Development of ultra-low mass and high-rate capable DLC-RPC for background reduction in MEG II experiment

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Outline

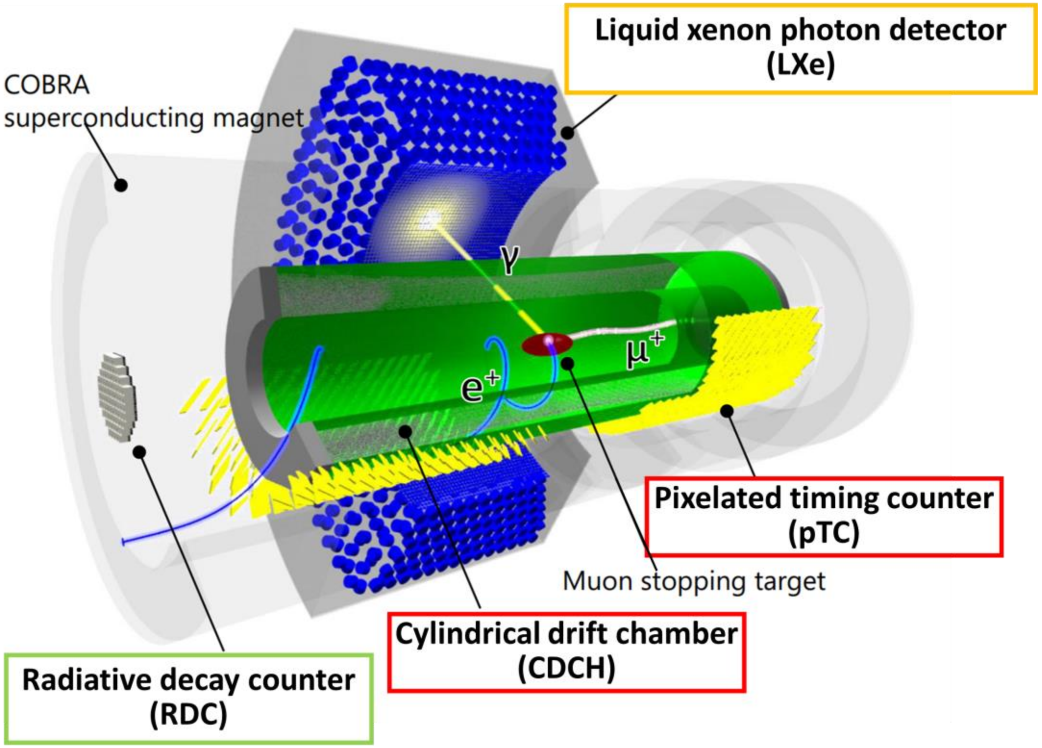
- Introduction
  - MEG II experiment
  - Radiative Decay Counter
  - DLC-RPC for upstream RDC
- Performance study
  - Timing resolution and efficiency for MIP at low rate
  - High-rate performance for low-momentum muon
- Summary and prospects

MEG II experiment

- MEG II searches for $\mu^+ \to e^+\gamma$ decay
  - Charged lepton flavor violating decays

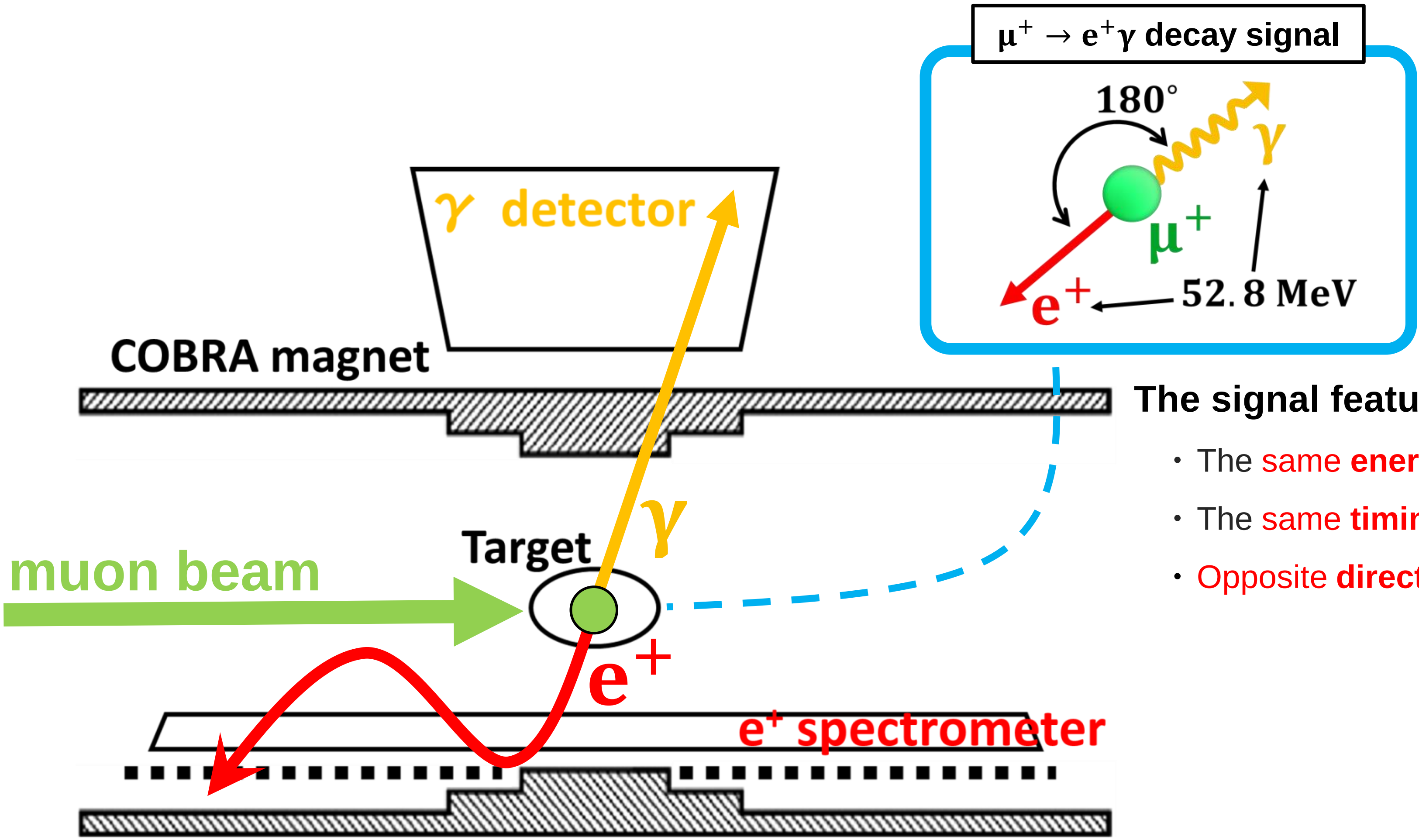
- Detects the energy, time, and direction of **e⁺** and γ coming from the decay of muons at the target
  - γ **detector**
    → • **Liquid Xe detector** (γ energy, time, and position)
  - **e^+ spectrometer**
    → • **Drift chamber** (e^+ energy and direction)
      • **Timing counter** (e^+ time)
      • **COBRA magnet** (Bending e^+ track)

- The MEG II experiment installs a new detector, **Radiative Decay Counter**
  - To identify background γ



How is the $\mu^+ \to e^+\gamma$ signal detected?

- Detect e^+ and γ and look for events with signal features

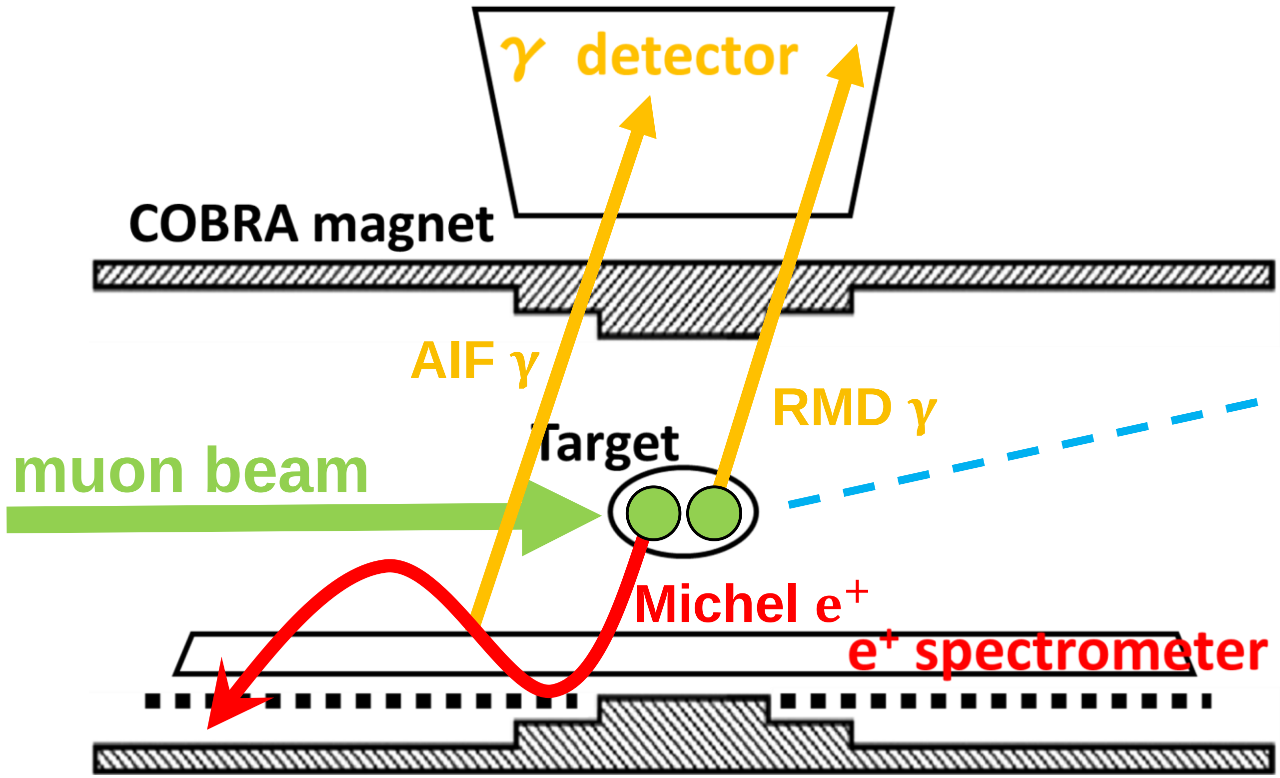


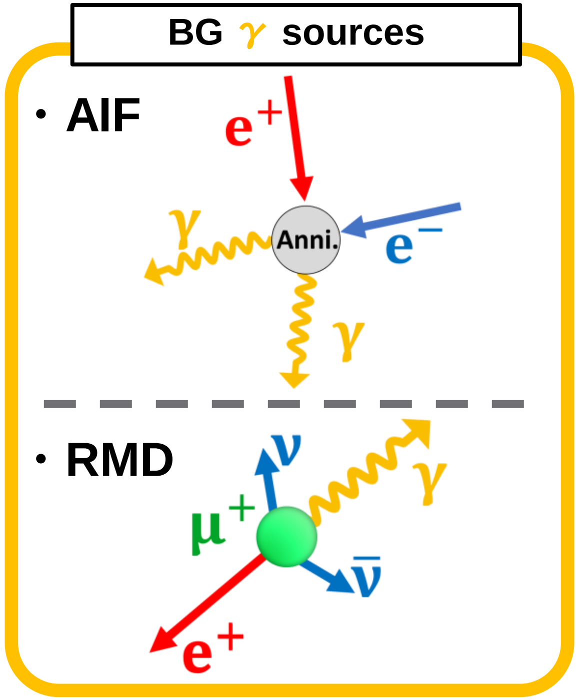
The signal features are

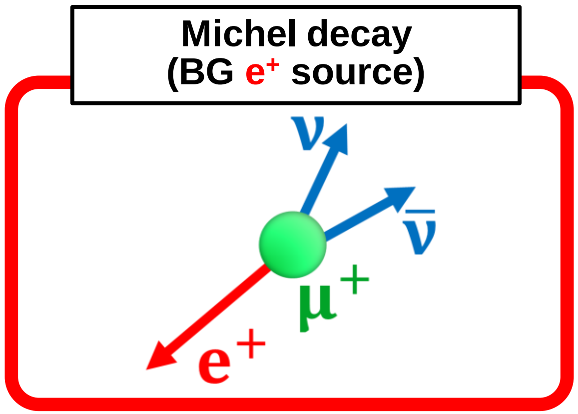
- The same **energy** (52.8 MeV)
- The same **timing**
- **Opposite direction**

What are the backgrounds?

- Accidental coincidence of **e⁺** and γ from **different** μ^+
  - Background **e⁺** → **Michel Decay**
  - Background γ → **Annihilation in Flight, Radiative Muon Decay**

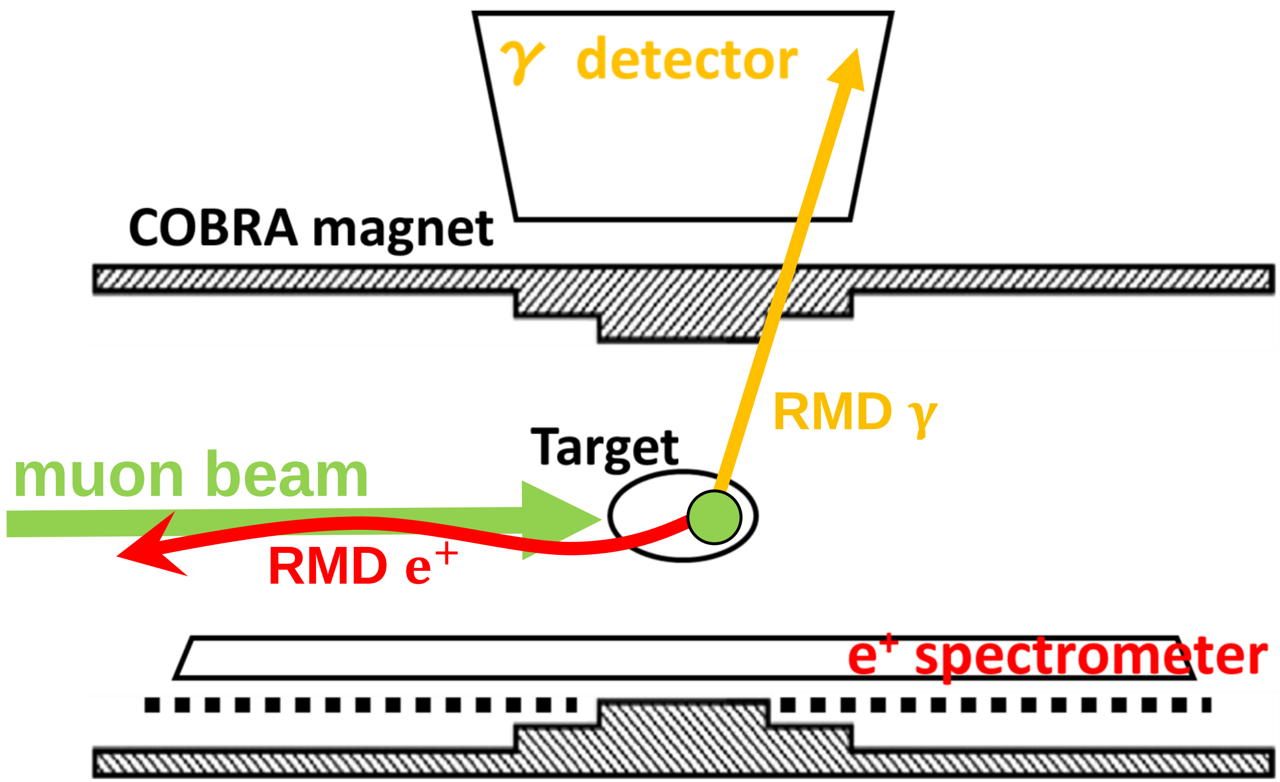


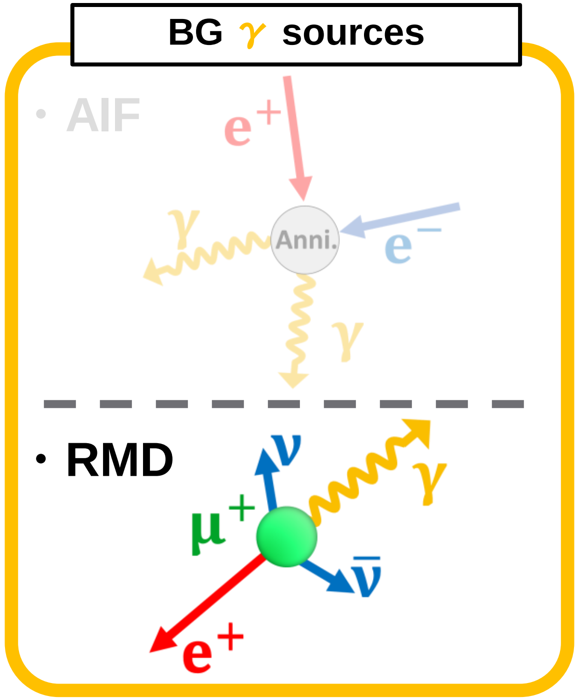


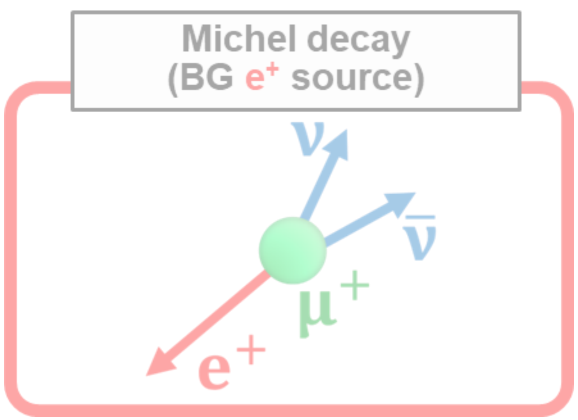


Why do we need a Radiative Decay Counter?

- RMD γ identified by detecting e^+ emitted together
  - Most of the e^+ have $1-5$ MeV energy
    → The e^+ distributes around muon beam axis
- **RDCs are installed in muon beamline**







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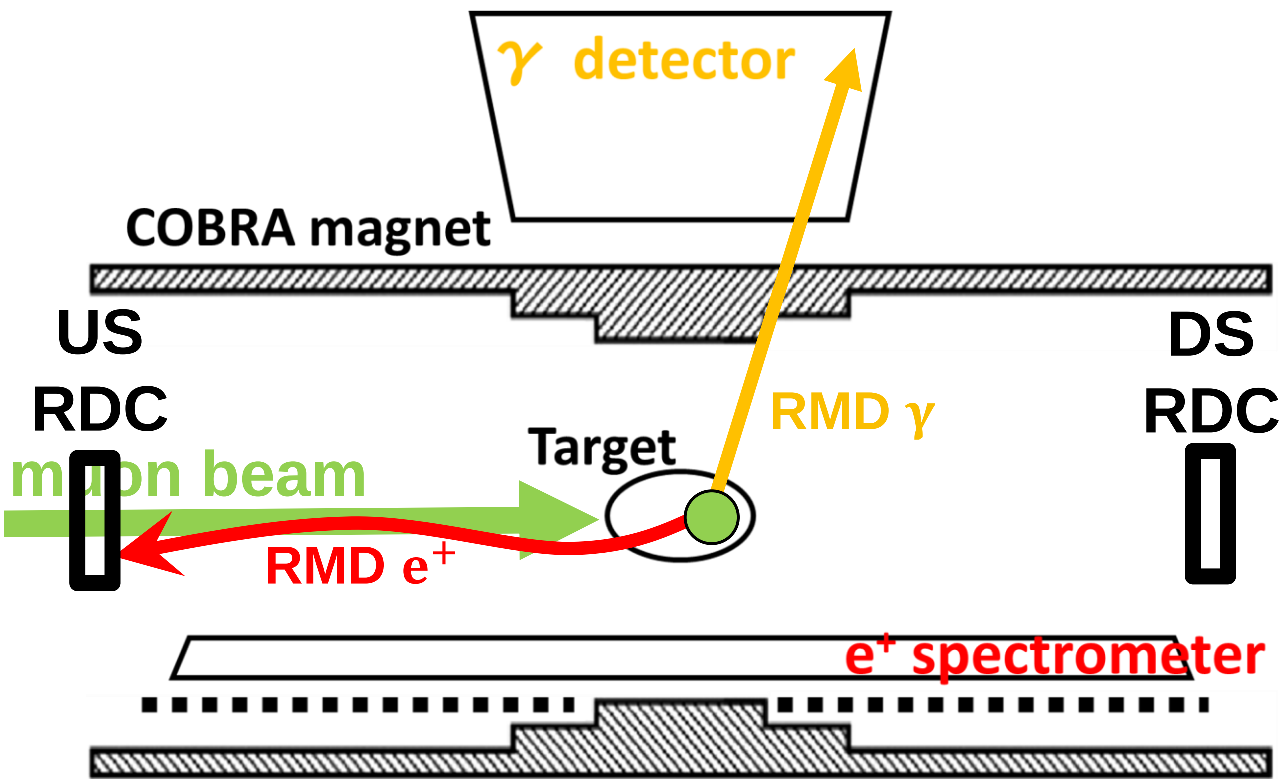
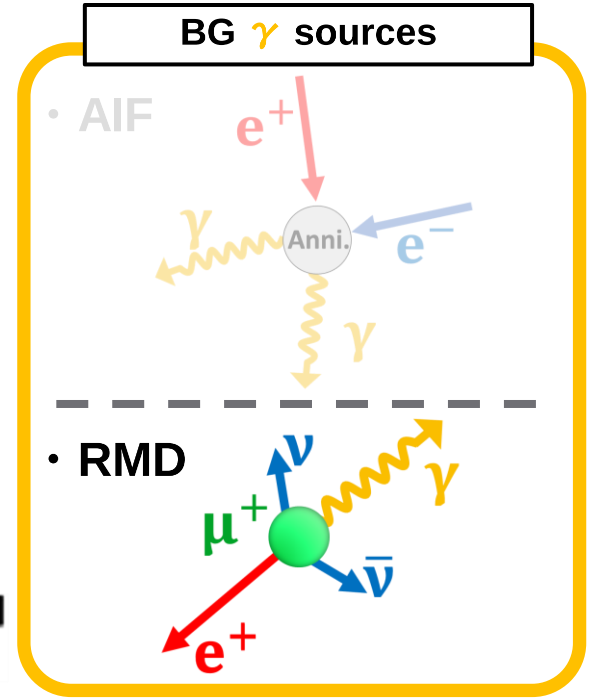
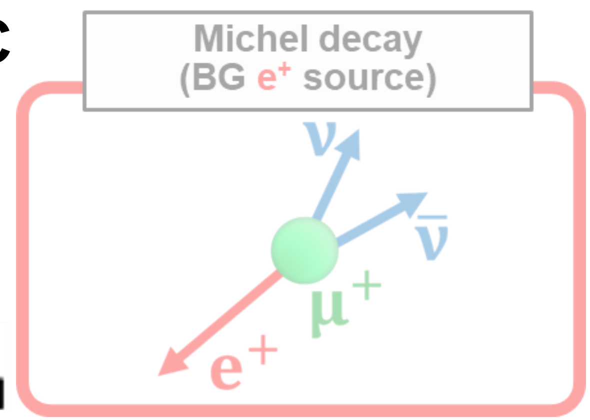






Radiative Decay Counter

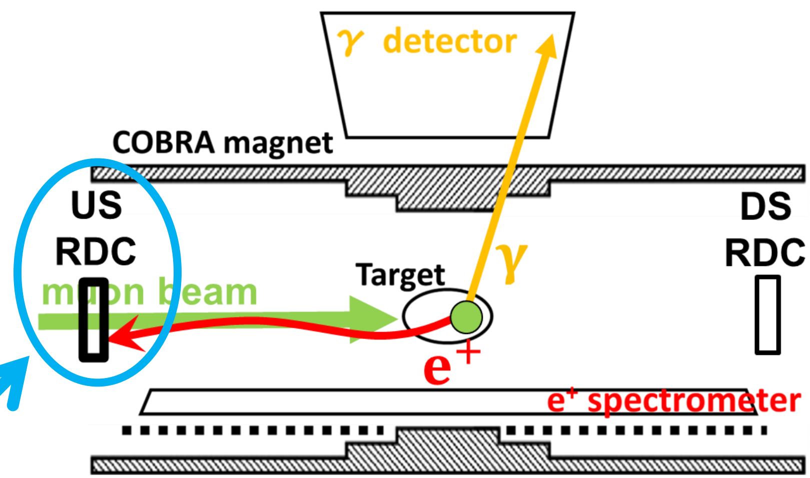
- Downstream RDC has already been installed

- **Upstream RDC is under development**
  - **High-rate** ($1 \times 10^8\ \mu/\mathrm{s}$, $4\ \mathrm{MHz/cm^2}$ at center), **low-momentum** ($28\ \mathrm{MeV/c}$) muon beam passes through

- Requirements to upstream RDC

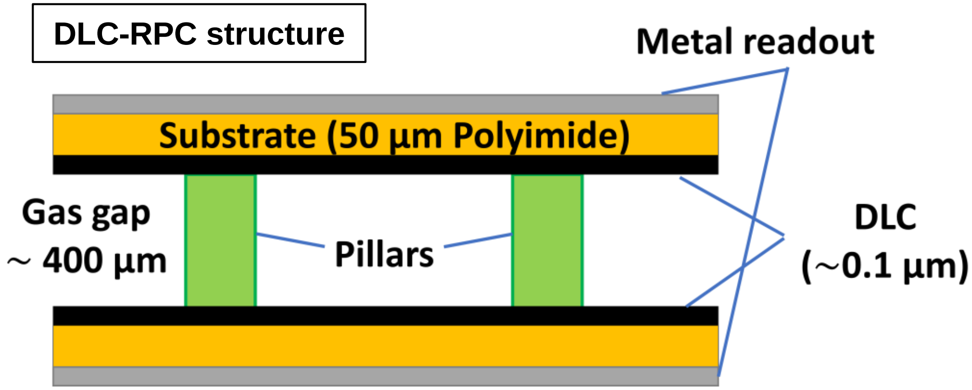
1. Material budget: $< \mathbf{0.1\%}$ radiation length
   ➡ muon beam with $28\ \mathrm{MeV}/c$ must pass through the detector
2. Rate capability: $\mathbf{4\ MHz/cm^2}$ of muon beam
3. Radiation hardness: $> \mathbf{60\ weeks}$ operation
4. MIP efficiency: $> \mathbf{90\%}$
5. Timing resolution: $< \mathbf{1\ ns}$
6. Detector size: $\mathbf{20\ cm}$ (diameter)

DLC-RPC for the upstream RDC



DLC-RPC structure

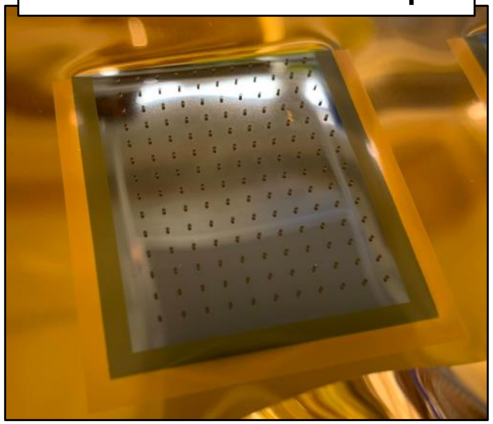
DLC-RPC structure



- DLC-RPC
  - Diamond-Like Carbon
    - **Sputtered on polyimide**
      → Achieves ultra-low mass
    - **Controllable resistivity**
      → Contributes to high-rate capability
  - Formation of pillars for spacer using **photo-lithography technology**
    → Pillars provide gas gap flatness

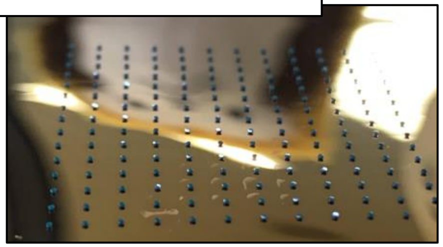
DLC sputtered on polyimide

DLC-RPC electrode sample



Pillars are 384 μm-t, 2.5 mm pitch in this sample

Pillars formed on DLC



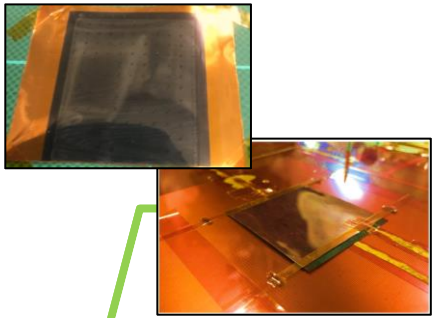
Production process of DLC-RPC electrodes was presented at WG6

R&D History

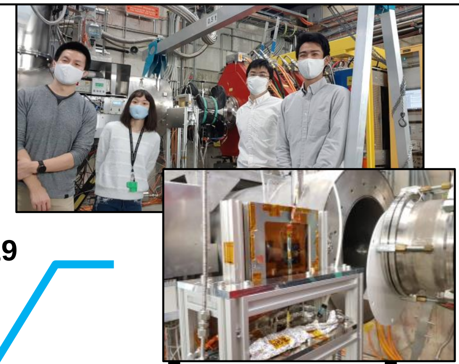
- A series of R&D began in 2016

Ref:https://conference-indico.kek.jp/event/70/contributions/1398/ (CLFV)
arXiv:2109.13525 (TIPP)

R&D for Fast Timing RPC R&D in Kobe



Beam test using low-momentum μ^+ beam



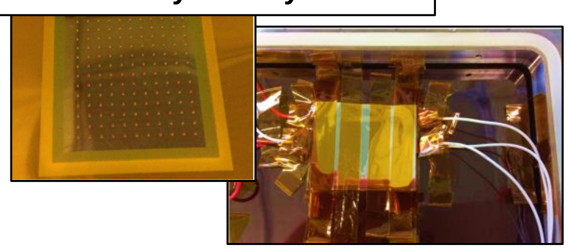
Reported at CLFV 2019 by A. Oya

Installation in 2023 !!

2016 2017 2018 2019 2020 2021 2022 2023

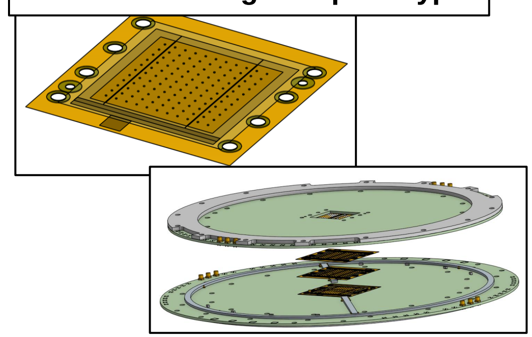
New design RPC ideas by A.Ochi
Adopted for Grant-in-Aid for Challenging Research (Exploratory)

R&D for MEG II US-RDC in the University of Tokyo



- **Reported at TIPP 2021 by A. Oya**
- **Adopted for Grant-in-Aid for Scientific Research**

Beam test using new prototype



DLC-RPC for upstream Radiative Decay Counter

➢MEG II DLC-RPC design → **4-layer DLC-RPC**

- Stacked to increase detection efficiency

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

n: number of layers, ϵ_n: n-layer efficiency, ϵ_1: single-layer efficiency

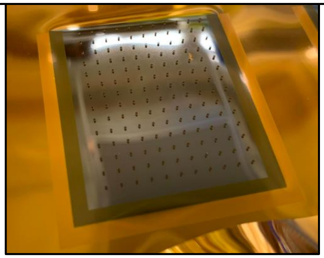
Material budget

- Polyimide 50 μm → 0.018% X_0
- Aluminum 30 nm → 0.0034% X_0

→ **0.095% radiation length**

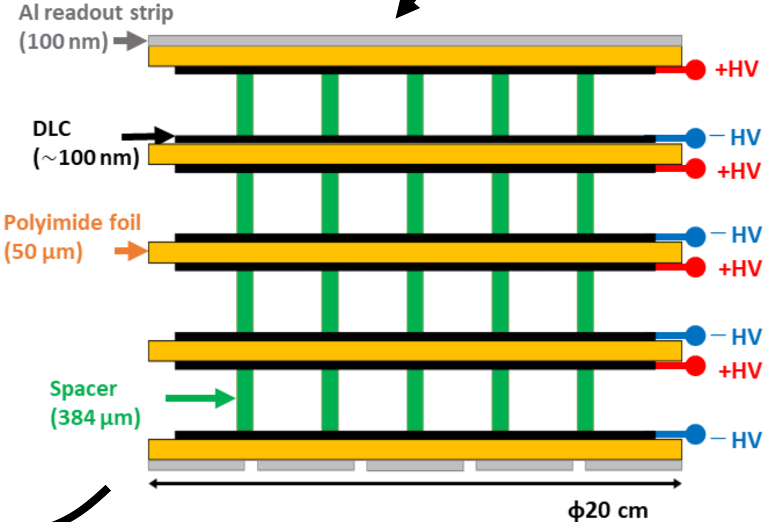
Achieved < 0.1% radiation length

DLC-RPC electrode sample

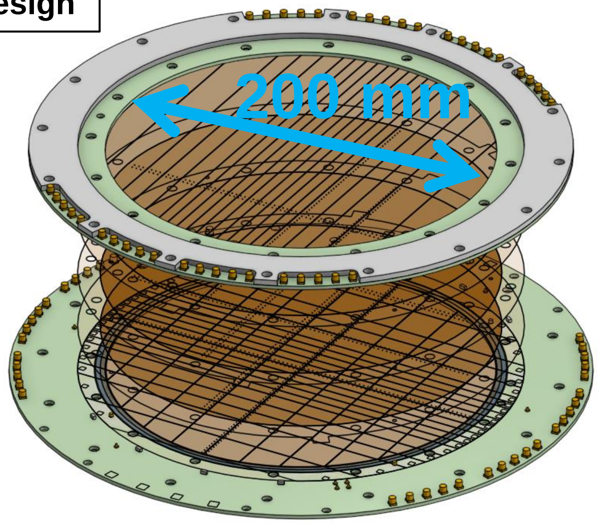


Pillars are 384 μm-t, 2.5 mm pitch in this sample

Multi-layer by Stacking



Current actual DLC-RPC design



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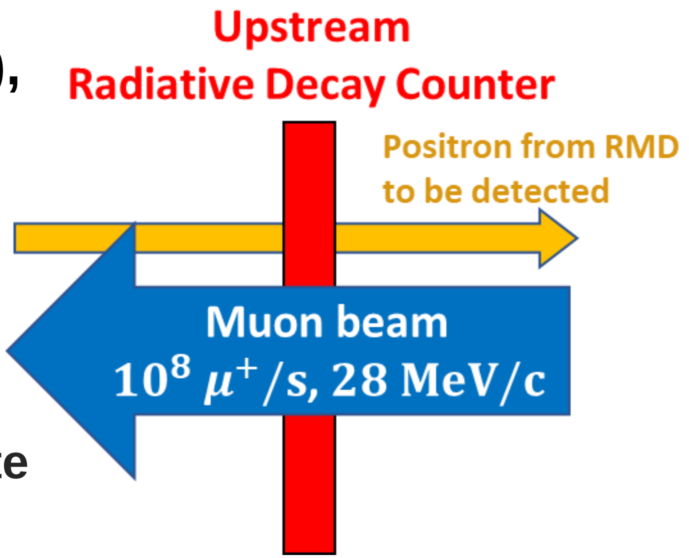
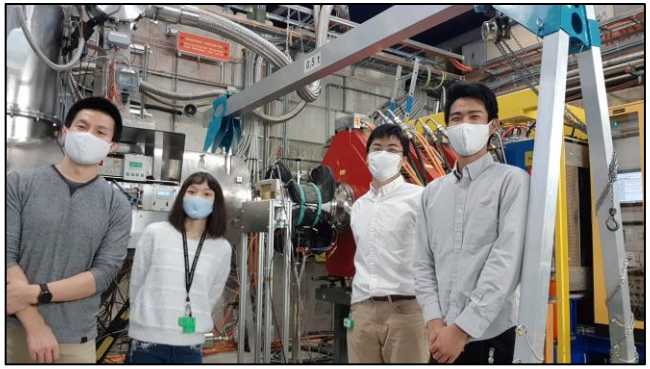
High-rate performance tests

➢**Goal:** MIP detection in a **high-rate ($\mathbf{4\ MHz/cm^2}$),**
low-momentum ($\mathbf{28\ MeV/c}$) muon beam

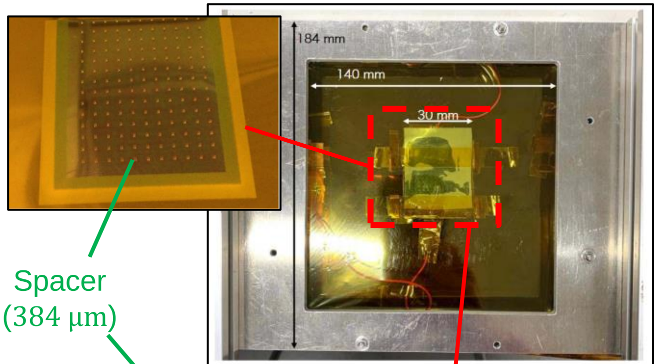


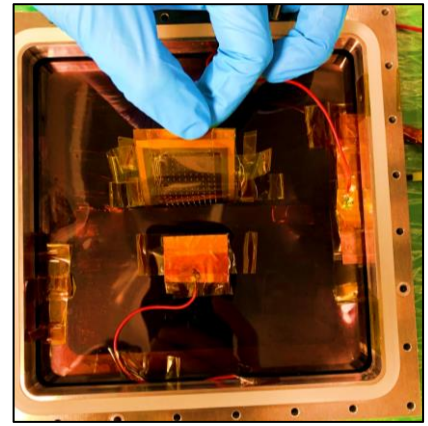
➢**Studies**

- **Efficiency and timing resolution for MIP at low rate**
  - Measurement with single- and multi-layer configuration
- **High-rate performance in low-momentum muon**
  - The beam test took place in December 2020
  - Muon beam at πE5 of Paul Scherrer Institut ($10^8\ \mu^+/s$)
  - Measurement of response to low-momentum muon
  - Voltage drop evaluation in high-rate low-momentum muon



Prototype detector for performance study

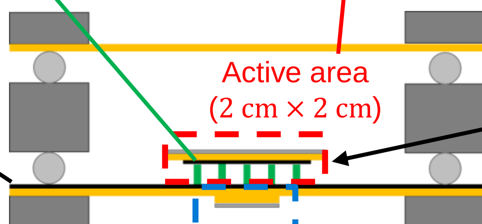




Spacer
(384 μm)

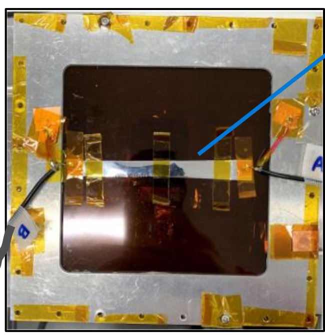
Polyimide foil
(50 μm)

DLC-coated
window

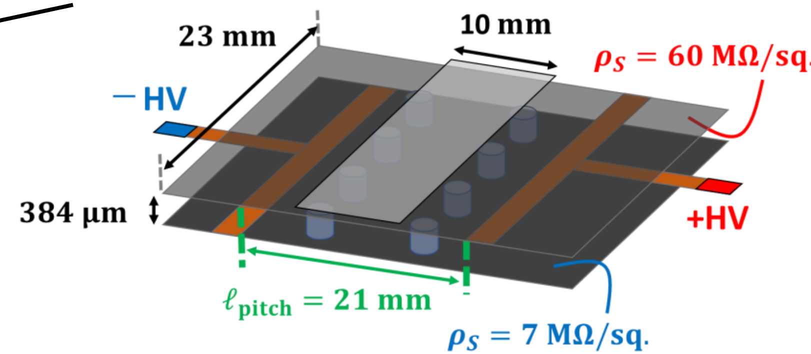


Active area
(2 cm × 2 cm)

Rubber for
gas tight

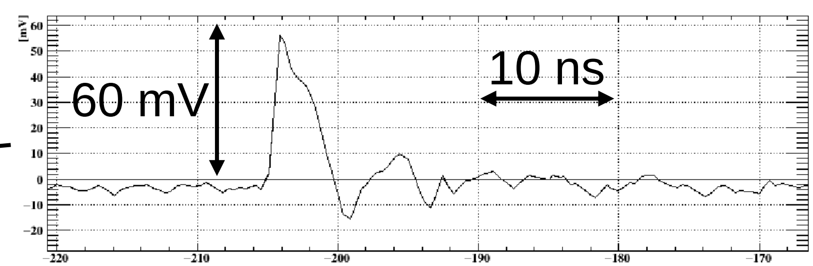


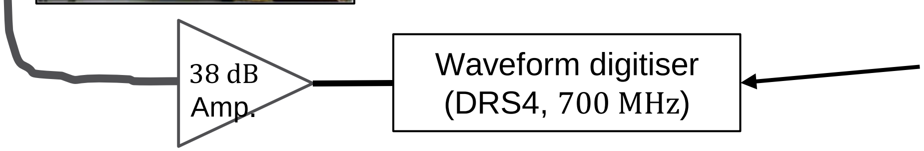
Aluminised polyimide
(~ 1 cm ×~ 10 cm / Al 100 nm)



Gas composition is
Standard RPC gas
($R134a/SF_6/i\text{-}C_4H_{10}$= 94/1/5)

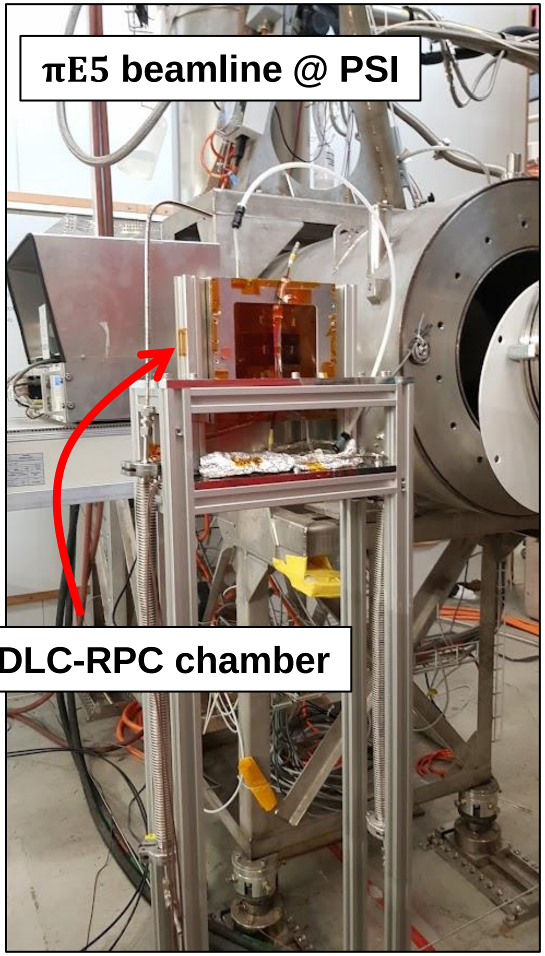
Example of acquired waveforms





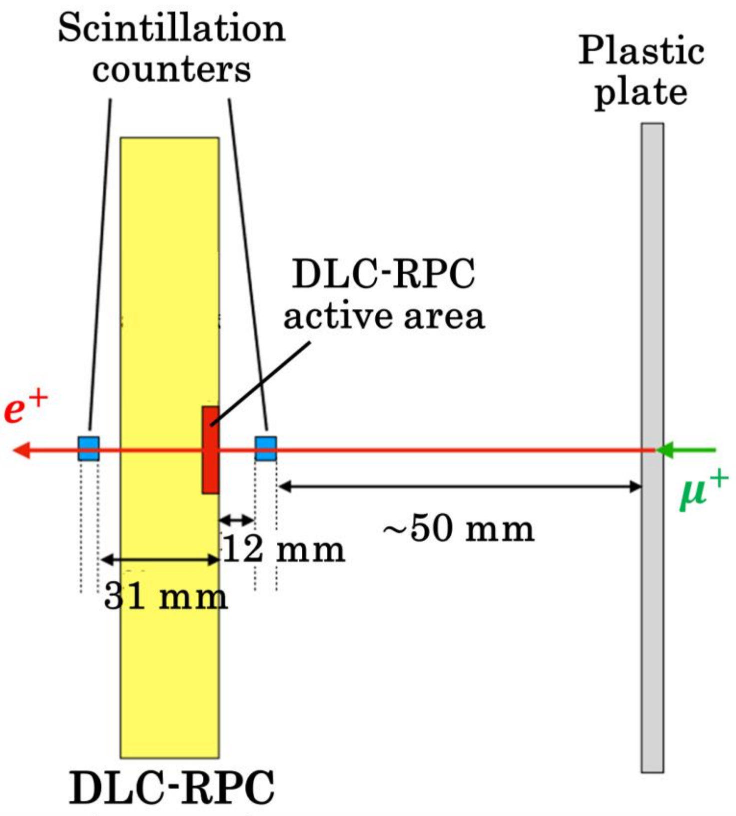
MIP detection with single-layer

- Test with positron from muon decay



- Positron from muon decay with $\mathcal{O}(1 - 10\ \mathrm{kHz/cm^2})$ rate

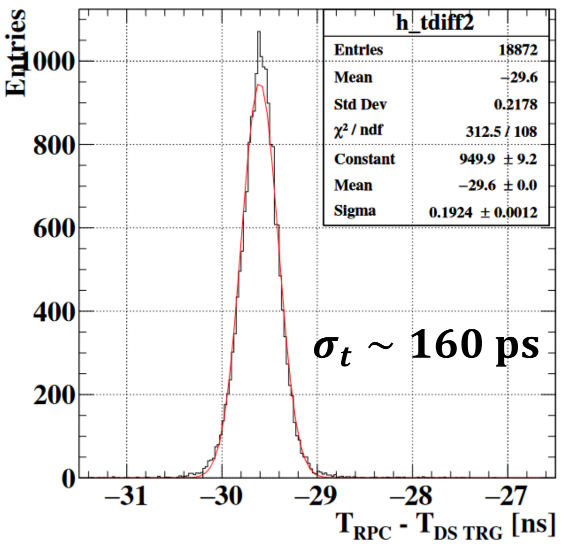
Setup



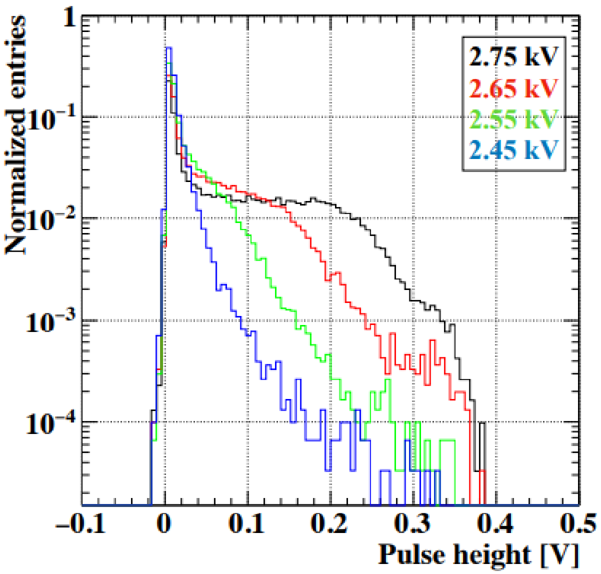
MIP detection with single-layer

- Timing resolution and efficiency are measured with single-layer

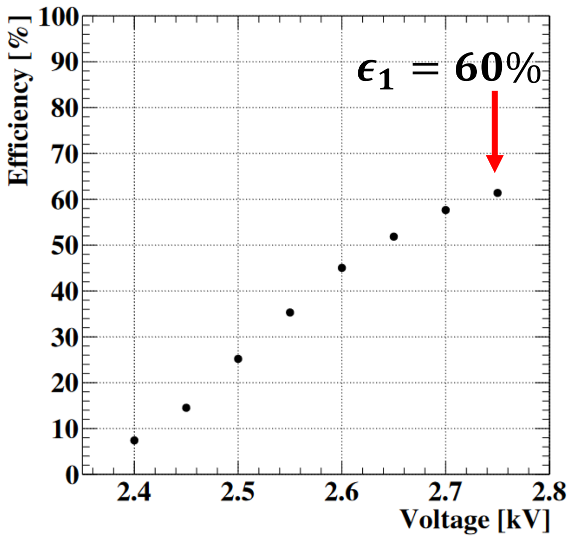
Time difference b/w DLC-RPC and DS Trigger for MIP e^+



Pulse height distributions



Efficiency for MIP e^+



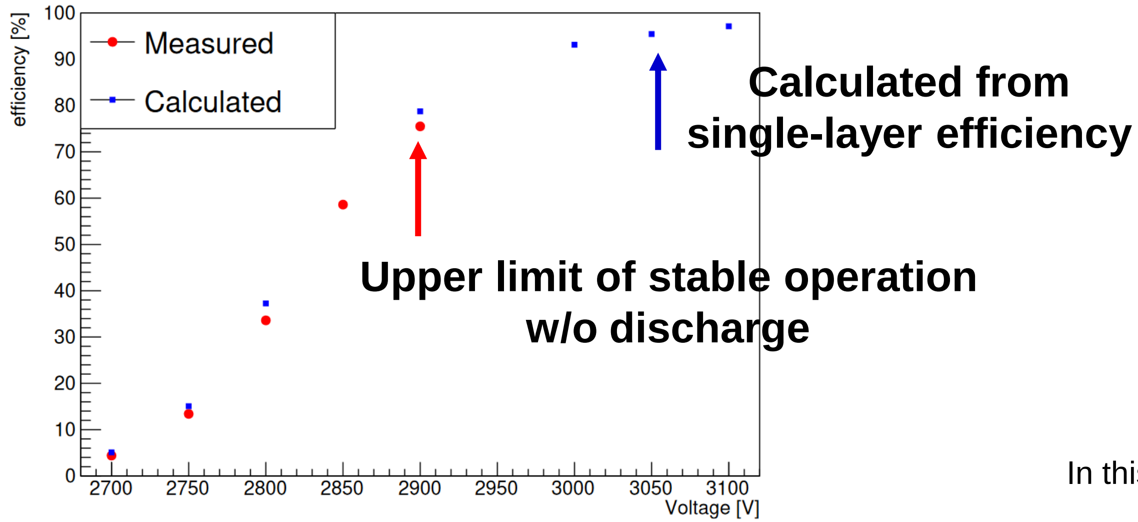
Requirements fulfilled for

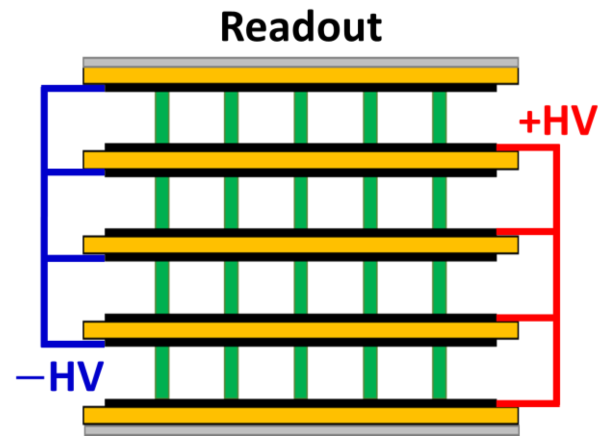
- **Timing resolution: < 1 ns**
- **Single-layer efficiency: $> 40\%$**
  - Required to achieve 90% in the 4-layer DLC-RPC from the equation $\epsilon_n = 1 - (1 - \epsilon_1)^n$

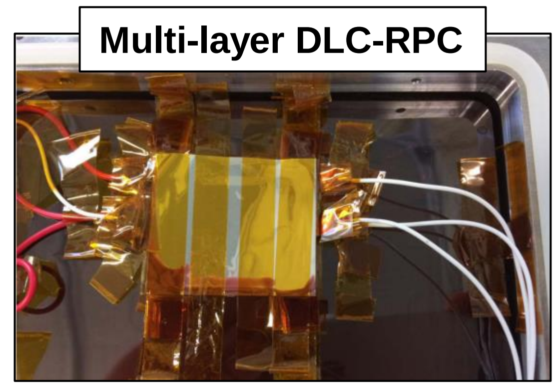
MIP detection with multi-layer

- Efficiency with 4-layer measured
  - Efficiency expected to improve as $\epsilon_n = 1 - (1 - \epsilon_1)^n$
  - Beta-ray from ^{90}Sr with $\mathcal{O}(1\ \mathrm{kHz/cm^2})$ rate

Efficiency of 4-layer DLC-RPC





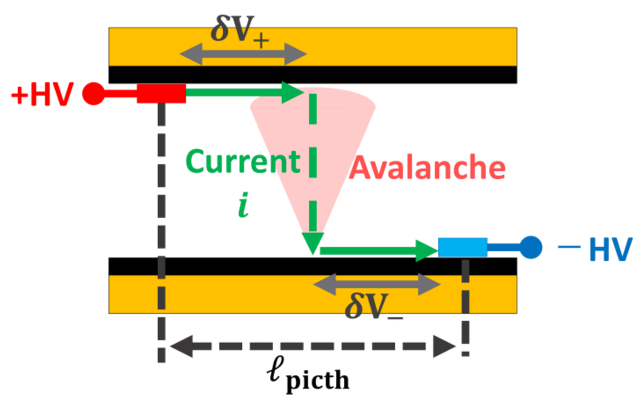


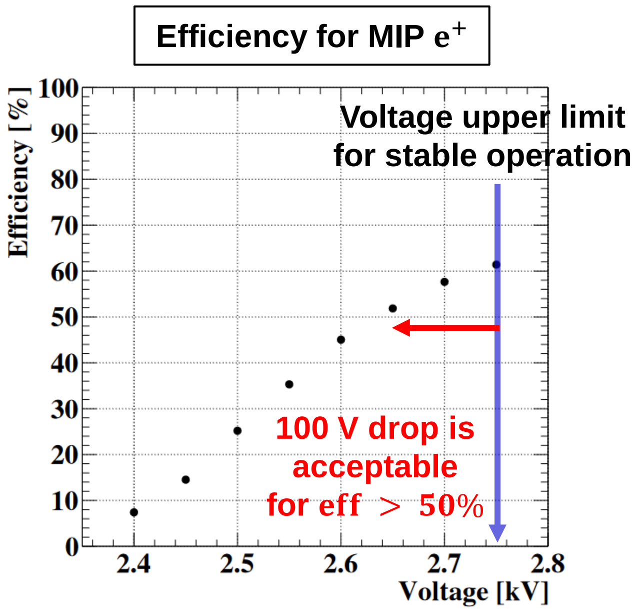
In this test, gas composition differs from other tests:
R134a / SF_6 = 93 / 7 %

- Measured efficiency with multi-layer found to follow the equation
  - **90% detection efficiency is achievable with 4-layer in low-rate**
  - Issue: Discharge due to electrode imperfect flatness

Rate capability of DLC-RPC

- **Determined by the voltage drop (δV) due to current on DLC**
  - $\nabla^2 \delta V(x,y) = Q_{mean}(V_{eff}) \cdot f(x,y) \cdot \rho_S$
    Avalanche charge / Hit rate / Surface resistivity
  - **Up to $\delta V = 100$ V can be acceptable**



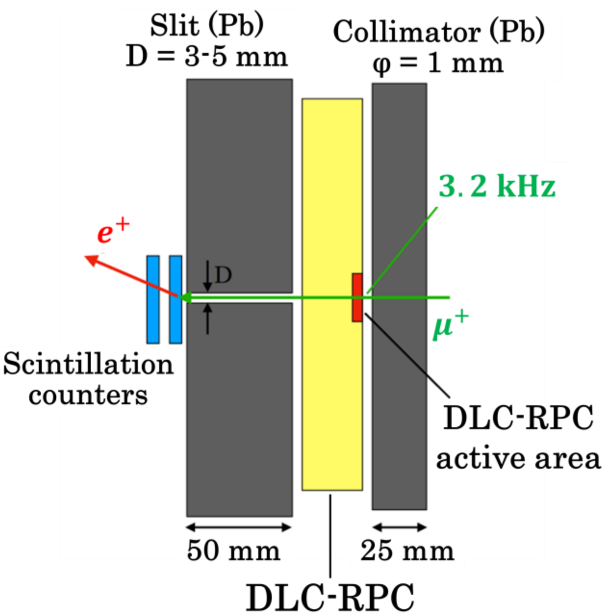


- Rate capability is evaluated by estimating voltage drop in low-momentum muon beam
  - Voltage drop estimated
    - By comparison of pulse height distribution in low-rate muon beam
    - Using voltage drop equation

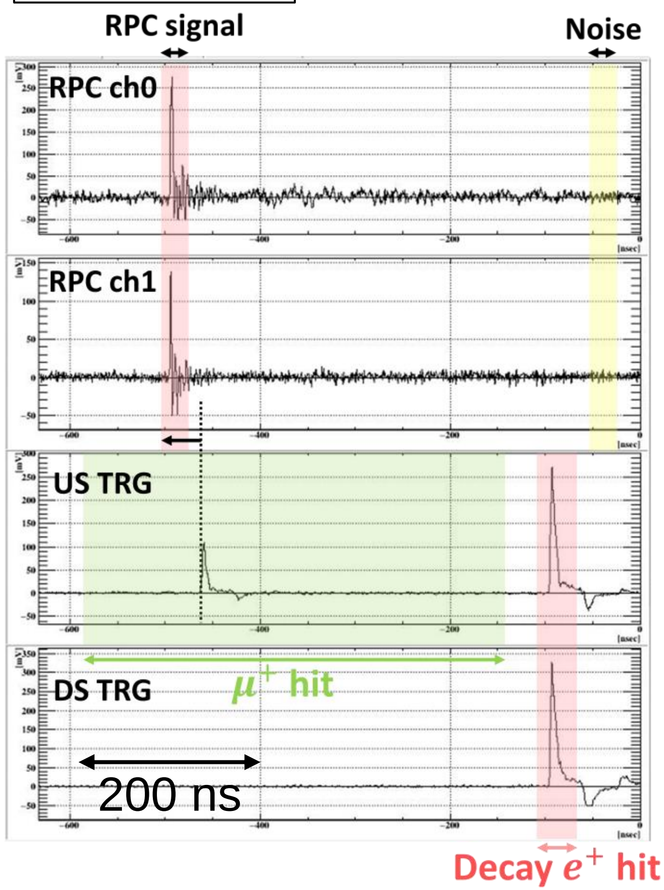
Response to low-momentum muon at low rate

- Measured low-momentum muon at low-rate (~3 kHz) to estimate the avalanche charge Q_{mean} of the muon beam

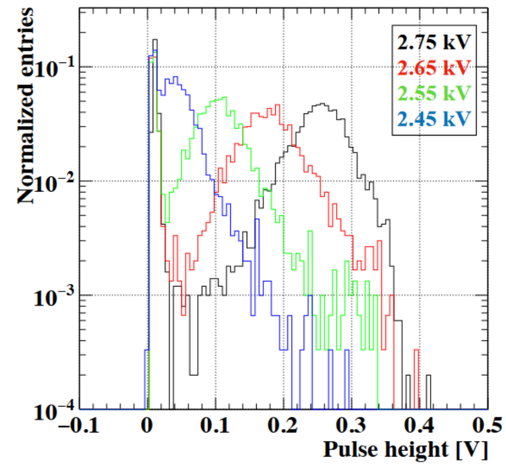
Setup



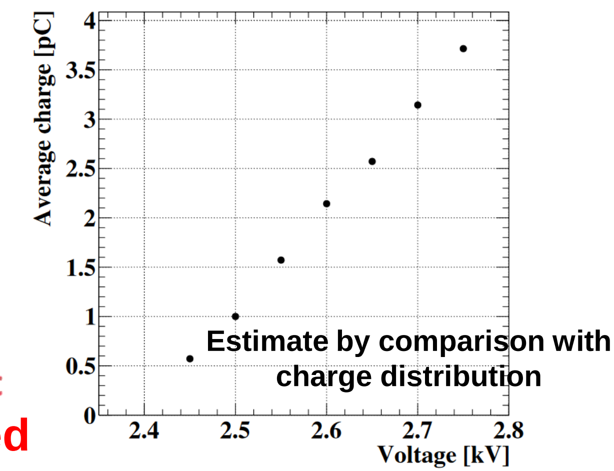
Event display



Pulse height distributions for low-momentum muon



Average charge of muon

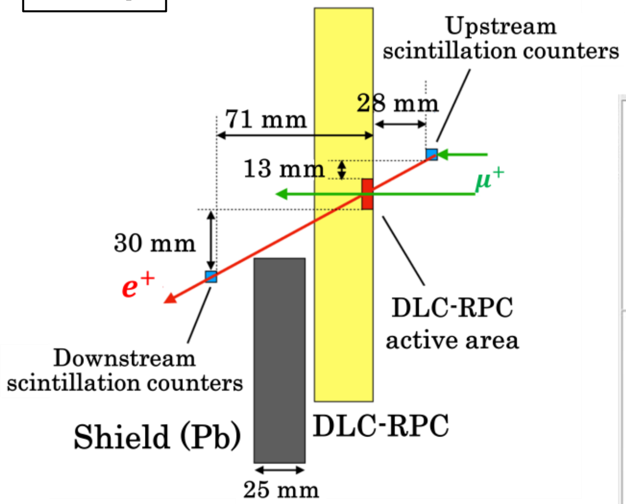


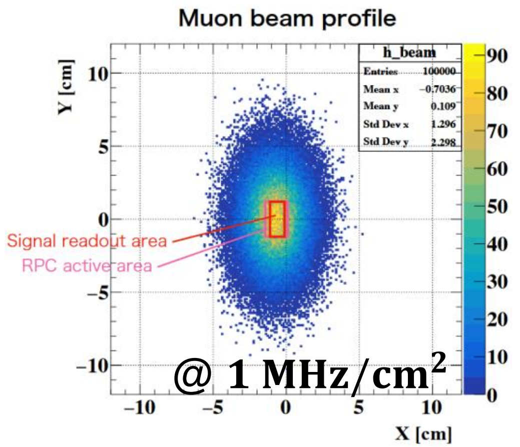
- **Low-momentum muon successfully passed and detected**

MIP detection in high-rate muon beam

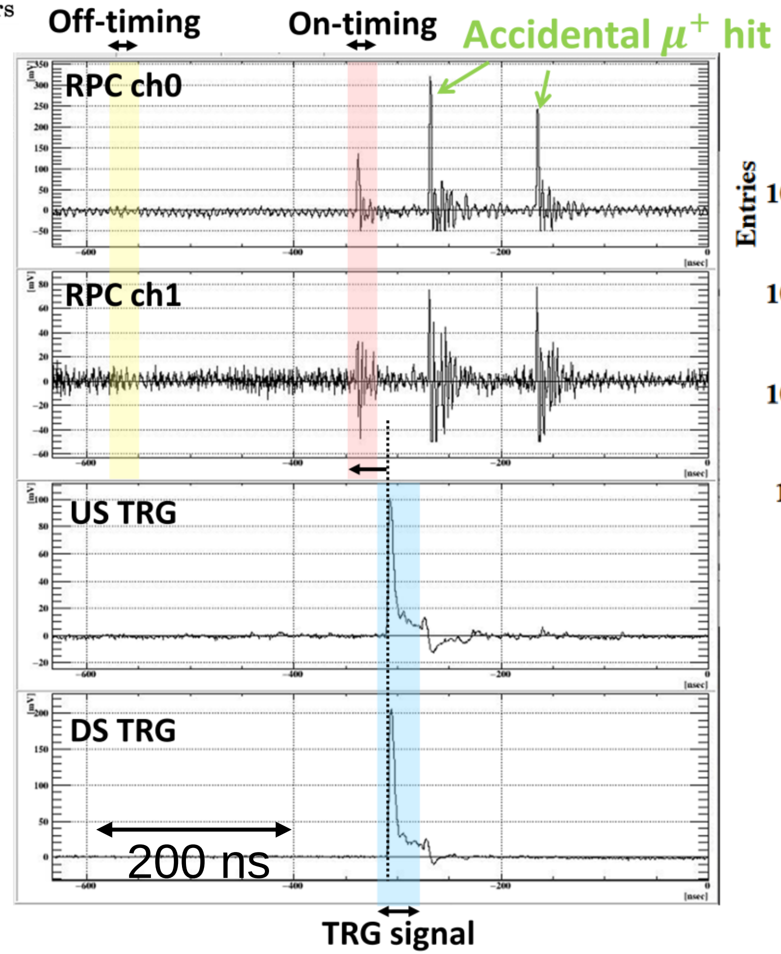
➢Measured MIP positron in high-rate and low-momentum muon beam

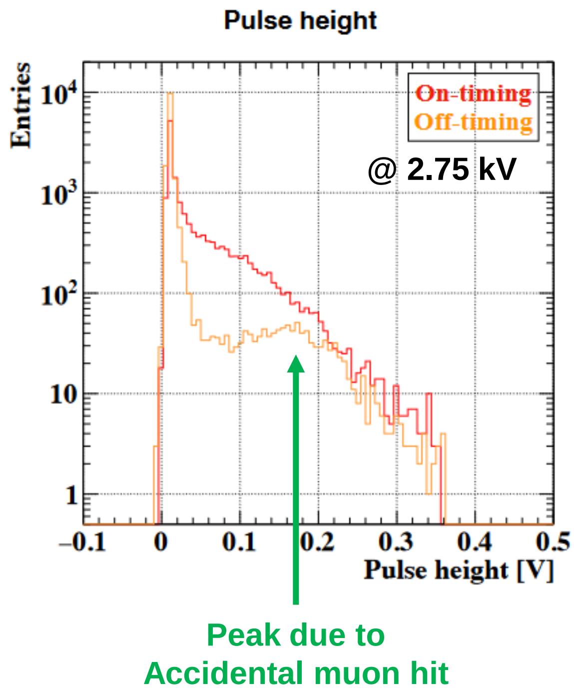
Setup





Event display

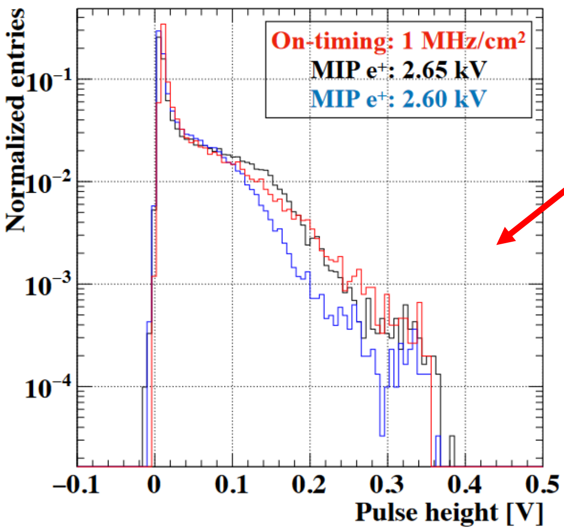




Rate capability estimation

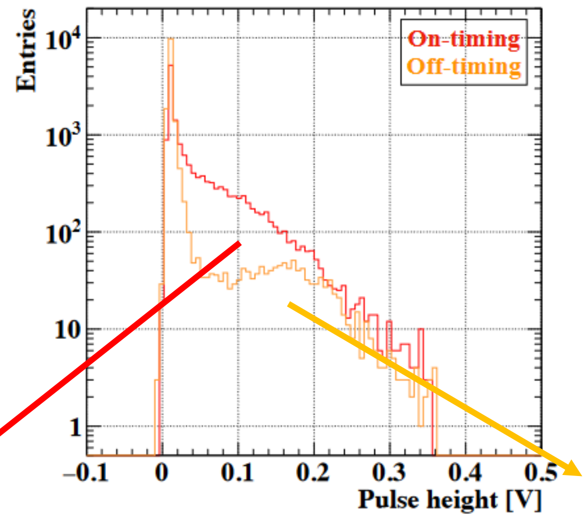
- Comparison of pulse height distributions

MIP @low-rate

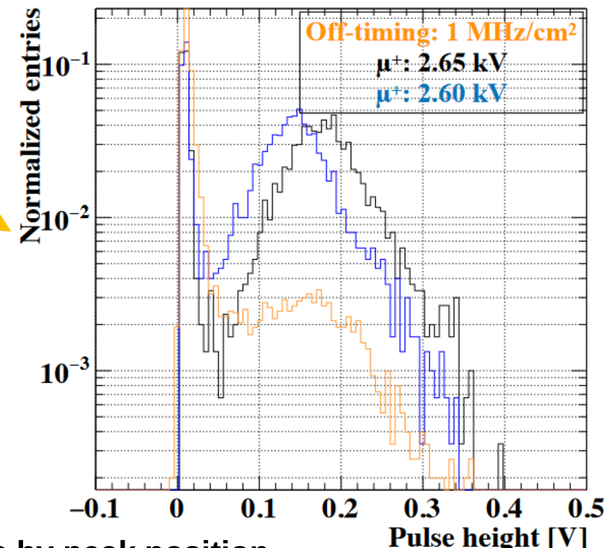


Different distribution above 0.1V due to accidental μ^+ hit

Pulse height @ high-rate 2.75 kV



μ @low-rate



Compare by peak position

- Voltage drop = $100 - 150$ V

- 50% MIP e^+ efficiency with single-layer
  → **Prototype detector has a rate capability of 1 $\mathrm{MHz/cm^2}$**

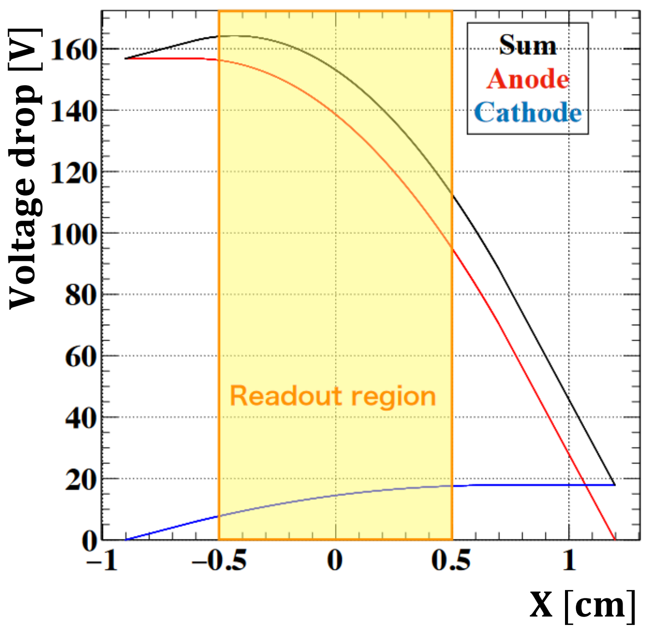
Rate capability estimation

➢Estimate the voltage drop from the following equation:

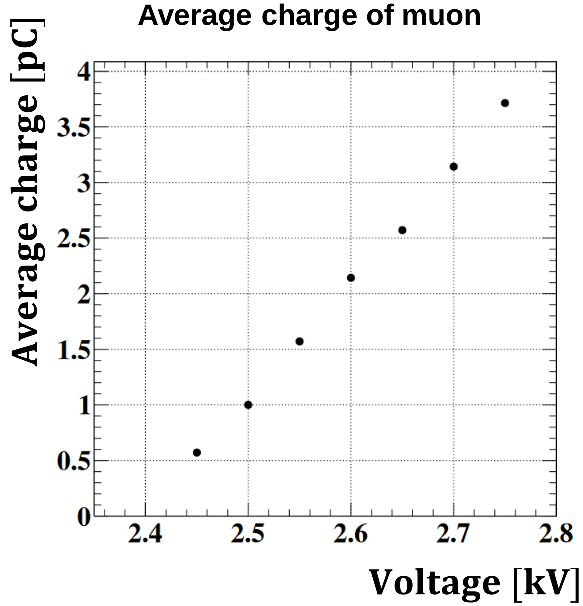
$$\nabla^2 \delta \mathrm{V}(x,y) = Q_{\mathrm{mean}}(\mathrm{V}_{\mathrm{eff}}) \cdot f(x,y) \cdot \rho_S$$

DLC surface resistivity
- Anode: $60\ \mathrm{M\Omega/sq.}$
- Cathode: $7\ \mathrm{M\Omega/sq.}$

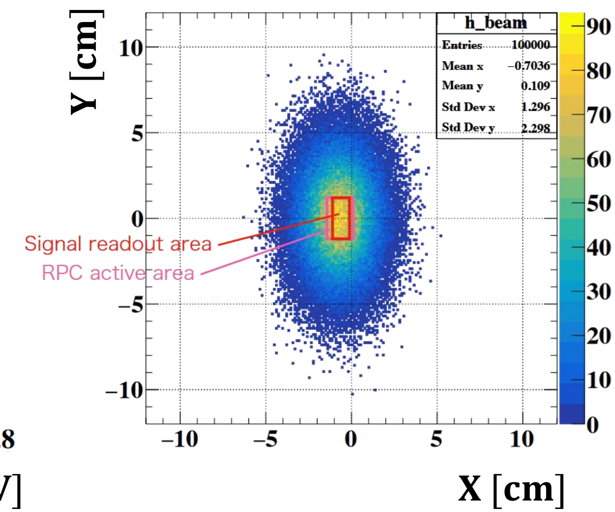
Voltage drop



Average charge of muon



Muon beam profile



➢Estimated voltage drop = $110-170\ \mathrm{V}$

→ Agreement at ~10% with evaluation by pulse height distribution

Outline

- Introduction
  - MEG II experiment
  - Radiative Decay Counter
  - DLC-RPC for upstream RDC
- Performance study
  - Timing resolution and efficiency for MIP at low rate
  - High-rate performance for low-momentum muon
- Summary and prospects

Summary

➢**Ultra-low mass and high-rate capable RPC with DLC electrodes** is under development for MEG II upstream Radiative Decay Counter

- Detector for MIP positron in high-rate muon beam background

➢Prototype DLC-RPC Performance

- **Achieved** requirements
  - Material budget: $\mathbf{0.095\%}$ **radiation length** → $< 0.1\%$ radiation length is achieved
  - Timing resolution: $\mathbf{160\ ps}$ with single-layer → $< 1\ \mathrm{ns}$ is achieved
  - MIP efficiency: $\mathbf{60\%}$ with single-layer → $> 40\%$ with single-layer is achieved

    NOTE: This detection efficiency in **low-rate** performance test
- **Not yet achieved** requirement
  - Rate capability: $\mathbf{1\ MHz/cm^2}$ of muon → $4\ \mathrm{MHz/cm^2}$ of muon is not achieved
    - At higher rate, detection efficiency is $< \mathbf{40\%}$ due to voltage drop

We should improve the electrodes to achieve the rate capability requirement

Prospects - Design for higher rate capability

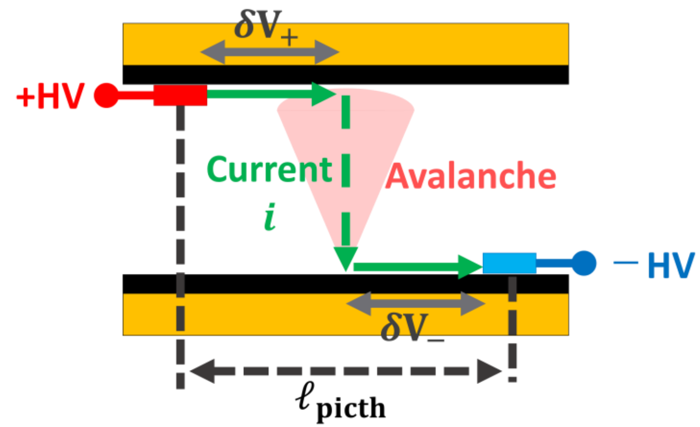
- Voltage drop follows:

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

Avalanche charge | Hit rate | Surface resistivity

→ **Distance from HV supply must be small and low surface resistivity are needed**

- $\delta V \propto \rho_S$, $\delta V \propto \ell_{\mathrm{pitch}}^2$

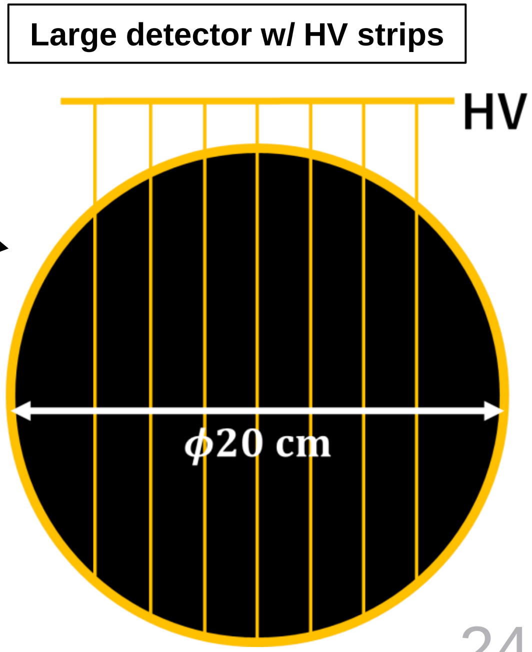


- In high-rate performance test, a small prototype was used

→ ℓ_{pitch} is small (21 mm)

- The ℓ_{pitch} needs to be smaller with Φ20 cm detector

Implement a strip HV supply line



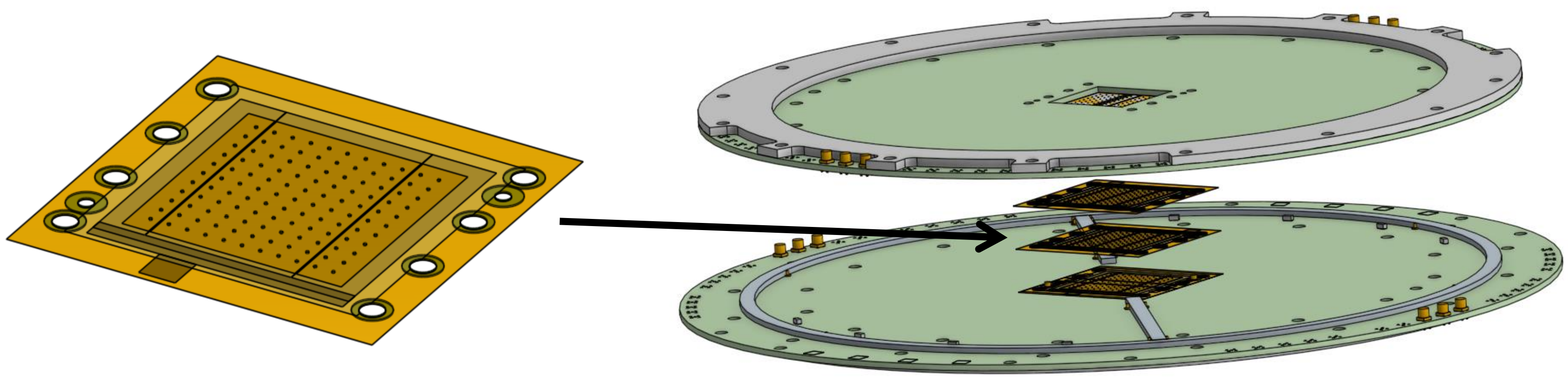
Details were presented by Kensuke at WG6

Prospects – Planed studies

- Planned studies
  - New prototypes with improved electrode structure under construction
  - Rate capability test using new prototypes in this year
    → If performance can be demonstrated with a prototype,
    the requirements can be achieved with a large detector
  - Work on another remaining requirement, **Radiation-hardness**
    - Accelerating aging test planned using fast neutron, X-ray

Aiming for installation next year

New prototype to be used in 2022 beam test



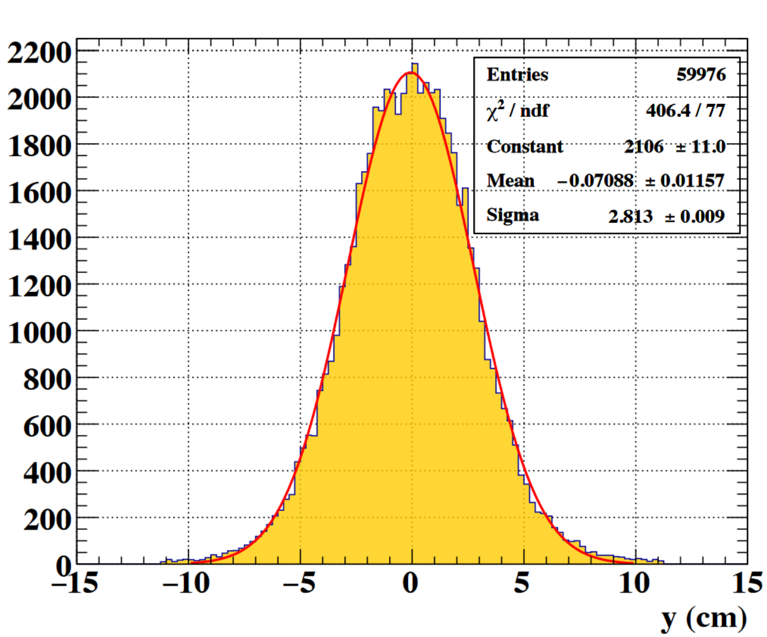
Backup

e^+ from RMD distribution and μ^+ beam profile

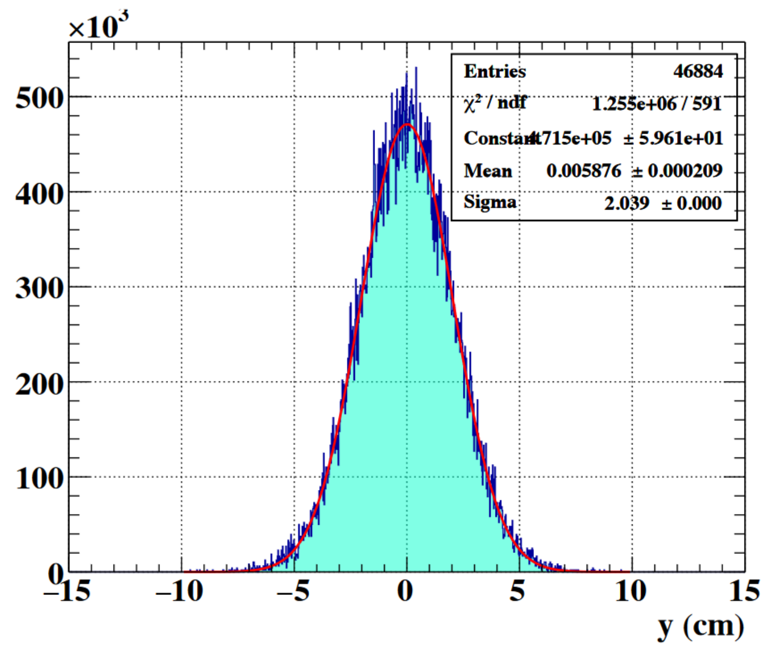
➢ Both positron from the RMD and muon beams are most abundantly distributed at the center of the beam line

→ **No holes can be drilled in the detector**

- Positrons are missed



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



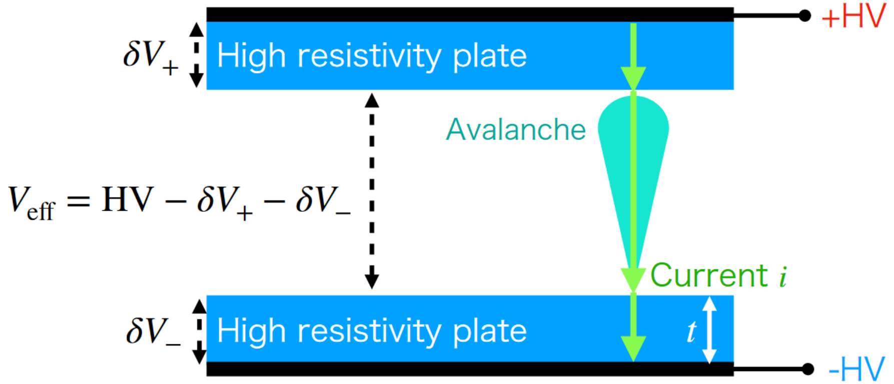
μ beam profile
$\sigma = 2.0$ cm

Rate capability

- The voltage drop due to high current on resistive electrodes
  - Current paths are different between conventional and DLC-RPC

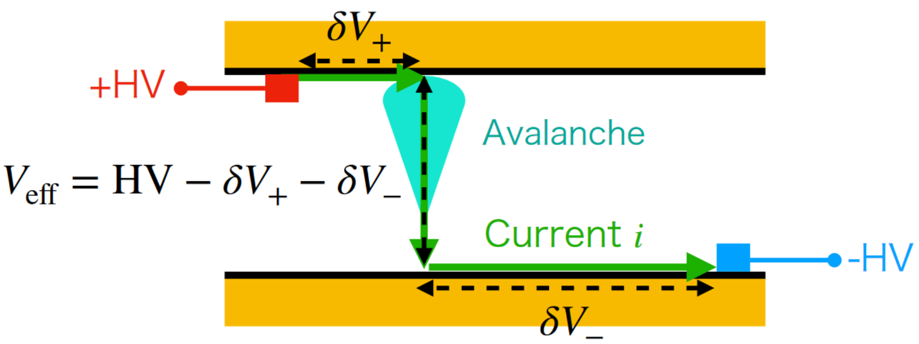
  ➡ In DLC-RPC, the distance between conductors affects voltage drop

(Conventional) bulk RPC



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

DLC-RPC



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

Response to low-momentum muon at low-rate

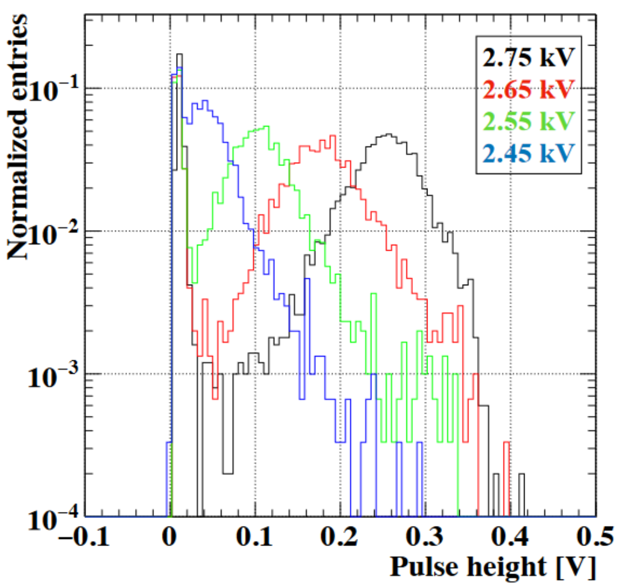
- Observed signal size for low-momentum muon is almost the same as for MIP positron

- Energy deposit: $\left(\frac{dE}{dx}\right)_{\mathrm{low-momentum}\ \mu} \sim 10 \times \left(\frac{dE}{dx}\right)_{\mathrm{MIP\ e^{+}}}$

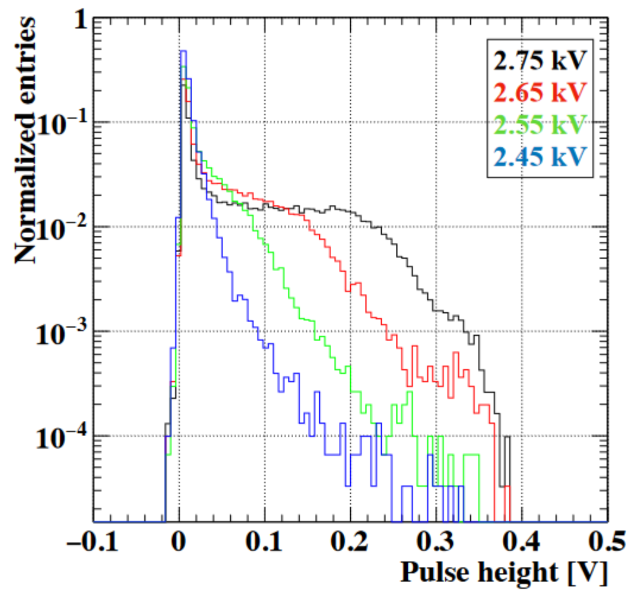
  → Avalanche charge **saturated due to the space charge effect**

  → **Better for rate capability** because voltage drop is mitigated

Pulse height distributions for low-momentum muon



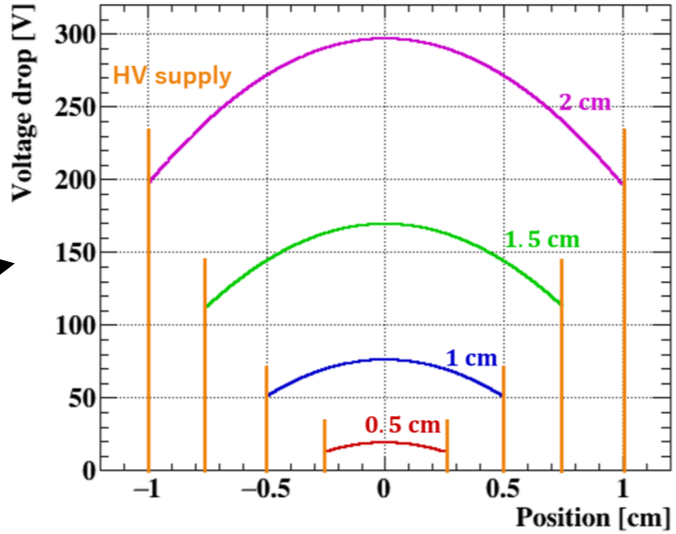
Pulse height distributions for MIP e^{+}



Design for higher rate capability

- Surface resistivity of DLC
  - Too low → Unstable operation due to discharge
  - Too high → Larger voltage drop
- Previous stability study
  - $1\ \mathrm{M\Omega/sq.}$: Unstable
  - $> 20 - 30\ \mathrm{M\Omega/sq.}$: Stable
  - → **Production with $\rho_S = 10\ \mathrm{M\Omega/sq.}$**
    - In this case, ℓ_{pitch} was designed to be **1 cm** so that $\delta \mathrm{V} < 100\ \mathrm{V}$

ℓ_{pitch} dependency of $\delta \mathrm{V}$ @ $\rho_S = 10\ \mathrm{M\Omega/sq.}$



- Option of parameters
  - If unstable operation with $\rho_S = 10\ \mathrm{M\Omega/sq.}$
    - $\rho_S = 20\ \mathrm{M\Omega/sq.}$, $\ell_{\mathrm{pitch}} = 8\ \mathrm{mm} \rightarrow \delta \mathrm{V} \sim 100\ \mathrm{V}$
    - Increase ρ_S and narrow ℓ_{pitch}

Kensuke presented manufacturing efforts to achieve this goal at WG6