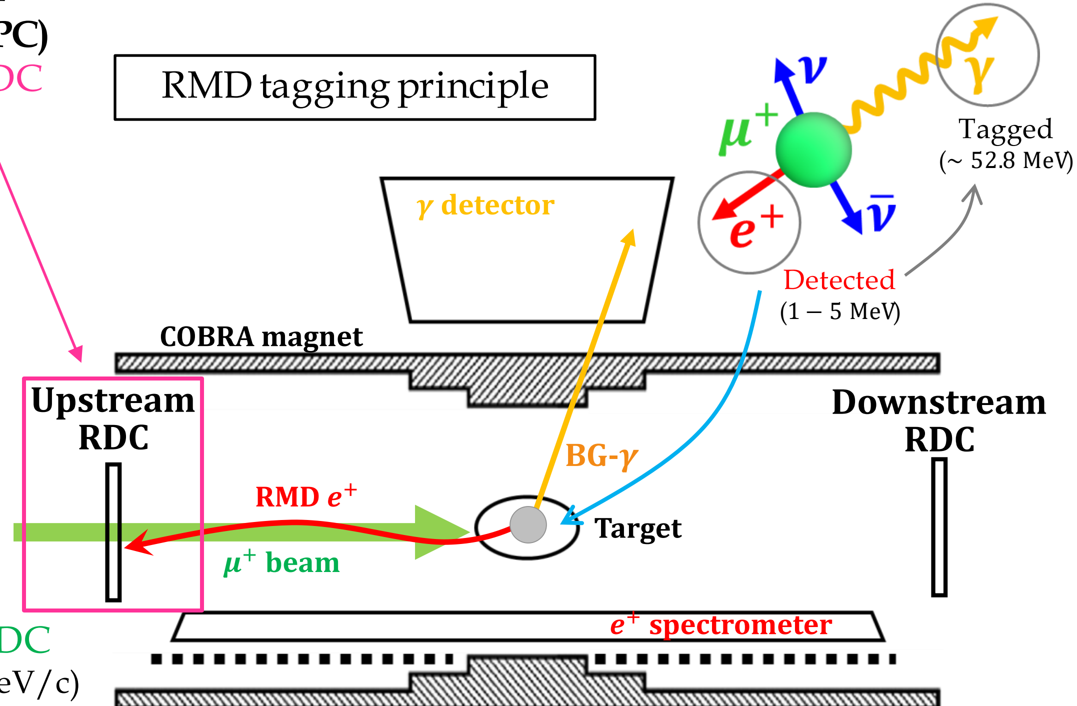


DLC-RPC for background suppression

Resistive Plate Chamber with Diamond-Like Carbon (DLC-RPC)
being developed as upstream RDC



First prototype; 4-layer DLC-RPC
(Reported at JPS2022 autumn, and JPS2023 spring)



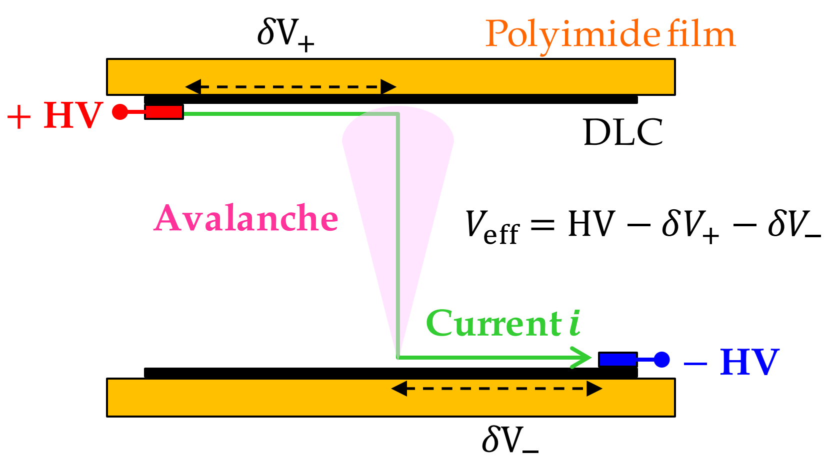
μ^+ beam at upstream RDC
- Low momentum (28 MeV/c)
- High intensity (7×10^7 /s)

➢ Requirements

- Material budget: < 0.1 % X_0
- Rate capability: up to **3 MHz/cm^2**
- Radiation hardness: ~ **100 C/cm^2**
- Detection efficiency: **> 90 %**
- Timing resolution: **< 1 ns**
- Detector size: **ϕ 16 cm**

Rate capability

- **Determined by a magnitude of the voltage drop** by the resistive electrode
  - Large current on the resistive electrodes at high rate
    ➔ Voltage drop δV reduces effective applied HV V_{eff}
    ➔ Gas gain reduction



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

HV supply should be segmented

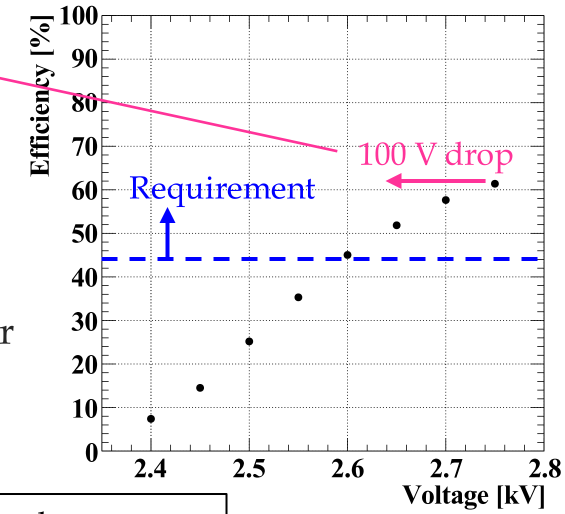
Q_{mean}: Average avalanche charge for μ^+ beam
f : Hit rate
ρ_s : Surface resistivity of DLC

Segmented HV supply for scalability

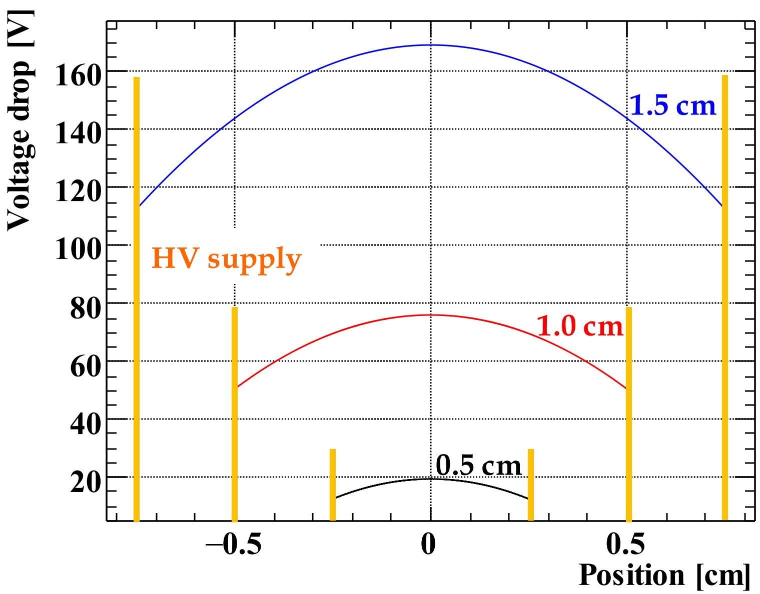
- Voltage drop δV is accepted up to **100 V drop**
  - Need 90 % e^+ of efficiency with 4-layer
    ➔ ~ 44 % with single-layer
    ($\epsilon_n = 1 - (1 - \epsilon_1)^n$, ϵ_n: n-layer efficiency)

- Need the 1.0 cm pitch of segmented HV supply
  - For the μ^+ beam, $Q_{\mathrm{mean}} \sim 2.7$ pC, $f = 3$ MHz/cm^2 at the center

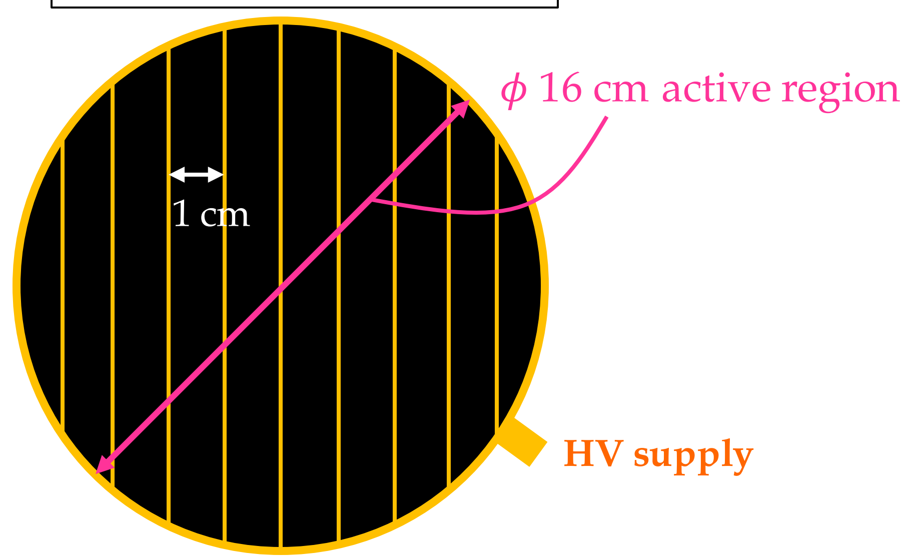
Single-layer DLC-RPC efficiency for MIP e^+



HV supply distance dependence of voltage drop
(Surface resistivity $\rho_S = 10$ MΩ/sq.)

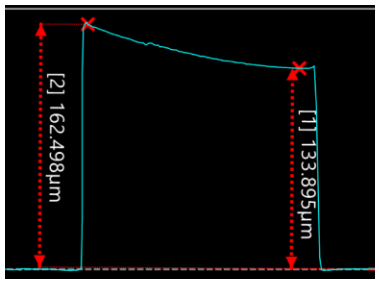


Segmented HV supply geometry

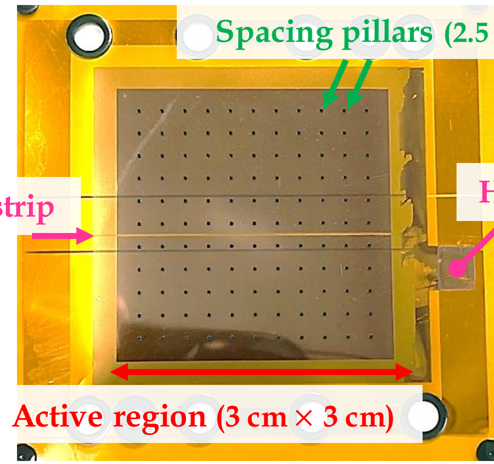


Problems in First prototype

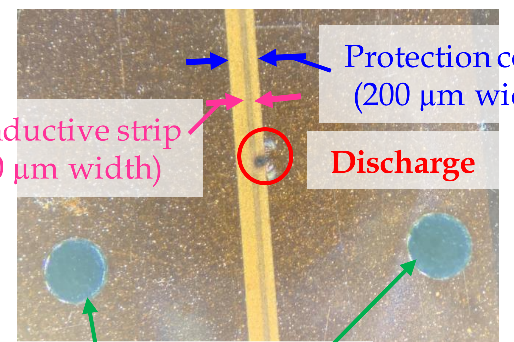
- First prototype for demonstration of 90 % e^+ efficiency in the μ^+ beam
  - Problems:
    - Non-uniform spacing pillars
      ➔ **Already solved** (reported at JPS 2023 spring)

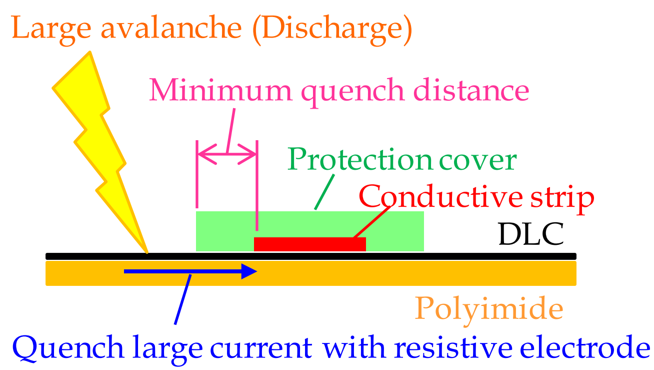


First prototype electrode



    - **Discharges at strip structures**





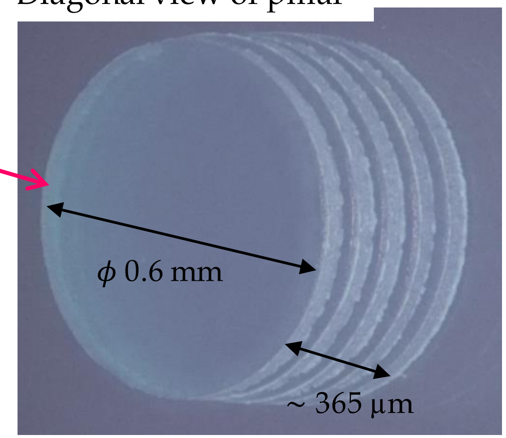
Less quench capability near the strips

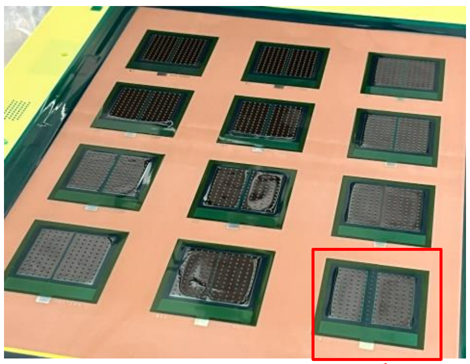
- **Need to investigate the effect of strip structure on operation**

Electrode with the conductive strip

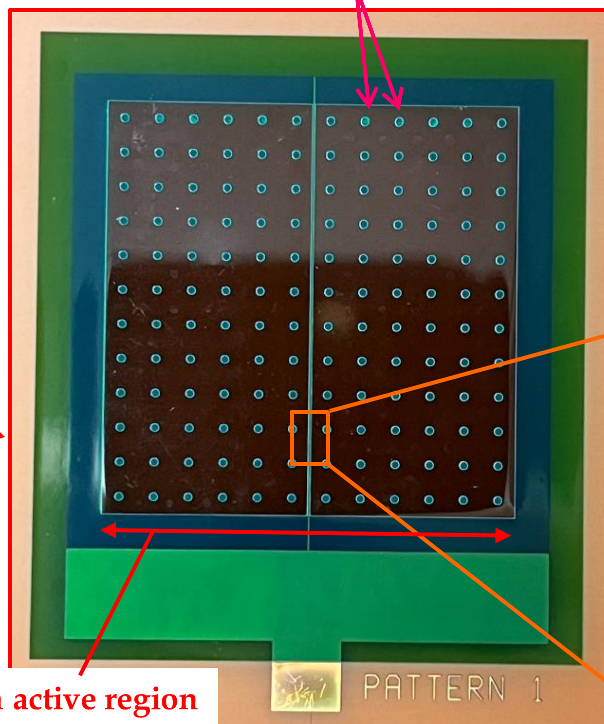
- Fabricated by CERN Micro-Pattern Technology Group
  - Electrodes have the protection cover; 0.2 mm – 1.8 mm width
    - Pillar: ϕ 0.6 mm in diameter with ~ 365 μm thick
    - Surface resistivity: 6 – 10 MΩ/sq.

Diagonal view of pillar

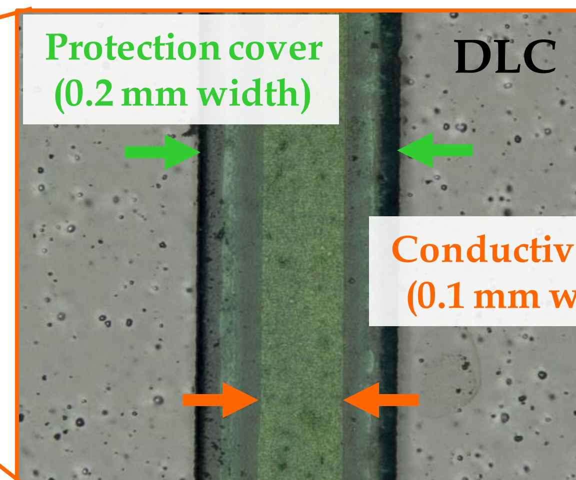




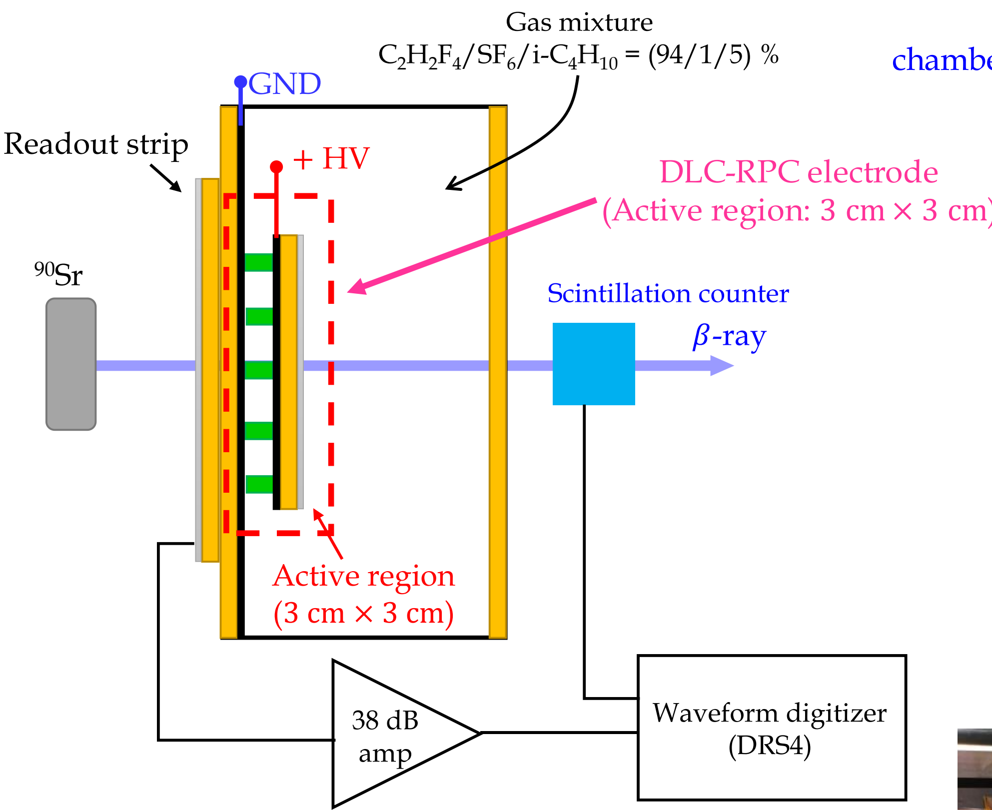
Pillars on DLC (2.5 mm pitch)



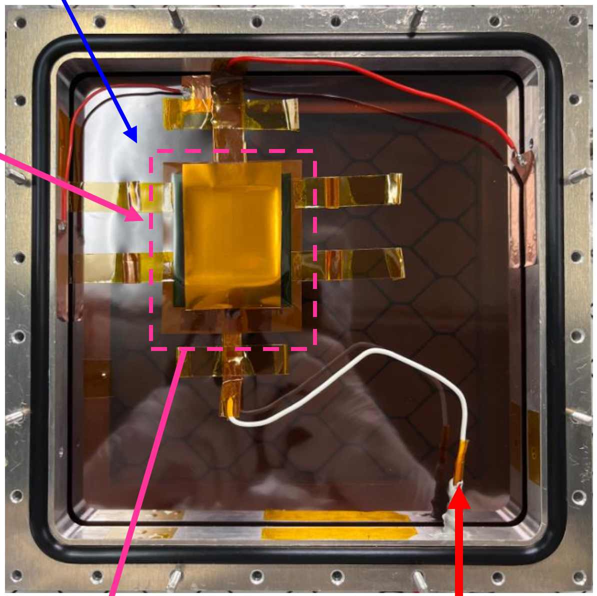
3 cm × 3 cm active region



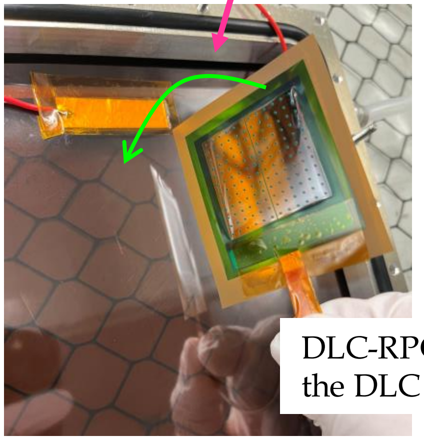
Test setup



DLC sputtered polyimide for
chamber window and cathode-side electrode (~ 12 MΩ/sq.)



+HV supply to the electrode

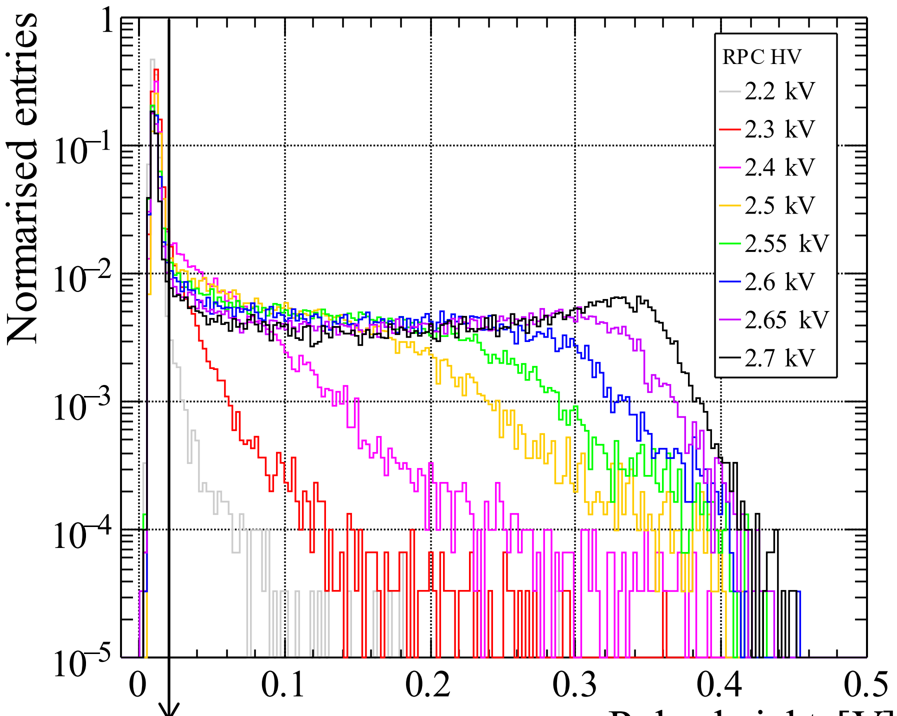


DLC-RPC electrode is fixed facing
the DLC sputtered polyimide window

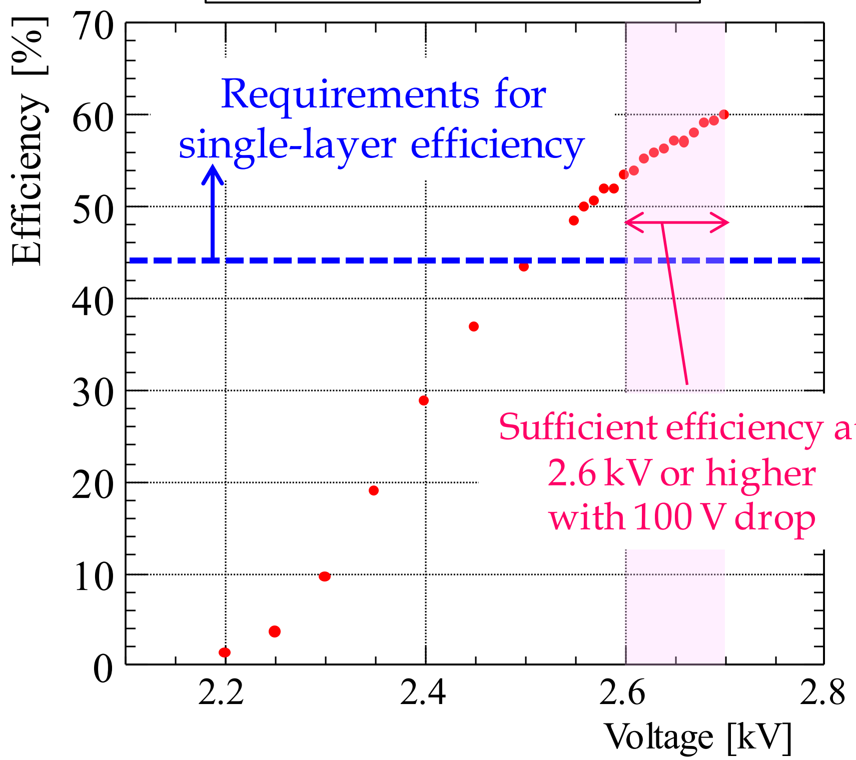
Performance for β-ray

- Measured the performance for β-ray using the electrode with strip
  - β-ray was irradiated locally and $\mathcal{O}(1)$ kHz rate by ϕ 2 mm collimator
    ➔ Negligible impact from strip structure
  - Environment: 24.0 ℃, 994.8 hPa, 55 %

Pulse height spectra

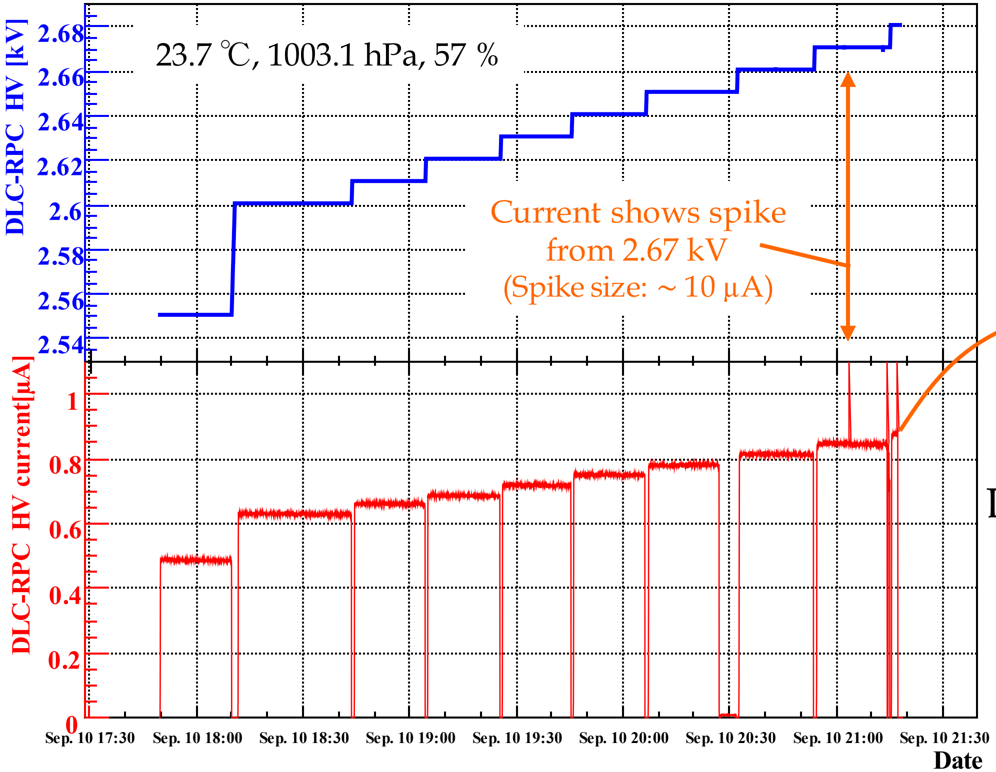


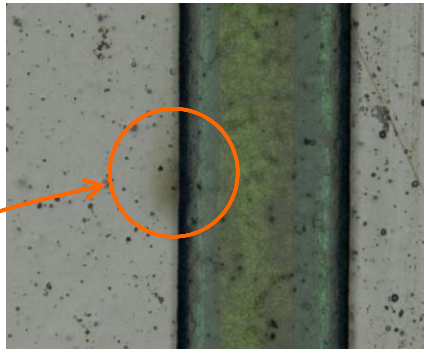
Detection efficiency



Current spikes at higher voltage

- Check the HV current behavior at each voltage in $\mathcal{O}$(100 kHz) β-ray
  - Used the electrode with 0.2 mm width of protection cover and 13.8 MΩ/sq of resistivity
    ➔ The margin of the cover and conductor is 50 μm
- If the quench capability for discharges becomes insufficient,
  current might show instability or large spikes at high gain region





Discharge at the strip structure
➔ Can quench up to 2.66 kV with 0.2 mm width of cover
- Effective voltage at 994.8 hPa: ~ 2.64 kV

Cover width dependence

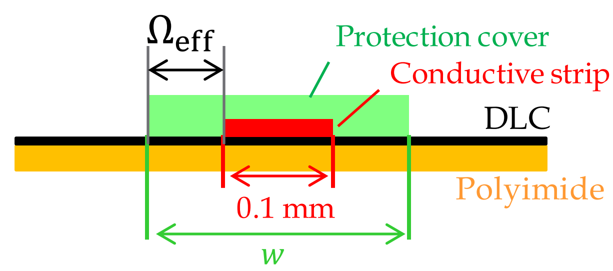
➢ Comparison between 0.2 mm and 0.8 mm of cover widths

Cover width w (mm)	Surface resistivity ρ_S (MΩ/sq.)	Effective resistance Ω_{eff} (kΩ)	Effective voltage limit at 994.8 hPa (kV)
0.2	13.8	23	2.64
0.8	6.75	79	2.65

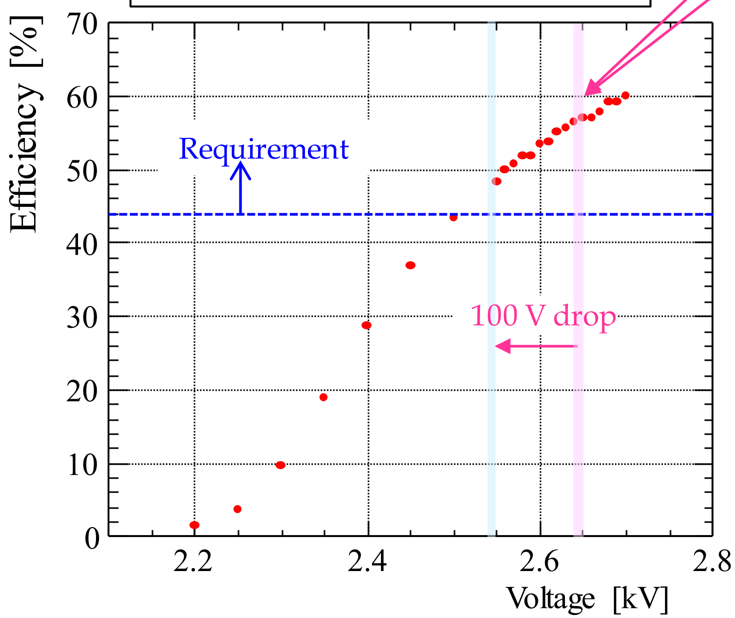
Ω_{eff}: Effective resistance in covered region

$$\Omega_{\mathrm{eff}} = \rho_S \cdot \frac{(w - 0.1)}{2 \cdot l}$$

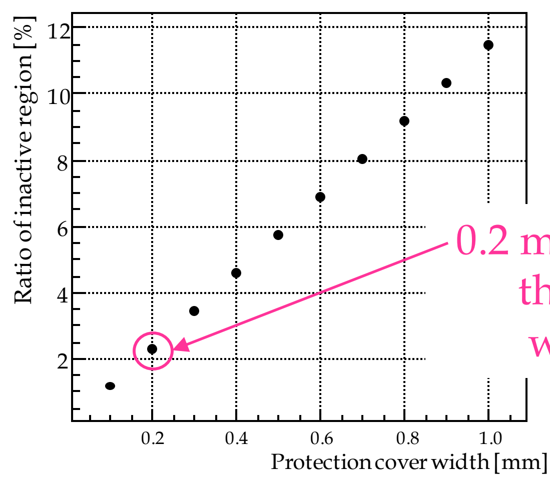
l: length of the strip (= active region size)



Detection efficiency (994.8 hPa)



Inefficiency fraction by protection cover



0.2 mm width of cover can reach the adequate performance with 2.3 % of inefficiency

Summary

- DLC-RPC has been developed for background reduction in MEG II
  - The high-intensity and low-momentum muon beam passes through this detector
- Conductive strips to improve the high-rate capability
  - Discharges occurred at the strip structure in First prototype
  - Need to investigate the effect of the strip structure on operation
- Operation test using the electrode with conductive strips
  - Can be operated up to 2.7 kV in $\mathcal{O}$(1 kHz) β-ray, and **reached 60 % of efficiency**
  - Operation without current spikes and instability can be **up to 2.64 kV with 0.2 mm width** of cover

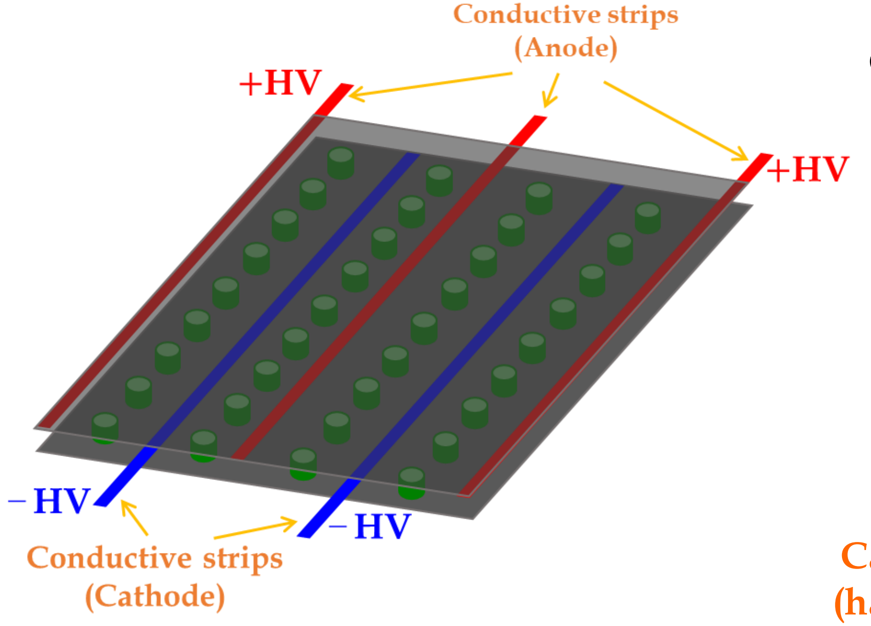
  ➔ **Even if considering the 100 V drop by the high-intensity muon beam,**
  this operation voltage fulfill the requirements

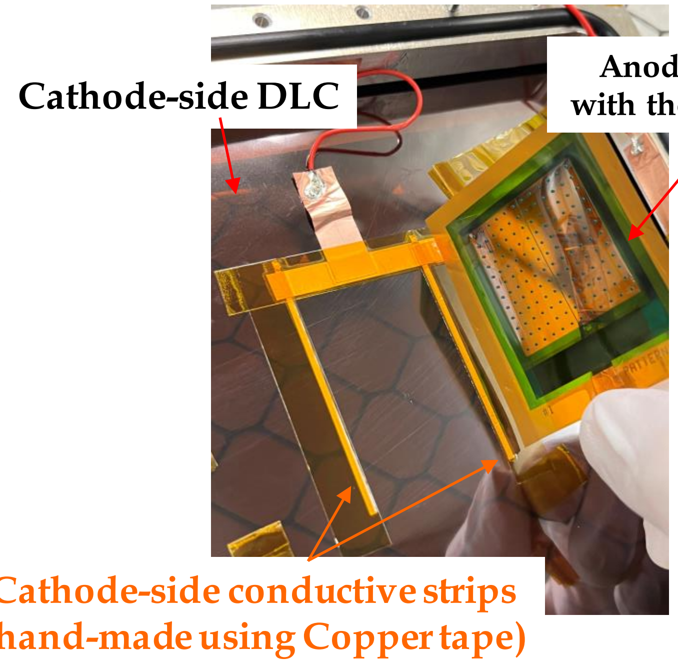
Prospects

- We need to consider the effects of the cathode-side conductive geometry
  - Conductive strips will be implemented on the cathode side as well

➔ Operation voltage might be suppressed with the cathode-side conductive strips

Full-scale design of conductive patterns



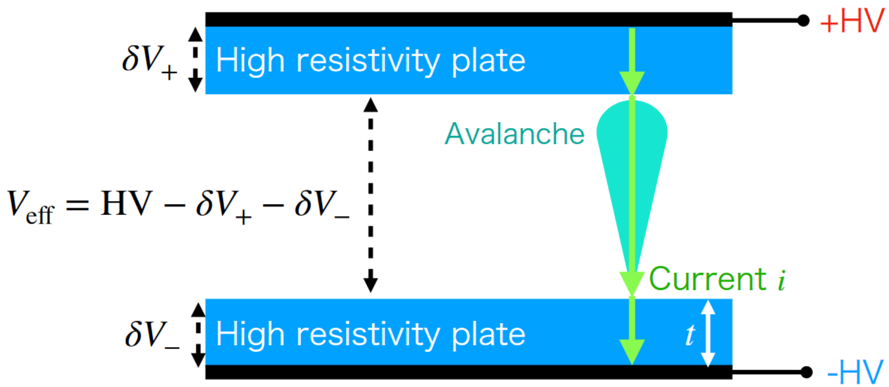


Need to investigate the quench capability including the contribution of cathode

Backups

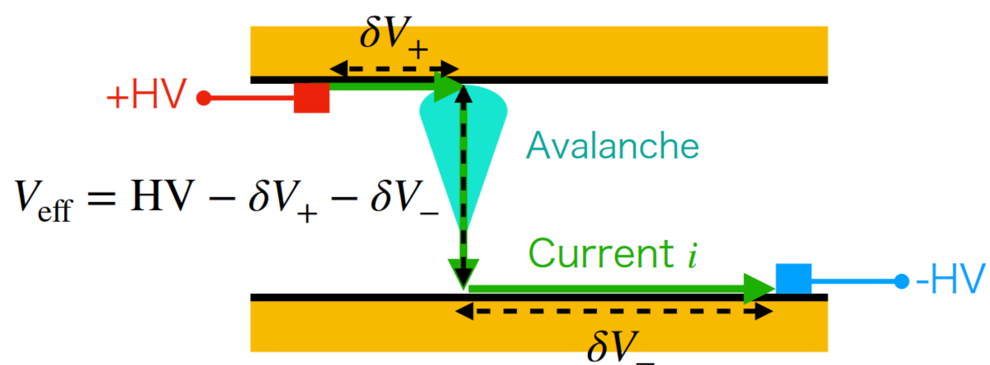
DLC-RPC

Conventional RPC



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

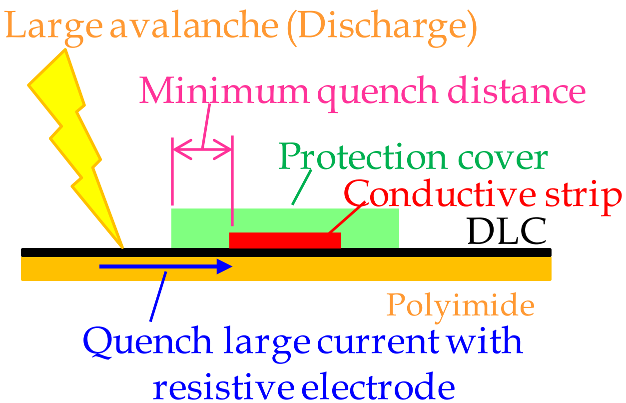
DLC-RPC



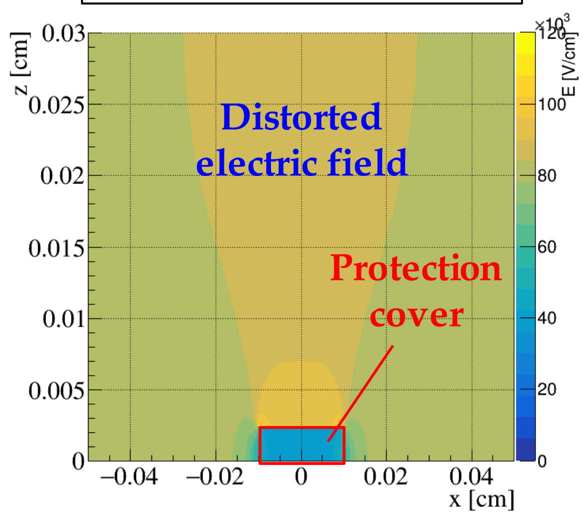
$$\nabla^2 \delta \text{V} = Q_{\text{mean}}(\text{V}_{\text{eff}}) \cdot f(x, y) \cdot \rho_S$$

Discharge at strip structure

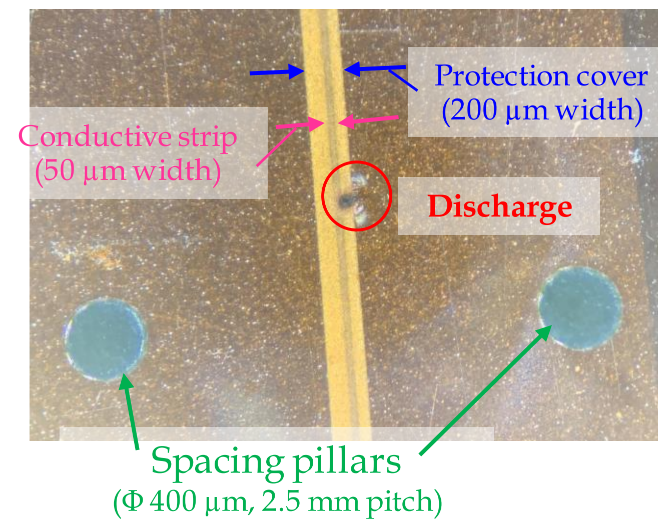
- Discharges likely occur near the strip structure
  - Lower quench capability
  - Electric field is distorted by protection cover



Simulated the electric field on the protection cover

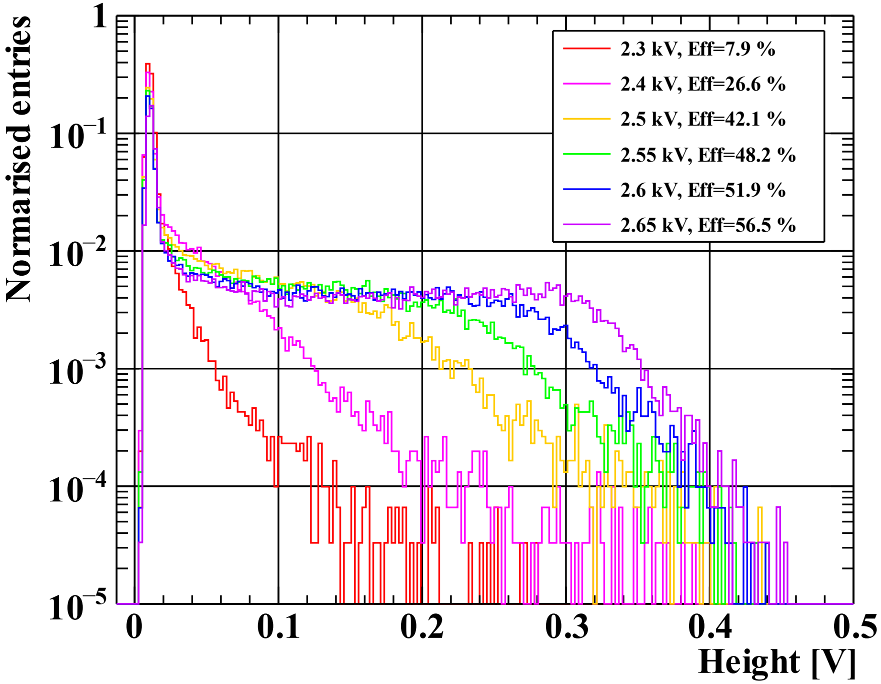


Discharge at strip

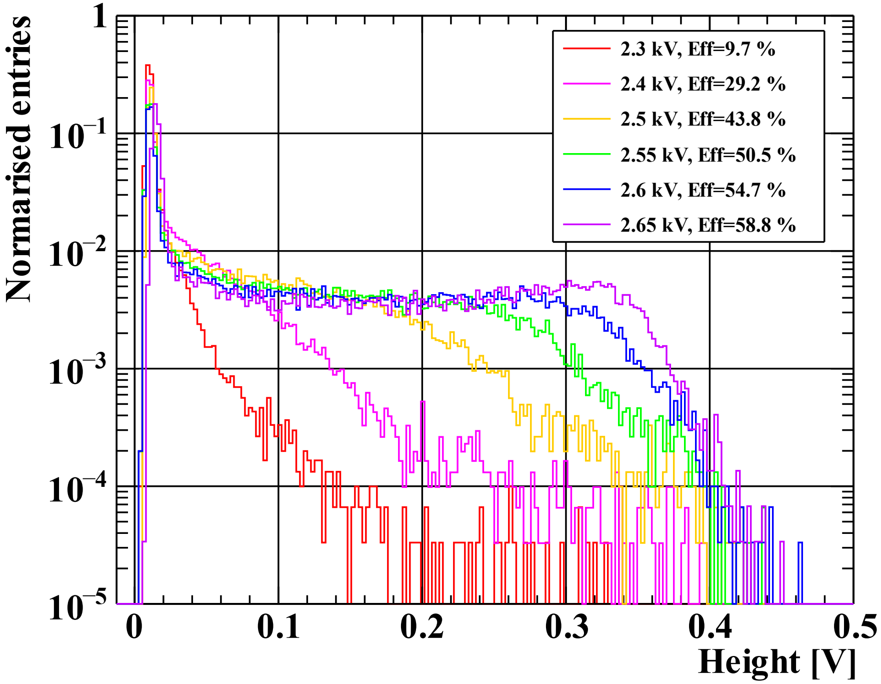


Pulse height spectra

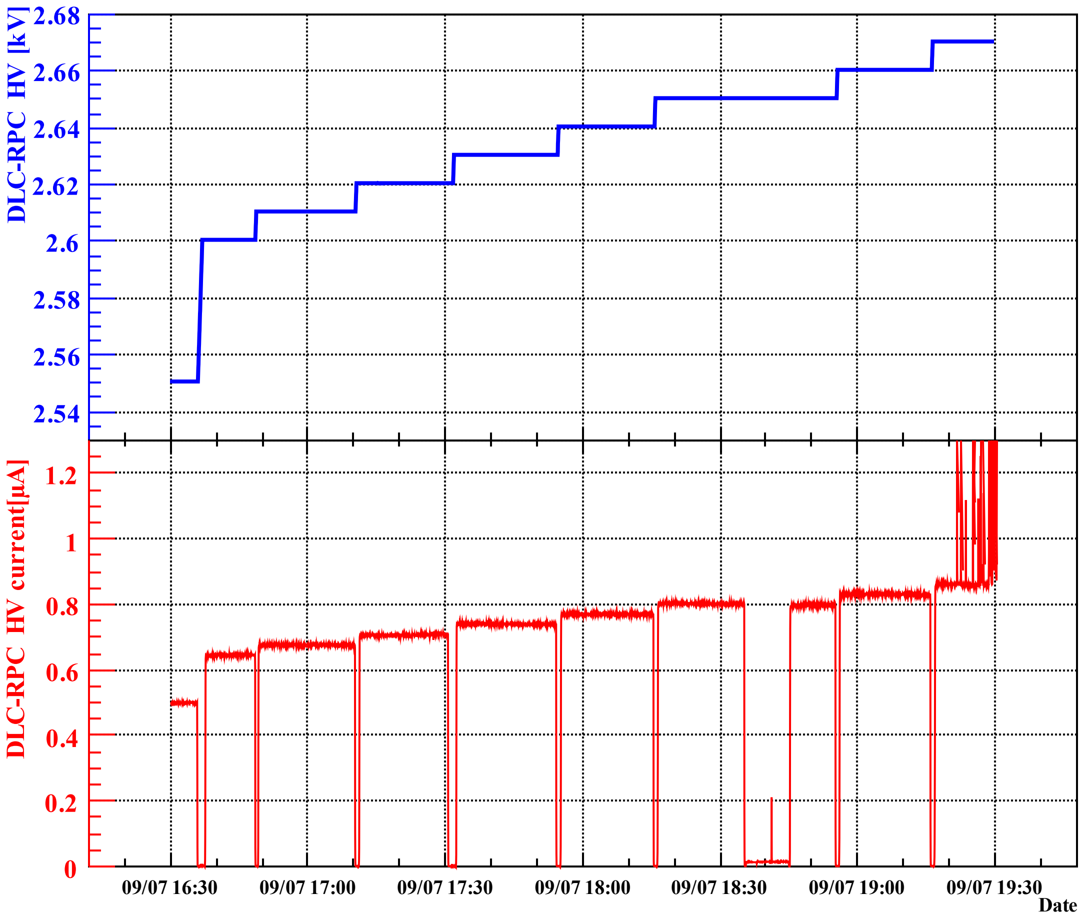
0.2 mm width of cover (1003.1 hPa)

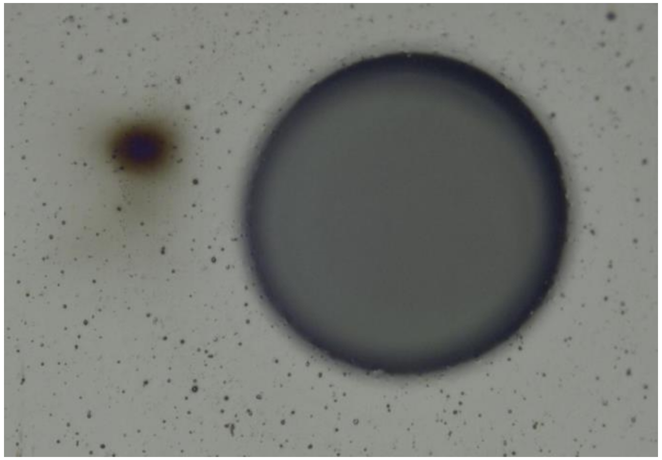


0.8 mm width of cover (998.4 hPa)



Test using 0.8 mm width of cover

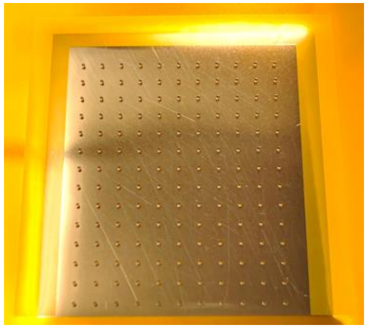




Transition of the DLC-RPC electrode

2019

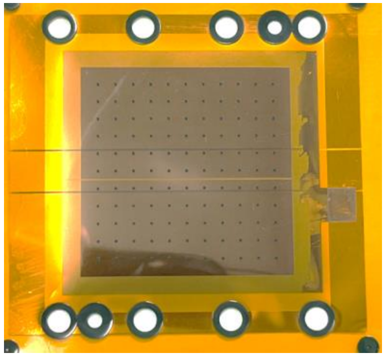
Demonstration of the principle of DLC-RPC



- No strip structure

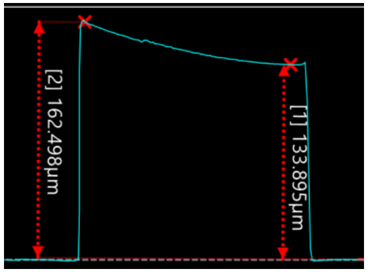
2022

Demonstration of 90 % e^+ efficiency in the μ^+ beam



- Unstable operation due to spacing pillar quality
- Discharges at strip structure

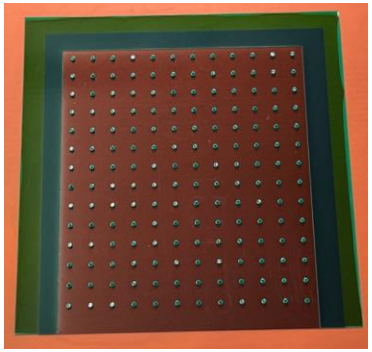
Distorted spacer



Discharge at strip

2023

Improved the spacer formation



- Uniform spacer
- No strip structure

Reported at JPS2023 spring

2024

Investigation of the strip structure

- Uniform pillars
- With strip structure

➢ **Investigate the effect of strip structure on operation**