Status of DLC-RPC Development for MEG II Experiment

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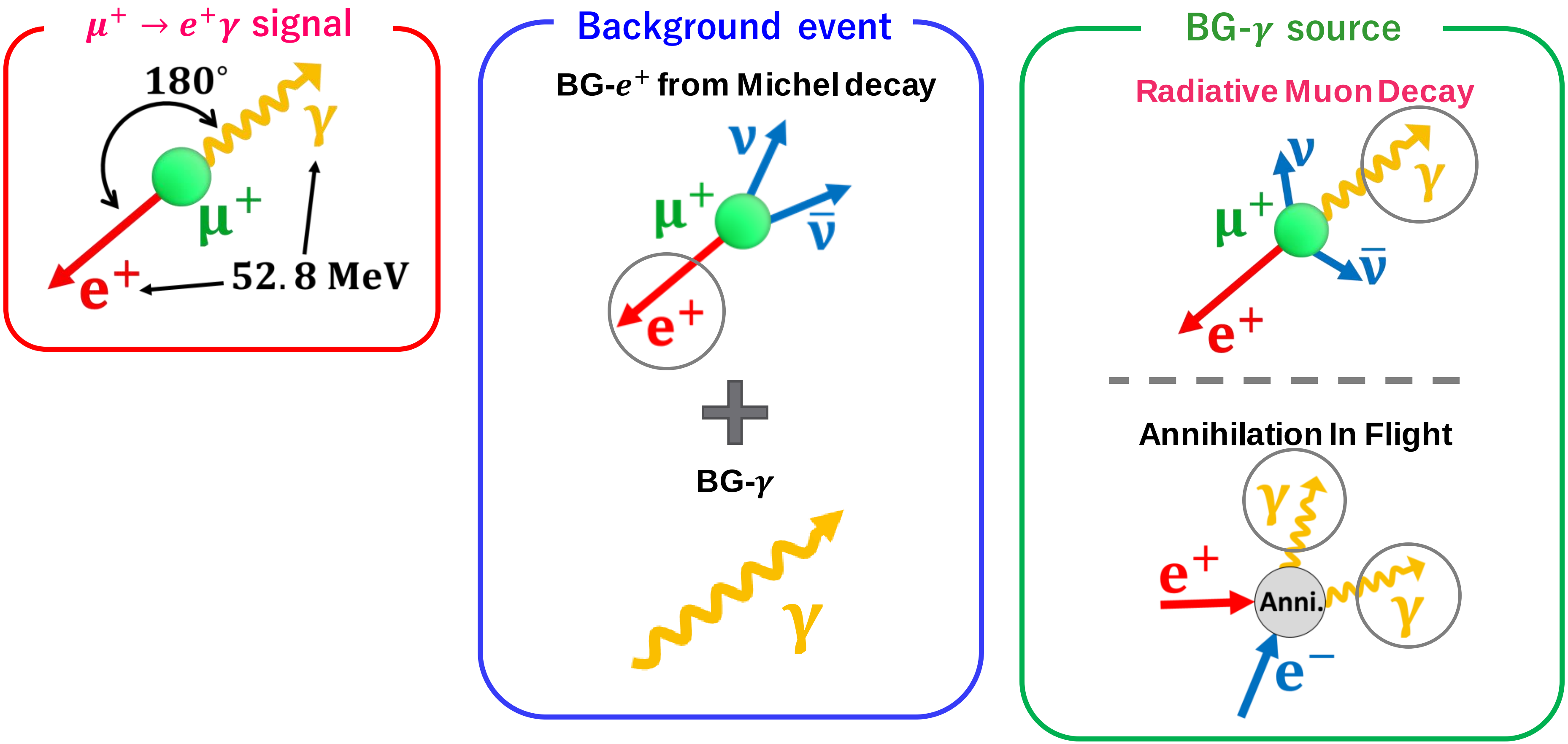
RD51 Collaboration Meeting
4th – 8th December 2023

Outline

- **Introduction**
  - MEG II experiment
  - RPC based on Diamond-Like Carbon electrode
- **Developments of DLC-RPC in 2023**
  - Aging test
  - Production of new electrodes
- **Summary and prospects**

Signal and background in MEG II

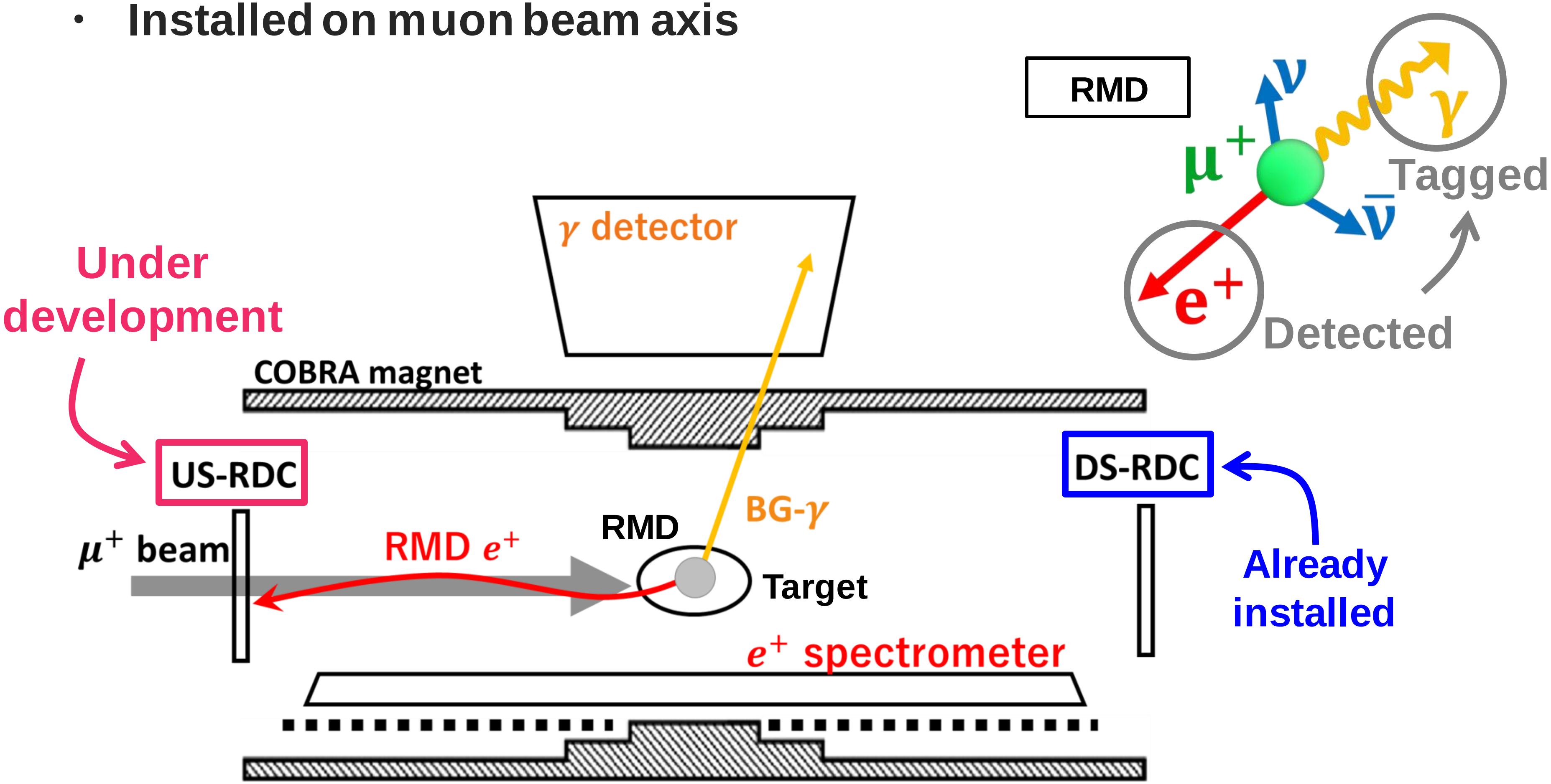
- MEG II searches for $\mu \to e\gamma$ decay
  - Charged lepton flavor violating process
- Main background is accidental background



Radiative Decay Counter; RDC

➢ Detectors for tagging BG-γ from Radiative Muon Decay

- Low energy e^+ is emitted when BG-γ is emitted from RMD
- Installed on muon beam axis

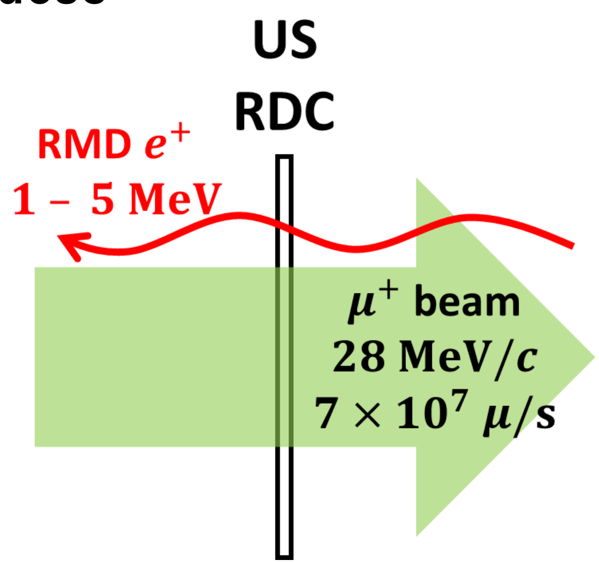


Requirements for upstream RDC

- Upstream RDC needs to detect e^+ from RMD in a **high-rate** $(7 \times 10^7\ \mu/s)$ and **low-momentum** $(28\ \mathrm{MeV/c})$ muon beam

1. Material budget: $< 0.1\ \%$ of radiation length
2. Rate capability: $2.9\ \mathrm{MHz/cm^2}$
3. Radiation hardness: $100\ \mathrm{C/cm^2}$ of irradiation dose
4. Detection efficiency: $> 90\ \%$ for MIP e^+
5. Time resolution: $< 1\ \mathrm{ns}$
6. Detector size: $20\ \mathrm{cm}$ diameter

Developing RPC based on Diamond-Like Carbon electrodes



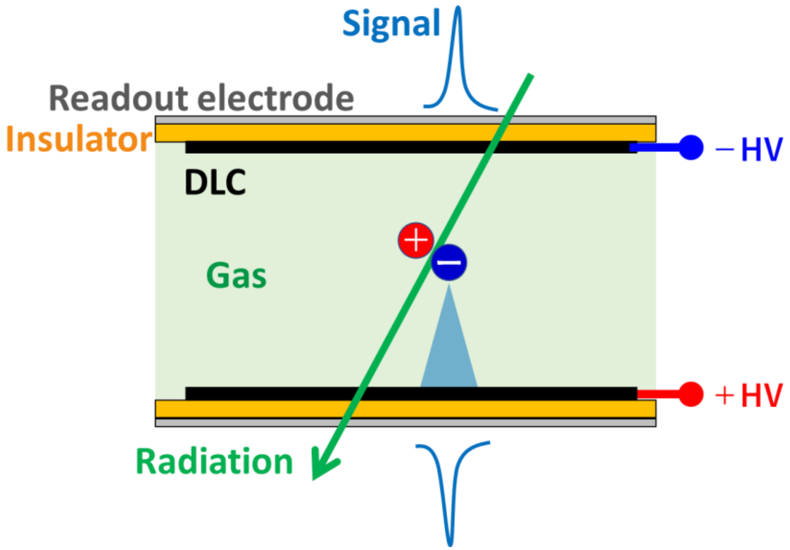
RPC based on DLC electrodes

- **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

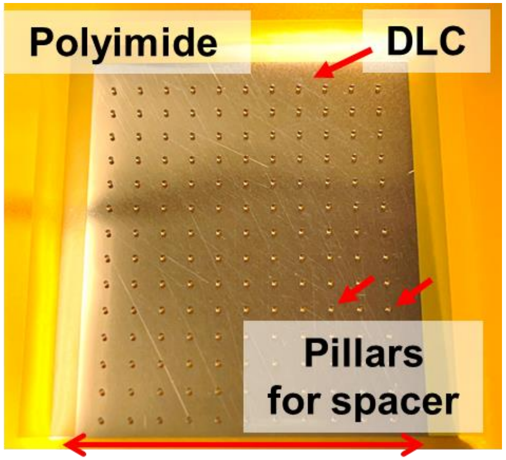


DLC-RPC for MEG II

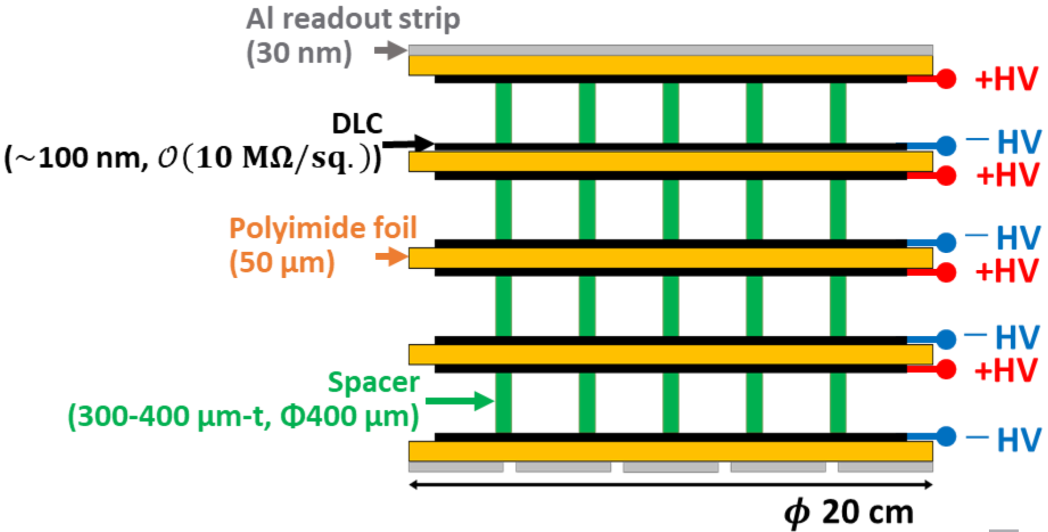
➢ **A series of R&D began in 2016** (As MEG Ⅱ upstream RDC, since 2018)

- Development using a small single-layer prototype
  - DLC sputtered on 50 μm-t polyimide foil
  - DLC surface resistivity: $\sim 40\ \mathrm{M\Omega/sq.}$
  - 384 μm-t pillars formed on DLC as spacers by photolithographic technology
- Full-scale detector will consist of 4 layers

Small prototype electrode



Concepts of full-scale detector



Performance of the prototype DLC-RPC

- **Status of the previous studies**

	Contents	Requirements	Performance of the prototype
○	Material budget	$< 0.1\% \, X_0$	$\sim 0.095\%$ (design with 4 layers)
×	Rate capability	$2.9\ \mathrm{MHz/cm^2}$	$1\ \mathrm{MHz/cm^2}$
?	Radiation hardness	$\sim 100\ \mathrm{C/cm^2}$	Investigated to $\sim 54\ \mathrm{C/cm^2}$
△	Detection efficiency	$> 90\%$	$> 40\%$ (with single layer), $> 90\%$ (calculated with 4 layers)
○	Timing resolution	$1\ \mathrm{ns}$	$160\ \mathrm{ps}$
×	Detector size	$\phi\ 20\ \mathrm{cm}$	$2\ \mathrm{cm} \times 2\ \mathrm{cm}$ (active region)

- **In 2020, rate capability, detection efficiency, and timing resolution were evaluated using the high-intensity muon beam**
  - A. Oya et al., 2022 J. Phys.: Conf. Ser. **2374** 012143
- **In 2023, radiation hardness was evaluated and development is ongoing to achieve the above requirements**

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Developments in 2023

➢ Accelerated aging test of DLC-RPC

- For evaluation of radiation hardness
- Using high-intensity *X*-ray beam
- Also refer to my presentation at Aging Workshop 2023

➢ New electrode development (today's main topic)

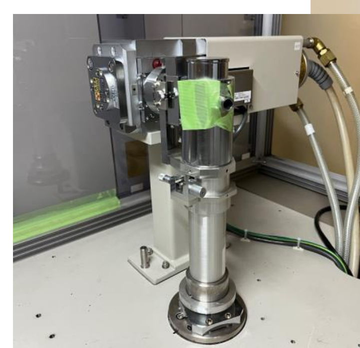
- For improvement of rate capability and operation with 4 layers
  - K. Yamamoto et al., Nucl. Inst. And Methods A **1054** (2023) 168450
- Problems with spacer formation
- Using new material for spacers

Requirement of radiation hardness

- **DLC-RPC is required to operate continuously during the one-year physics run in the MEG II experiment**
  - Physics run period: $20\ \text{weeks/year}$
  - Rate of muon beam at the center: $2.9\ \text{MHz/cm}^2$
  - Average avalanche charge of muon: $3\ \text{pC}$

  ➔ **Total irradiation dose in one year: $\sim 100\ \text{C/cm}^2$**

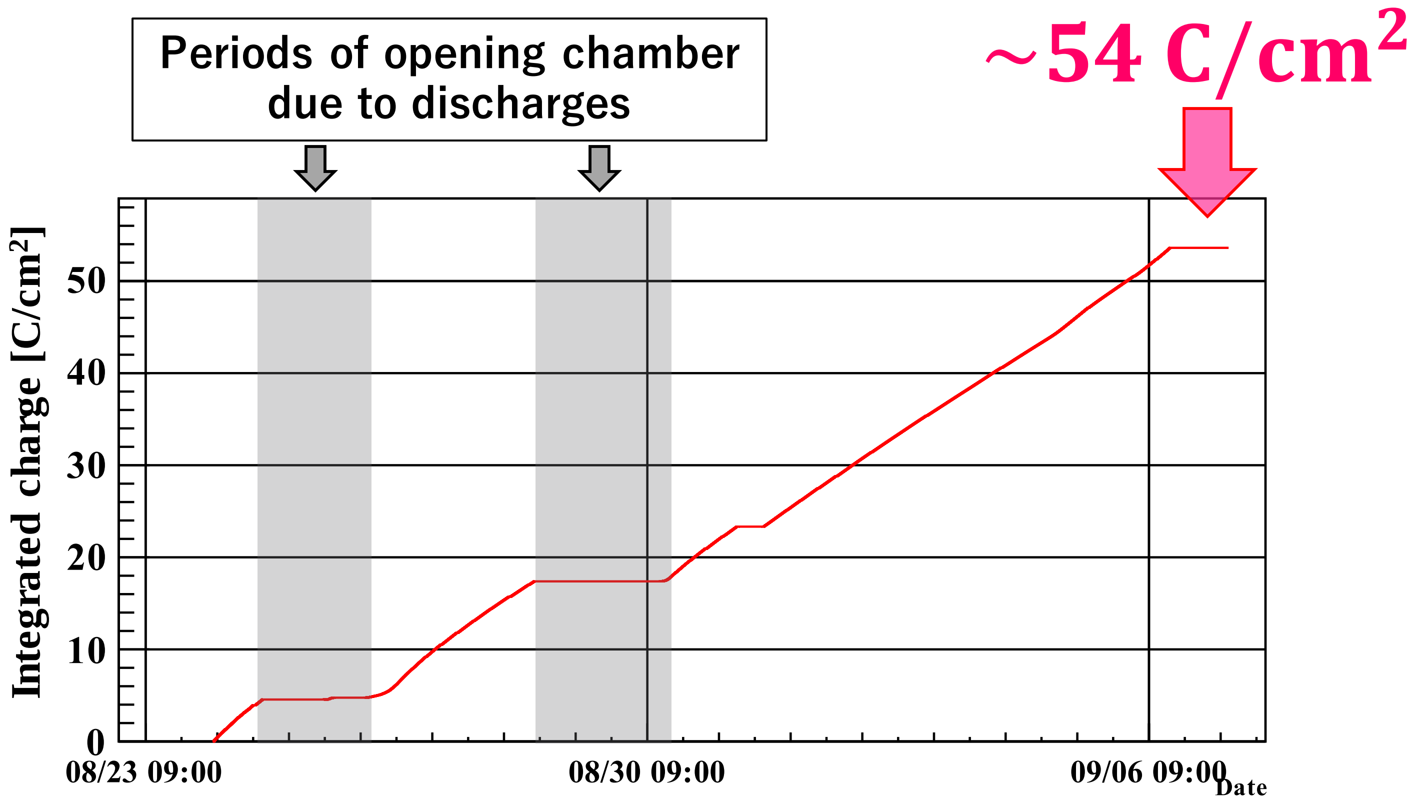
- **Carried out an accelerated aging test in 2023**
  - Using an X-ray generator at KEK
    - Cu target ($8\ \text{keV}\ X$-ray)
    - Localized beam: $\sim 5.7\ \text{GHz/cm}^2$
  - Total irradiation dose was compared by integrated charge



Aging test in 2023

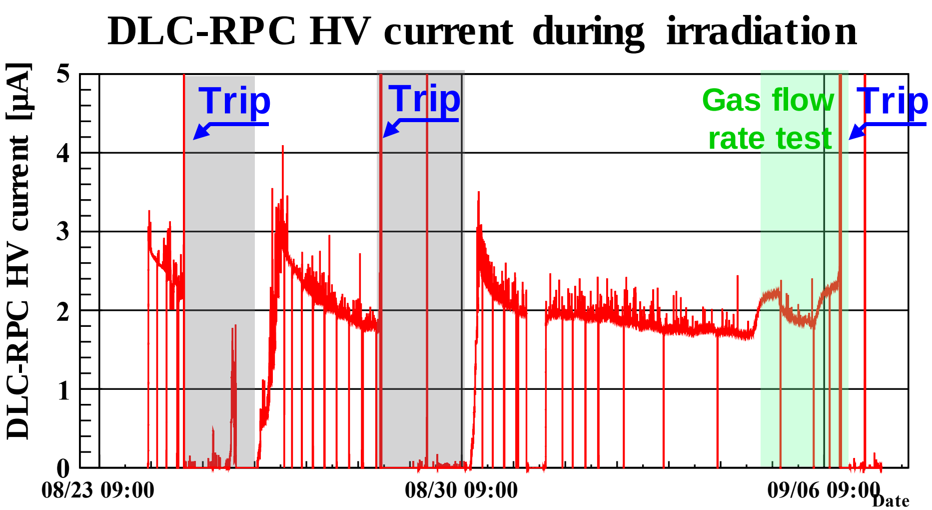
- Test period: 17th Aug. – 11th Sep.

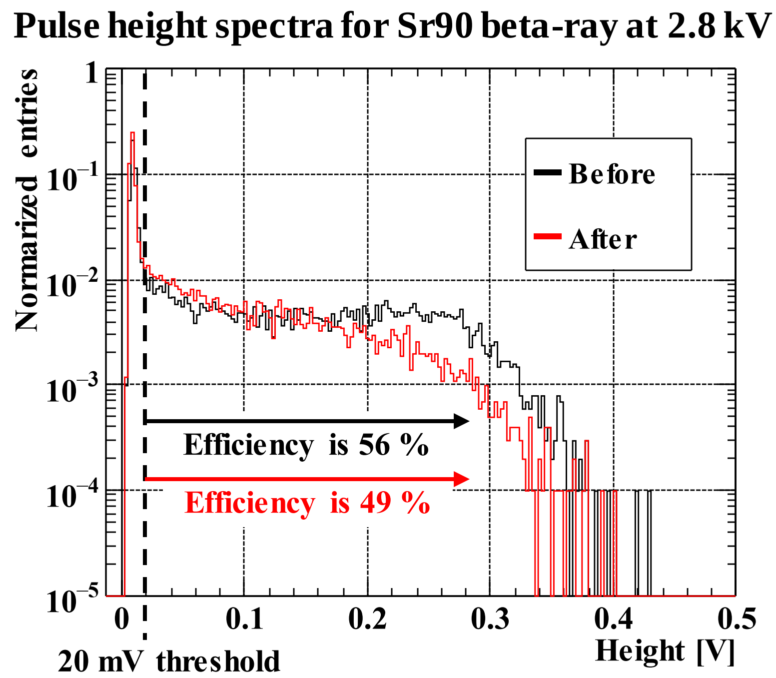
- **Integrated charge flowed over DLC-RPC electrodes:**



Gas gain degradation by irradiation

- **DLC-RPC gain decreased during *X*-ray irradiation**
  - Not correlated to *X*-ray generator output
  - Also the degradation of performance for beta-ray has occurred

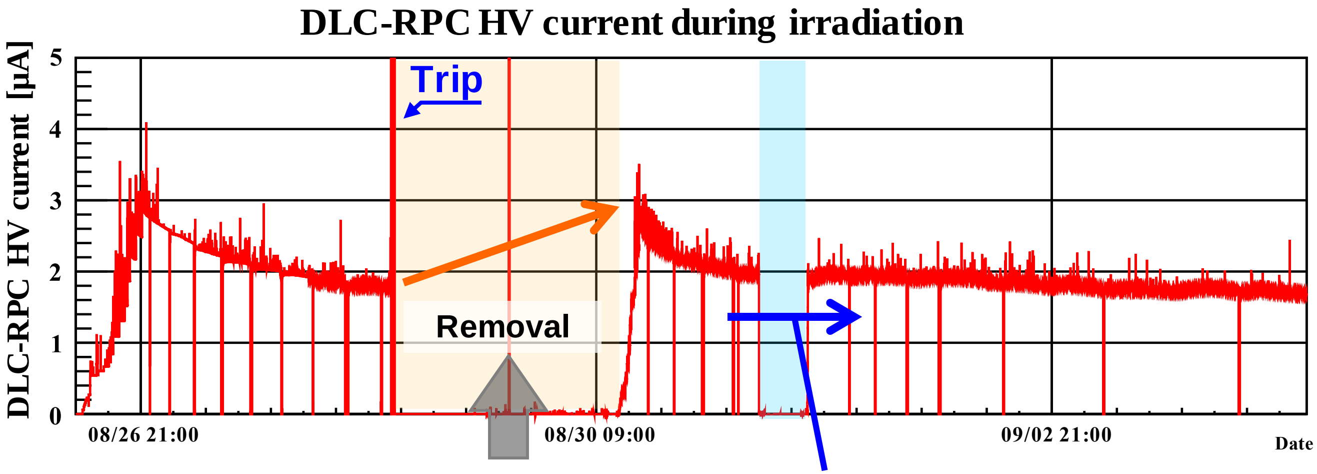


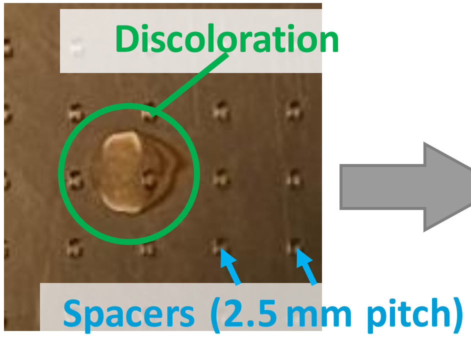


Average pulse height reduced by 21 %

Deposition caused the degradation

- **Formed insulators on DLC electrodes after irradiation**
  - The resistivity of DLC was increased: $\sim 60\ \mathrm{M\Omega} \rightarrow \mathcal{O}(100)\ \mathrm{M\Omega}$
  - After the removal of the deposition,
    the DLC-RPC gas gain and the resistivity were recovered





The gas gain was not recovered without the removal of the deposition

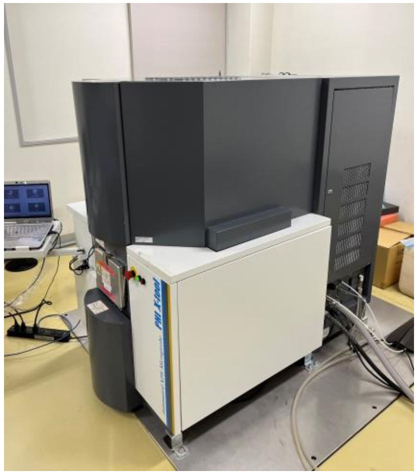
- Gas flow without X-ray irradiation
- High voltage was turned off

Electrode surface analysis

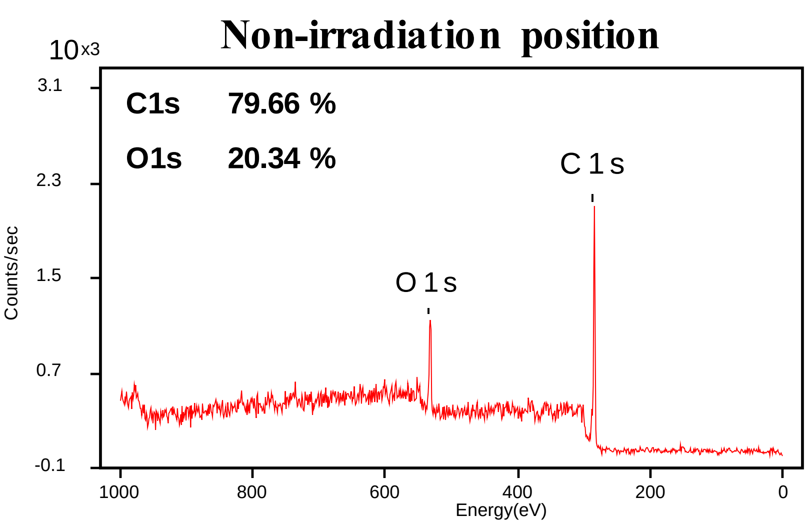
- Using *X*-ray photoelectron spectroscopy

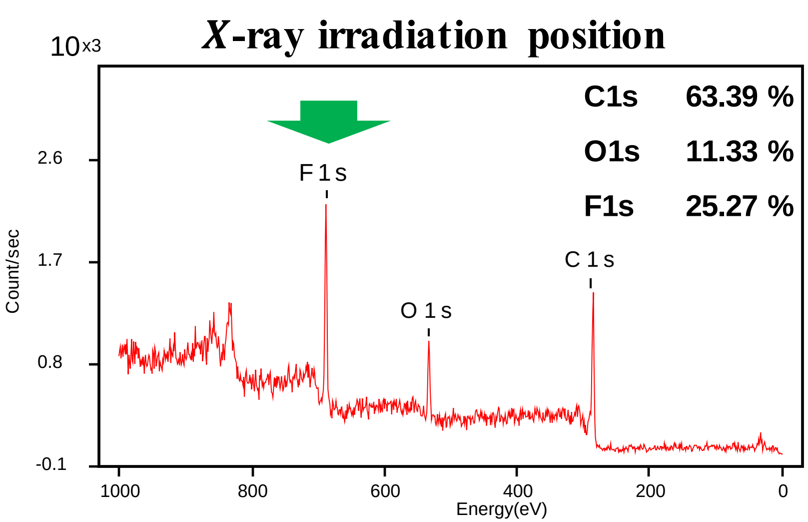
- **Fluorine deposited on DLC electrodes**
  - Fluorine was contained in gas (Freon/iC_4H_{10}/SF_6)
  - SF_6 might create fluorine during an avalanche

$$SF_6 + e^- \rightarrow SF_6^{-*}, \quad SF_6^{-*} \rightarrow SF_5^- + F$$



Ulvac-phi, Inc.
PHI X-tool





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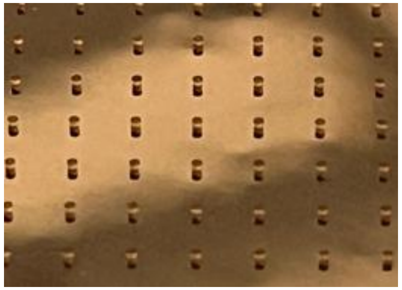
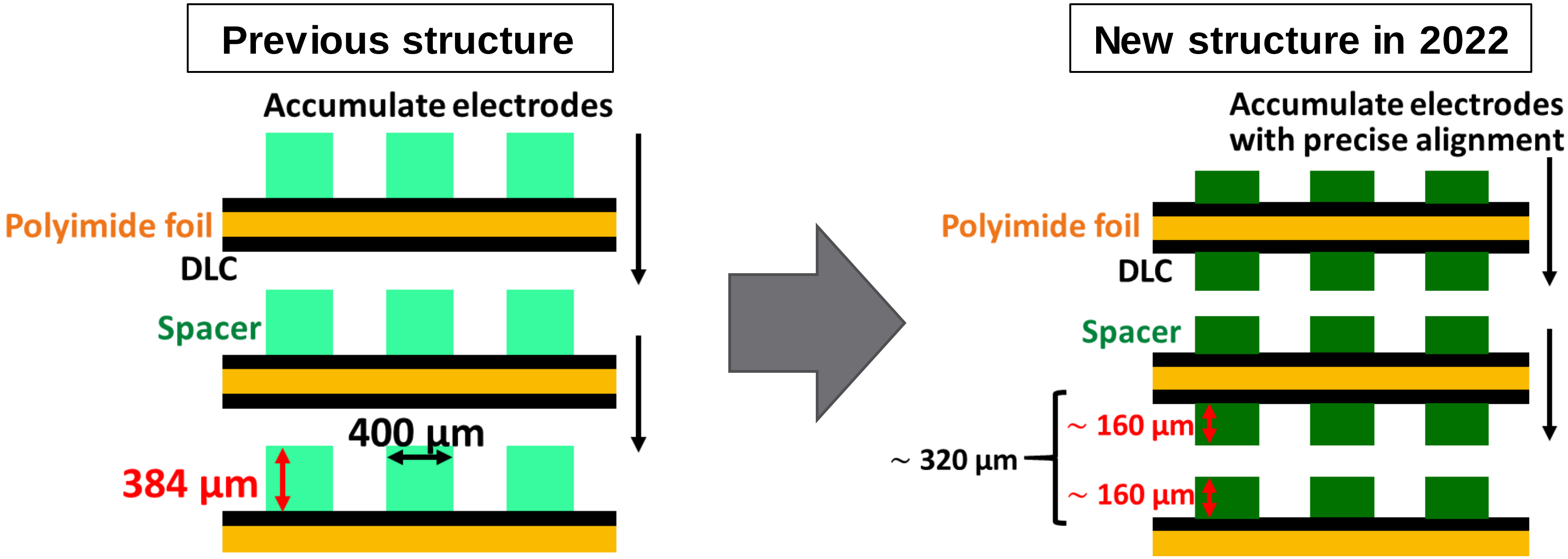
Spacer formation in 2022

- Spacers are formed by photolithographic technology
  - Previous spacer material production cancellation



- New spacer material was used in 2022
  - > 300 μm-thick spacers cannot be formed
    ⇔ 300 μm gap thickness needed for enough efficiency
  - ➔ Doubly accumulate ~ 200 μm-thick spacers

Kensuke reported in RD51 meeting in June 2022

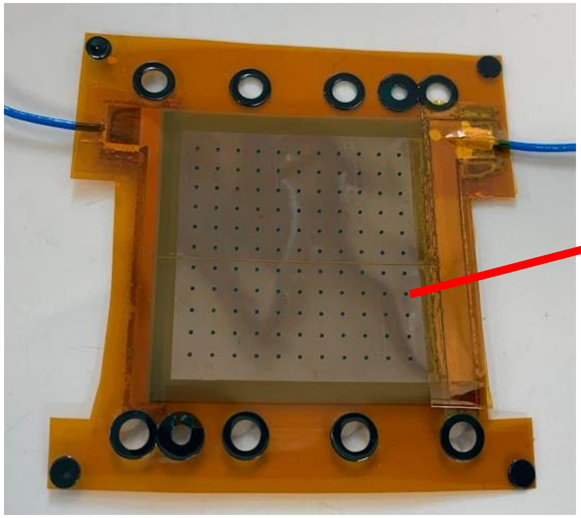


Problems with spacer formation

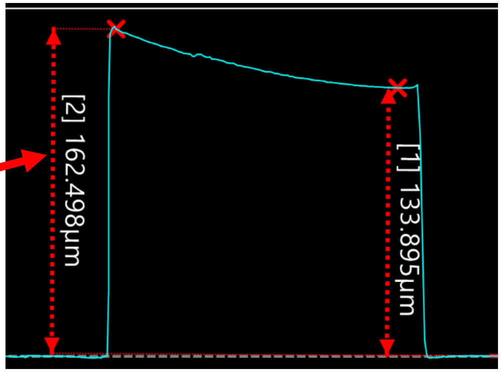
➢ **Main problem: spacer quality**

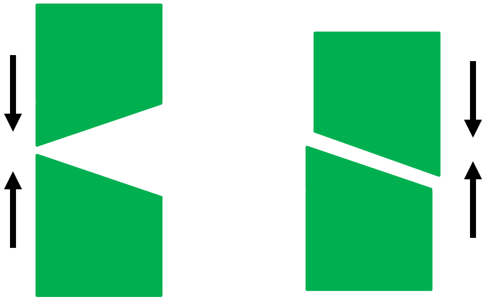
- **Thickness variation: ~ 20 μm**
- **Distorted shape**

Electrode sample in 2022



Profile of the spacer





Doubly accumulated the distorted spacers caused

- **The distortion of the electric field**
- **The distortion of the uniformity of the gap**

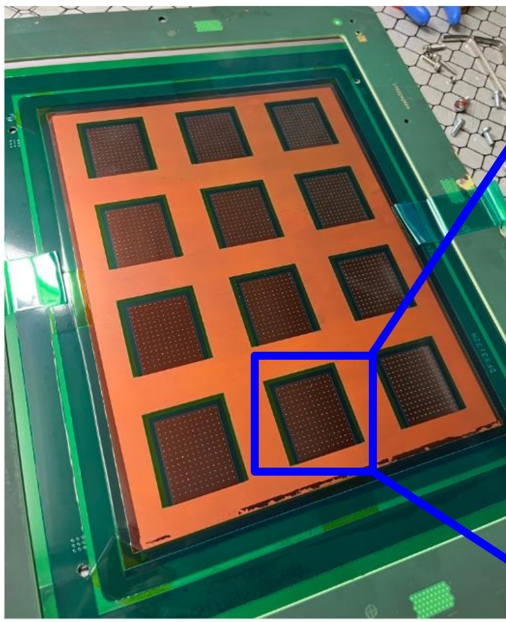
➔ It made operation impossible

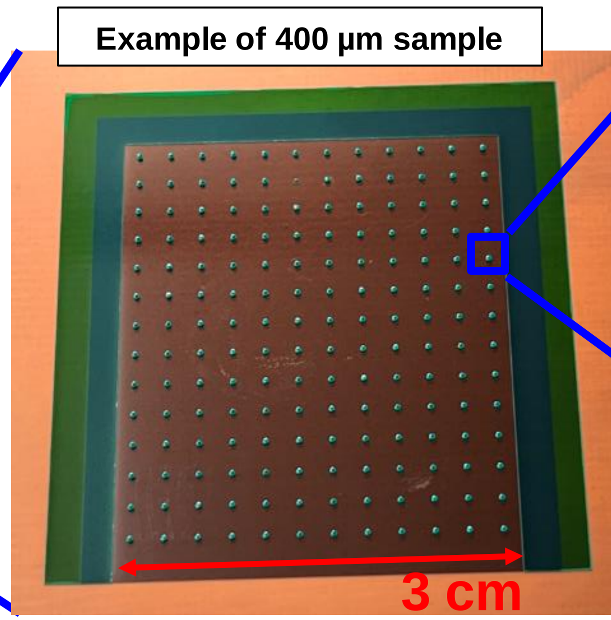
We must improve the spacer quality

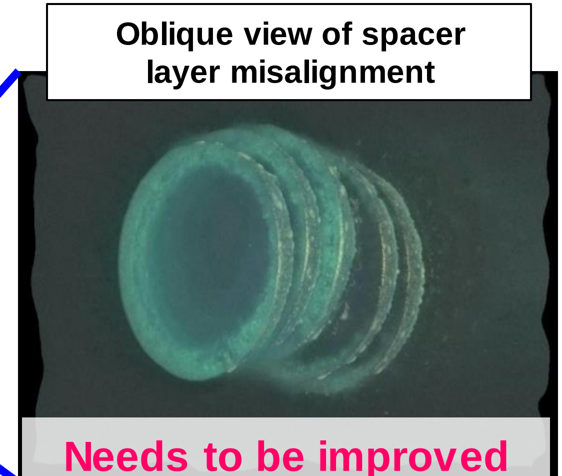
➔ Spacer formation test at CERN in 2023

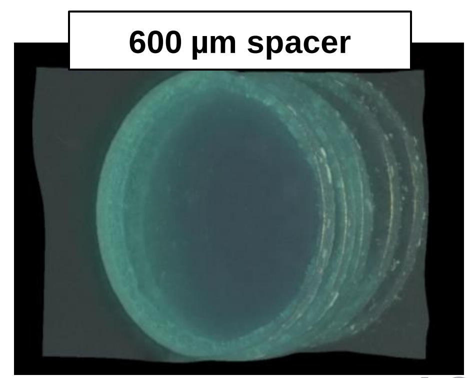
New electrode samples

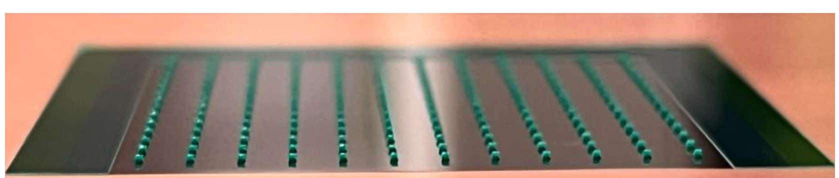
- Electrodes with new spacers were produced at CERN
  - 375 μm-thick spacers (nominal): 75 μm-thick resist × 5 layers
  - Various diameters are 400 μm, 500 μm, 600 μm
  - <u>Thanks to Rui De Oliveira!</u>





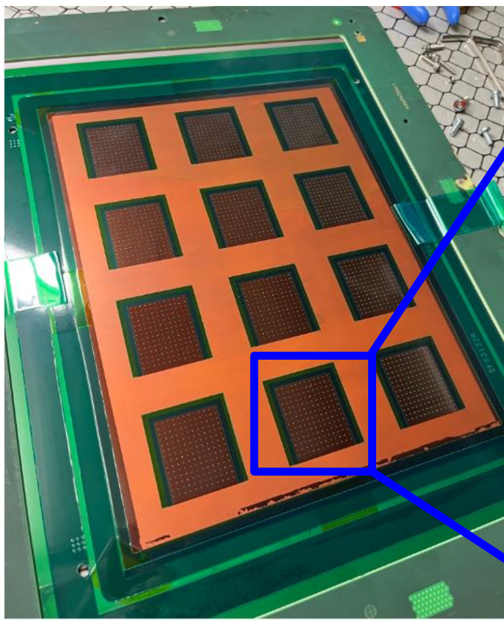




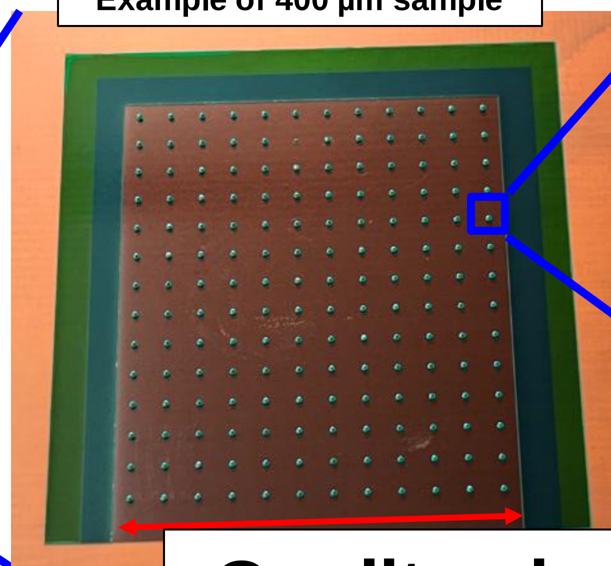


New electrode samples

- Electrodes with new spacers were produced at CERN
  - 375 μm-thick spacers (nominal): 75 μm-thick resist × 5 layers
  - Various diameters are 400 μm, 500 μm, 600 μm
  - <u>Thanks to Rui De Oliveira!</u>

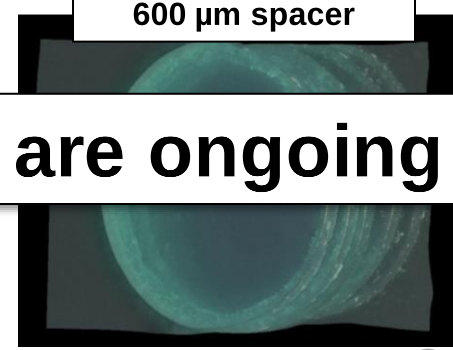


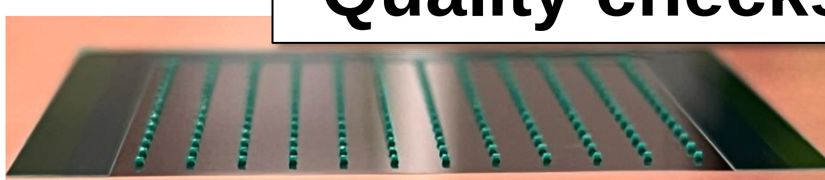
Example of 400 μm sample



Oblique view of spacer layer misalignment

600 μm spacer





Quality checks are ongoing

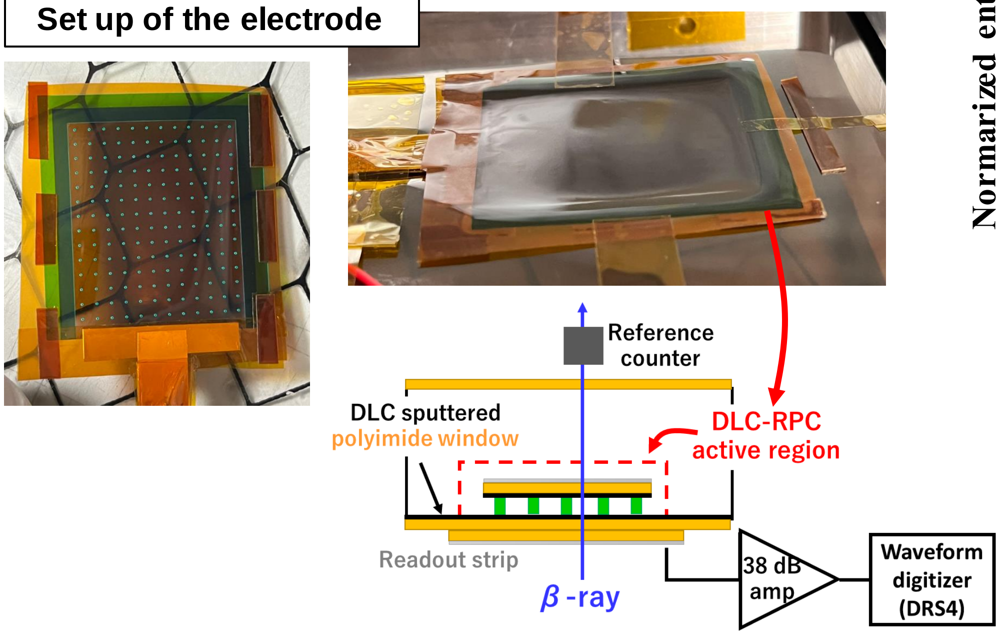
Operation test of the new electrode

- **Investigation of the working point of the new electrode**
  - Expected working point is 2.75 – 2.8 kV
  - Tripped at 2.8 kV in this test

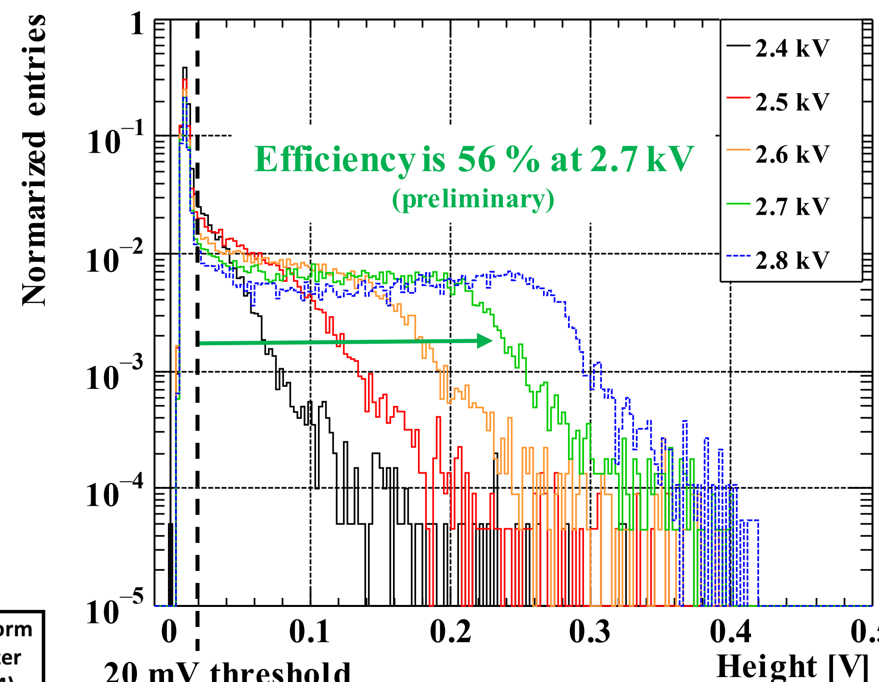
- **The new electrode was working as expected**

  ➔ Aim for stable operation at WP

Set up of the electrode



Pulse height spectra for Sr90 beta-ray



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Summary

- DLC-RPC is under development for MEG II upstream RDC
  - A high-rate and low-momentum muon beam must pass through
- X-ray accelerated aging test was carried out
  - Total irradiation dose: $\sim 54\ \mathrm{C/cm^2}$
    - Expected irradiation dose in MEG II is $\sim 100\ \mathrm{C/cm^2}$
  - Fluorine deposited and formed insulator on DLC electrodes and it caused the degradation of the DLC-RPC gas gain
    - Detection efficiency for Sr90 beta-ray: $56\ \% \rightarrow 49\ \%$
- Production and test of new electrode samples
  - Spacer formation using new material
  - The new electrode was working as expected

Prospects

- **Confirming the usefulness of the new electrode sample**
  - Quality check of new spacers is ongoing
  - We aim to stably operate at WP
- **Production of a new module**
  - To achieve the rate capability in an actual muon beam and detection efficiency with 4 layers
- **Performance test will be carried out using a high-intensity muon beam at PSI in 2024**

Acknowledgements

➢ **This work was supported by**

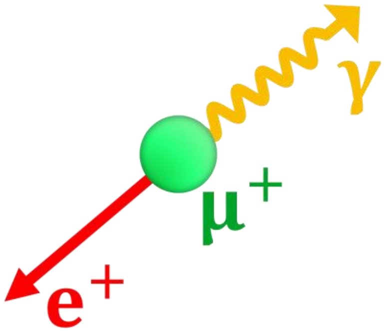
- **The KEK Detector R&D Platform**
- **JSPS KAKENHI Grant Number JP21H04991**
- **JST SPRING, Grant Number JPMJSP2148**
- **Kobe Univ. Research Facility Center for Science and Technology**

Backup

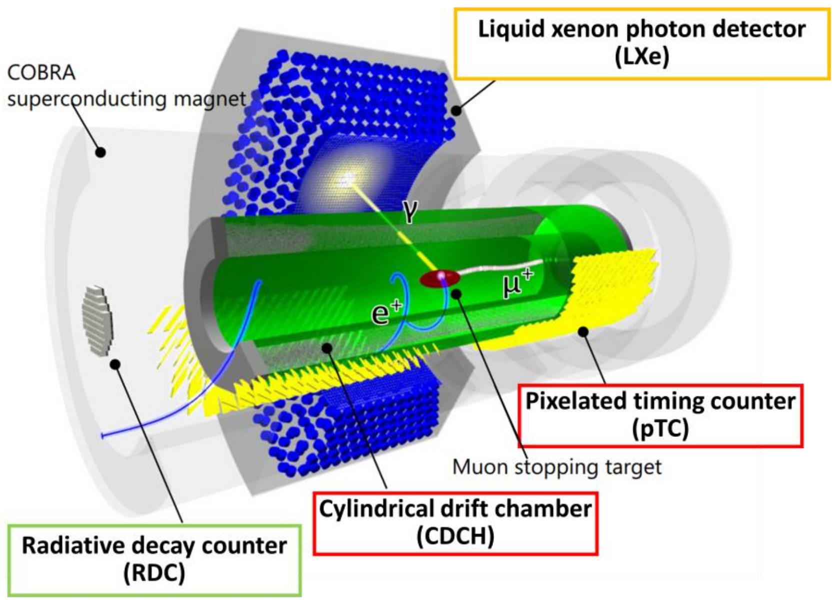
MEG II experiment at PSI

- Searches for $\mu^+ \to e^+\gamma$ decay at Paul Scherrer Institut
  - Charged lepton flavor violating process
    - Prohibited in the Standard Model
    - The new physics predicts observation

➔ **Clear evidence for new physics**

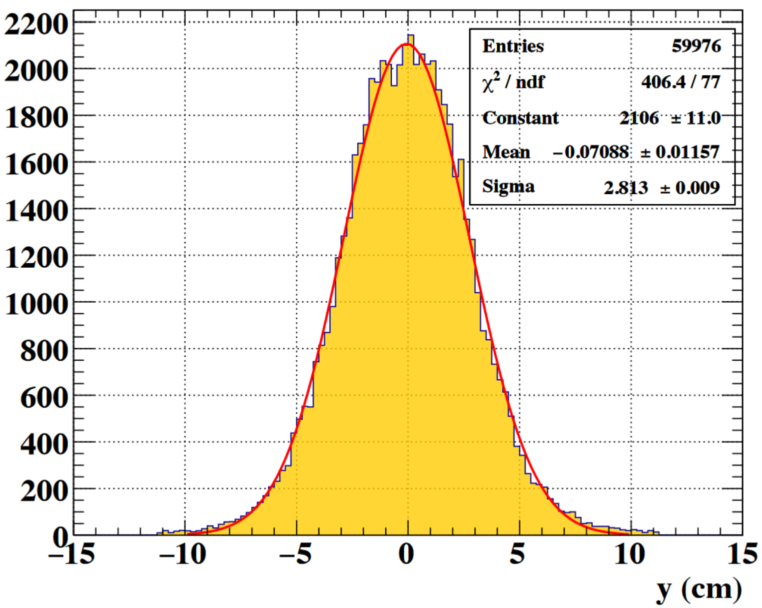


- MEG II apparatus

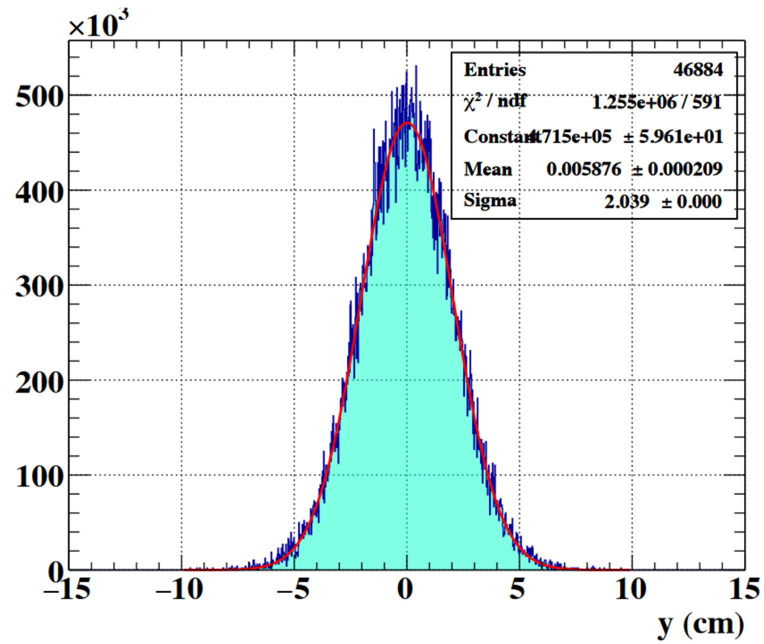


e^+ distribution from RMD

- RMD e^+ are most distributed at the center of the beam line same as muon beam profile
- No holes can be drilled in the detector
  - RMD e^+ are missed

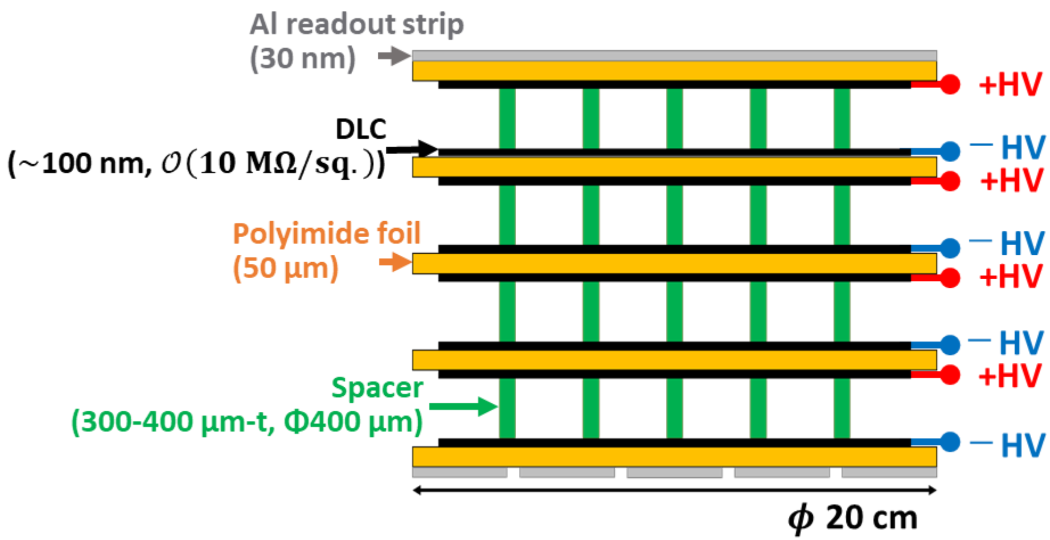


RMD e^+ ($E_\gamma > 48$ MeV)
$\sigma = 2.8$ cm



μ^+ beam profile
$\sigma = 2.0$ cm

Material budget



	Material budget
Polyimide $50\ \mu\mathrm{m}$	$0.0175\ \%\ X_0$
Aluminum $30\ \mathrm{nm}$	$0.0034\ \%\ X_0$
Gas $2\ \mathrm{mm}$	$\sim 0.001\ \%\ X_0$
DLC $\sim 100\ \mathrm{nm}$	negligible

Detection efficiency

- Detection efficiency of n-layer RPC is approximated

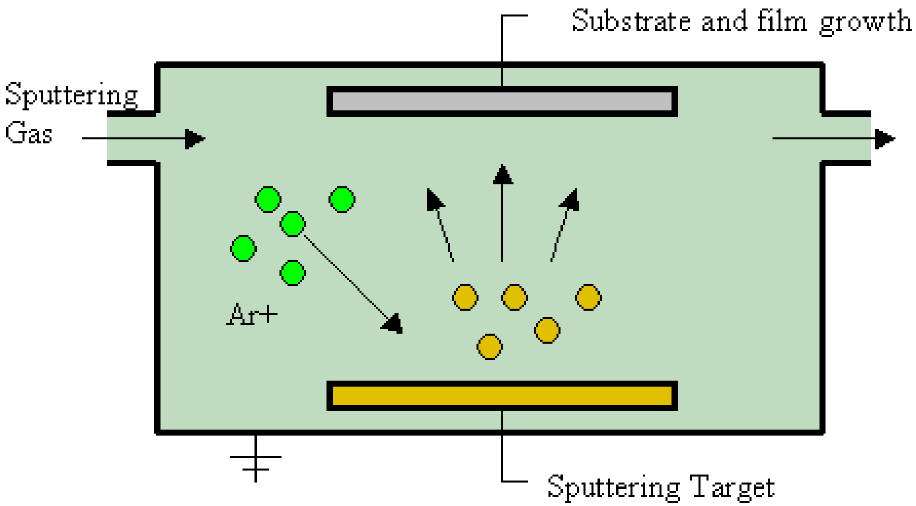
$$\epsilon_n = 1 - (1 - \epsilon_1)^n$$

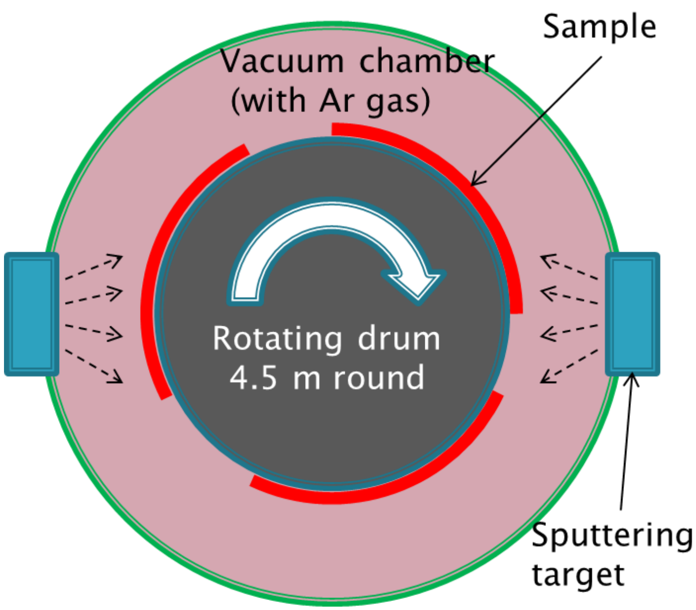
- If more than $90\ \%$ of efficiency is required with 4-layer, the detection efficiency of each layer is required $\sim 40\ \%$ from the above equation

DLC sputtering

➢ Sputtering method

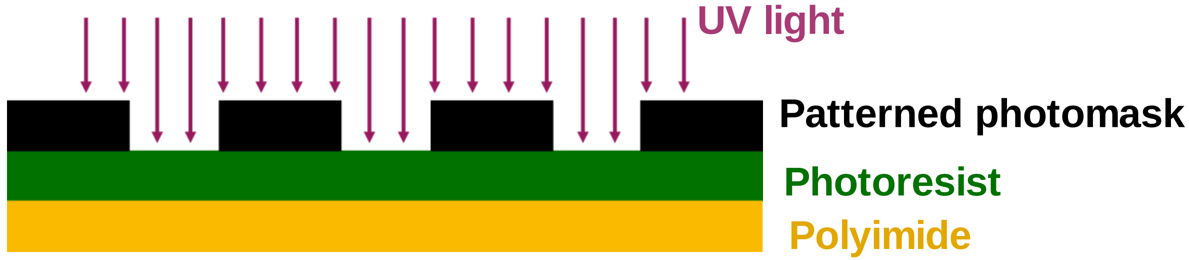
1. Inert gas (mainly Ar) is added in a vacuum
2. Provides a negative charge to a deposition material
   ➔Ionising gas atoms by glow discharge
3. Gas ions collide with target at high velosity
4. Tapped target constituent particles adhere to and are deposited on the substrate surface
   ➔Forms thin films





Photolithographic technology

1. Masked and exposed to UV light



2. Dissolve non-exposed areas with a developer

3. Pillar is completed

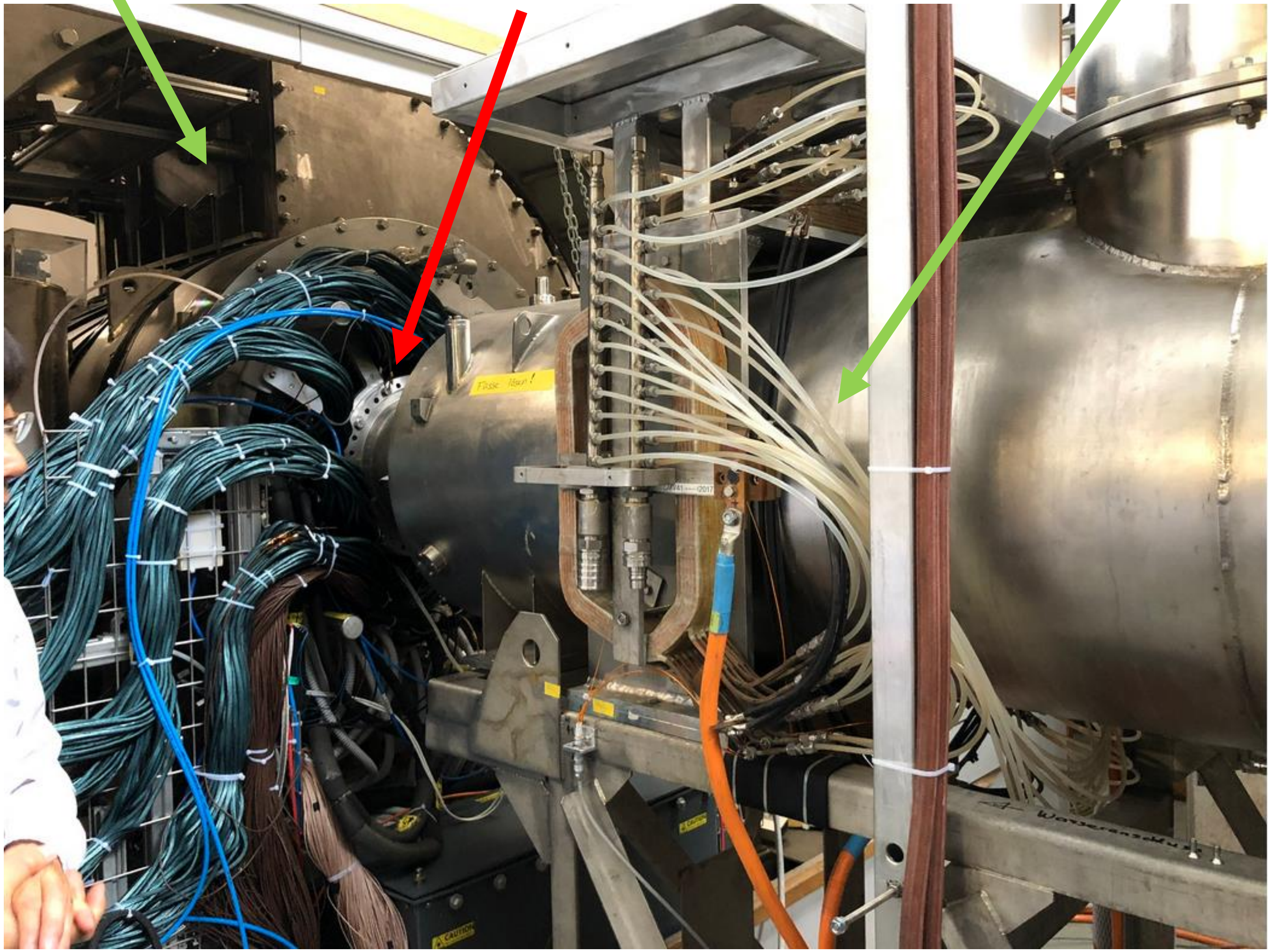
4. Heat harden（Baking)

Detector installation

MEG II detectors

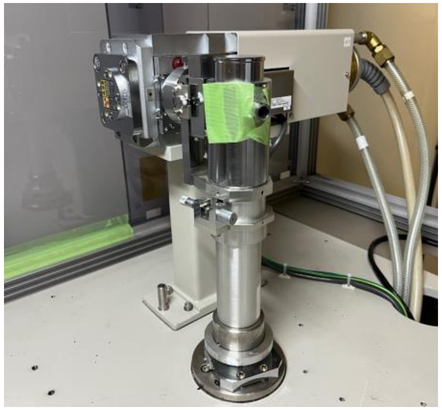
Installation position of DLC-RPC

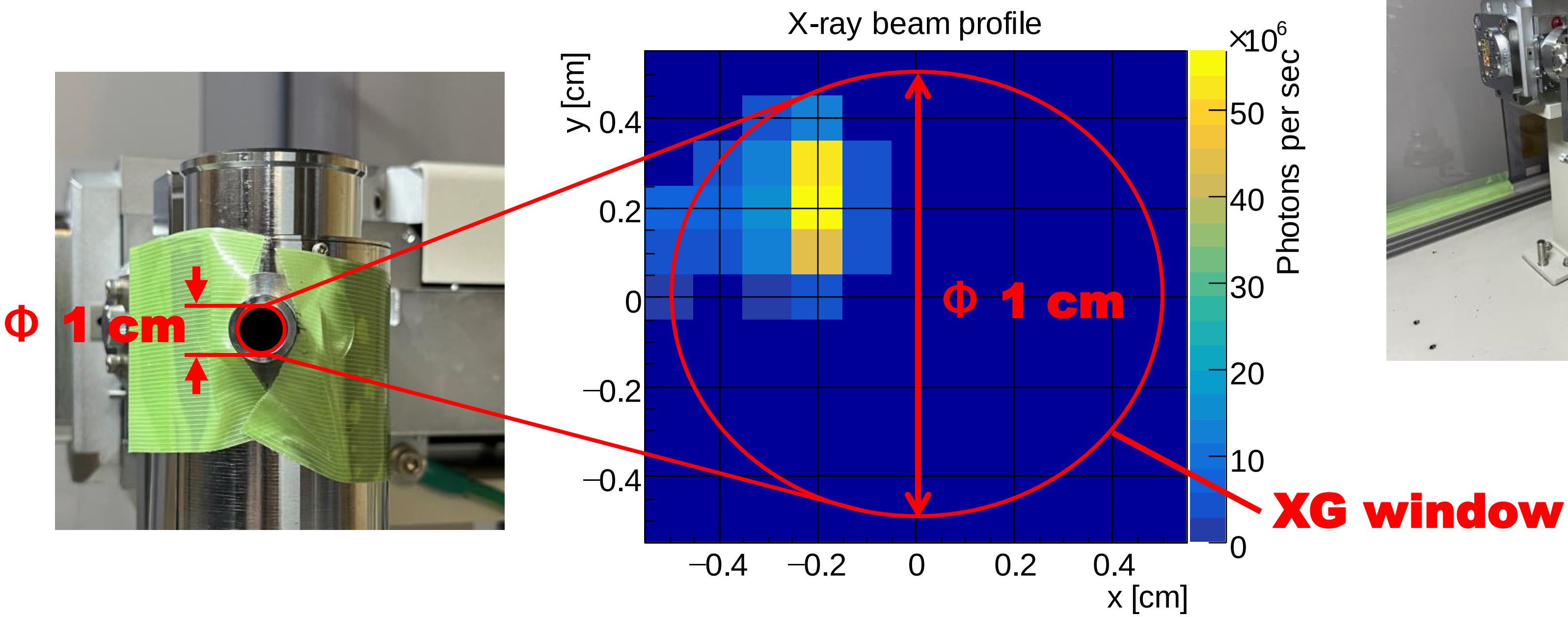
Beam transport solenoid



DLC-RPC irradiation campaign in 2023

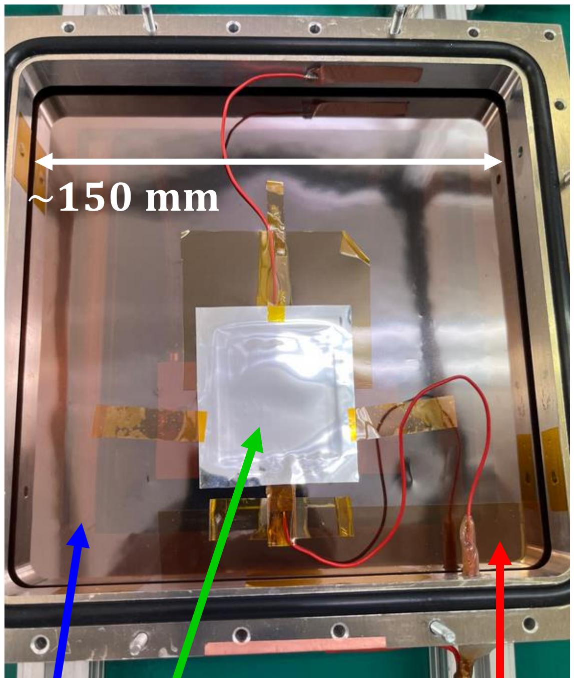
- **Using X-ray generator at KEK**
  - Test period : Aug. 17th 2023 – Sep. 11th 2023
  - X-ray generator properties
    - Cu target with monochromator ($8\ \mathrm{keV}$ X-ray)
    - Maximum power $1.8\ \mathrm{kW}$
    - Beam profile is localized: $\sim 5.7\ \mathrm{GHz/cm^2}$
      - MEG II environment: $2.9\ \mathrm{MHz/cm^2}$





Setup of inside the chamber

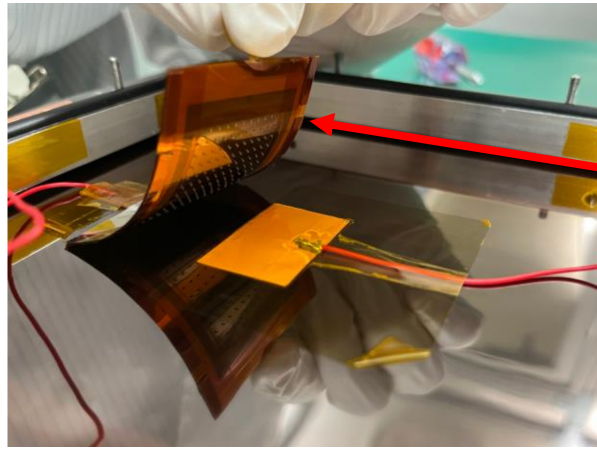
Inside the chamber

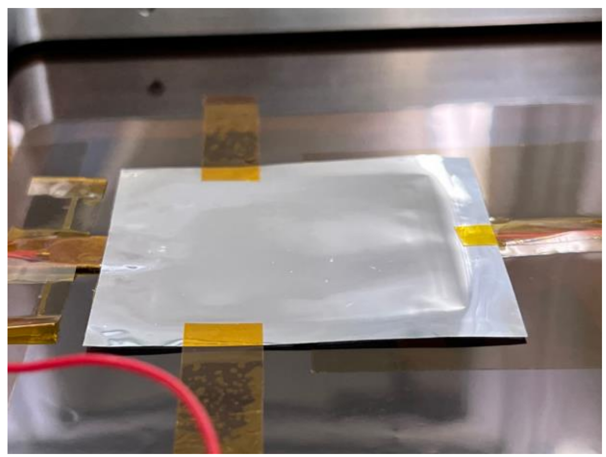


DLC-RPC electrode sample

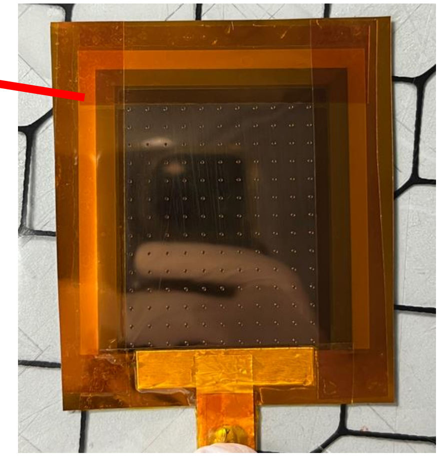
HV supply line

DLC sputtered chamber window

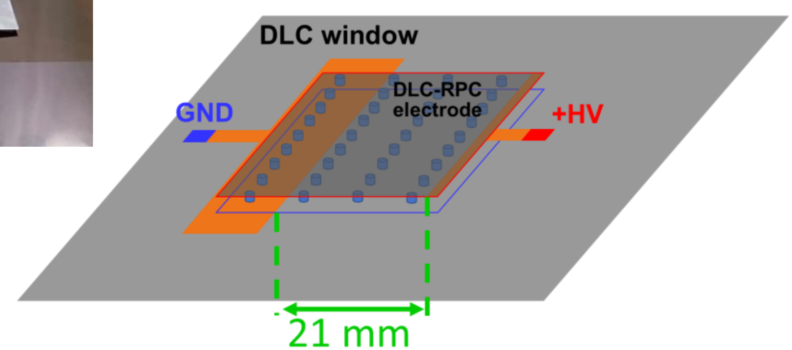




DLC-RPC electrode sample



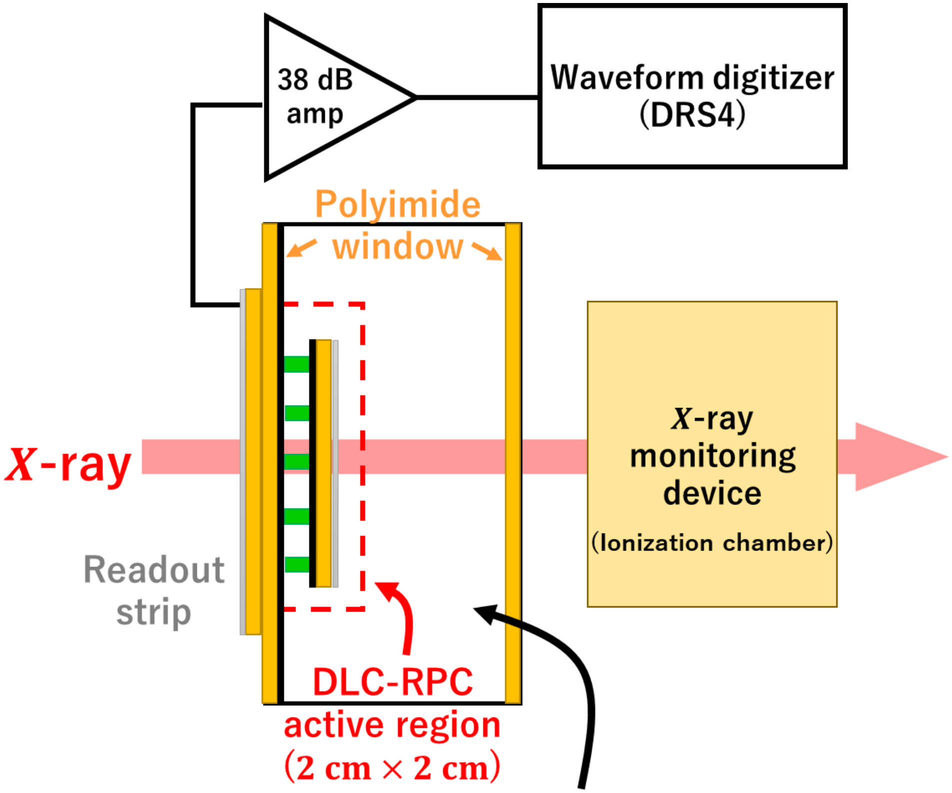
Scheme of configuration



Distance between conductors

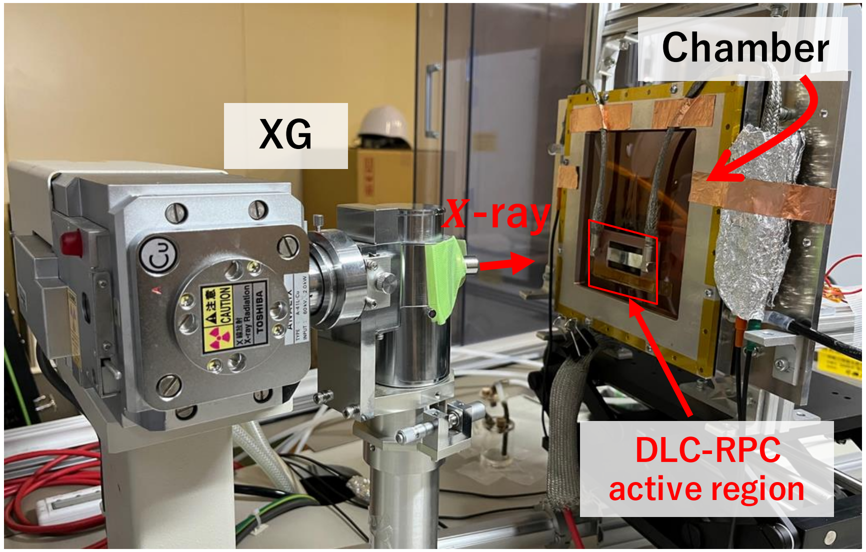
Setup of irradiation test

Setup schematic



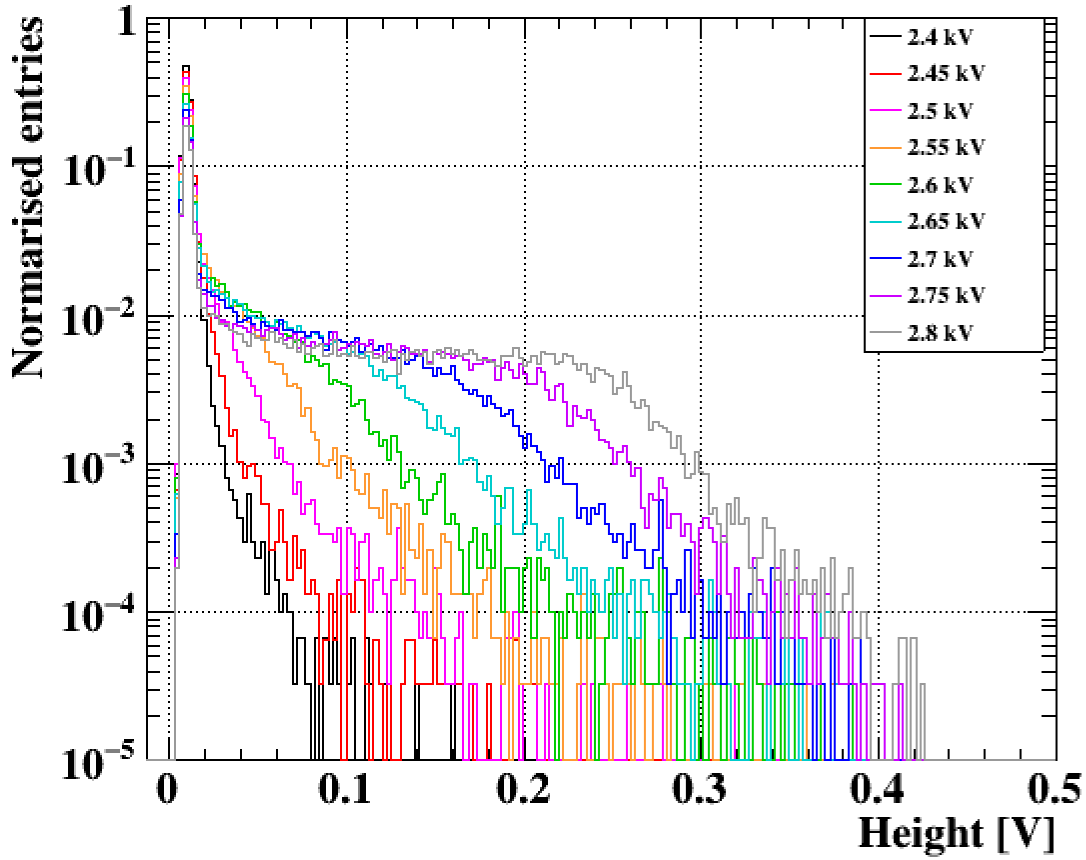
Gas mixture is standard RPC gas
Freon (R134a)/iC4H10/SF6 = (94/5/1) %

Front of the chamber



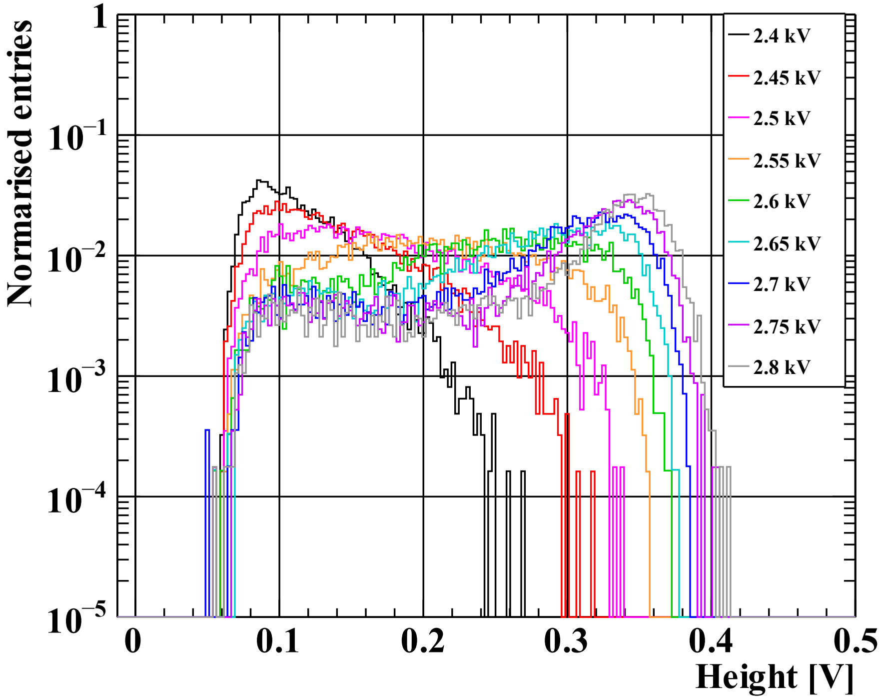
X-ray generator is very close to the chamber window during irradiation

Pulse height spectra for beta-ray

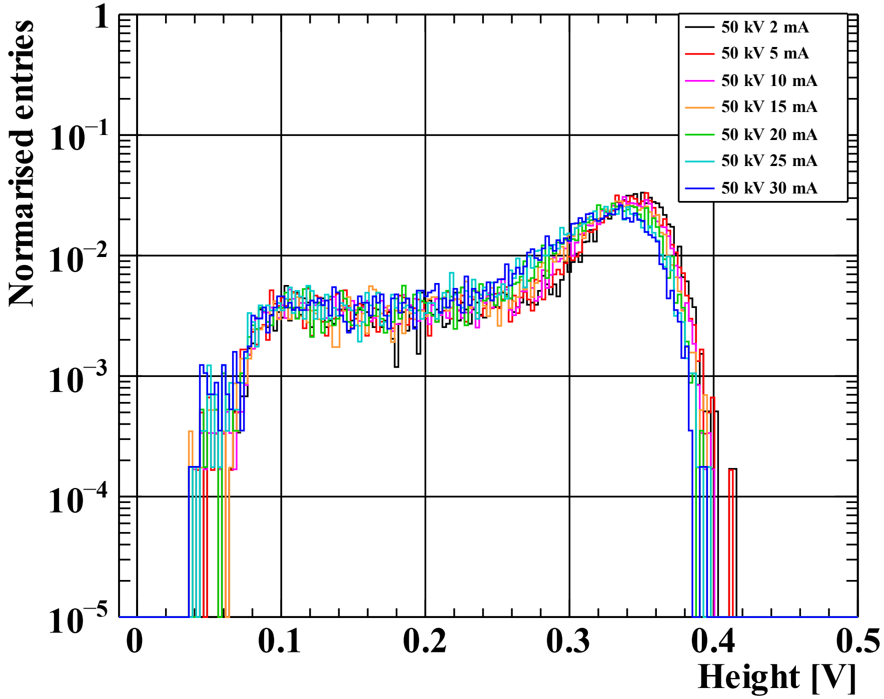


Pulse height spectra for X-ray

DLC-RPC HV scan with minimum X-ray intensity

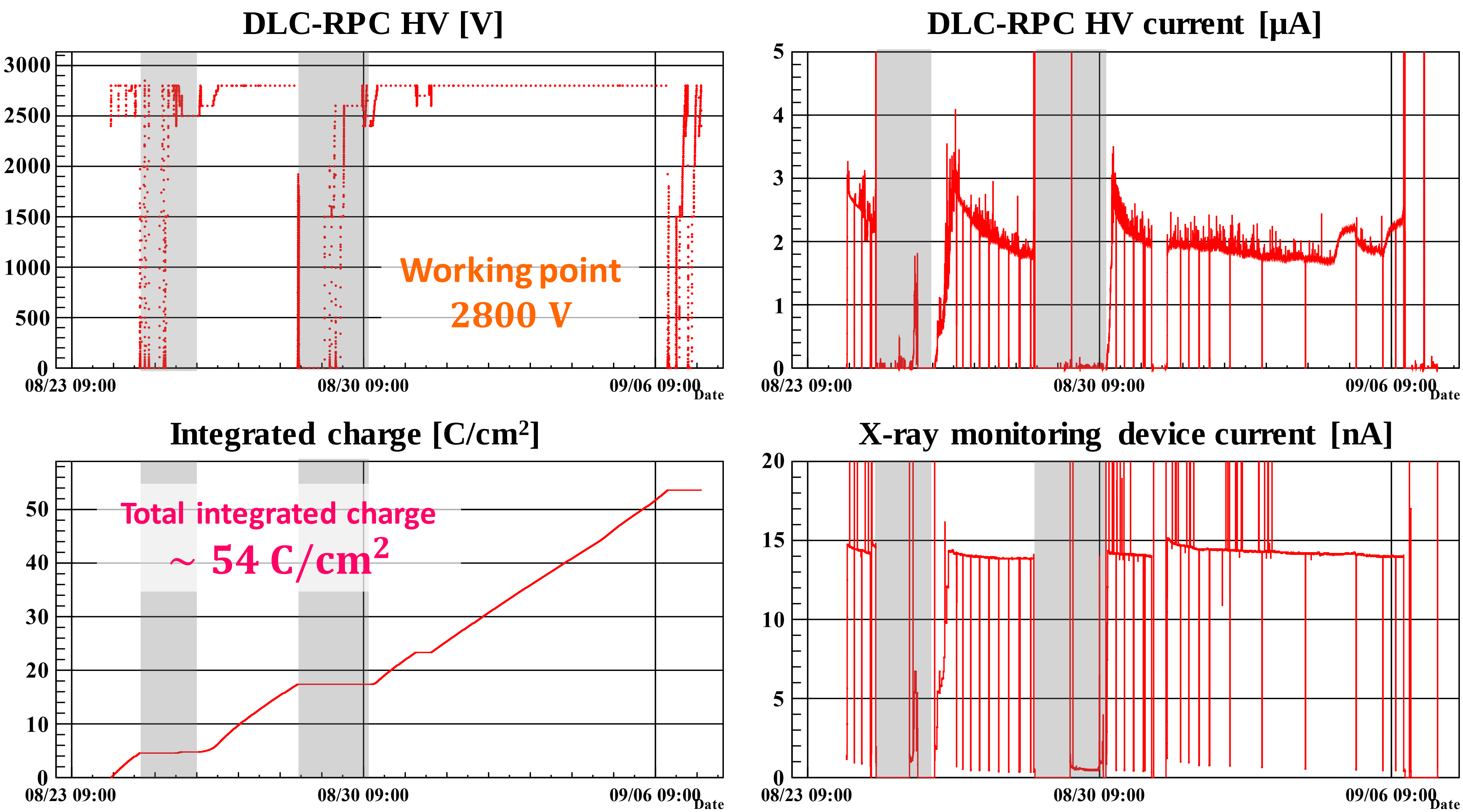


X-ray intensity scan



DLC-RPC status during *X*-ray irradiation

- Shaded period: opening chamber due to discharges



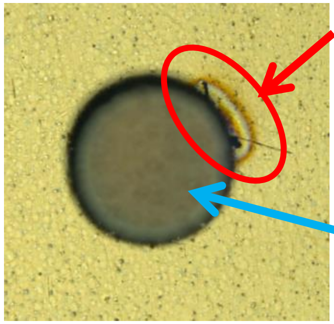
Discharge problems

- Discharges via spacers often occur
  - Once discharges at the spacer occurs, it made continuous operation impossible
  - In addition, discharges via the spacer can occur repeatedly even after cleaning with alcohol wiping or air spray

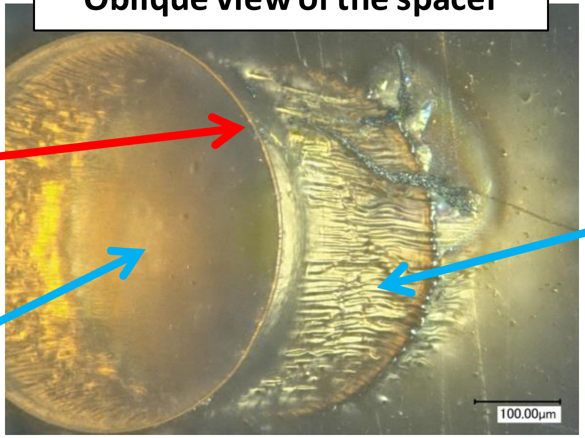
➔ Discharge via spacers must be suppressed for long-term stability

- Improve quality control of cleanliness
- Discharge due to irradiation near the spacer even without dust ➔ optimize spacer design

Top view of the spacer



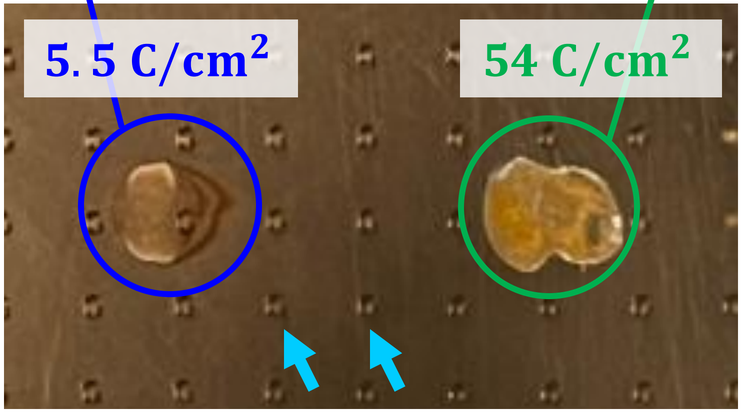
Oblique view of the spacer



Other aging effect: DLC electrode defect

- **DLC peeled off by irradiation and discharges**
  - **Difficult to distinguish between the effects of irradiation and discharges**
  - **DLC has not peeled in a location with low total irradiation and no discharges**
    - **Further irradiation might cause DLC to peel off as well**

DLC not peeled off **DLC peeled off**



Spacers (2.5 mm pitch)

Fluorine sources

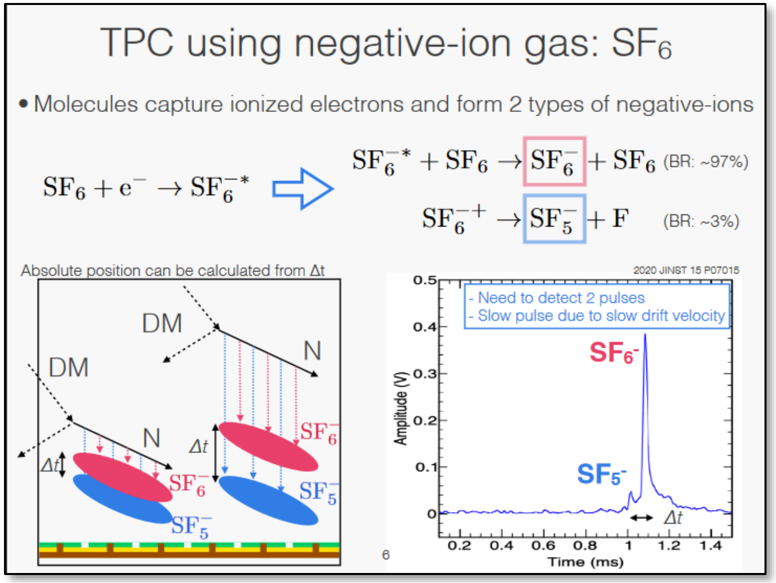
- **Freon (R134a/C2H2F4) is stable**
  - **We think fluorine might not separated**

- **SF_6 might create fluorine during avalanche**

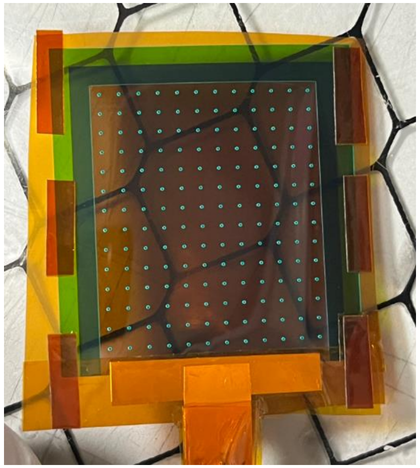
$$\mathbf{SF_6 + e^- \rightarrow SF_6^{-*}, \quad SF_6^{-*} \rightarrow SF_5^- + F}$$

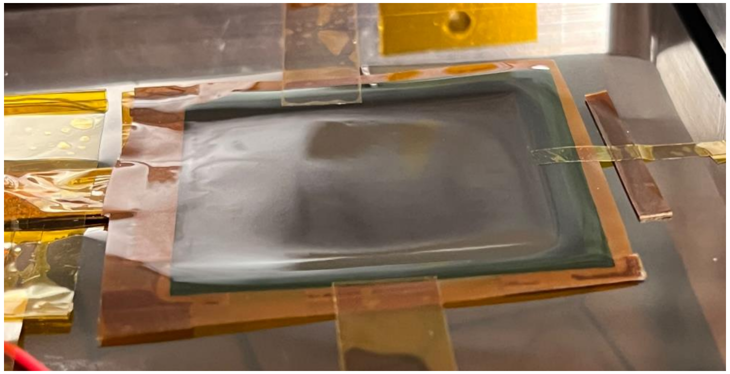
  - **Dark matter searches group at Kobe Univ. is using above reaction for TPC**

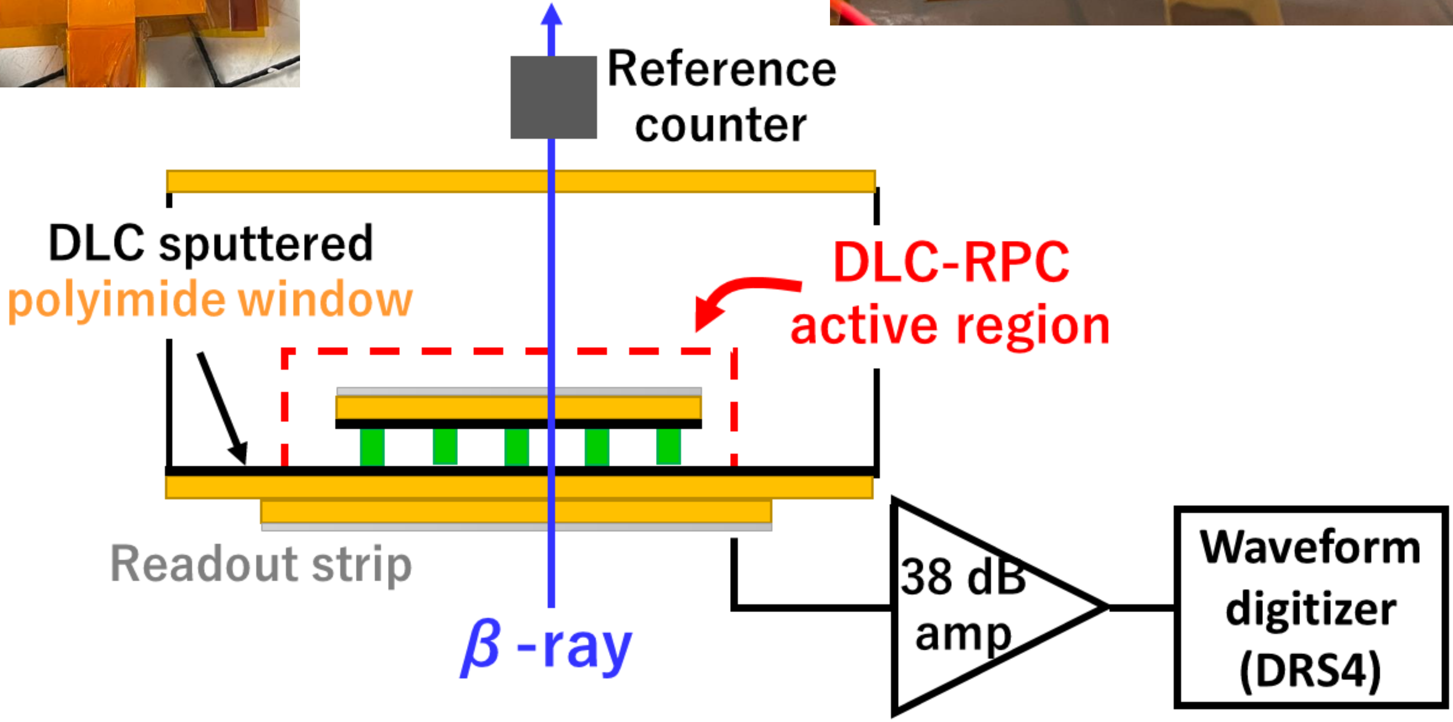
MPGD2022, Satoshi Higashino's presentation
https://indico.cern.ch/event/1219224/contributions/5130778/



Setup scheme

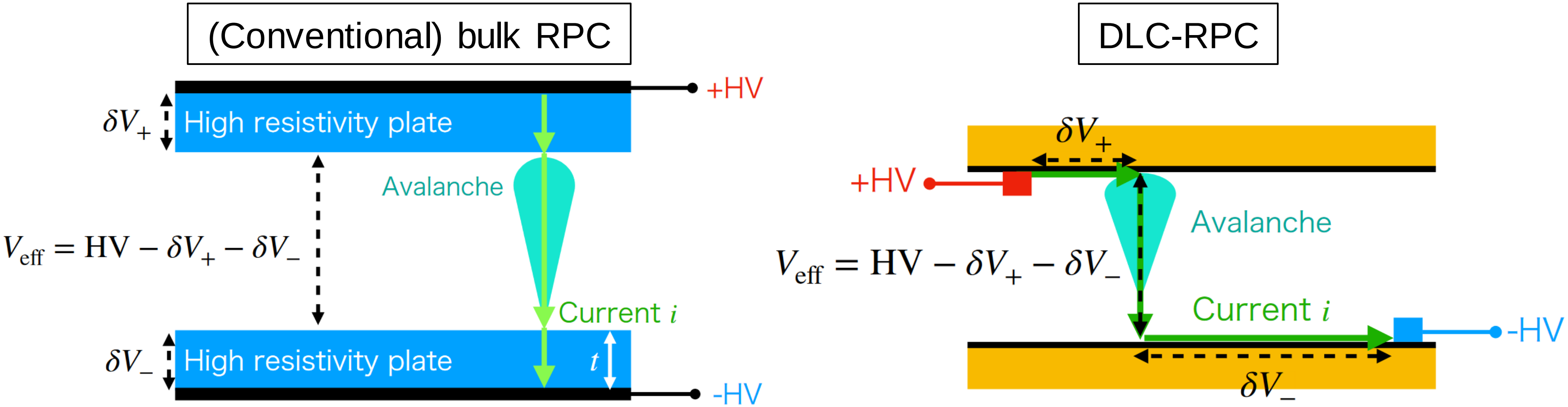






Rate capability

- **Large current on resistive electrodes at a high rate**
  - ➔ Voltage drop δV reduces effective applied HV V_{eff}
  - ➔ Gas gain reduction
- **Current paths are different between conventional and DLC-RPC**
  - ➡ The distance between conductors affects voltage drop



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

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

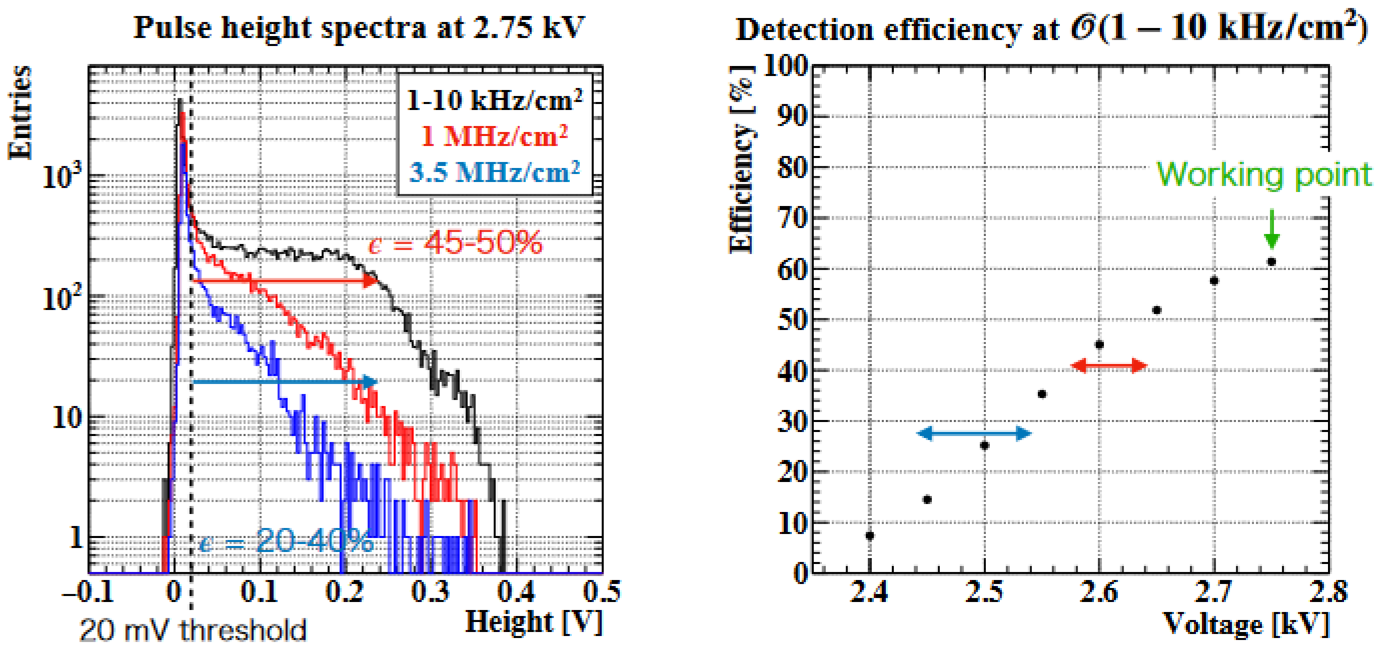
- Kensuke Yamamoto's presentation at the RPC2022 conference
- https://doi.org/10.1016/j.nima.2023.168450

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

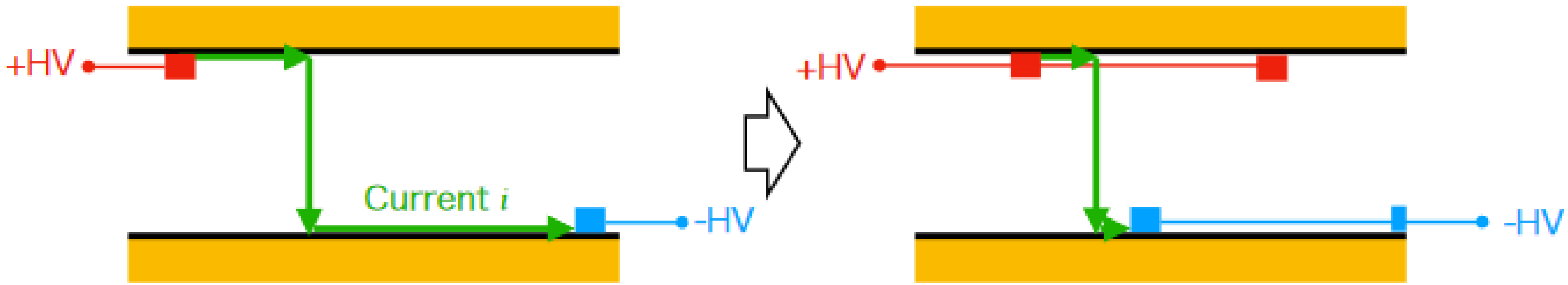


- Kensuke Yamamoto's presentation at the RPC2022 conference
- https://doi.org/10.1016/j.nima.2023.168450

Electrode to be improved

- Voltage drop should be suppressed for higher rate capability
  - HV supply segmented for short current flow (1 cm pitch)
    - **Voltage drop ∝ (current flow distance)^2**
    - Need also for scalability
  - **Resistivity should be low** (10 MΩ/sq.)
    - Voltage drop ∝ (sheet resistivity)
    - Not too low for stable operation

➜ Voltage drop will be 60-80 V at 4 MHz/cm^2



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