MEG II実験の背景ガンマ線識別を目的としたRPC検出器の高レート耐性を実現するデザインの研究

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Core-to-Core Program

MEG II
Mu - E - Gamma collaboration

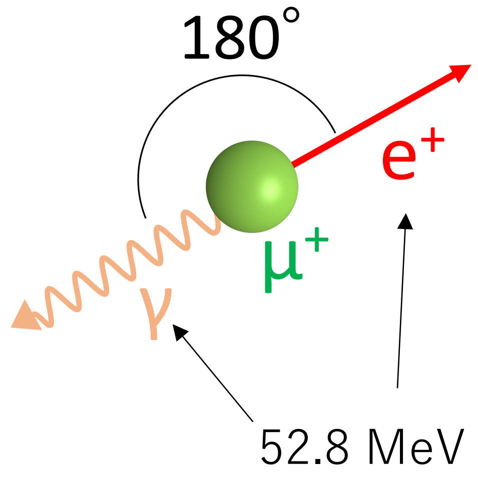
ICEPP
The University of Tokyo

KOBE UNIVERSITY

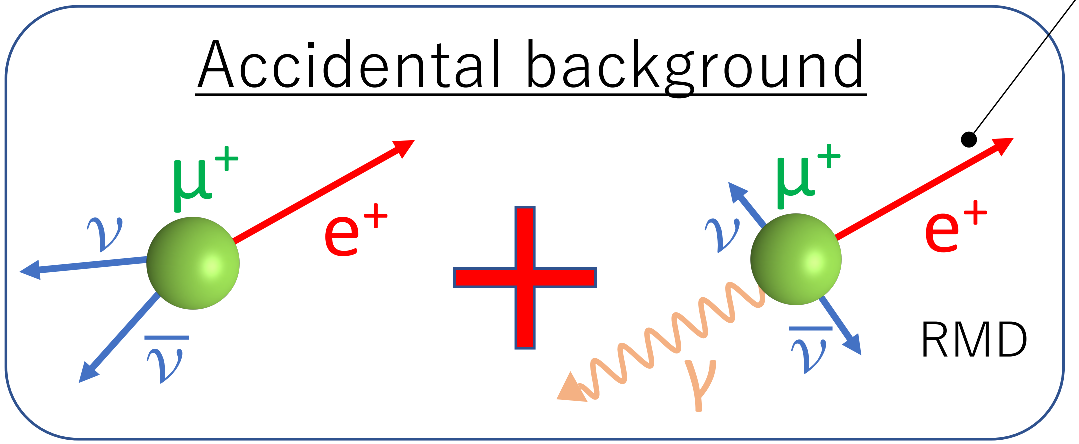
Outline

- Introduction
  - Motivation
  - Requirements to the detector
  - Concepts of the detector design
  - Prototype
- Detector design optimization
- Summary

MEG II experiment

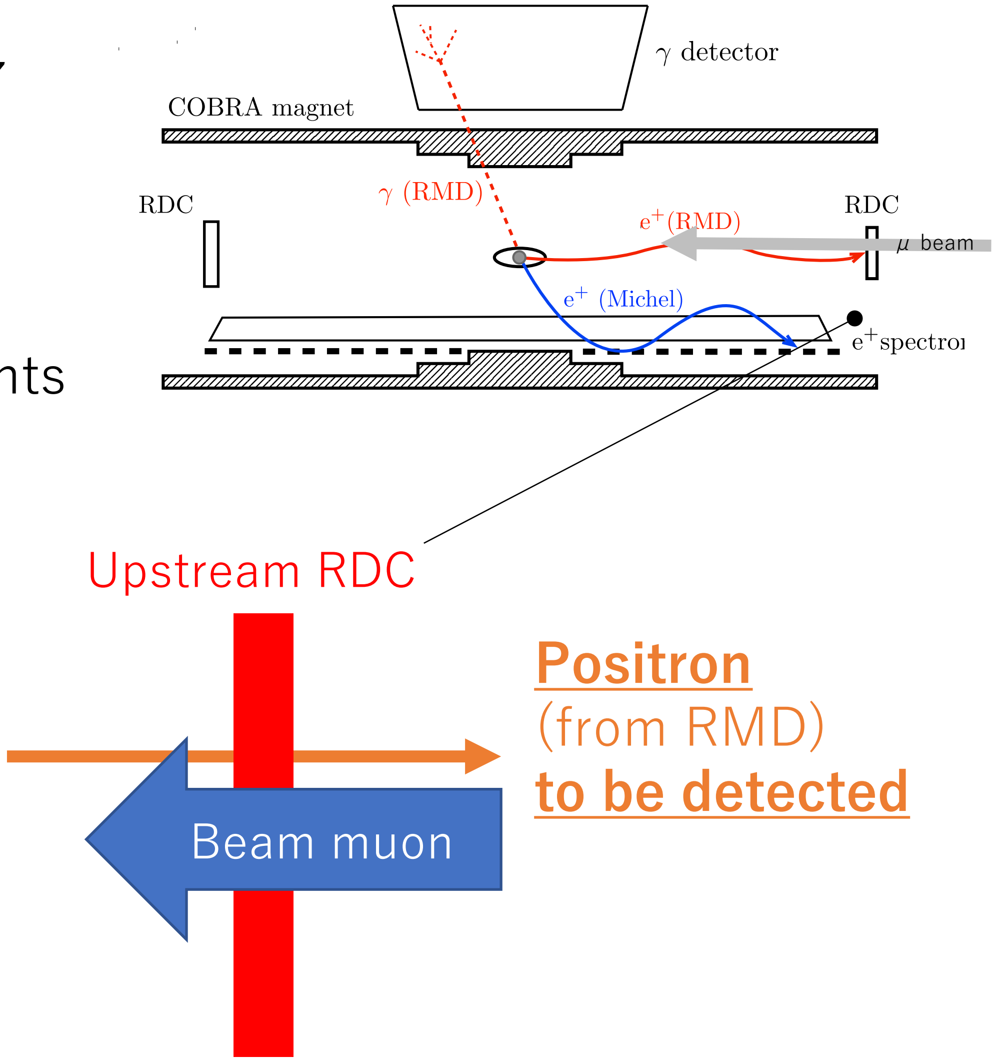


- MEG II will search for $\mu \rightarrow e\gamma$ decay
  - Signal identified by energy, timing and direction of e and γ
- Background suppression is crucial
  - Main BG source: Accidental coincidence of BG-e and BG-γ
  - One of BG-γ source: Radiative muon decay (RMD: $\mu \rightarrow e\nu\nu\boldsymbol{\gamma}$)
    → Can be identified by detecting low energy (1 – 5 MeV) positron associated with RMD



Radiative Decay Counter (RDC)

- RDC: Detector for positron from $\mu \to e\nu\nu\gamma$
  - Downstream RDC: Already constructed
  - Upstream RDC has to be operational in high-intensity low-momentum muon
    → Still under development with challenging requirements



- Requirements to upstream RDC
  1. Material budget: $< 0.1\%\ X_0$
  2. Rate capability: 4 MHz/cm^2 of muon (21 MeV/c)
  3. MIP efficiency: 90% MIP efficiency
  4. Timing resolution: < 1 ns time resolution
  5. Radiation hardness: > 60 weeks operation
  6. Detector size: 20 cm (diameter)

Possible design of upstream RDC

- Resistive Plate Chamber with Diamond-Like Carbon electrodes
  - RPC→ Fast response (< 1 ns resolution)
  - DLC→ Controllable resistivity (with mixed structure of sp^2 and sp^3)
    Low mass design (sputtered on thin Kapton films)

Independent HV supply for different layers
→smaller HV than glass MRPC

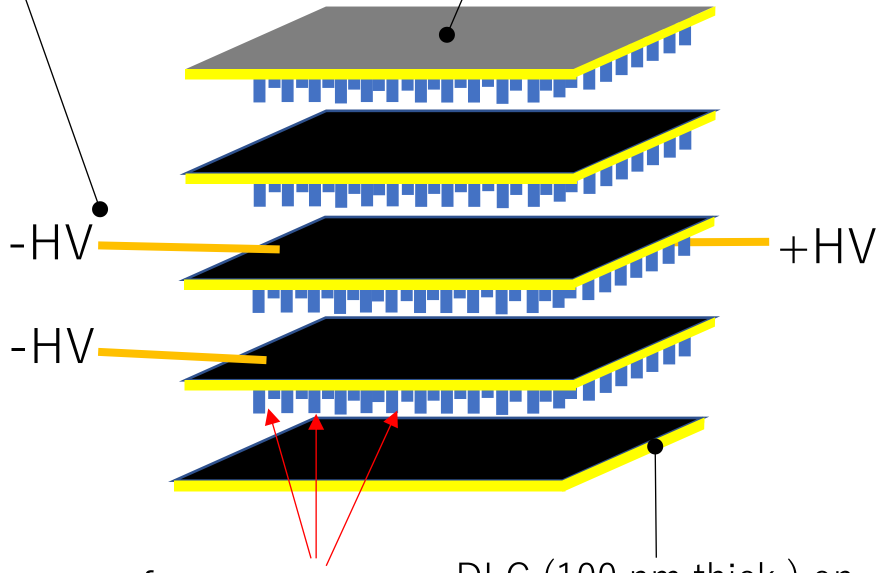
Material budget

- Kapton 50 μm → 0.018% X_0
- Al 100 nm → 0.0012% X_0

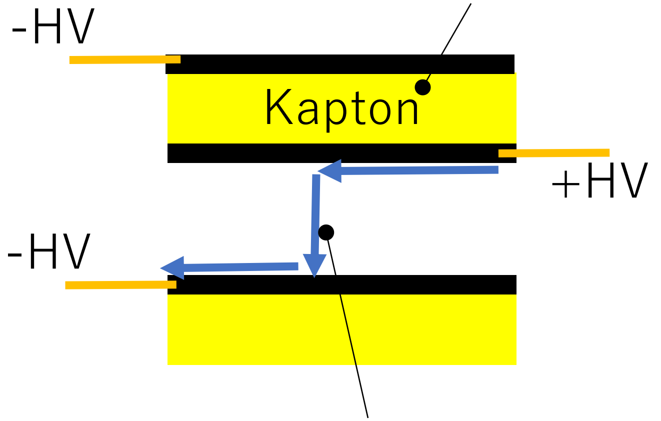
→ < 0.1% X_0 with 4-layer

Efficiency

- $1-\epsilon_n = (1-\epsilon_1)^n$
- ϵ_n: n-layer efficiency
- $\epsilon_1 > 40$ % required



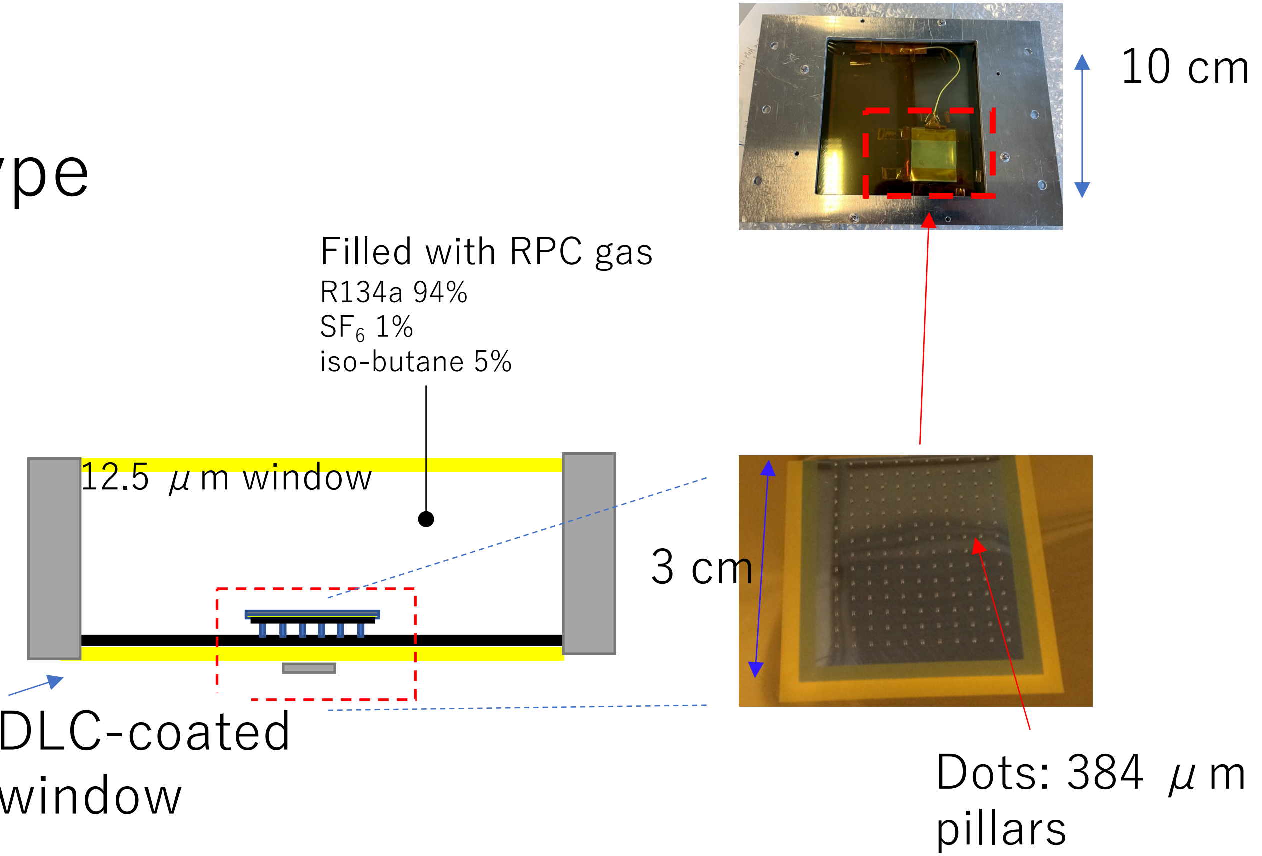
Decouple HV of different layers



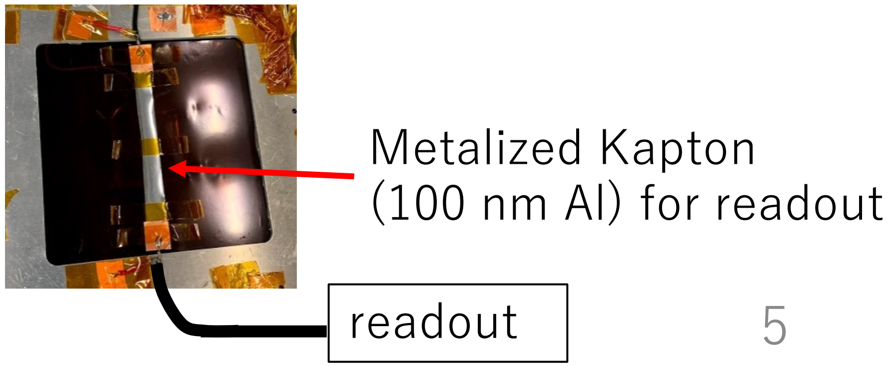
Avalanche **current** flows on the **DLC surface**

Status of studies

- Studies with 3 cm × 3 cm prototype
  (Reported in last JPS)
  - Design with < 0.1 % X_0
  - Performance evaluation
    - Efficiency
    - Timing resolution
    - Performance in high-rate μ-beam



- Today's talks
  - **High-rate capability of larger scale (20 cm) detector has been found non-trivial → This talk**
  - Signal pileup suppression → Next talk



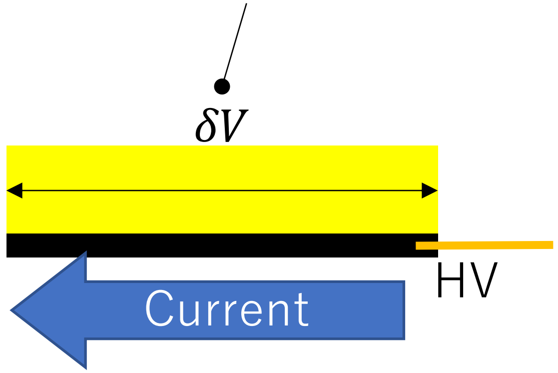
Outline

- Introduction
- Detector design optimization
  - Introduction to rate capability
  - Resistivity optimization
  - HV supply optimization
- Summary

Rate capability of RPC

- Rate capability
  - Determined by the voltage drop due to high current on DLC electrodes
    → Confirmed by test with high-rate muon beam
    (Reported in JPS2021-spring)

Larger δV with larger distance



- With DLC electrodes, voltage drop follows:

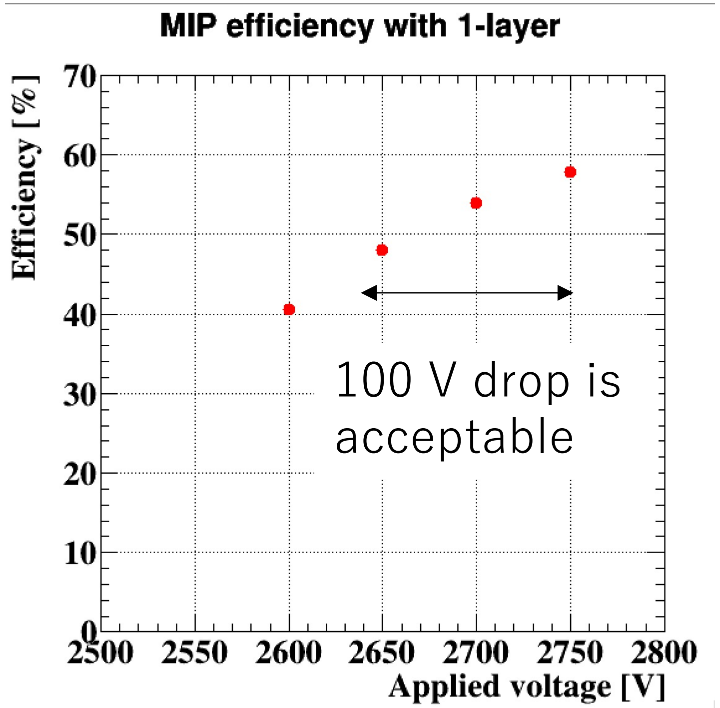
$$\nabla^2\,\delta V(x,y) = \underbrace{Q_{mean}\left(V_{eff}\right)}_{\text{Avalanche charge}} \cdot \underbrace{f(x,y)}_{\text{Hit rate}} \cdot \underbrace{\rho}_{\text{Surface resistivity}}$$

→ Design must be optimized to keep δV at a reasonable level

Status of rate capability studies

- Known parameters in $\nabla^2\, \delta V(x,y) = \underbrace{Q_{mean}(V_{eff})}_{\text{Avalanche charge}} \cdot \underbrace{f(x,y)}_{\text{Hit rate}} \cdot \underbrace{\rho}_{\text{Surface resistivity}}$

  - **Requirements to δV**: $< \sim$**100 V**
    → Determined by the voltage to achieve 40 % with single-layer
  - **Avalanche charge**: **3 pC** for low-momentum muon
    → Measured in 2020 with low-momentum muon beam
  - **Hit rate**: **4 MHz/cm^2** at the center

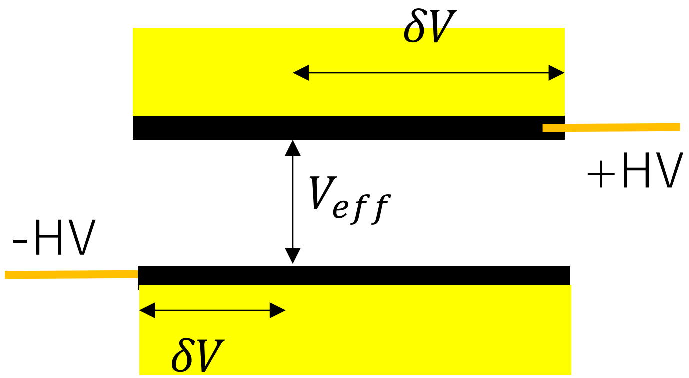


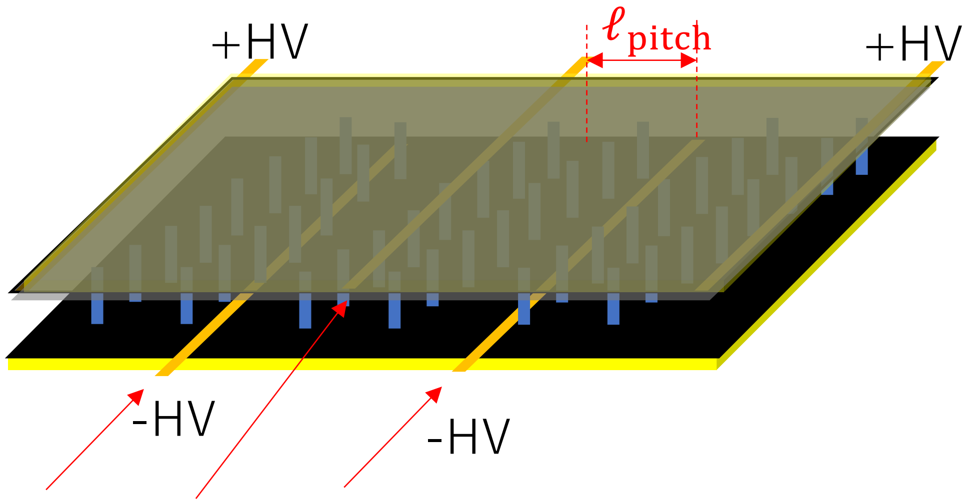
Studies to be completed

- Parameters which remained to be determined in

$$\underbrace{}_{}\nabla^2\, \delta V(x,y) = \underbrace{Q_{mean}(V_{eff})}_{\text{Avalanche charge}} \cdot \underbrace{f(x,y)}_{\text{Hit rate}} \cdot \underbrace{\rho}_{\text{Surface resistivity}}$$

- **Surface resistivity**
- **Boundary condition** of the equation
  → Depends on geometry of HV supply



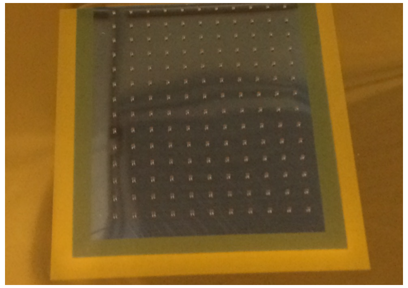


Surface resistivity study

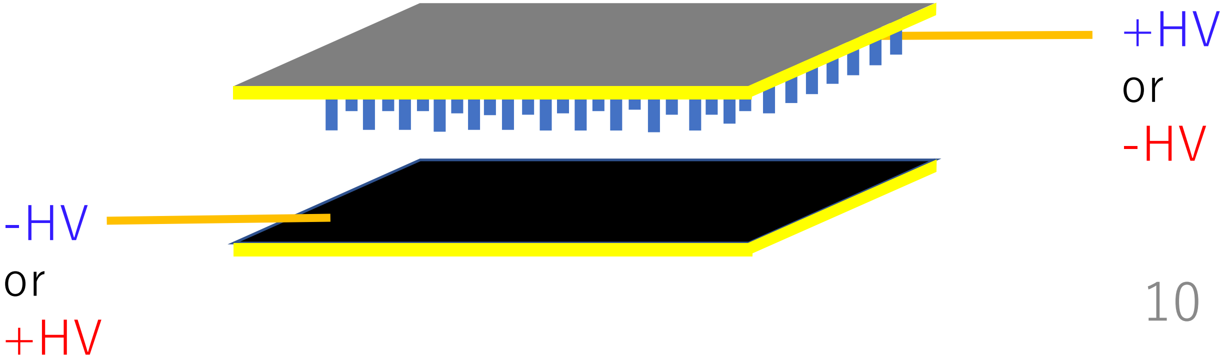
- The effect of surface resistivity
  - Small resistivity: Higher rate capability
  - Large resistivity: Discharge suppression

  → **Optimization required**

- Optimization study
  - Stability with several resistivity
    - $\lesssim 1\ \mathrm{M\Omega/sq}$
    - $20 - 30\ \mathrm{M\Omega/sq}$ (position dependent)
    - $50 - 70\ \mathrm{M\Omega/sq}$ (position dependent)
  - Direction of electric field
    - Which direction is better to suppress discharge ?

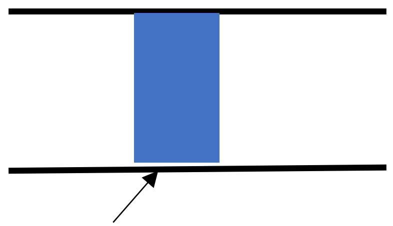


Spacers are attached to one side



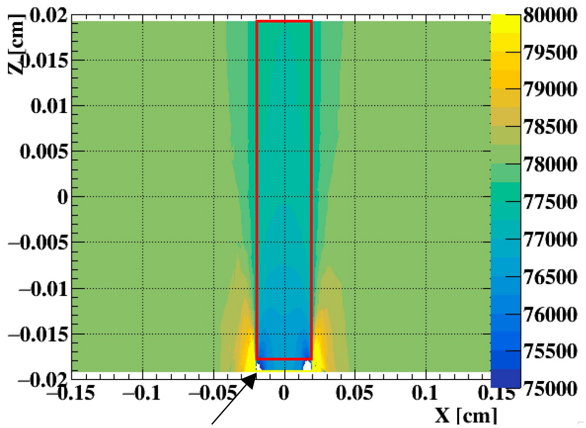
Result of optimization

- The direction of electric field
  - The spacer face must be +HV
    → Independent from resistivity
  - Possible cause:
    Edge effect of E-field at floated spacer bottom



Some spacers can be floated

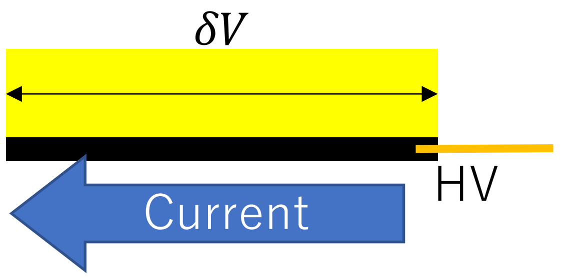
E field strength (simulation)



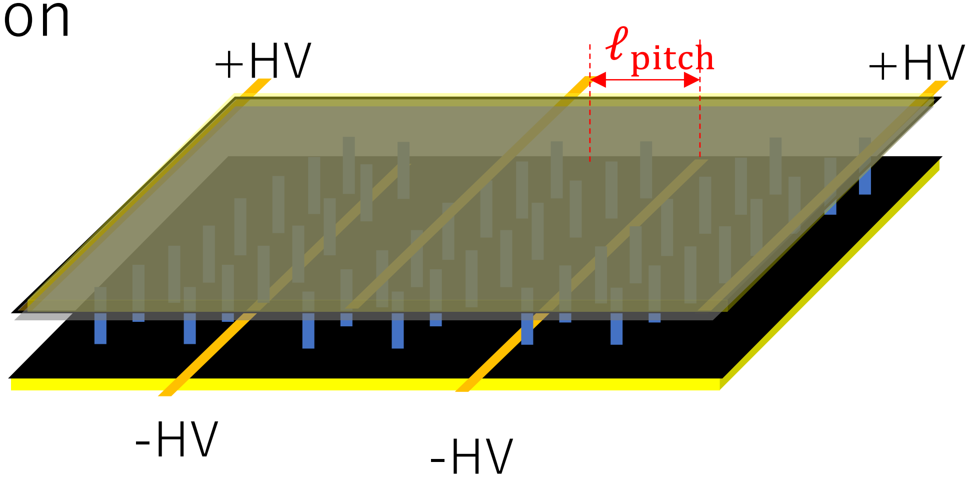
Floated region
(Red box: Spacers)

- Surface resistivity
  - Resistivity of +**HV** electrodes (with spacers)
    - 1 MΩ/sq: Instable so far
    - ≥ 20 – 30 MΩ/sq: Stable enough
    - ~10 MΩ/sq: Further study is required
  - Resistivity of –**HV** electrodes (without spacers)
    - < 1 MΩ/sq possible with high enough resistivity of +HV electrode

Study on HV supply geometry



- $\nabla^2 \delta V(x,y) = Q_{mean}(V_{eff}) \cdot f(x,y) \cdot \rho$
  - The distance from HV supply must be small
    → Strip geometry
  - Studies underway for technical implementation



- Simulation of δV in MEG II beam
  - Purpose
    - Decide ρ and ℓ_{pitch}
  - One example configuration
    - ρ: 10 MΩ/sq for both anode and cathode
    - ℓ_{pitch}: 1 cm

    → $\delta V \sim 100$ V ($\delta V < 100$ required)

Possible variations of the design for MEG II

- Parameter dependence
  - Pitch of HV supply strips: $\boldsymbol{\delta V \propto \ell_{pitch}^2}$
  - DLC resistivity: $\boldsymbol{\delta V \propto \rho}$

- Possible design and concerns

	ℓ_{pitch}	ρ: +HV side	ρ: -HV side	Concern
1	1 cm	10 MΩ/sq	10 MΩ/sq	10 MΩ/sq not tested
2	1 cm	20 MΩ/sq	1 MΩ/sq	DLC damage from discharge may be severe with large asymmetry
3	8 mm	20 MΩ/sq	O(10) MΩ/sq	Large inactive region (Strip area is inactive)

+ Bad DLC resistivity control (×5 fluctuation)

➡ Further studies are planned

Outline

- Introduction
- Detector design optimization
- Summary and prospect

Summary and prospect

- High-rate capable and ultra-low mass RPC with DLC is under development for MEG II upstream RDC

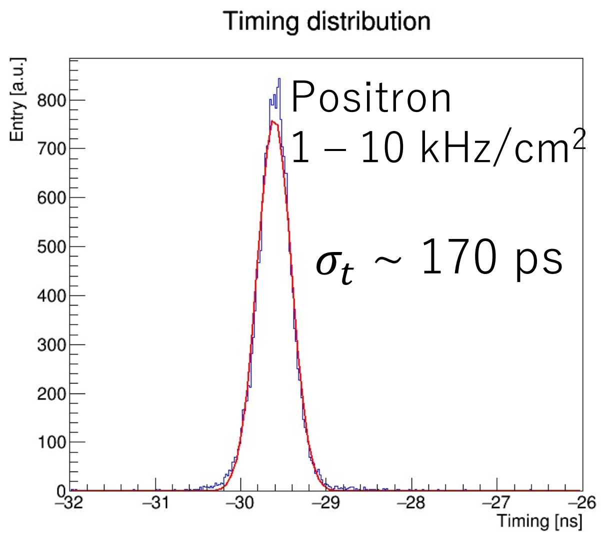
- Studies on design optimization are presented
  - Motivation: To achieve high-rate capability with a full-scale detector
  - Study1: Resistivity optimization
  - Study2: HV supply optimization

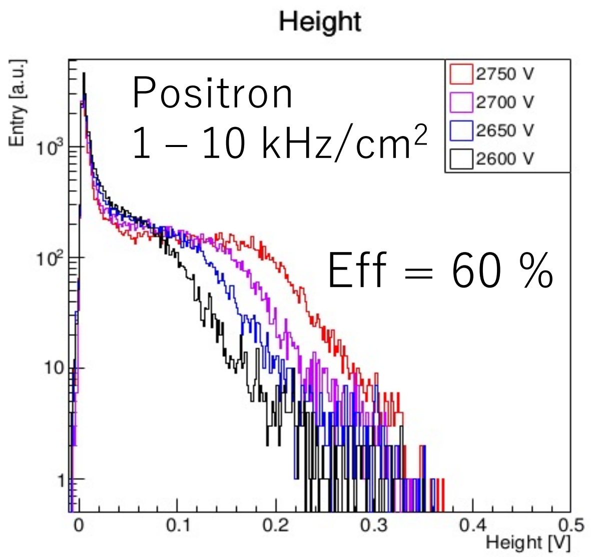
- Planned studies
  - Implementation of strip geometry
  - DLC resistivity control
  - Further optimization
  - Operation in a longer time scale

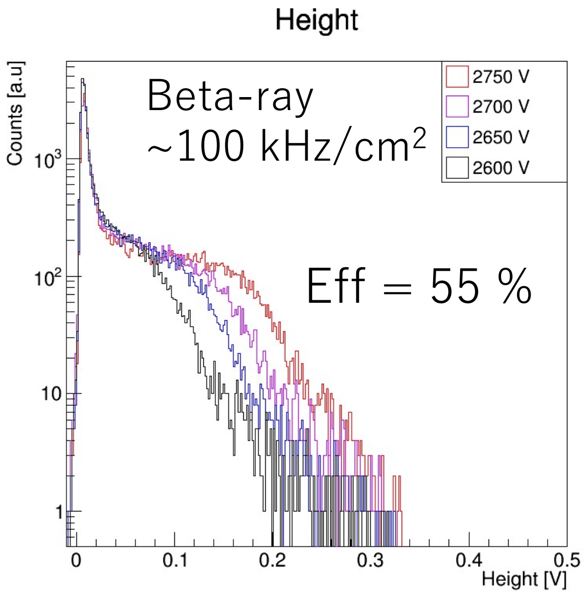
Backup

MIP detection with single-layer

- Timing resolution and efficiency are measured with single layer
  - Positron from muon decay with O(**1 – 10 kHz/cm²**) rate
  - Beta-ray from ^{90}Sr (~MBq) with ~ **100 kHz/cm²** rate

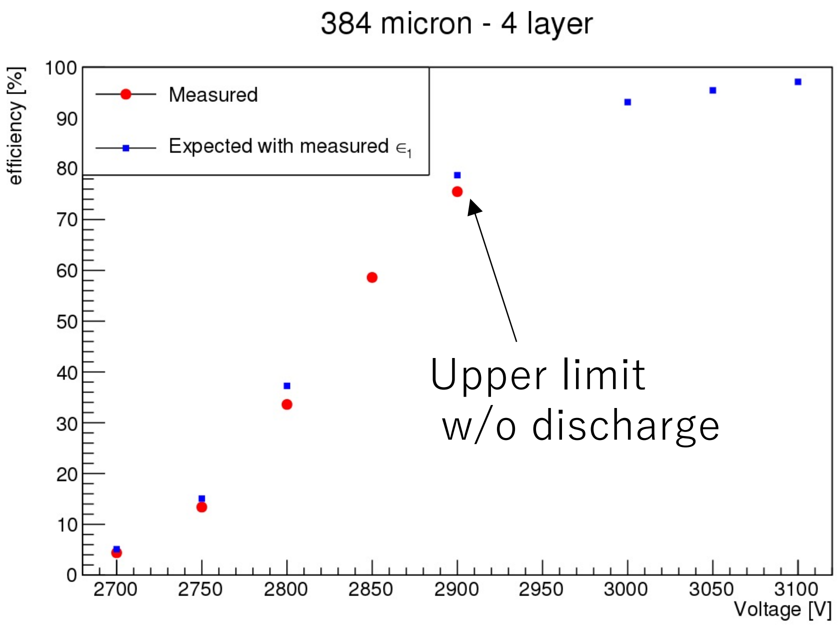


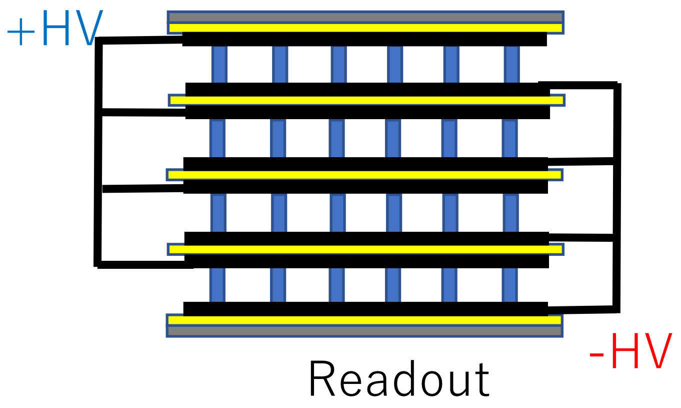




MIP detection with multi-layer

- Efficiency study with multi-layer
  - Efficiency expected to improve as $1-\epsilon_n = (1-\epsilon_1)^n$
  - Efficiency with four layers measured
    - Beta-ray from ^{90}Sr
    - Rate: O([1 kHz/cm^2])





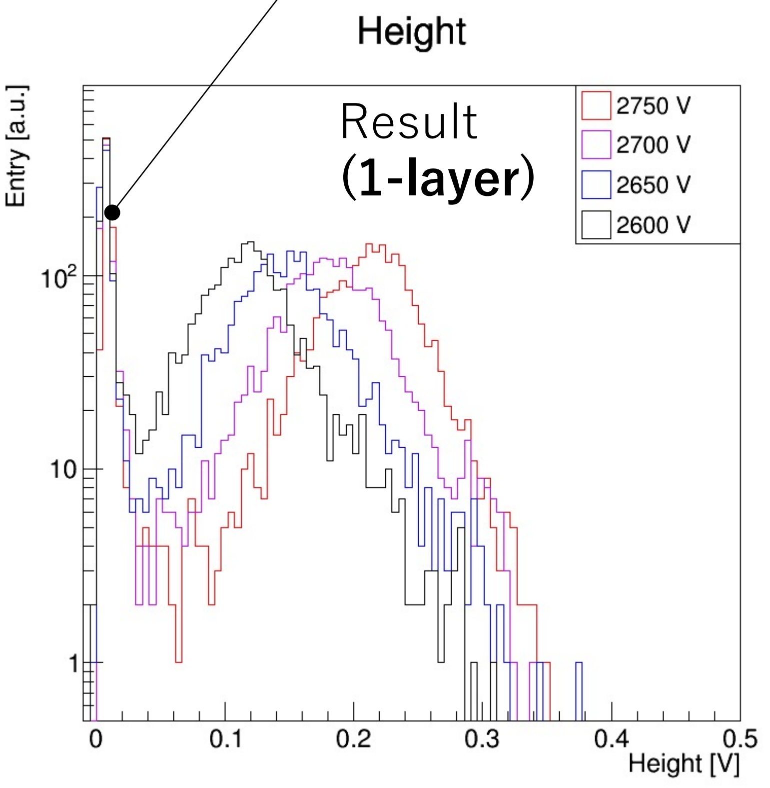
Gas is different from other tests:

R134a	93%,
SF_6	7%

- Issue: discharge at lower voltage than single layer
  - Probably because of imperfect flatness of electrodes

Response to low-momentum muon at low rate

Accidental trigger
due to BG radiation

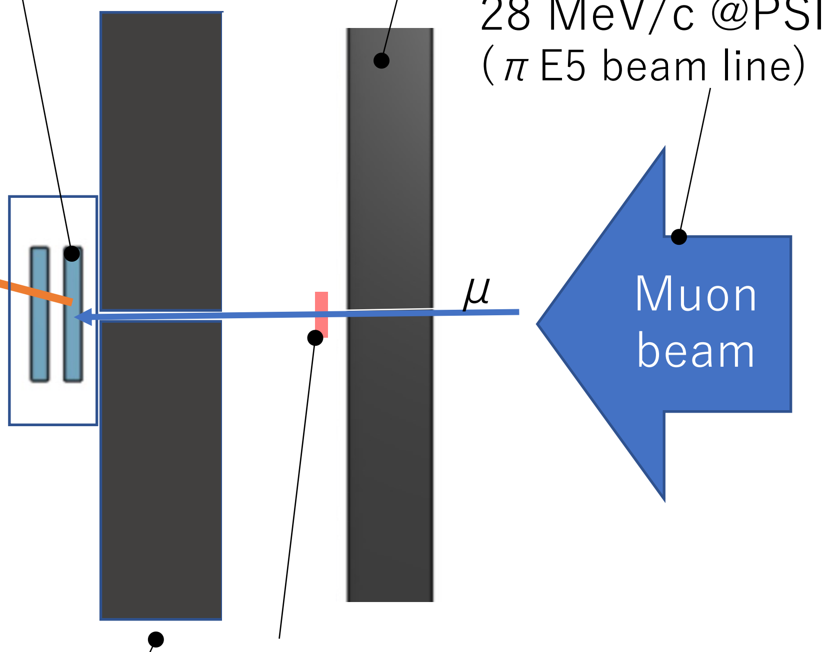


Decay positron
going downstream
(Not to see positron's hit in RPC)

Muons stop in trigger
counter (front one)

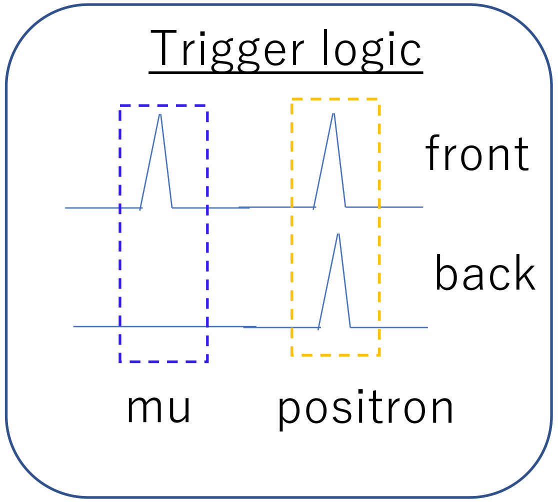
Pb collimator
→ **Rate reduced to ~ kHz/cm²**

28 MeV/c @PSI
(π E5 beam line)



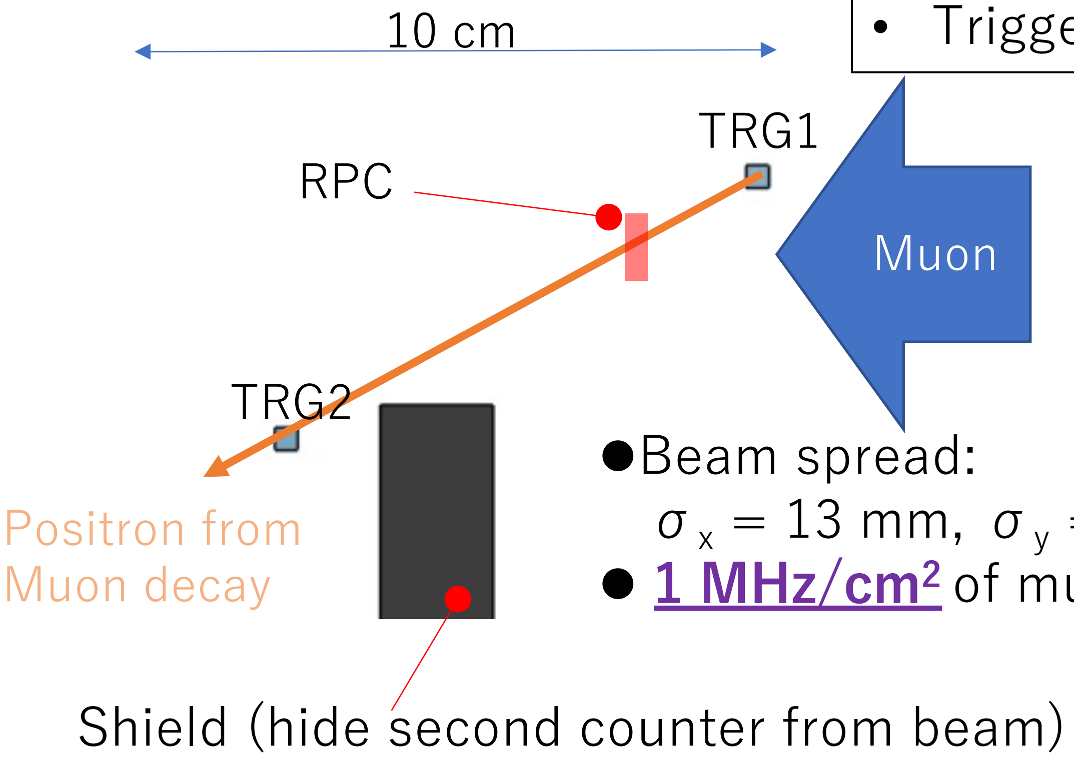
RPC

Pb slit
(Shield for BG radiation)

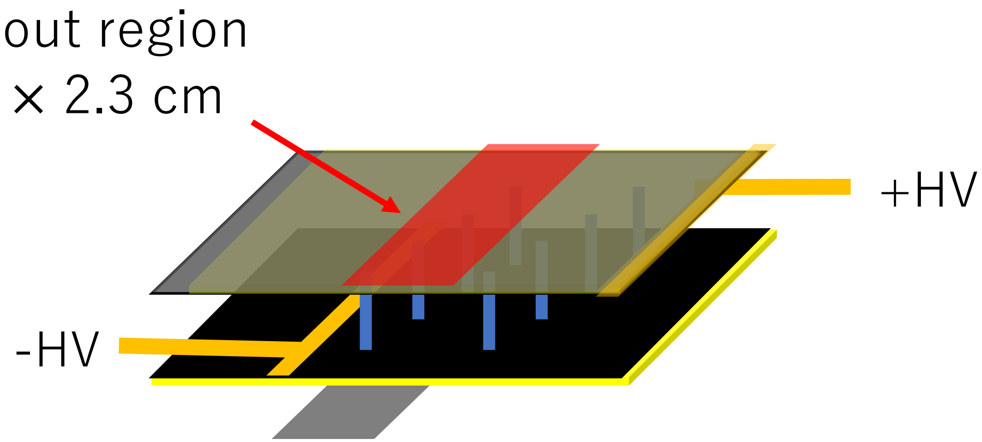


Voltage drop evaluation in high rate muon beam

- RPC is exposed to low-momentum beam at high-rate
- Trigger on positron from muon decay going through RPC



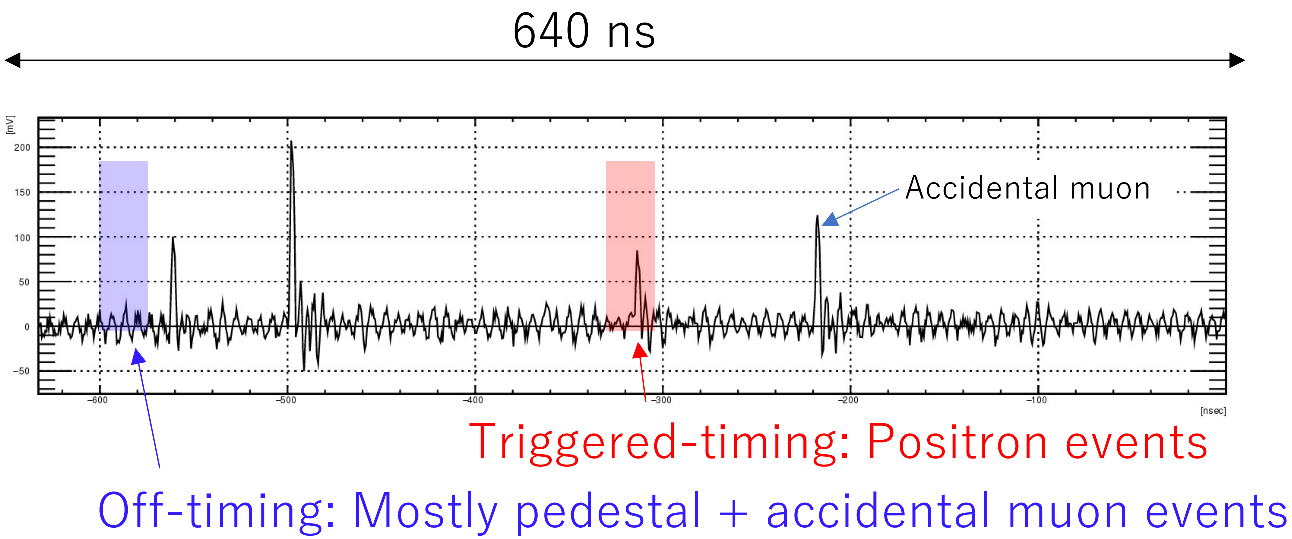
- Beam spread:
  $\sigma_x = 13$ mm, $\sigma_y = 23$ mm
- **1 MHz/cm²** of muon at the center

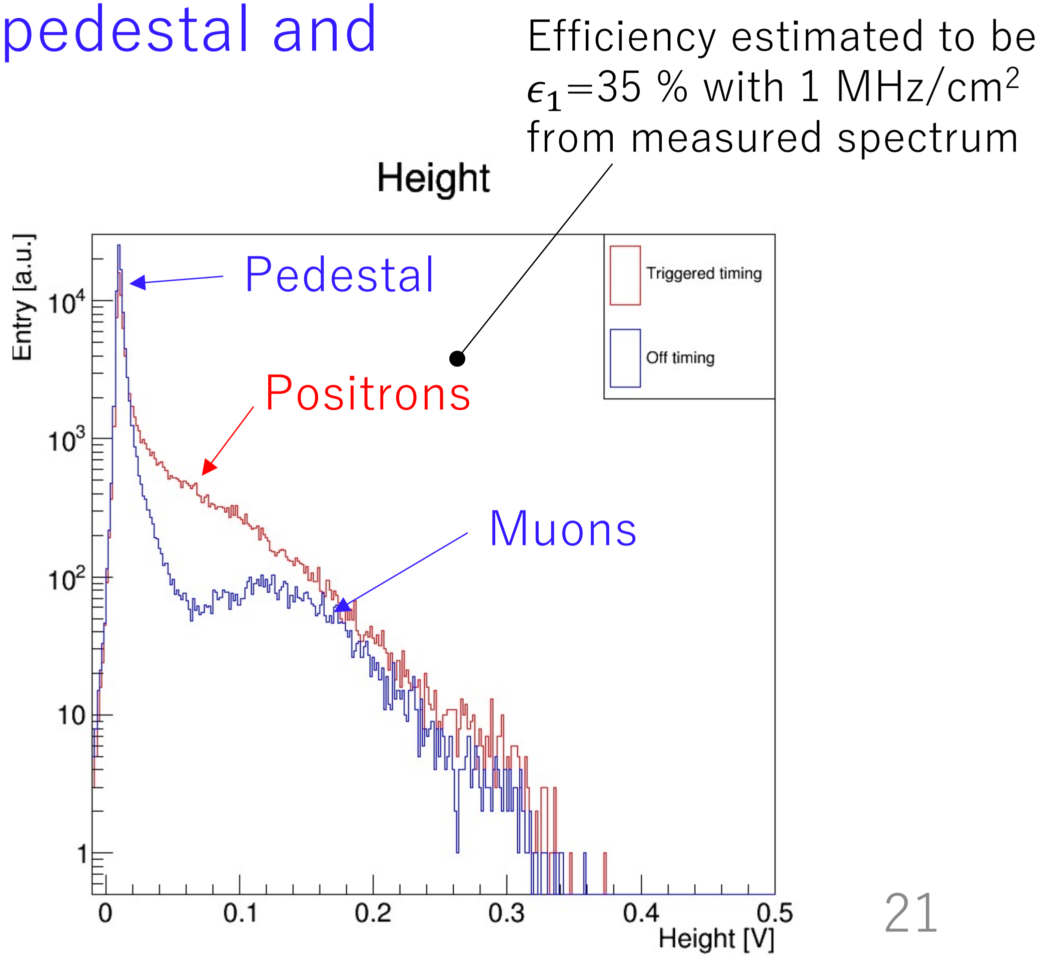


Gas: R134a 94%,
SF_6 1%,
iso-butane 5%

Voltage drop evaluation in high rate muon beam

- Waveform analysis
  - On-timing window (30 ns) for MIP performance evaluation
  - Off-timing window (30 ns) for evaluation of pedestal and accidental muon events



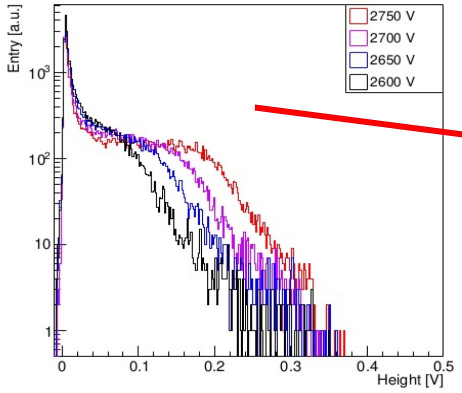


Hit rate: 2.1 MHz (> 60 mV) in 2.3 cm^2 readout area
(Evaluated with probability of finding > 60 mV hit inside 30 ns window)
→ Agree with beam profile

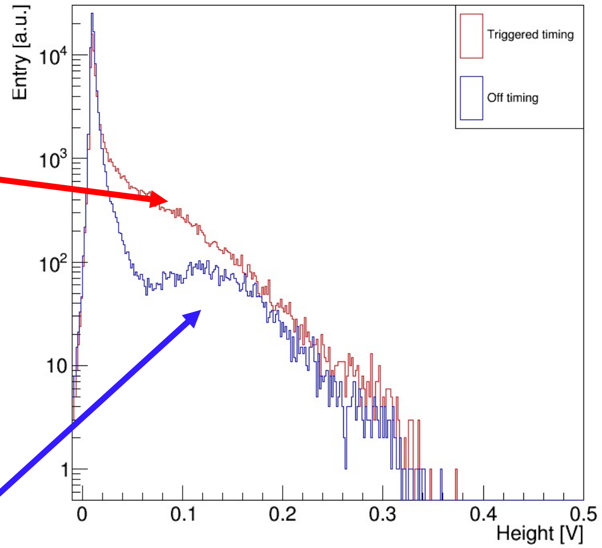
Voltage drop evaluation in high rate muon beam

Observed voltage drop

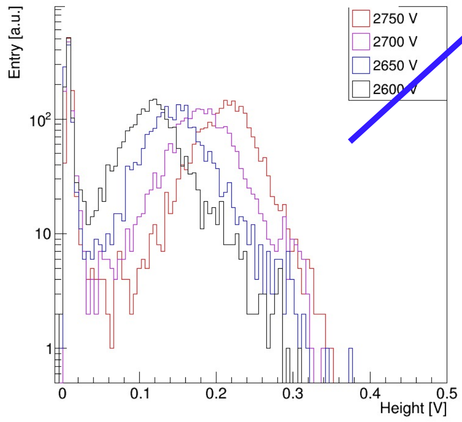
MIP @**low rate**



High-rate test



μ @**low rate**



100 – 150 V drop
explains spectra

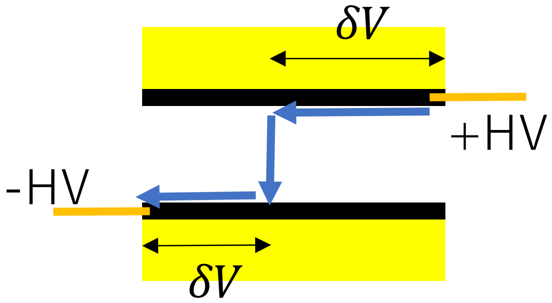
Expected voltage drop

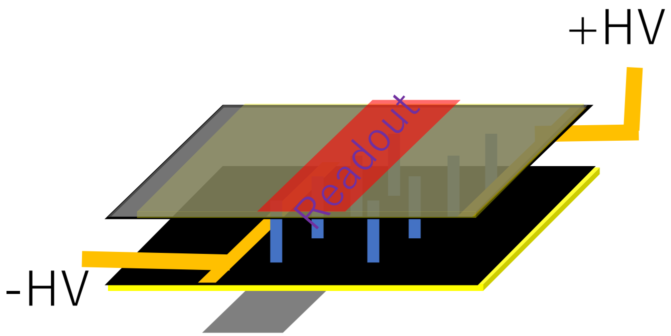
Calculated with

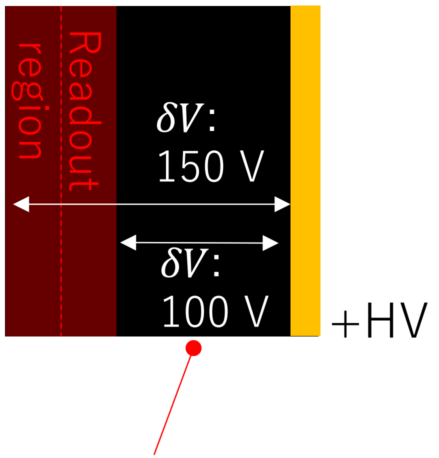
$\nabla^2 \delta V(x,y) = Q_{mean}(V_{eff}) \cdot f(x,y) \cdot \rho$

Parameters for calculation

- $\boldsymbol{\rho}$: **60 MΩ/sq** for anode and **7 MΩ/sq** for cathode
- $\boldsymbol{Q_{mean}}$: **2.3 pC** = 6.5 μA/2.8 MHz (Observed current/ estimated hit rate)





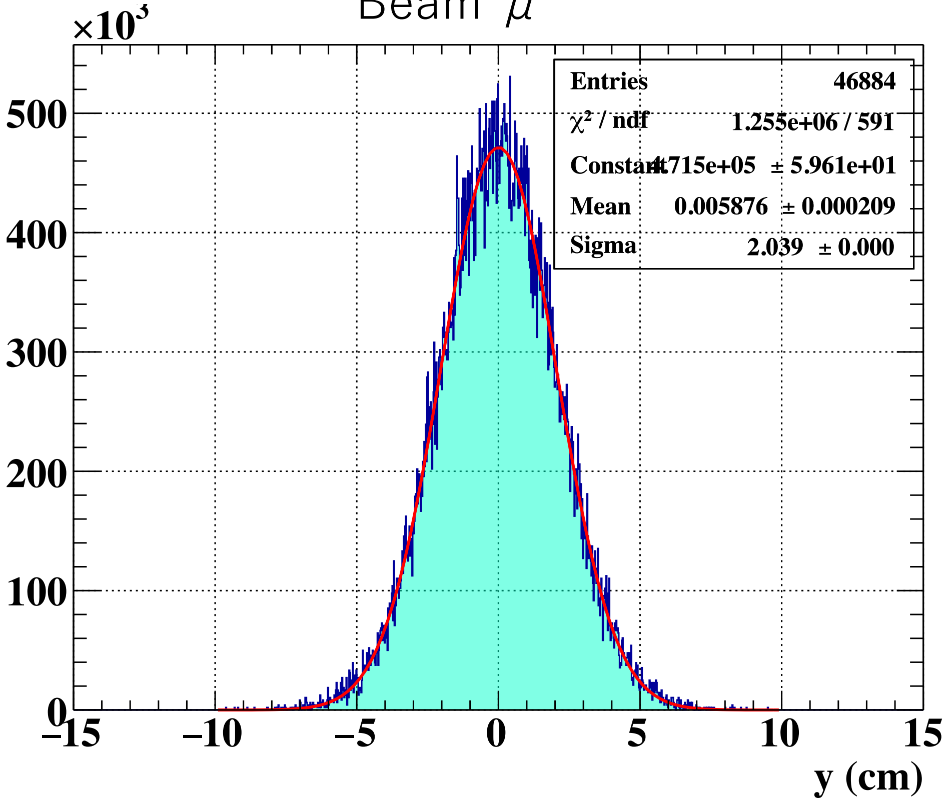


100 – 150 V drop
is expected

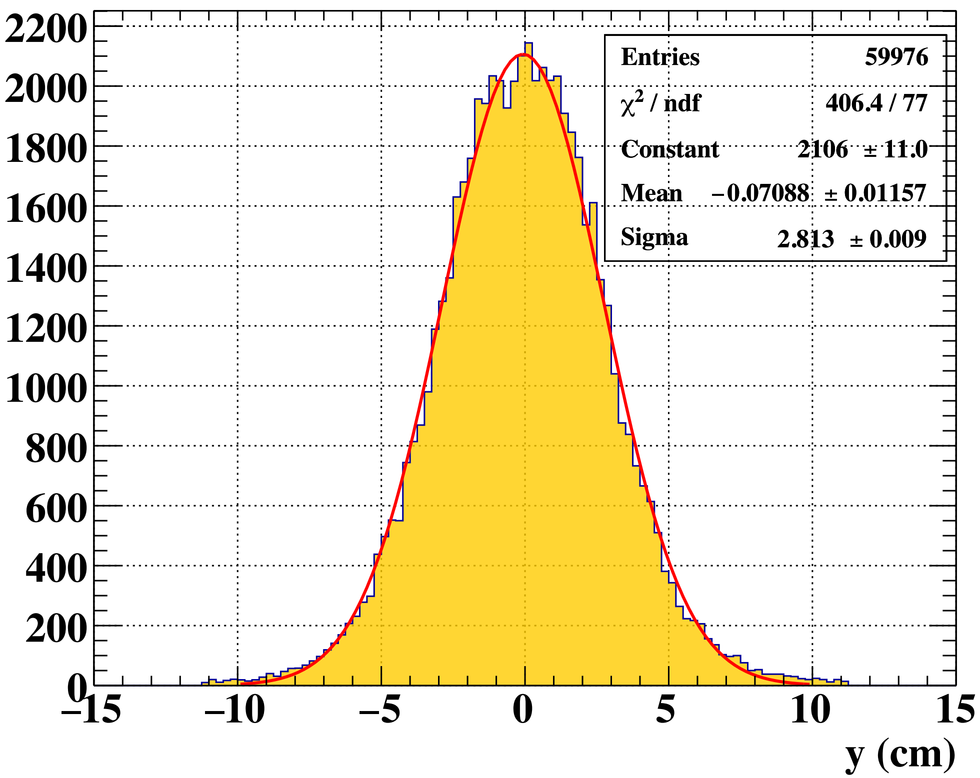
Sum of δV for +HV and –HV side

- Distribution of particles hit position at upstream RDC
  - Beam μ: $\sigma = 2$ cm
  - RMD positron: $\sigma = 2.8$ cm

Beam μ



RMD positron



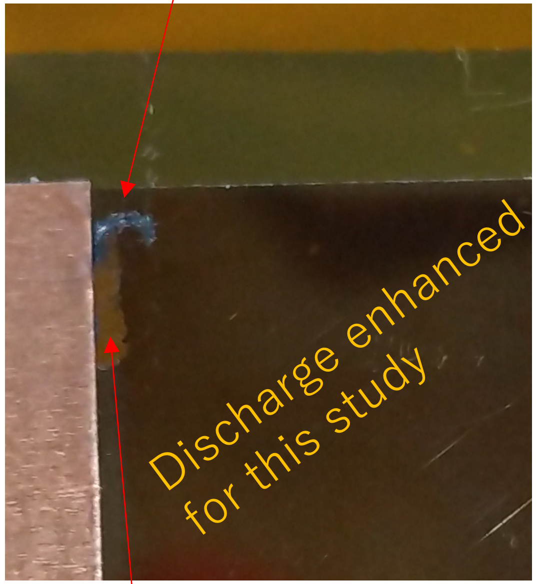
Concerns

- DLC resistivity control
  - **The resistivity precision limited** for DLC sputtering
    - Both over and under fluctuation with up to a factor $\times 5$
  - If necessary, can be reduced by annealing to some extent
    - $\times \sim 0.5$ when annealed with 200°C
    - Systematic studies underway

- DLC damage caused by discharge
  (Concerns in a long time-scale)
  - **Evaporation of DLC**
    → Further study required with a longer time scale
  - **Asymmetric discharge**
    - Formation of conductive damage on +HV side
    - Appears when -HV resistivity is much smaller than +HV one

  → Investigation in progress

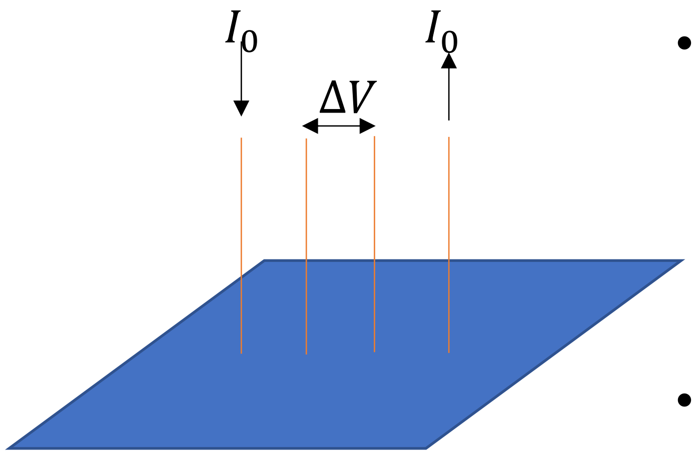
Conductive damage



DLC evaporated

Surface resistivity study

- Technical aspect of DLC surface resistivity measurement
  - O(10) MΩ/sq measured with 4-point method



- Four probes are placed in a equal pitch
  - Source I_0 and measure ΔV
  - Large enough input impedance of voltage-probe
  - Surface resistivity $= \frac{\pi}{\log 2} \cdot \frac{\Delta V}{I_0}$
- (Remarks) Resistivity is found to be position dependent