Development of the high-rate capable DLC-RPC based on the current evacuation pattern

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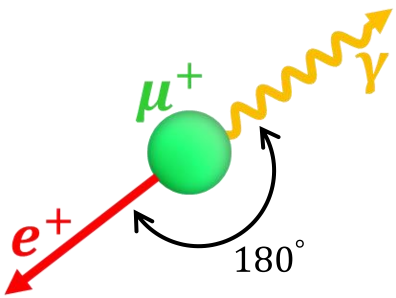
Outline

- Introduction
  - MEG II experiment
  - DLC-RPC for background suppression in MEG II
  - First prototype in 2022
- Improved DLC-RPC electrodes
  - Higher and uniform spacing pillars and current evacuation pattern
- Performance test
  - Performance for β-ray
  - Behavior in high-gain environment
  - Long-term stability
- Summary & prospects

MEG II experiment

- Searches for $\mu^+ \to e^+\gamma$ decay using the world's highest-intensity μ^+ beam
  - Charged lepton flavor violating process
    → Evidence for new physics
  - The physics run period: from 2021 to 2026
- Dominant background is an accidental coincidence of BG-e^+ and BG-γ

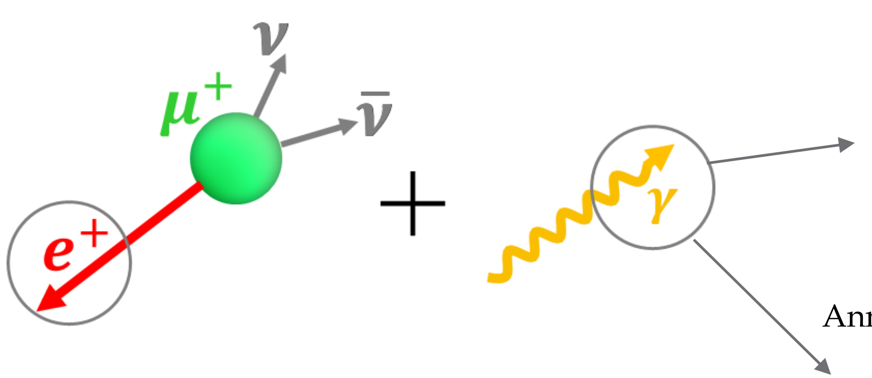
Signal

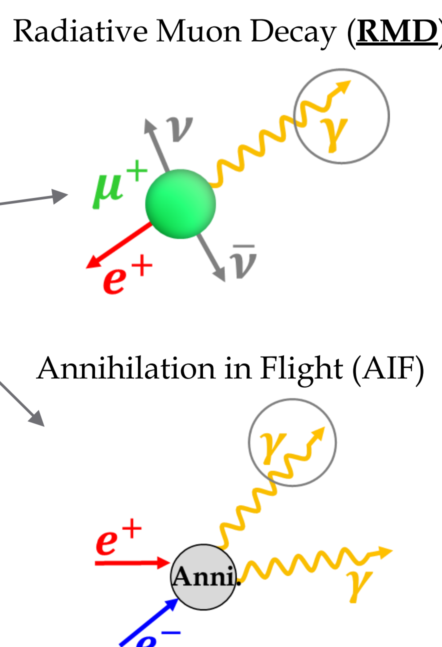


e^+ and γ

- Both have 52.8 MeV
- Opposite direction
- The same timing

Accidental background



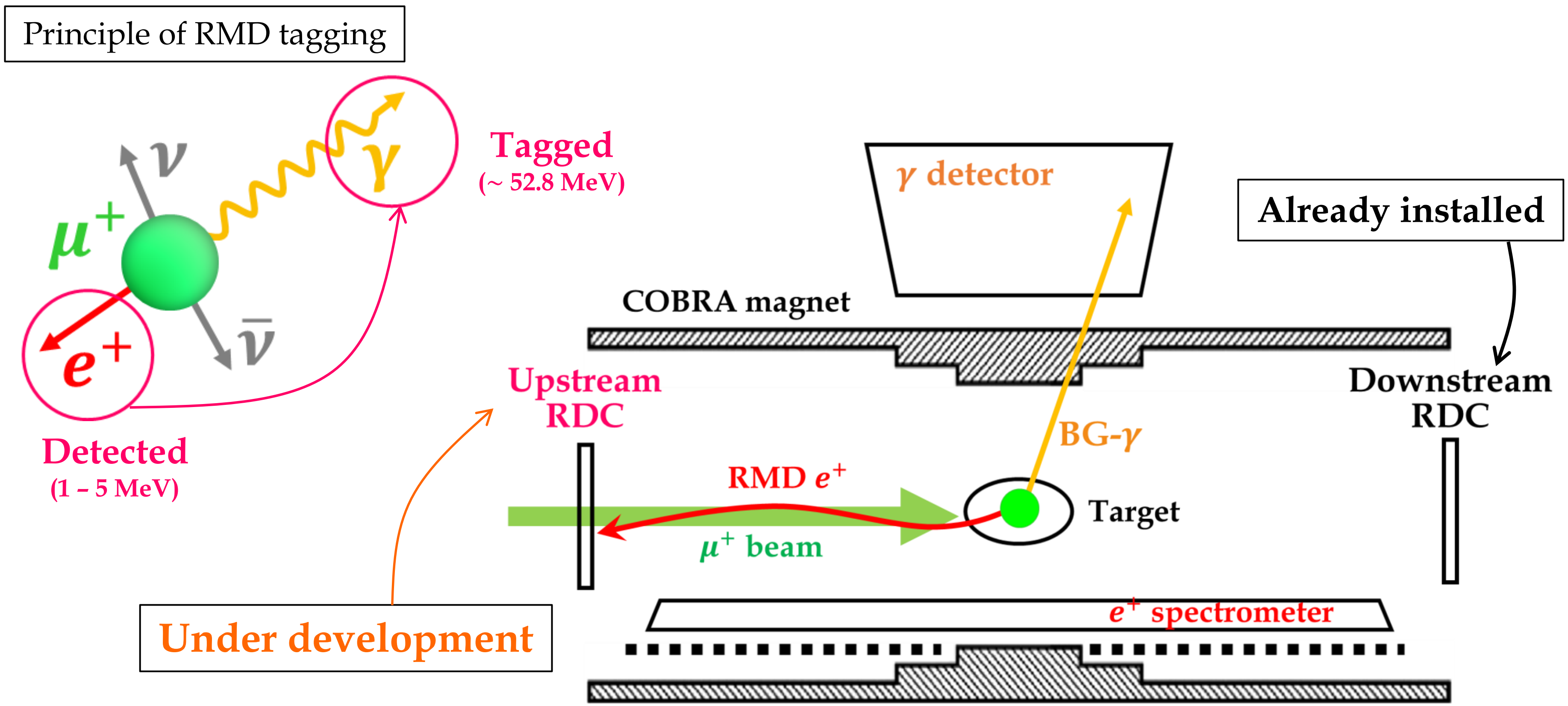


Signal-like accidental coincidence of BG-e^+ and BG-γ with ~ 52.8 MeV

Radiative Decay Counter (RDC)

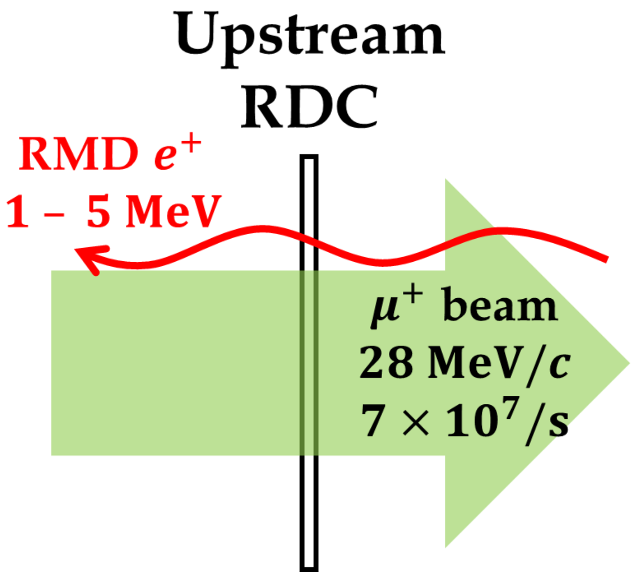
- Detectors for tagging **BG-γ** from RMD
  - RMD e^+ is distributed on μ^+ beam line when BG-γ has signal-like energy

  → **RDCs are installed on μ^+ beam line**



Challenges for upstream RDC

- **Needs to detect low-energy RMD e^+ in a high-intensity and low-momentum μ^+ beam**
  - Signal : e^+ with 1 – 5 MeV
  - Background : μ^+ with 7×10^7 /s at 28 MeV/c



- Requirements
  - Material budget : < 0.1 % of radiation length
  - Rate capability : up to 3 MHz/cm^2
  - Radiation hardness : 20 weeks operation
  - Detection efficiency : > 90 % for MIP
  - Timing resolution : < 1 ns
  - Detector size : 16 cm in diameter

Our solution: DLC-RPC

What is the DLC-RPC?

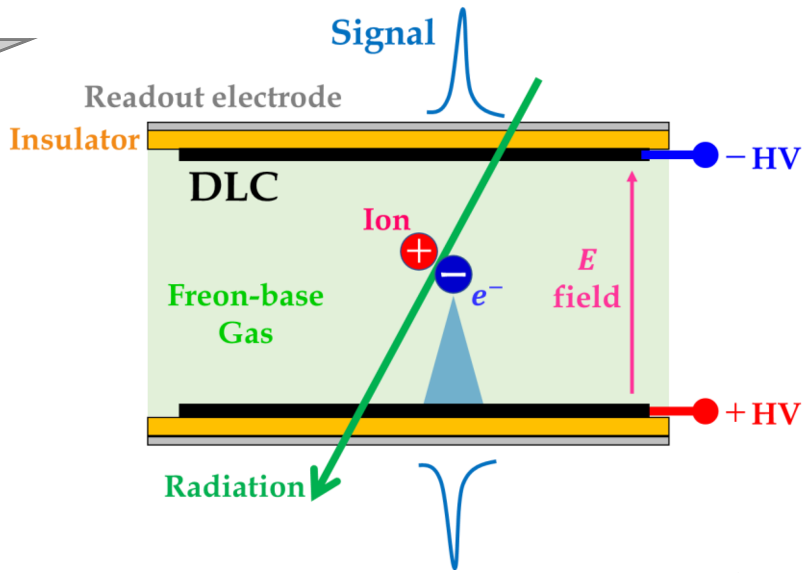
- **Resistive Plate Chamber with Diamond-Like Carbon electrodes**
  - New RPC idea by A. Ochi (2016)

- Resistive Plate Chamber
  - Gaseous detector
  - Fast response
  - High detection efficiency (by multi-layering)

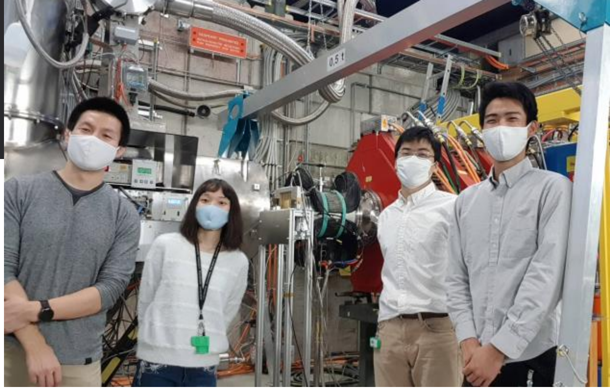
×

- Diamond-Like Carbon
  - High resistance thin-film
  - Small material budget
  - Controllable resistivity

- DLC-RPC
  - Extremely low mass by sputtered-DLC electrodes on thin-film
  - High-rate capability by low resistivity of DLC electrodes

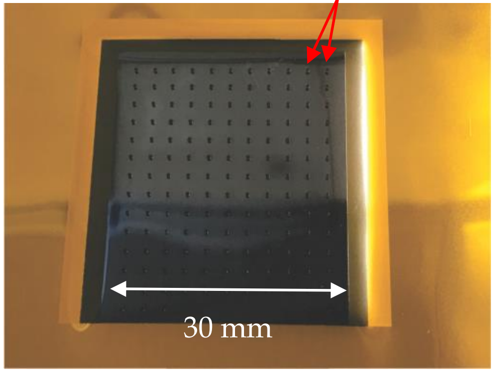


Demonstration in 2020

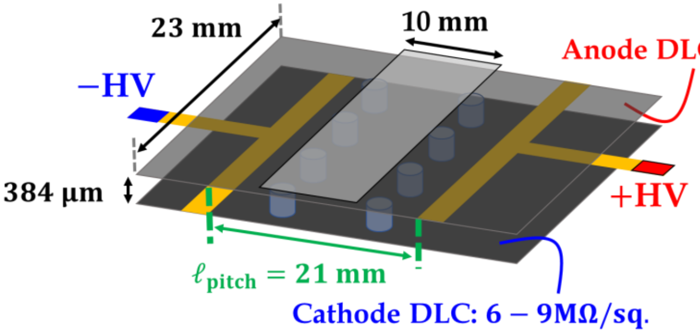


- Demonstration using the actual μ^+ beam
  - Atsuhiko Ochi reported at MPGD2022
  - K. Ieki, NIM A 1064 (2024) 169375

Spacing pillars (0.4 mm thick, 2.5 mm pitch)



Setup schematic



Active region: ~ 2 cm × 2 cm

Requirements

- Rate capability: 3 MHz/cm^2
- Detection efficiency: 90 % (with 4-layer)
- Timing resolution: < 1 ns

Demonstrations

- 1 MHz/cm^2
- > 50 % in 1 MHz/cm^2 (with a single layer)
- 180 ps

Need improvements

- Rate capability → Suppress performance reduction by a high particle rate
- Detection efficiency → Multi-layering
- Detector scalability → 2 cm × 2 cm → ϕ 16 cm

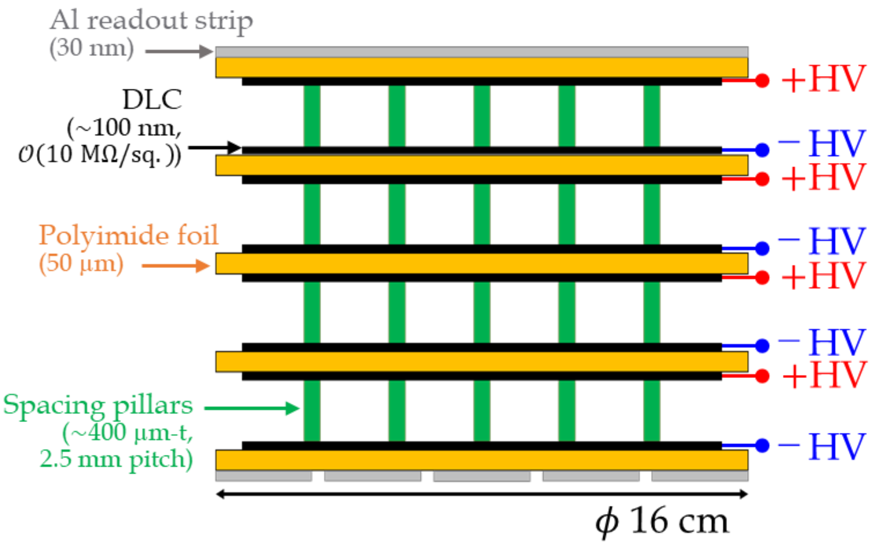
DLC-RPC design for MEG II

- **4-layer DLC-RPC**
  - PI foil can be stacked up to 5 sheets due to the material budget

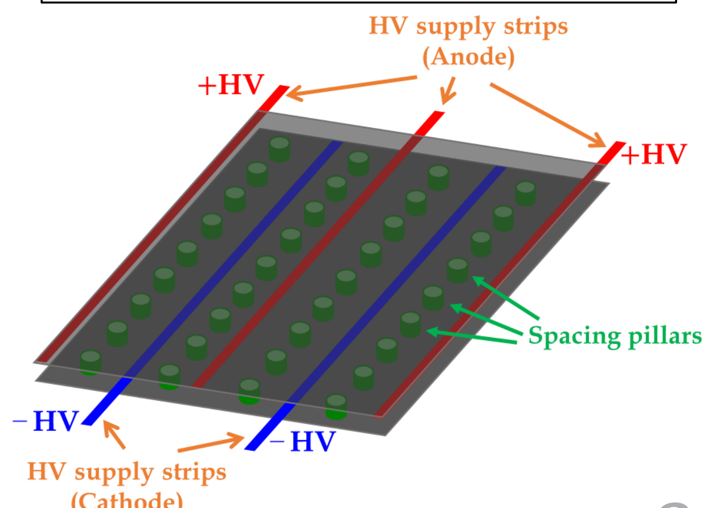
- **Gas gaps are supported by spacing pillars**
  - Spacing pillars are formed by photolithographic technology

- **Segmented HV supply for fast current evacuation and scalability**
  - Also, HV is applied to each layer independently
    - Electrodes decoupled by PI substrate

Schematic of DLC-RPC design for MEG II

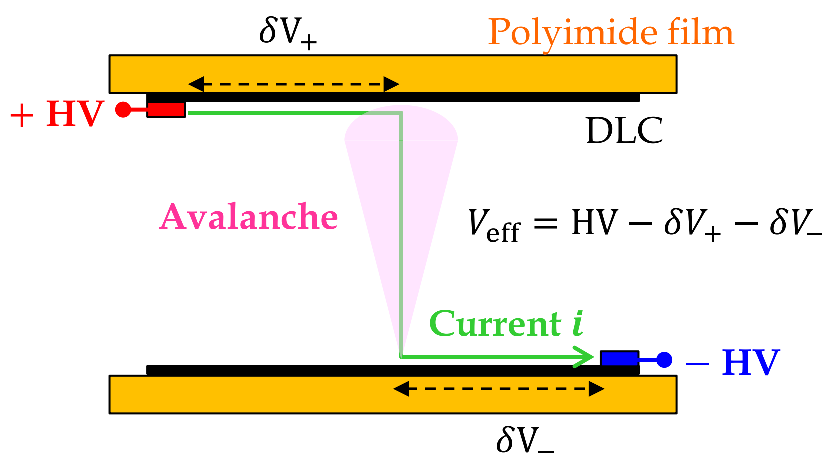


Schematic of segmented HV supply



Rate capability

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

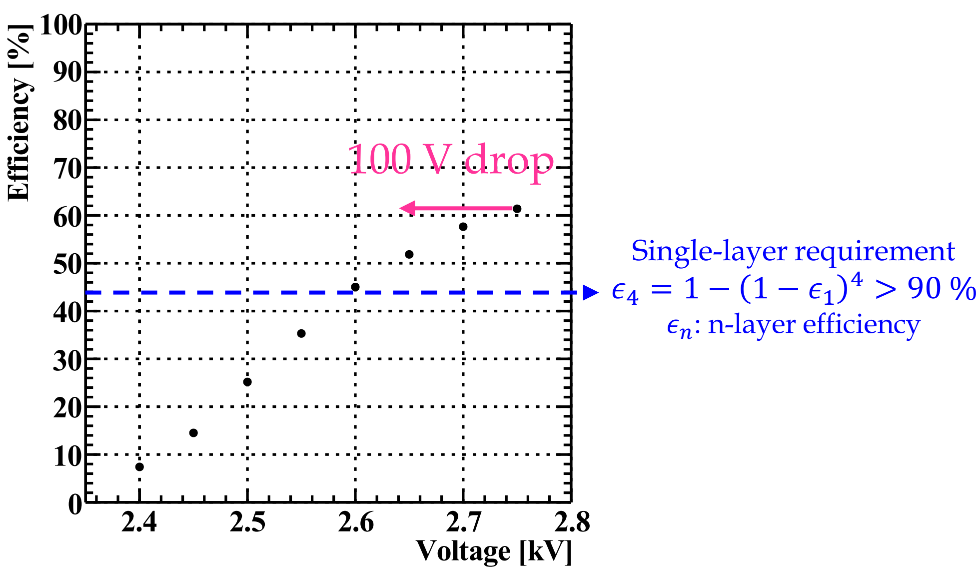


$$\nabla^2 \delta V(x,y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \times f(x,y) \times \rho_s$$

HV supply should be segmented

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

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

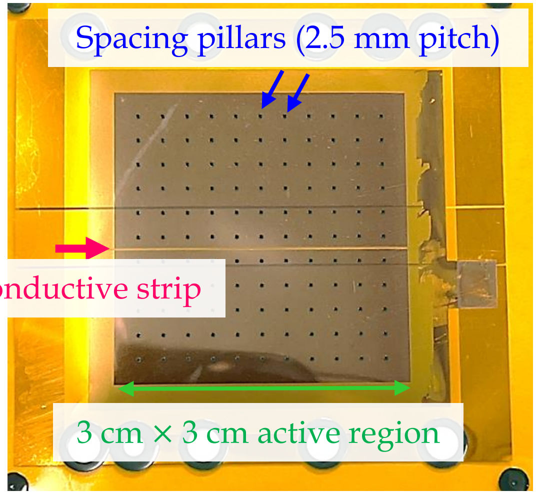


Voltage drop can be acceptable up to 100 V

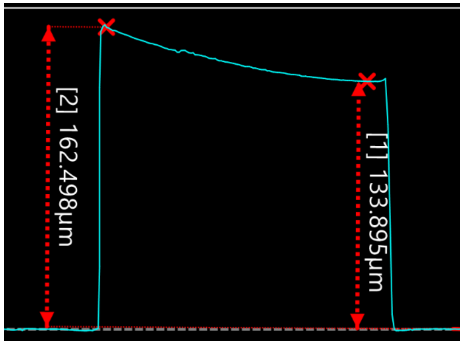
Prototype with current evacuation pattern

- For demonstration of 90 % efficiency in a 1×10^8 /s of μ^+ beam
  - A. Ochi reported at MPGD2022
  - The prototype had
    - ~ 10 MΩ/sq of surface resistivity
    - 1 cm pitch of conductive strips
    - (the two items above) } Voltage drop < 100 V
    - ~ 160 μm thick spacing pillars
      - Facing these spacing pillars each other from both gas gaps, created a gap over 300 μm thick

Prototype electrode



- Problem of non-uniform pillars



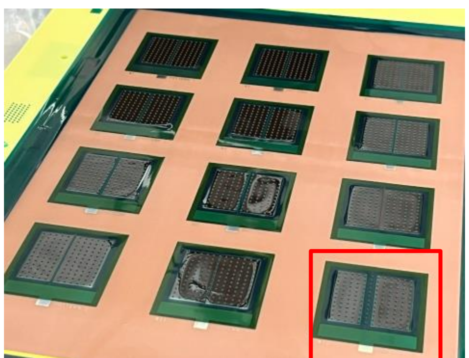
Large variations: ~ 20 μm thick

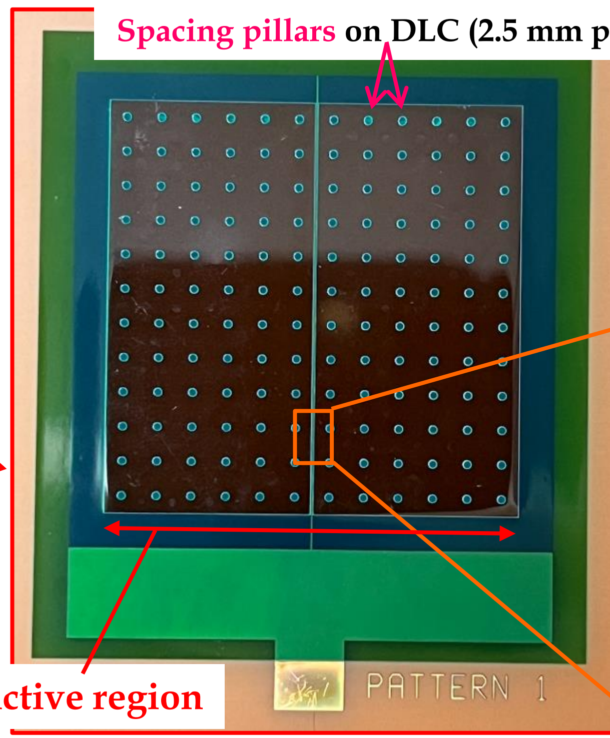
→ Distorted the electric field

CERN Micro-Pattern Technology Workshop deals with the material which can form uniform pillars
→ Retry to validate the strip structure

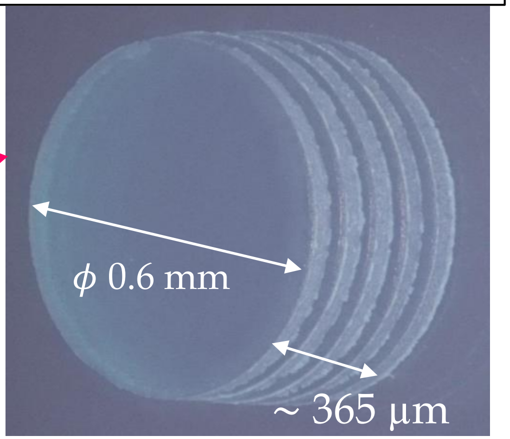
Improved DLC-RPC electrode

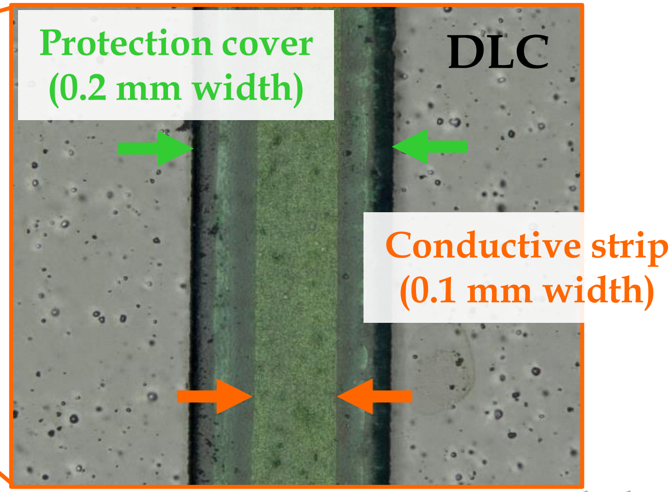
- Fabricated by CERN Micro-Pattern Technology Group
  - Spacing pillar: ϕ 0.6 mm in diameter with **365 ± 5 µm thick**
  - Surface resistivity of DLC: **6 – 15 MΩ/sq**
  - Electrodes have a conductive strip
    - The protection cover is 0.2 mm – 1.8 mm width



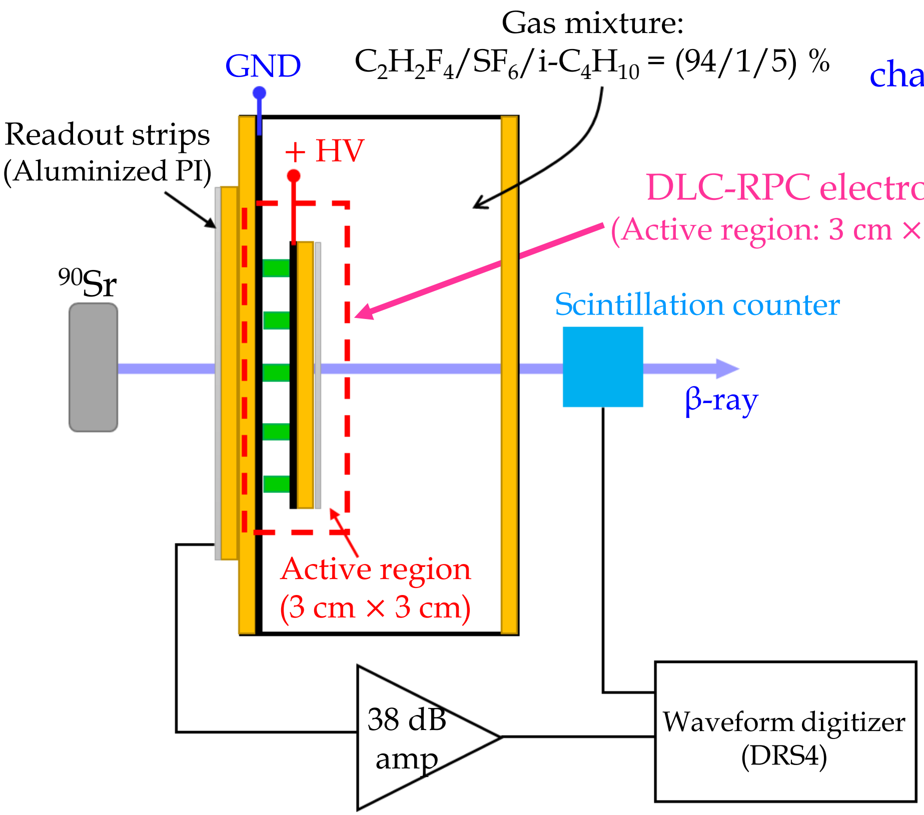


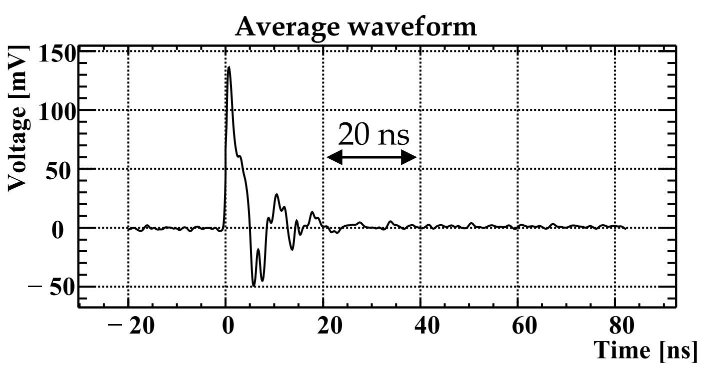
Diagonal view of spacing pillar





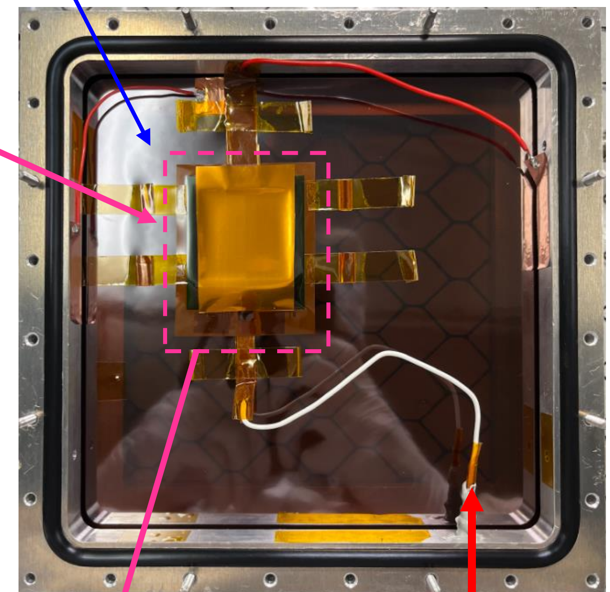
Test setup



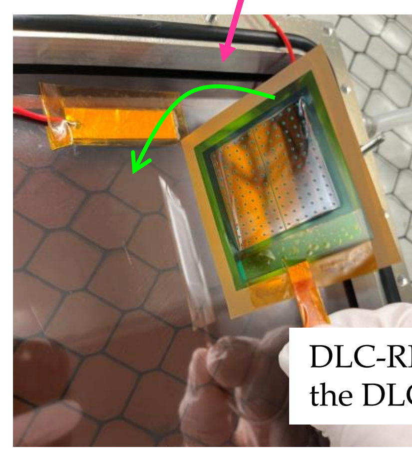


DLC sputtered polyimide for chamber window and cathode-side electrode (~ 12 MΩ/sq.)

DLC-RPC electrode
(Active region: 3 cm × 3 cm)



+HV supply to the electrode

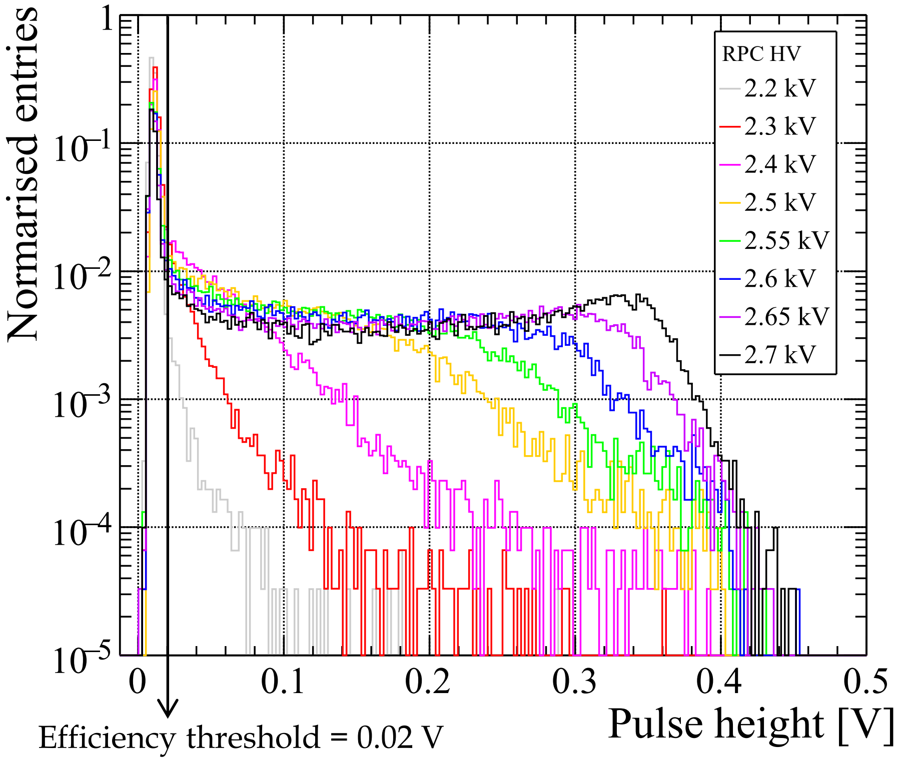


DLC-RPC electrode is fixed facing the DLC sputtered polyimide window

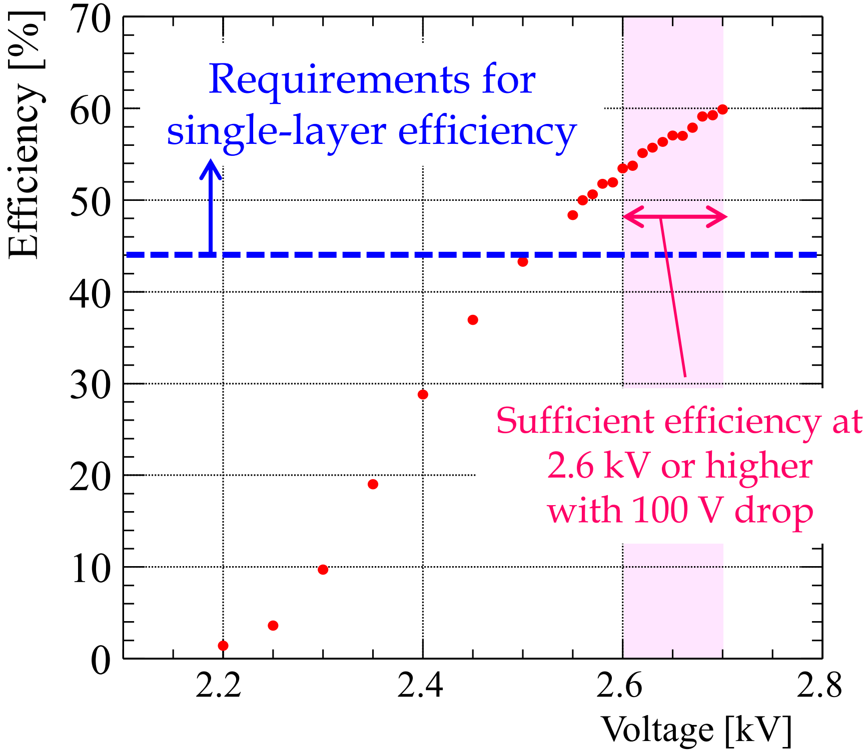
Performance for β-ray

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

Pulse height spectra

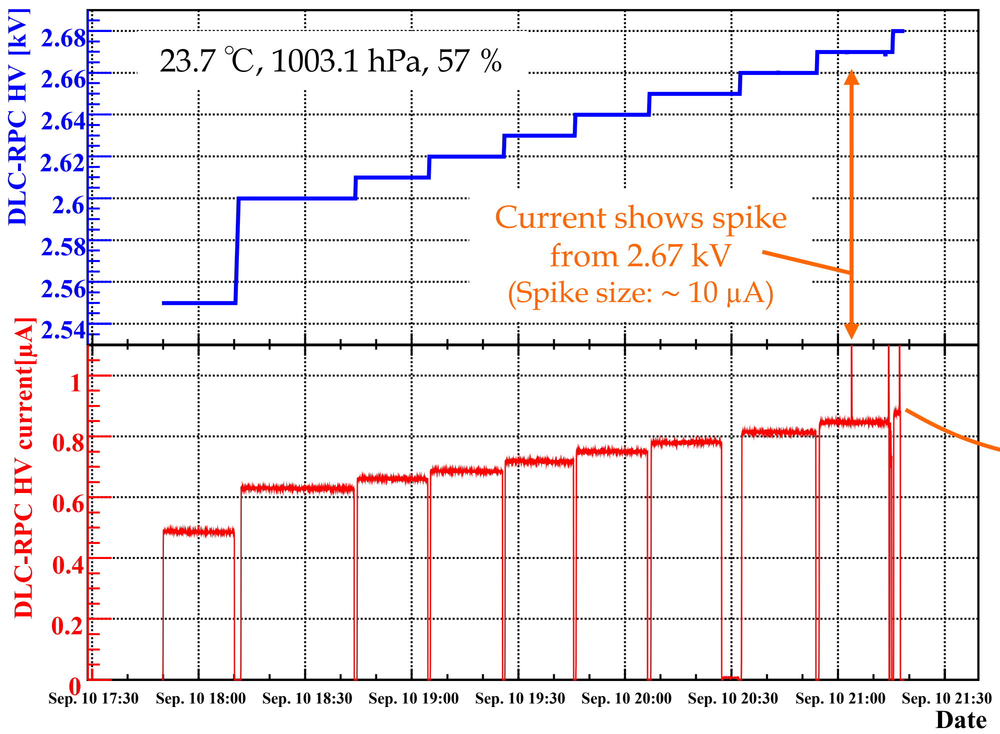


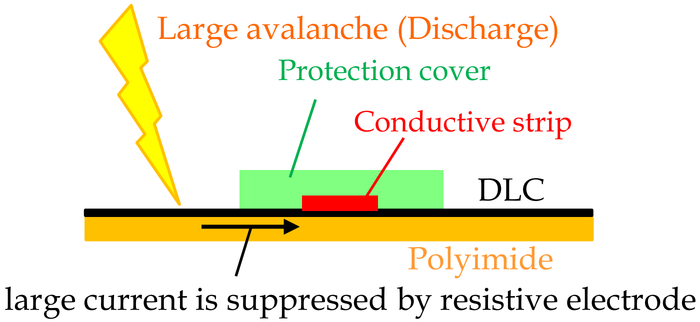
Detection efficiency

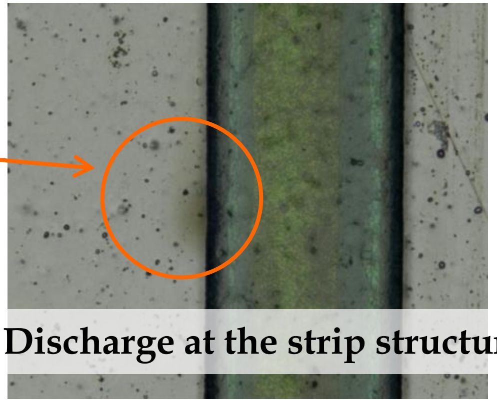


Behavior at high-gain environment

- Measured 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







Maximum voltage was suppressed due to insufficient quench around the strip

Cover width dependence

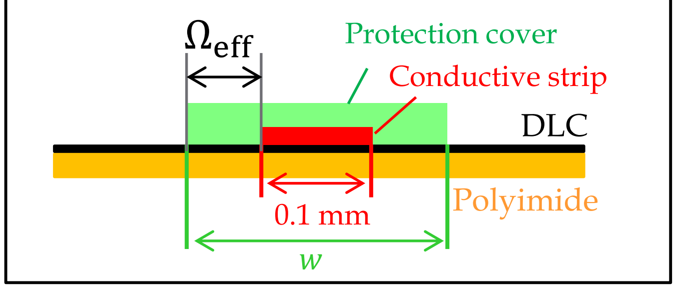
- Comparison between 0.2 mm and 0.8 mm of cover width

Cover width w (mm)	Surface resistivity ρ_S (MΩ/sq.)	Effective resistance Ω_{eff} (kΩ)	Maximum voltage at 994.8 hPa (kV)	Dead-zone in ϕ 16 cm full-scale design	
				Protection cover	Spacing pillars (ϕ 0.6 mm)
0.2	13.8	23	2.64	2.3 %	4.5 %
0.8	6.75	79 (× 3.5)	2.65	9.1 % (× 4)	

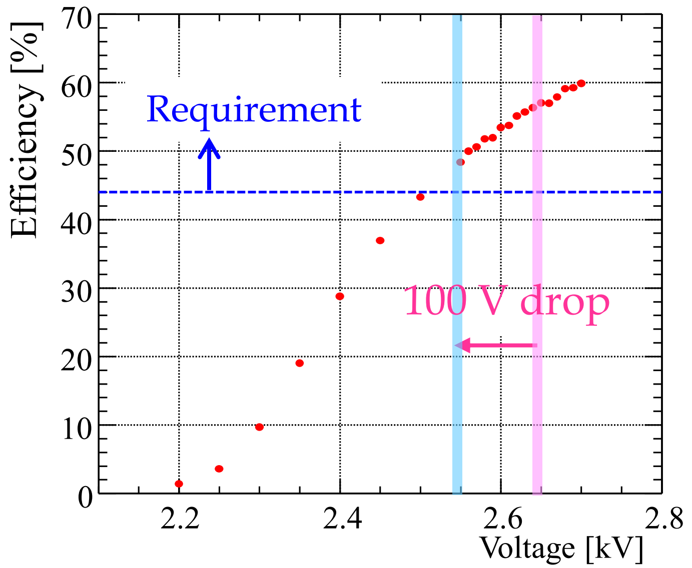
Ω_{eff}: Effective resistance in covered region

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

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



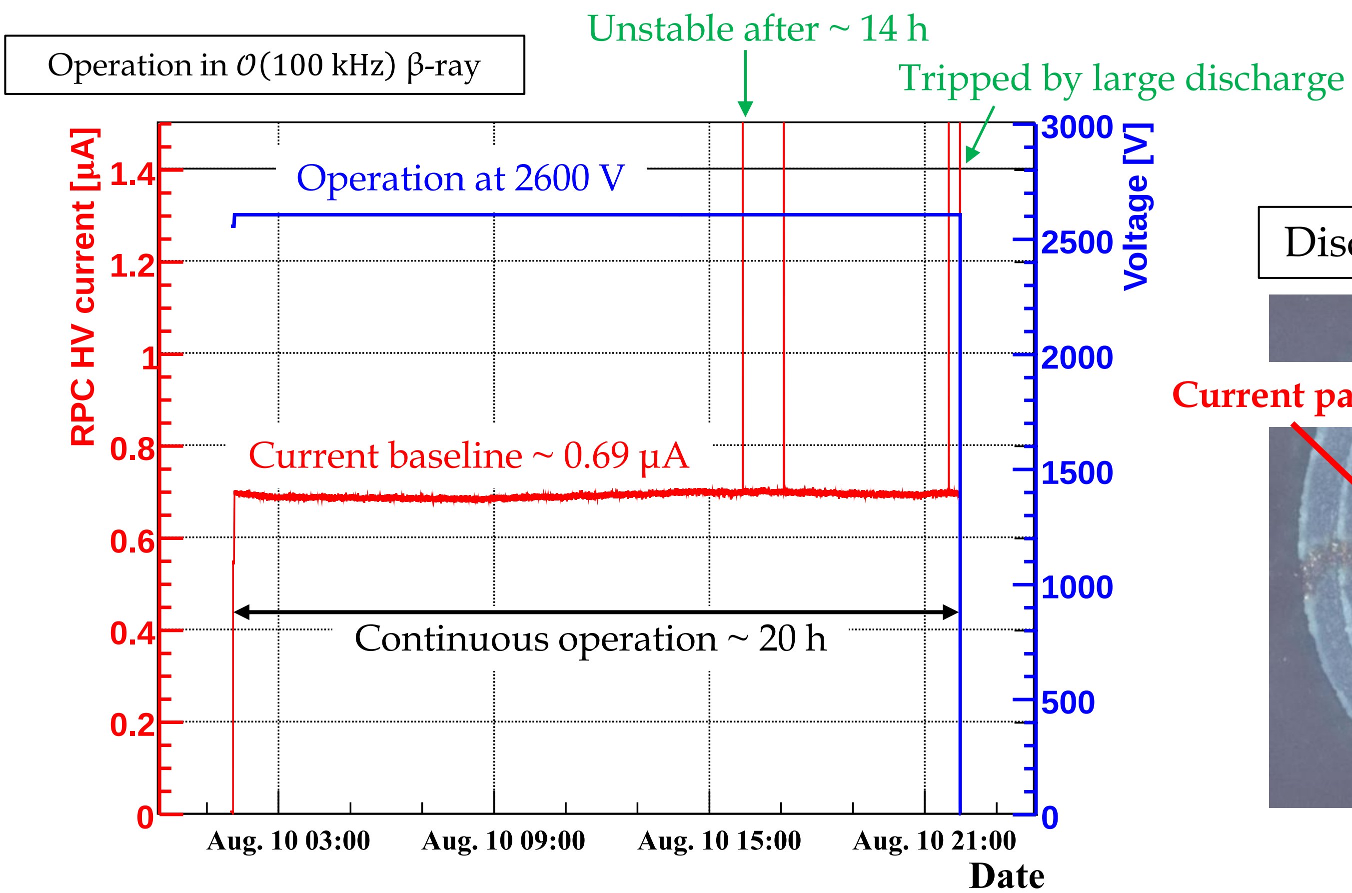
Detection efficiency in the active region (994.8 hPa)



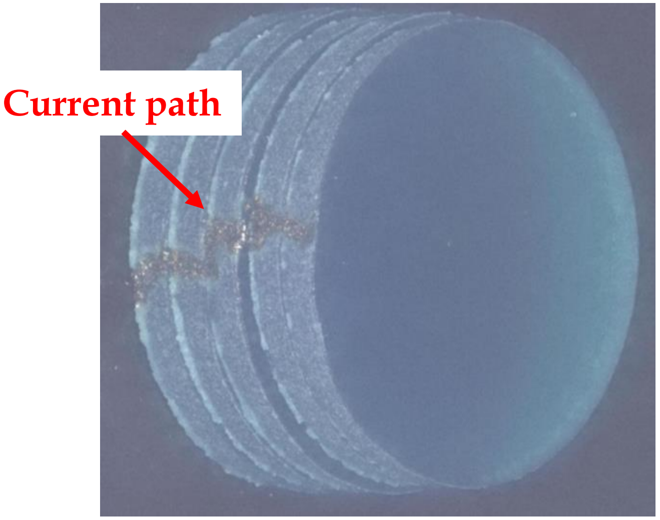
0.2 mm width cover can meet the efficiency requirements considering the dead zone and voltage drop during short-term operation

Long-term stability

- DLC-RPC is required continuous operation for 20 weeks
- However, over time, instability in operation appears

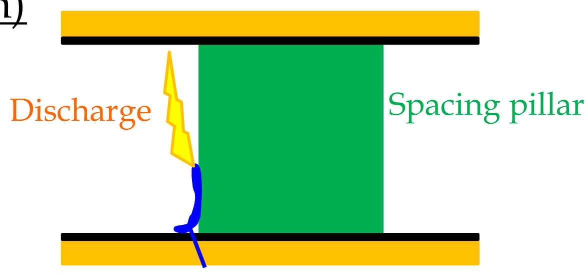


Discharge via spacing pillar



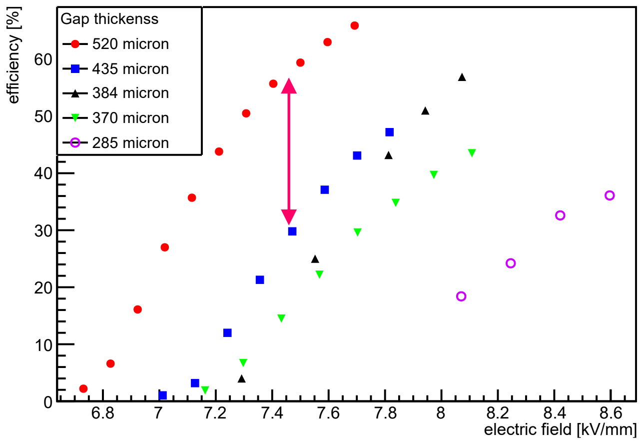
Possible scenarios and measures

- Ionic contaminations (resist residuals/fluorine deposition)
  - They can become the path of the current
    → They can be removed by cleaning
    - Fluorine deposition: M. Takahashi NIM A 1066 (2024) 169509



- Surface resistivity is too low
  - Creating sparks with enough energy to burn the polymer
    → Try to adjust to a bit higher resistivity (~ 20 MΩ/sq)

Gap thickness dependence of efficiency



- The electric field is too strong
  - Can cause an excessive gas avalanche or creeping discharge
    → Try to taller the spacing pillars (~ 500 μm thick)
    - Technically feasible

- Damages are accumulated on the side of the spacing pillars
  - Avalanche charges might burn the spacing pillar material
    → To be investigated the robustness of material to sparks

Summary

- DLC-RPC is under development for background suppression in MEG II
  - Planned to be installed in a high-intensity and low-momentum μ^+ beam
    → Required to have extremely low-mass budget and high-rate capability
  - Consists of thin-film materials and low-resistivity electrodes
  - First prototype in 2022 was prevented from stable operation
    - Non-uniform spacing pillars

- New DLC-RPC electrode with current evacuation pattern
  - Fabricated by CERN MPT Workshop
  - Prototype has ~ 365 μm thick of spacing pillars, and 6 – 10 MΩ/sq of surface resistivity

- Performance of new DLC-RPC electrode
  - Detection efficiency for β-ray was reached ~ 60 %
  - Discharge near the strip can be suppressed up to 2.66 kV

  } Meets the requirement for single-layer efficiency

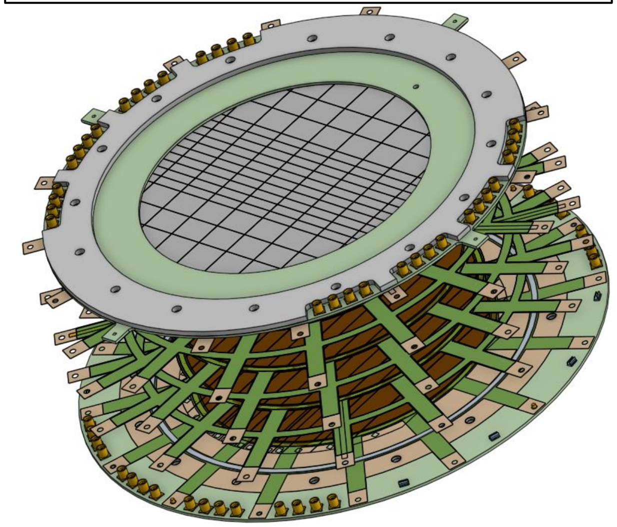
  - Became unstable during long-term operation
    → Under investigating cause and measures

Prospects

- Need to investigate what makes the operation unstable
  - Fabricate new electrodes with higher resistivity or higher spacing pillars
  - Investigate the behavior by higher rate irradiation
    → Distinguish between damages are accumulated or not

- The next prototype design is ongoing
  - Demonstration of 90 % efficiency in 7×10^7 μ^+ beam
    - With 4-layer DLC-RPC, ϕ 16 cm active region, and segmented HV supply
  - Aim to complete the next prototype production by the end of March 2025

Design draft of the next prototype



Aim to demonstrate the requirements for upstream RDC using the next prototype in 2025

Backup

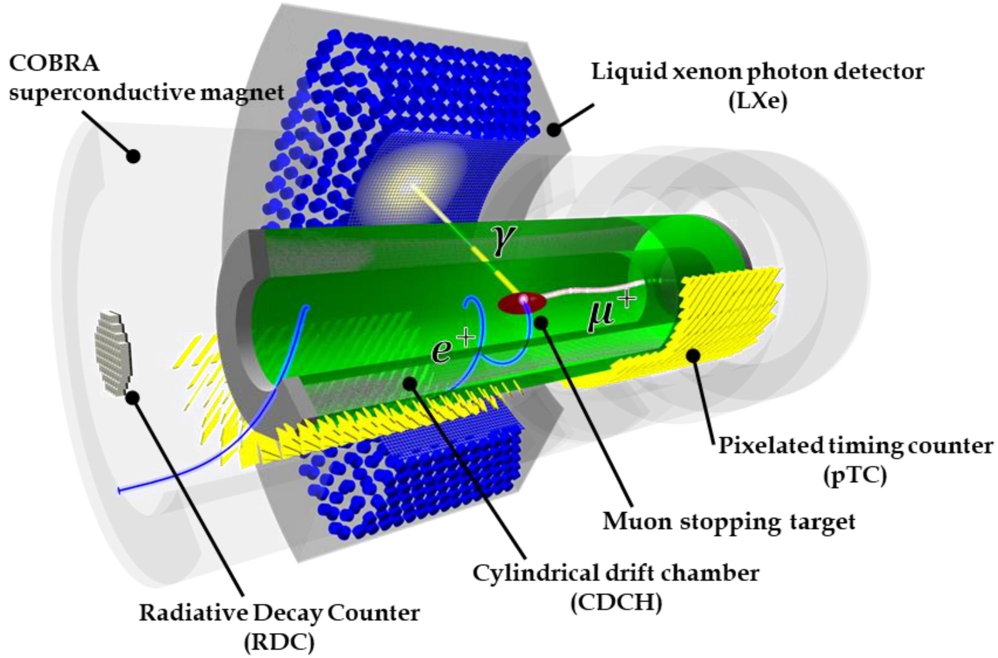
MEG II experiment at PSI

- Search for $\mu^+ \rightarrow e^+\gamma$ decay with target sensitivity of 6×10^{-14}
  - Charged lepton flavor violation channels
    - Strongly suppressed down to $\mathcal{O}(10^{-54})$ in SM + ν osc.
    - Predicted with $\mathcal{O}(10^{-12} - 10^{-14})$ in BSM, e.g. SUSY
  - Using the world's highest intensity μ^+ beam at Paul Scherrer Institut (PSI)

- Physics run started in 2021
  - Sensitivity 8.8×10^{-13} for 2021 data

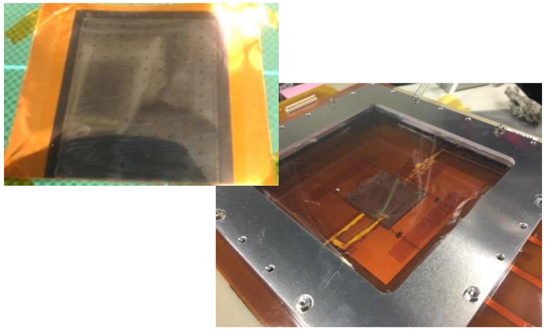
*K.Afanaciev, et al., Eur. Phys. J. C 84 (2024), 214

MEG II apparatus

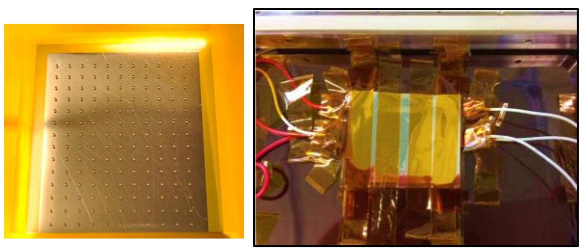


R&D history

R&D for fast timing RPC

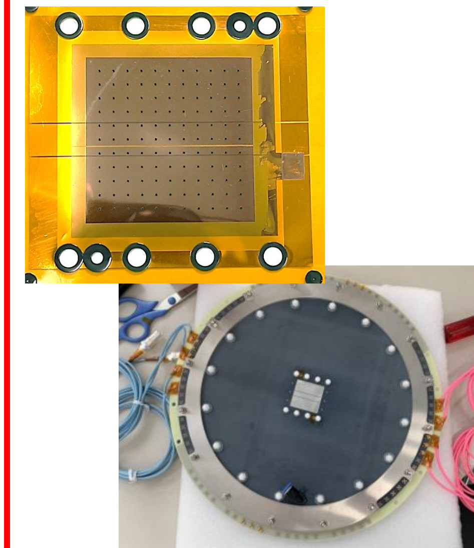


Test bench for MEG II



μ^+ beam test at PSI

First prototype



Reported at MPGD2022
by A. Ochi

2016 2017 2018 2019 2020 2021 2022 2023 2024

New RPC idea by A. Ochi
Adopted for Grant-in-Aid for Challenging Research

Reported at CLFV2019 by A. Oya

Reported at TIPP2021 by A. Oya

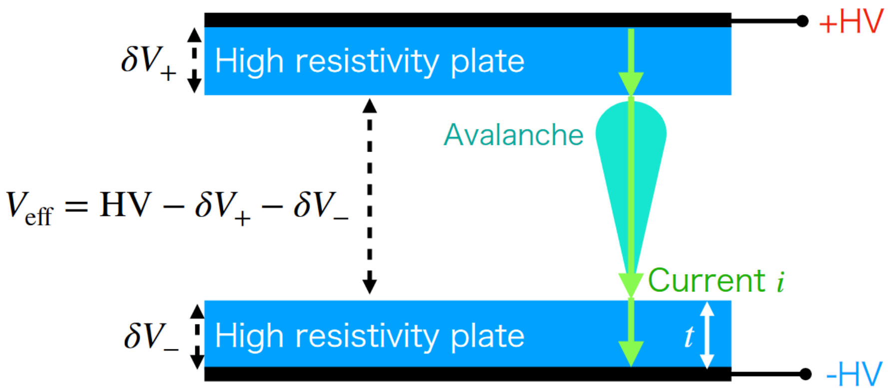
Reported at RPC2022
by K. Yamamoto

Reported at AgingWorkshop2023
by M. Takahashi

Conventional RPC and DLC-RPC

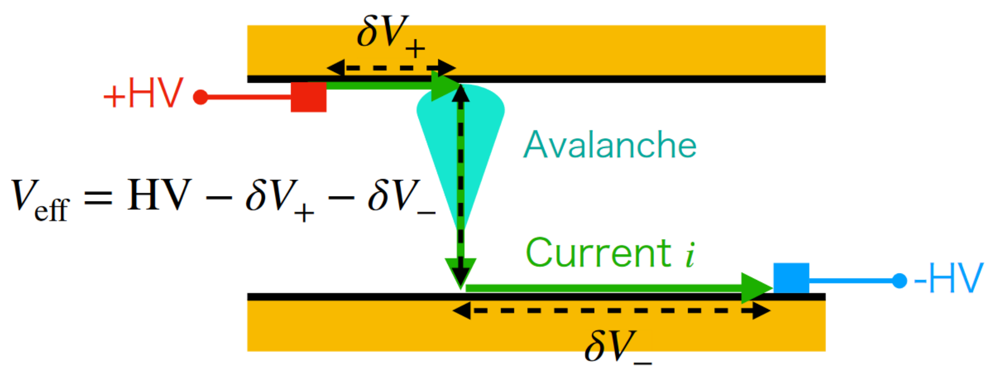
- Differences between conventional RPCs (glass RPC) and DLC-RPC (surface RPC)

Conventional RPC



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

DLC-RPC

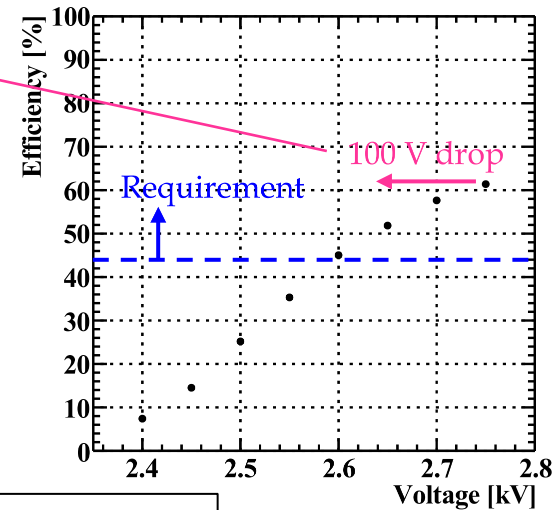


$$\nabla^2 \delta \mathrm{V} = Q_{\mathrm{mean}}(\mathrm{V_{eff}}) \cdot f(x, y) \cdot \rho_S$$

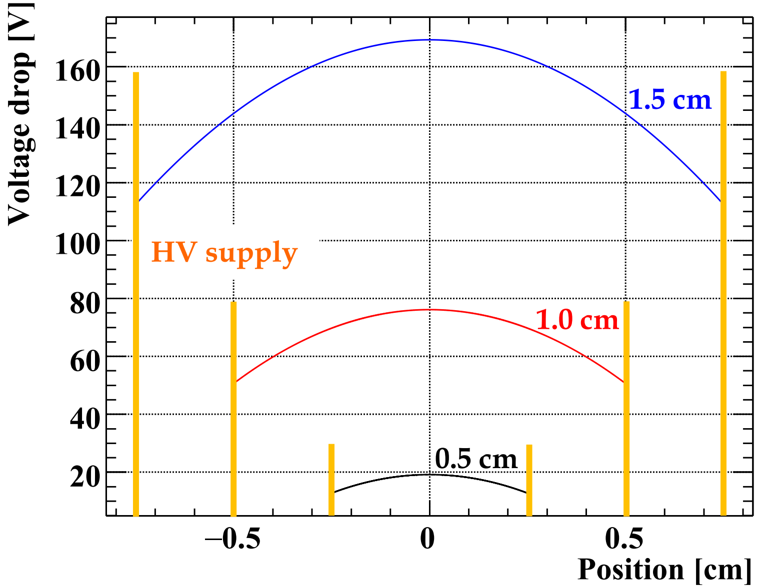
Segmented HV supply for scalability

- 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

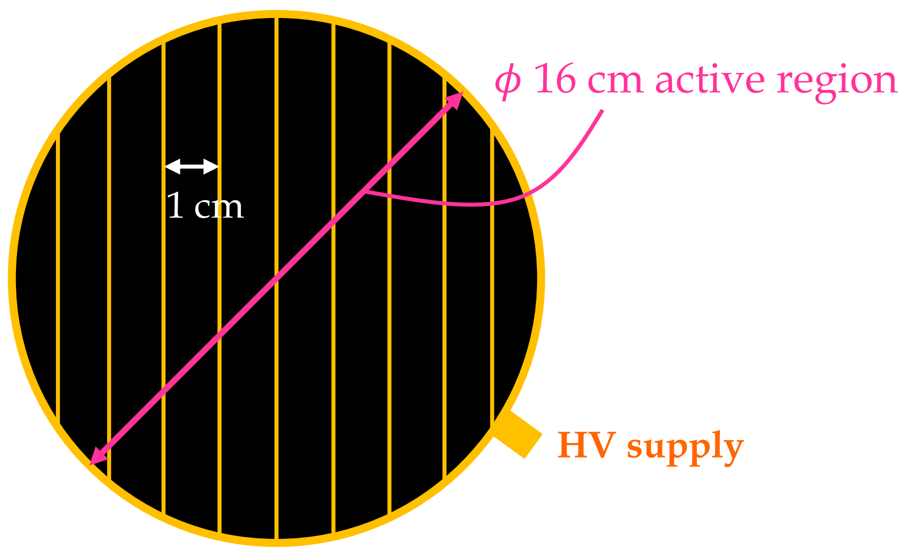
Single-layer DLC-RPC efficiency for MIP e^+



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



Segmented HV supply geometry



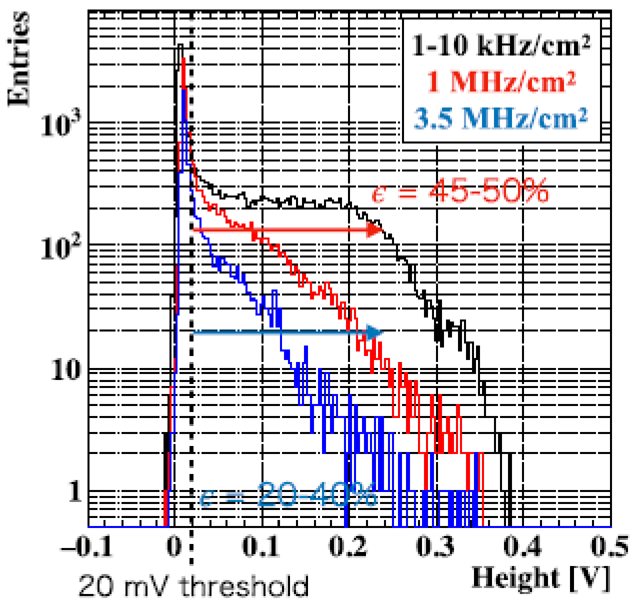
Performance at high rate

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

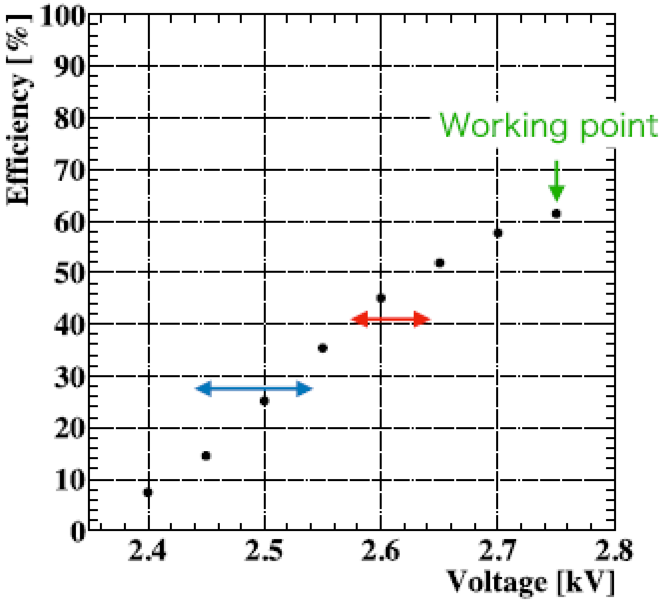
Calculated voltage drop:
- 110-170 V at 1 MHz/cm²
- 210-310 V at 3.5 MHz/cm²

➡ 1 MHz/cm² rate capability

Pulse height spectra at 2.75 kV



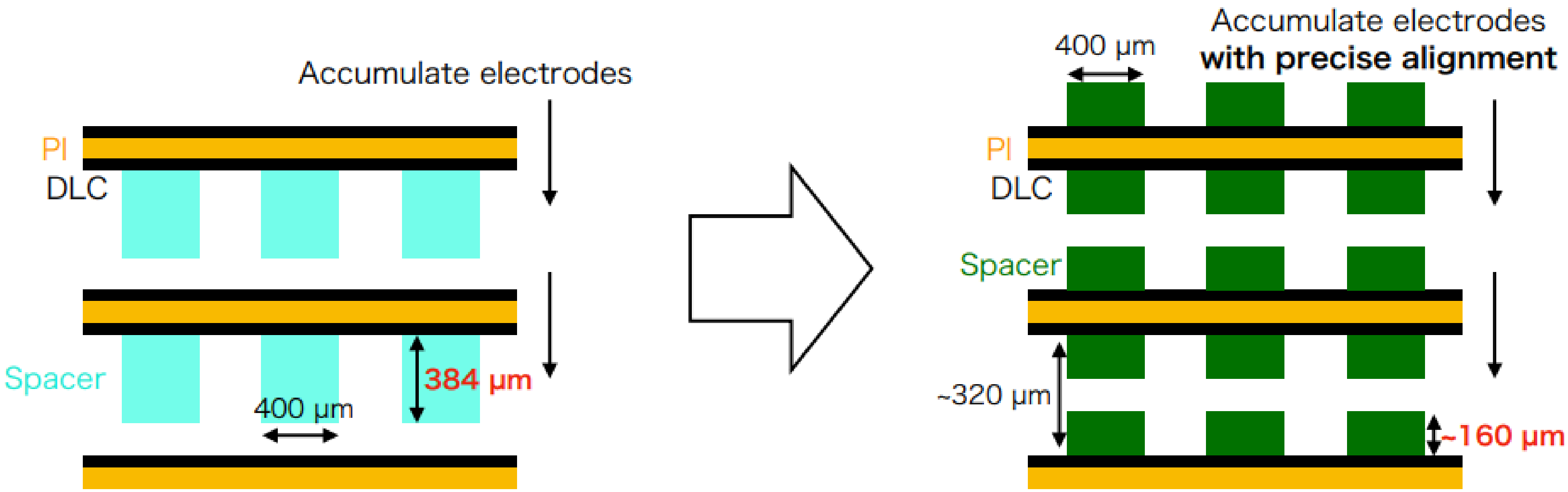
Detection efficiency at $\mathcal{O}(1-10\ \mathrm{kHz/cm^2})$



Spacer formation

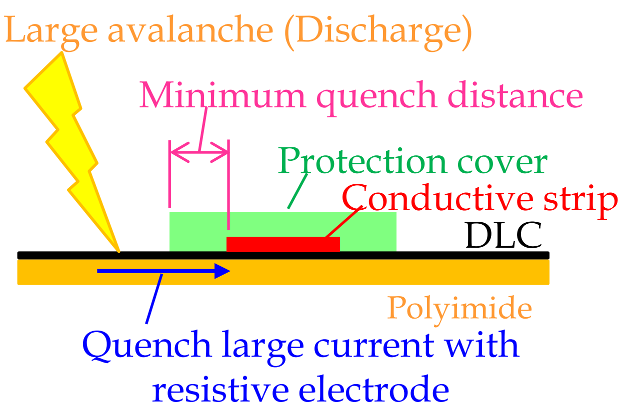
- Previous spacer material production cancellation

➡ 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**

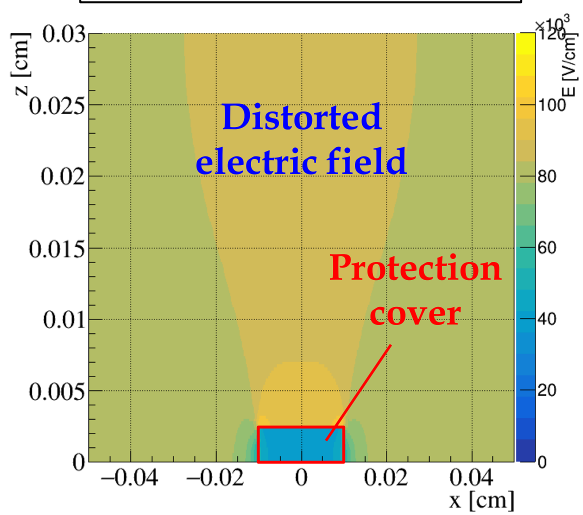


Discharge at strip structure

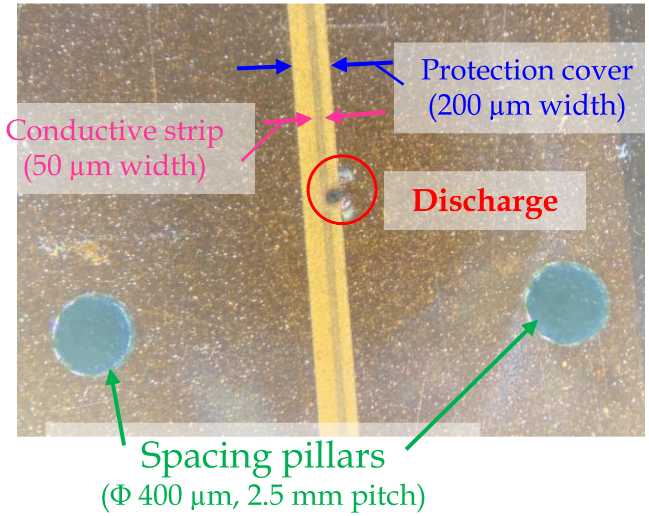
- Discharges likely occur near the strip structure
  - Lower quench capability
  - Electric field is distorted by protection cover



Simulated the electric field on the protection cover

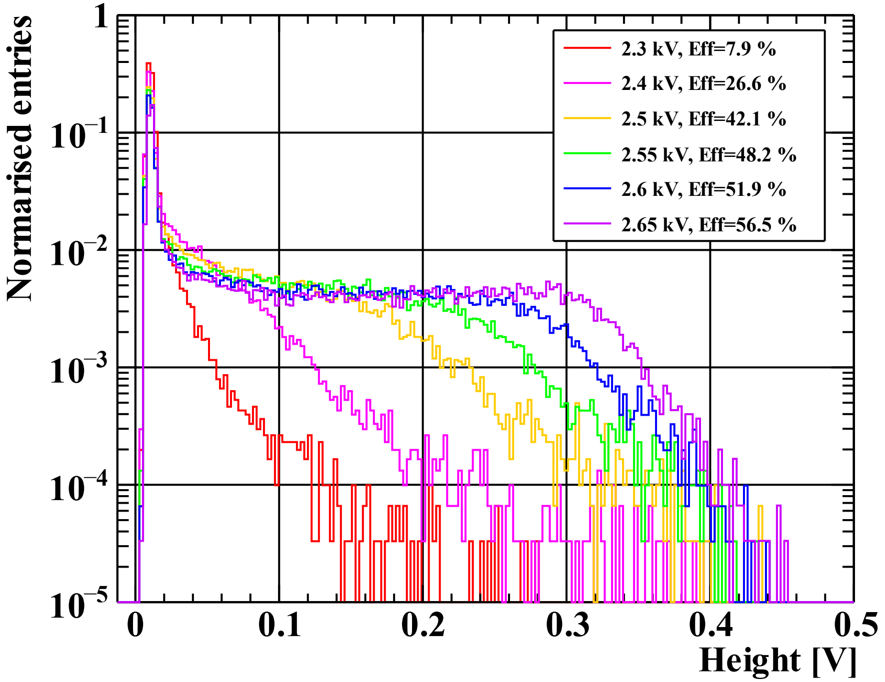


Discharge at strip

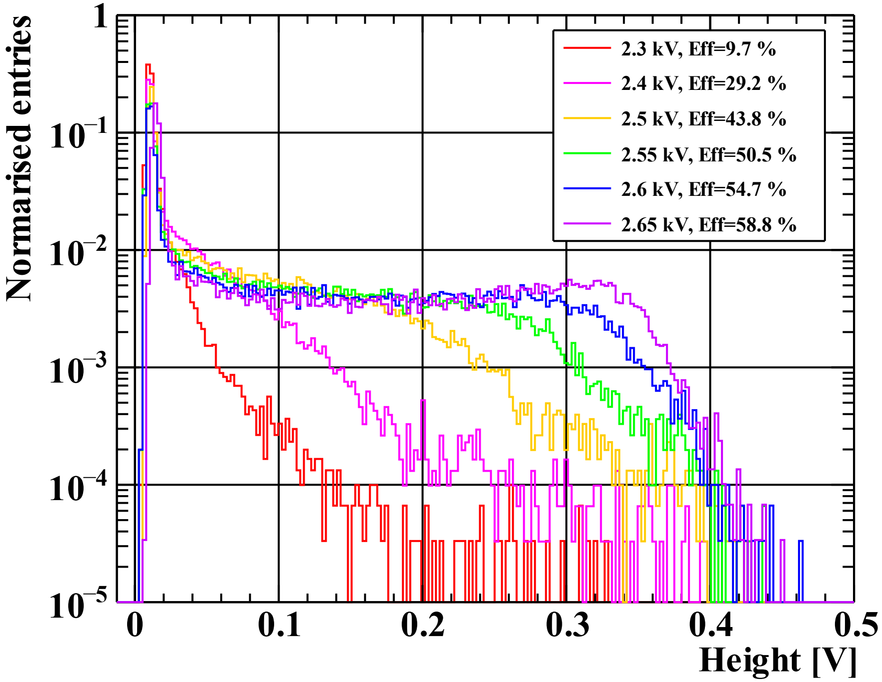


Pulse height spectra of each cover widths

0.2 mm width of cover (1003.1 hPa)

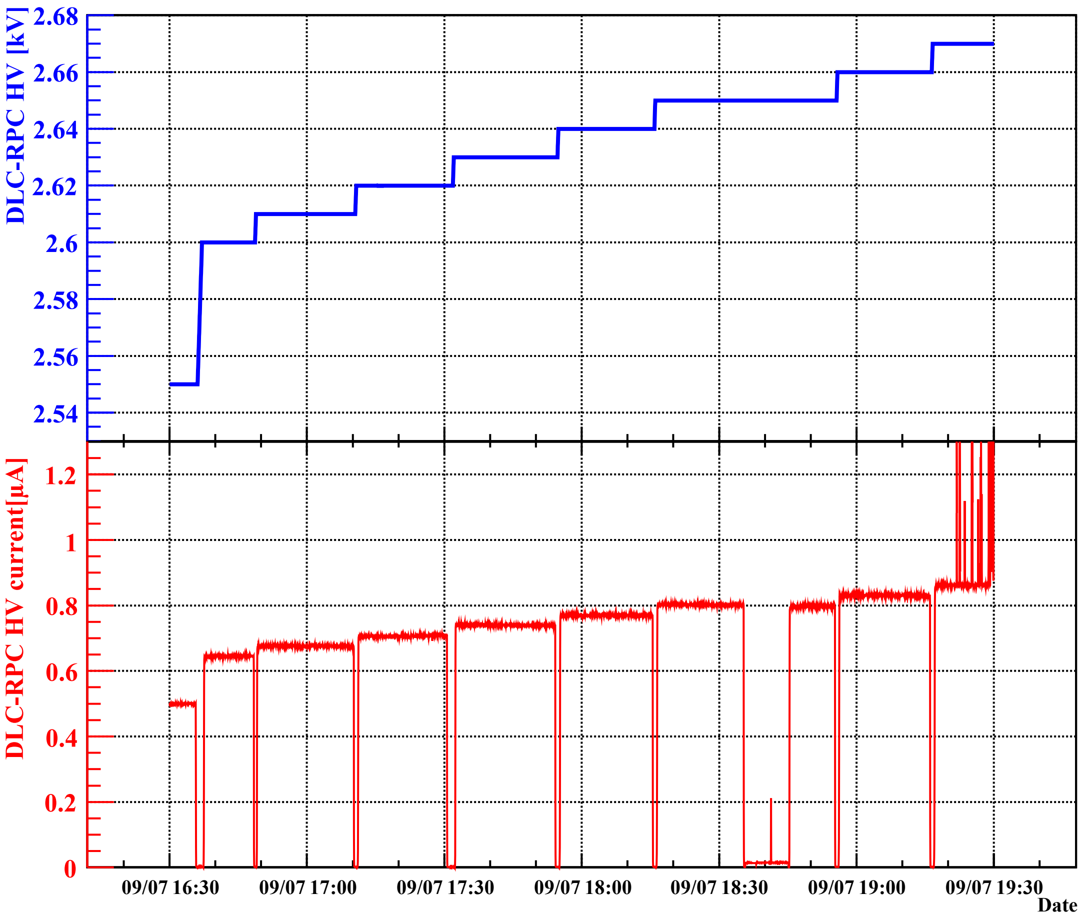


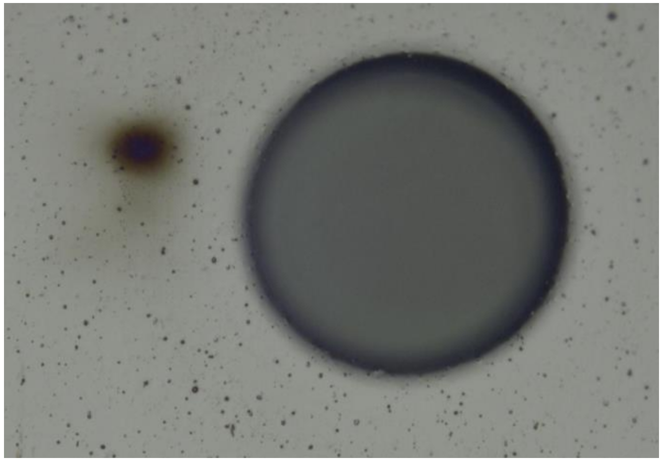
0.8 mm width of cover (998.4 hPa)



Test using 0.8 mm width of cover

- ➢ Unstable at 2.67 kV (998.4 hPa)

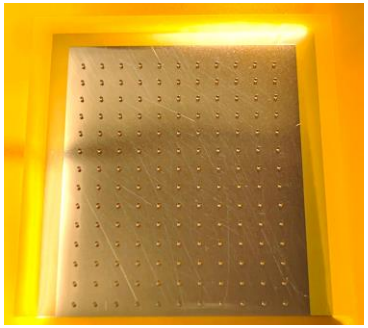




Transition of the DLC-RPC electrode

2019

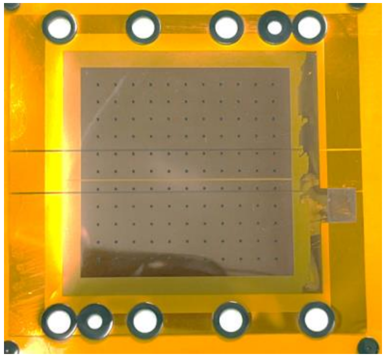
Demonstration of
the principle of DLC-RPC



- No strip structure

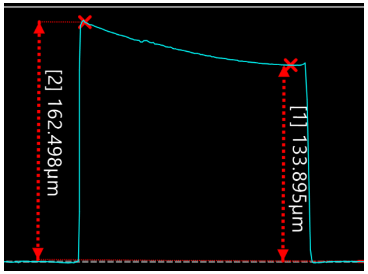
2022

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



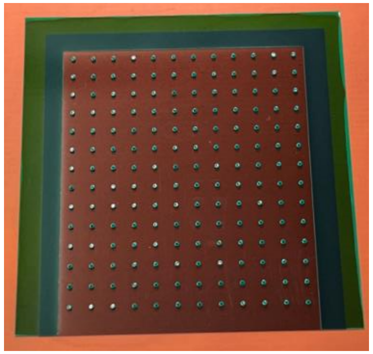
- Unstable operation due to spacing pillar quality

Distorted spacer



2023

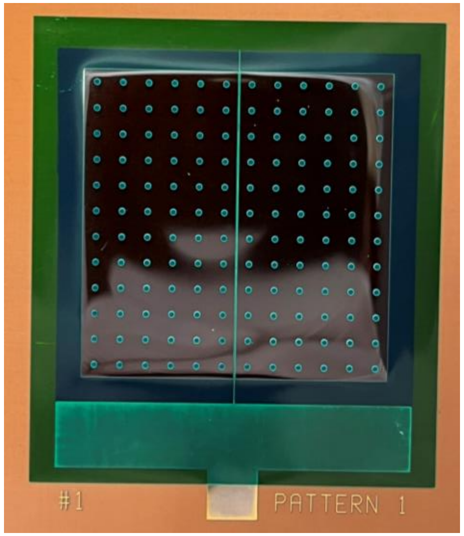
Improved the spacer formation



- Uniform spacer
- No strip structure

2024

Investigation of
the strip structure



- Uniform pillars
- With strip structure