MEG II 実験における背景事象抑制に向けた超低物質量RPCの読み出しに関する研究

講演番号 19aG22-2

(講演番号 19aG22-1 との連続講演)

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Outline

- Introduction
  - MEG II
  - RPC
  - Pileup inefficiency
  - Prototype RPC readout
  - Suppress ringing tail

- Lab test

- Summary & prospects

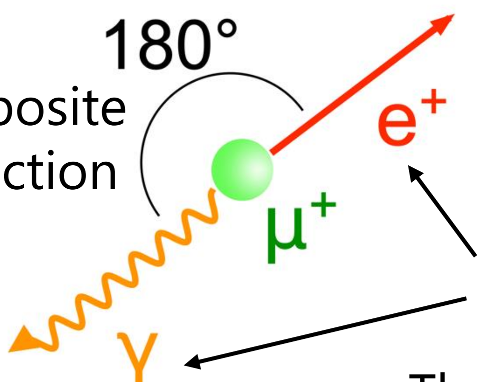
MEG II signal

- MEG II searches for charged lepton flavour violating decay: $\mu^+ \to e^+\gamma$

- MEG II signal is identified by the kinematics

Signal

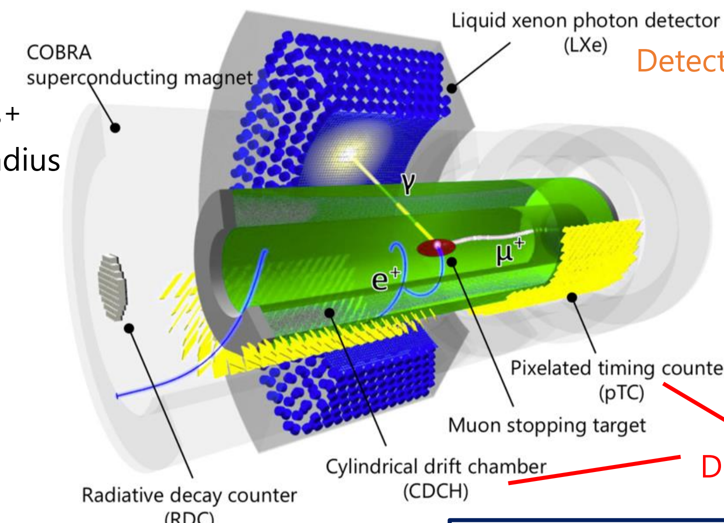
Opposite direction



Both 52.8 MeV

The same timing

Bends signal e^+ w/ constant radius



Detect γ

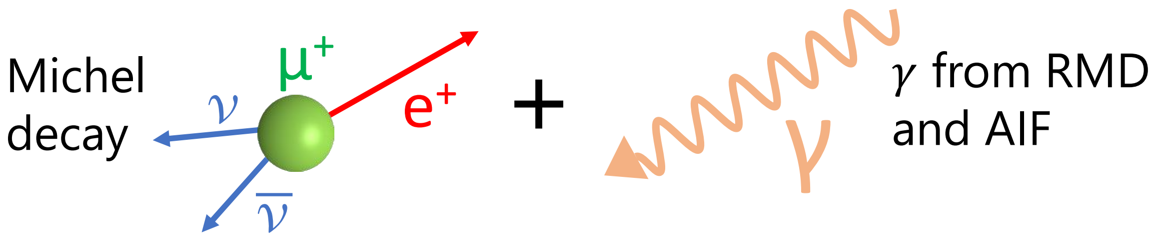
Detect e^+

Detect background e^+

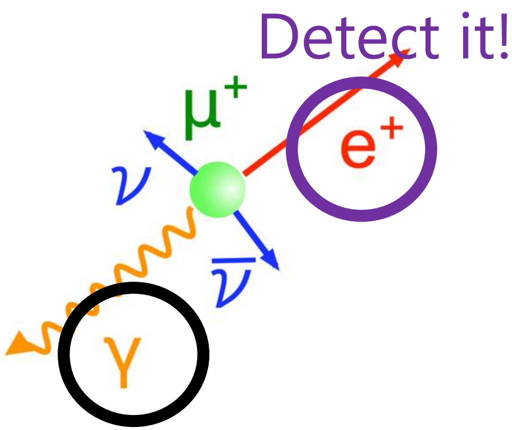
Use the most intense μ beam: DC and beam rate $\sim 7 \times 10^7\ /s$

MEG II background

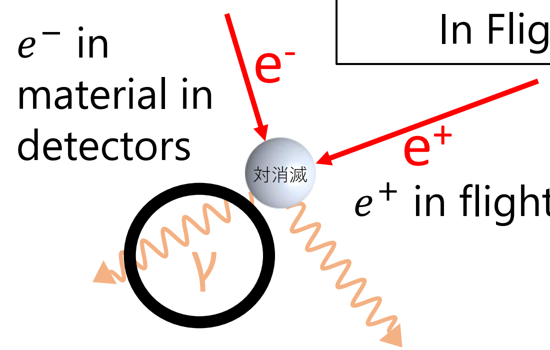
Dominant background = Accidental BG
= Coincidence of e^+ from Michel decay and γ from RMD or AIF



RMD: Radiative Muon Decay



AIF: Annihilation In Flight

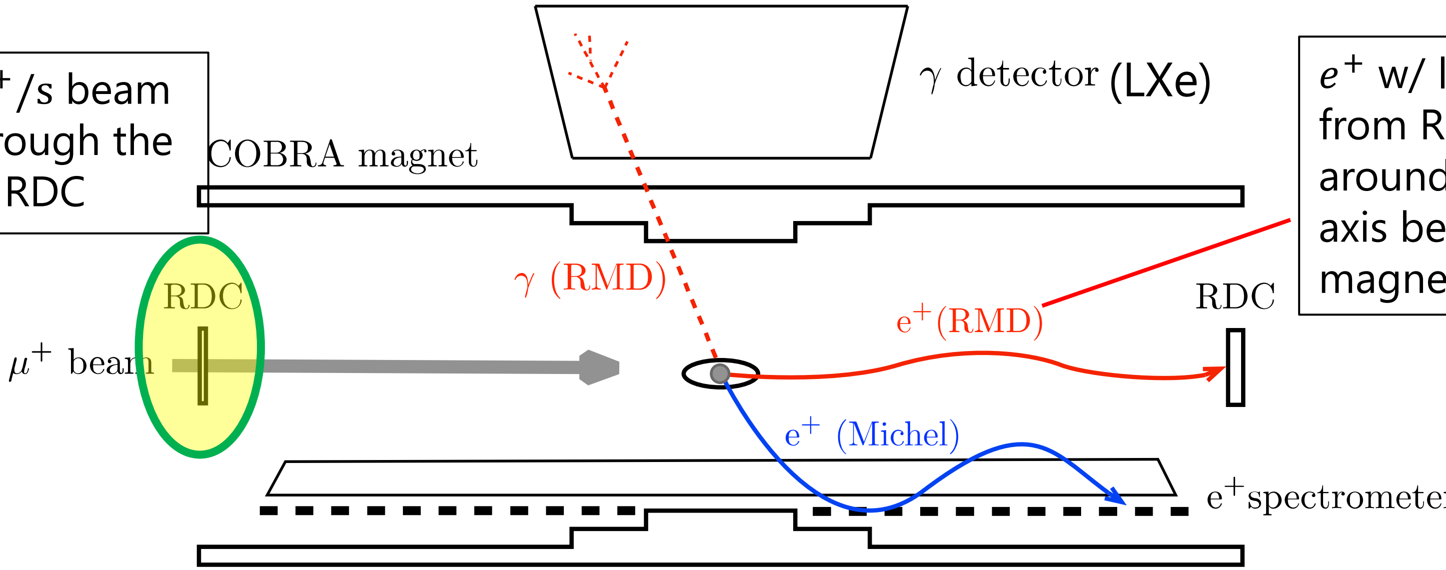


Detect e^+ with low energy (1-5 MeV) from RMD to identify γ from RMD

BG identification detectors

- Radiative decay counters (RDCs) are installed in both upstream and downstream to detect e^+ from RMD

$7 \times 10^7\ \mu^+/s$ beam passes through the upstream RDC



e^+ w/ low energy from RMD flights around the beam axis because of magnetic field

The upstream RDC has strict requirements because it has to be passed through by $7 \times 10^7\ \mu^+/s$ beam and to detect e^+ from RMD

Upstream RDC requirements

1. Material budget: $< 0.1\% X_0$

   (← μ^+ beam passes through the detector)

2. 90% efficiency for e^+ with 1-5 MeV
3. 1 ns time resolution

   (← RMD identification with time difference b/w e^+ & γ)

4. Rate capability & radiation hardness

   (← $7 \times 10^7 \mu^+/s$ with 21 MeV/c & > 60 weeks run)

5. Detector size: 20-cm diameter

   (← 45% acceptance in the one RDC, 90% in total incl. downstream)

→ Candidate for the upstream RDC is ultra-low material resistive plate chamber (RPC)

Proposed RPC design for MEG II

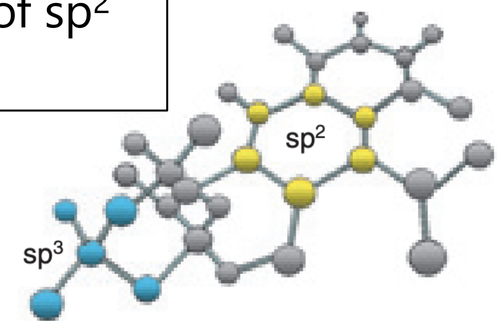
- Gas: R134a (Freon) based
- DLC is used as resistive electrodes

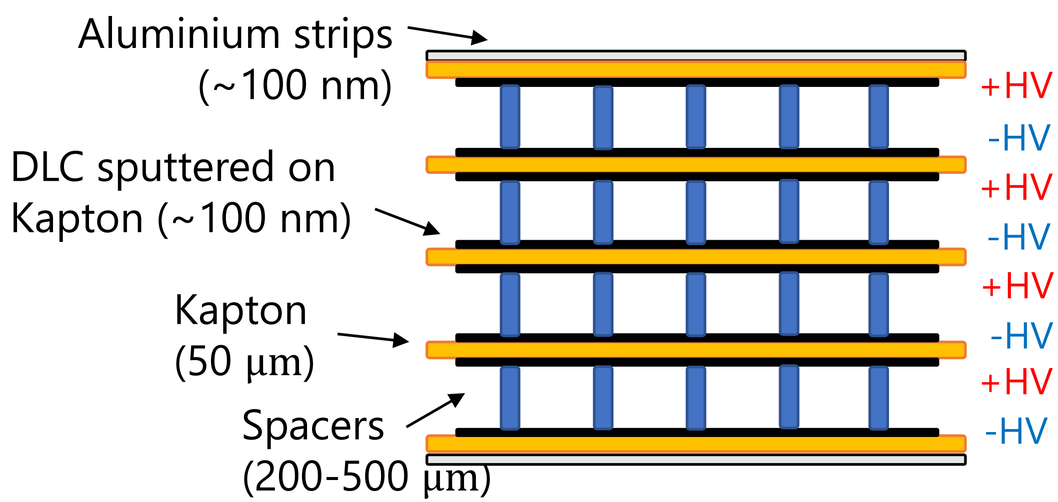
→ Achieve ultra low-material budget

- Aluminised Kapton readout strips are
  - at both anode and cathode
  - orthogonal to each other

→ Readout region is segmented

Diamond like carbon (DLC) has mixed structure of sp^2 bond and sp^3 bond



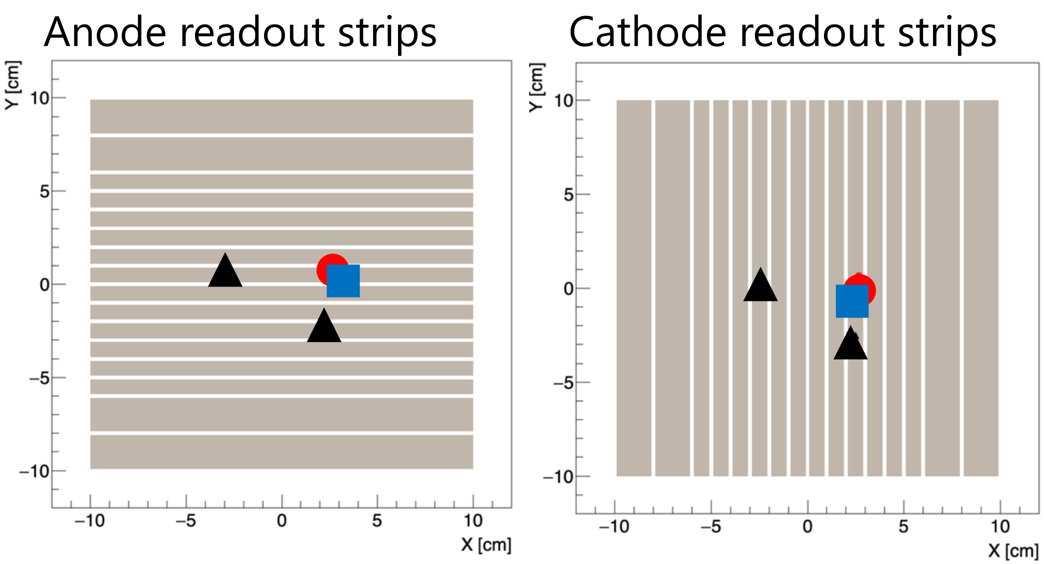


Pileup of μ^+ beam & RMD e^+

Requirements for RPC

- 90% efficiency for 1-5 MeV e^+
- Rate capability
  ($10^8 \mu/s$ with 21 MeV/c)

Pileup of high-rate μ^+ beam and RMD e^+ causes inefficiency for RMD e^+



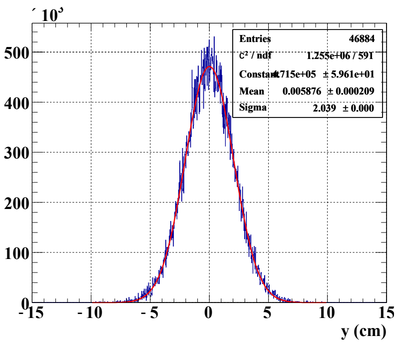
●: RMD e^+ ■: μ^+ at the same position as RMD e^+
▲: μ^+ in the same strip as RMD e^+

- The segmented design can reduce pileup
- Calculate probability of the pileup
  - ● & ■ at the same region at the same timing
  - ● & ▲ in the same strip at the same timing

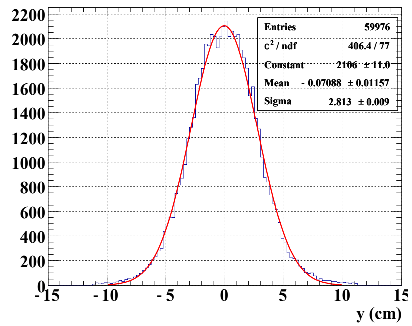
Pileup of μ^+ beam & RMD e^+

- Calculate pileup probability p_i per readout segmented region as a function of signal duration
- Calculate total pileup inefficiency P from p_i

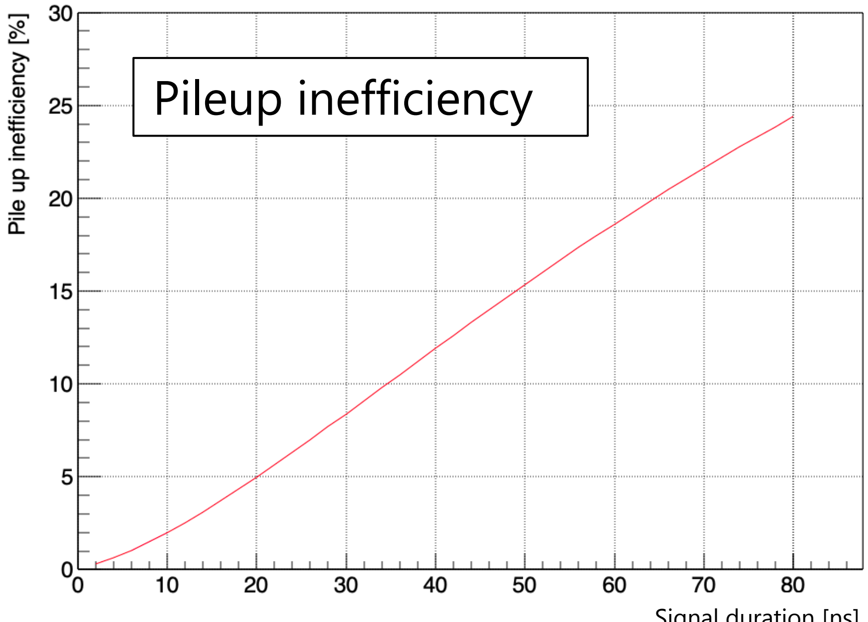
- Inefficiency due to pileup is small enough (< 2.0%) if signal duration within 10 ns



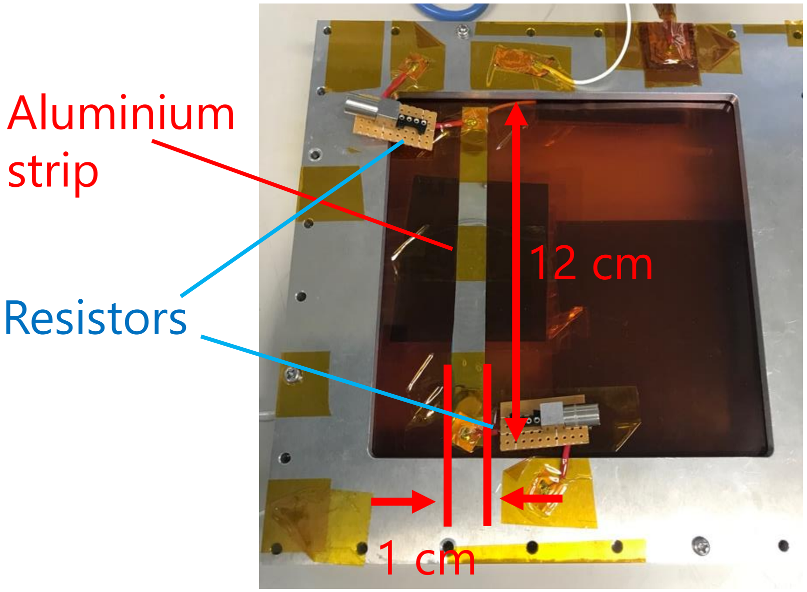
μ^+ beam divergence
$\sigma = 2.0$ cm

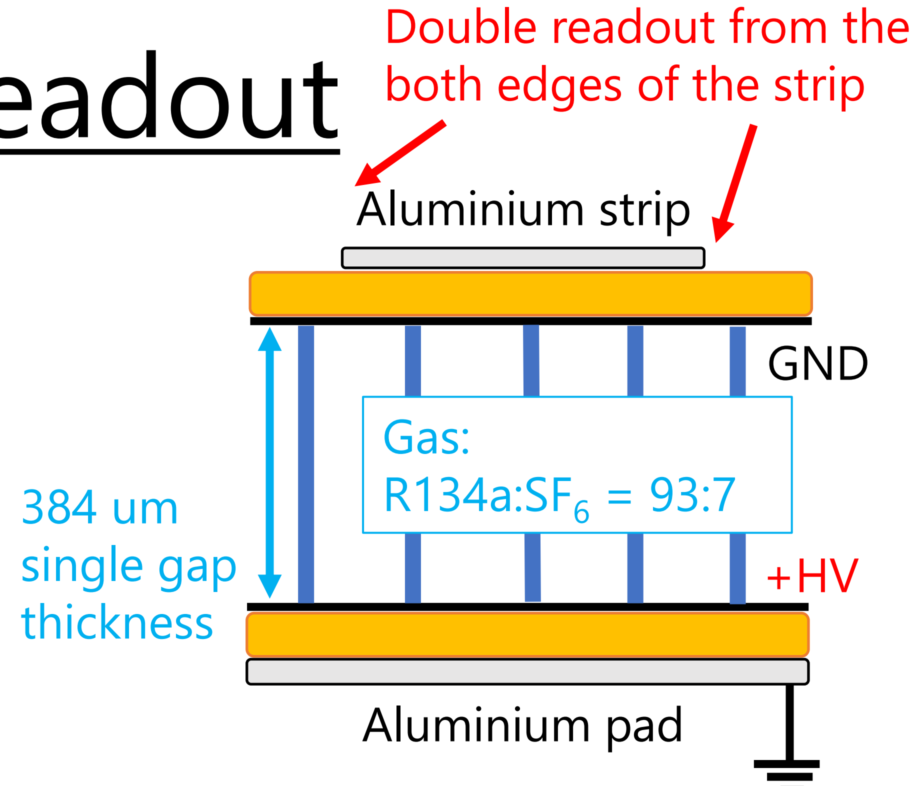


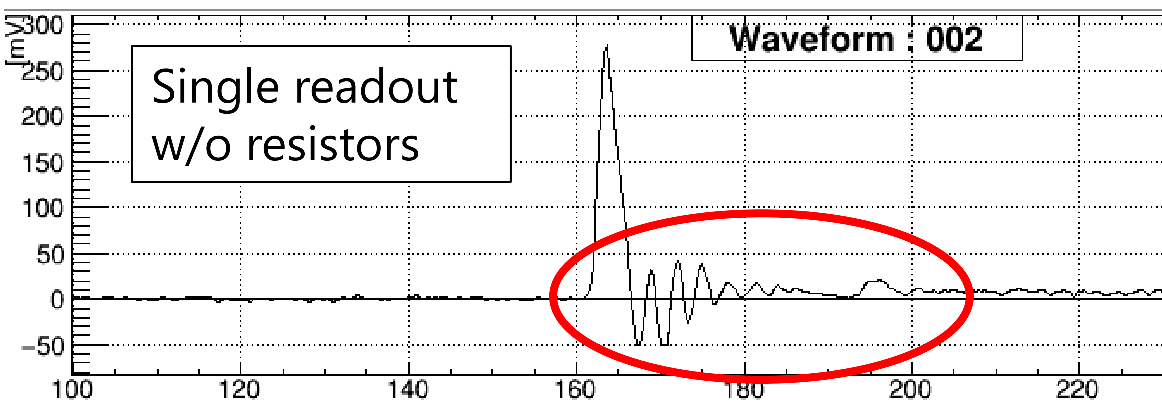
RMD e^+ divergence
$\sigma = 2.8$ cm



Prototype RPC readout



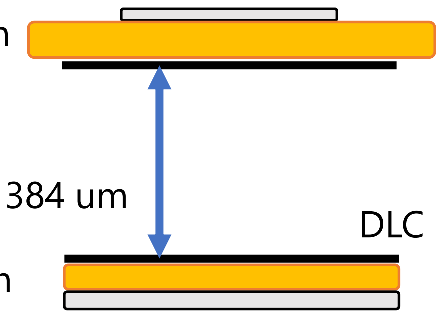




Ringing tail was observed because of

- reflection due to impedance mismatching?
- resonance due to stray RLC structure?

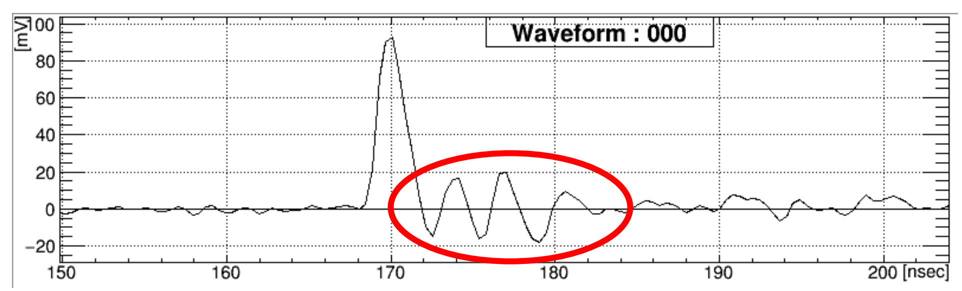
Suppress the ringing



- Characteristic impedance of the aluminium strip is estimated at 13.2 Ω
- Co-axial cable with characteristic impedance of 50 Ω will be used for signal transmission b/w the strip and readout electronics
- Possible solutions:
  - Improve impedance matching at preamplifier

    ← Not easy to place preamplifier near RPC due to limited space
  - Insert resistors to damp the ringing

Suppress the ringing as much as possible w/o preamplifier



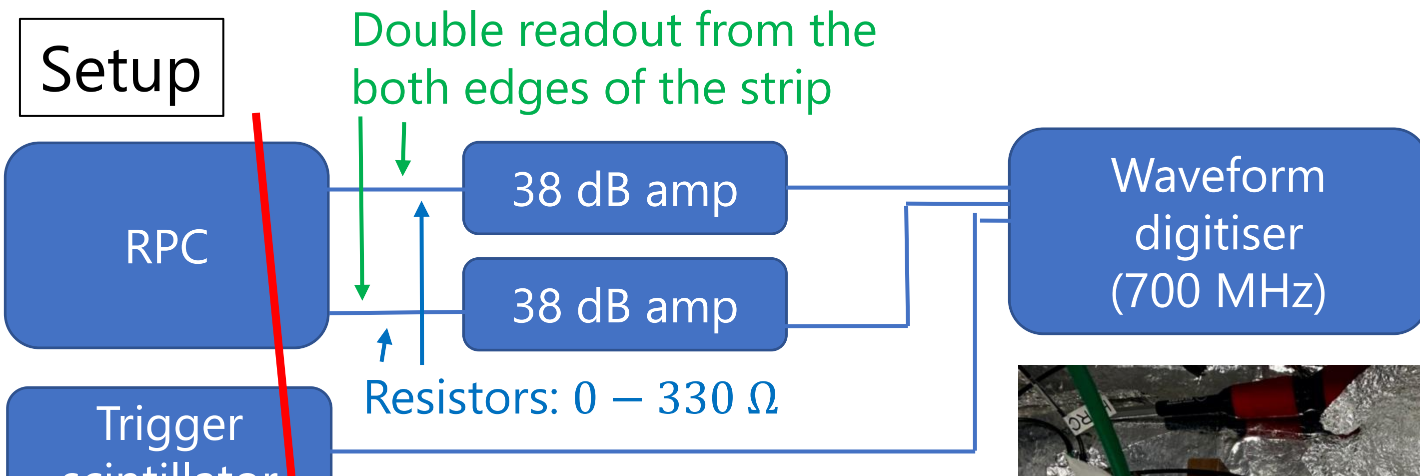
→ Insert resistors b/w the strip & co-axial cable to damp it

Outline

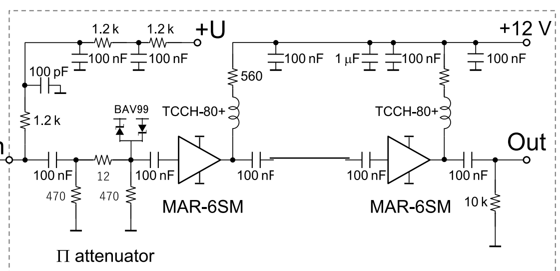
- Introduction
- Lab test
  - Setup and purposes
  - Effect of resistors on ringing
  - Effect of resistors on RPC performance
- Summary & prospects

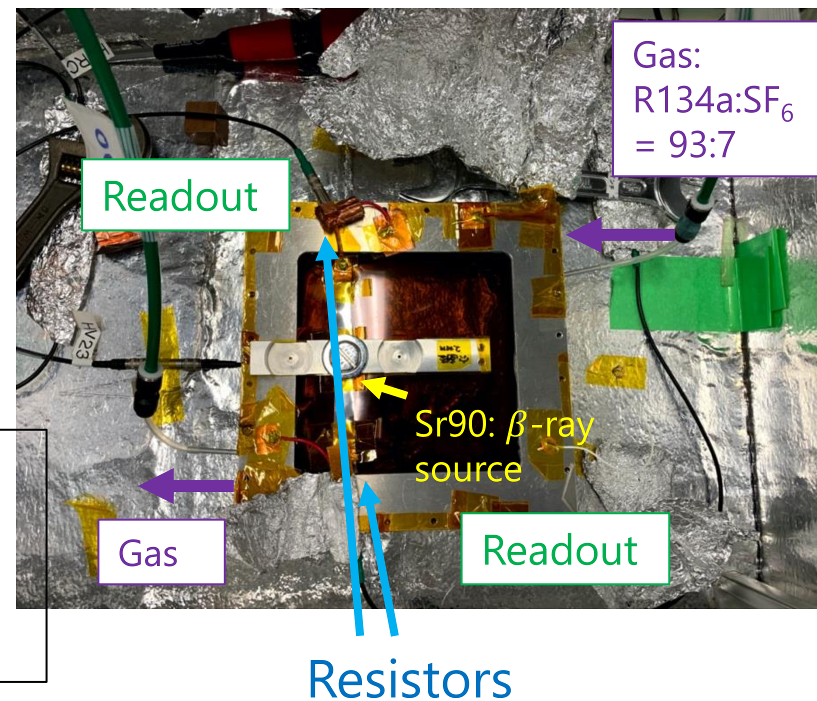
Lab test on effect of resistors

Setup



38 dB amplifier





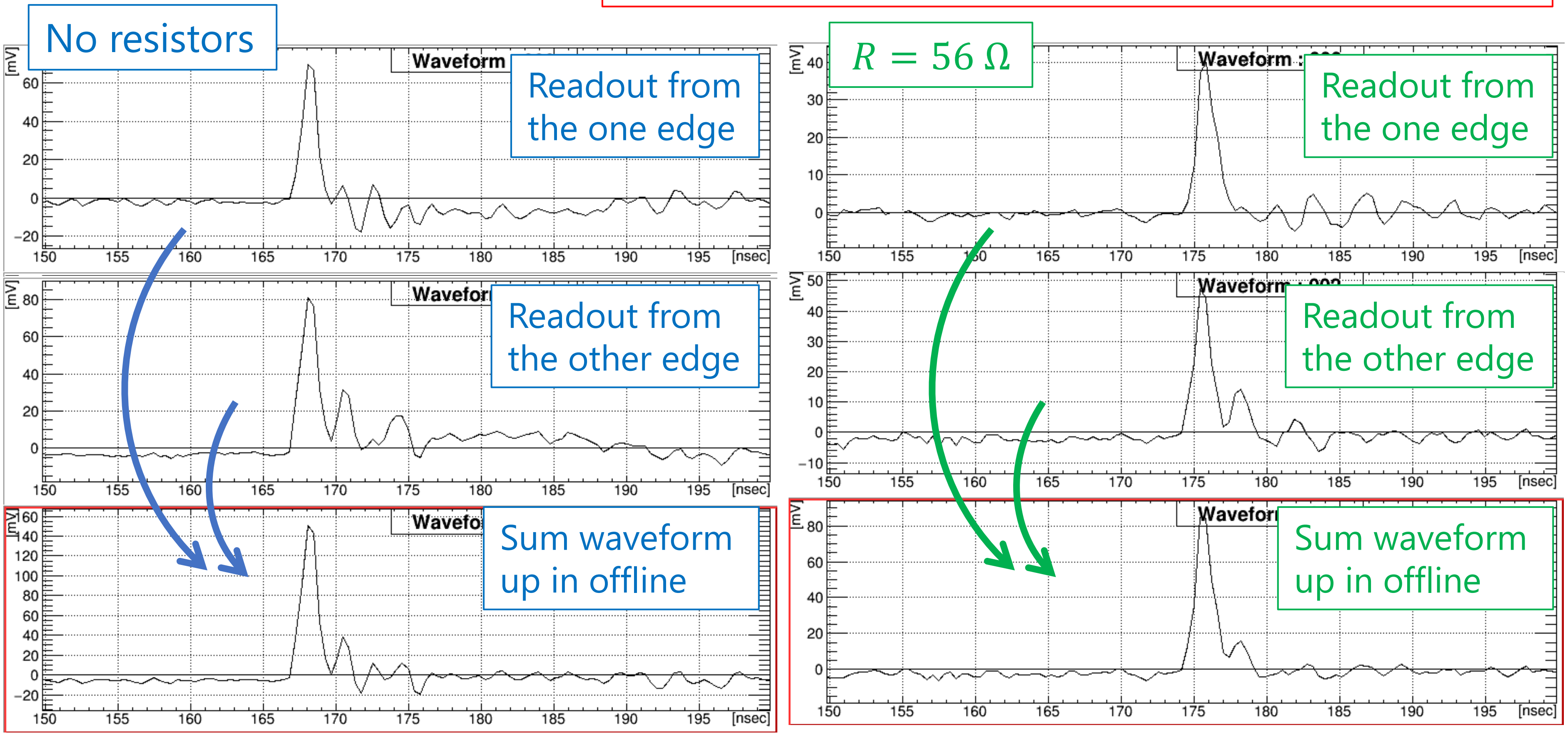
Purposes:

- Examine how much resistors suppress ringing
- Examine how much resistors deteriorate RPC performance

Waveform

Inserted resistors

- change ringing tail
- suppress ringing only in summed waveform

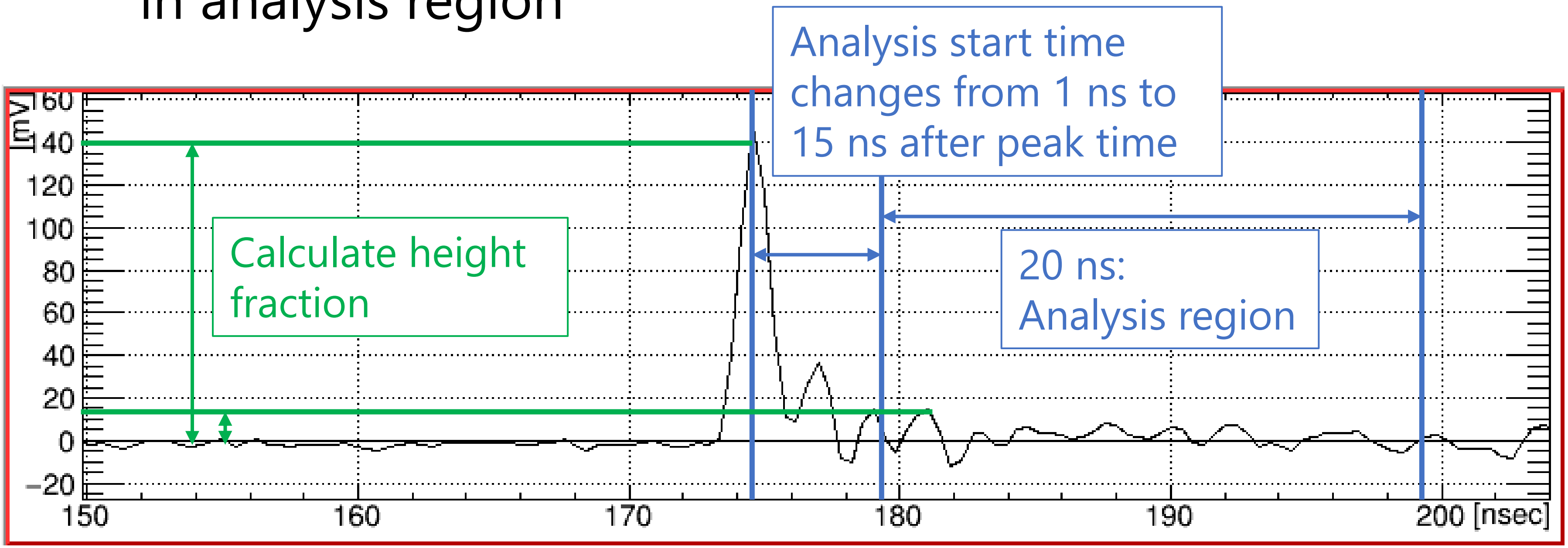


- How fast was ringing suppressed?
- How much was ringing suppressed?

Next slide

Analyze height after peak

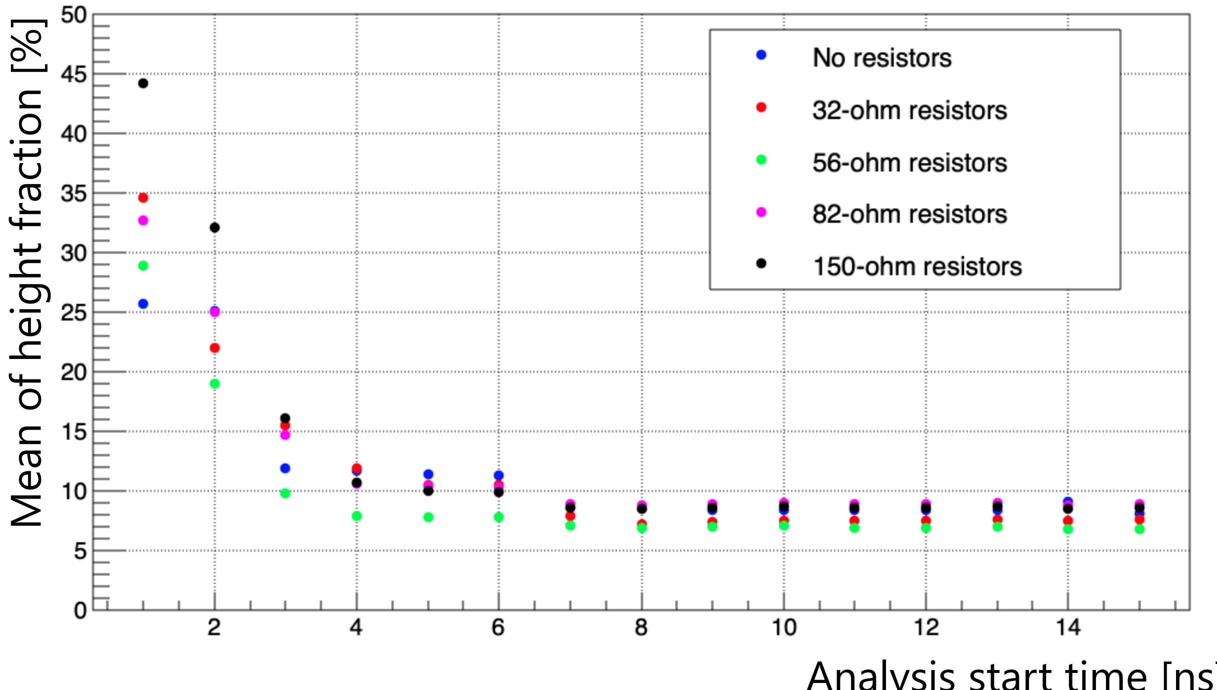
- Investigate how fast and how much ringing was suppressed
- "Analysis start time" is defined as start time of 20-ns analysis region
- Calculate the ratio of signal height to maximum height in analysis region



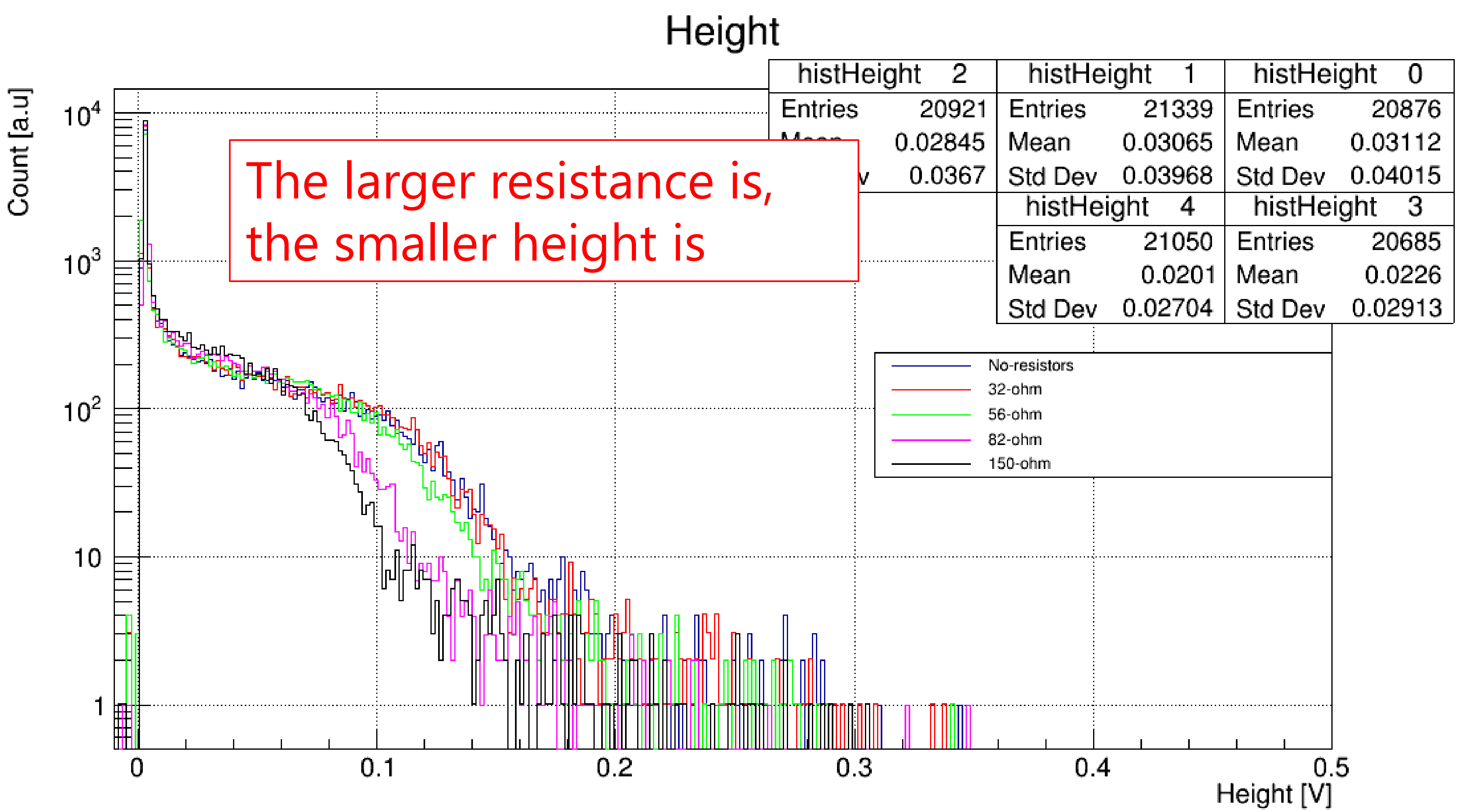
Height fraction

- 56 Ω resistors suppressed ringing little faster than the others
- However, this improvement is not enough

Height fraction vs Time after peak time



Height distribution

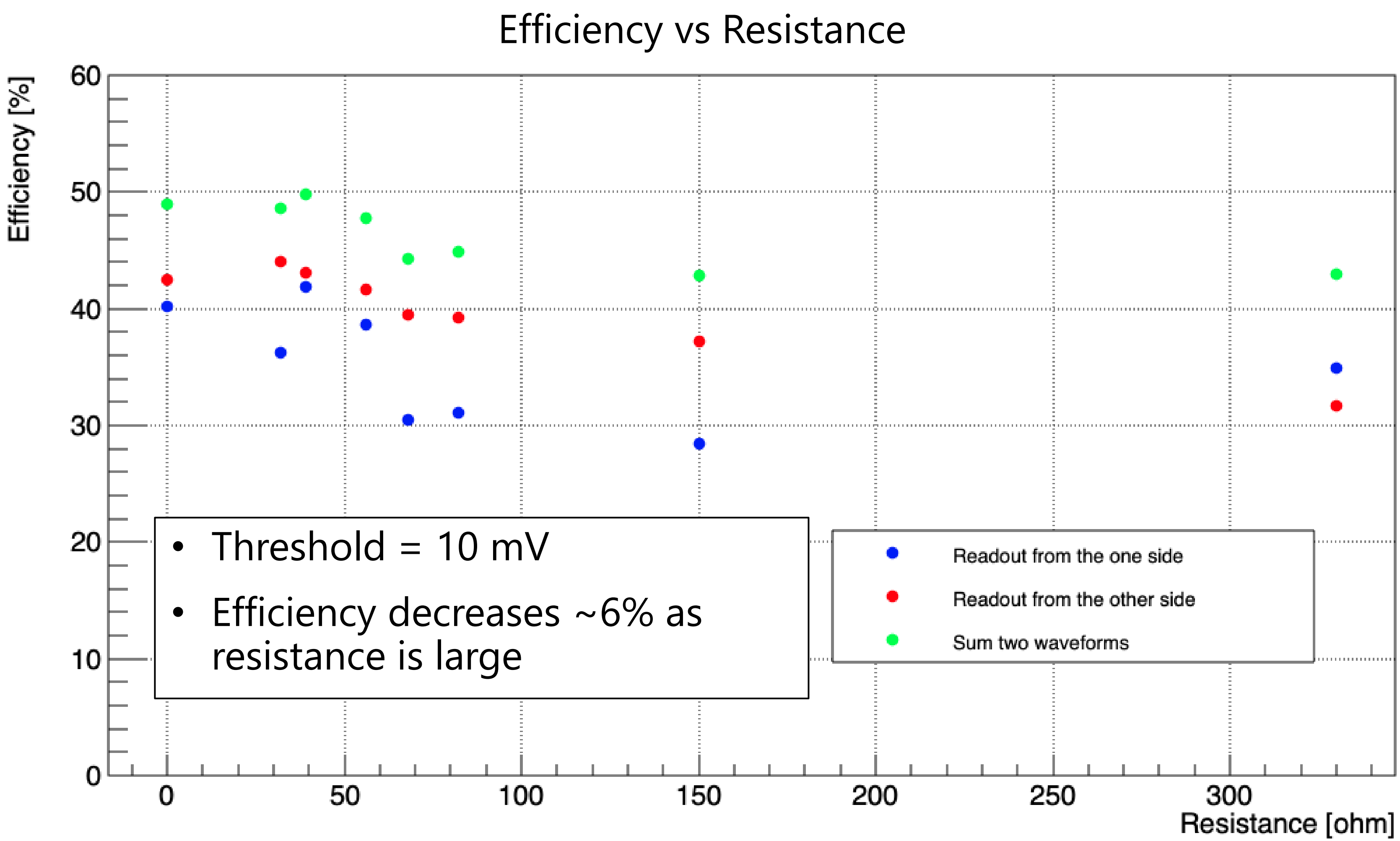


The larger resistance is,
the smaller height is

Efficiency

Achieve 40% single layer efficiency w/ any resistance

→ 90% four-layer efficiency can be achieved even if inserting resistors according to $\epsilon_n = 1 - (1 - \epsilon_1)^n$



- Threshold = 10 mV
- Efficiency decreases ~6% as resistance is large

Outline

- Introduction
- Lab test
- Summary & prospects

Summary & prospects

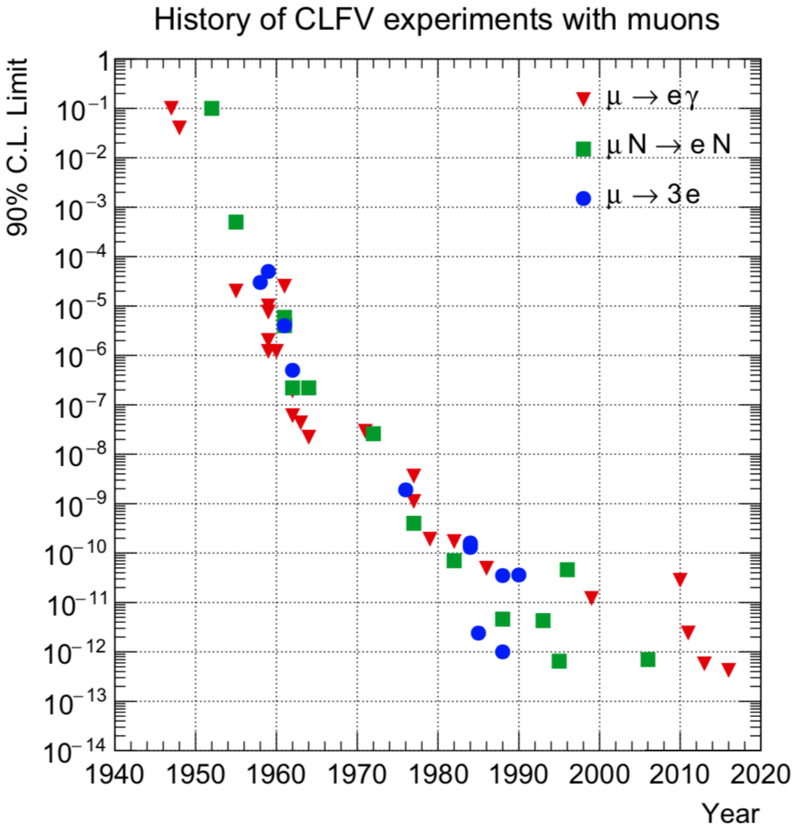
- Summary
  - Readout w/o resistors generated ringing
  - Resistors inserted b/w Al readout strip & LEMO cable change waveform and suppress ringing in summed waveform
  - They also made signal height smaller

- Prospects
  - Explain waveform theoretically or by simulation
  - Optimise readout and resistance

Backups

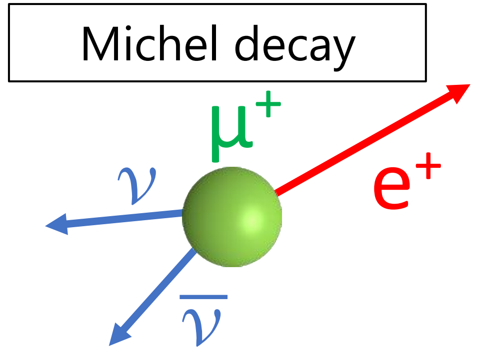
Physics of $\mu^+ \to e^+\gamma$

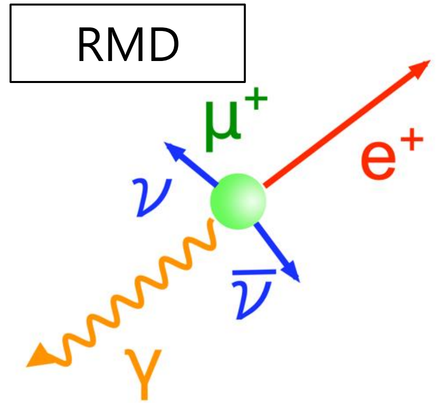
- Charged lepton flavour violation (cLFV) is forbidden in the standard model (SM)
  - In the SM, $\mathcal{B}(\mu \to e\gamma) < 10^{-50}$
- Some physics models beyond the SM (SUSY-GUT, SUSY-seesaw) say $\mathcal{B}(\mu \to e\gamma)$ is $10^{-11} - 10^{-14}$
- MEG experiment gave the upper limit of $\mu \to e\gamma$ 5.3×10^{-13} for the branching ratio
- $\mu \to e\gamma$ observation strengthen makes models beyond SM

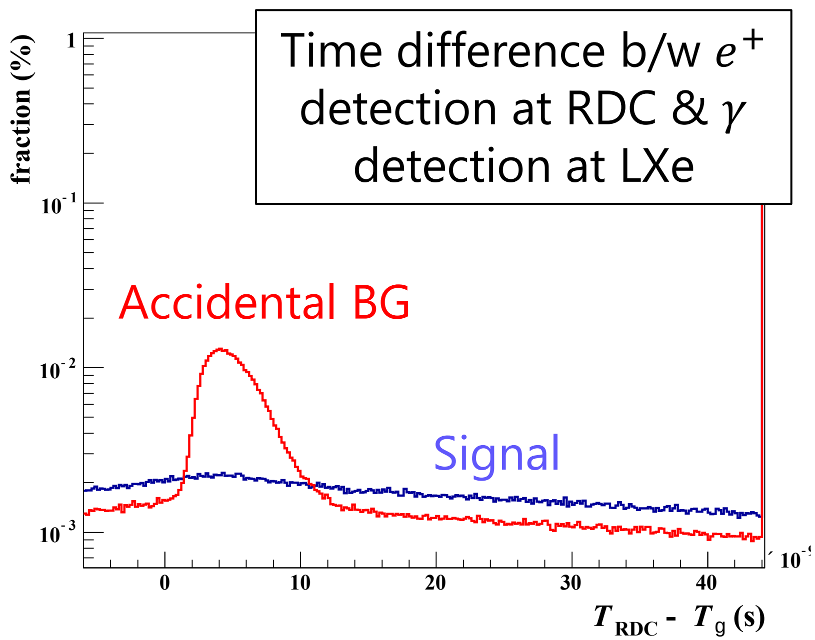


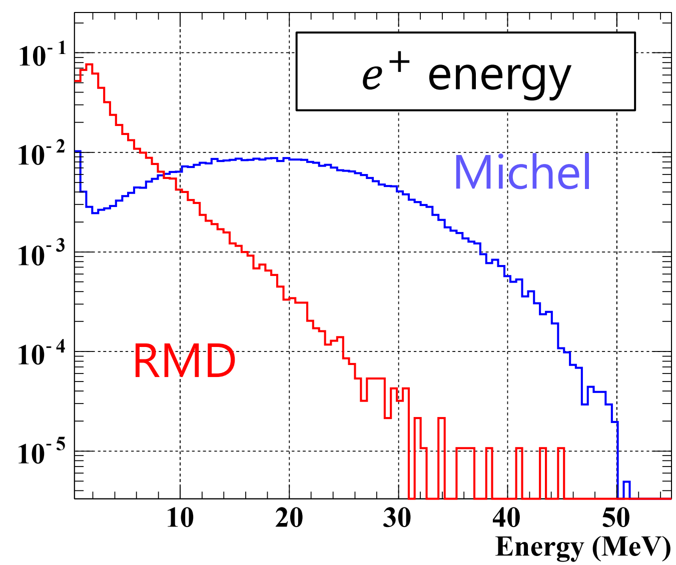
BG properties

- RMD γ is identified from
  - RMD e^+ energy
  - Time correlation b/w e^+ & γ



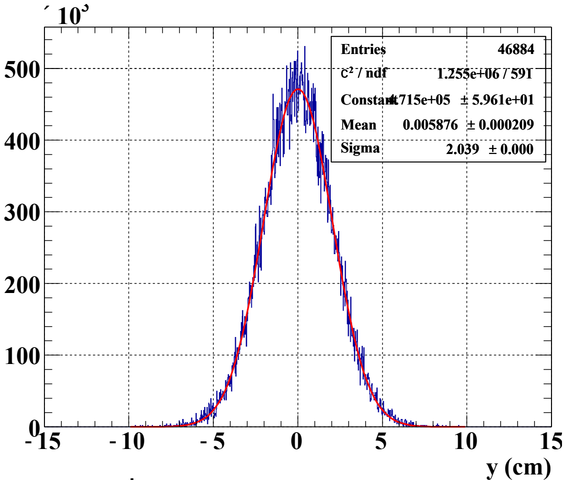




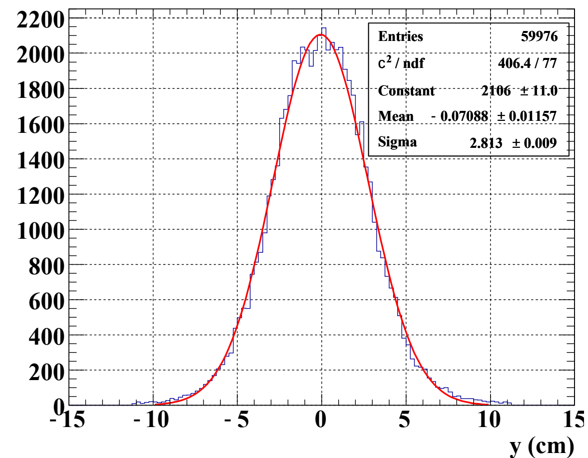


Pileup

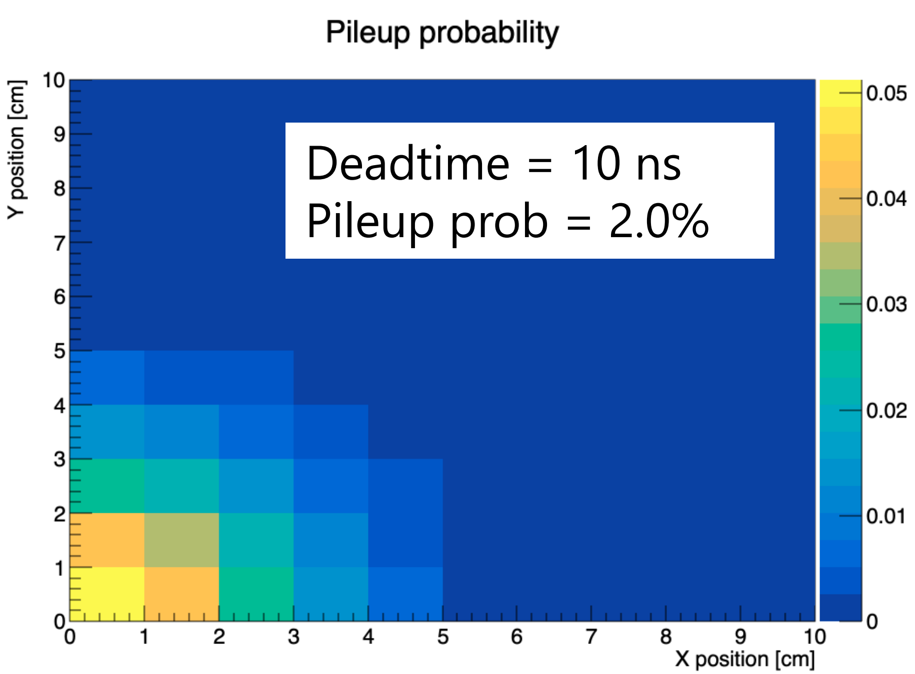
- Calculate pileup probability per readout region in which Al strips overlap

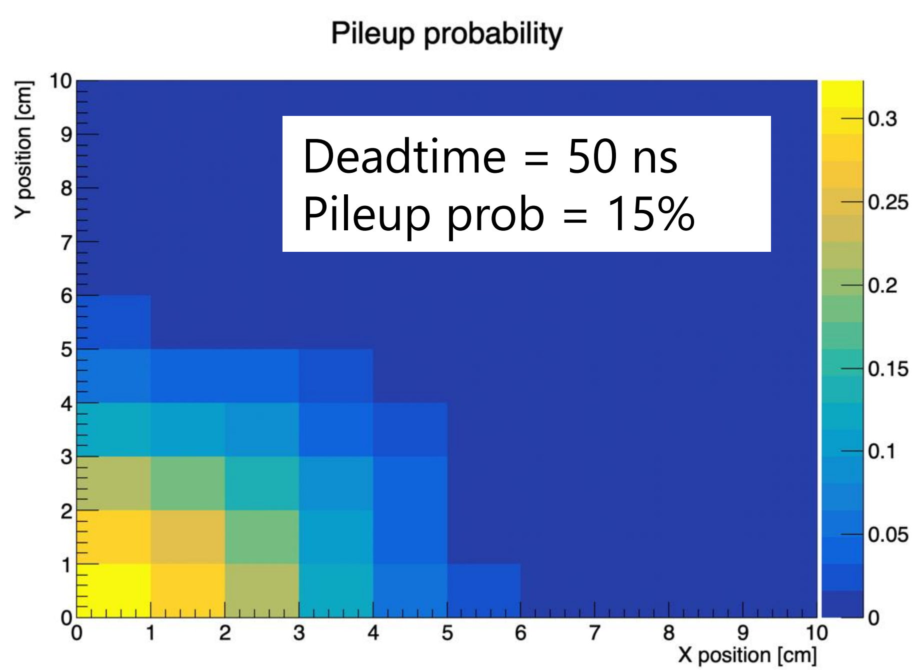


μ^+ beam divergence
$\sigma = 2.0$ cm



RMD e^+ divergence
$\sigma = 2.8$ cm





Pileup calculation

- P_i: pileup probability per readout segmented region
- ρ_i: probability to detect RMD e^+ in the segmented region (= 2.8 cm)
- Total pileup probability is given by
- $\sum_{strips=256} P_i \, \rho_i$
- Probability of time difference t b/w continuous μ^+:
- $p(t) = \frac{1}{\tau}\exp\left(-\frac{t}{\tau}\right)$, where $\frac{1}{\tau}$ is μ^+ rate in region i
- Probability of pileup of μ^+ beam & RMD e^+ in region i:
- $P_i = 1 - \exp\left(-\frac{t_{dead}}{\tau}\right)$, where t_{dead} is deadtime when we cannot distinguish μ^+ & RMD e^+

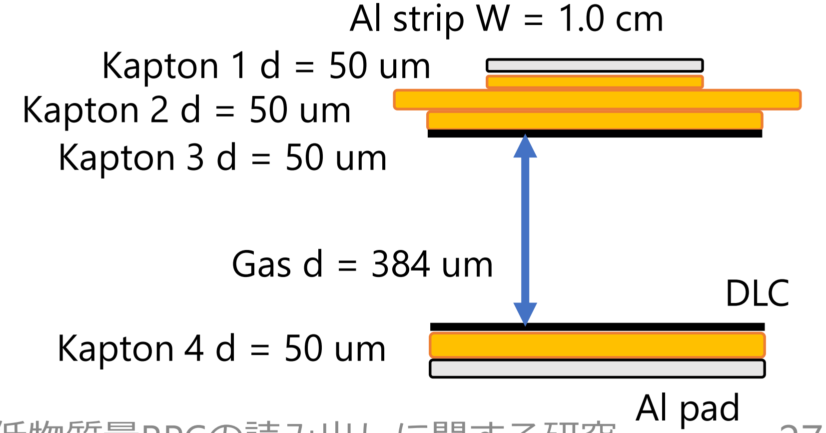
Resistance per length

- Surface resistivity $R_S = 1.1\ \Omega/\mathrm{sq}$
- → $R = \frac{R_S}{W} = 110\ \Omega/\mathrm{m}$
- where W is width of Al strip, that is 1 cm

Property		Units	Aluminum Metallized Polyimide Film Typical Value	
			LR-PI 100AM	LR-PI 200AM
Backing Thickness		μm	25	50
Aluminum Thickness		μm	0.2-0.5	0.2-0.5
Tensile Strength		MPa	≥140	≥130
Elongation		%	≥45	≥45
Shrinkage, at 150℃		%	0.20	0.20
Surface Resistivity	The side of PI Film	Ω	$\geq 1 \times 10^{12}$	$\geq 1 \times 10^{12}$
	The side of Aluminum	Ω	$<10^3$	$<10^3$

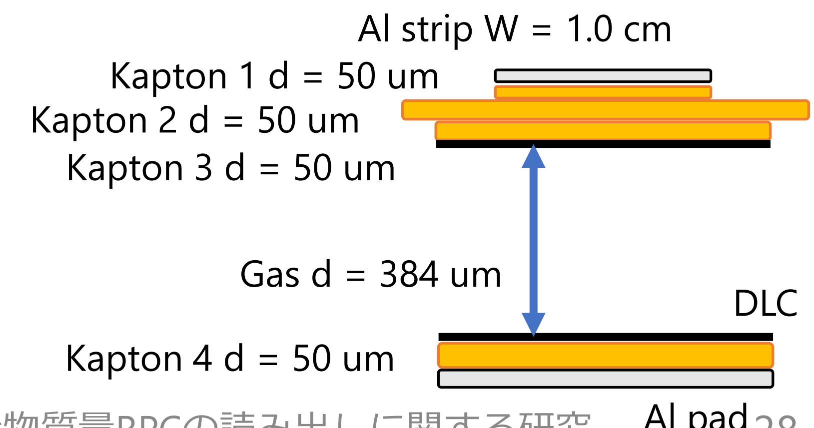
Capacitance per length

- Think of geometry like this figure
- Ignore DLC plate because DLCs are sputtered on kaptons
- Kapton's relative permittivity $\varepsilon_r = 3.3$
- Give strip charge per length q
- From Gauss's raw, electric field is
- $q = \varepsilon_0 \varepsilon_r E W \rightarrow E = \frac{q}{\varepsilon_0 \varepsilon_r W}$



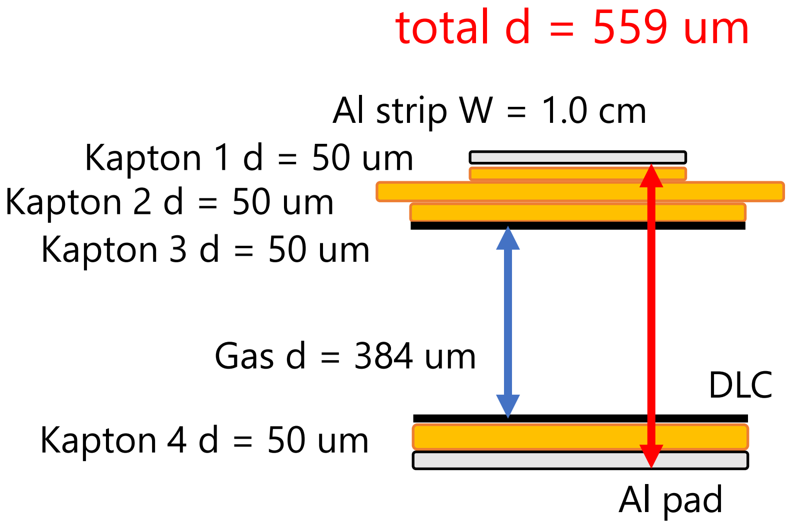
Capacitance per length

- From the field, potential diff b/w Al strip and Cu pad is
- $V = \int_0^d \frac{q}{\varepsilon_0 \varepsilon_r W} dx = \frac{qd}{\varepsilon_0 \varepsilon_r W}$
- From $V = \frac{q}{C}$,
- $C_i = \frac{\varepsilon_0 \varepsilon_r W}{d}$
- From $C_i = \frac{\varepsilon_0 \varepsilon_r W}{d}$, where C_i is capacitance per length in layer i
- Total capacitance $C = 202\ \mathrm{pF/m}$



Inductance per length

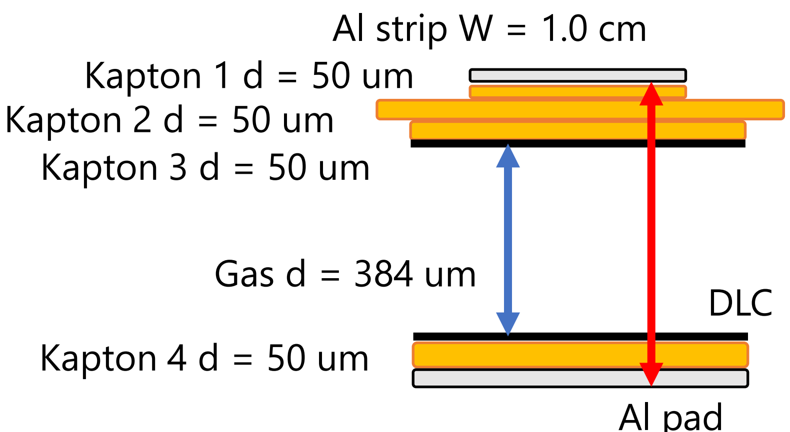
- Think of geometry like this figure
- Assume current J flows only in Al strip (No current in Cu pad)
- From Ampere's raw, magnetic field is
- $2W\mu B = J \rightarrow B = \frac{\mu J}{2W}$
- Permeability $\mu = \mu_0$



Inductance per length

- Magnetic flux Φ is
- $\Phi = \int \frac{\mu_0 J}{2W} dS = \frac{\mu_0 J}{2W} d$
- From Φ, calculate V, L
- $V = -\frac{d\Phi}{dt} = -\frac{\mu_0 d}{2W}\frac{dJ}{dt} = -L\frac{dJ}{dt} \rightarrow L = \frac{\mu_0 d}{2W}\ \mathrm{H/m}$
- $L = 35\ \mathrm{nH/m}$

total d = 559 um

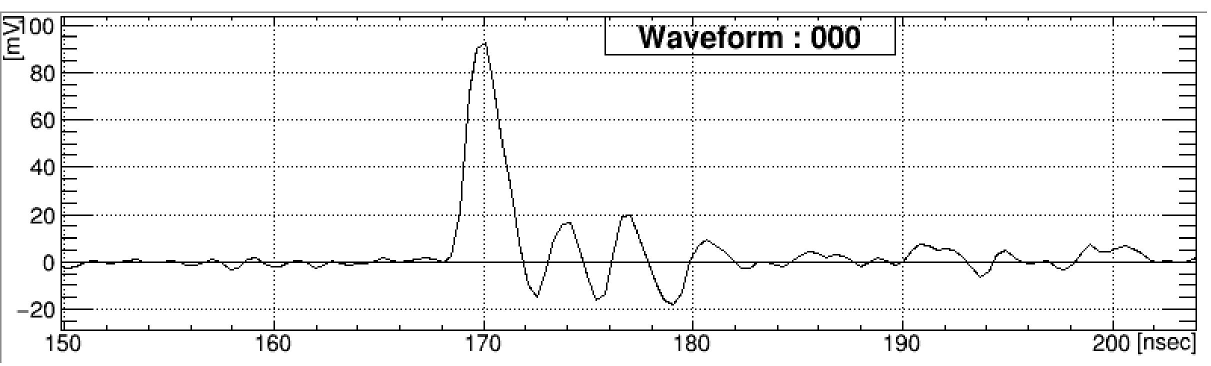


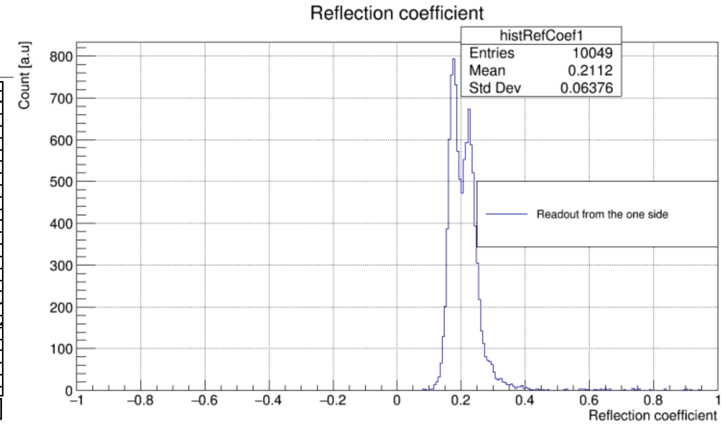
Characteristic impedance

- Need to consider resistance R because we cannot ignore loss
- Characteristic impedance is
- $|Z_0| = \sqrt{\frac{R^2+(\omega L)^2}{(\omega C)^2}}$
- where ω is angular frequency
- Assume signals are triangle waves whose width is 4 ns
- In this case, assume $\omega = 785\ \mathrm{rad/\mu s}$
- → $|Z_0| = \sqrt{\frac{R^2+(\omega L)^2}{(\omega C)^2}} = 13.2\ \Omega$

Reflection

- Characteristic impedance of Al strip: $Z_S = 13.2\ \Omega$
- Characteristic impedance of LEMO cable: $Z_0 = 50\ \Omega$
- Reflection coefficient $r = \frac{Z_0 - Z_S}{Z_0 + Z_S} = 0.58$
- In lab test, $r \sim 0.21$ ← Smaller than expectation



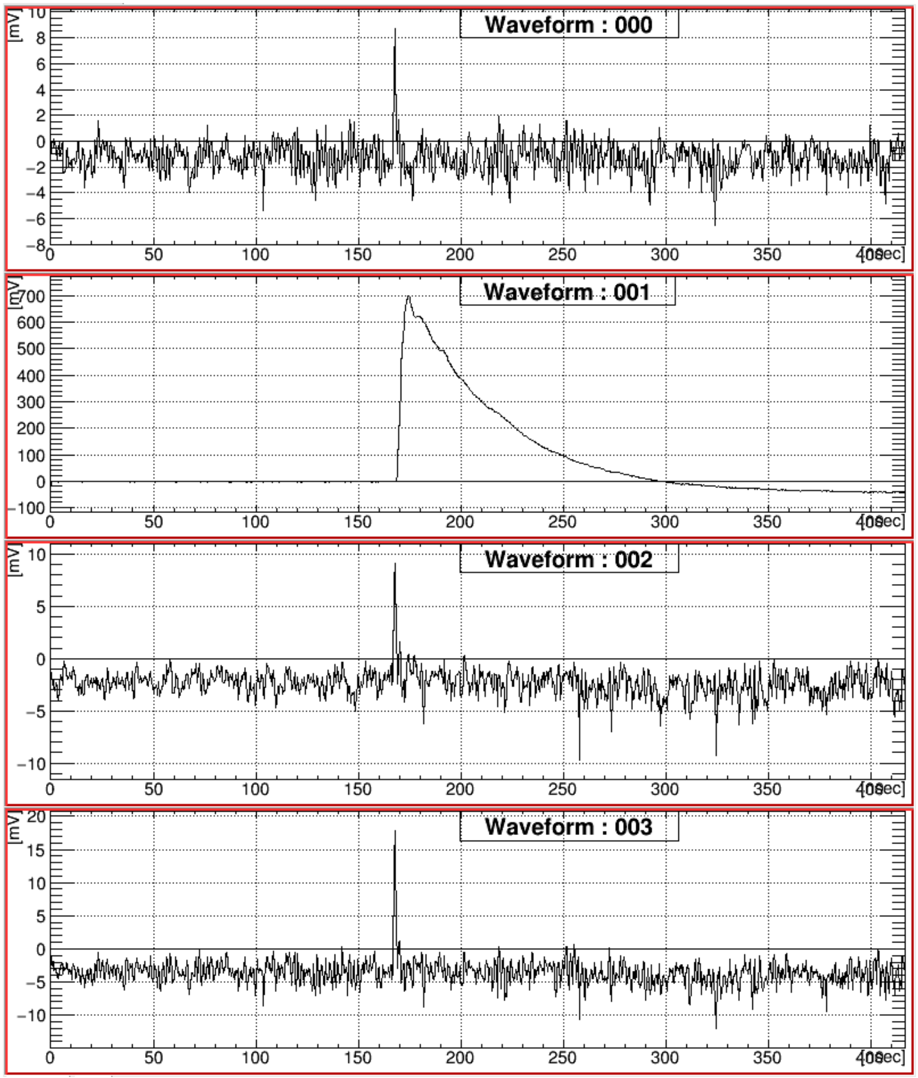


Both readouts w/o resistors

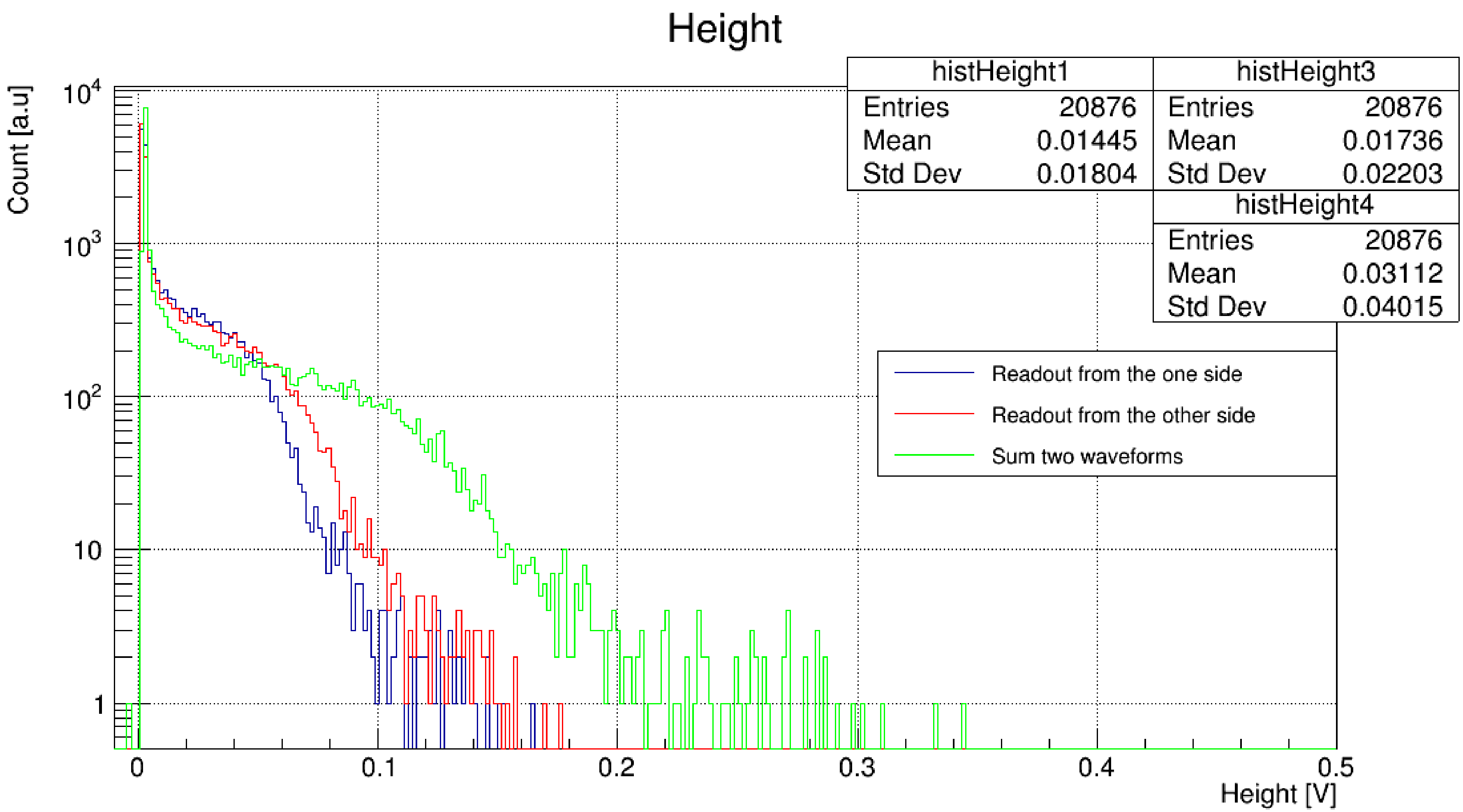
- Sum waveform up when readout from both sides of strip
- In some events, height is over threshold by summing up

→ Efficiency:

  - Ch 0: 40.2%
  - Ch 2: 42.5%
  - Ch 3 (sum): 49.0%



Both readouts w/o resistors



Both readouts w/o resistors