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

鈴木 大夢(神戸大理)

神戸大理, 東大素セ[A], 東大理[B]

大谷 航[A], 大矢 淳史[A],越智 敦彦,高橋 真斗

潘 晟[A] 山本 健介[B] 李 維遠[B], 他MEG IIコラボレーション

2024年9月18日

日本物理学会第79回年次大会

Table of contents

Introduction

DLC-RPC in the MEG II experiment

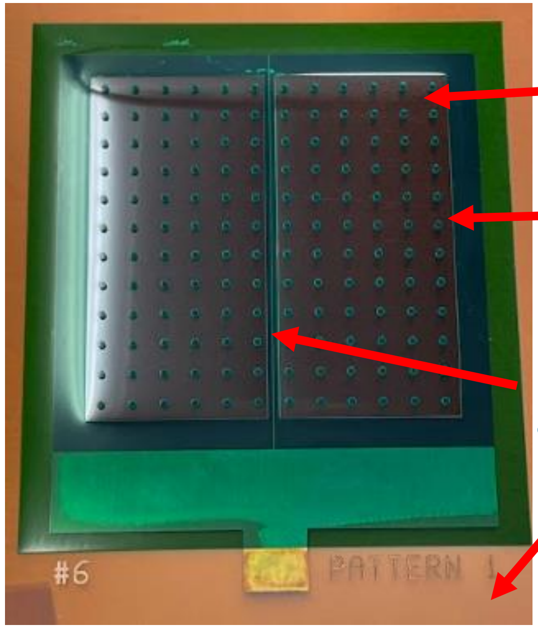
DLC-RPC:Resistive Plate Chamber with Diamond-Like Carbon electrodes

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

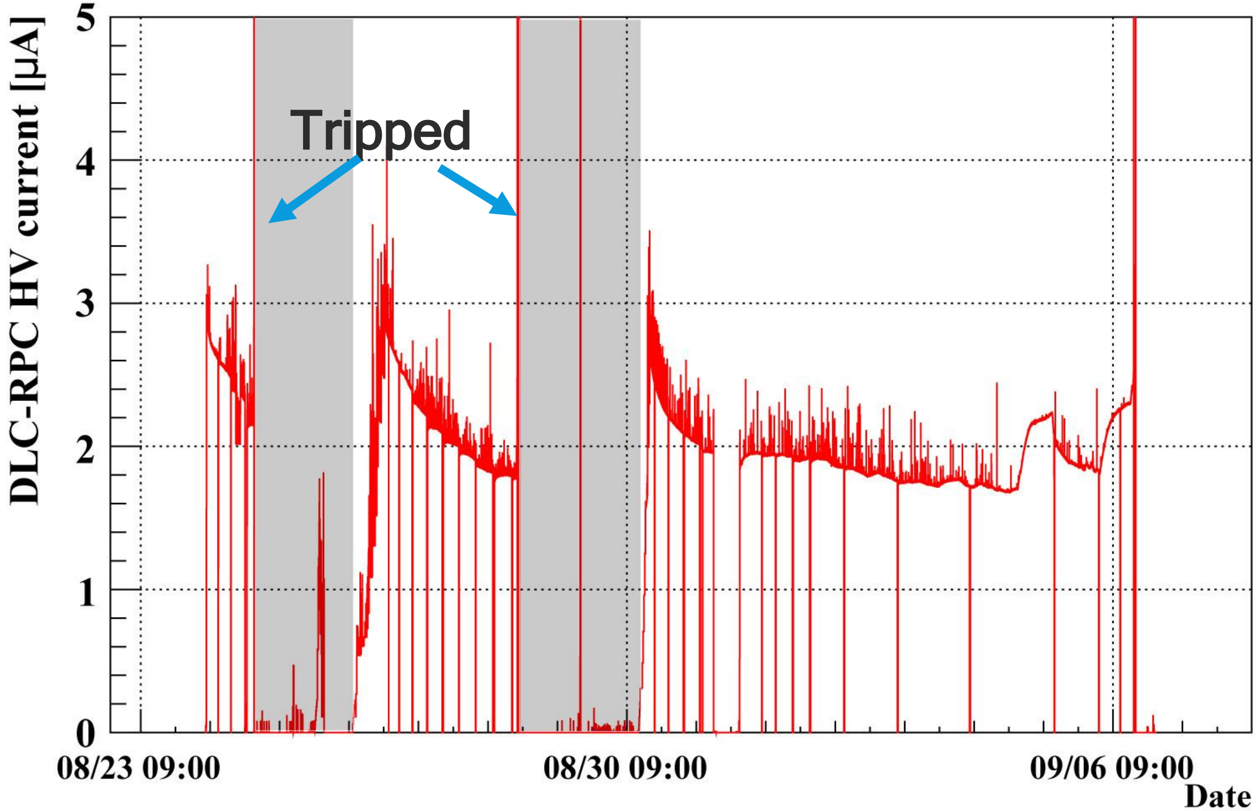
Requirements for the DLC-RPC

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



Discharges in the past tests

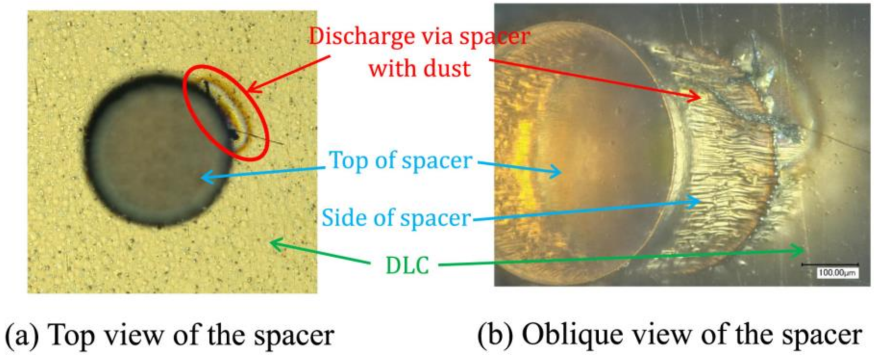


M. Takahashi, et al., Nucl. Instrum.Methods A,1066 (2024),169509

- ◆Irradiation tests with muons or X-rays have done to evaluate the rate capability and aging.
- ◆Discharges on the DLC-RPC have prevented the operation.

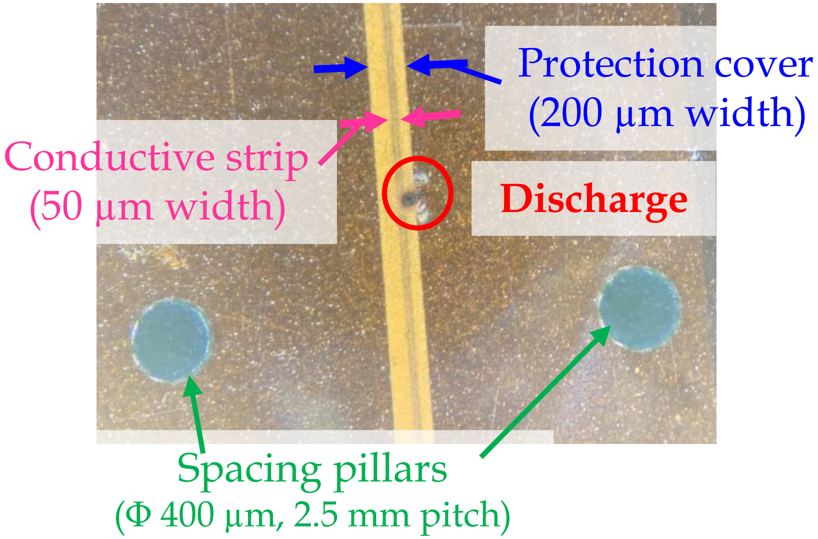
What induces discharges

Where discharges happen

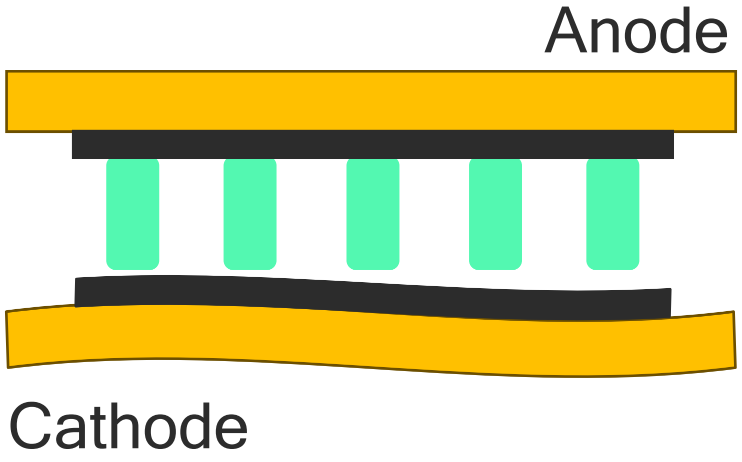


(a) Top view of the spacer (b) Oblique view of the spacer

Pillars



Protection covers



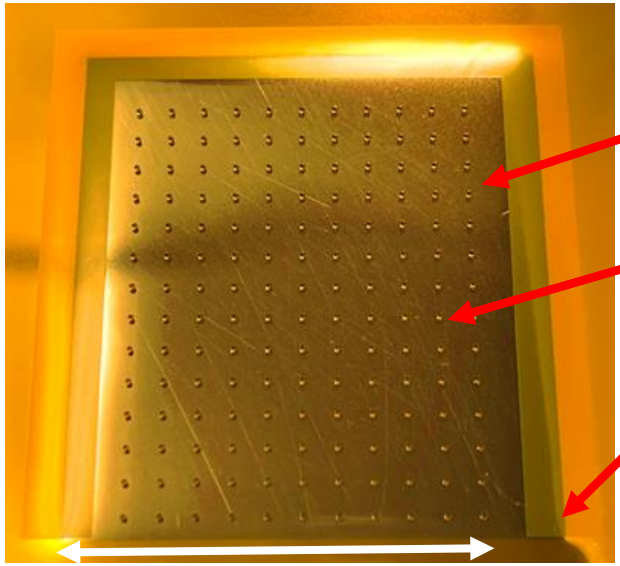
Flatness issues

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

Electrode type change

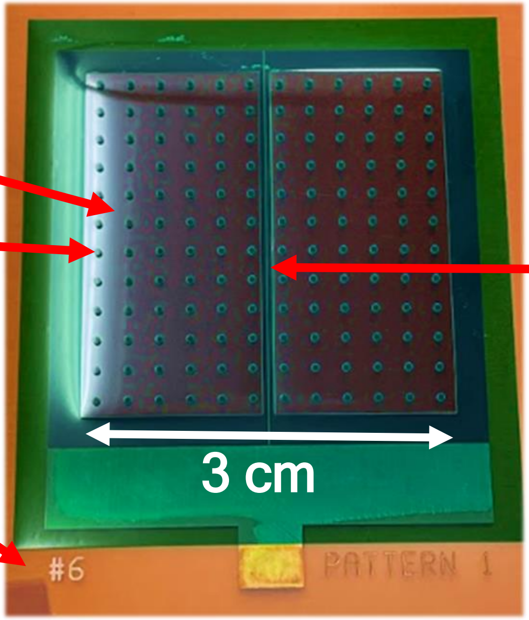
Sample used in the past tests



3 cm

Surface resistivity: 40 MΩ/sq.

New sample



3 cm

Surface resistivity: 6 MΩ/sq.

DLC

Pillar
(2.5 mm pitch)

Polyimide foil

Conductive strip
+Protection cover

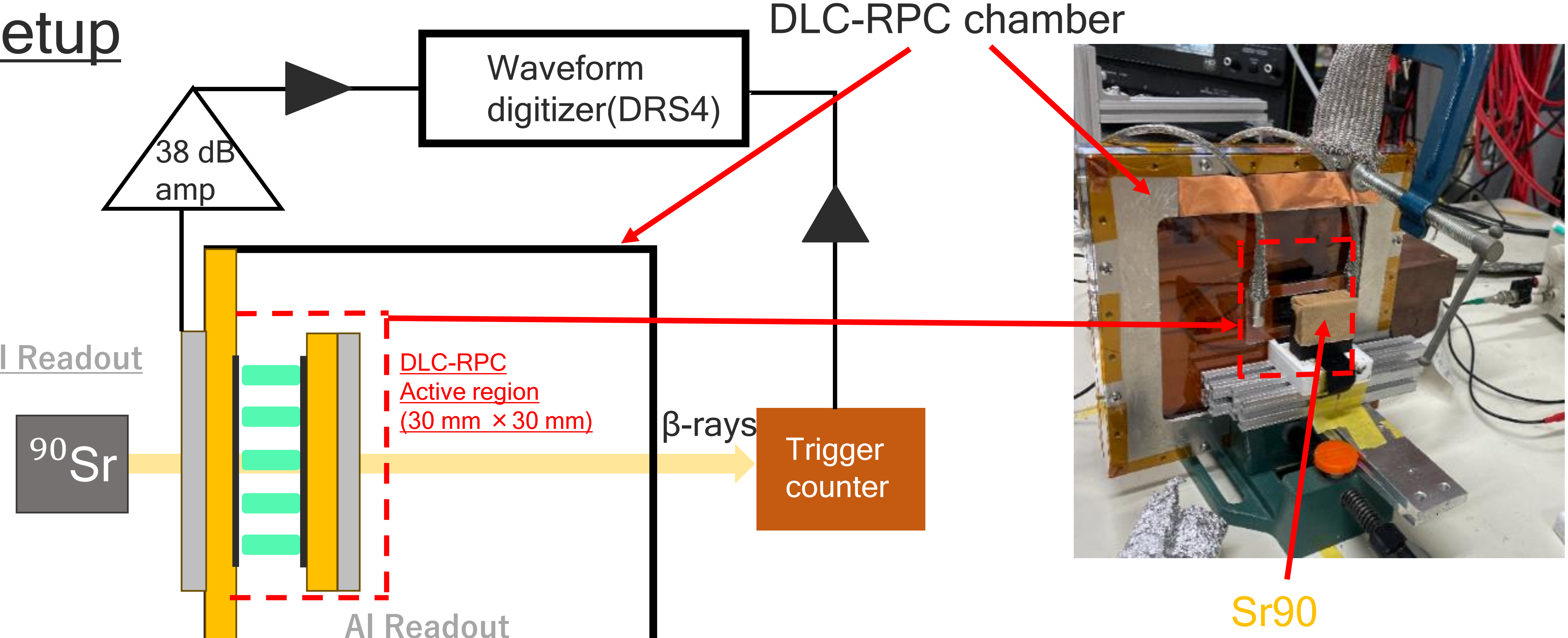
Changes

- Material of the pillars
- Conductive strips

Examine the operation with this sample under irradiation

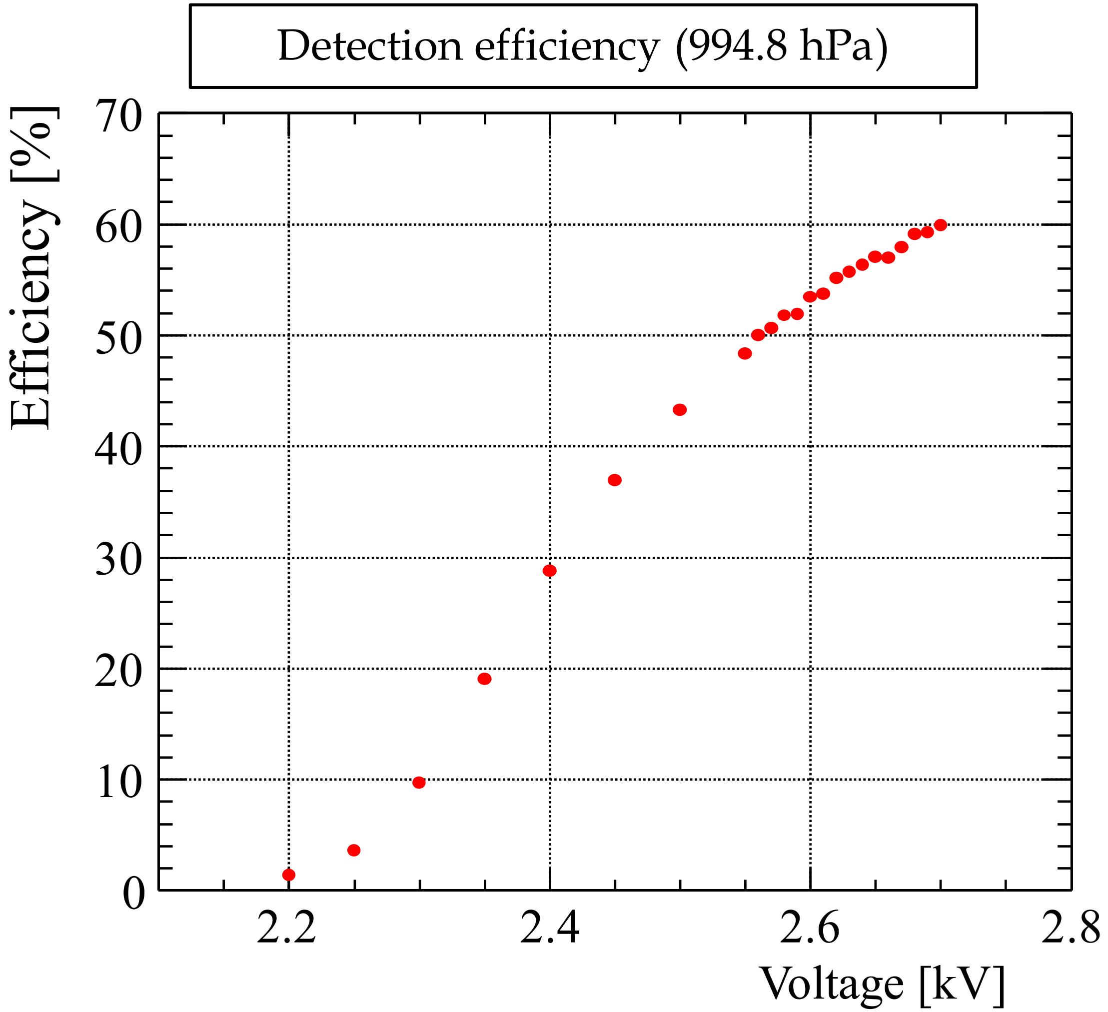
Long-term operation

Setup



Gas: $C_2H_2F_4$(R134a)/SF_6/ i-C_4H_{10}= (94/1/5)%

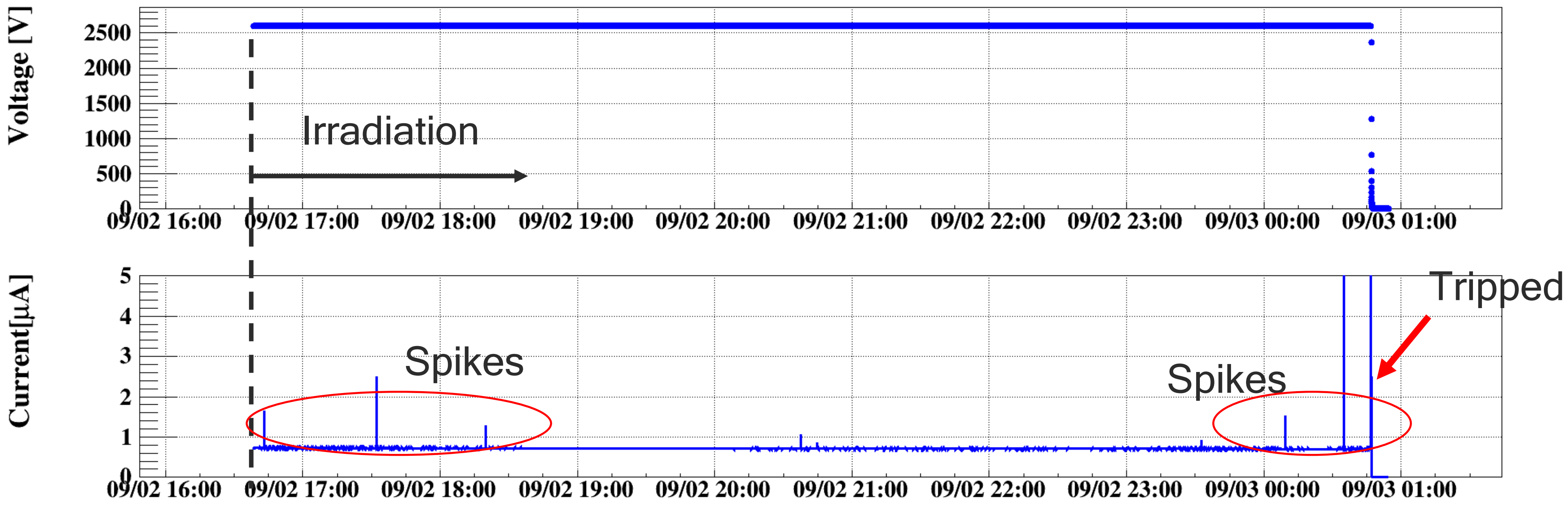
Procedure



- Minimum Operating Voltage: 2600 V
  Based on the previous discussion regarding its sufficient detection efficiency and the gain.
- Two β-ray rates
  - High rate: $\mathcal{O}(100)$kHz
  - Low rate: $\mathcal{O}(10)$kHz

Long-term operation

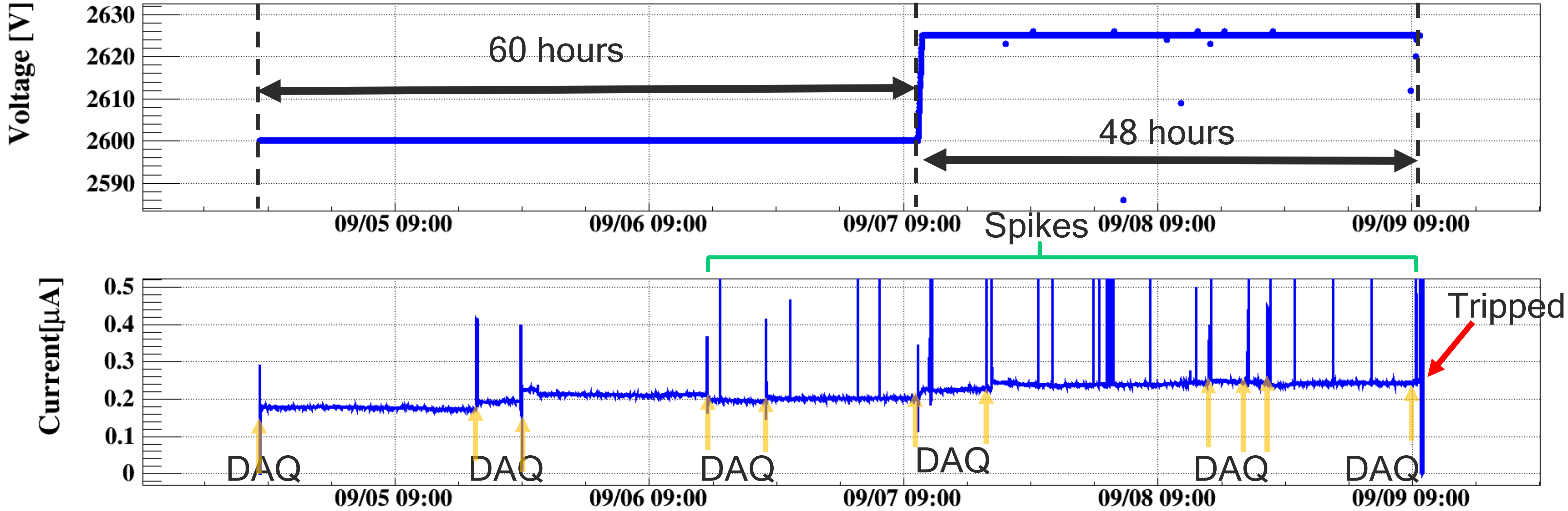
Result of a test with β-rays ($\mathcal{O}$(100)kHz)



- The operation lasted for 8 hours.
- The detector could operate for no more than 4 - 8 hours under this condition.
- Spikes started occurring and large ones terminated the operation.

Long-term operation

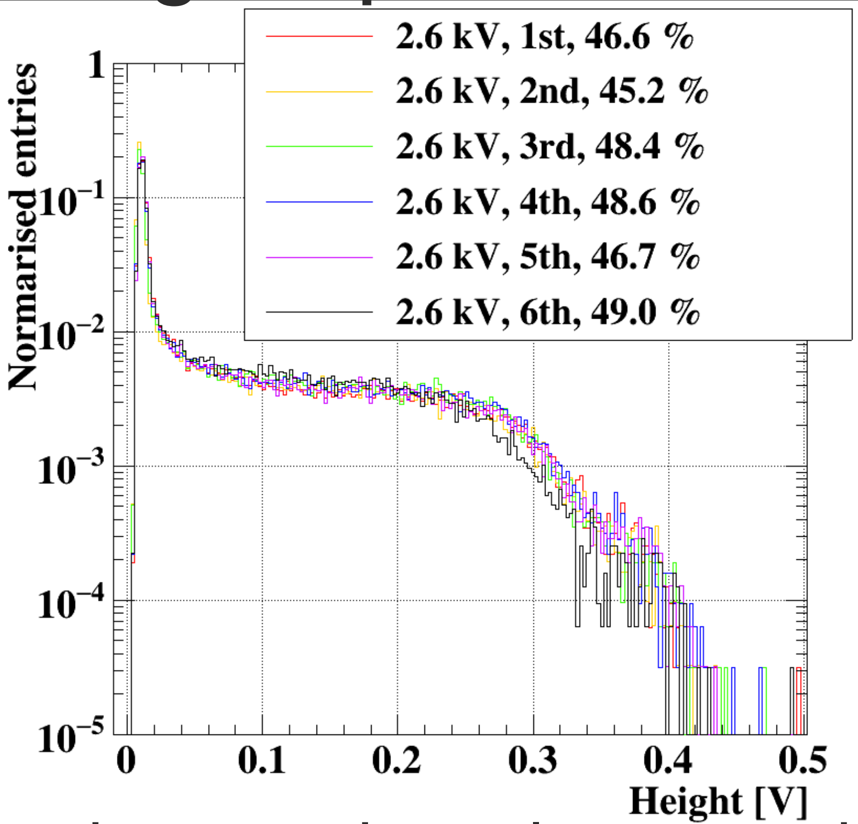
Result of a test with β-rays ($\mathcal{O}$(10)kHz)

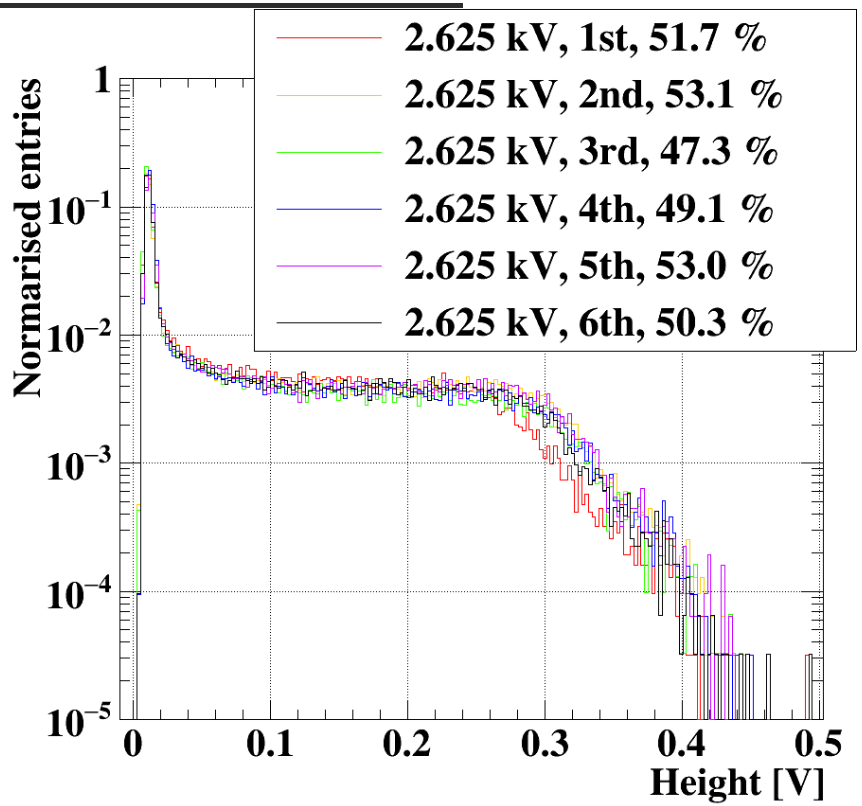


- Spikes began during the second half of the period of 2600 V.
- Frequent spikes at 2625 V→Less stable than 2600 V
- Current fluctuation was due to variations of the atmospheric conditions and imprecise positioning of the RI.

Long-term operation

Pulse-height spectra at 2600 V and 2625 V

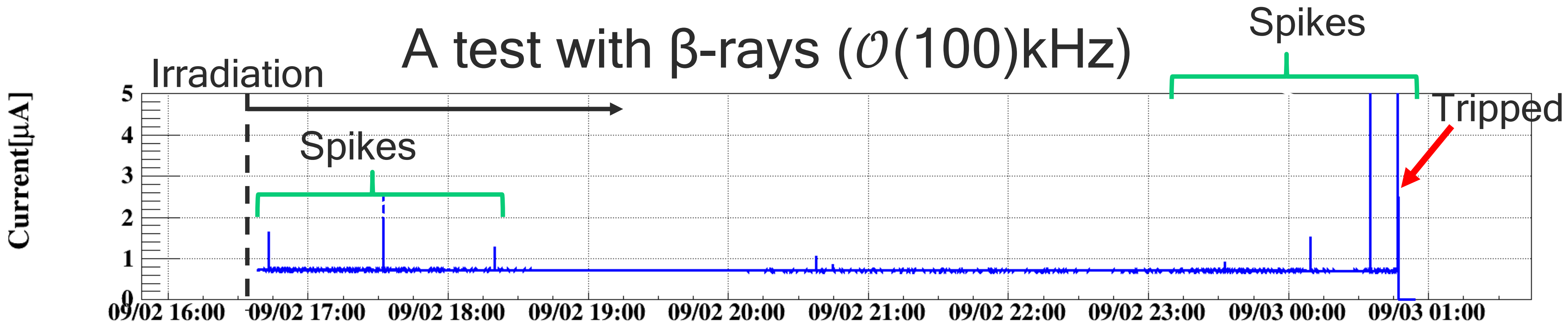




- DAQ at the operation voltage was done six times during the long-term operation.
- No change of the pulse-height spectra during each periods
  →Consistent performance at each voltage in terms of the detection

Long-term operation

Comparison with the high-rate radiation



- The lower intensity is, the longer the operation gets.
- High-intensity radiation causes large discharges which terminate the operation earlier.

➡ Not tolerant to high-intensity ones and the resistivity is too low?

➡ Higher resistivity electrodes and lowering operating voltage are needed.

Summary & Prospects

Summary

◆DLC-RPC requires 20 weeks operation in the MEG II experiment

- Discharges stop the operation and cause damages to the detector.

◆Long-term operation

- Tests with new electrodes was done to investigate the discharges.
- The operation is hindered easily with the high-rate radiation.
- Obtained pulse-height spectra showed that the long-term operation did not influence on the performance at 2600 V and 2625 V
- However, discharges ended up occurring at a certain point in the period even with the low-rate one.

Summary & Prospects

Prospects

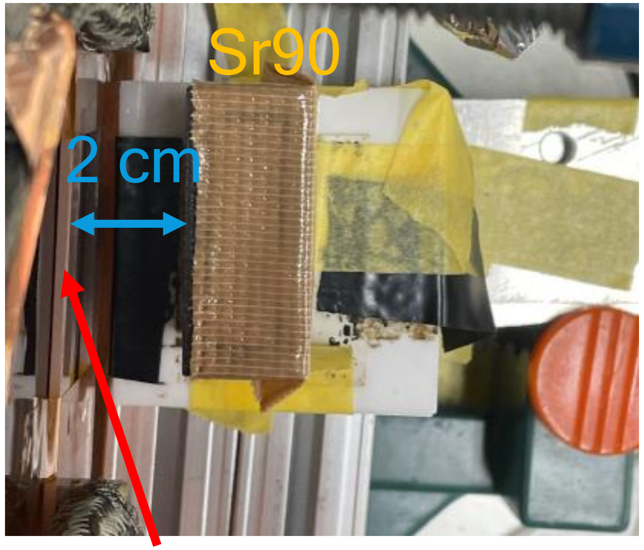
- ◆Investigating the weak point of the structure for a high-intensity radiation
  - Around the pillars
  - Conductive strips
  - Resistivity
- ◆Survey for the proper operation for the long-term stability
  - Operating voltage
- ◆Fabricating the next module to test the performance in a high-intensity muon beam
  - Designing
  - Operation
    - Satisfy 90 % detection efficiency for MIP, the rate capability of 3 MHz/cm^2, and the radiation hardness of 100 C in 20 weeks operation.

Backup

Long-term operation

Procedure

- Condition the detector
  - Raising the voltage gradually
  - Irradiation at lower voltages
- Place a Sr90 2 cm from the detector
  - Accumulate integrated charge as much as in the past tests
  - Examine the influence by lowering the intensity
- Begin long-term irradiation at the operation voltage
- Put Sr90 is put 0 cm from the detector to do DAQ in 10 minutes

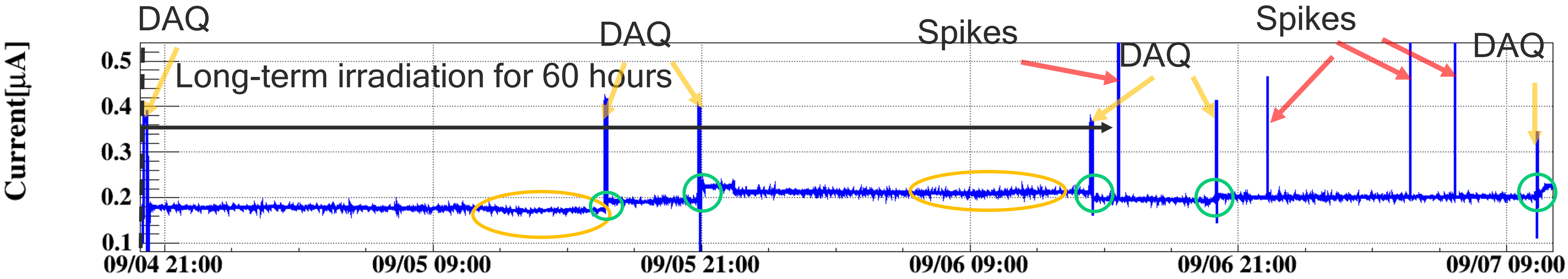


DLC-RPC active region

Long-term operation

Results

- After the conditioning, the DLC-RPC was being irradiated.
- Some spikes happened during the second half of the irradiation period.

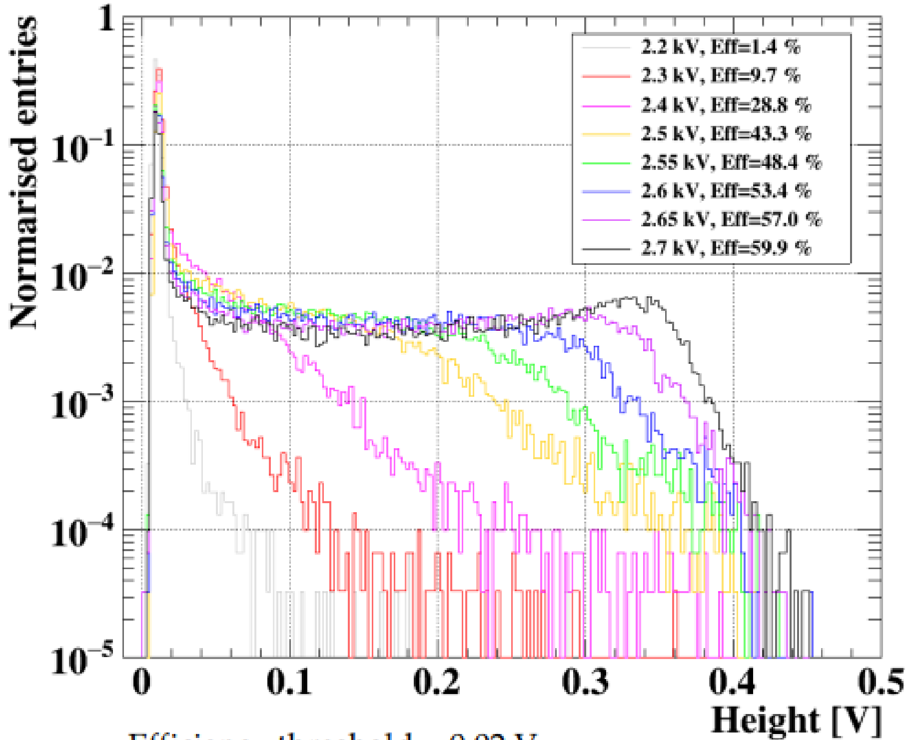


- Fluctuation of current
  - The temperature change
  - Imprecise positioning of the RI

Long-term operation

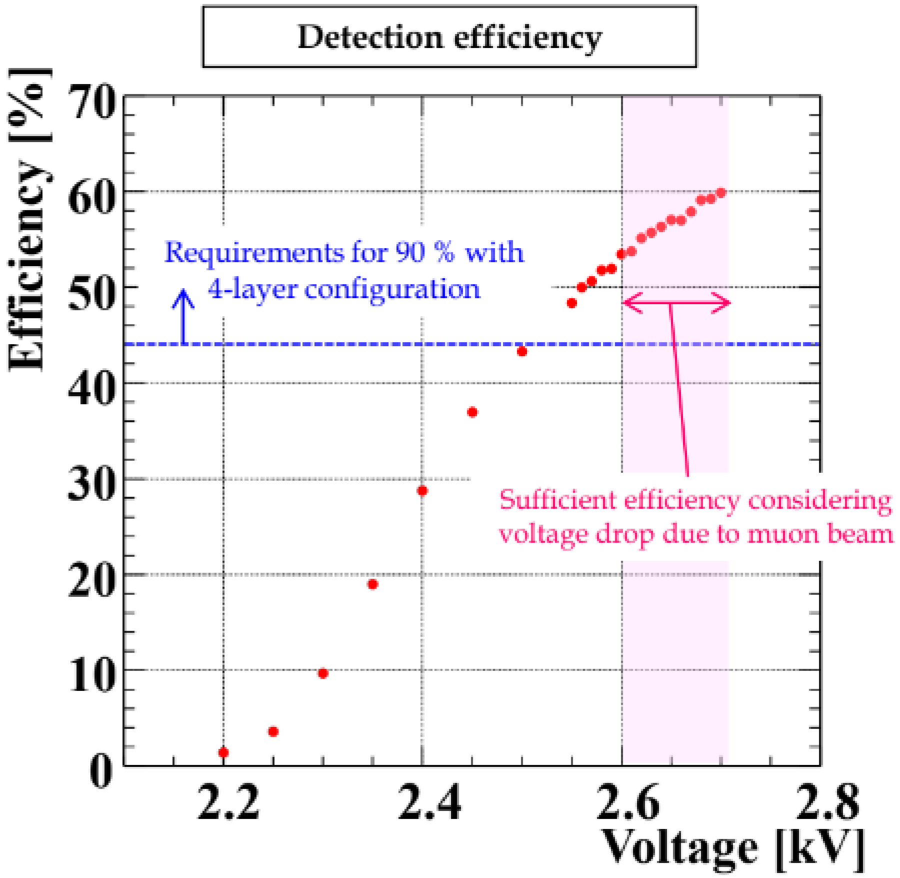
Procedure

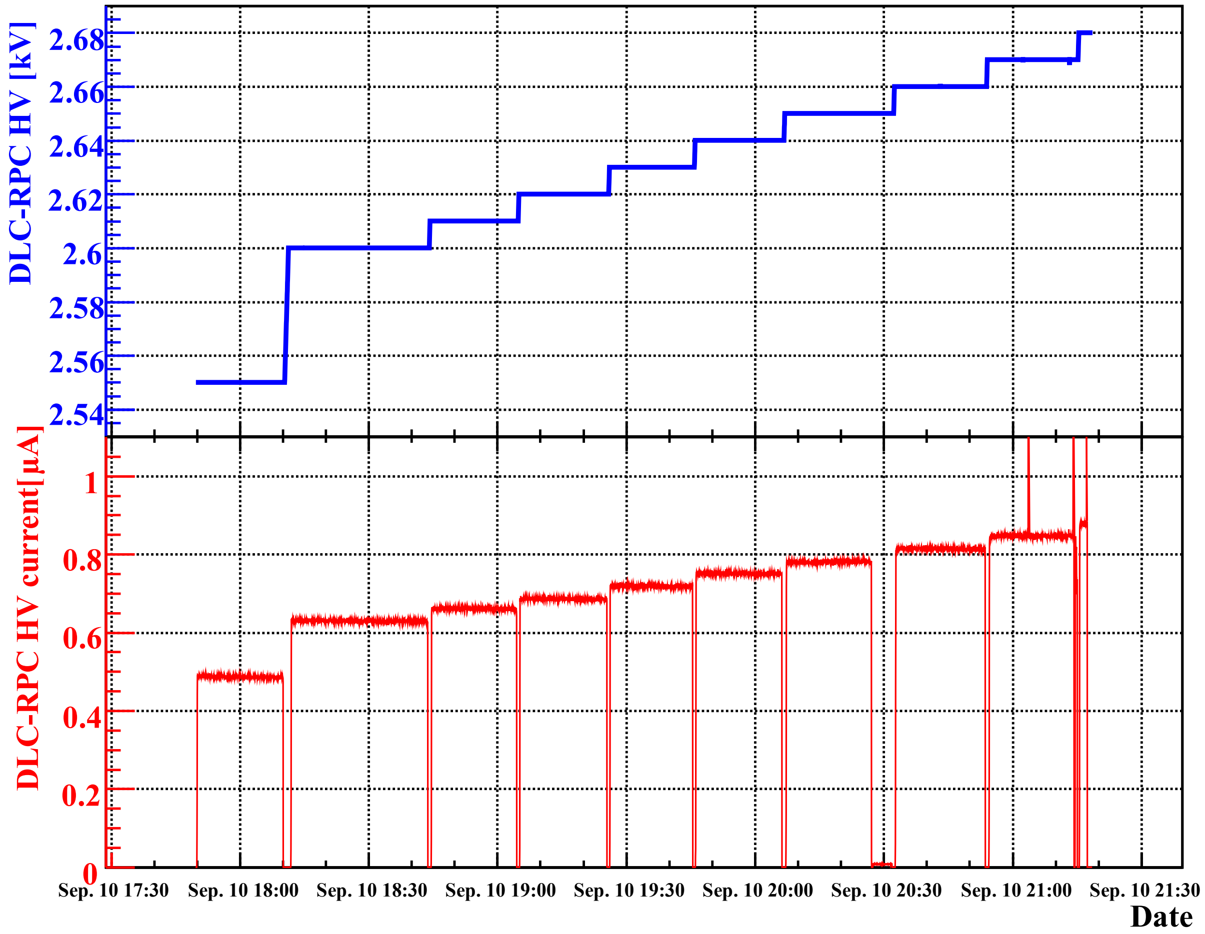
Pulse height spectra in the previous talk



Efficiency threshold = 0.02 V

- Minimum Operating Voltage: 2600 V
  Based on the previous discussion regarding its sufficient detection efficiency and the gain.
- β-ray is irradiated during the operation.
- Comparison
  - High rate
  - Low rate

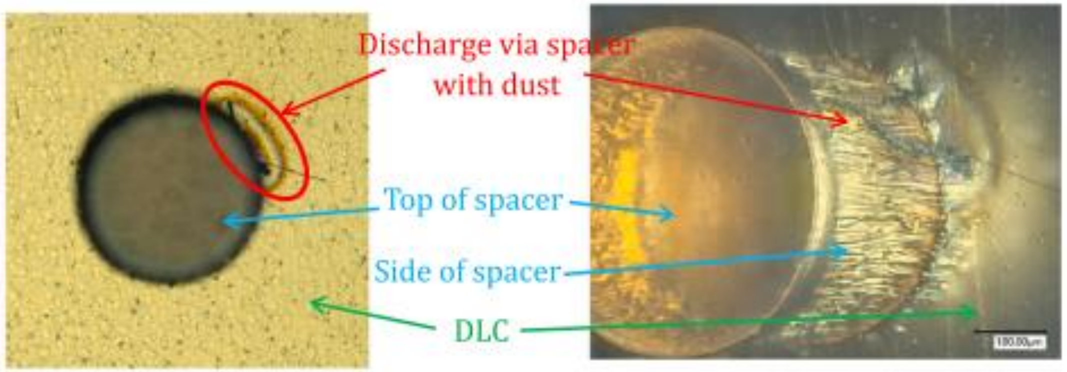

Detection efficiency
Efficiency [%]
Voltage [kV]
Requirements for 90 % with
4-layer configuration
Sufficient efficiency considering
voltage drop due to muon beam
0
10
20
30
40
50
60
70
2.2
2.4
2.6
2.8


DLC-RPC HV [kV]
2.54
2.56
2.58
2.6
2.62
2.64
2.66
2.68
DLC-RPC HV current[μA]
0
0.2
0.4
0.6
0.8
1
Sep. 10 17:30
Sep. 10 18:00
Sep. 10 18:30
Sep. 10 19:00
Sep. 10 19:30
Sep. 10 20:00
Sep. 10 20:30
Sep. 10 21:00
Sep. 10 21:30
Date

What induces discharges

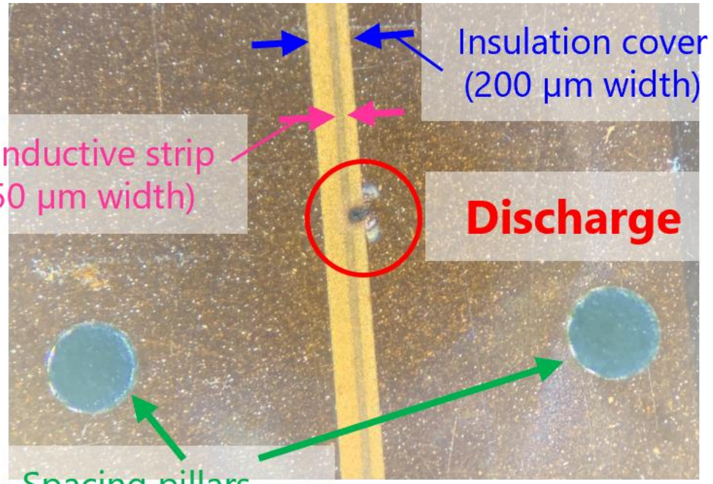
Main factors

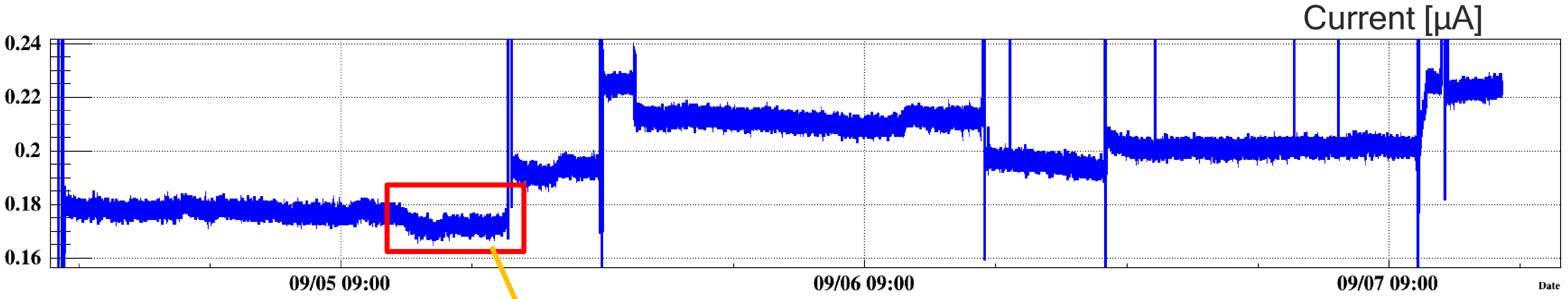
1. Pillars
   - Distort the electric field or enha amplification
2. Conductive strip cover
   - Insufficient quenching
3. Flatness issues
   - Setup or the bad structure of the electrodes→Non-flatness
   - Non-uniform electric field
4. Contamination
   - Sparks caused by dusts between the gap



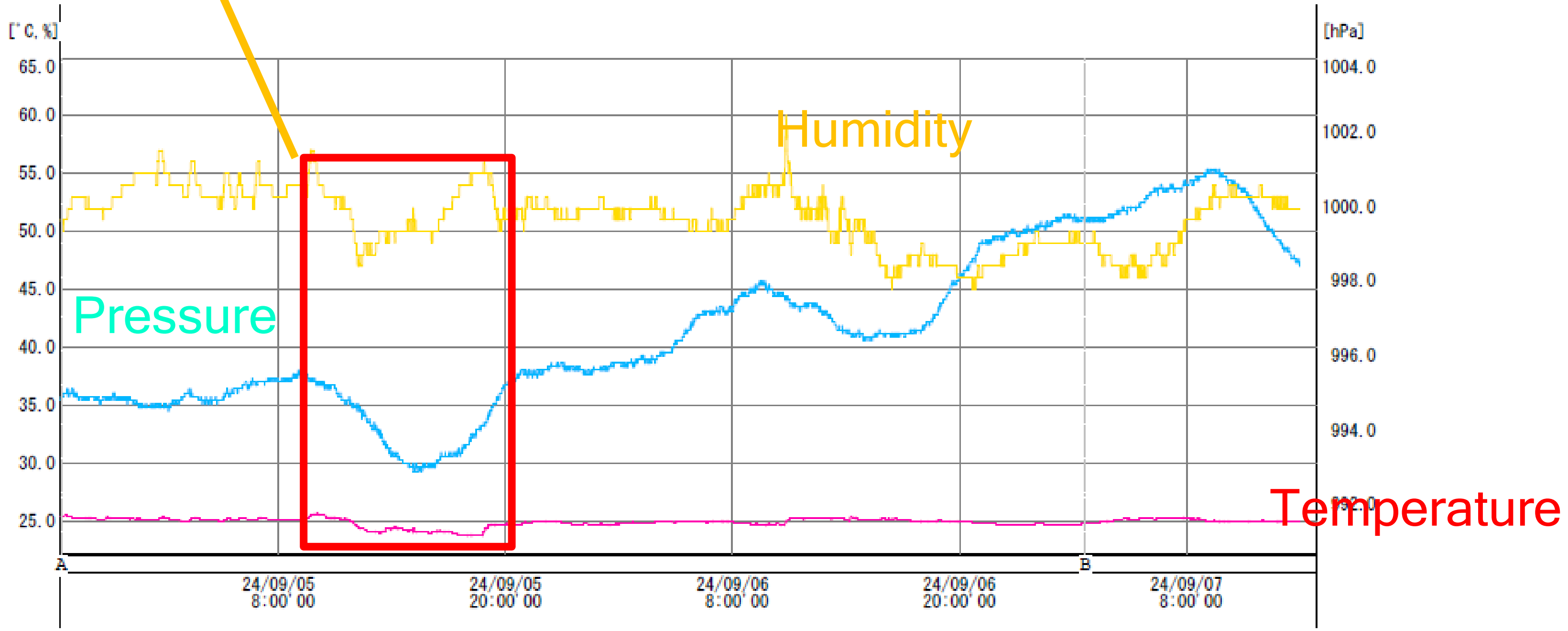
(a) Top view of the spacer (b) Oblique view of the spacer

Fig. 10. Discharge via a pillar.





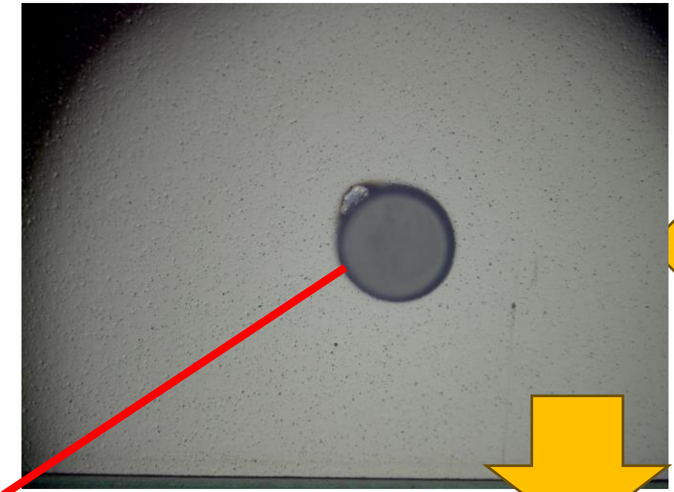
Current [μA]
0.24
0.22
0.2
0.18
0.16
09/05 09:00
09/06 09:00
09/07 09:00
Date

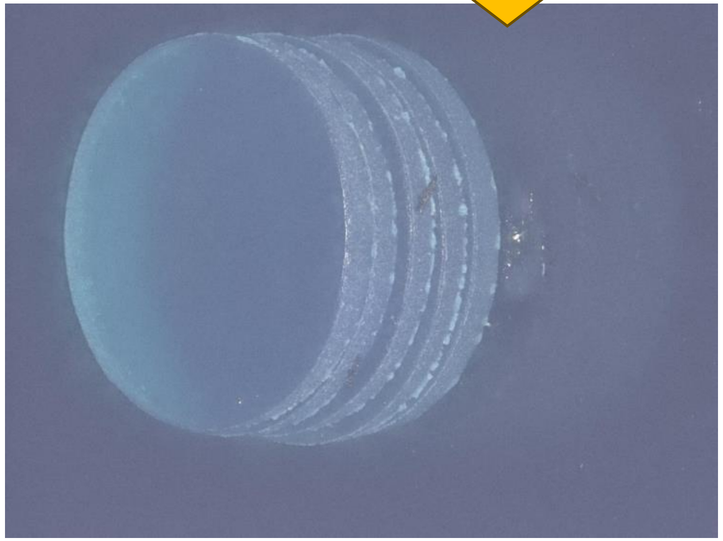


[°C, %]
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
[hPa]
1004.0
1002.0
1000.0
998.0
996.0
994.0
Humidity
Pressure
Temperature
A
B
24/09/05 8:00'00
24/09/05 20:00'00
24/09/06 8:00'00
24/09/06 20:00'00
24/09/07 8:00'00

Discharge marks

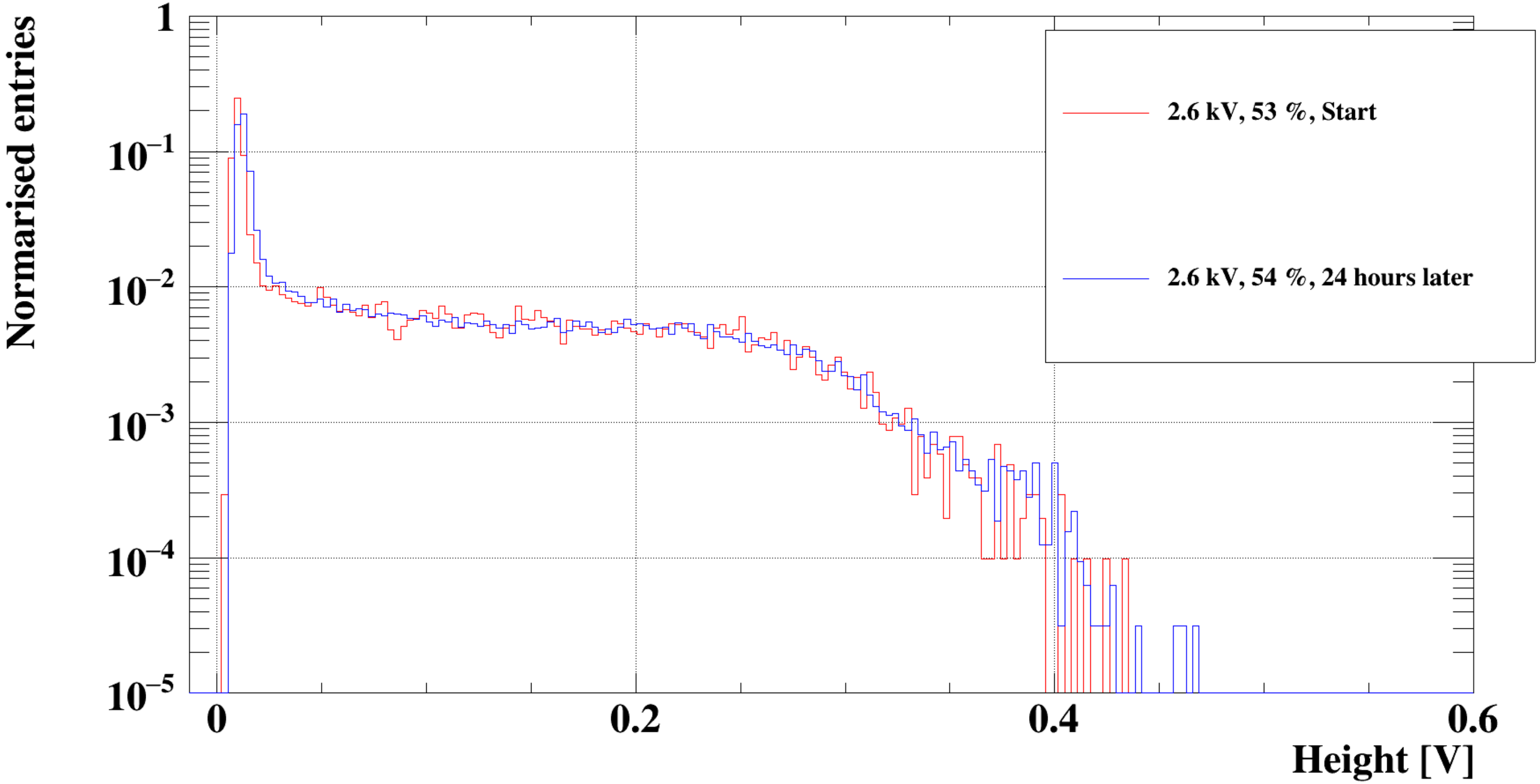
Anode



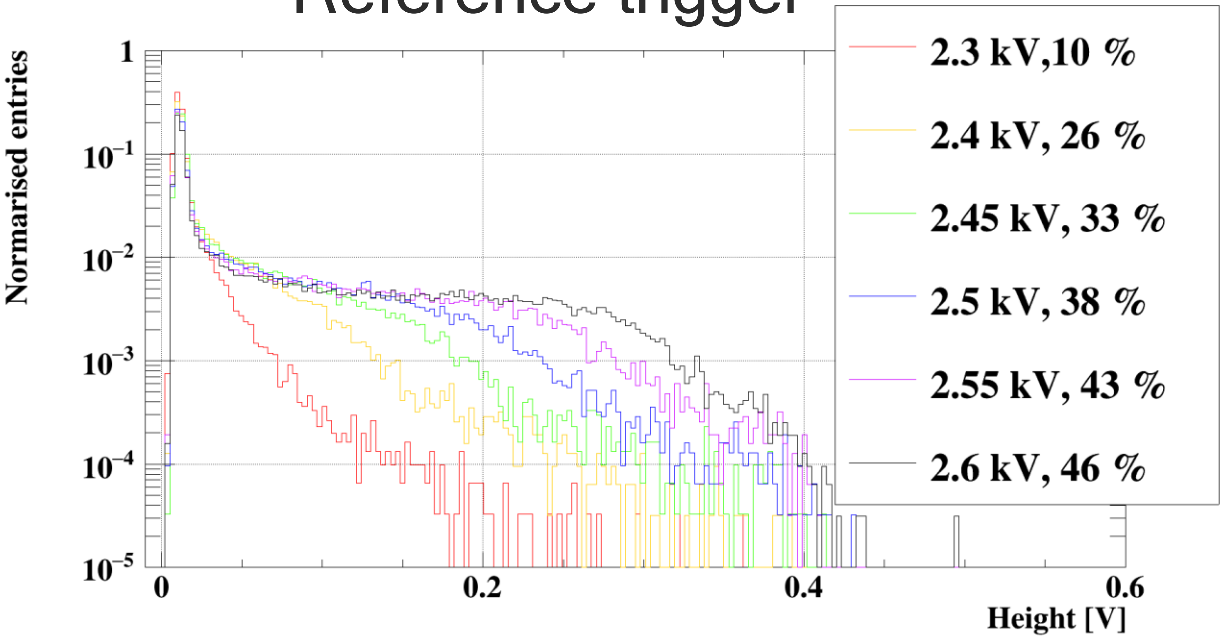


Cathode

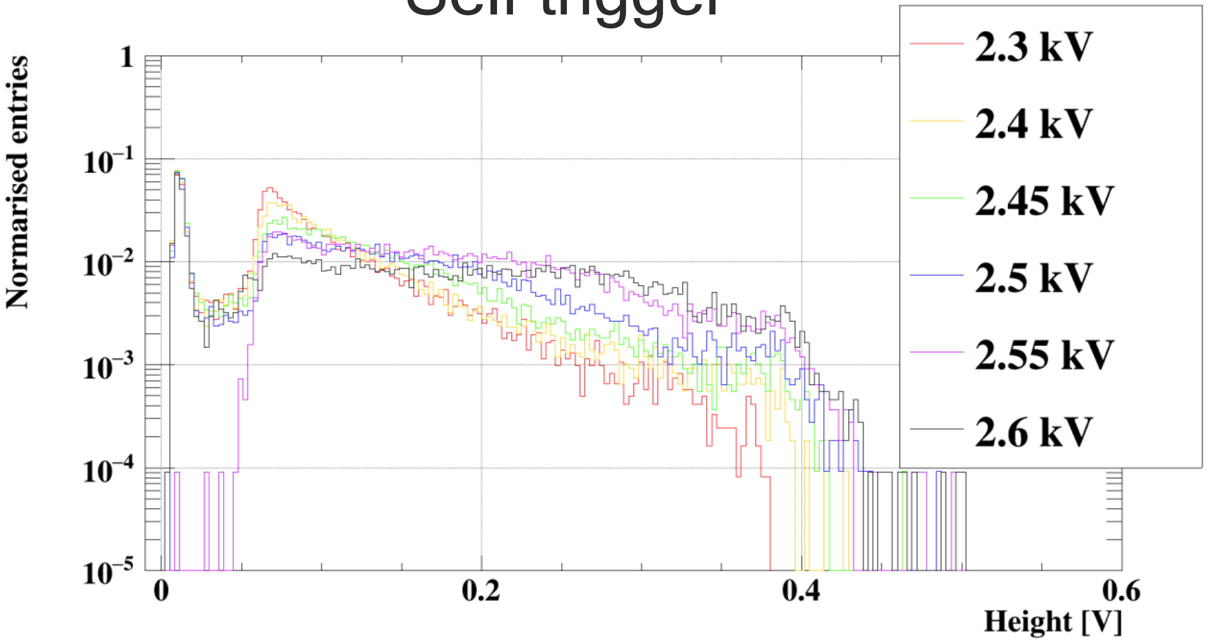
Pulse-height distribution
Comparison between the start and 24 hours later



Reference trigger

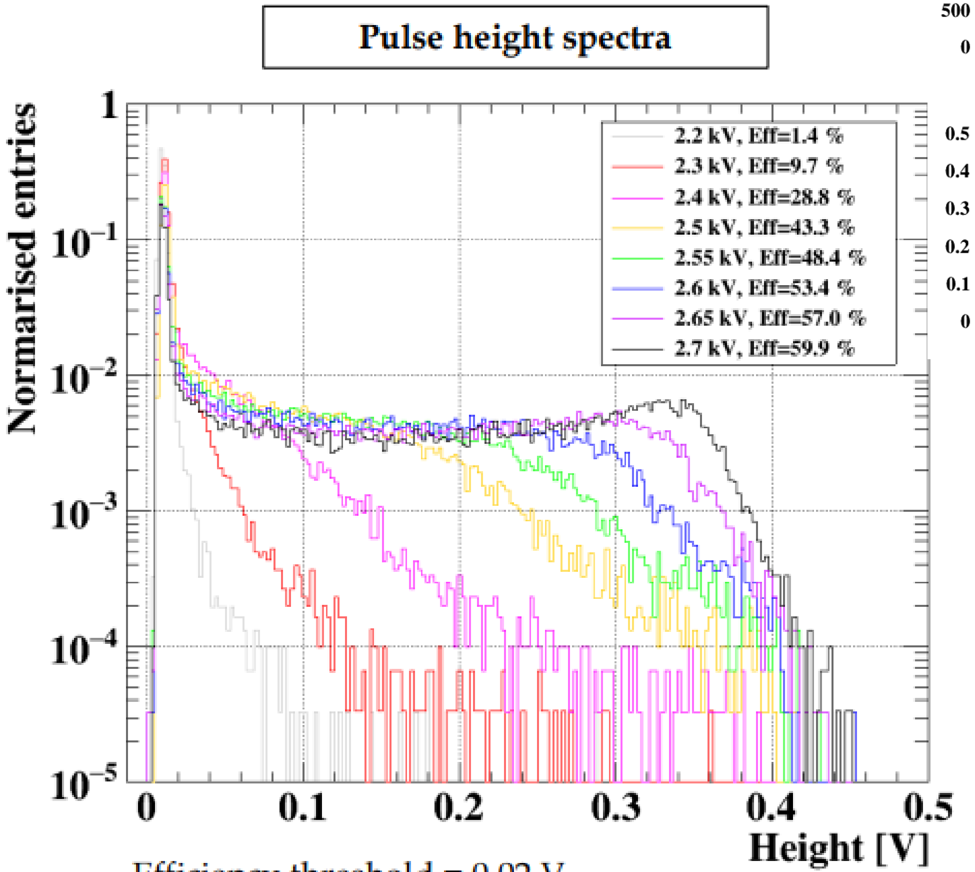


Self trigger

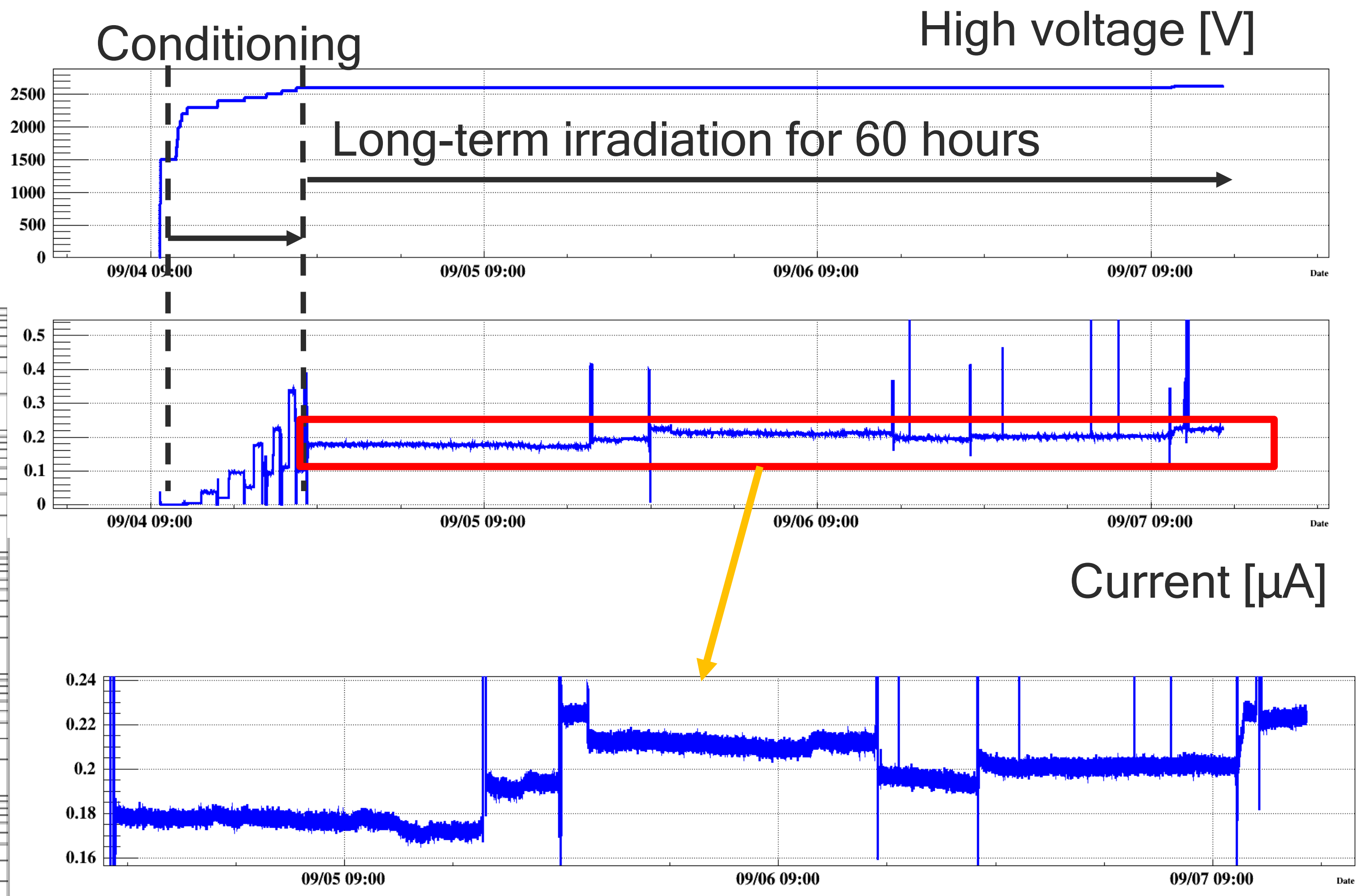


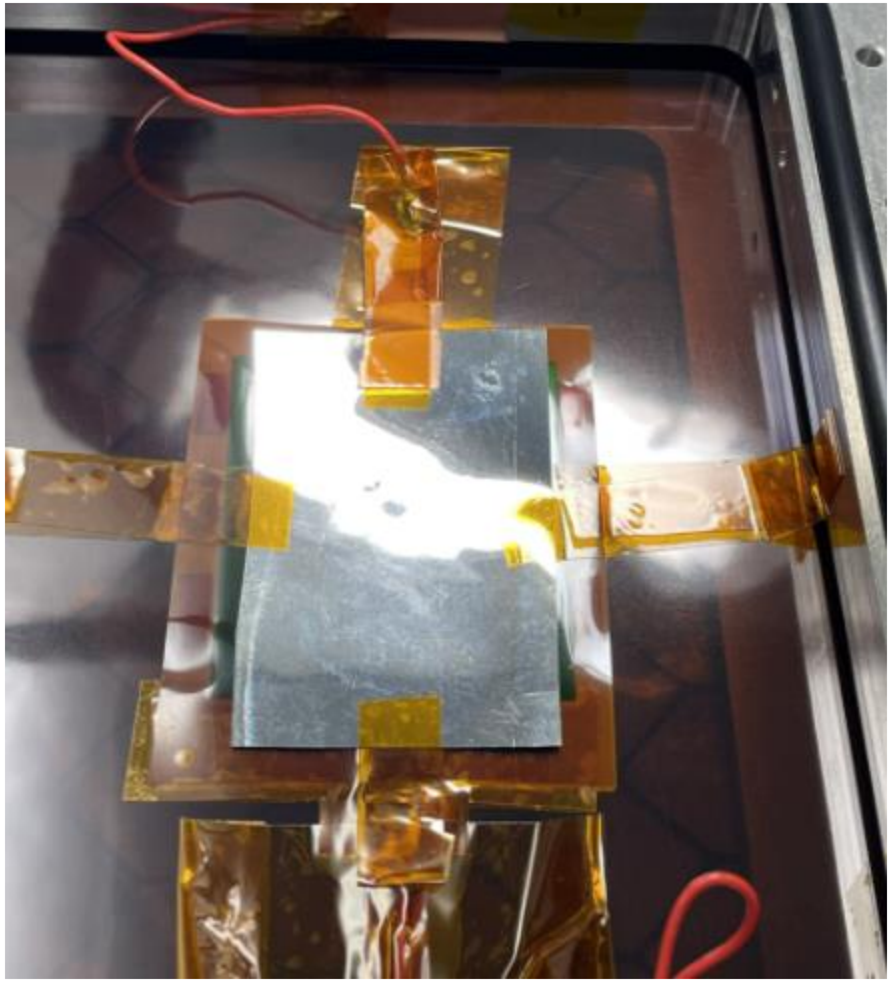
Long-term irradiation

Results



Efficiency threshold = 0.02 V

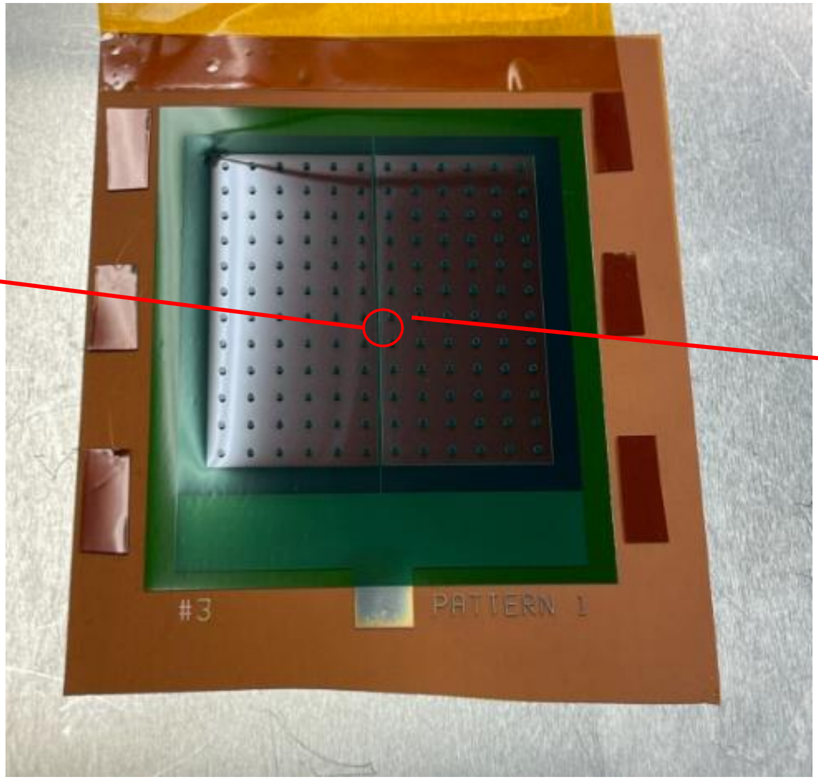


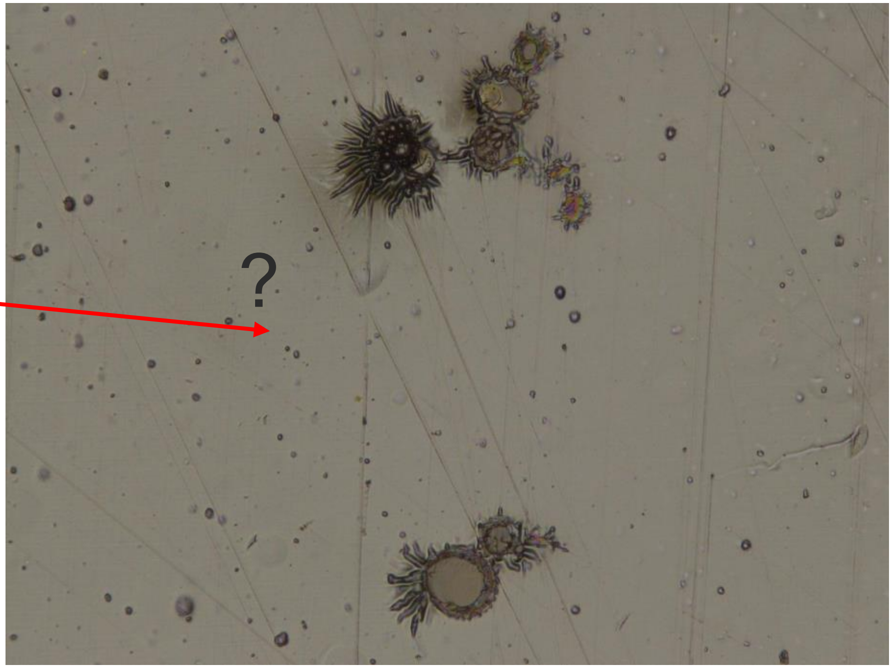


Discharge marks

Anode

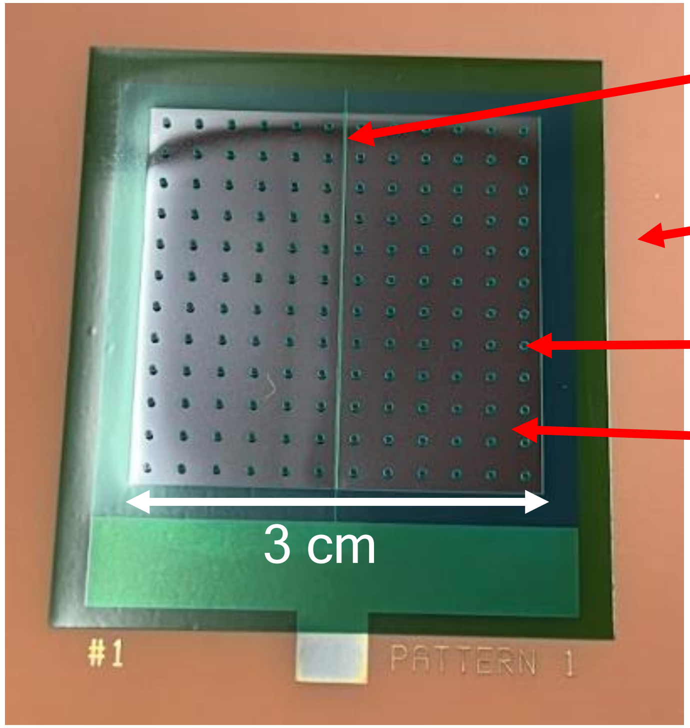
Cathode

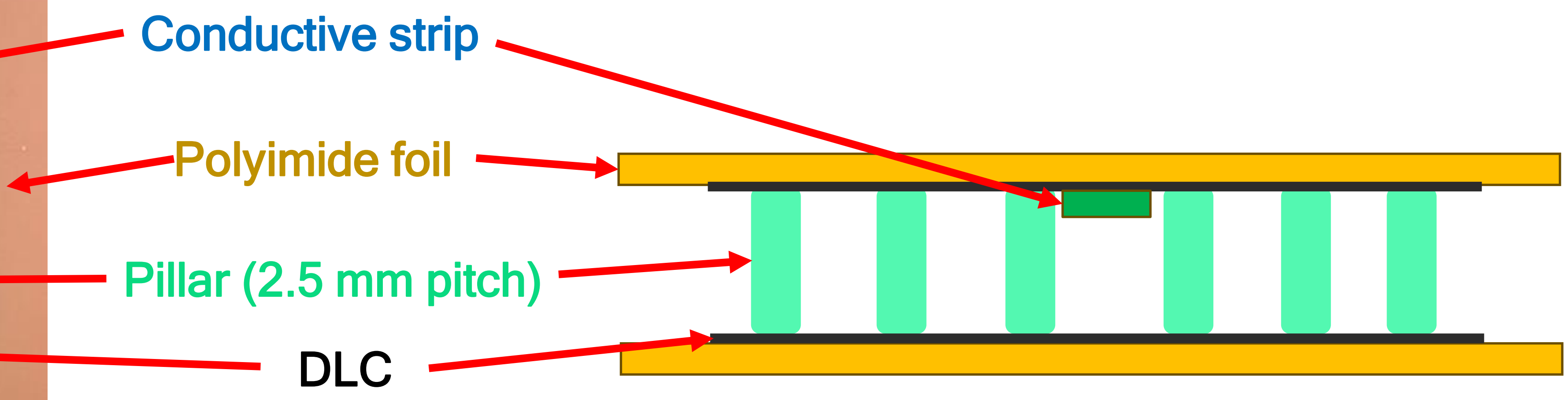




These marks were not removed completely.

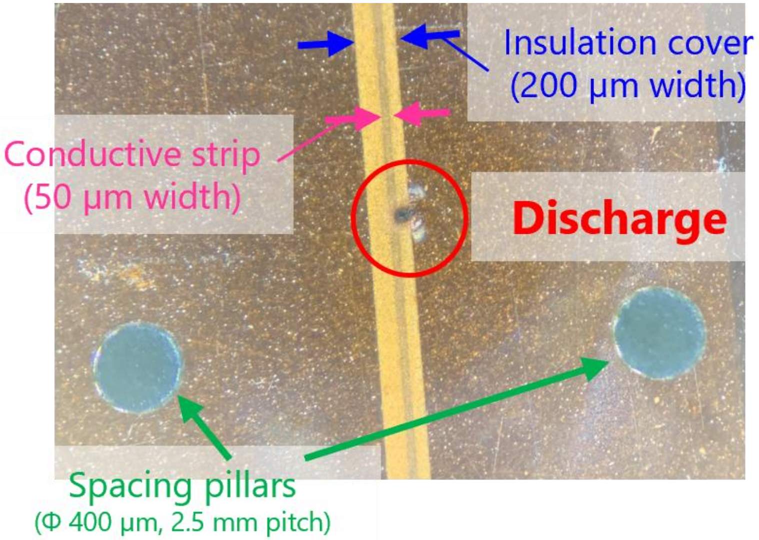
DLC-RPC and the upstream RDC





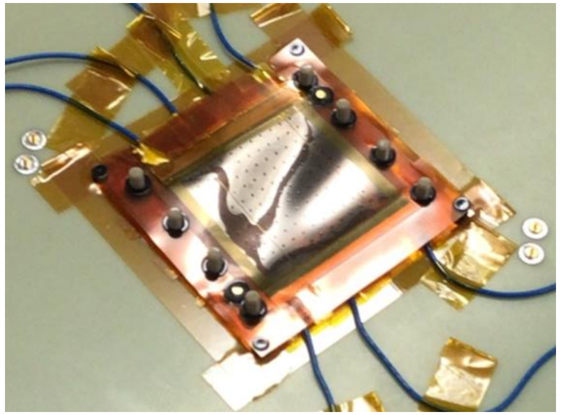
What induces discharges

1. Flatness issues
2. Dusts
3. Pillars
4. Inadequate conditioning and baking with an RI
5. Resist cover



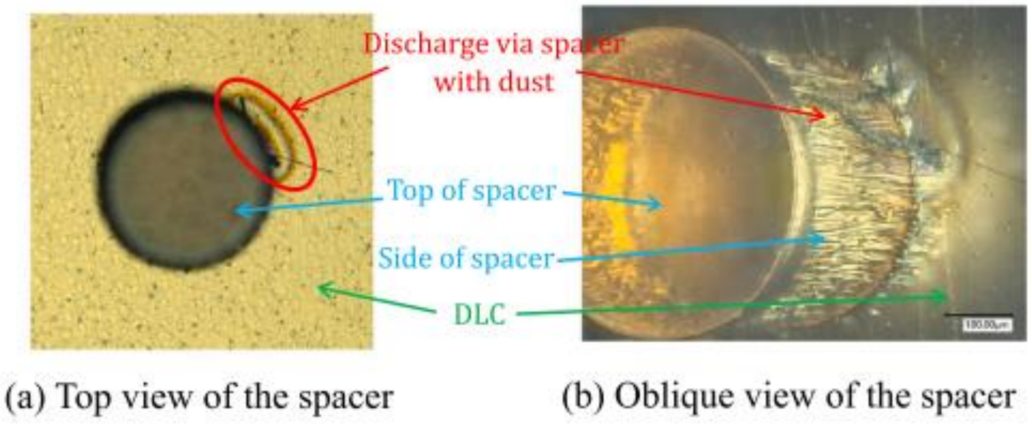
高橋真斗, 日本物理2024 年春季大会, 2024 年3月21 日

Non-flatness of electrodes



Introduction

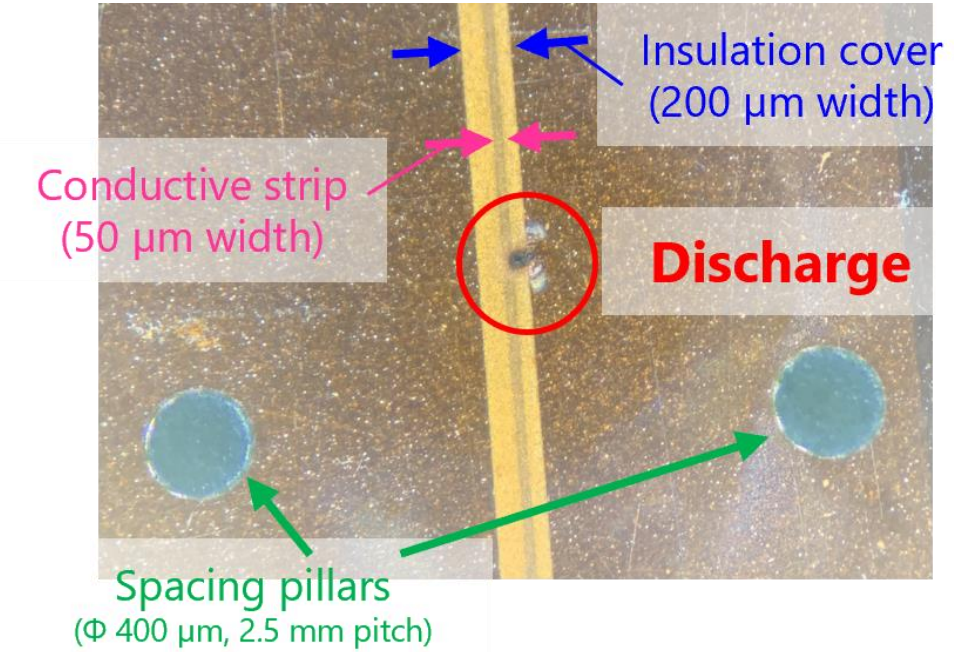
Discharges in the past tests



(a) Top view of the spacer (b) Oblique view of the spacer

Fig. 10. Discharge via a pillar.

Masato Takahashi., et al.
Nucl. Instrum.Methods Phys.Res.Sect A,1066 (2024), Article 169509

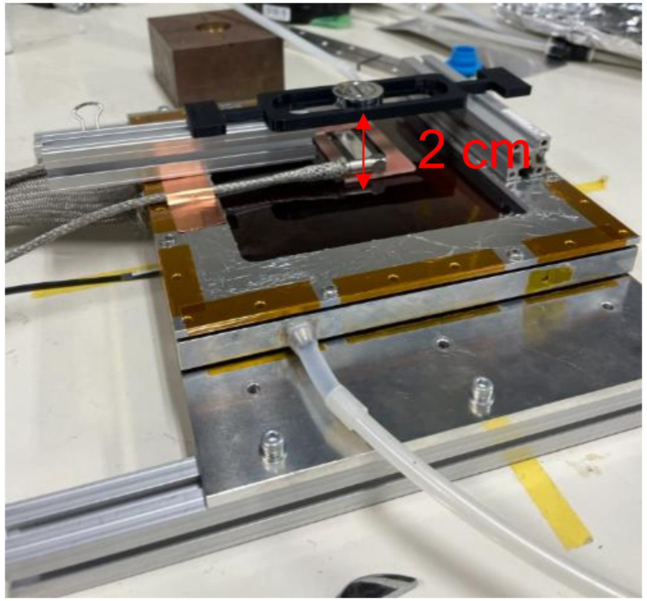


高橋真斗, 日本物理2024 年春季大会, 2024 年3 月21 日

- ◆Discharges on the DLC-RPC have hindered the operation.
  - ◆Via a pillar
  - ◆Along an Insulation cover

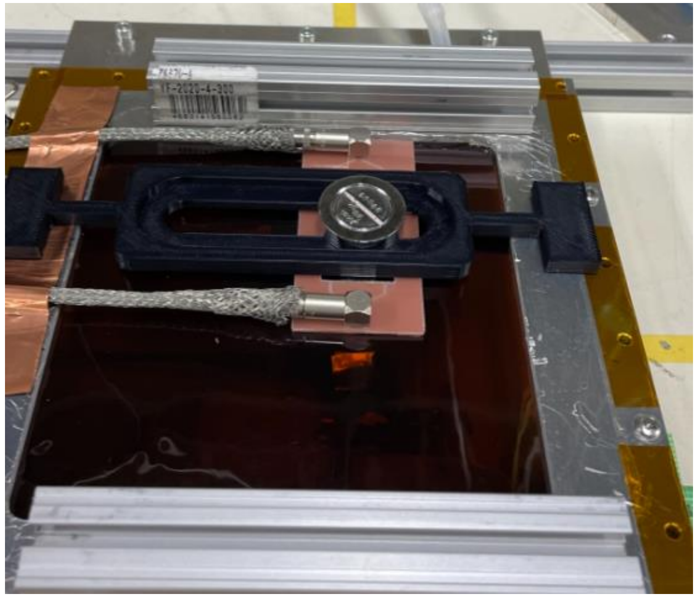
Procedure

- Conditioning at 1500 V w/o an RI for 1 hour
- Raising the voltage from 1500 V～2000 V by increments of 100 V in 5 min
- Irradiated at 2000 V w/o a collimator for 5 min (2 cm above for 2.5 min, 0 cm for 2.5 min)
- Same as above at 2100 V (2 cm above for 5 min, 0 cm for 5 min)
- Same at 2200 V (2 cm above for 7 min, 0 cm for 7 min)



Irradiation 2 cm above

To bake dusts in the wider area of the electrode.

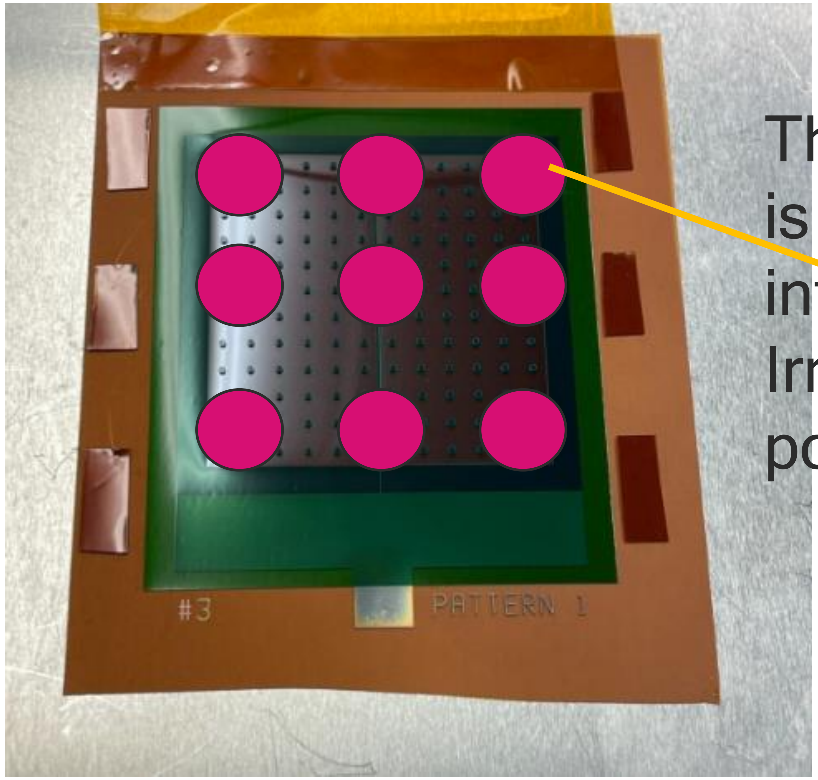


Irradiation 0 cm above

Procedure

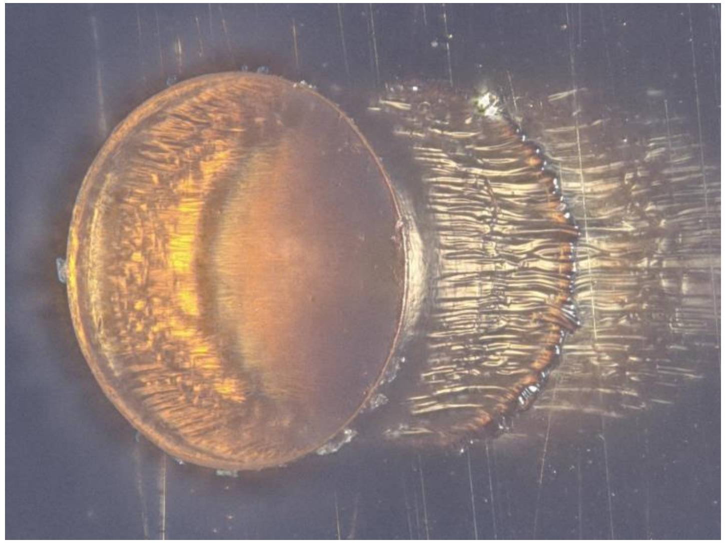
- 2300 V
  - 2 hours irradiation in total
  - Position Scanning
  - DAQ
- 2400 V:Same procedure as 2300 V
- 2450 V:Same procedure
- 2500 V:Same, but irradiation time is shortened to 1 hour in total
- 2600 V:Same and long-term irradiation is started
- DAQ several times and once 24 hours later

Position scanning

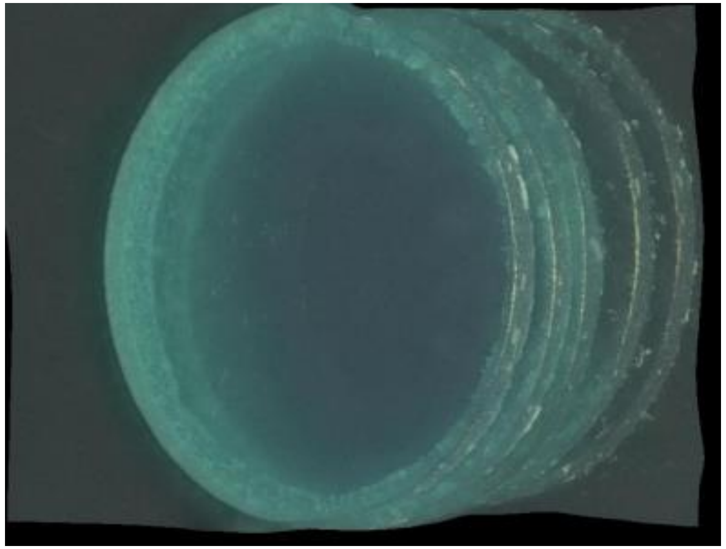


The active region is roughly divided into 9 points
Irradiated at each point

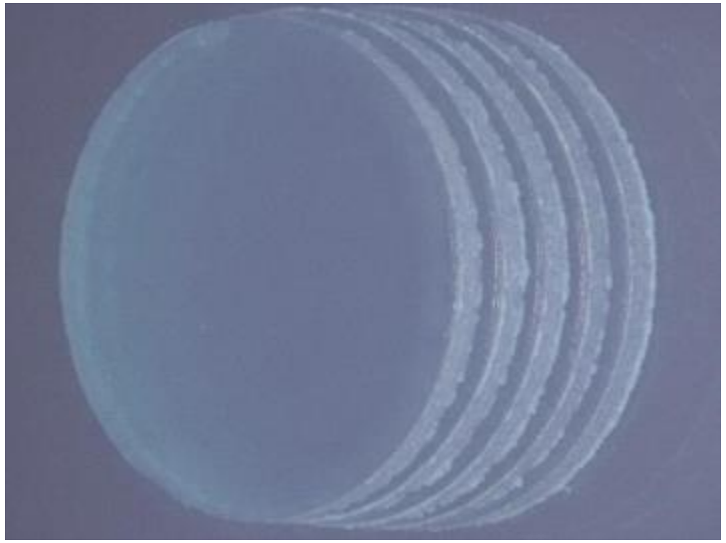
Old pillar



New pillar in 2023



New pillar in 2024

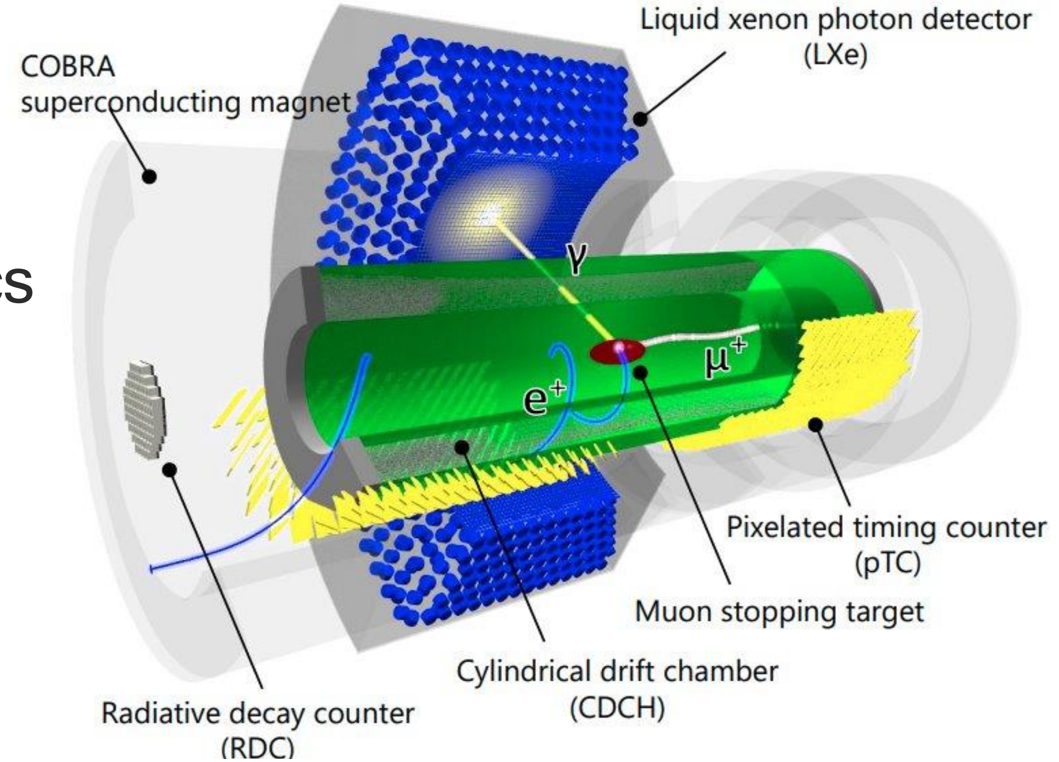


Pyralux
Dupont

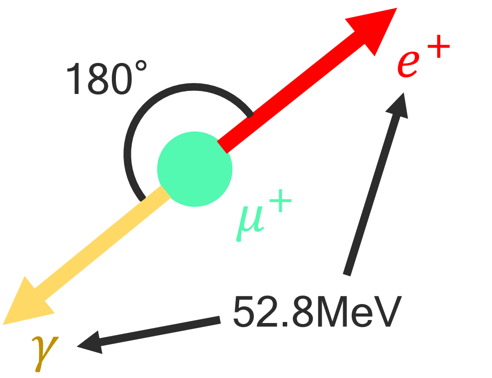
Dynamask
Eternal

MEG II experiment

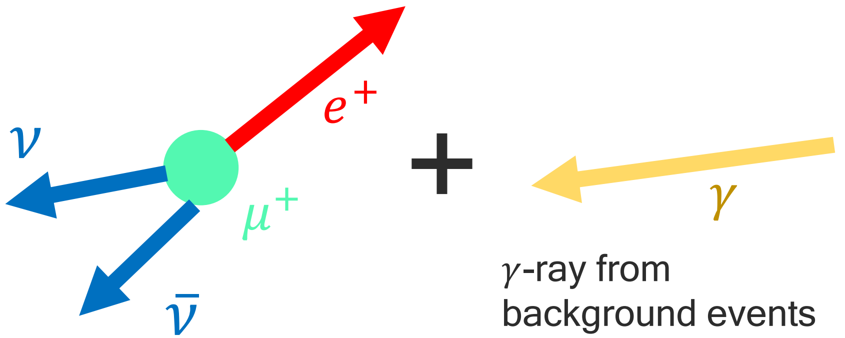
- Searches for the $\mu \to e\gamma$ decay
- Charged lepton flavor violation process (cLFV)
- Discovery would be an evidence for new physics
- Aims for a sensitivity of 6×10^{-14} (MEG: 5.3×10^{-13})



Signal



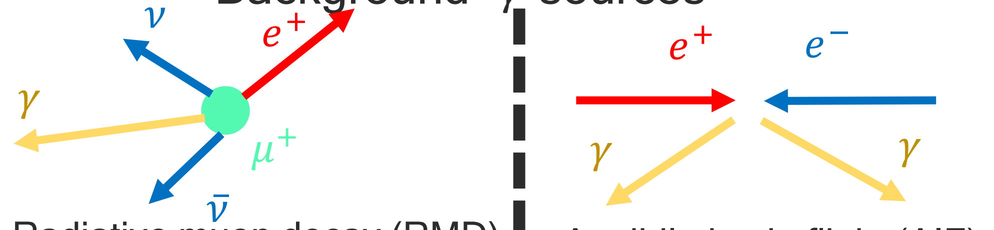
Accidental Background



Michel decay

γ-ray from background events

Background- γ sources



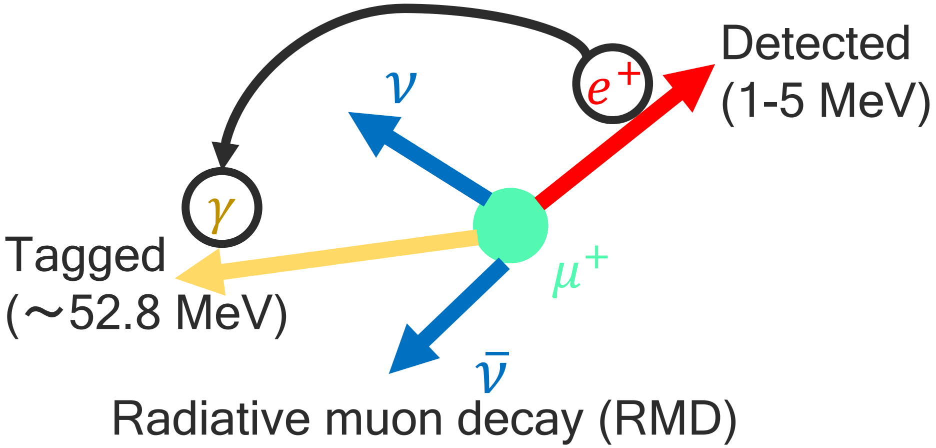
Radiative muon decay (RMD)

Annihilation in flight (AIF)

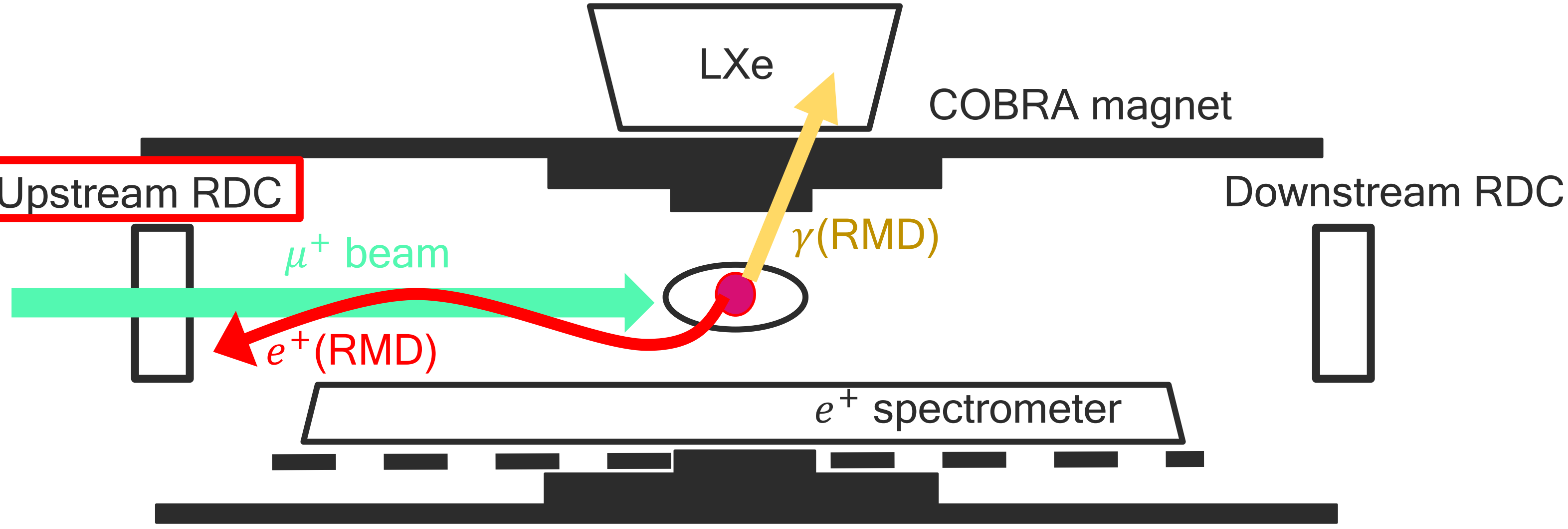
Introduction

Radiative decay counter (RDC)

- Detecting low momentum e^+ and tagging BG-γ from the RMD
- Reducing the background events



Under development



μ^+ beam at the upstream RDC

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

Requirements for the upstream RDC

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

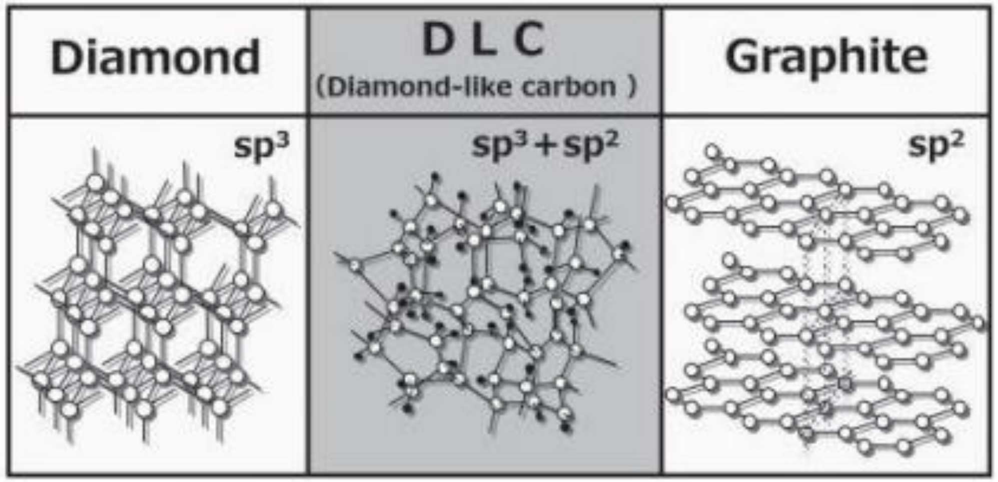
DLC-RPC: Resistive Plate Chamber with electrodes based on Diamond-Like Carbon

Introduction

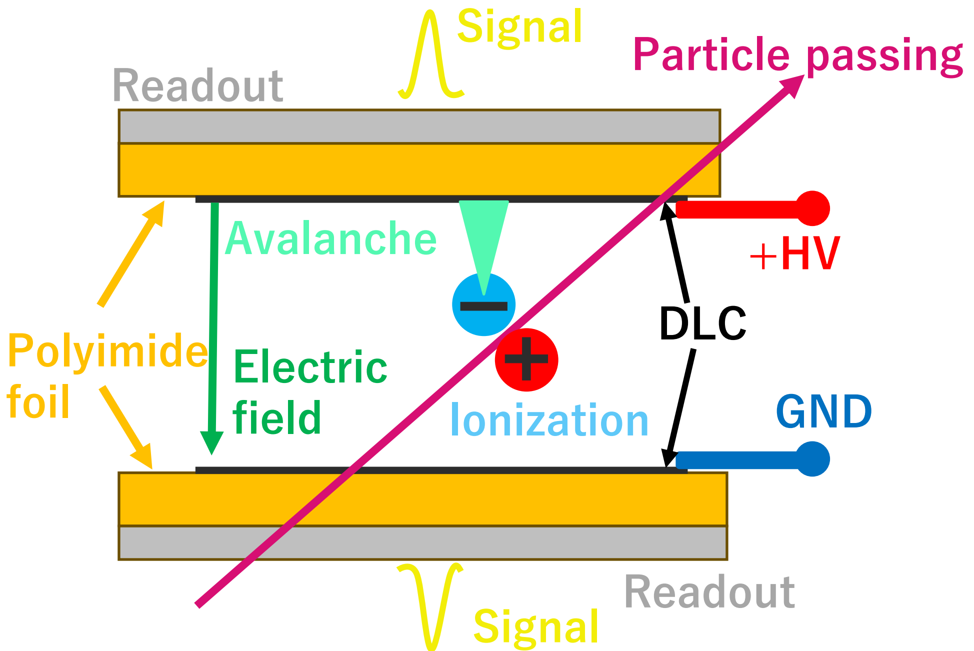
DLC-RPC

Diamond-Like Carbon (DLC)
- High resistivity and thin film
- Adjustable resistivity

Resistive Plate Chamber (RPC)
- Gaseous detector consisting of parallel plate electrodes
- Fast timing efficiency
- Higher detection efficiency by stacking layers
(Detection efficiency of n-layers: $\epsilon_n = 1 - (1 - \epsilon_1)^n$)



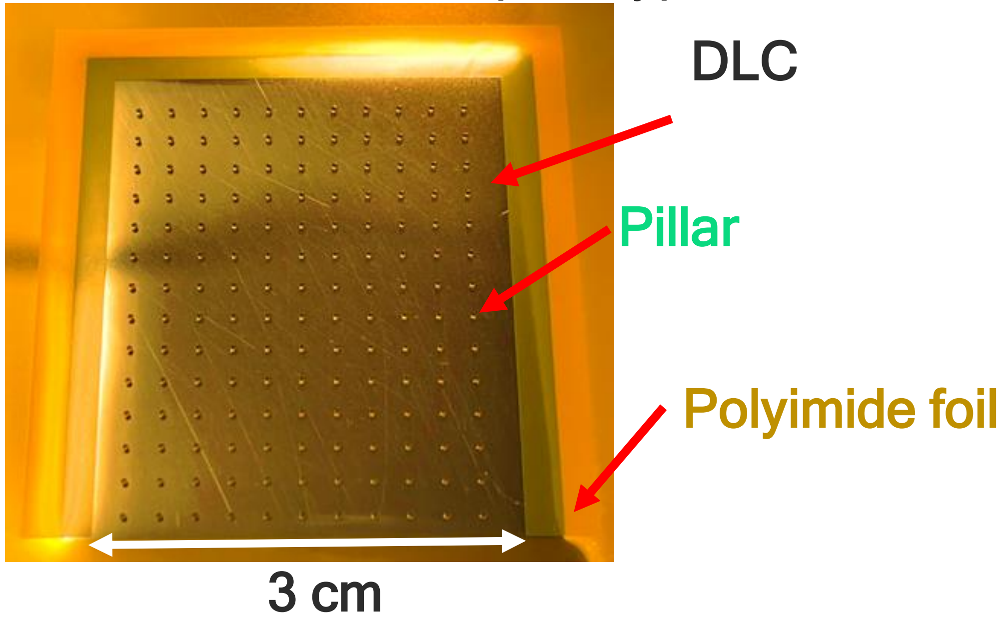
PCS Instruments, The Science Behind Diamond like Coatings (DLC), https://pcs-instruments.com/articles/the-science-behind-diamond-like-coatings-dlcs/, December 3, 2021



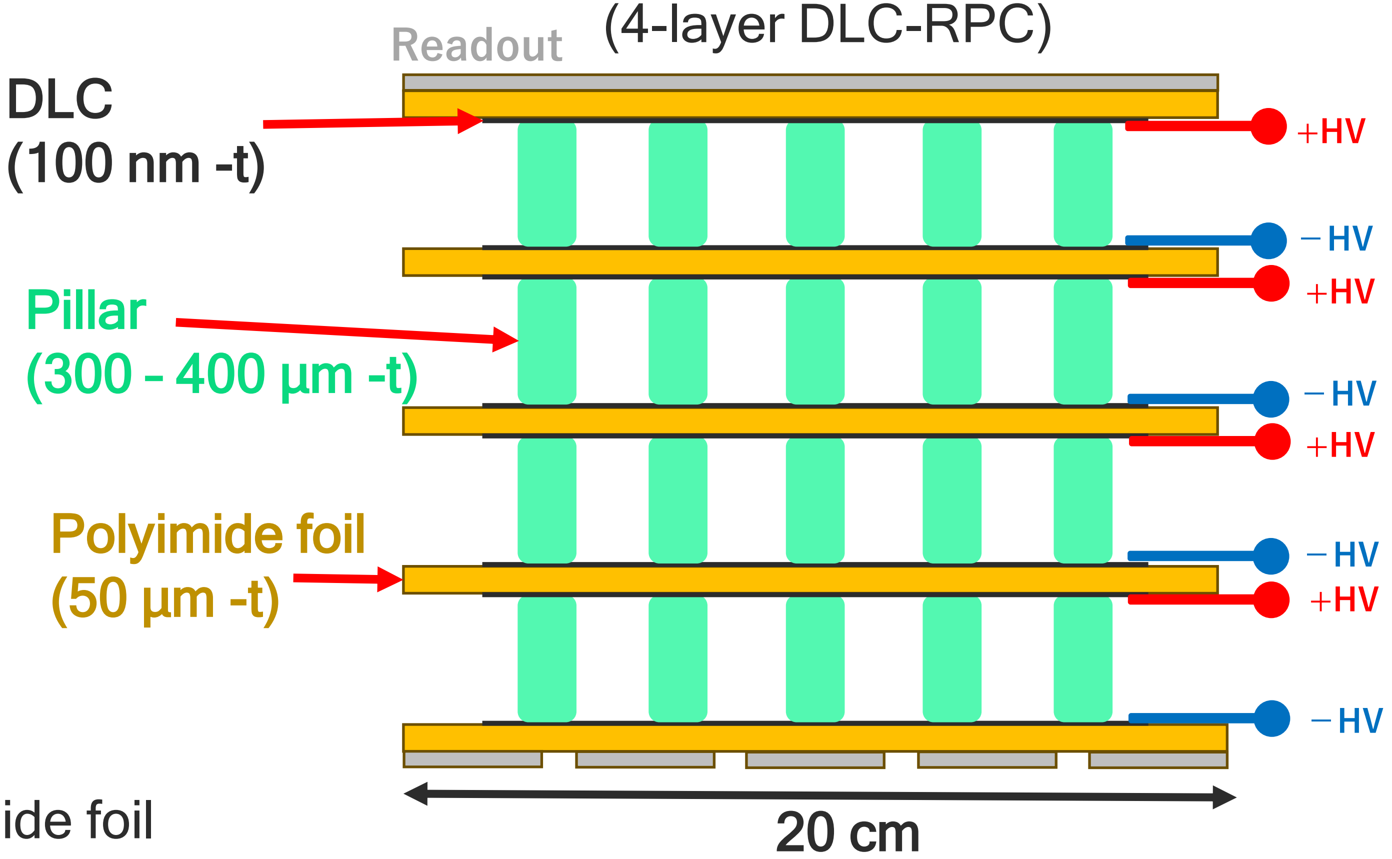
Operation principle of DLC-RPC

DLC-RPC

An electrode for a small prototype



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



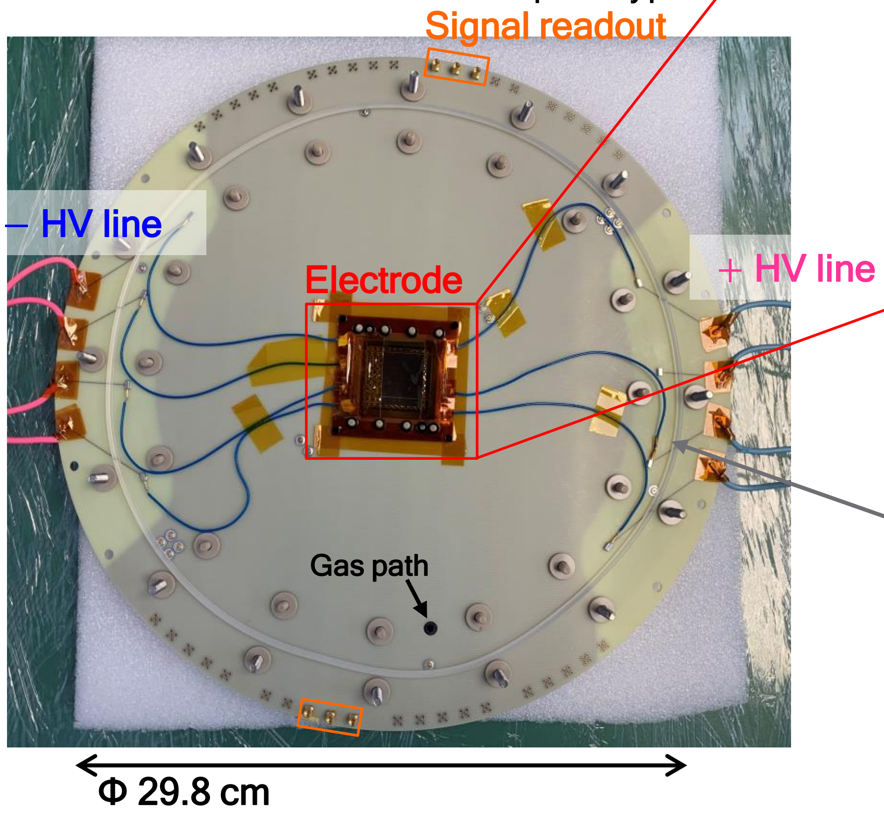
- DLC sputtered on a 50 μm thickness polyimide foil
- Pillars to sustain a gap between electrodes
- More than 40 % detection efficiency with a single layer is required.
  →90 % efficiency with 4 layers

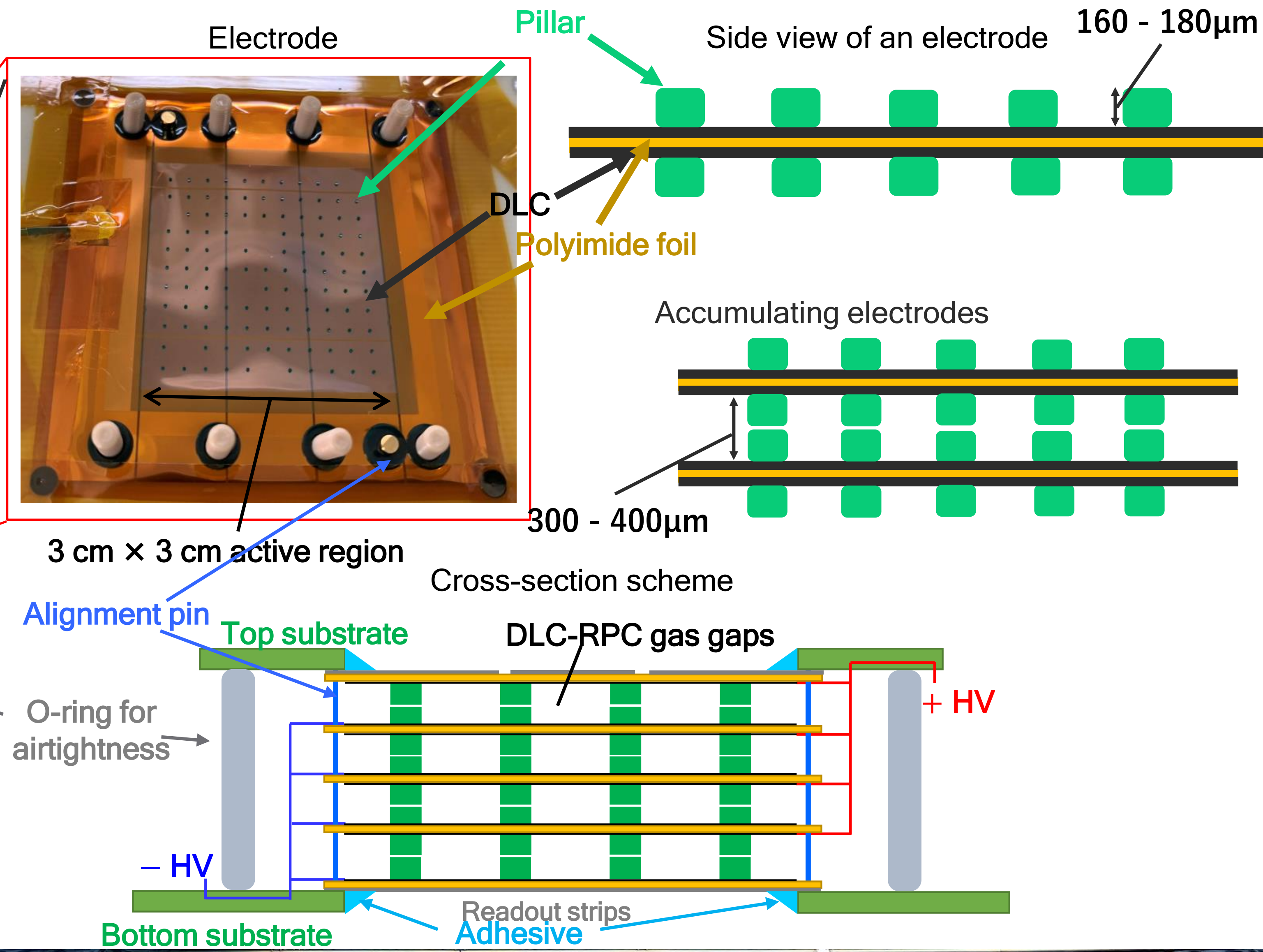
First prototype

Module

Designed for the evaluation of the rate capability in a high-rate muon beam
(JPS 2022 autumn, 6pA421,
JPS 2023 spring, 23pT2-5)

Inner overview of First prototype





First prototype

Issues

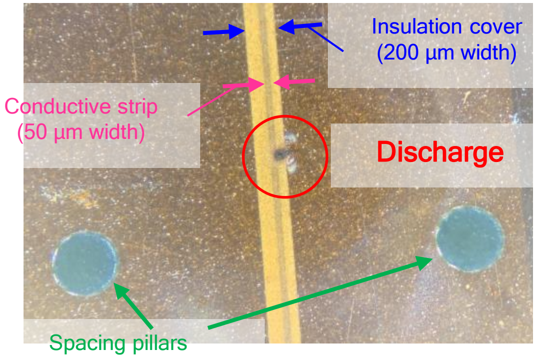
1.Distortion of an electric field

- Inhomogeneous pillars that made the non-uniform gap
- Fixing method that causes the thin-film electrode to be distorted

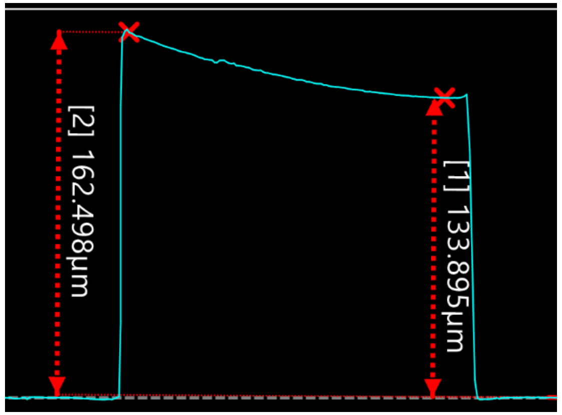
2.Insufficient quench

Unstable operation

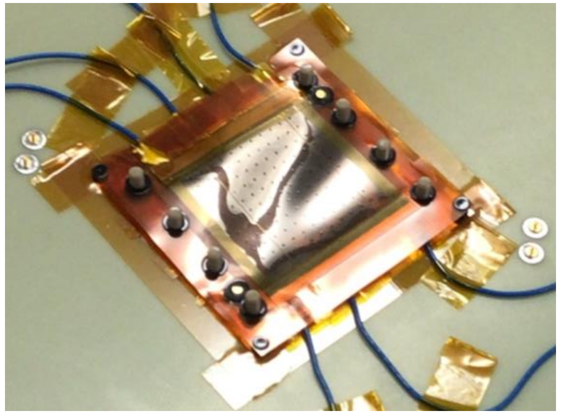
Discharge at conductive strip



Distorted spacing pillar

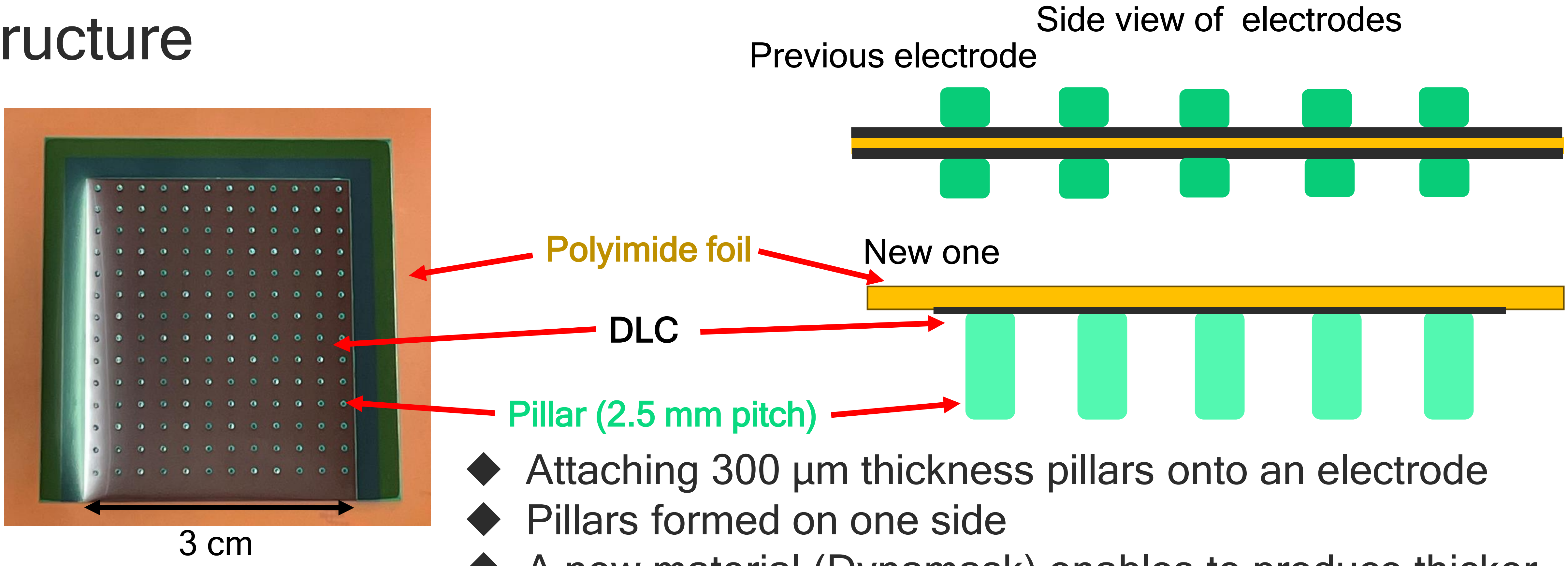


Non-flatness of electrodes



Production of new electrodes

Structure

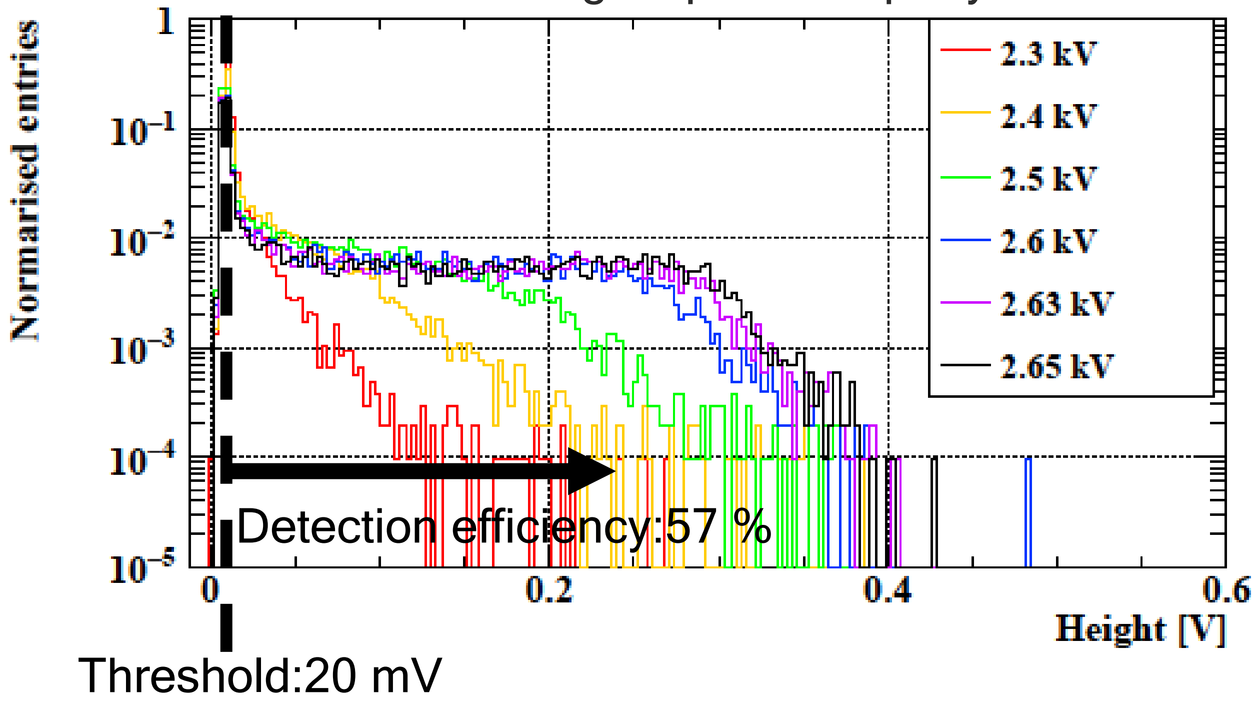


- Attaching 300 µm thickness pillars onto an electrode
- Pillars formed on one side
- A new material (Dynamask) enables to produce thicker pillars

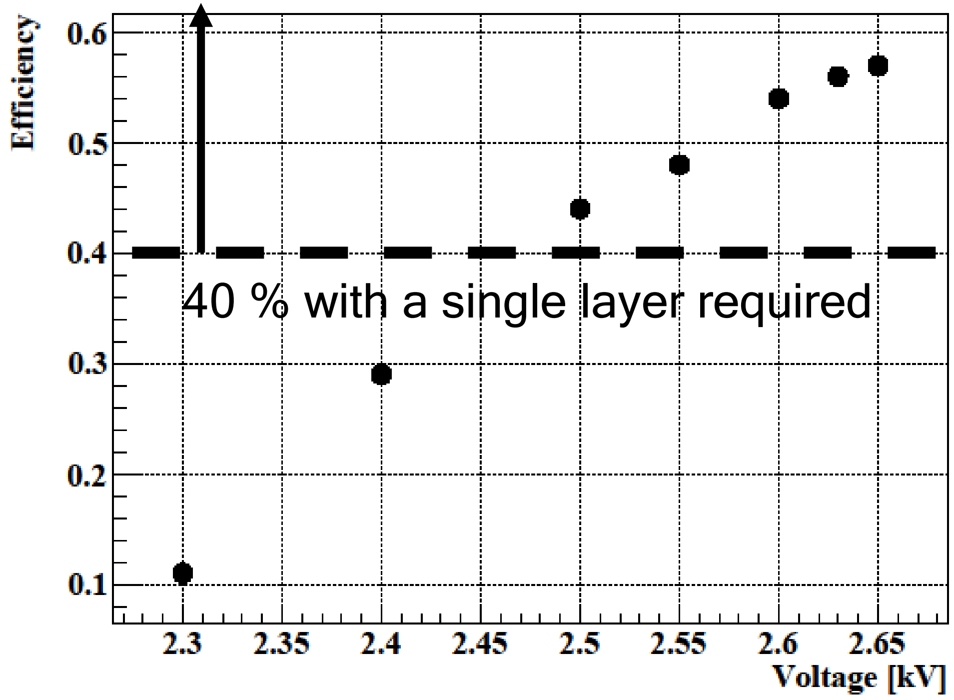
Performances with new electrodes

Result

Pulse height spectra of β rays



Detection efficiency vs applied voltage



- 57 % detection efficiency was achieved at 2.65 kV.
- The operation will be performed at 2.63 kV for its stability.