Radiation Hardness Studies of RPC Based on Diamond-Like Carbon Electrodes for MEG II Experiment

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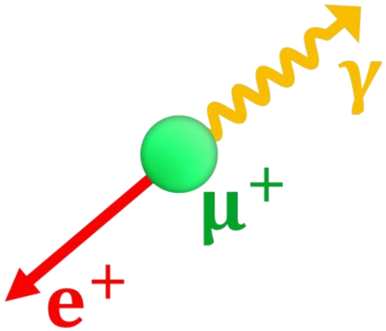
Outline

- Introduction
  - MEG II experiment
  - Radiative Decay Counter
  - RPC based on Diamond-Like Carbon electrodes
- Radiation hardness of DLC-RPC
  - DLC-RPC irradiation campaign 2023
  - Results of aging test
- Summary and prospects

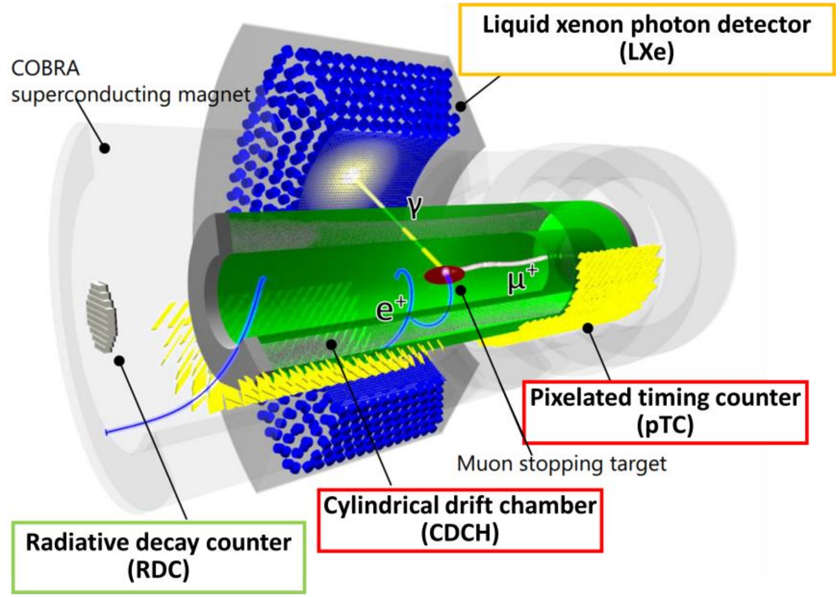
MEG II experiment at PSI

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



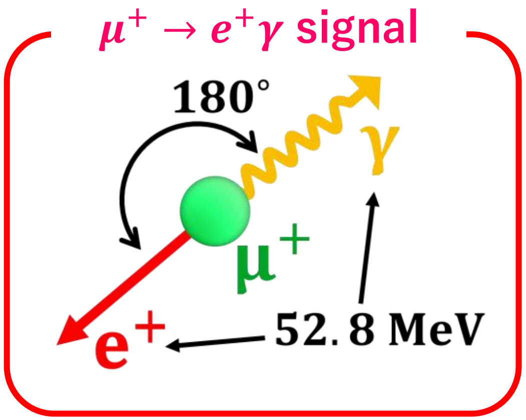
➔ Clear evidence for new physics

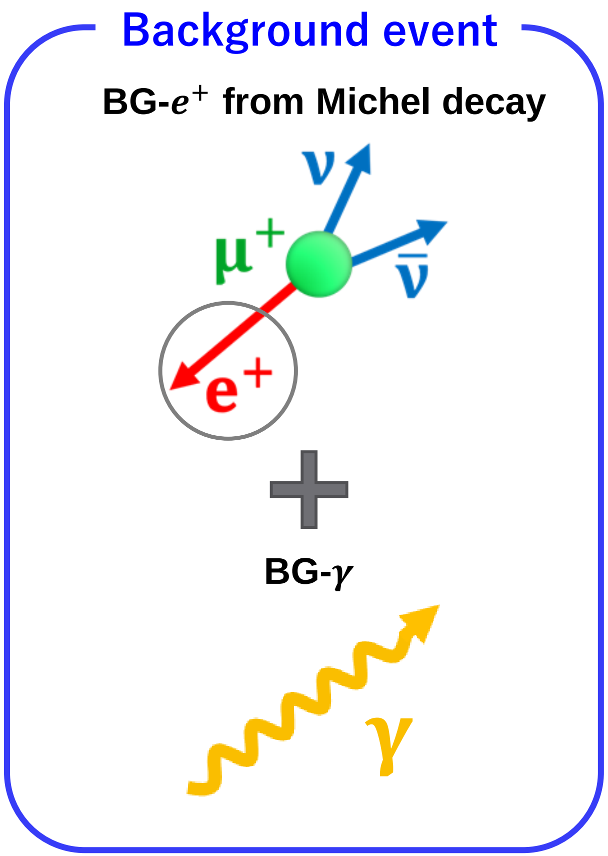
- MEG II apparatus

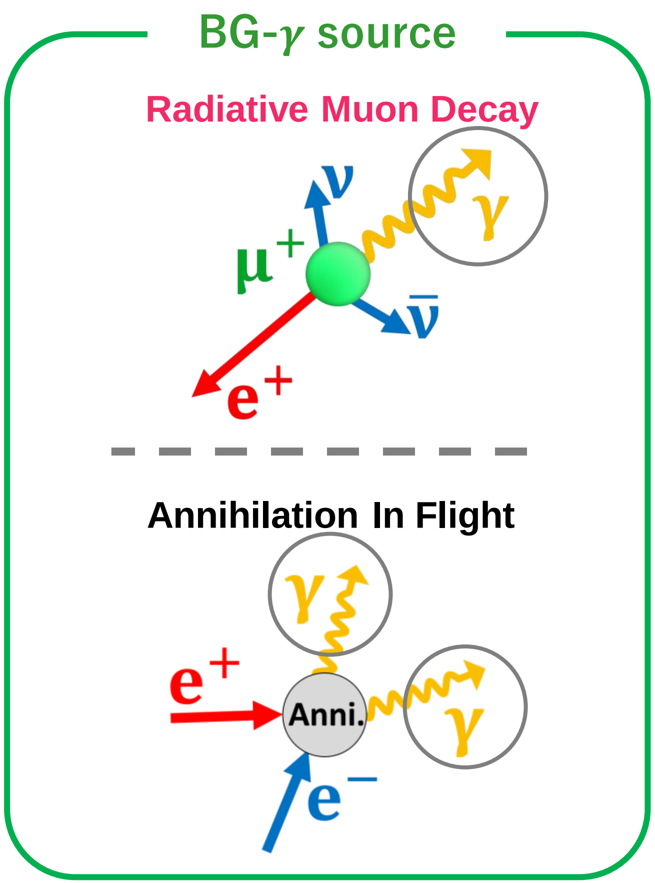


Signal and background in MEG II

- Main background is accidental background
  - Accidental coincidence between BG-γ and BG-e^+



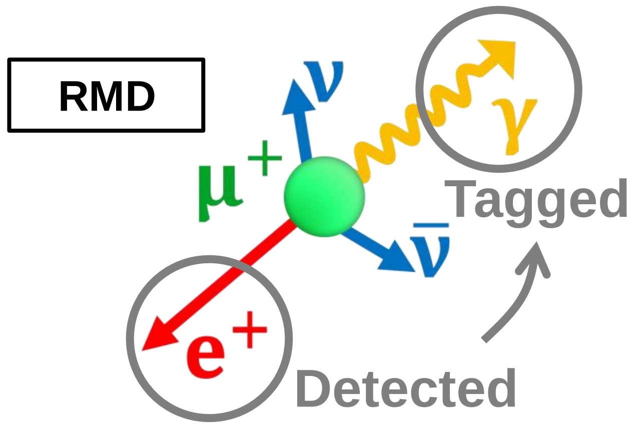


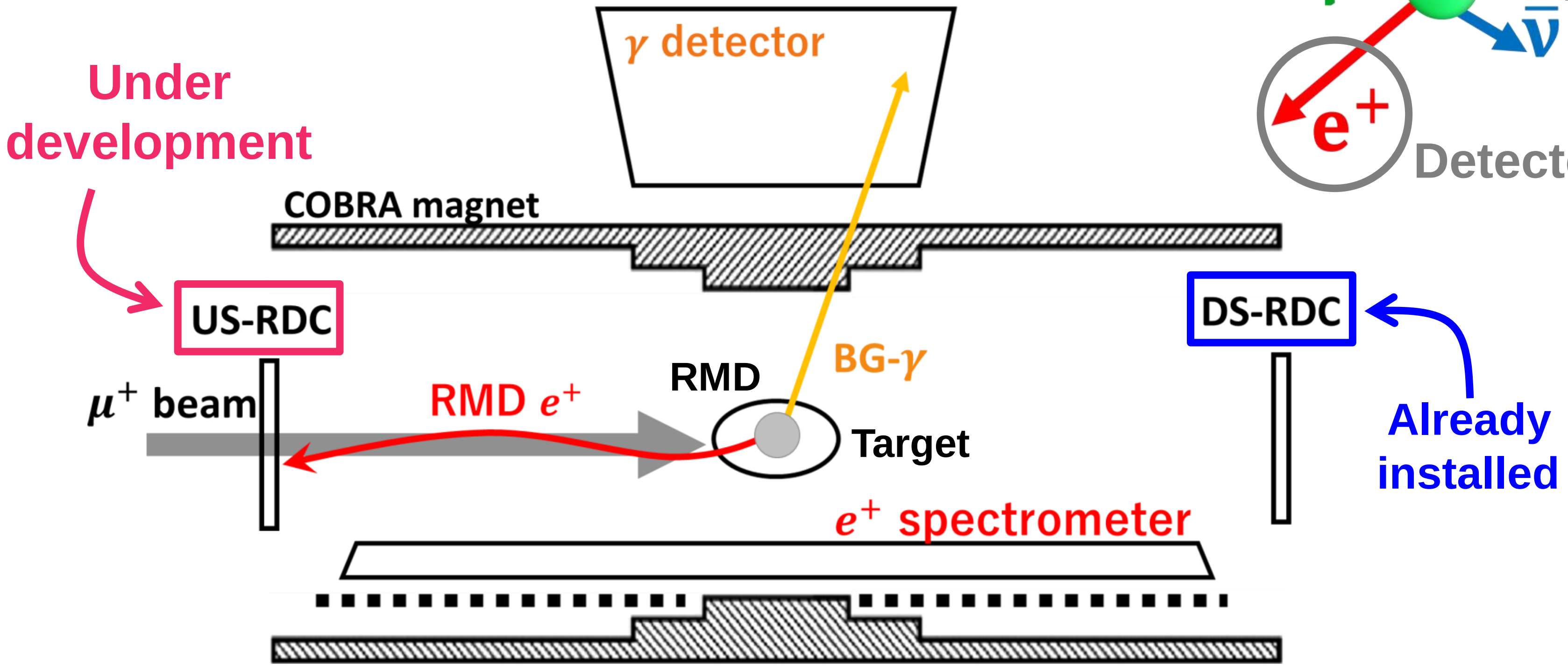


Radiative Decay Counter; RDC

➤ 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

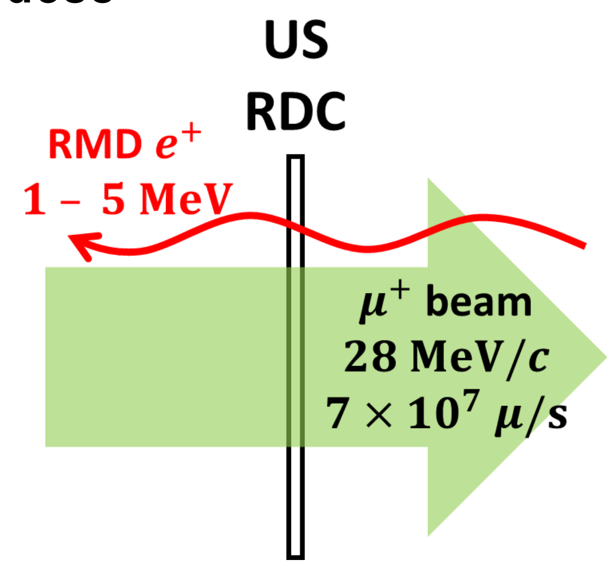




Requirements for upstream RDC

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

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

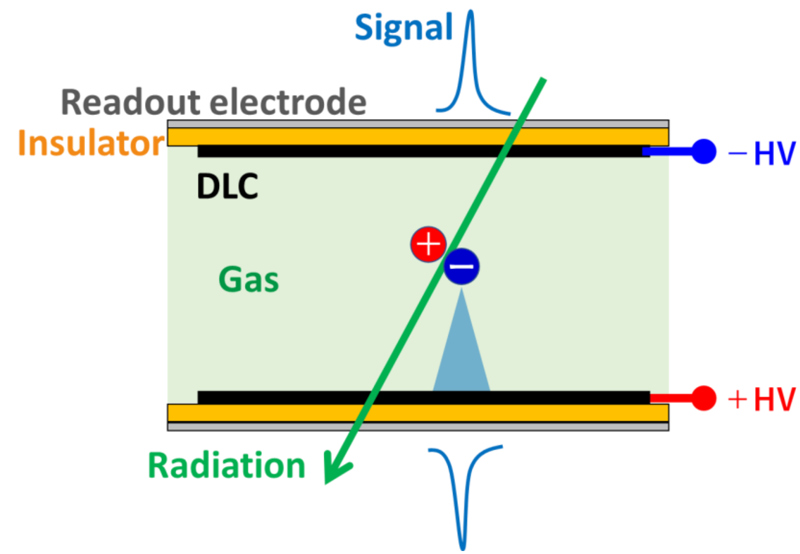
RPC based on DLC electrodes

- **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

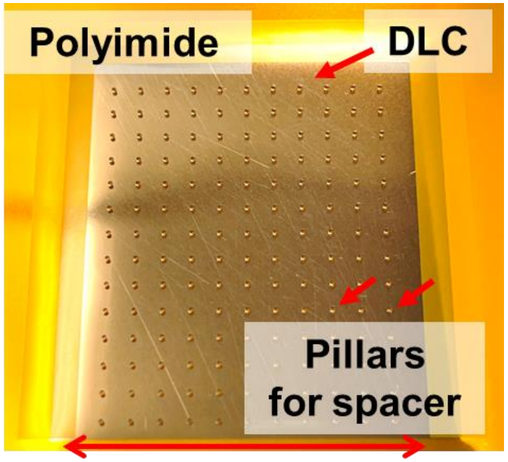
- **DLC-RPC**
  - Extremely low mass by sputtered-DLC electrodes on thin-film
  - High-rate capability by low resistivity of DLC electrodes



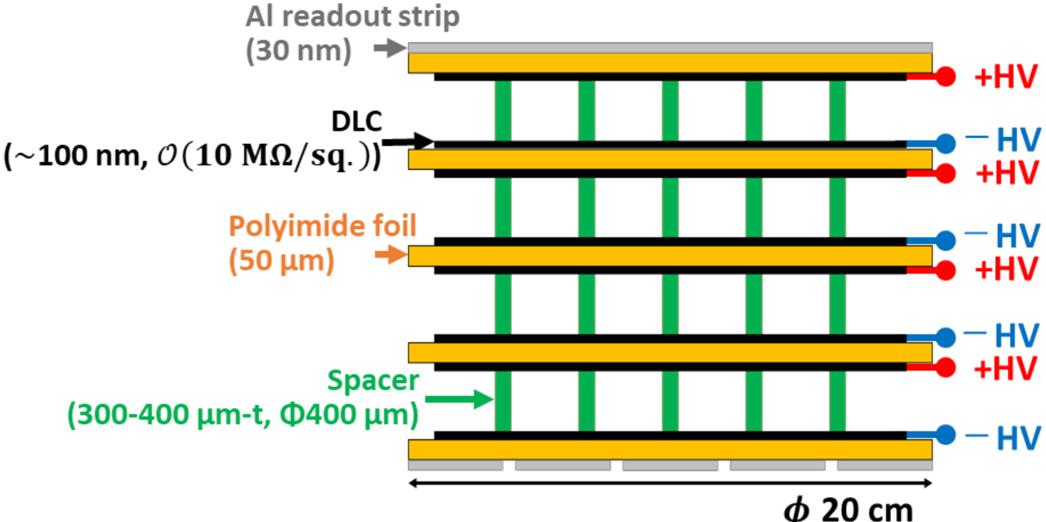
DLC-RPC for MEG II

- 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 be 4 layers

Small prototype electrode



Concepts of full-scale detector



Performance of the prototype DLC-RPC

- Performance test using a muon beam at PSI in 2020
  - Developing electrode design to improve rate capability
  - Using a 4-layer prototype in the next beam test

➔ Expect to achieve requirements of rate capability and detection efficiency

	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	$\sim 100\ \mathrm{C/cm^2}$	Not evaluated
△	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)

- Radiation hardness needs to be evaluated

Radiation hardness of DLC-RPC

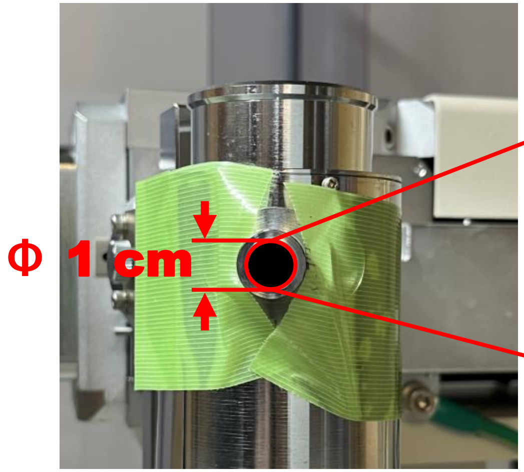
- **Require continuous operation** during the physics run in the MEG II experiment
  - Physics run period : $20\ \mathrm{weeks/year}$
  - Rate of muon beam at the center : $2.9\ \mathrm{MHz/cm^2}$
  - Average avalanche charge of muon : $3\ \mathrm{pC}$

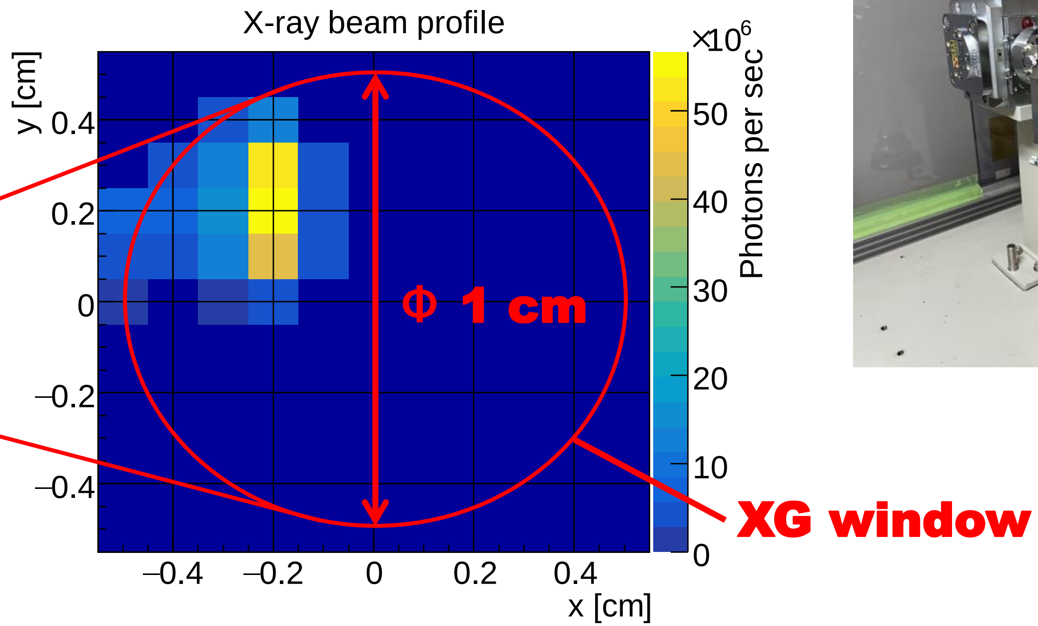
  ➔ **Irradiation dose in 1 year: $\sim 100\ \mathrm{C/cm^2}$**

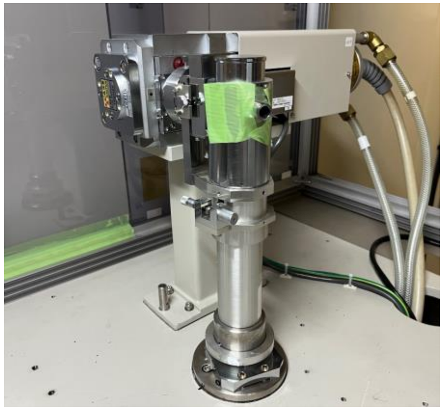
- Carried out accelerated aging tests using high-intensity beam to evaluate the radiation hardness of DLC-RPC
  - Total irradiation dose was compared by integrated charge

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: $2.9\ \mathrm{MHz/cm^2}$

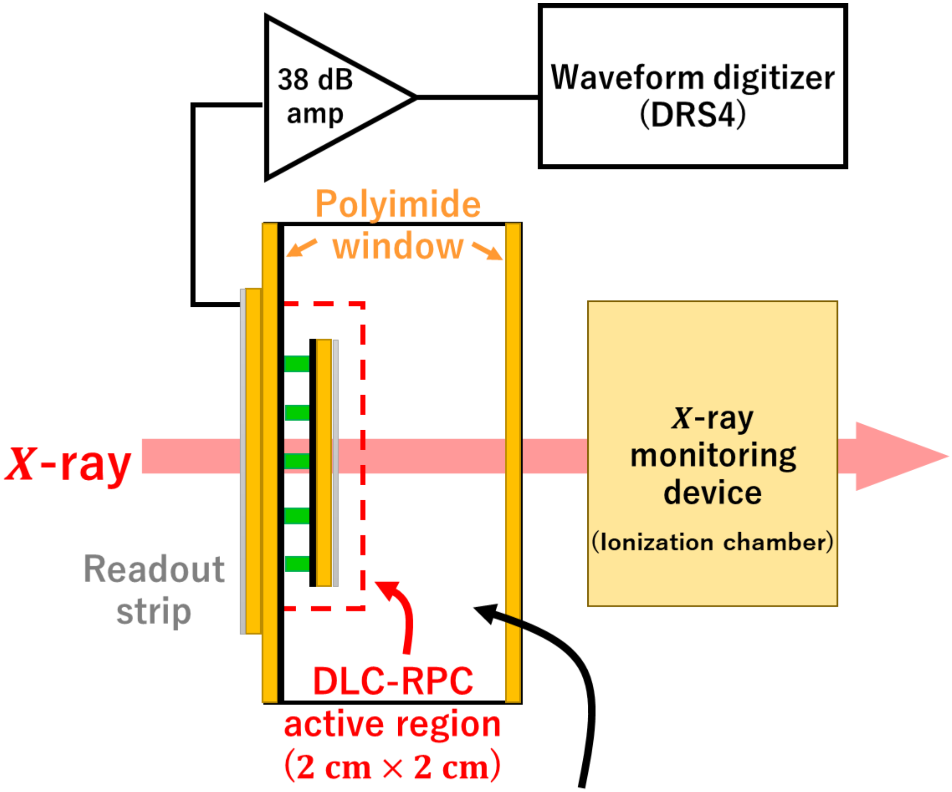






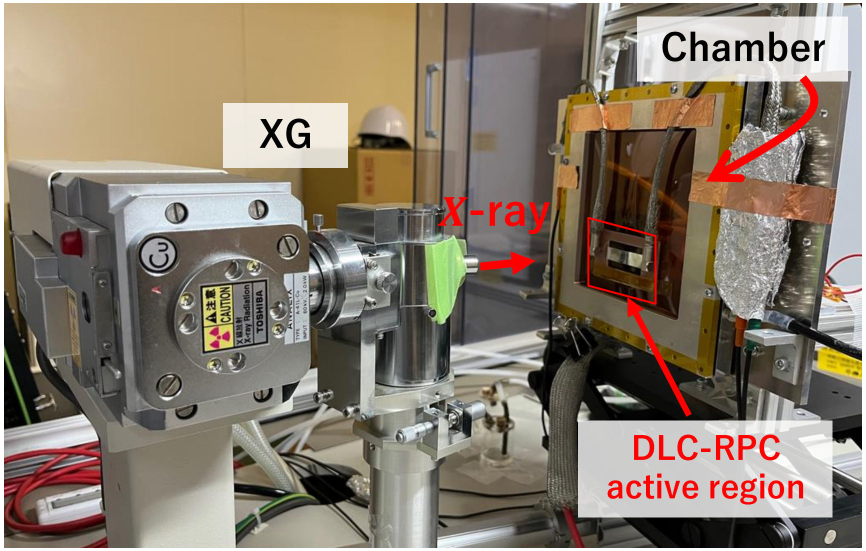
Setup of irradiation test

Setup schematic



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

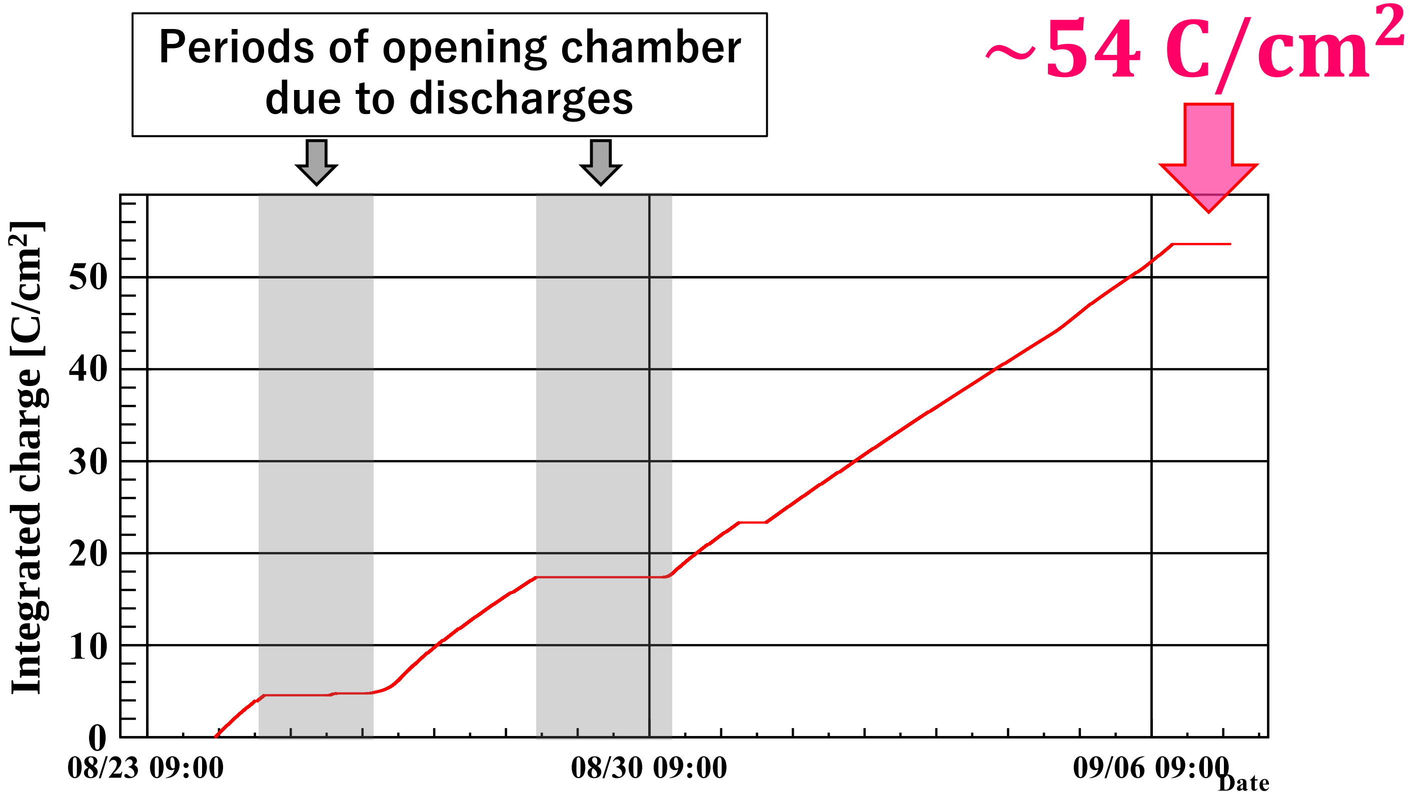
Front of the chamber



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

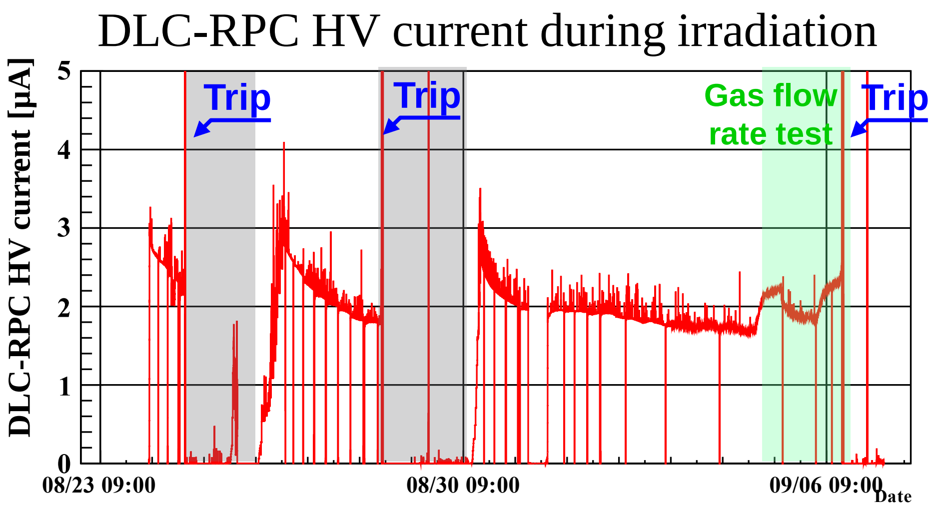
Irradiation dose in this test

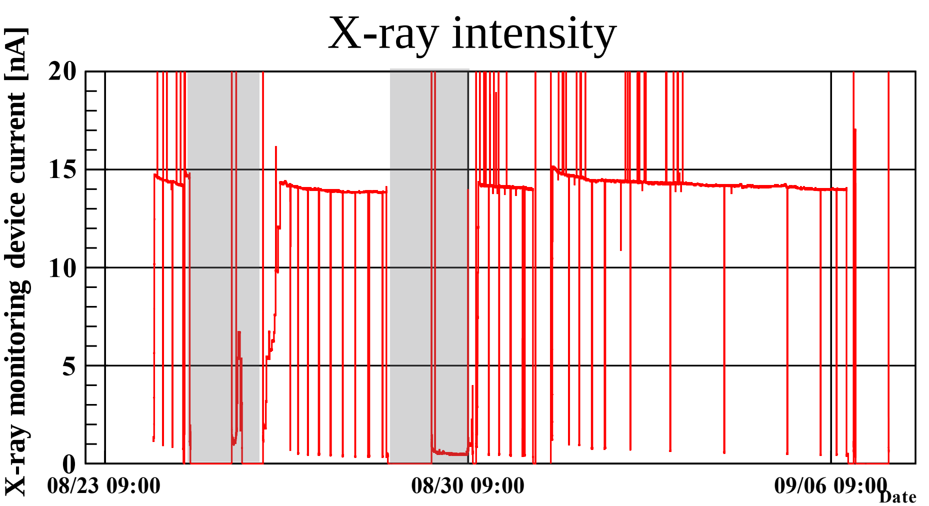
- During X-ray irradiation:
  - DLC-RPC was operated at 2800 V
- Integrated charge flowed over DLC-RPC electrodes:

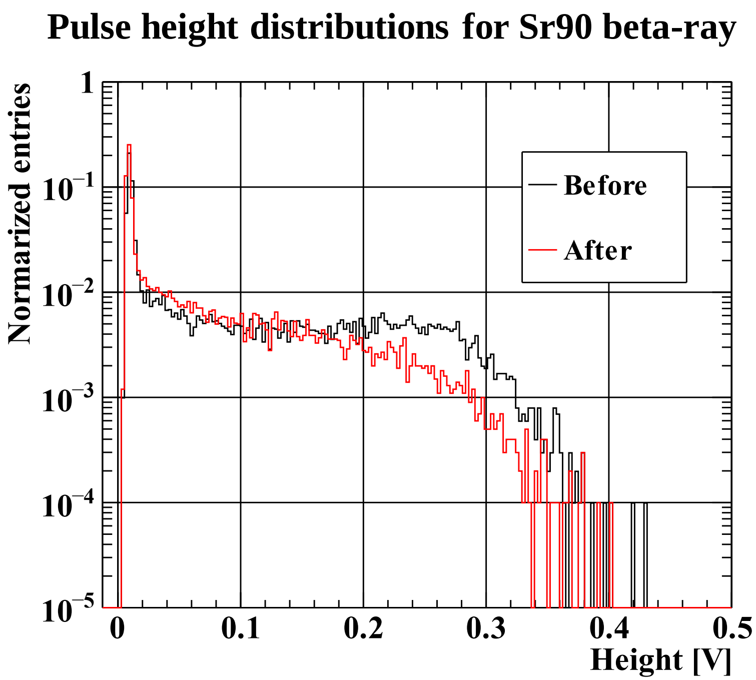


Gas gain changes

- DLC-RPC gain decreased during X-ray irradiation
  - Not correlated to X-ray generator output





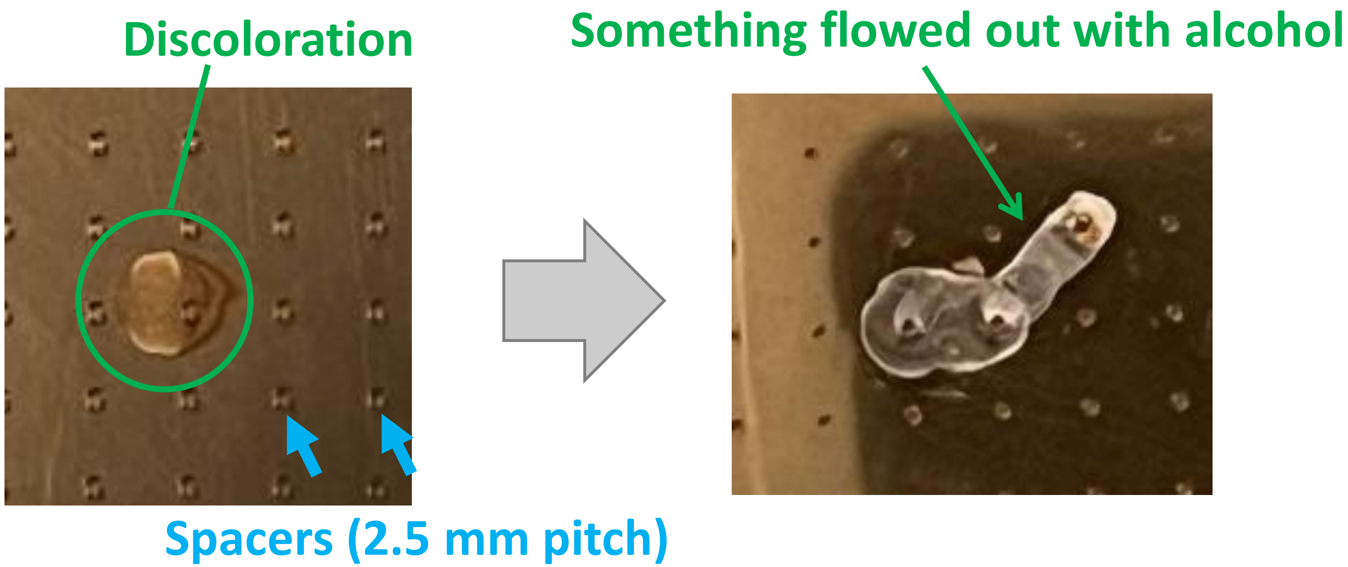


Average pulse height reduced by 21 %
Detection efficiency: 56 % → 49 %
(threshold is 20 mV)

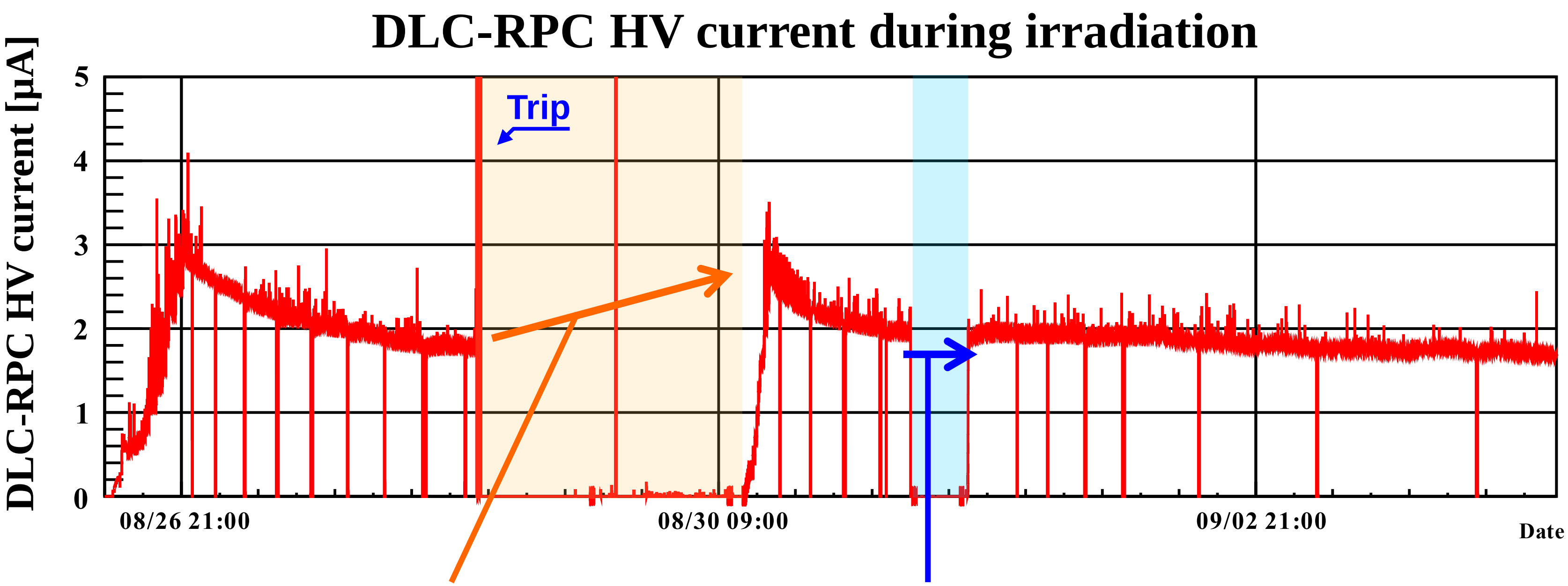
Deposition on DLC

- Discoloration of DLC and increased resistivity of DLC
  - Resistivity increased: $\sim 60\ \mathrm{M\Omega} \rightarrow \mathcal{O}(100)\ \mathrm{M\Omega}$
    - It might affect the rate capability of DLC-RPC
  - When alcohol was flushed,
    something flowed out and resistivity was recovered

➔ Insulator was formed on DLC



Evidence of gain reduction due to deposits



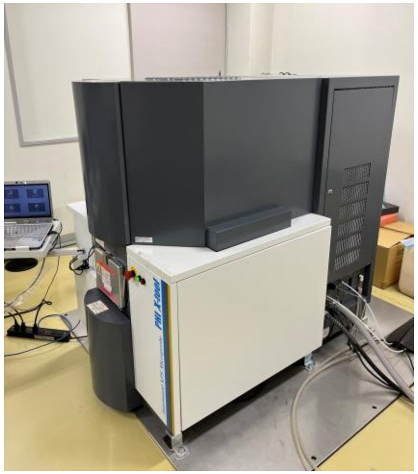
- **Performance recovery**
  - Wiped DLC electrodes with alcohol to remove deposits
- **Performance NOT recovery**
  - Gas flow without X-ray irradiation
  - High voltage OFF without X-ray irradiation

➔ **Deposits on DLC caused DLC-RPC gain reduction**

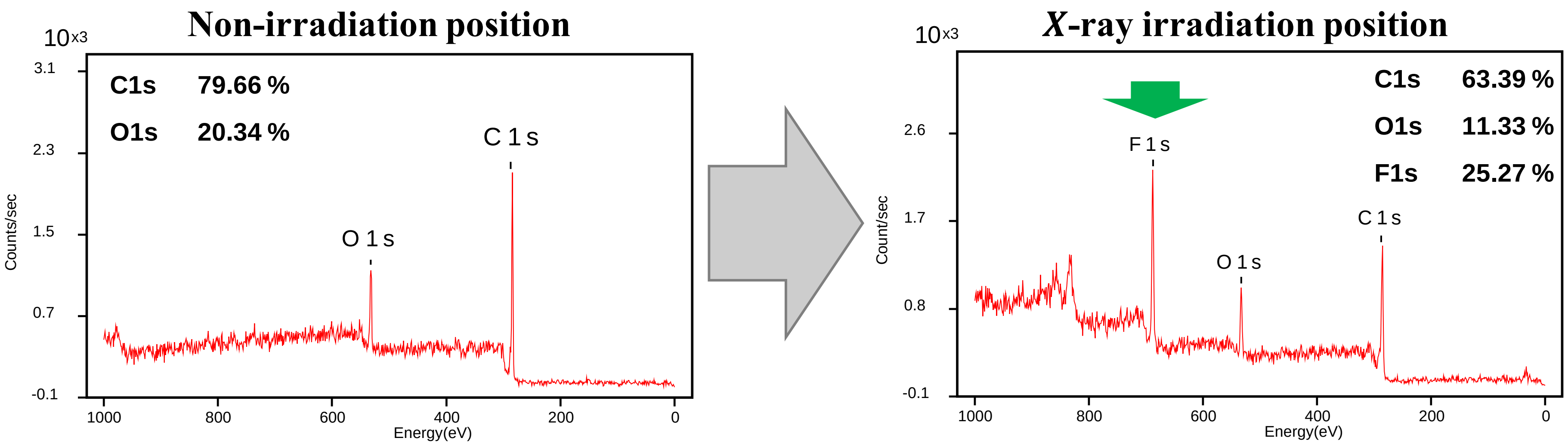
Electrode surface analysis

- 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

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



Ulvac-phi, Inc.
PHI X-tool



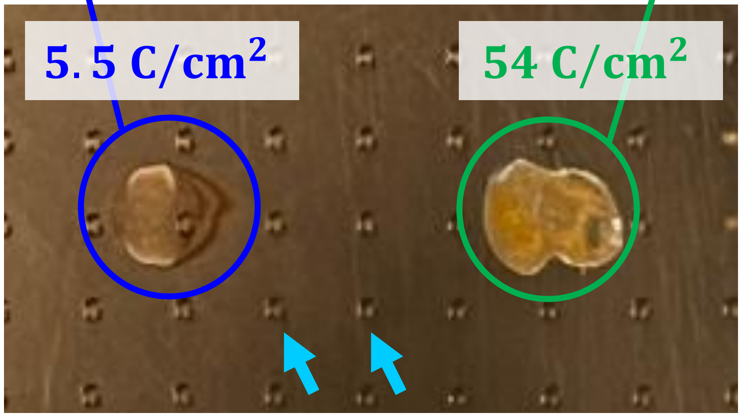
DLC electrode defect

➢ 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



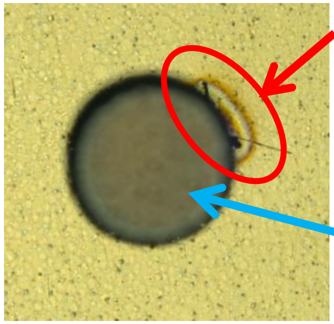
Spacers (2.5 mm pitch)

Discharge problems

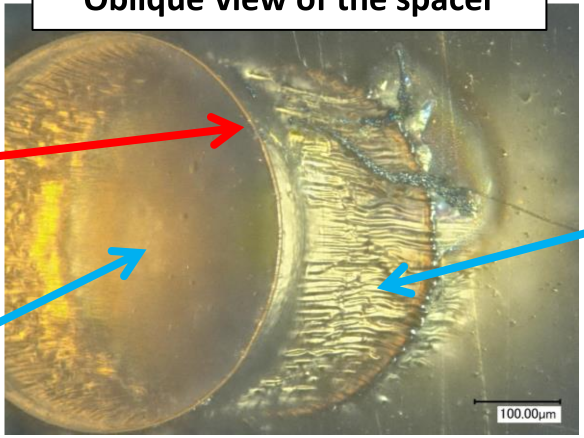
- Discharges via spacers often occur
  - Once discharges at the spacer occurs, it made continuous operation impossible
  - In addition, discharges via the spacer can occur repeatedly even after cleaning with alcohol wiping or air spray

➔ 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

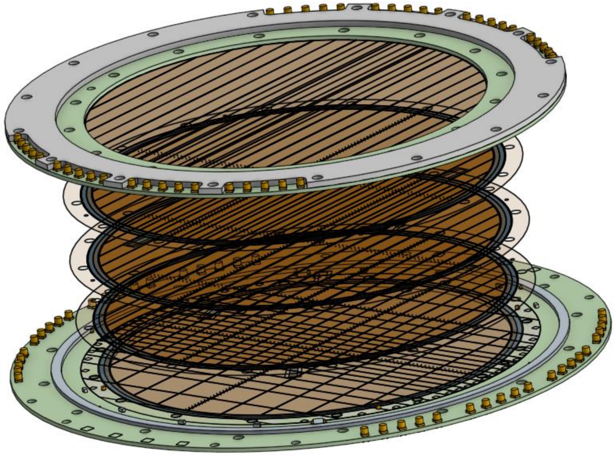


Summary

- DLC-RPC is under development for MEG II upstream RDC
  - A high-rate and low-momentum muon beam must pass through
  - Expected irradiation dose is $\sim 100\ \mathrm{C/cm^2}$
- X-ray accelerated irradiation test was carried out
  - Long-term operation under more severe conditions than the MEG II environment
    - MEG II : $2.9\ \mathrm{MHz/cm^2}$ of muon, In this test: $\sim 5.7\ \mathrm{GHz/cm^2}$ of X-ray
  - Total irradiation dose: $\sim 54\ \mathrm{C/cm^2}$
  - Discharges via spacers prevented stable operation twice
- Aging effects
  - Fluorine deposition on DLC electrodes
  - Degradation of DLC-RPC gas gain
    - Detection efficiency for Sr90 beta-ray: $56\ \% \rightarrow 49\ \%$
  - Defects of DLC electrodes

Prospects

- Investigate methods and designs to reduce or recover the aging effects
- Improvements are needed to suppress discharges via spacers for stable operation
- Aiming for installation in the physics run in 2025
  - Performance test using small-size prototype detector and high-intensity muon beam at PSI
  - Production of full-scale detector (Φ20 cm)



Full-scale detector design (Φ 20 cm)

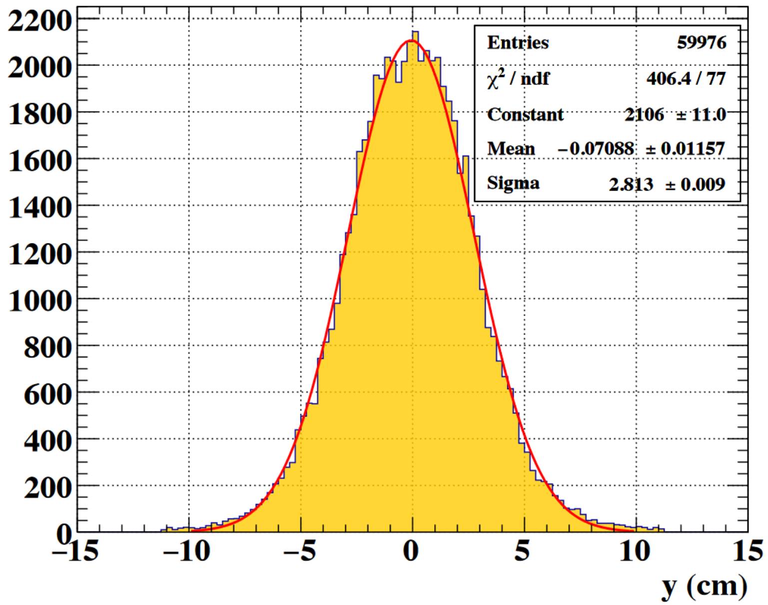
Acknowledgements

- 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

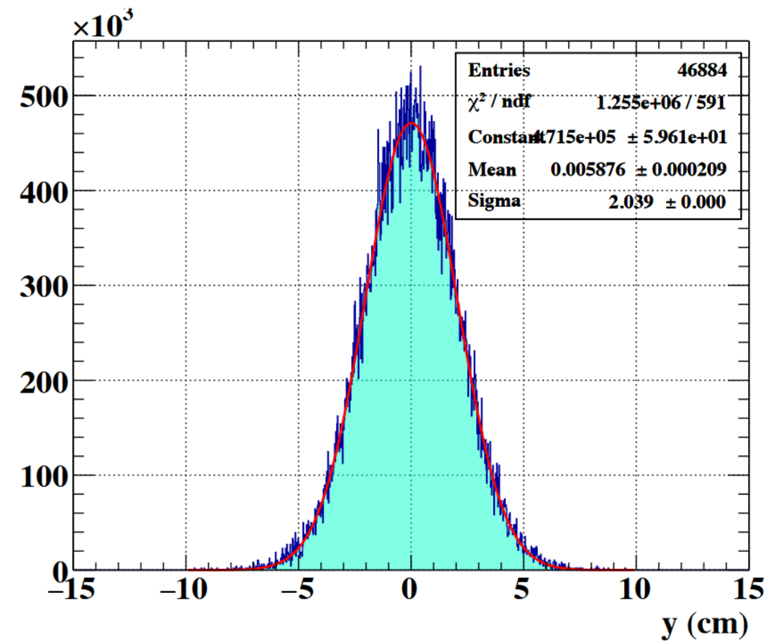
Backup

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

Detection efficiency

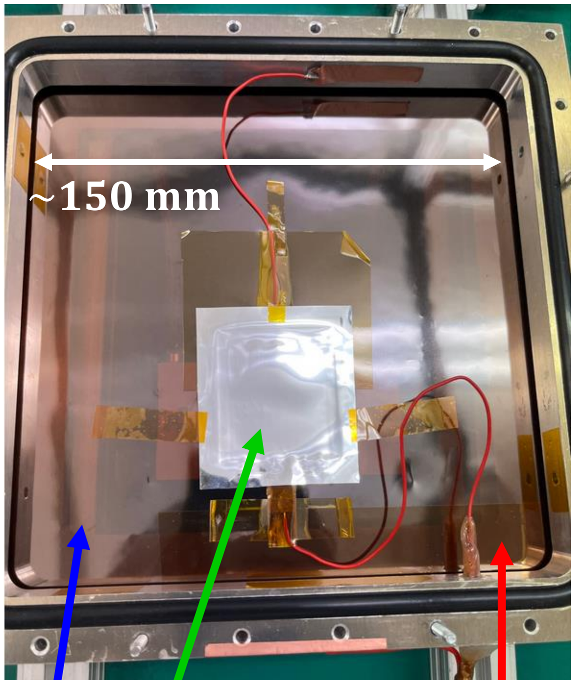
- Detection efficiency of n-layer RPC is approximated

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

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

Setup of inside the chamber

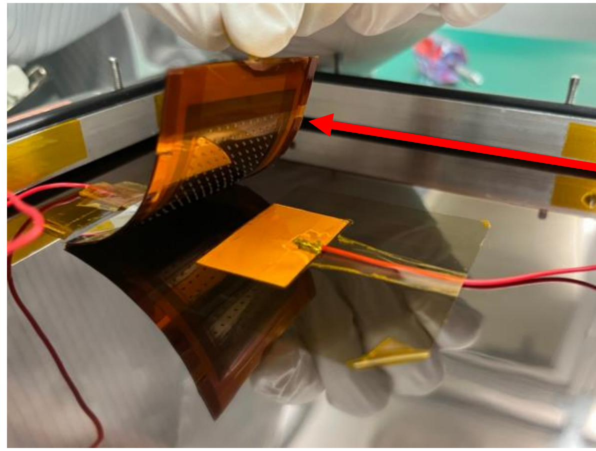
Inside the chamber

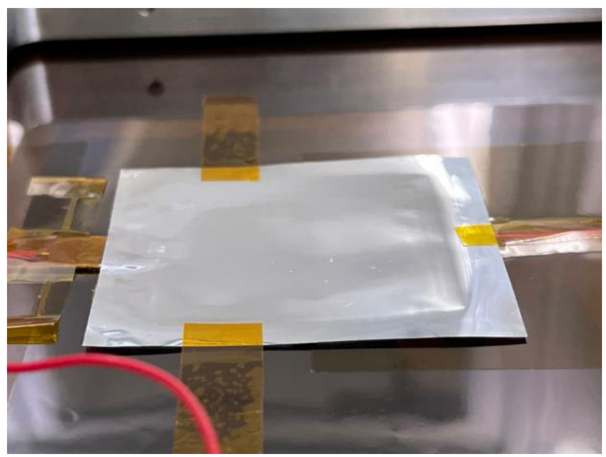


DLC-RPC electrode sample

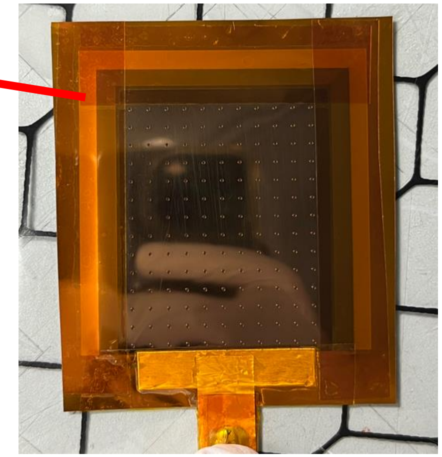
HV supply line

DLC sputtered chamber window

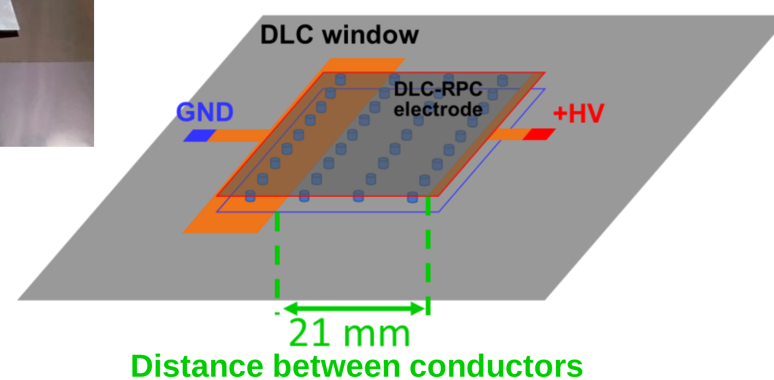




DLC-RPC electrode sample

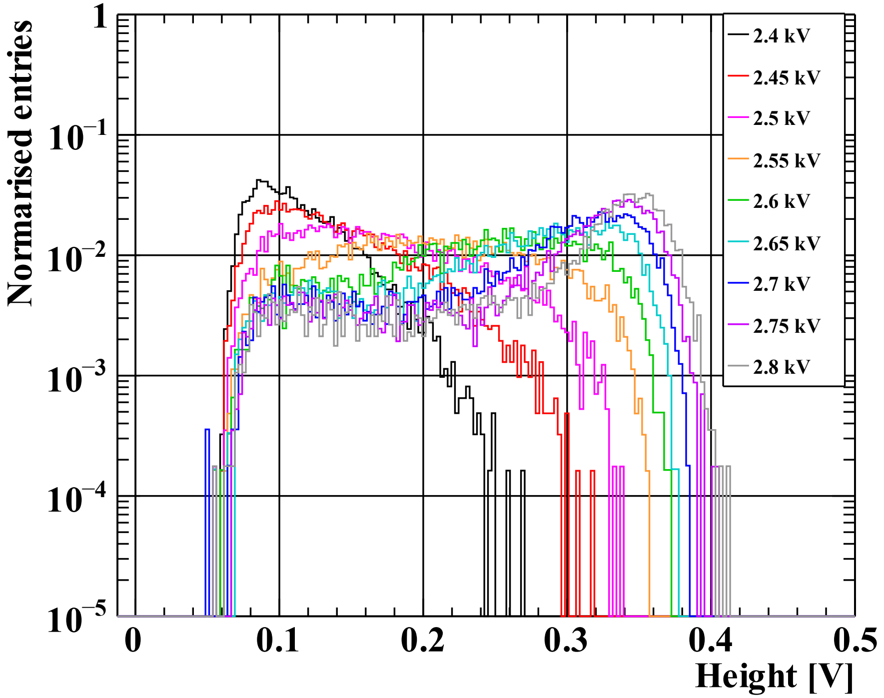


Scheme of configuration

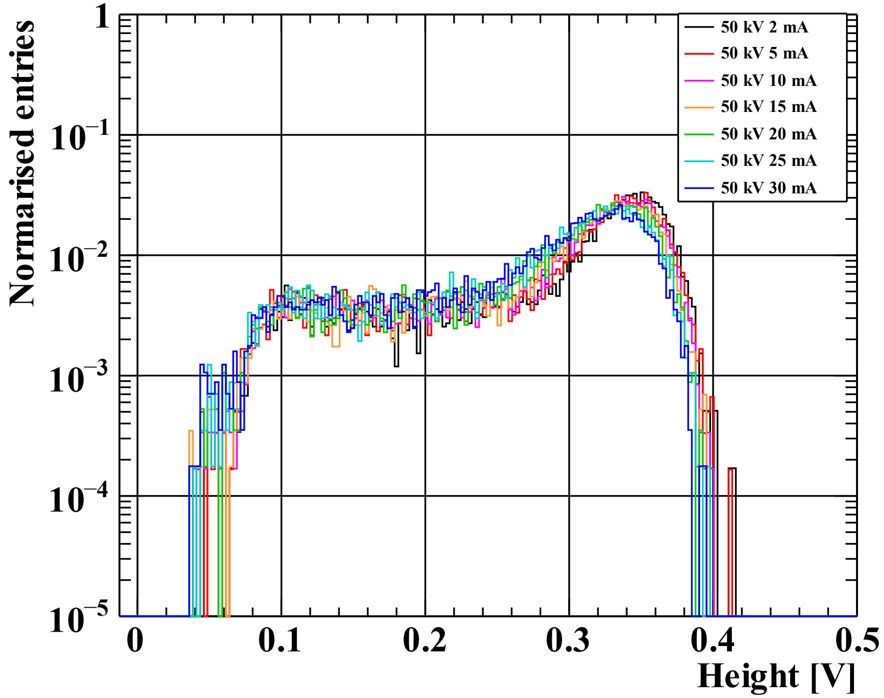


Pulse height distribution for *X*-ray

DLC-RPC HV scan with minimum *X*-ray intensity



X-ray intensity scan



Fluorine sources

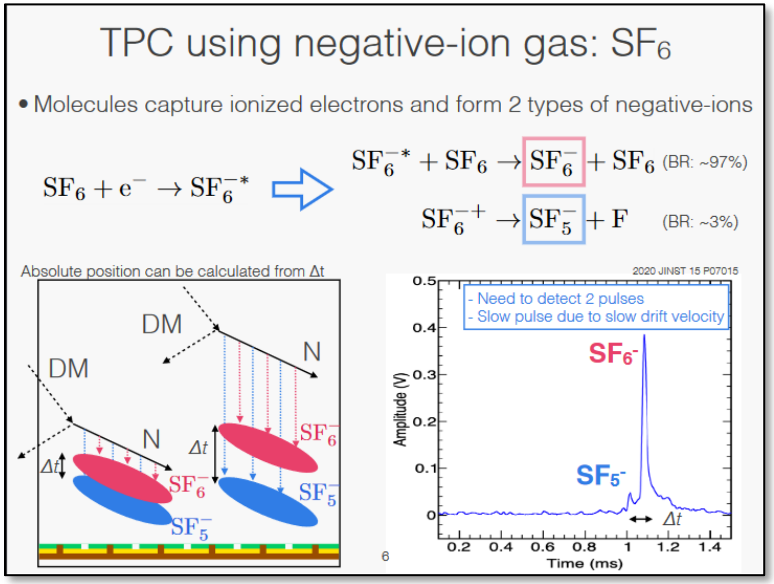
- Freon (R134a/C2H2F4) is stable
  - We think fluorine might not separated

- SF_6 might create fluorine during avalanche

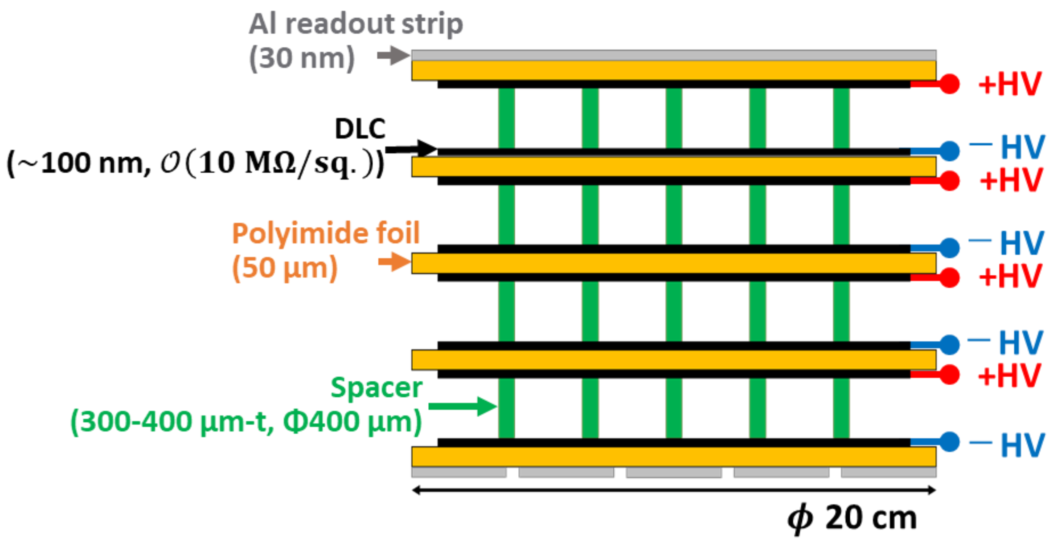
$$\mathbf{SF_6 + e^- \rightarrow SF_6^{-*}, \quad SF_6^{-*} \rightarrow SF_5^- + F}$$

  - 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/



Material budget



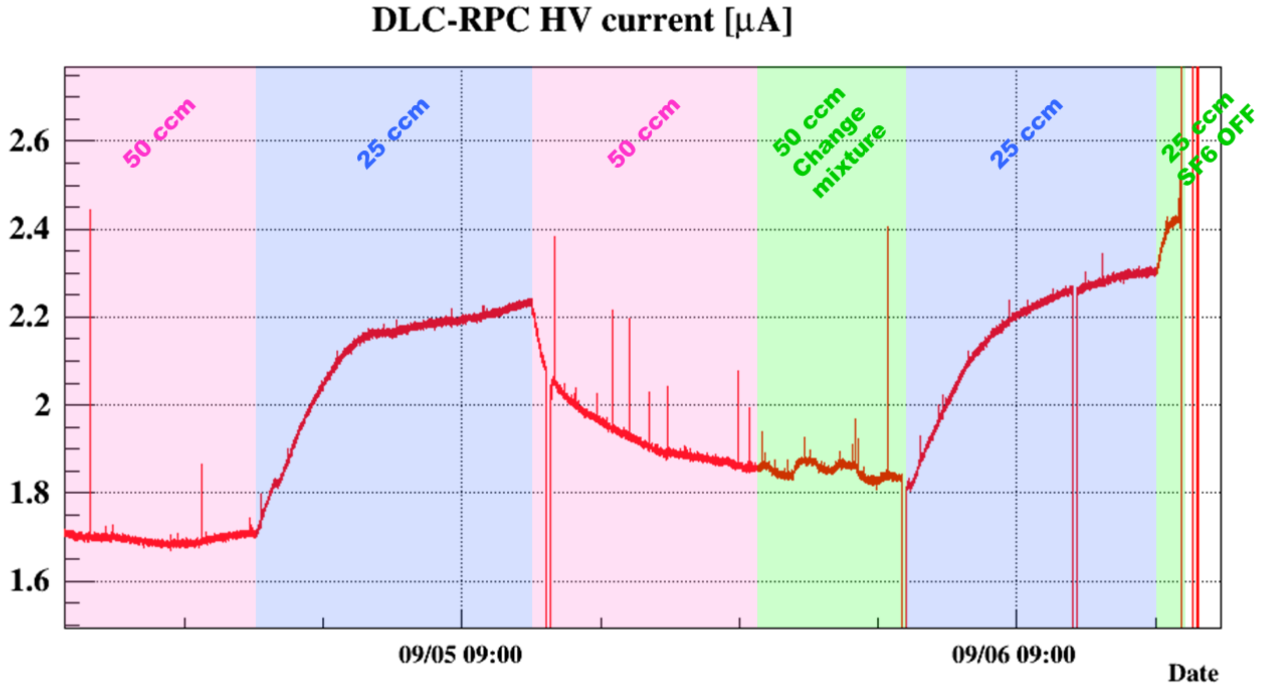
	Material budget
Polyimide $50\ \mu\mathrm{m}$	$0.0175\ \%\ X_0$
Aluminum $30\ \mathrm{nm}$	$0.0034\ \%\ X_0$
Gas $2\ \mathrm{mm}$	$\sim 0.001\ \%\ X_0$
DLC $\sim 100\ \mathrm{nm}$	negligible

Resistivity measurement

- **Probe with solder lines**
  - To avoid damaging the DLC

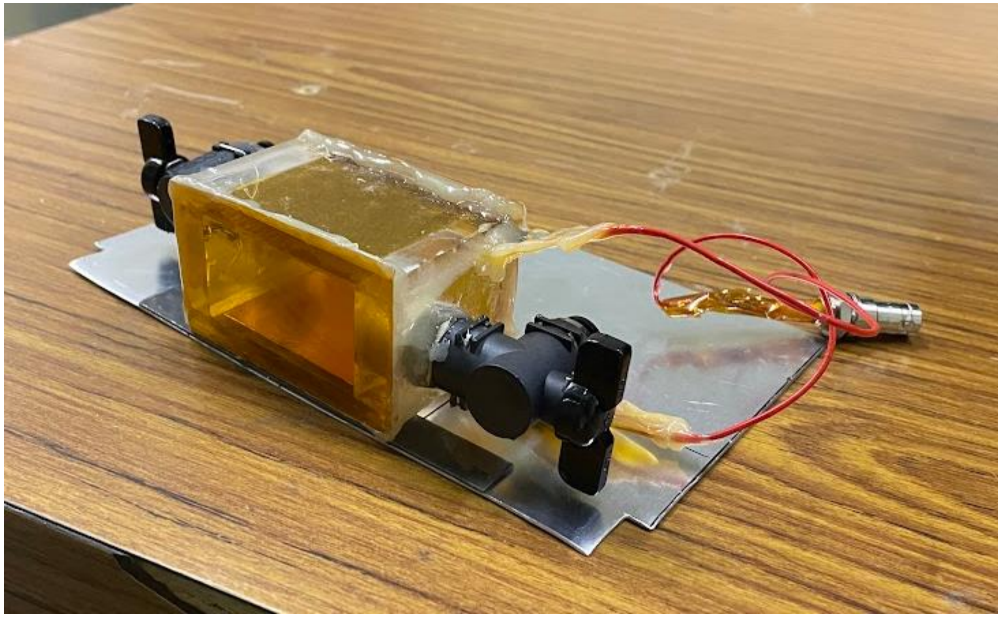
Gas flow study

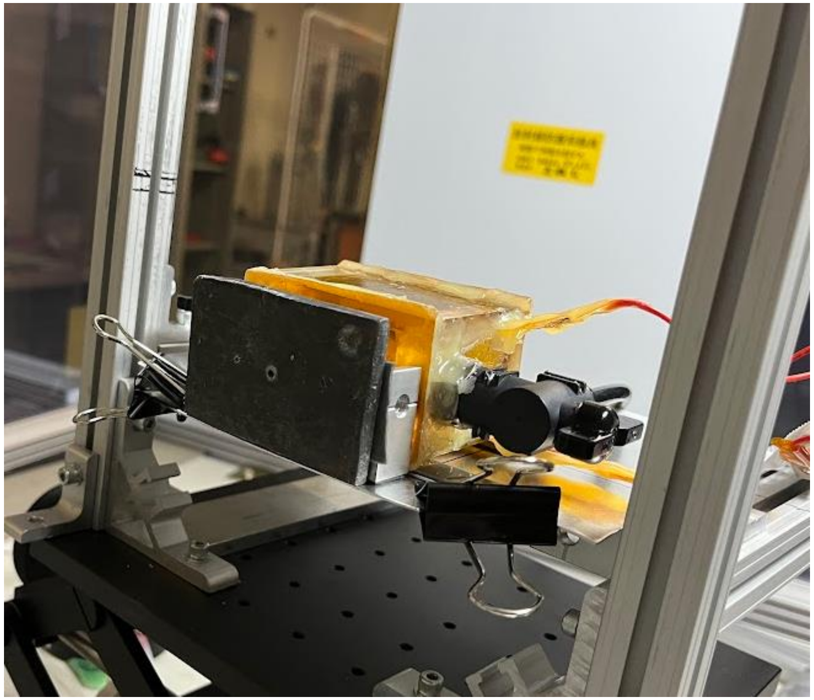
- DLC-RPC operated in high-flow rate and low-flow rate
  - High-flow rate (~50 mL/min) / low-flow rate (~25 mL/min)
  - Gas mixture did not change
- Not replicated after the aging test
  - Exhaust lines were very long in the KEK environment



Ionization chamber

- Hand-made ionization chamber
  - Filled with argon gas
- Pb collimator (Φ 1 mm) for profile measurement



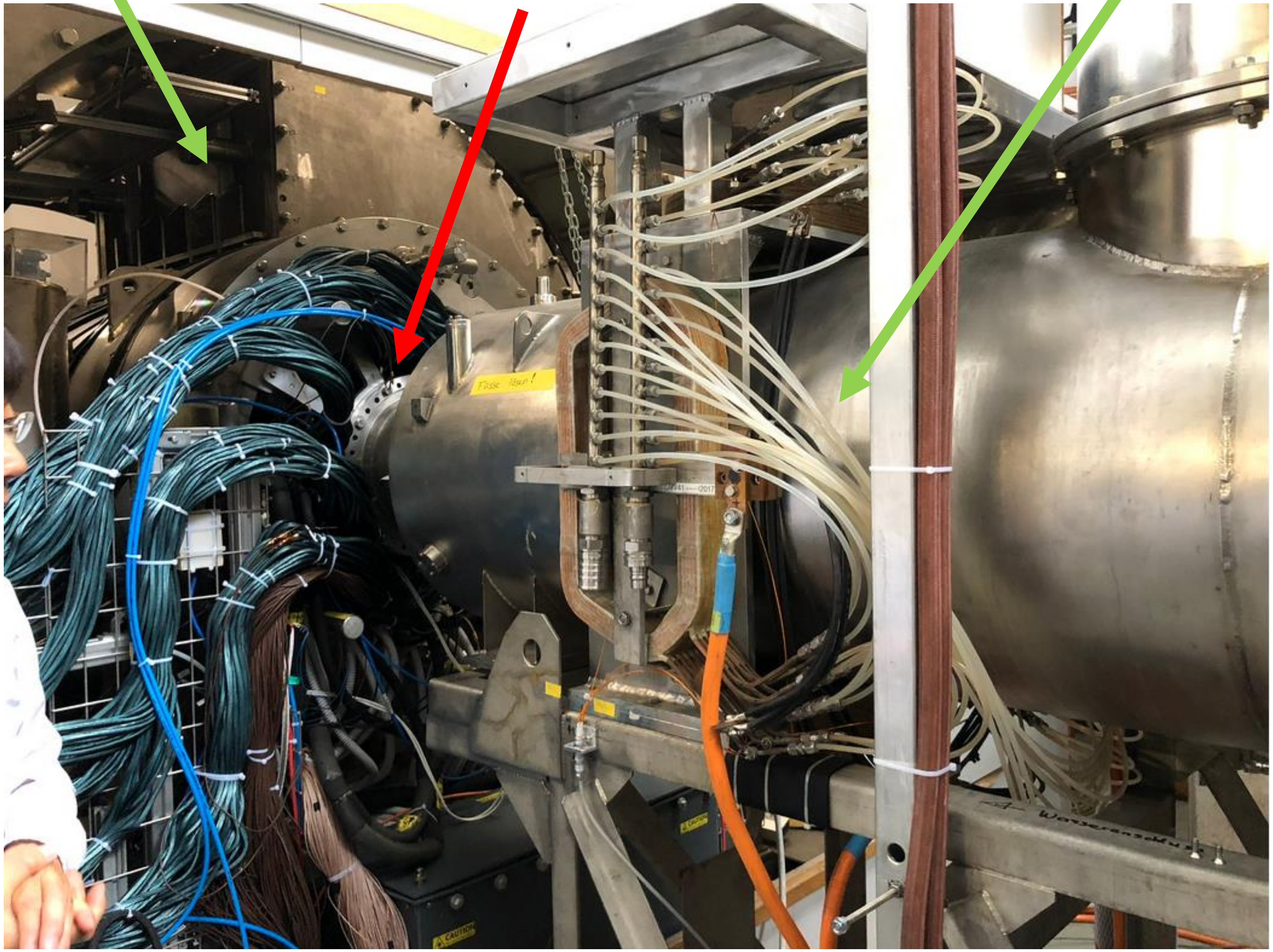


Detector installation

MEG II detectors

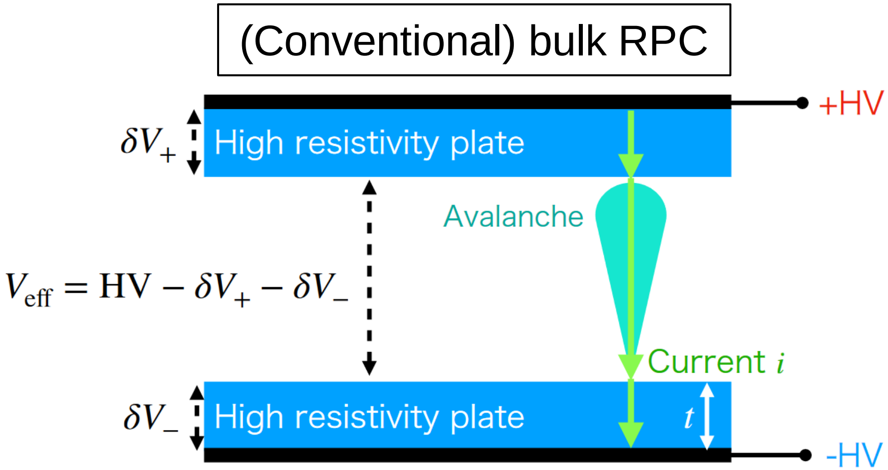
Installation position of DLC-RPC

Beam transport solenoid

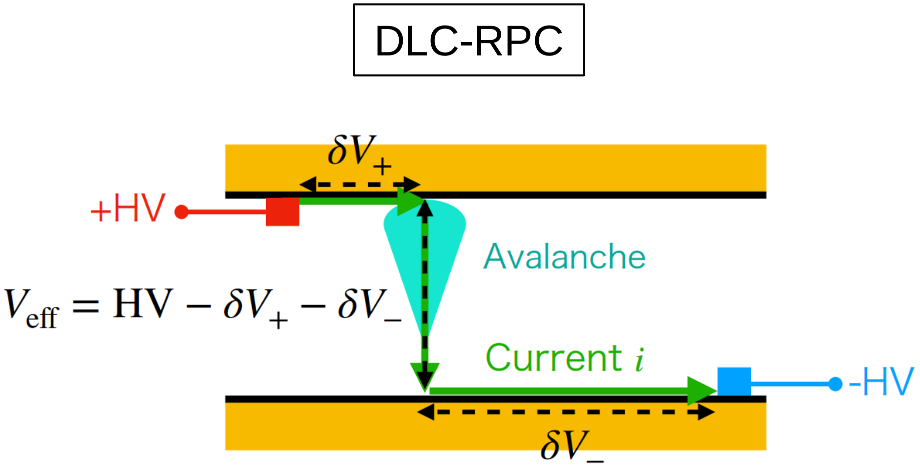


Rate capability

- 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



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



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

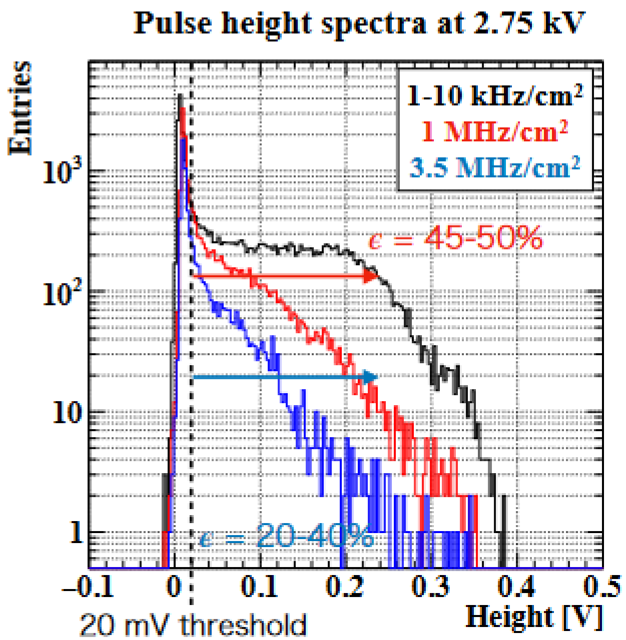
- Kensuke Yamamoto's presentation at the RPC2022 conference
- https://doi.org/10.1016/j.nima.2023.168450

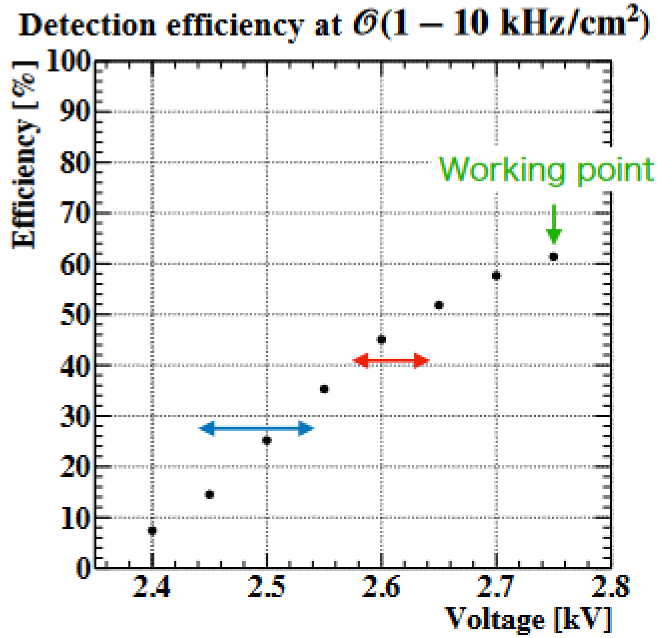
Performance at high rate

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



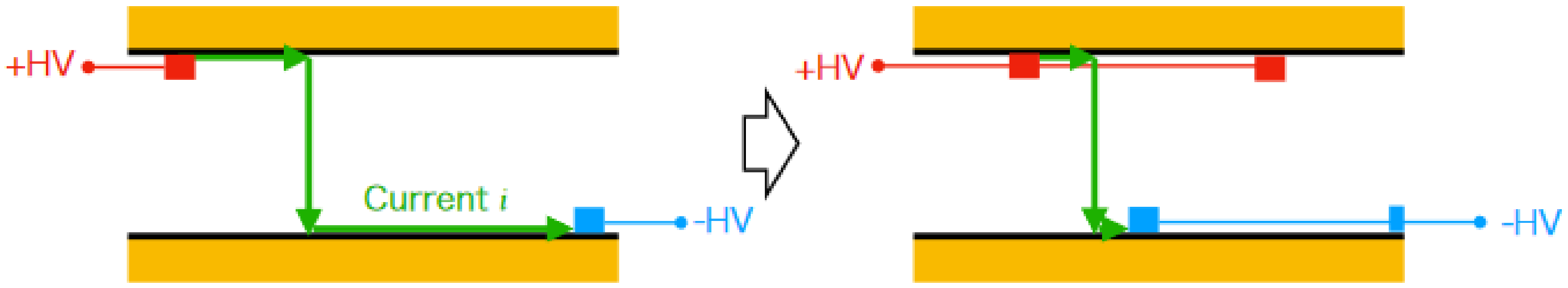


- Kensuke Yamamoto's presentation at the RPC2022 conference
- https://doi.org/10.1016/j.nima.2023.168450

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

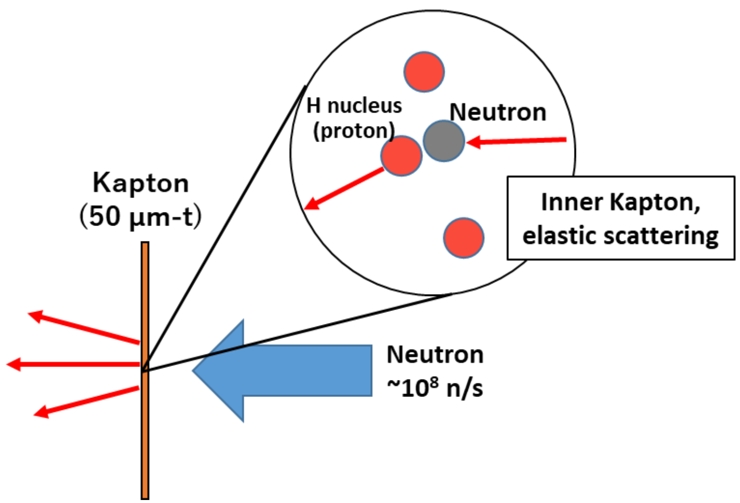


Neutron irradiation campaign 2022

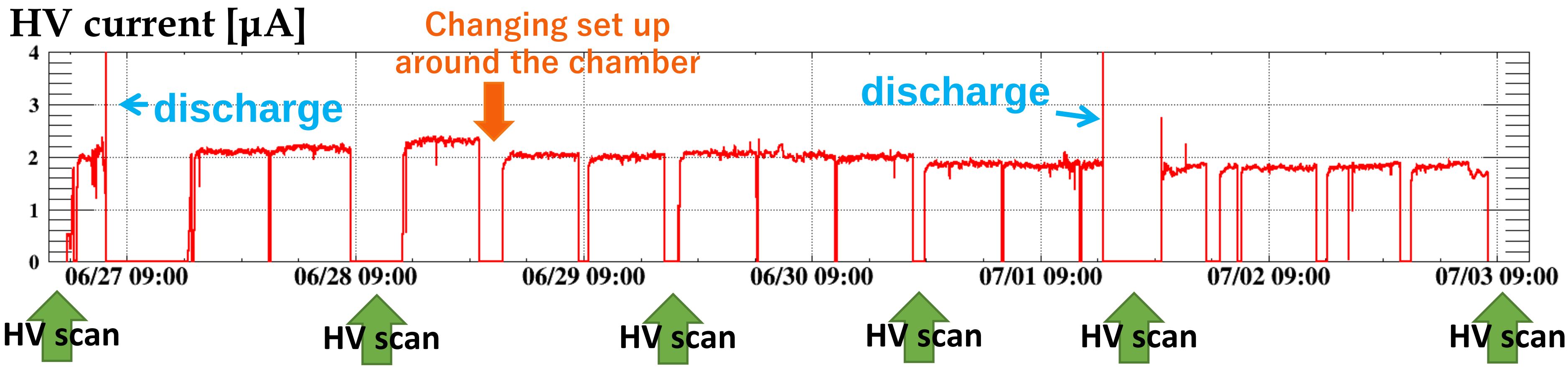
- Test period: Jun. 22nd 2022 – Jul. 2nd 2022

- Neutron irradiation facility at Kobe Univ.
  - $^{9}\mathrm{Be} + \mathrm{d} \rightarrow {}^{10}\mathrm{Be} + n + 4.35\ \mathrm{MeV}$
    - Deuteron energy: 3.0 MeV
    - Neutrons energy: Peak at ~2.5 MeV
  - Number of neutrons $\mathcal{O}(10^{8})\ n/\mathrm{s}$

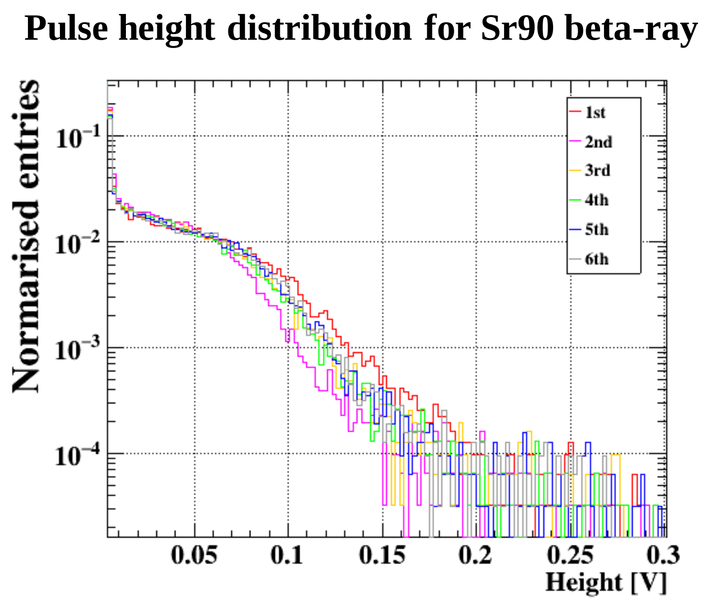
- Energy deposits of recoil protons by neutrons



Performance during irradiation

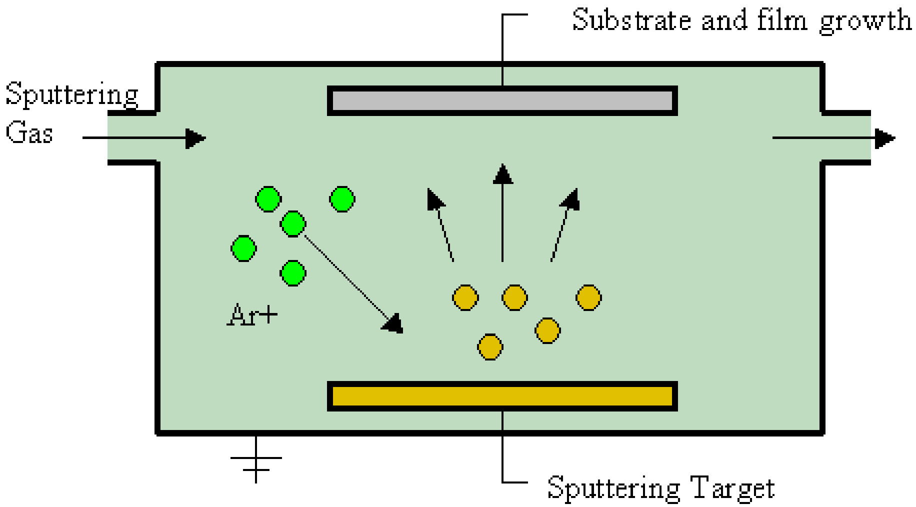


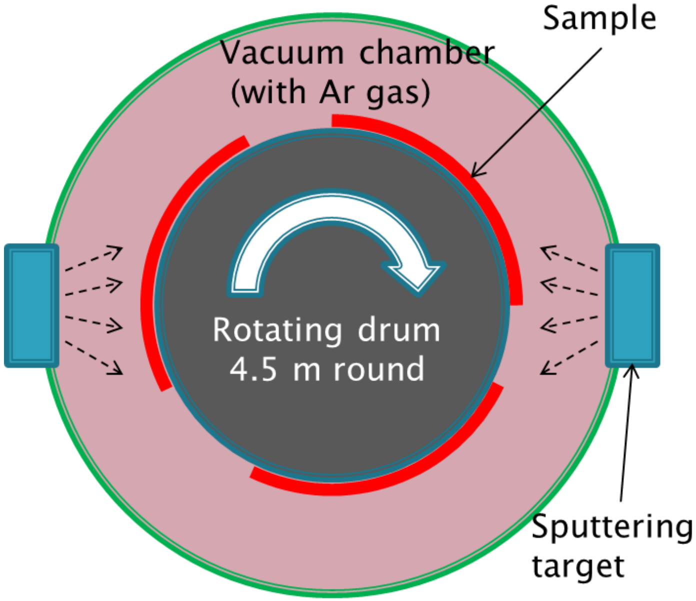
- Total integrated charge was ~165 mC/cm^2
- Pulse height distribution for Sr90 beta-ray was agreement at ~ 5 %
- Fluorine deposition was also observed
- Other aging effects was not observed



DLC sputtering

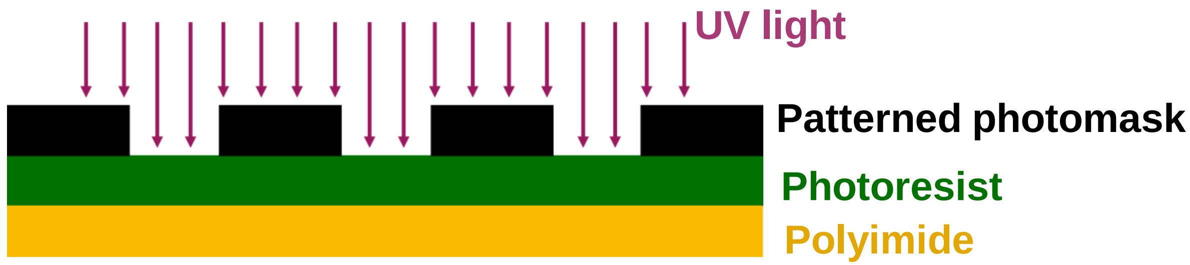
- **Sputtering method**
  1. Inert gas (mainly Ar) is added in a vacuum
  2. Provides a negative charge to a deposition material
     ➔Ionising gas atoms by glow discharge
  3. Gas ions collide with target at high velosity
  4. Tapped target constituent particles adhere to and are deposited on the substrate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





Photolithographic technology

1. Masked and exposed to UV light



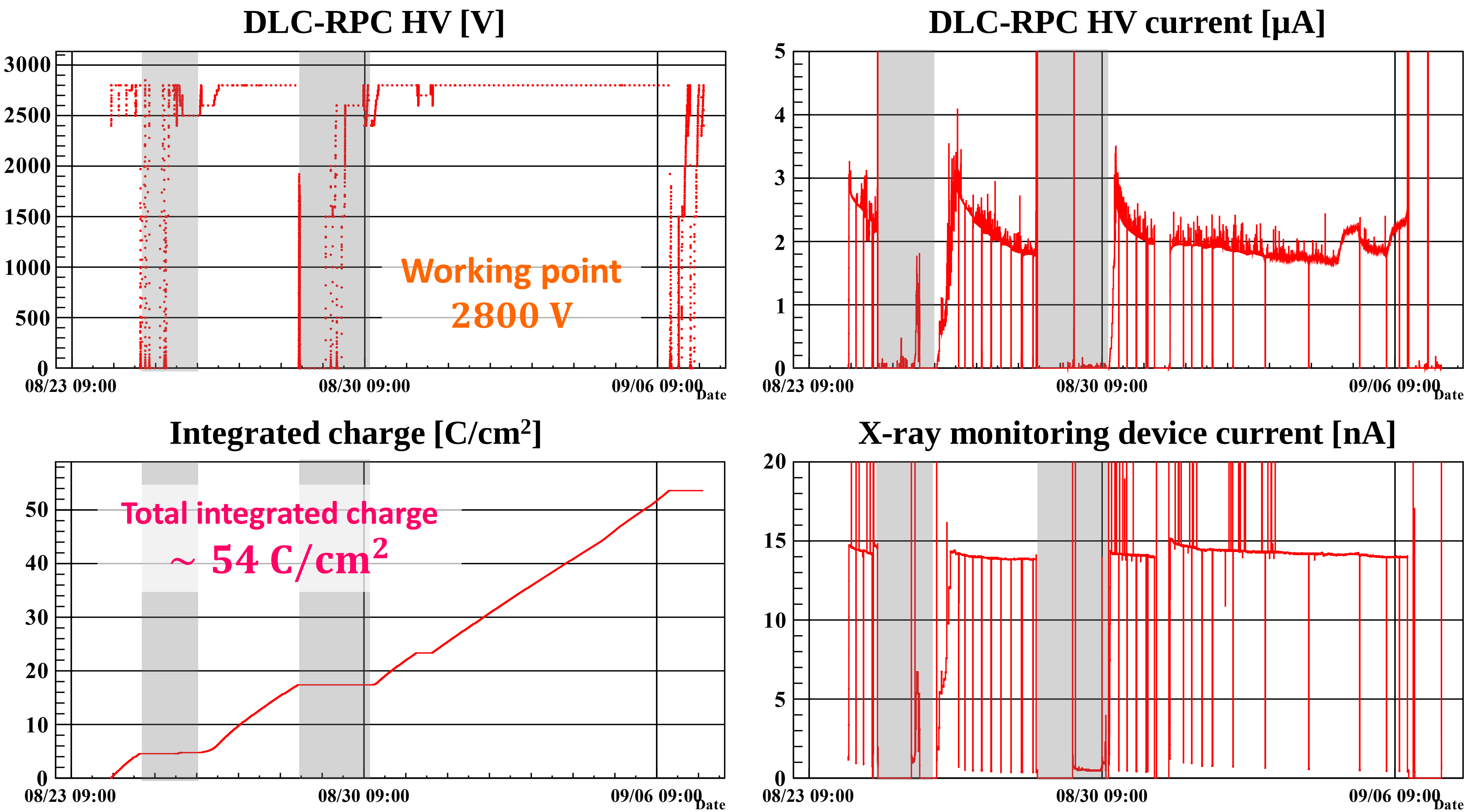
2. Dissolve non-exposed areas with a developer

3. Pillar is completed

4. Heat harden (Baking)

DLC-RPC status during *X*-ray irradiation

- Shaded period: opening chamber due to discharges



Extrapolate to MEG II

- Continuous operation: ~ 6 days with $\sim 37\ \mathrm{C/cm^2}$
- Expected irradiation dose in MEG II: $\sim 100\ \mathrm{C/cm^2}$
  - Using the X-ray generator is expected to take more than 16 days