MEG II実験に向けたDLC-RPCの レート耐性向上のための電極構造の最適化

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

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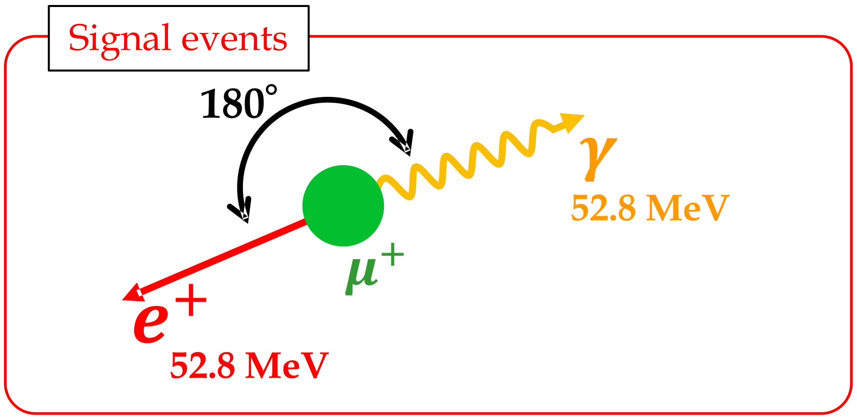
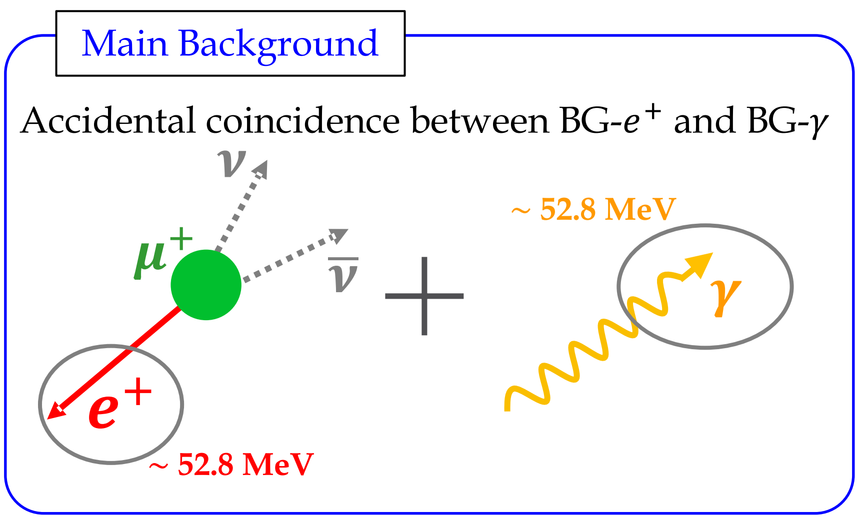
Outline

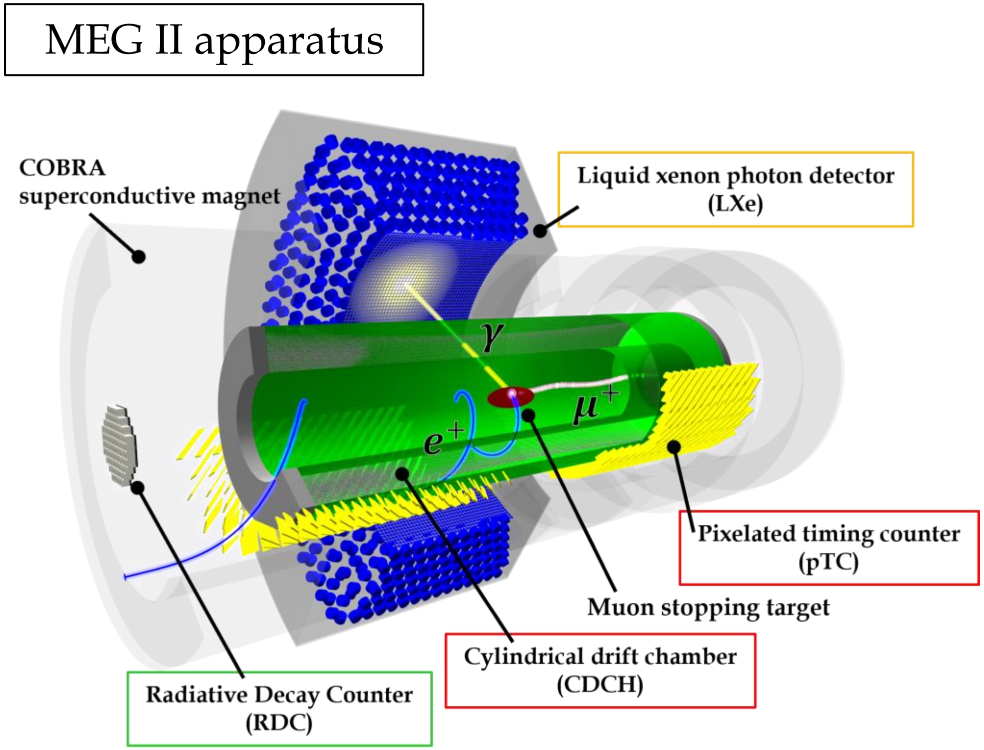
- Introduction
  - MEG II experiment
  - DLC-RPC for background suppression in MEG II
  - Conductive strip for high-rate capability
  - Previous studies
- Quenching capability of strip structure
  - Motivation of this test
  - Test setups
  - Result of measurements
  - Discussions on parameters
- Summary and prospects

MEG II experiment

- Searches for $\mu^+ \to e^+\gamma$ decay at Paul Scherrer Institute (PSI)
  - $\mu^+ \to e^+\gamma$ is a charged lepton flavor violating channel





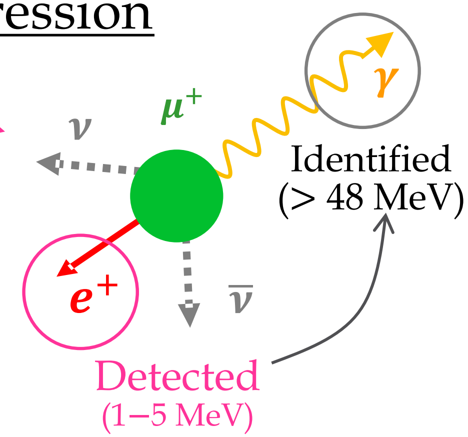


Identification of background γ-rays

- Radiative Decay Counter (RDC) for background suppression

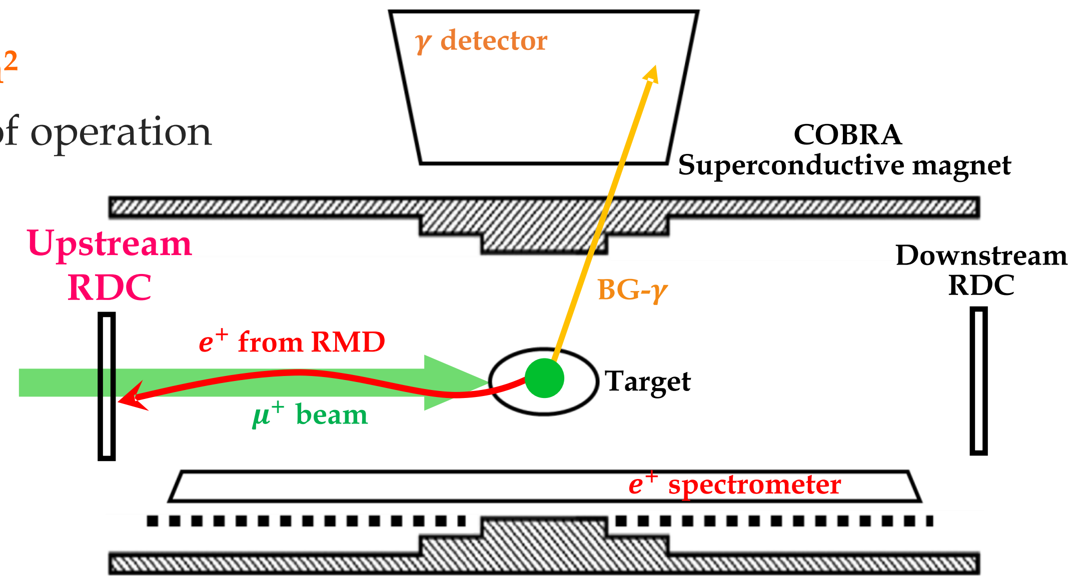
  ➔ **Identifies background γ-rays from radiative muon decay by detecting low-energy e^+ emitted simultaneously**

  - For upstream RDC, a high-intensity and low-momentum μ^+ beam passes through it
    $7 \times 10^7\ \mu^+/s$ — $28\ \mathrm{MeV}/c$



- Requirements for upstream RDC

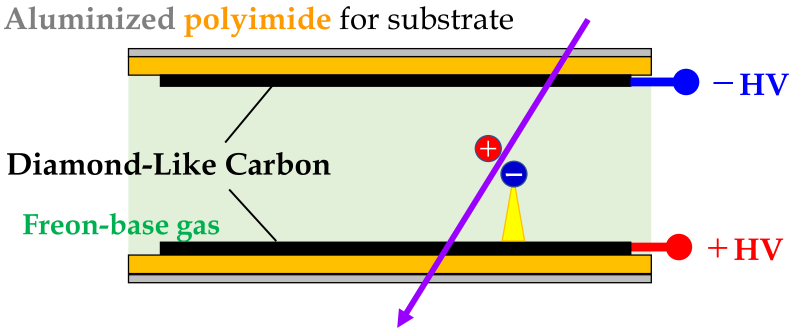
  - Material budget: $< 0.1\ \%\ X_0$
  - Rate capability: up to $3\ \mathrm{MHz/cm^2}$
  - Radiation hardness: **20 weeks** of operation
  - Detection efficiency: $> 90\ \%$
  - Timing resolution: $< 1\ \mathrm{ns}$
  - Detector size: ϕ **16 cm**



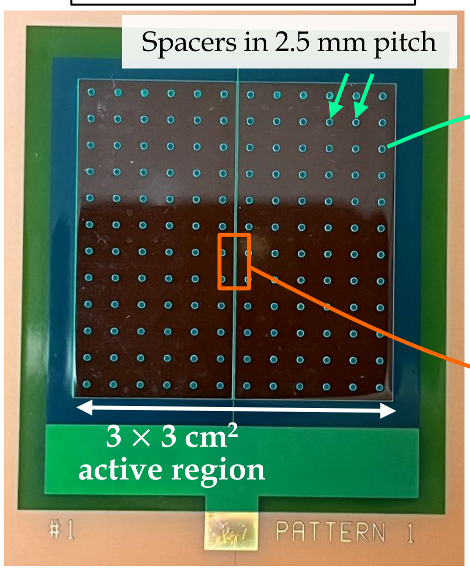
DLC-RPC for upstream RDC

- **Resistive Plate Chamber with Diamond-Like Carbon electrodes**
  - Consists of thin-film materials
- **Prototype electrodes in 2024**
  - 365 ± 5 μm thickness of spacer
  - 6 – 15 MΩ/sq surface resistivity of DLC
  - **Conductive strip structure**
    (0.2 – 1.0 mm width of protection cover)

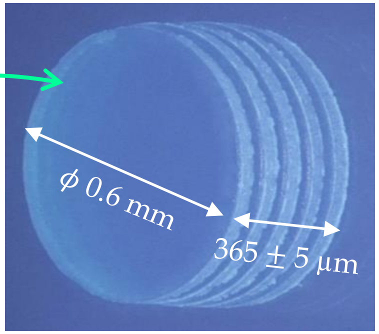
DLC-RPC structure



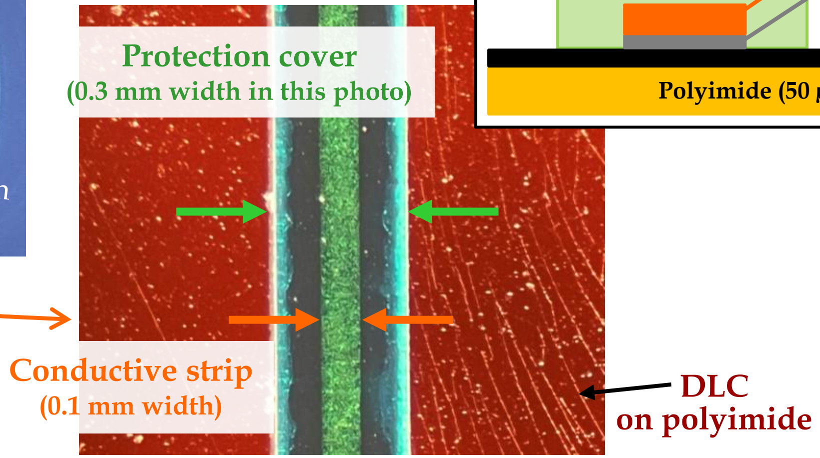
Prototype electrode

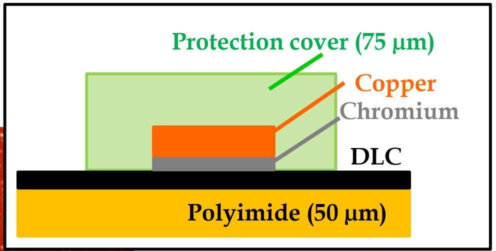


Diagonal view of spacer



Conductive strip structure

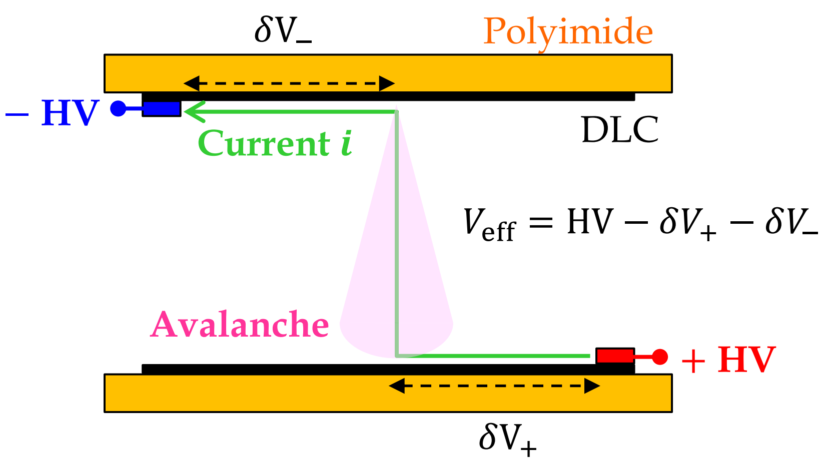




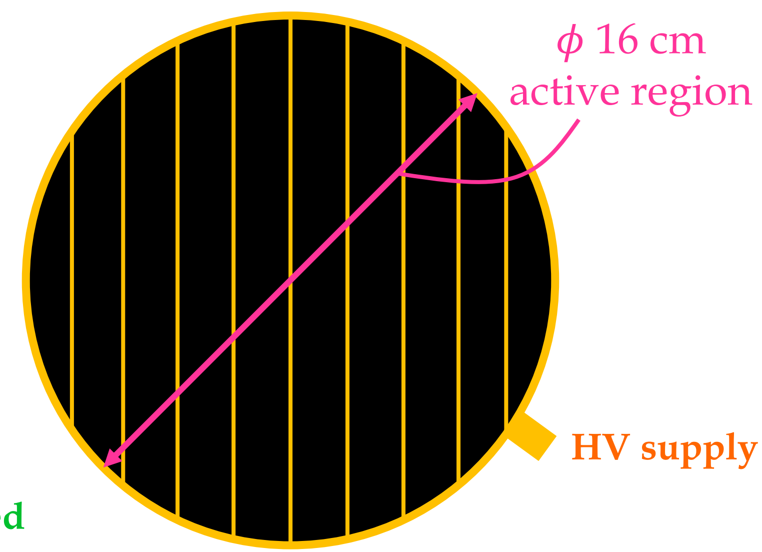
Conductive strip for high-rate capability

➢ Rate capability is determined by the magnitude of the voltage drop

- Large current on the resistive electrode at a high-rate environment
  ➔ Voltage drop δV reduces effective applied HV V_{eff} ➔ **Gas gain reduction**



Segmented HV supply geometry



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

HV supply should be segmented

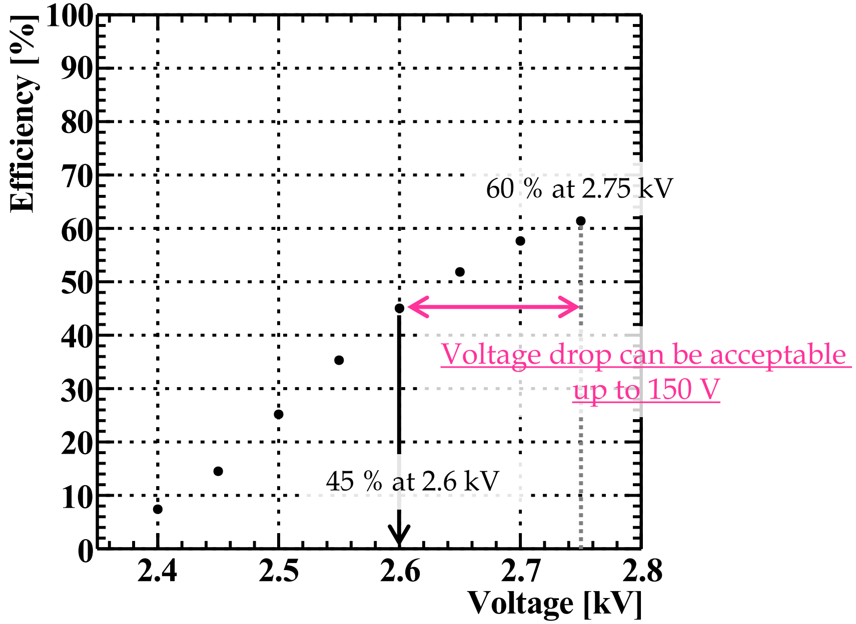
Low resistivity caused instability

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

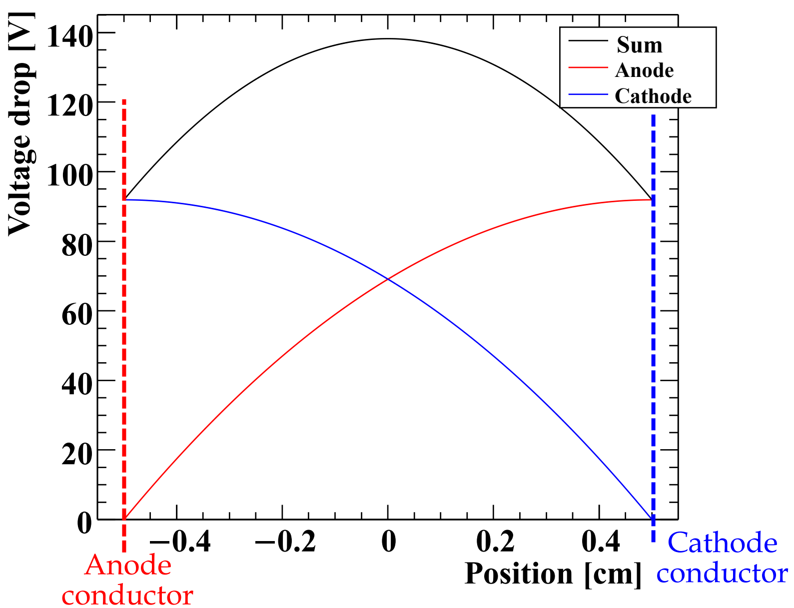
Acceptable voltage drop

- The DLC-RPC for MEG II will consist of **4 active layers**
  - The material budget requirement limits the active layer
  - Detection efficiency of each layer needs to be more than 45 %
    - $\epsilon_n = 1 - (1 - \epsilon_1)^n$, ϵ_n: n-layer efficiency (> 90 %)

Single-layer efficiency for MIP e^+



Example calculation of voltage drop δV



Voltage drop δV will be down to ~ 140 V in the 3 MHz/cm^2 μ^+ beam with
- surface resistivity: 25 MΩ/sq
- distance of conductor: 1 cm

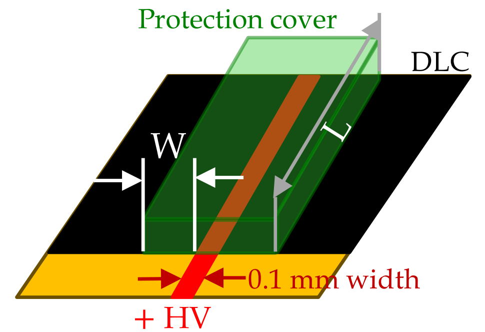
Previous studies

- Reported at the JPS meeting in autumn 2024 (18aWA203-6, 18aWA203-7)
  - Investigation of the discharge quenching capability with different protection cover widths
    - Adequate voltage could be applied with minimum width (0.2 mm)

Results with each protection cover widths

Cover width w (mm)	Resistivity ρ_S (MΩ/sq)	Effective resistance R_{anode} (MΩ)	Maximum voltage (kV)
0.2	13.8	23	2.64
0.8	6.75	79	2.65

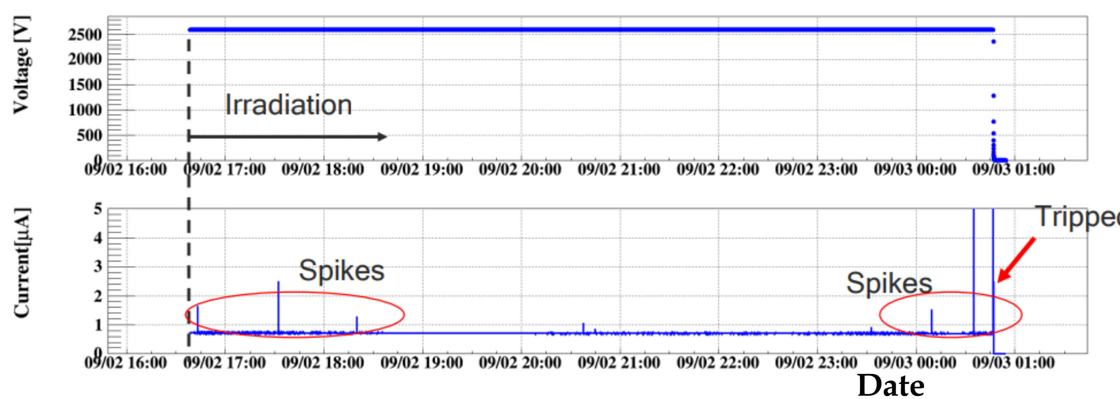
Required voltage: 2.6 kV



Effective resistance R_{anode} is a resistance in a covered region:
$R_{\mathrm{anode}} = \rho_S \times W/L, \quad L = 30$ mm

- Measured stabilities in long-term operations
  - Discharges occurred during long-term operations and prevented operations

History of long-term operation



Today's topics

➢ Need further investigation of strip structure and long-term operations

1. Discharge quenching capability under higher intensity irradiation
   (**This talk**, 高橋真斗 18aT2-1)
   - A higher intensity of β-rays was used
     - Intensity is locally equivalent to **1 − 10 MHz/cm²** (previous: 10 kHz/cm²)
   - To validate the effective resistance dependency, increased cover width variation

2. What are the causes and measures for discharges in long-term operation?
   (鈴木大夢 18aT2-2)
   - Investigation of causes for discharge problems
   - Investigation of operating parameters for stable operations

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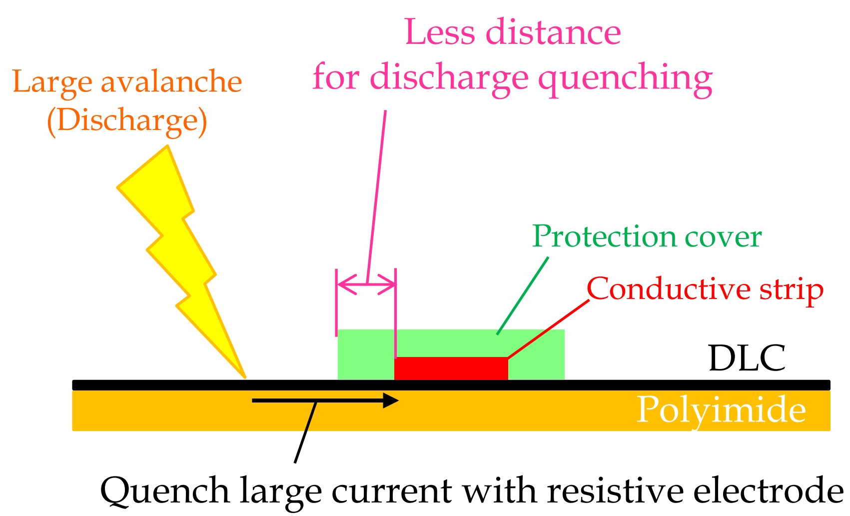
  - Conductive strip for high-rate capability
  - Previous studies
- **Quenching capability of strip structure**
  - **Motivation of this test**
  - **Test setups**
  - **Result of measurements**
  - **Discussions on parameters**
- Summary and prospects

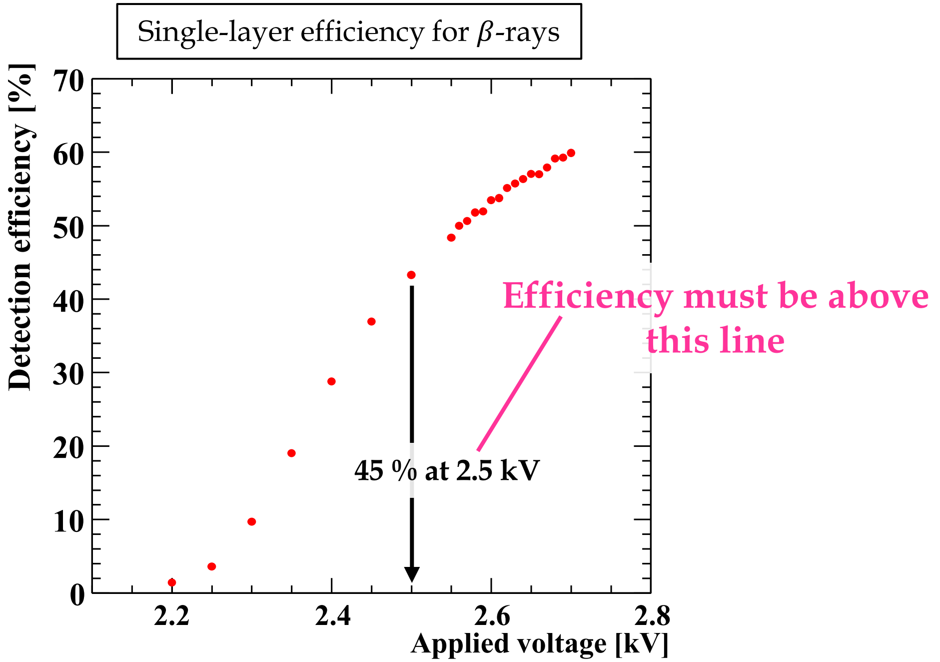
Motivation of this test

➢ How wide does the protection cover need to be to apply a voltage that will obtain adequate detection efficiency?

- Short distance to conductors makes strip construction prone to electrical discharges
  ➔ Reduces a maximum operating voltage
- In addition, voltage drop δV by the μ^+ beam will also reduce an effective voltage

➔ The efficiency requirement must be met with this voltage reduction

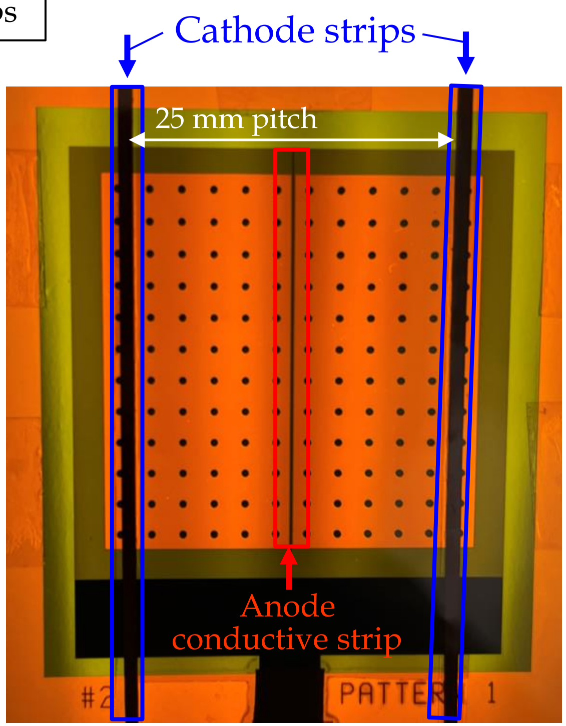




Test setups: electrode configuration

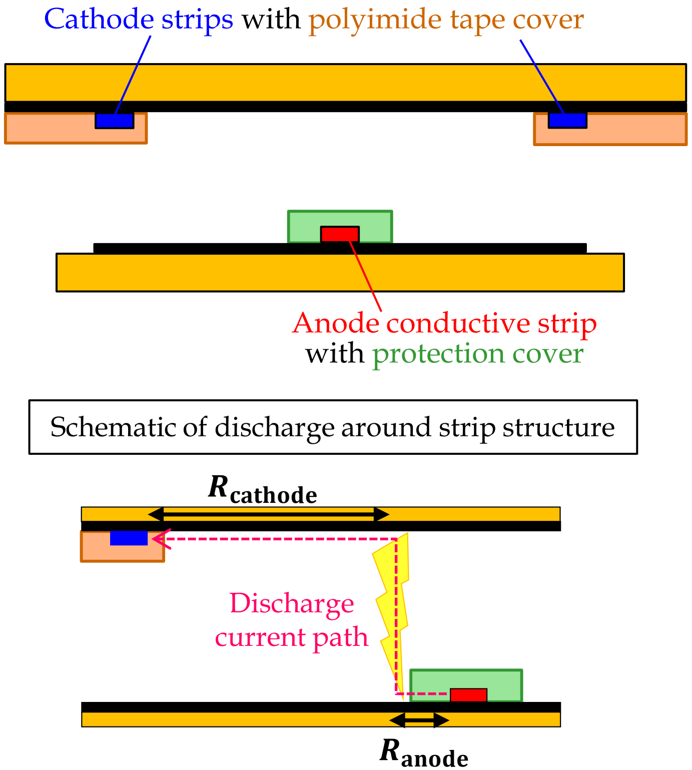
- Different widths of protection cover were used (0.2 mm – 1.0 mm)
- Strip structures were installed on the anode and cathode side alternately

Installed hand-made cathode strips



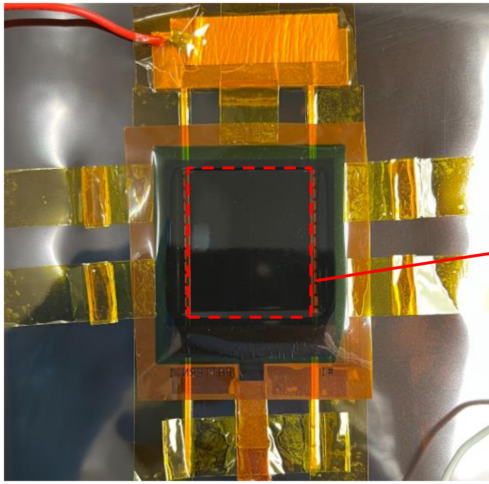
Outside of cathode strips is covered with polyimide tape

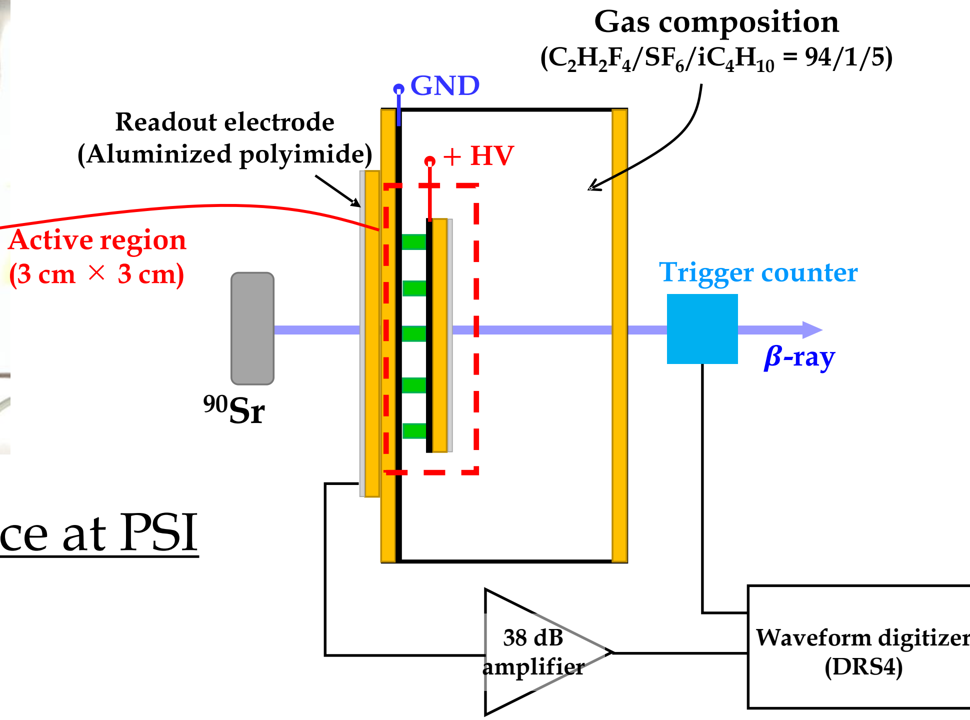
Cross-section schematic of a gas gap geometry



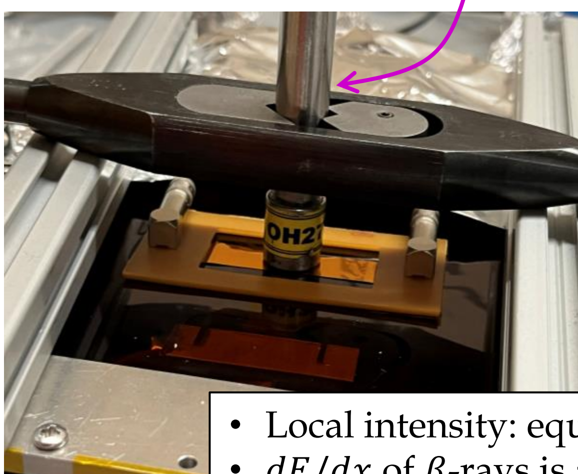
$R_{\mathrm{anode(cathode)}}$ is effective resistance that works on quenching against discharges around anode strip

Test setup: measurement setup

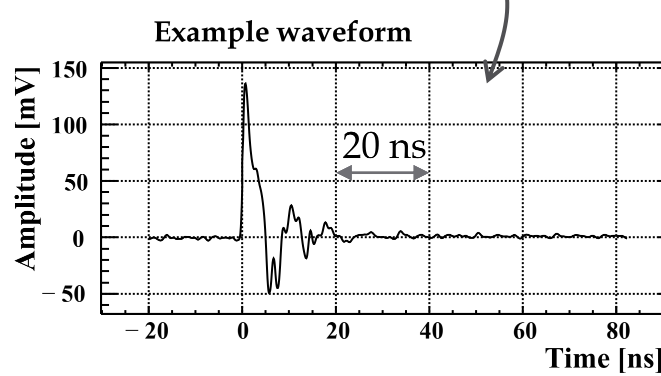




➢ High intensity β-ray source at PSI



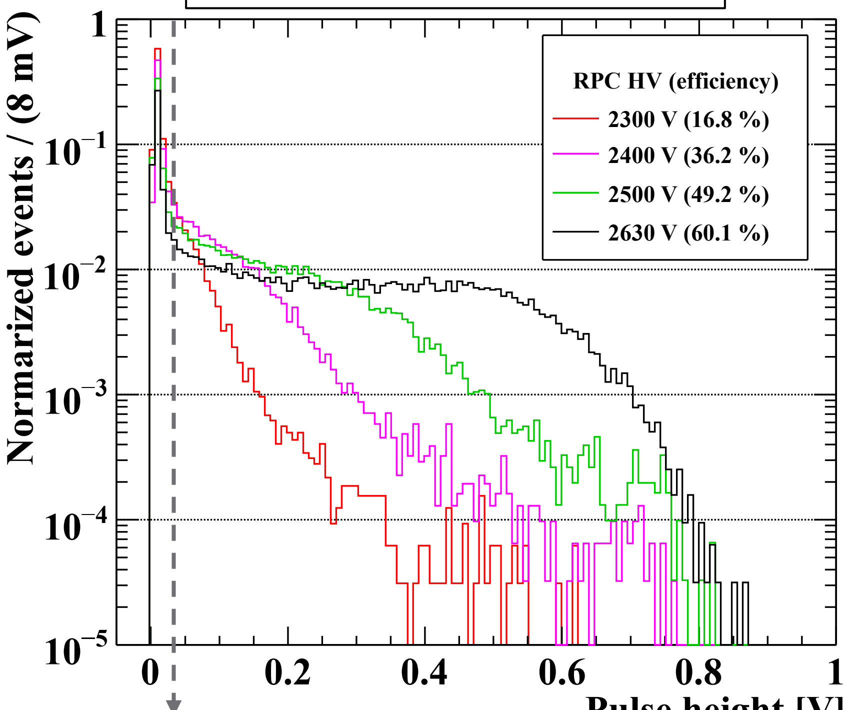
- Local intensity: equivalent to **1 − 10 MHz/cm²**
- dE/dx of β-rays is about **1/10** of beam μ^+
  ➔ Up to 1/3 the intensity of the μ^+ beam



Performance for high-intensity β-rays

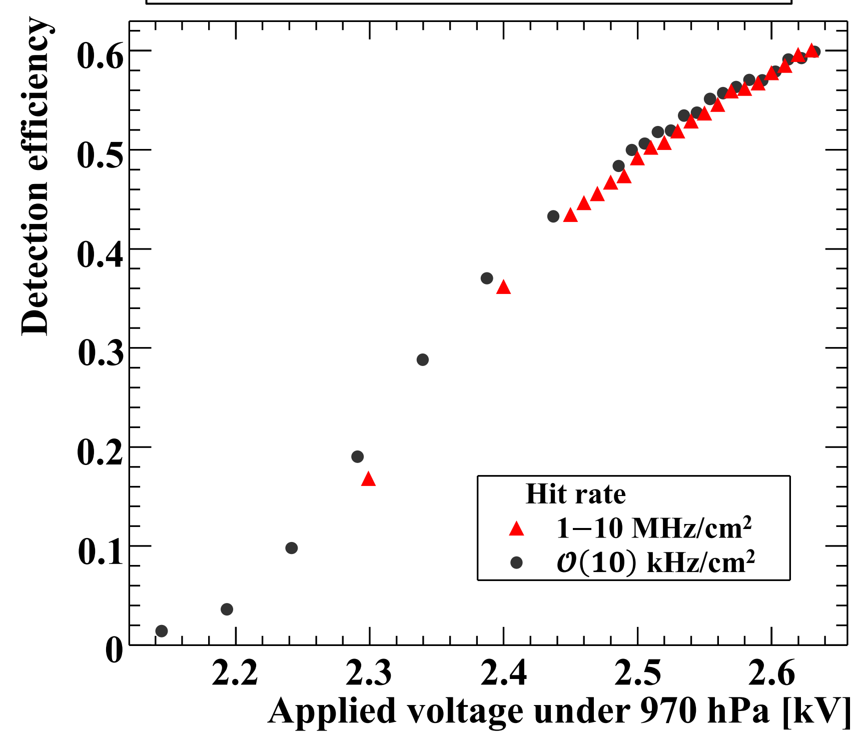
➢ Measured pulse heights and detection efficiencies for triggered events

Pulse spectra measured at PSI



30 mV signal threshold

Comparison of detection efficiencies



➢ Performance was consistent across measurements at two different hit rates

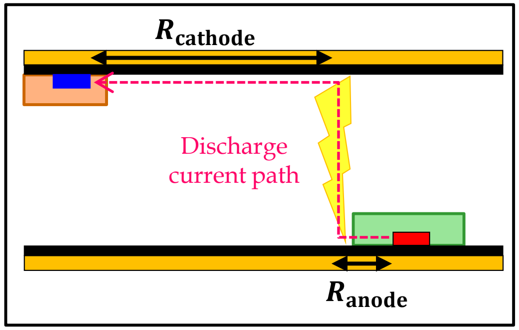
- Applied voltages were converted by the relationship between electric field and pressure (E/p)

Result of measurements

- Measured whether a target voltage has been reached with different widths
  - Target voltage: a voltage exceeding the required efficiency even after considering voltage drops by the μ^+ beam
  - Voltage drop: calculated by configurations (resistivities and distance of conductors)

Cover width	Surface resistivity		Distance of conductors	R_{anode}	$R_{cathode}$	Results
	Anode	Cathode				
0.2 mm	11.8 MΩ/sq	11 MΩ/sq	12.5 mm	0.02 MΩ	4.6 MΩ	Not reached
0.2 mm	11.8 MΩ/sq	14 MΩ/sq	14 mm	0.02 MΩ	6.5 MΩ	Not reached
0.3 mm	13.5 MΩ/sq	11 MΩ/sq	12.5 mm	0.05 MΩ	4.5 MΩ	Not reached
0.4 mm	14.5 MΩ/sq	14 MΩ/sq	14 mm	0.07 MΩ	6.5 MΩ	✓
0.6 mm	11.0 MΩ/sq	14 MΩ/sq	14 mm	0.09 MΩ	6.4 MΩ	✓
1.0 mm	10.0 MΩ/sq	11 MΩ/sq	14.5 mm	0.15 MΩ	5.2 MΩ	✓

- $R_{anode} > 0.07$ MΩ is needed for quenching discharges
- $R_{cathode}$ did not seem to be effective for quenching
  - This asymmetric quenching capability might be related to mobility of charges at each electrode (Ions/electrons)



Discussions on parameters

Parameter optimization

Optimized parameters: **Strip pitch, Resistivity, Cover width**

Constraints: **Voltage drop, Effective resistance, Occupancy**

$\boldsymbol{\delta V = 100 - 150\ \mathrm{V}}$ $\boldsymbol{R_{\mathrm{anode}} > 0.07\ \mathrm{M\Omega}}$

Example of parameter settings

- **Conditions**
  - 3 cm × 3 cm of active region
  - Strip pitch: 10 mm
  - Cover width: 0.4 mm

Resistivity: 20 MΩ/sq

- $\delta V \sim 110$ V
- $R_{\mathrm{anode}} \sim 0.1$ MΩ

Parameters will be optimized,
and a full-scale design will be finalized soon

Summary and prospects

- DLC-RPC is being developed for background suppression in MEG II
  - Consists of thin-film materials due to a high-intensity and low-momentum μ^+ beam
  - Needs to detect low-energy e^+ in the μ^+ beam
- Measured the discharge quenching capability at strip structure under high-intensity β-rays
  - Local intensity of β-rays was equivalent to $\mathbf{1 - 10\ MHz/cm^2}$
  - For the discharge phenomena around the strip structure,
    - **anode-side effective resistance R_{anode} needed to be more than 0.07 MΩ**
    - cathode-side effective resistance R_{cathode} did not contribute so much

➔ **Optimize the resistivity and cover width in an actual design to meet this resistance value in the future**

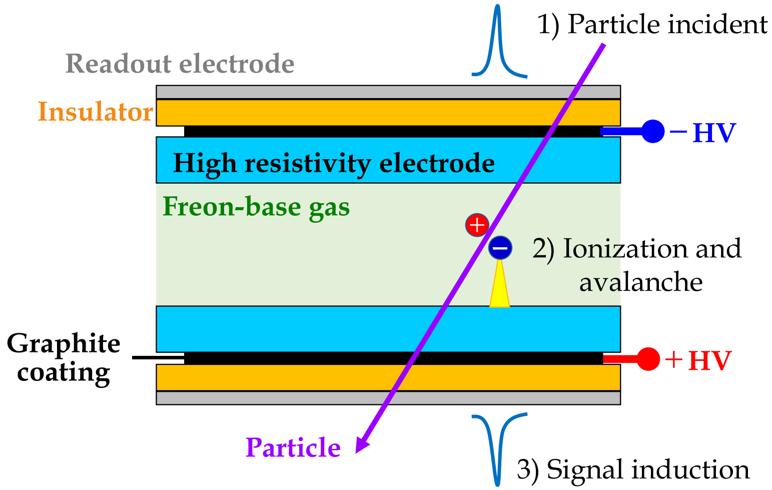
- Including a **safety factor**
  - Minimum requirement is $R_{\text{anode}} > 0.07$ MΩ ➔ Considering safety factor **3**: > 0.2 MΩ

- Investigation of the problems and measures in long-term operation
  ➔ See next talk (鈴木大夢, 18aT2-1)

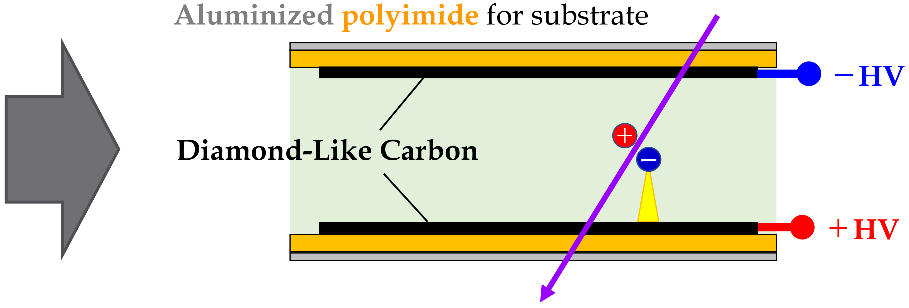
Backup

DLC-RPC

Structure and principle of Resistive Plate Chamber (RPC)



Structure of the DLC-RPC



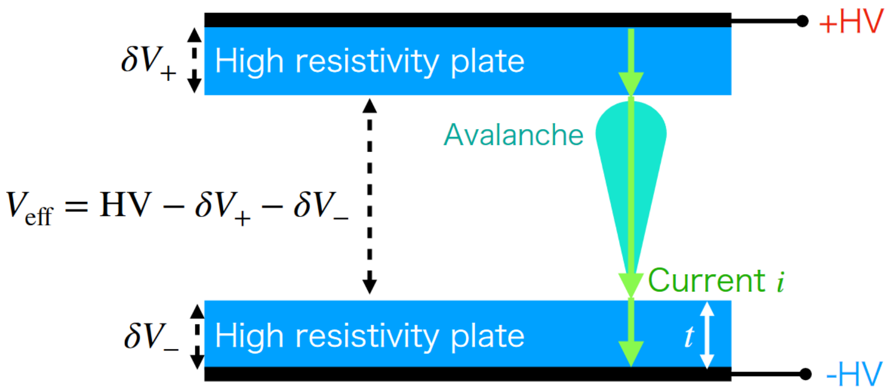
- **Discharges can be suppressed by voltage drops of high resistivity electrode**
- **Fast time response** and **good time resolution** by no drift region and thin avalanche gap
- **High detection efficiency** can be achieved by stacking active gas gaps
  - $\epsilon_n = 1 - (1 - \epsilon_1)^n$

- **Diamond-Like Carbon (DLC)** is used as a resistive electrode
- **Ultra-low mass design**
  - Aluminized polyimide is used as substrates of detector
  - DLC is sputtered onto thin polyimide film

Conventional RPC and DLC-RPC

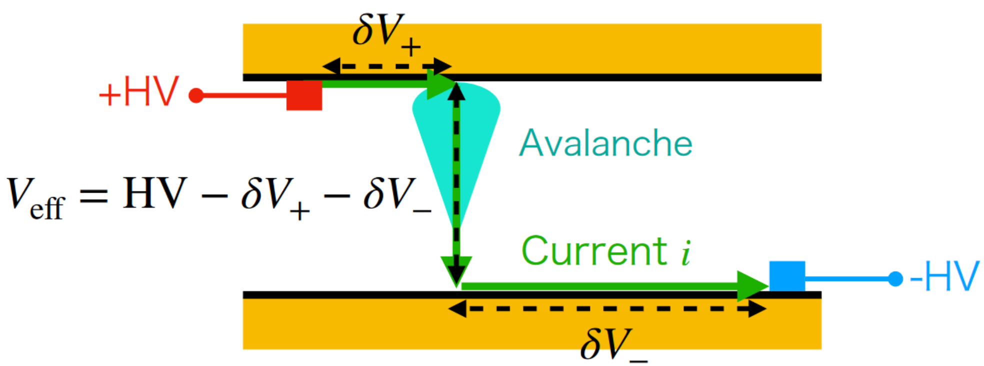
- Differences between conventional RPCs (glass RPC) and DLC-RPC (surface RPC)

Conventional RPC



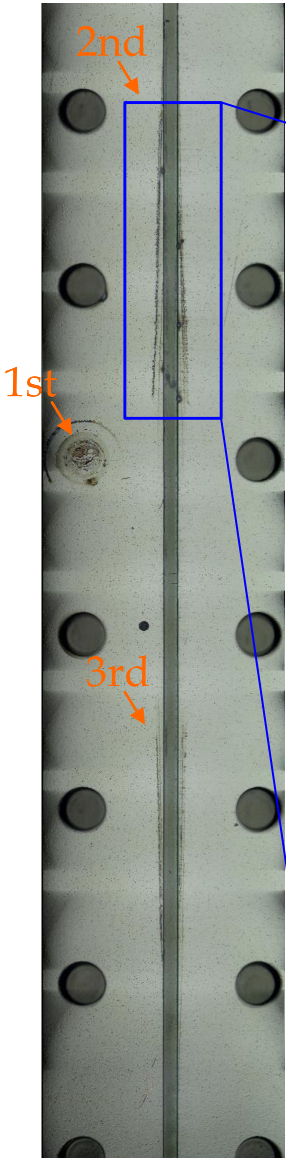
$$\delta\text{V} = Q_{\text{mean}}(\text{V}_{\text{eff}}) \cdot f(x, y) \cdot \rho_V \cdot t$$

DLC-RPC

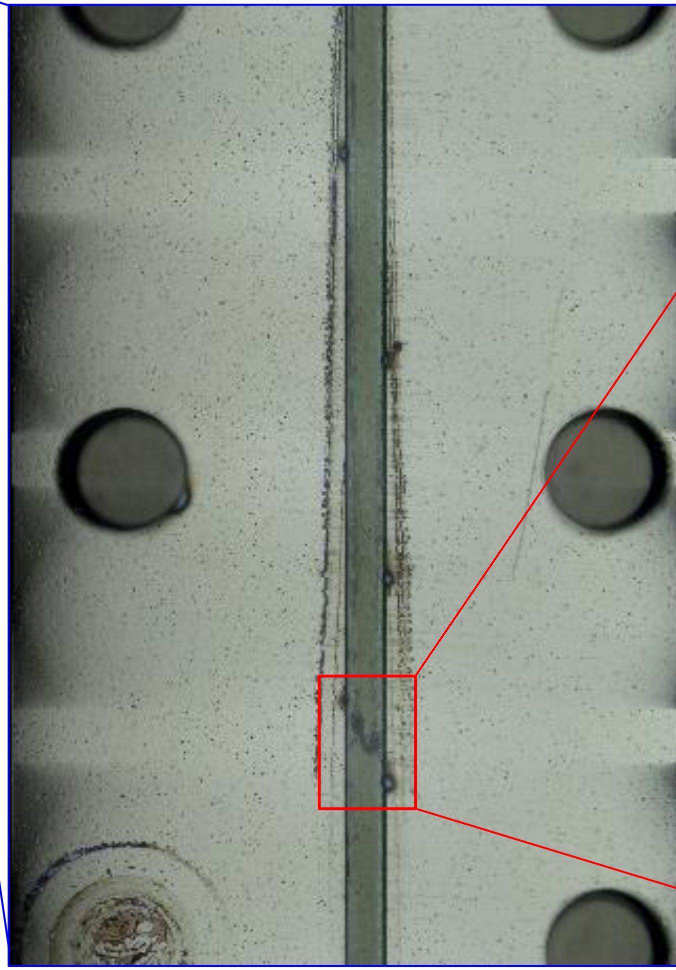


$$\nabla^2 \delta\text{V} = Q_{\text{mean}}(\text{V}_{\text{eff}}) \cdot f(x, y) \cdot \rho_S$$

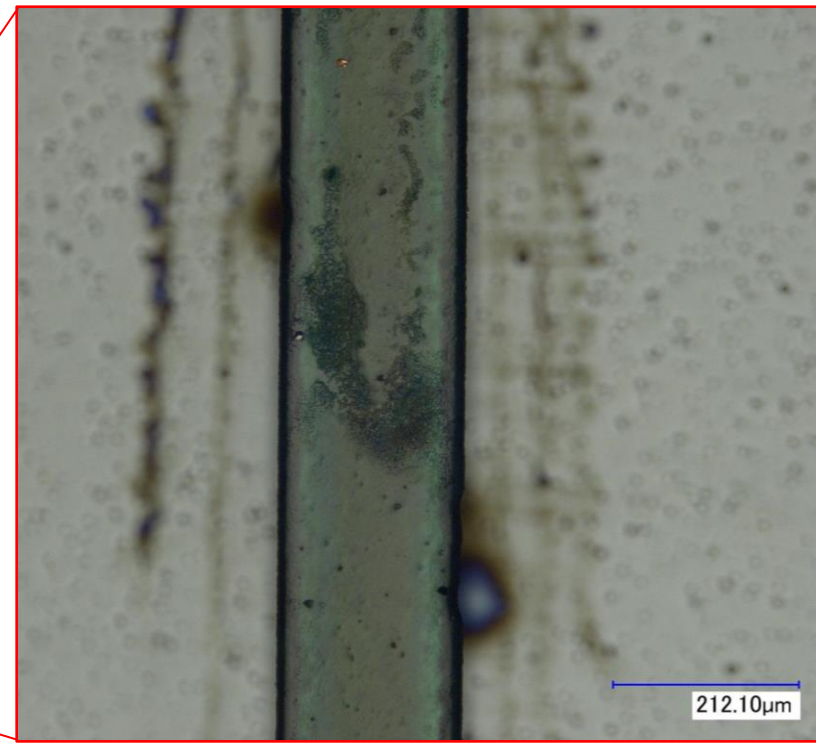
Discharges around the strip



A sample with the most terrible damage

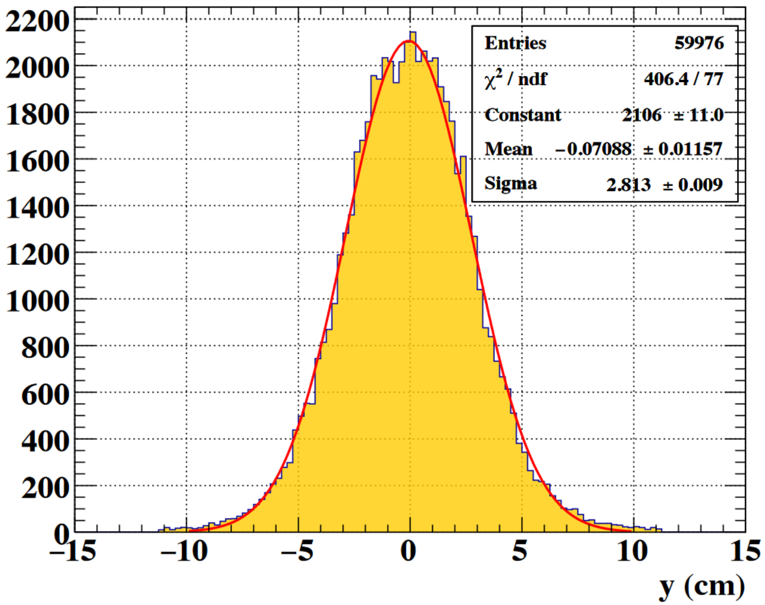


Smoothness was lost in one part of the cover

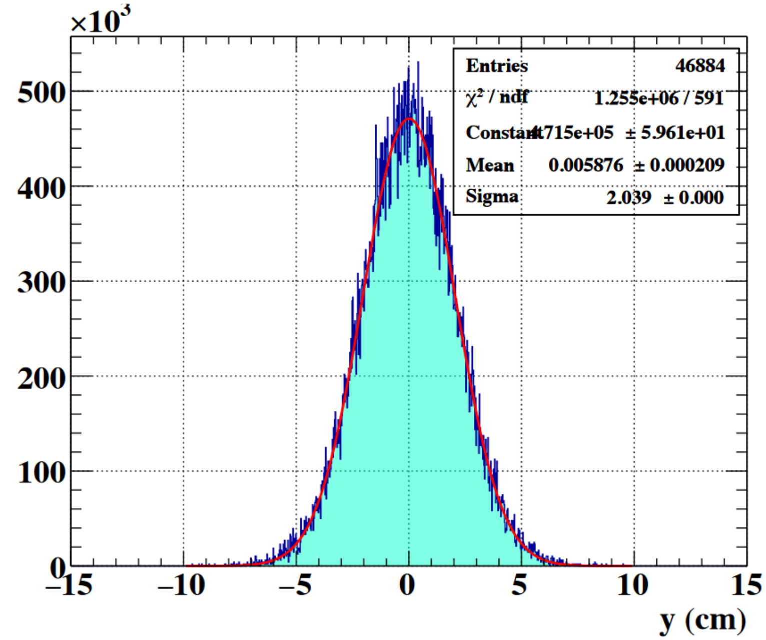


e^+ and μ^+ distributions

➢ MC simulation



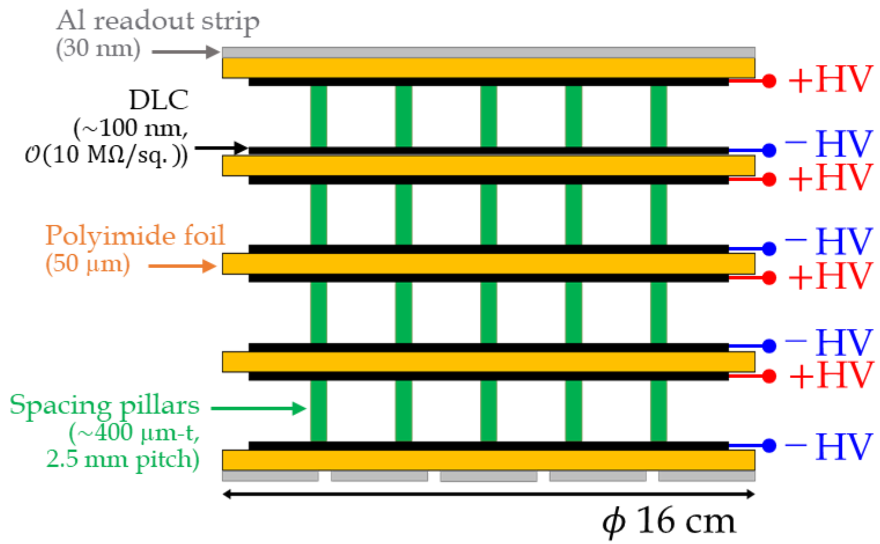
RMD e^+ ($E_\gamma > 48$ MeV)
$\sigma = 2.8$ cm



μ^+ beam profile
$\sigma = 2.0$ cm

DLC-RPC for MEG II

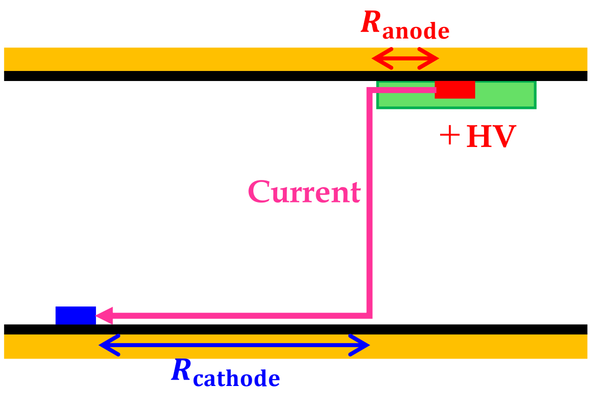
- Up to 4 active layers
  - Limited by material budget



Material	Material budget
Polyimide 50 μm	0.0175 % X_0
Aluminum 30 nm	0.0034 % X_0
Gas 2 mm	~0.001 % X_0
DLC ~100 nm	negligible

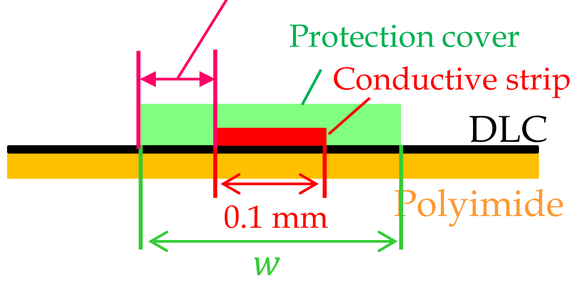
➢ Definition of $R_{\text{anode}}/R_{\text{cathode}}$

- Surface resistivity $\rho_S = R \times w/l \iff R = \rho_S \times l/w$

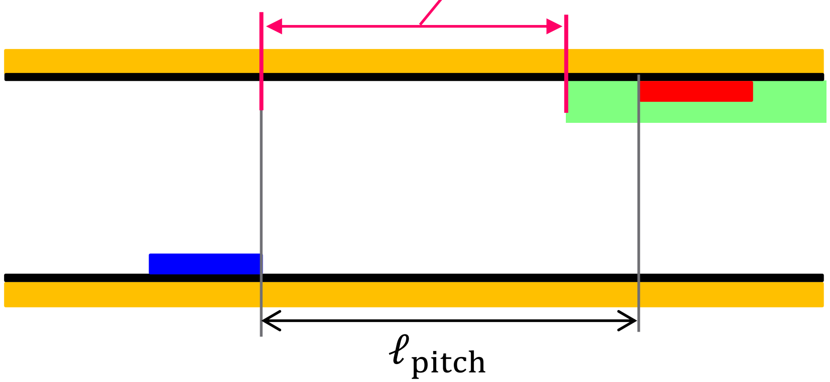


$$R_{\text{anode}} = \rho_{S_{\text{anode}}} \cdot \boxed{\frac{(w - 0.1\ \text{mm})}{2}} \cdot \frac{1}{d}$$

d: length of the strip (= 30 mm)
0.1 mm is a width of the conductive pattern

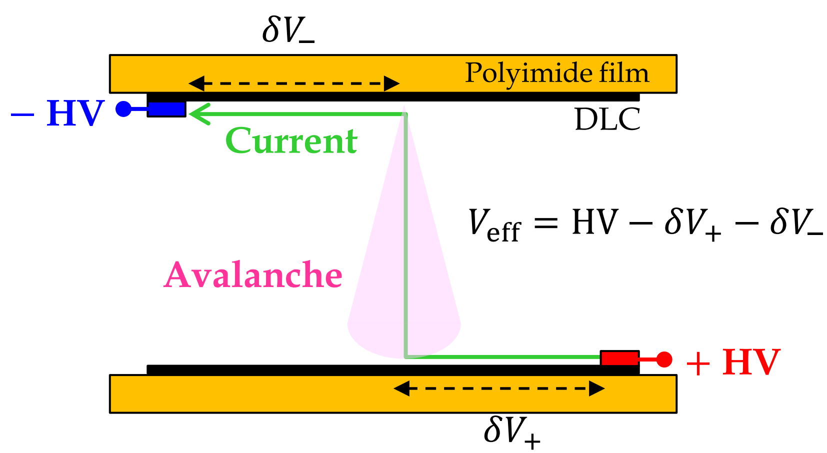


$$R_{\text{cathode}} = \rho_{S_{\text{cathode}}} \cdot \boxed{\left(\ell_{\text{pitch}} - \frac{(w - 0.1\ \text{mm})}{2}\right)} \cdot \frac{1}{d}$$

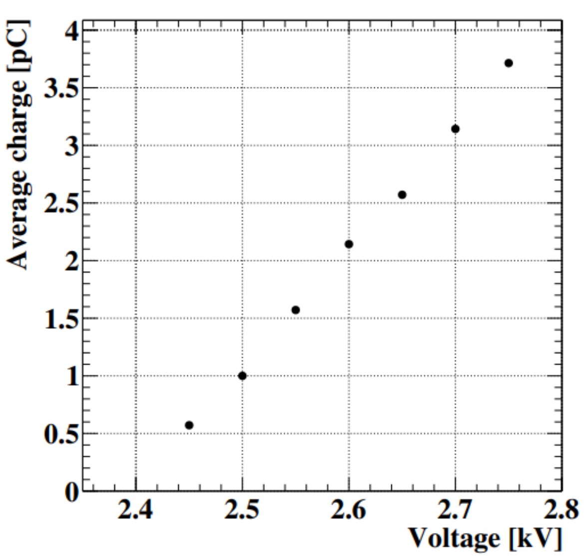


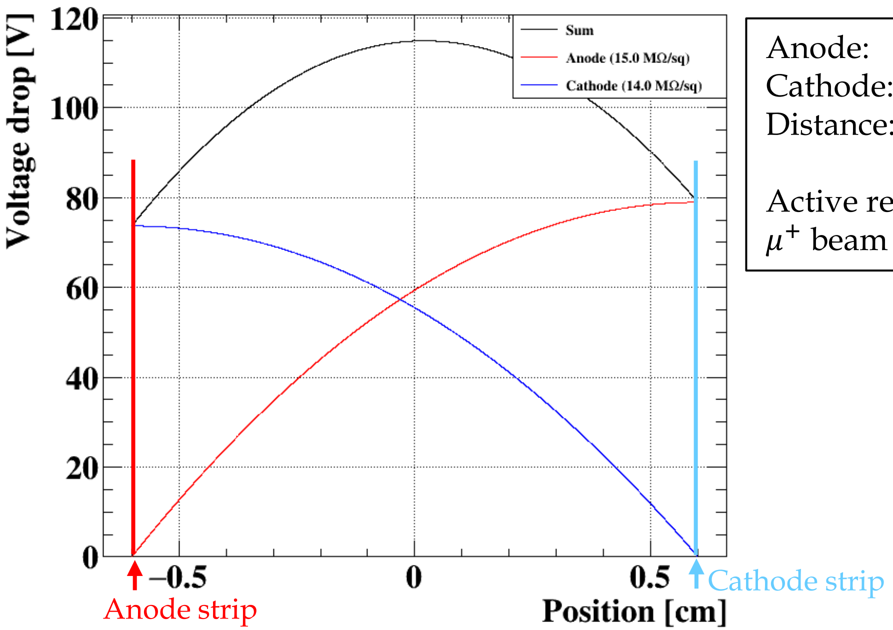
Voltage drop calculation

- Voltage drop at (x, y)
  - $\nabla^2 \delta V(x,y) = Q_{\mathrm{mean}}(V_{\mathrm{eff}}) \times f(x,y) \times \rho_S$
    - $Q_{\mathrm{mean}}(V_{\mathrm{eff}})$: Average avalanche charge
    - $f(x,y)$: Hit rate at (x,y)
    - ρ_S: surface resistivity



Average avalanche charge for μ^+ beam





Anode: 15 MΩ/sq
Cathode: 14 MΩ/sq
Distance: 12 mm

Active region: 3 cm × 3 cm
μ^+ beam rate: 3 MHz/cm^2

Requirements and current status

- DLC-RPC needs to detect low-energy e^+ in a high-intensity and low-momentum μ^+ beam
  - Signal : e^+ with $1-5$ MeV
  - Background : μ^+ with 28 MeV/c at 7×10^7 μ^+/s

Contents	Requirements	Reached specs
Material budget	< 0.1 % X_0	**0.095** % $\boldsymbol{X_0}$ with 4 active layers (in design)
Rate capability	Up to 3 MHz/cm^2	**1 MHz/cm^2**
Radiation hardness	$\sim$ 100 C/cm^2	Investigated up to $\sim$ **54 C/cm^2**
Detection efficiency	$>$ 90 % for MIP	**50** % with single-layer
Time resolution	< 1 ns	**180 ps**
Detector size	ϕ 16 cm	**2** $\times$ **2 cm^2** of active region

- Performances were measured using prototype electrodes
  - Used the DLC-RPC electrode with $\sim$ 40 MΩ/sq and 2 cm × 2 cm of active region

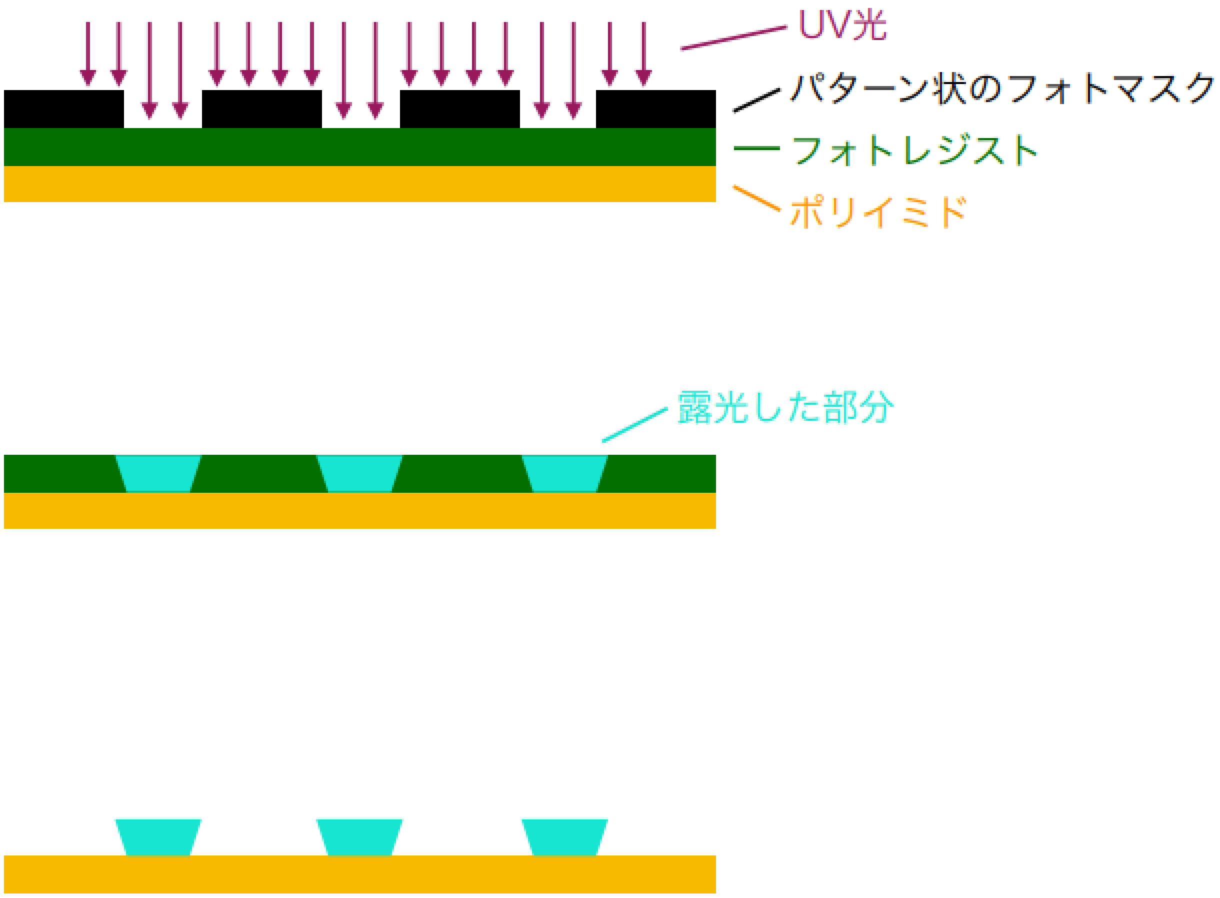
    Ref) K. Ieki NIM A 1064 (2024) 169375, M. Takahashi, NIM A 1066 (2024) 169509

Photolithographic technology

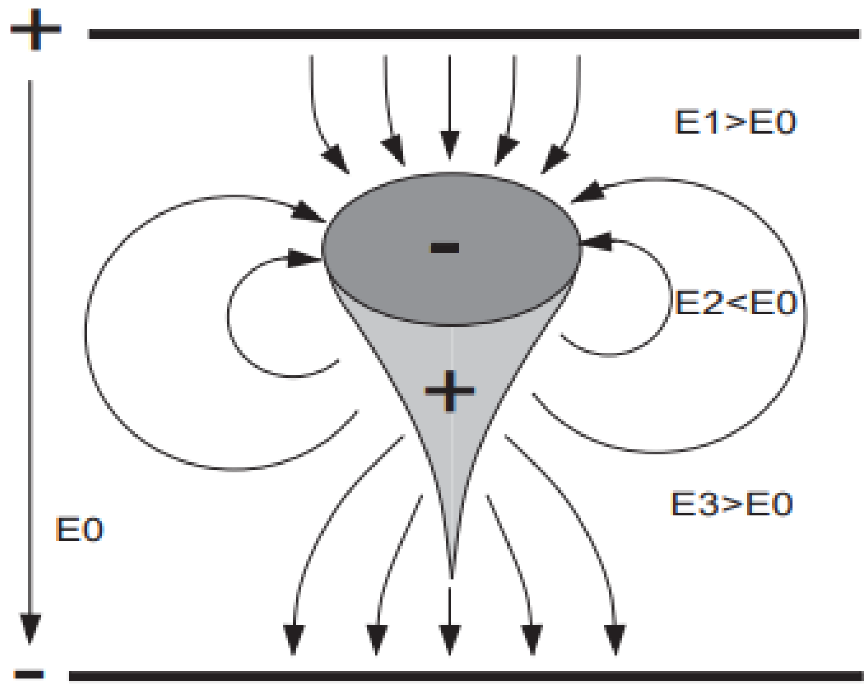
1. マスクをかけて
UV光で露光する

2. 現像液によって
非露光領域を溶かす

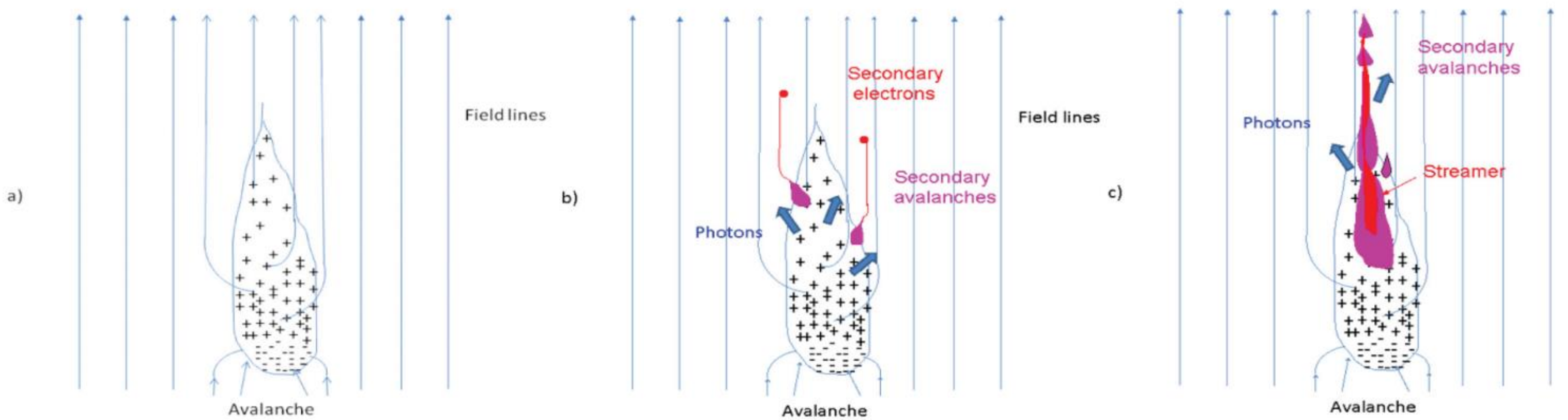
3. ピラーが完成する



Space charge effect



Streamer



a)
Field lines
Avalanche
b)
Secondary electrons
Field lines
Secondary avalanches
Photons
Avalanche
c)
Secondary avalanches
Photons
Streamer
Avalanche

Sputtering process