MEG II実験に向けたDLC-RPCの長期動作における放電への対策

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Outline

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  - DLC-RPC in the MEG II experiment
  - Performances for a high-intensity muon beam
  - Investigation of the operation with high-rate β-rays
- ◆Possible scenarios of discharges
- ◆Strategy to investigate the gap size
- ◆Long-term operation
  - Setup
  - Result
- ◆Measures
- ◆Summary & Prospects

DLC-RPC in the MEG II experiment

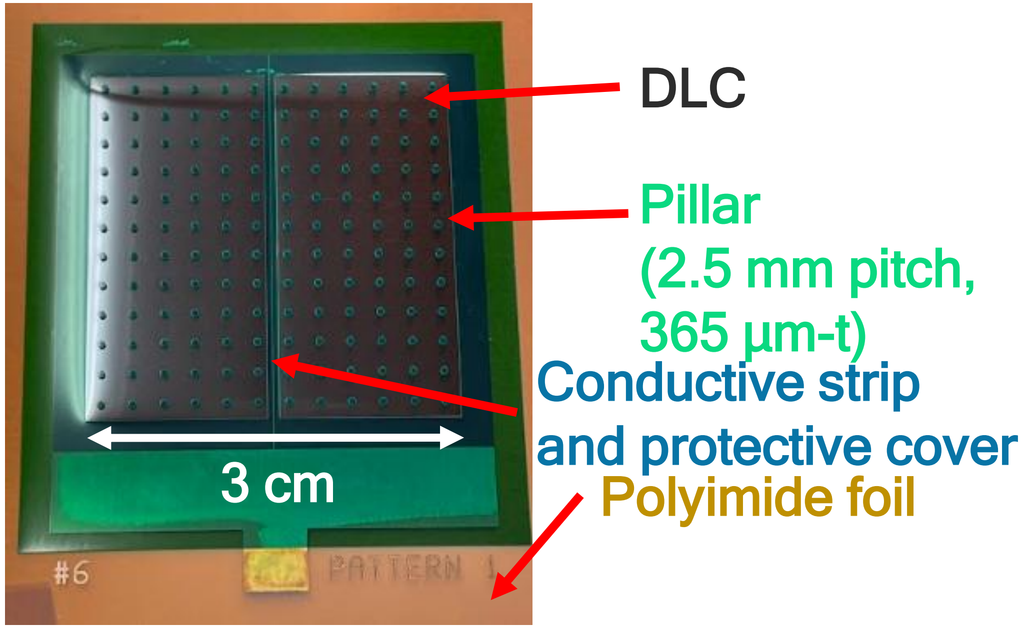
DLC-RPC: Resistive Plate Chamber with Diamond-Like Carbon-based electrodes

- High intensity (7×10^7 /s)
- Low momentum (28 MeV/c)

Requirements for the DLC-RPC

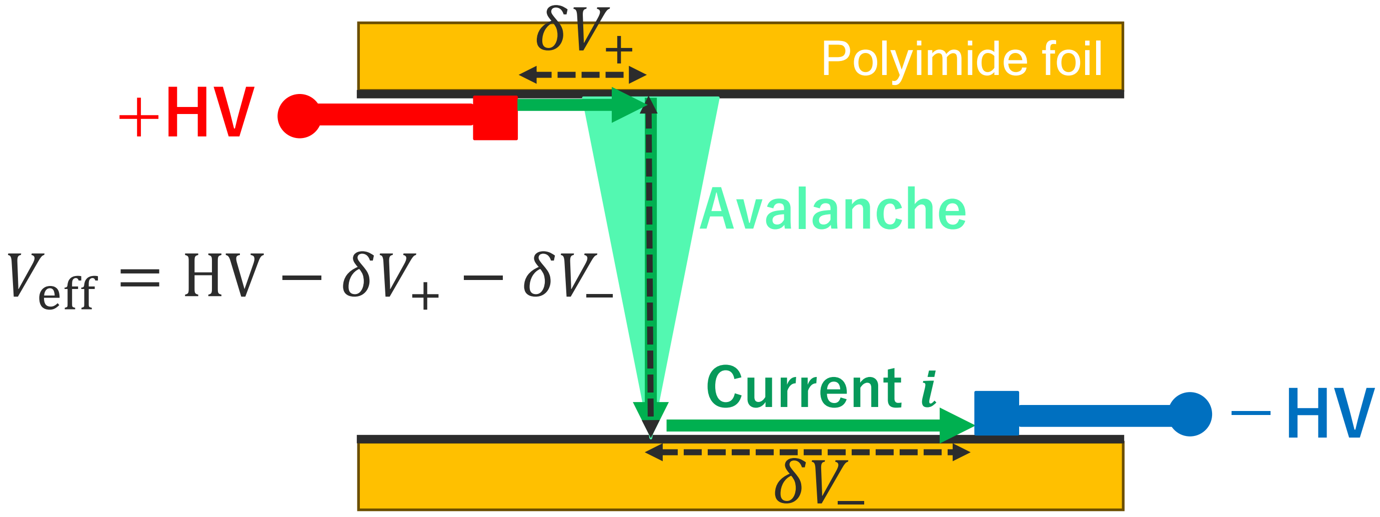
1. Material budget: < 0.1 % X_0
2. Rate capability: 3 MHz/cm^2
3. Radiation hardness: ∼100 C/cm^2 in 20 weeks operation
4. Detection efficiency: > 90 % for MIP
5. Timing resolution: < 1 ns
6. Detector size: 16 cm Φ

An electrode for a small prototype

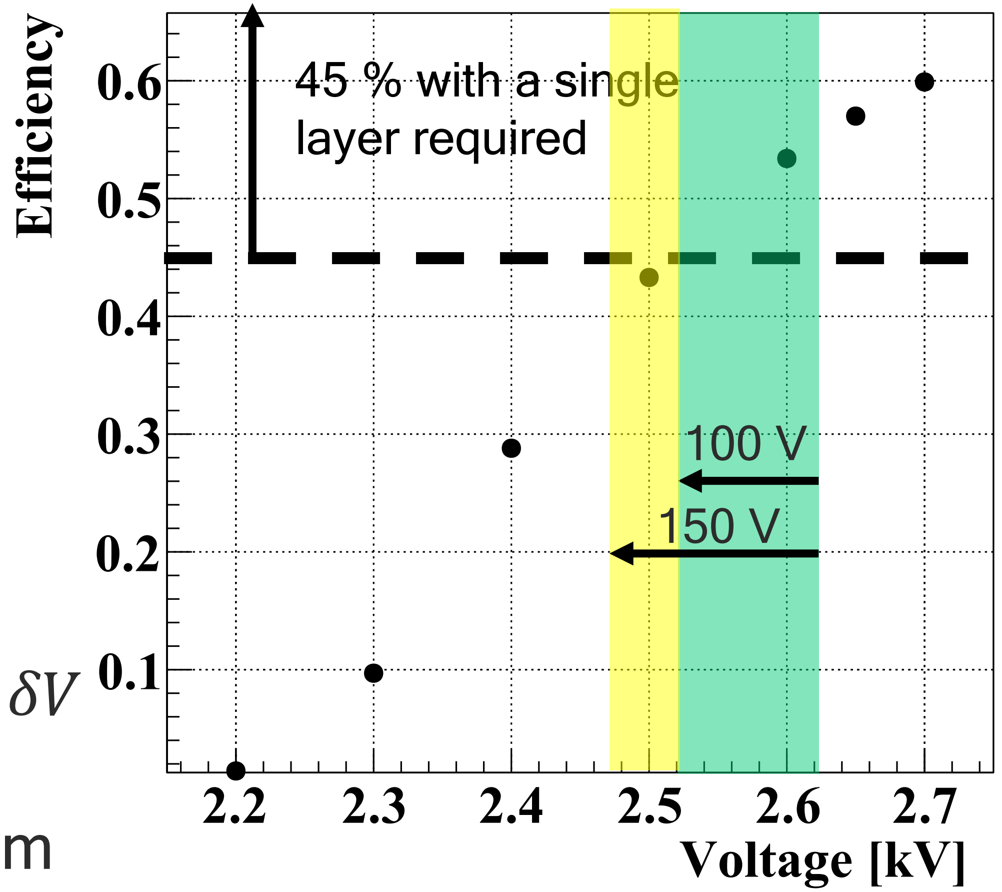


Surface resistivity: 6 – 15 MΩ/sq.

Performances for a high-intensity muon beam



Detection efficiency vs applied voltage

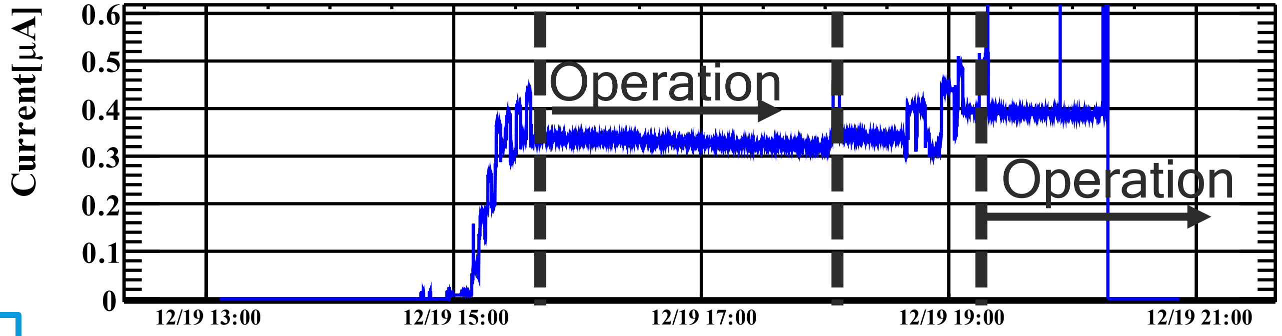


- Segmented HV supplies to suppress a voltage drop δV at a small pitch
  - Aiming δV ~100 - 150 V in a high-rate muon beam
  - Target voltage: A voltage (efficiency: 45 %) + δV

Investigation of the operation with high-rate β-rays

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	✓

Result of quenching capability
in the previous talk



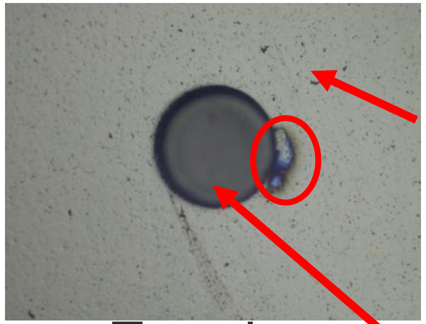
Current history of an operation

- A certain cover width size is required to operate at the target voltage (previous talk).
- β-rays with the rate of 1 - 10 MHz/cm^2 were used.
- The operation lasted for 1 - 2 hours level.
- Discharges ended up terminating it.
- By lowering the voltage by 50 V, the operation could be prolonged.

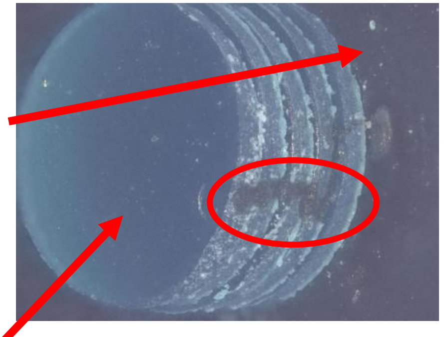
It may be difficult to operate in a high-intensity muon beam.

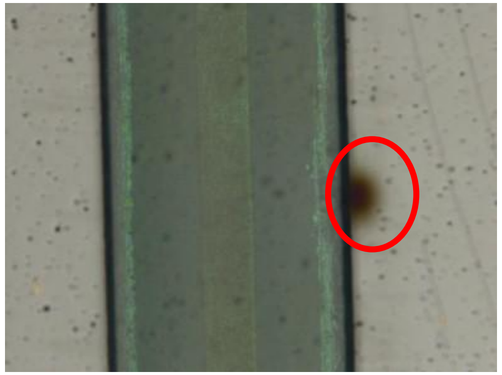
Possible scenarios of discharges

Where discharges happen



Top view

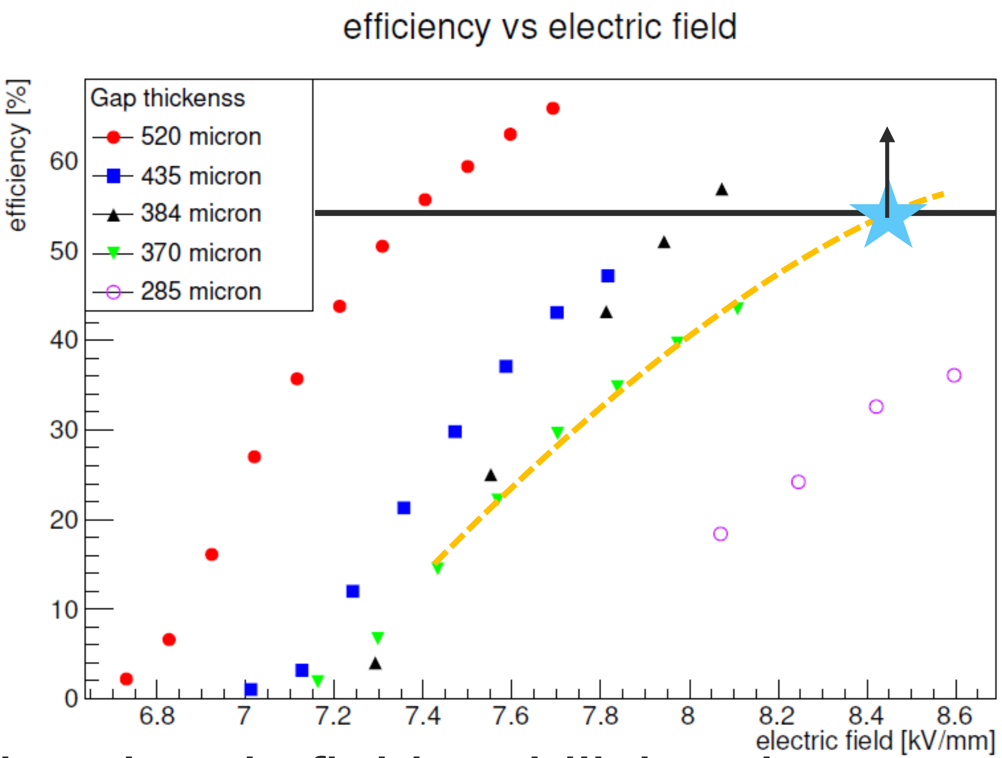

Oblique view


Protective covers

Possibilities

- A strong electric field induces large avalanches.
- Large avalanche energy causes damage accumulation.→Discharges
- Investigate the electric field and gas gap for long-term stability
    - Difficult to fabricate detectors with various gap sizes

Strategy to investigate the gap size

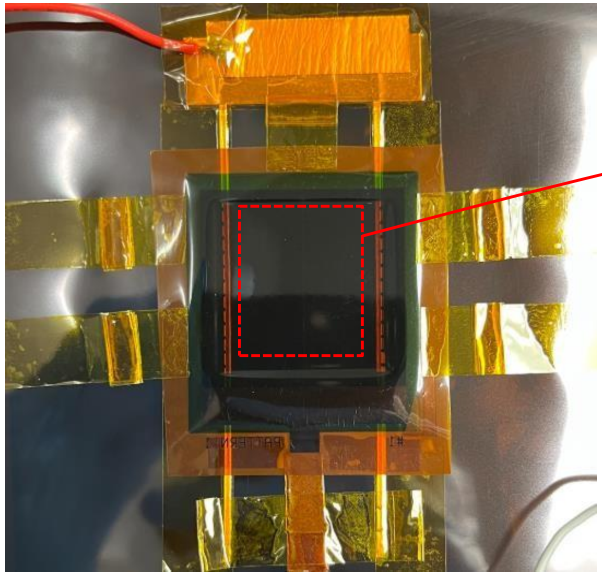


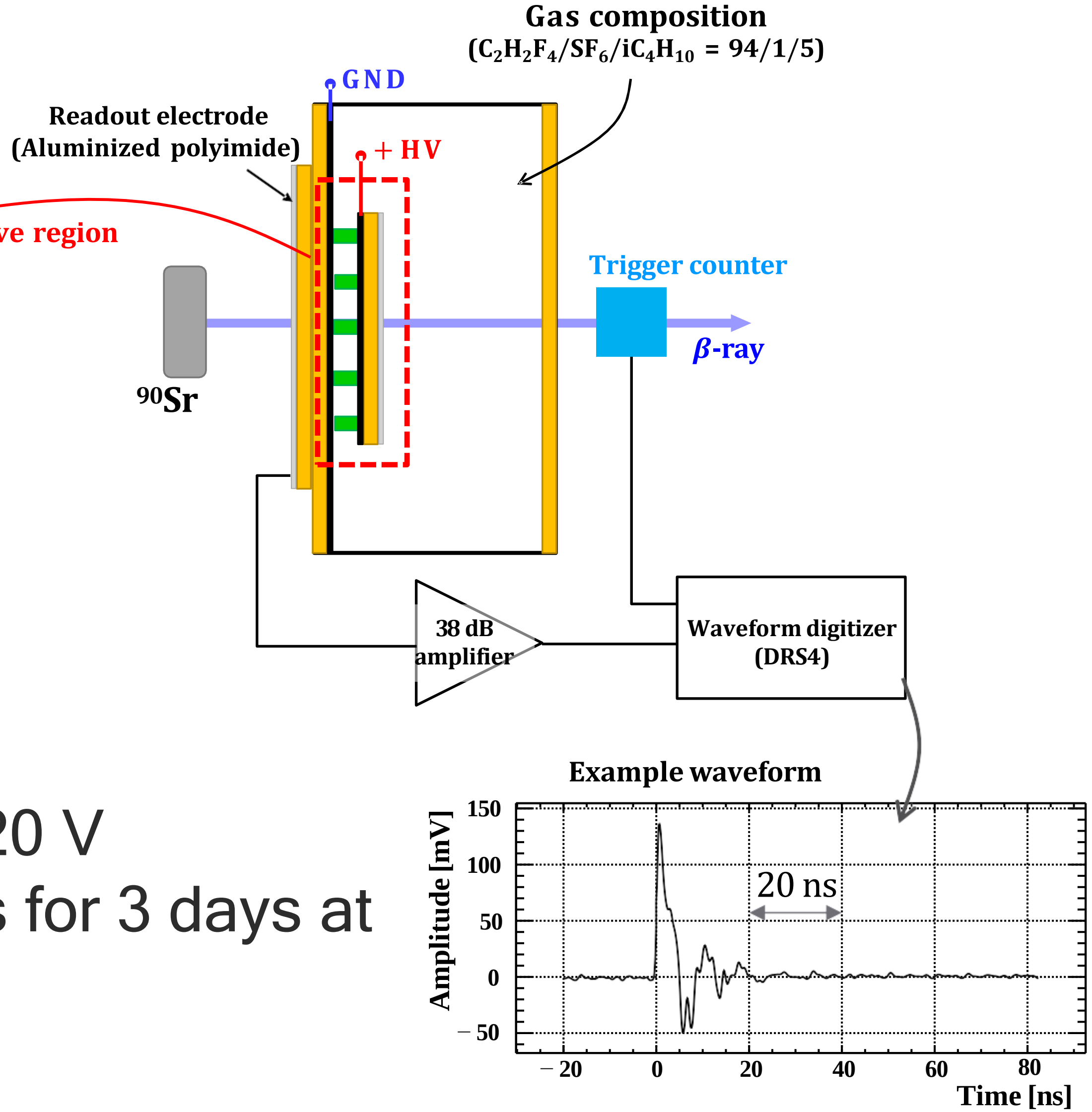
Target efficiency
(55 %)

Oya. A, Master's thesis,
The University of Tokyo, 2020

- Investigate the electric field stabilizing the operation
  - Apply several low voltages to weaken the electric field
  - $E = V/d$ =const.
  - The tested DLC-RPC gap size: 365 μm
  - Figure out the electric field and estimate the required gap size for long-term stability

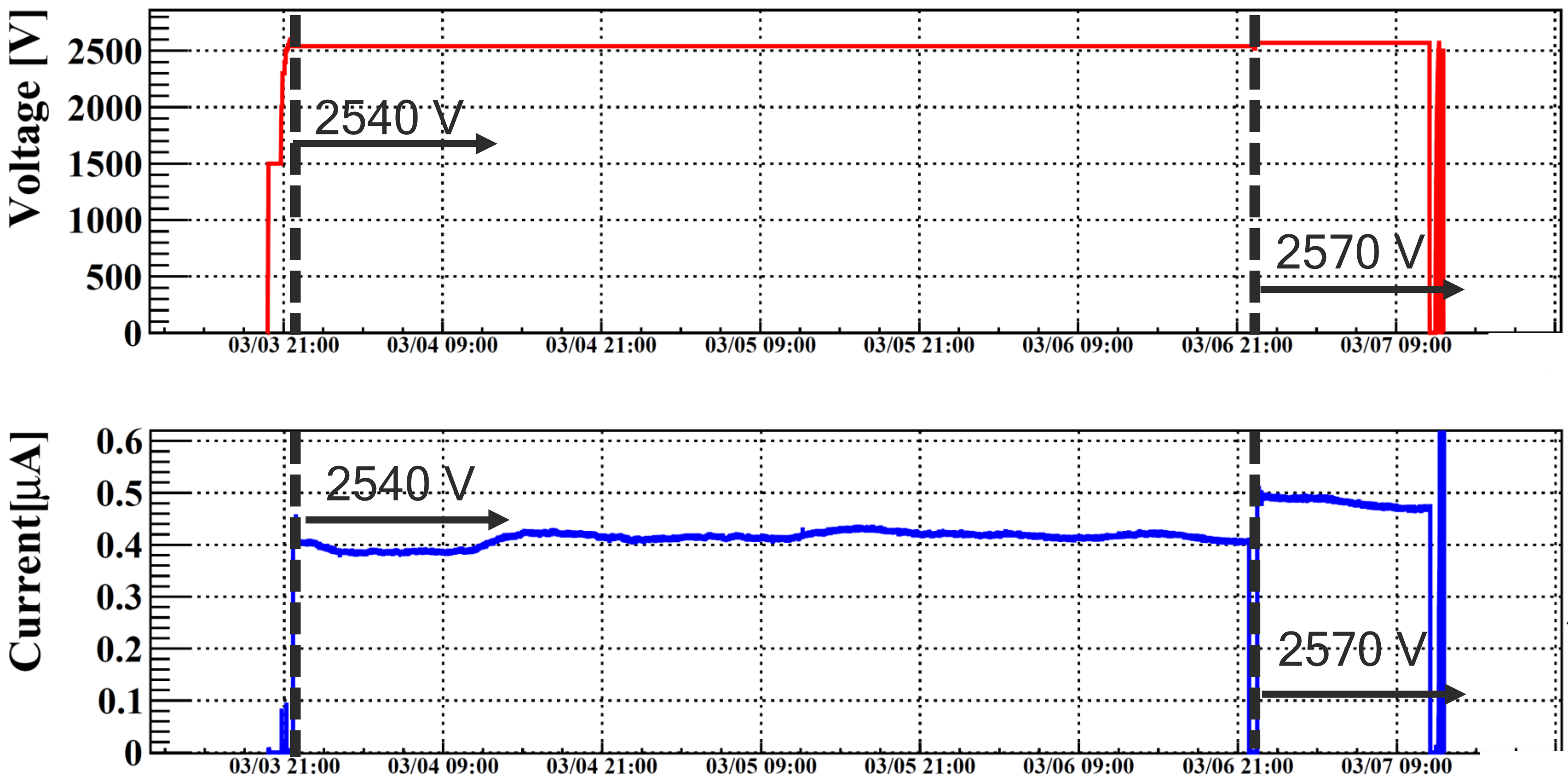
Setup





- Target voltage: 2620 V
- Tested voltage: 2540 V, 2570 V, 2620 V
- Measure whether the operation lasts for 3 days at each voltage

Result of the operation with lower voltages

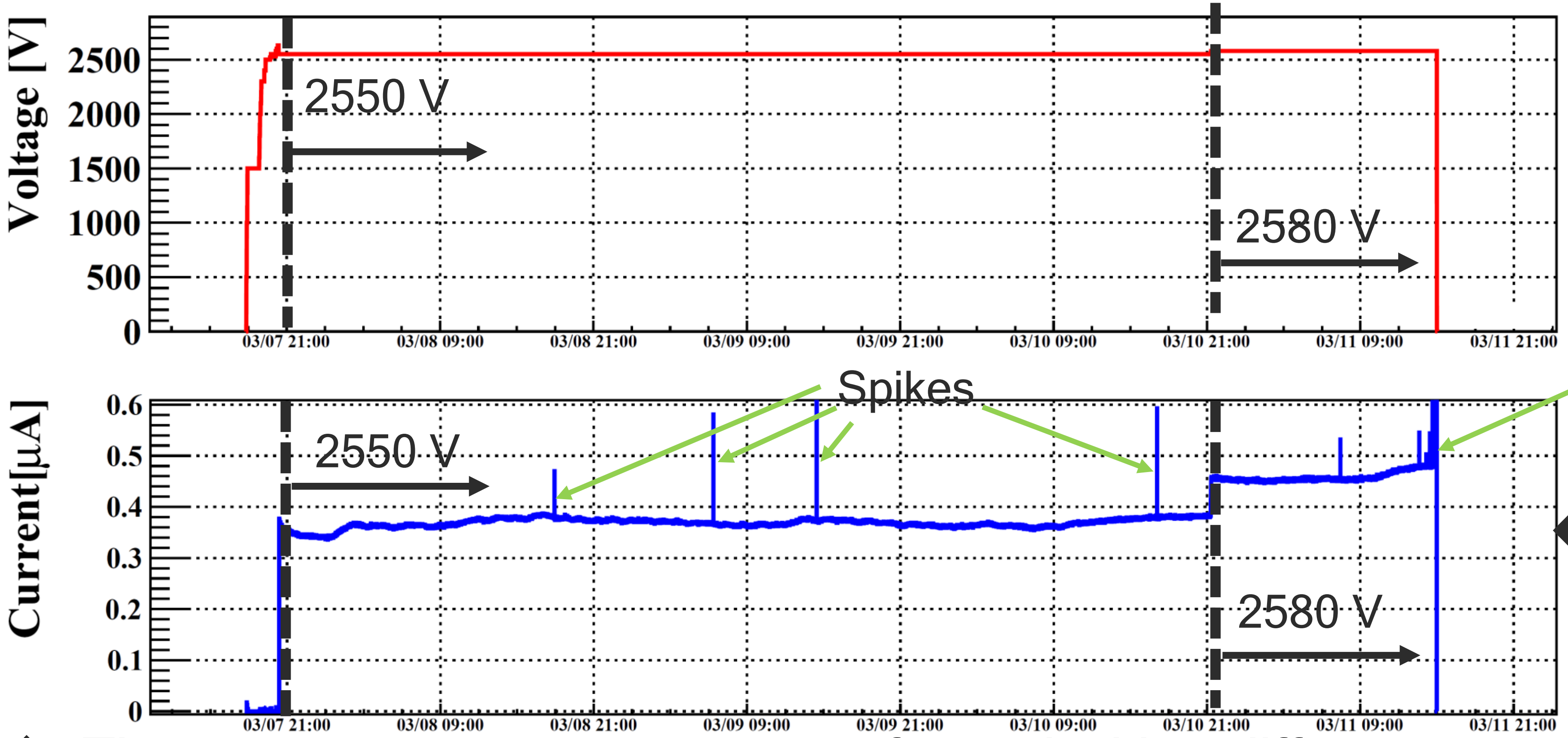


Atmospheric pressure: 1006.2 hPa
Temperature: 21.6℃
Humidity: 18 %

- Surface resistivity
  - Anode: 15 MΩ/sq.
  - Cathode: 11.4 MΩ/sq.

- The operation at 2540 V (Efficiency: 48 %) lasted for 3 days.
- The voltage of 2570 V (Efficiency 50 %) induced discharges, halting the operation.
- The current fluctuation was due to the change in the atmospheric pressure.

Reproducibility and resistivity



Atmospheric pressure: 1011.2 hPa
Temperature: 24.2 ℃
Humidity: 9 %

- Surface resistivity
  - Anode: 12 MΩ/sq.
  - Cathode: 11.4 MΩ/sq.

- The same measurement was performed with a different sample.
- The applied voltage was different due to the atmospheric pressure
- The reproducibility was good.
- Resistivity can affect stability.→Need to adjust

Measures

- ◆ Discharges leading to critical damage were not observed at 2540 V (Efficiency: 48 %).
- ◆ The voltage with efficiency of 48 % could realize stable operation, the target voltage (Efficiency: about 55%) is required though.

Electric field for long-term stability

- ◆ The electric field is calculated from the result,

$$E = V/d = 2.54\ \text{kV}/0.365\ \text{mm} = 7.0\ \text{kV/mm}.$$

- ◆ To reach 2620 V with the stable electric field, the gap size of 376 μm will be required.
- ◆ A pillar consists of 5 layers 75 μm-t resist and thickness is adjusted by adding another layer discretely.→One layer will be added to increase the gas gap.
- ◆ Originally, the size was designed to 375 μm. (Shrunk)
- ◆ The gap size will be adjusted to 450 μm to exceed 376 μm.

Summary & Prospects

Summary

- ◆ DLC-RPC requires to operate for 20 weeks in the MEG II experiment
    - Breakdowns by discharge must not happen.
- ◆ Operation with high-rate β-rays
    - Difficult to operate at high voltages, making an electric field strong.
- ◆ Investigation in terms of operating voltages and electric fields
    - ◆ A strong electric field may be excessive for stable operation.
        - Inducing large avalanches
        - Damage accumulation
    - ◆ The stable operation was realized at 2540 V.
- ◆ Measures
    - ◆ Adjust the gap size from 365 μm to 450 μm

Summary & Prospects

Prospects

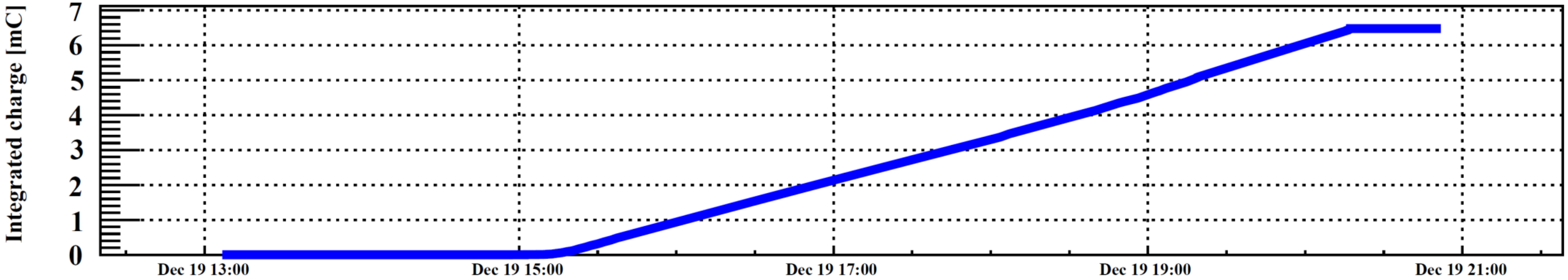
- Fabrication of the full-scale prototype module in 2025
  - Consideration of the gap size will be included.
    - Gap size: 365 μm→450 μm
  - Adjustment of parameters
    - Resistivity
      - Investigated in the range of 6 - 15 MΩ/sq., planning to increase it to about 20 MΩ/sq. to suppress discharges
- Performance evaluation with a high-intensity muon beam at PSI

Backup

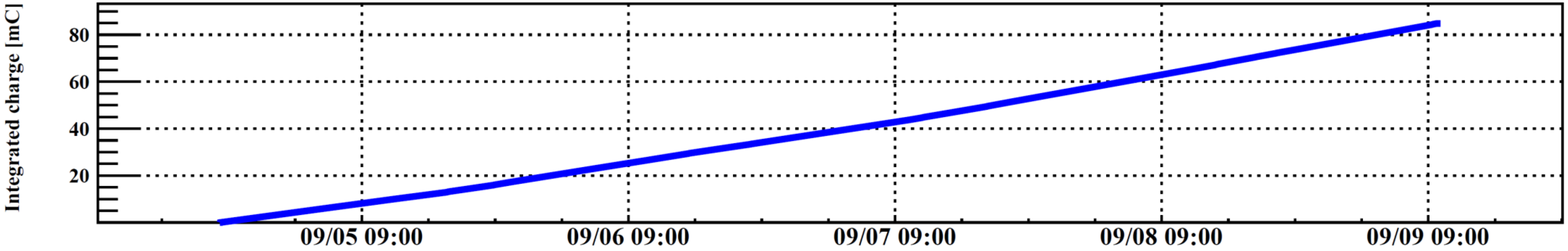
Rate dependency and charging-up

- Avalanches can cause electrons to accumulate on insulators, such as pillars and protective covers.
- As a more integrated charge was obtained with the low-rate β-rays compared to the high-rate ones, no dependence of the charge.
- Charging-up is eliminated from the possible scenario.

High rate
(1 - 10 MHz/cm^2)



Low rate
(∼100 kHz/cm^2)



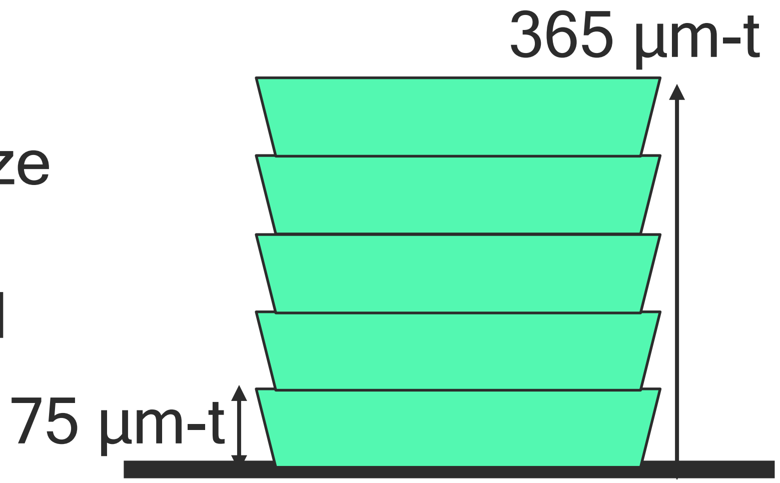
Measures

- Discharges leading to critical damage were not observed at 2540 V (Efficiency: 48 %).
- The voltage with efficiency of 48 % could realize stable operation, the target voltage (Efficiency: about 55%) is required though.

Electric field for long-term stability

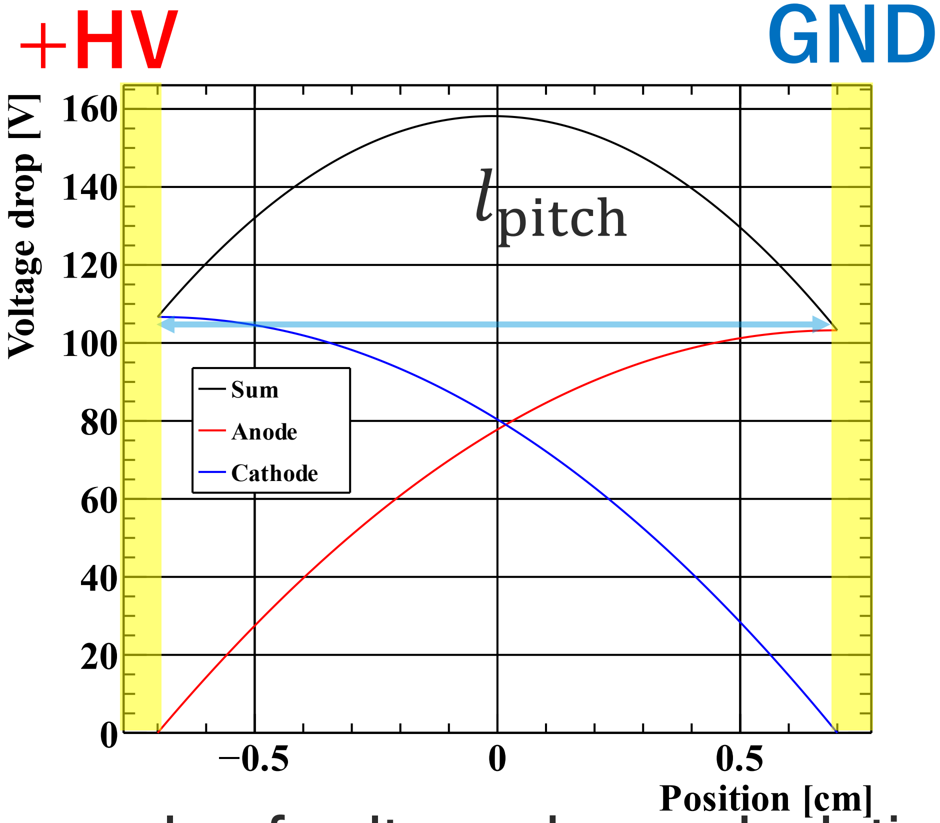
- The electric field is calculated from the result,

  $E = V/d =$2.54 kV/0.365 mm = 7.0 kV/mm.
- To reach 2620 V with the stable electric field, the gap size of 376 μm will be required.
- To realize stable operation, the gap size will be adjusted from 365 μm to 376 μm.
- Because a pillar consists of 5 layers 75 μm-t resist

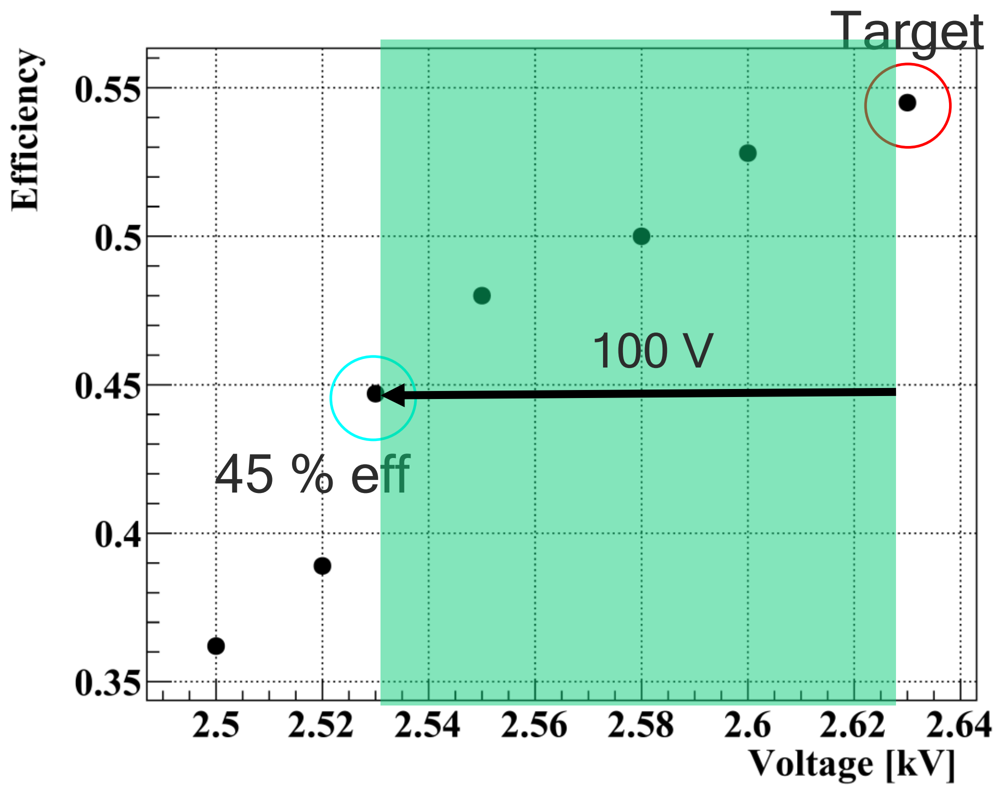


Side view of a pillar

Determination of operating voltage



An example of voltage drop calculation



- Voltage drop is calculated with the pitch of conductors and resistivities.
- Target voltage: voltage with 45 % efficiency
  + the voltage drop = 2600 V - 2630 V.

Current status

Requirements	Goal	Current status	✔ or ×
Material budget	< 0.1 % X_0	∼0.095 %X_0 (4 layers)	✔
Rate Capability	3 MHz/cm^2	1 MHz/cm^2	×
Radiation hardness	∼100 C/cm^2 in 20 weeks operation	∼54 C/ cm^2	×
Detection efficiency	> 90 %	85 % (4 layers)	(✔)
Timing resolution	<1 ns	160 ps	✔
Detector size	16 cm Φ	3 cm × 3cm	×

Long-term operation

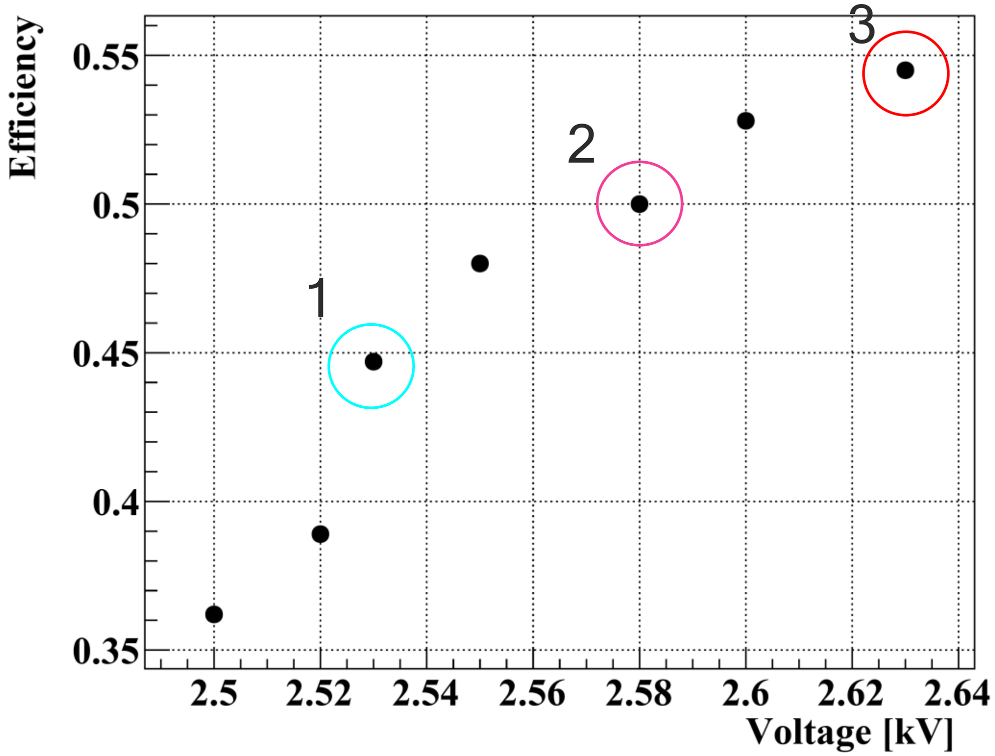
◆Motivation

- A strong electric field induces large avalanches inducing breakdowns
  - Assess how strong E-field does not induce those
  - Apply several voltages under the target one.
  - Determine the criterion for long-term stability

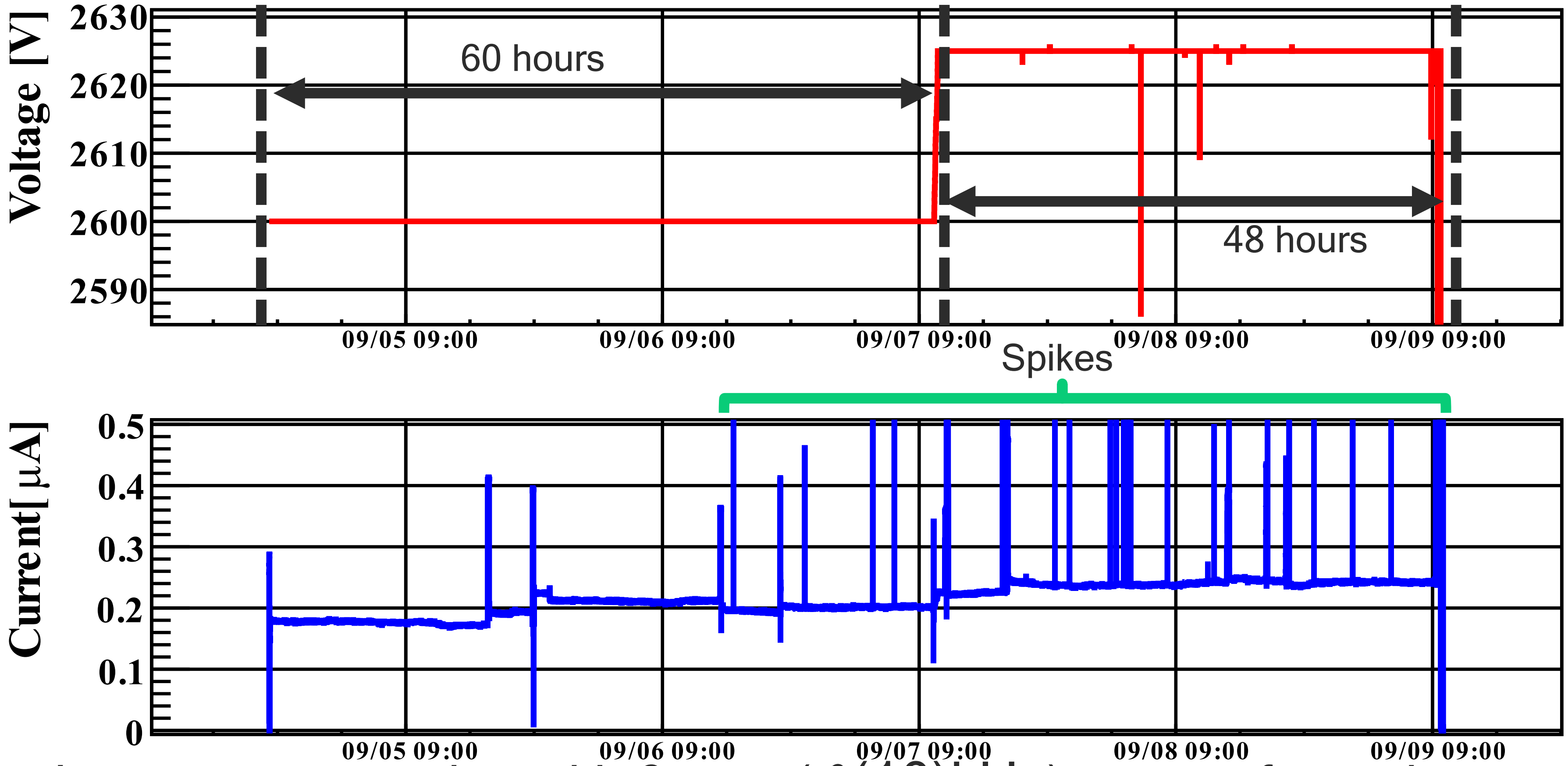
◆Procedure

- Apply voltages in three steps
  1. A voltage with efficiency of 45 %
  2. A middle voltage with efficiency of 50 %
  3. The target voltage with efficiency of 55 %
- Measure whether the operation lasts for 3 days at each voltage

Detection efficiency vs applied voltage



Previous long-term operation test

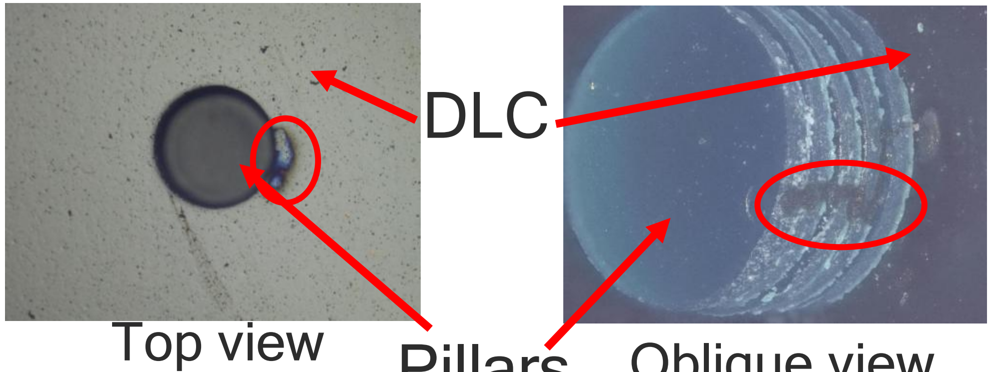


JPS meeting in fall, 2024 (18aWA203-7)

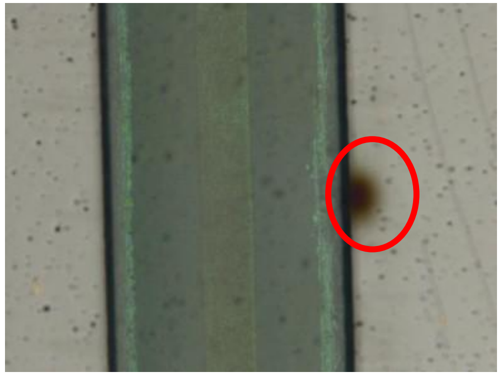
- Long-term operation with β-rays ($\mathcal{O}(10)$kHz) was performed.
- Discharges ended up happening, and the operation was terminated.
- The causes were not explained clearly.

Possible scenarios

Where discharges happen



Top view   Oblique view



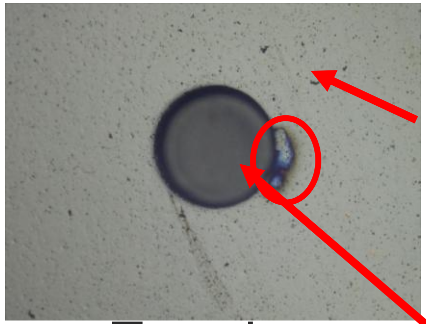
Protective covers

Possibilities

- **Accumulated damage**
  - Discharges can occur when a certain amount of damage is stored.
- **High-intensity radiation**
  - Such radiation induces large gas amplification potentially leading to fatal damage.
- **Unstable structure**
  - Positions where discharges happen easily
- **High operating voltage**
  - A strong electric field also strengthens avalanche and causes breakdowns.

Possible scenarios of discharges

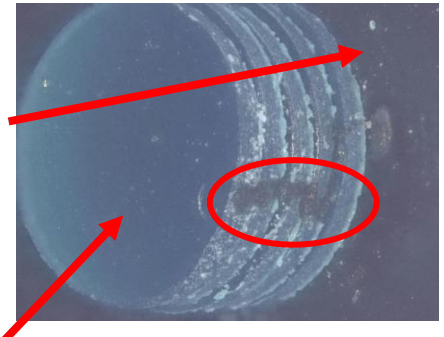
Where discharges happen



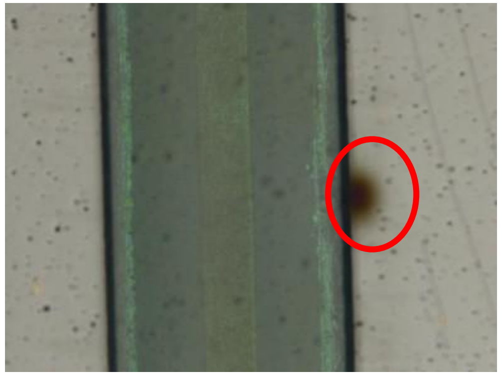
Top view

DLC

Pillars



Oblique view



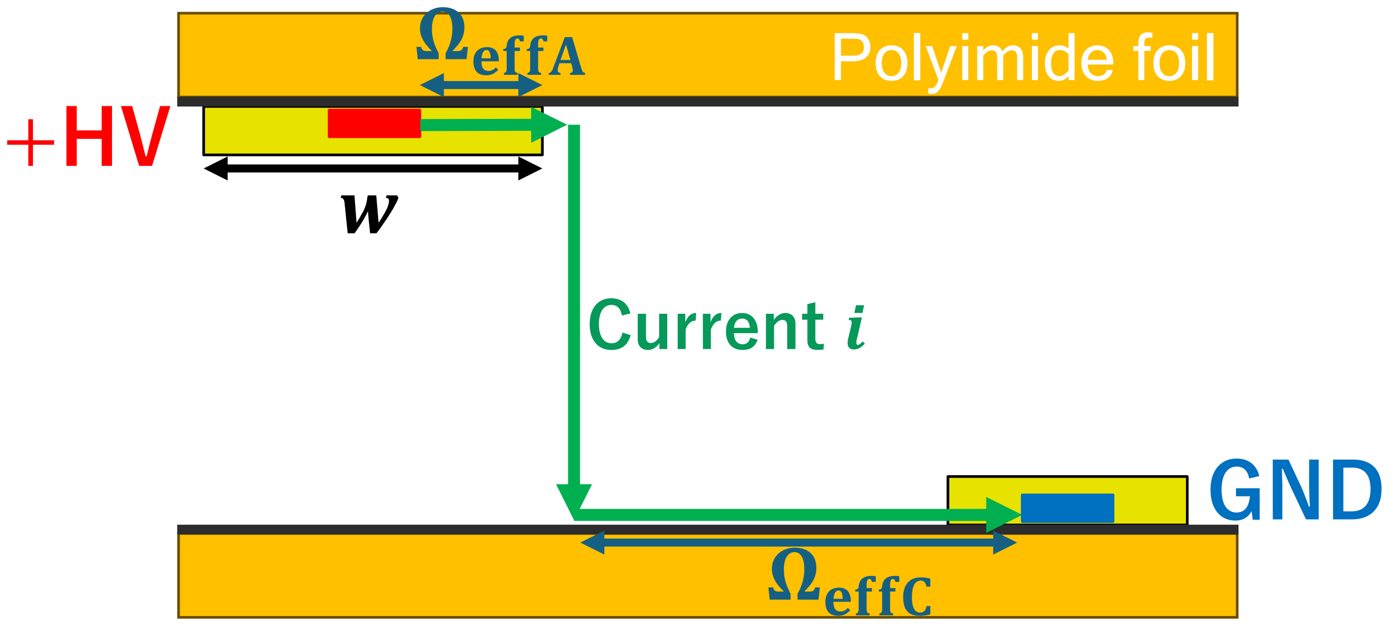
Protective covers

Possibilities

- Discharges
  - Damage accumulation
    - Large avalanche energy → Burns polymers of insulators (pillars and covers)
      - High operating voltage → Focused!
      - Low resistivity
  - Charging-up

◆Motivation

- A strong electric field induces large avalanches inducing breakdowns
  - Assess how strong E-field does not induce those
  - Apply several voltages under the target one.
  - Determine the criterion for long-term stability



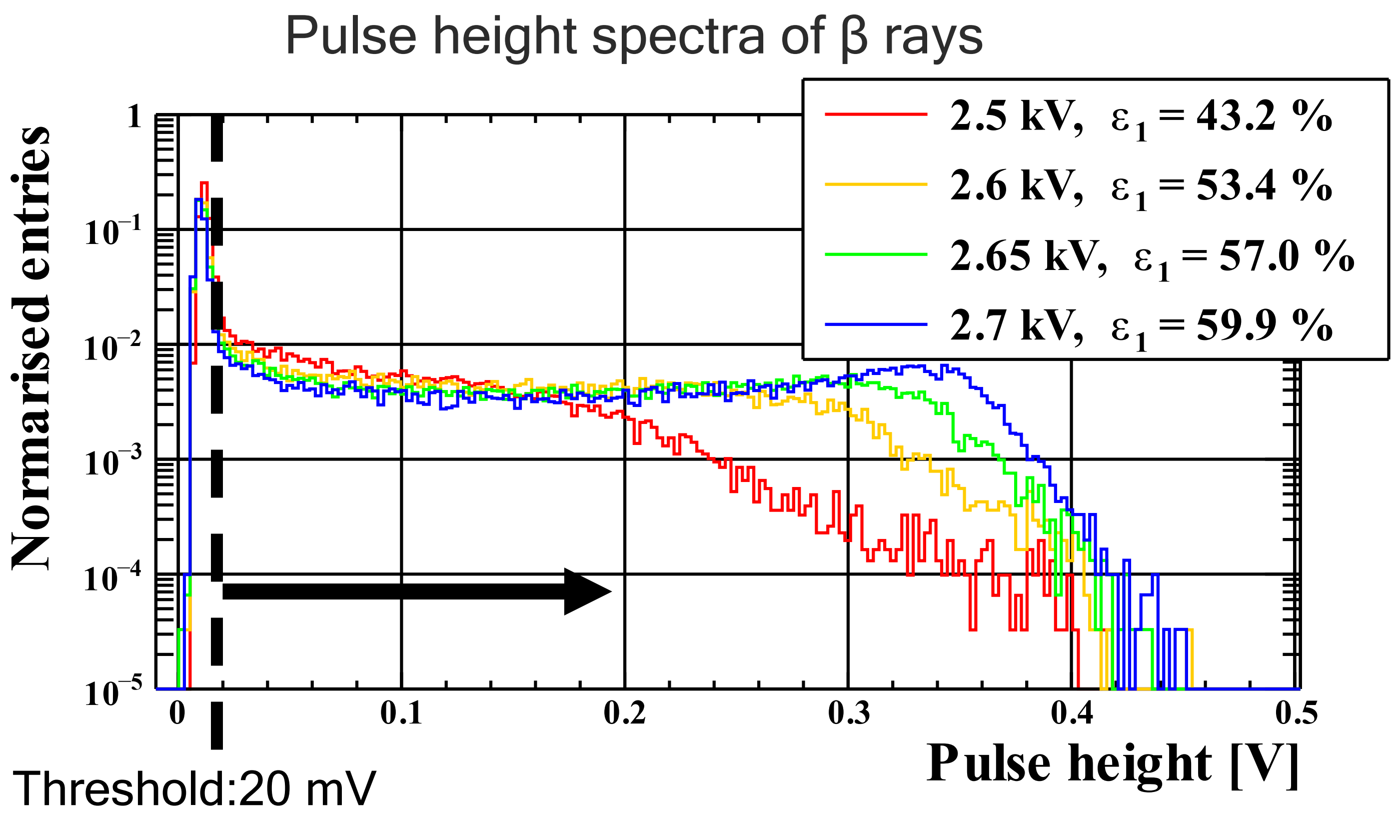
$$\Omega_{effA} = \rho_{sA} \cdot \frac{w - 0.1}{2 \cdot k}$$

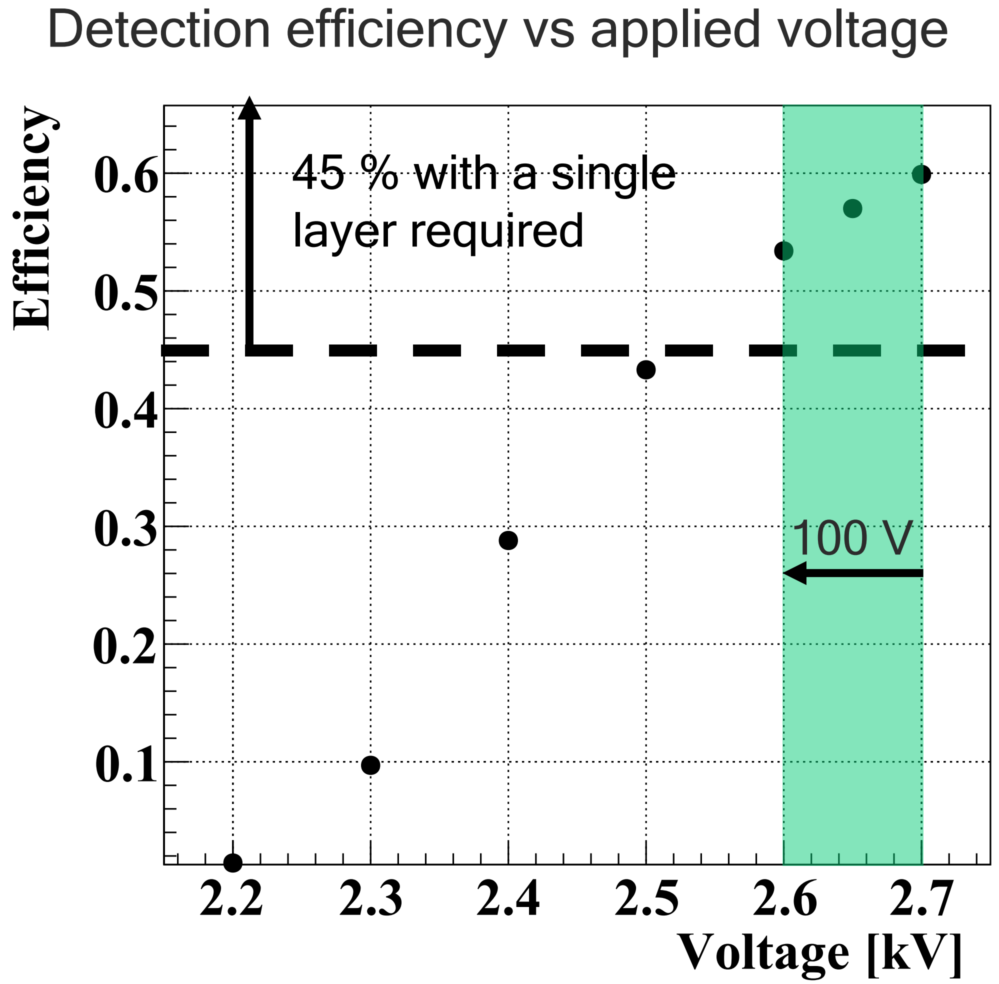
ρ_s is the surface resistivity.
k: length of the strip.

Quenching large current and protecting HV supply by the cover

- A protection cover is mounted over the conductive strip
- The wider the cover becomes, the more it suppresses the current.
- Determining the cover width w

Performance

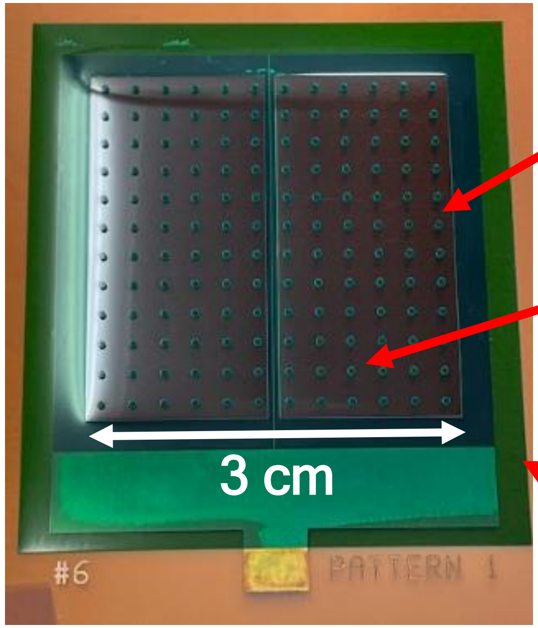




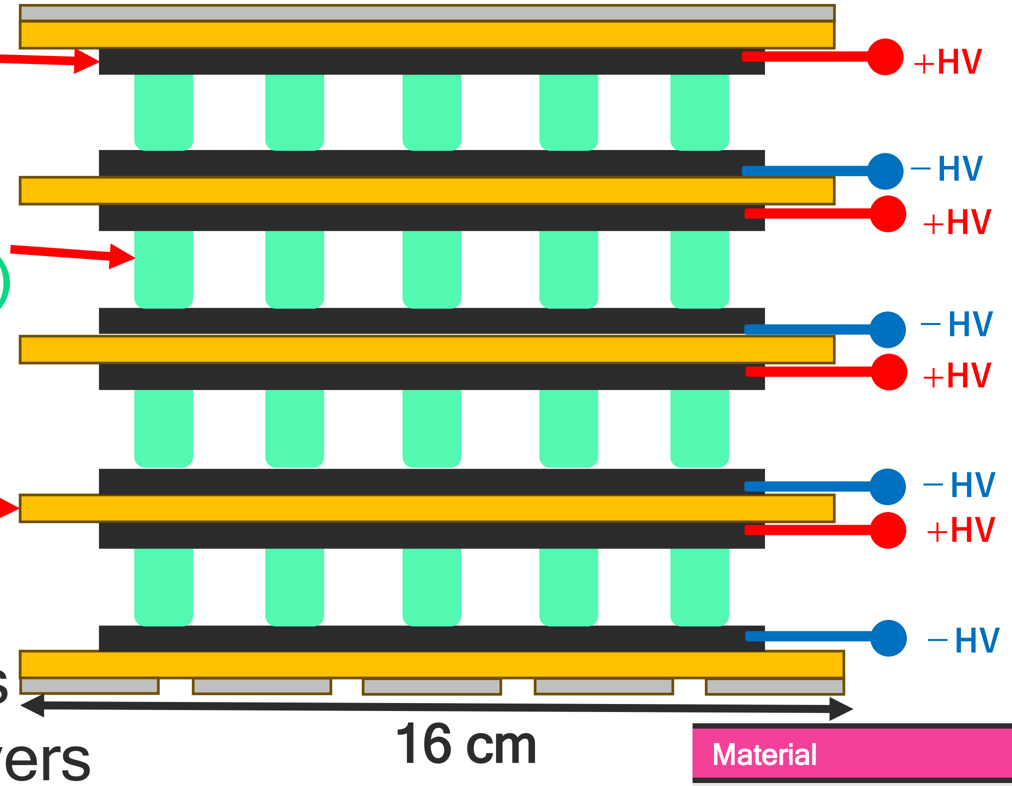
- Target voltage: voltage with 45 % efficiency + the expected voltage drop = 2600 V - 2630 V depending on the atmospheric pressure

The structure

An electrode on a small prototype in 2024



The structure of DLC-RPC for MEG II
(4-layer DLC-RPC)

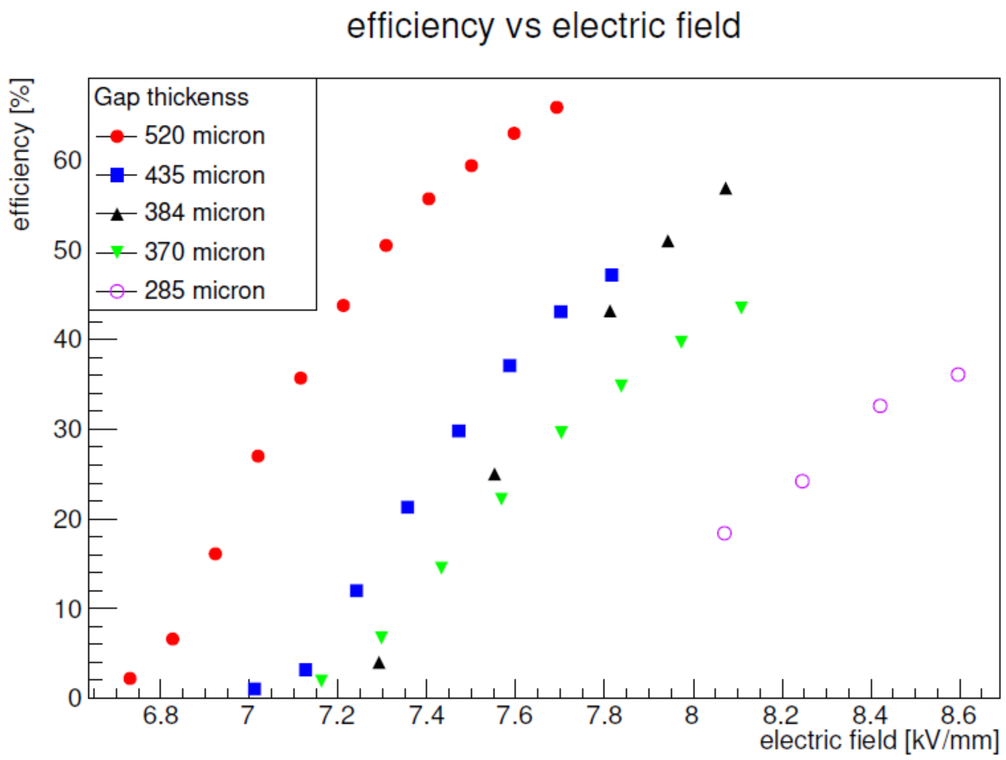


Material	Material budget
50 μm-t polyimide foil	0.0175 $\%X_0$
30 μm-t aluminum strip	0.0034 $\%X_0$
2mm-t Gas	0.001 $\% X_0$

- Pillars to sustain gaps between electrodes
- Higher detection efficiency by stacking layers
  (Detection efficiency of n-layers: $\epsilon_n = 1 - (1 - \epsilon_1)^n$)
- More than 45 % detection efficiency with a single layer is required.
  →90 % efficiency with 4 layers

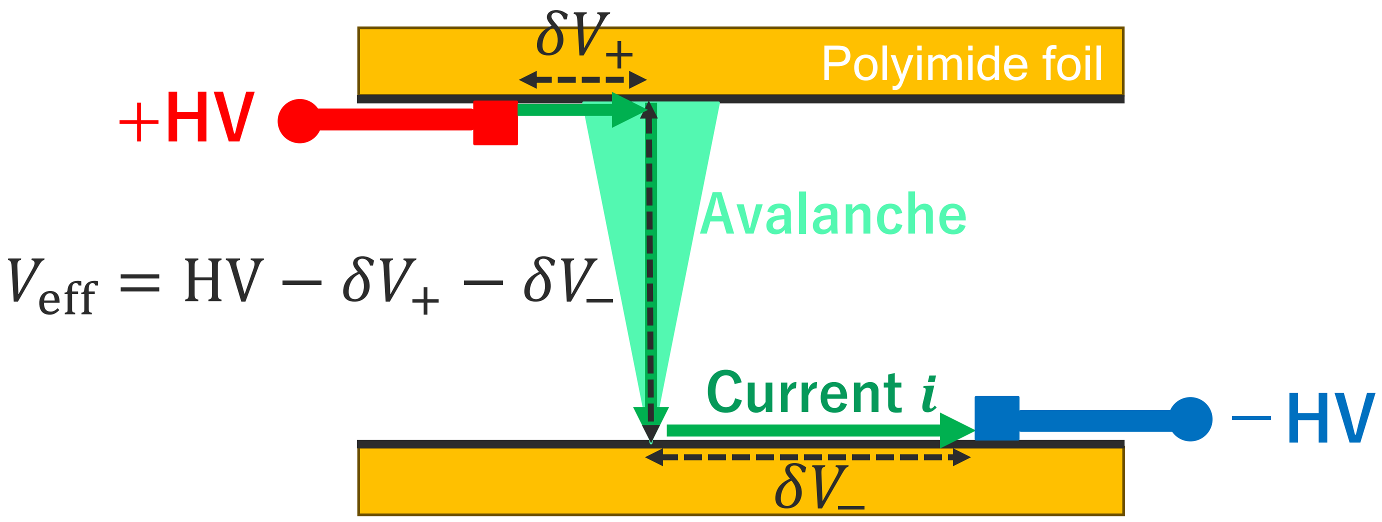
Measures

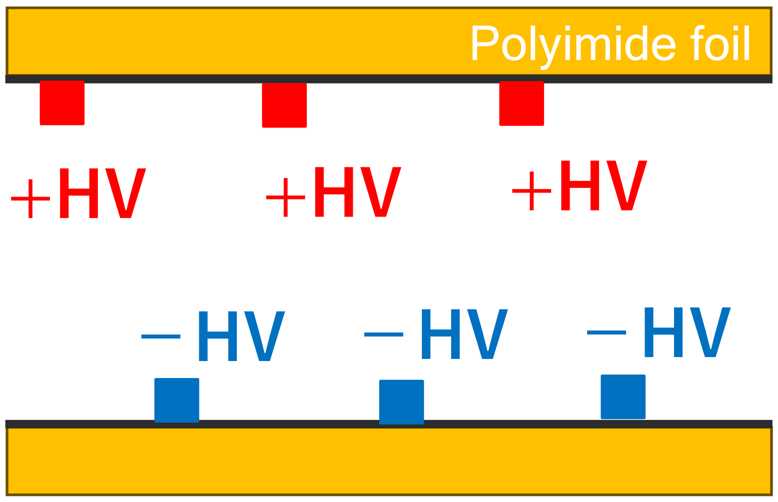
- An electric field was so strong that discharges could cause breakdowns.
- Long-term stability can be realized with weak E-fields
- To weaken the electric field, enlarge the gas gap
- Balancing weak electric fields and efficiencies
- The gap size of the tested DLC-RPC: 365 µm
- The electric field at 2540 V: 7.1 kV/mm
- The gap size needs to be more than 500 µm.



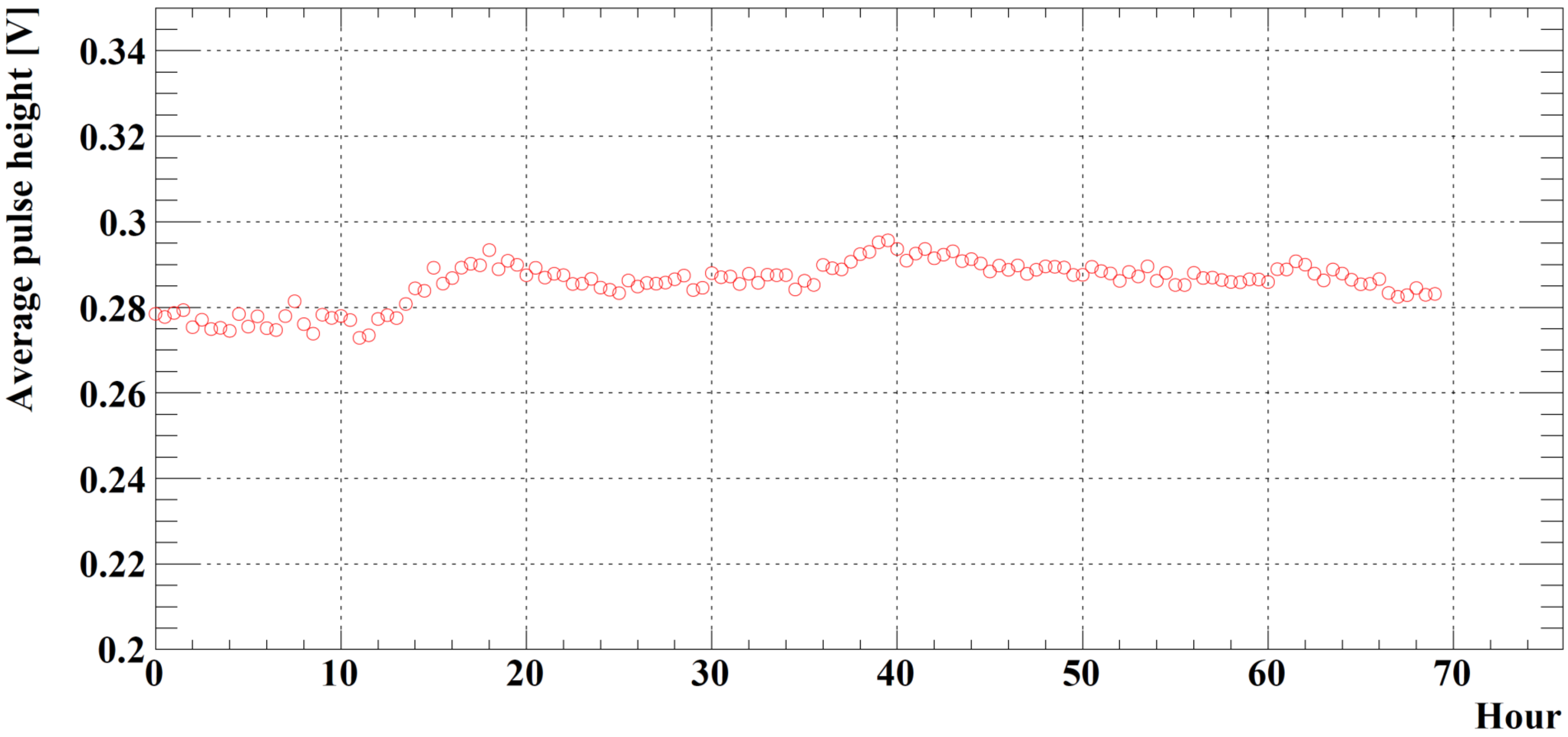
Oya. A, Master's thesis,
The University of Tokyo, 2020

Rata capability & scalability





- Avalanches from muon beam→Current→Voltage drop δV by flowing current
- Voltage drop δV reduces the applied V →Gas gain reduction⟵Need to suppress
- Segmented HV supplies to suppress voltage drops at a small pitch
  - δV depending on the distance and the rate
  - Enlargement of the detector
  - Aiming δV ~100 V in a high-rate muon beam→Higher voltage should be applied.



Average pulse height [V]
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0
10
20
30
40
50
60
70
Hour

Determination of the operating voltage as a compromise

- Discharges leading to critical damage were not observed at 2540 V.
- 2540 V (Target voltage - 80 V) could realize stable operation.
- Discharges happened on the protection cover, as shown below after the operation at 2570 V (Target voltage - 100 V).
- It implies that large avalanches occurred at a weak point.

Discharge marks

Anode

Cathode