Development of a picosecond-timing Cherenkov detector using gaseous photomultiplication

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Introduction

High time resolution, **large area** are recent trends for Cherenkov and scintillation detectors in particle physics and nuclear experiments, for example, TOP counter at Belle II, TORCH for LHCb upgrade 2, and future upgrade…

Performance of existing photodetectors

	Single-photon time resolution	Sensitive area	Cost / area
SiPM (FBK near ultra violet, NUV)[1]	$\sigma = 63.9$ ps	3 mm × 3 mm	Middle
1” MCP-PMT[2] (Hamamatsu, Channel diameter=10 μm)	$\sigma = 30$ ps	23 mm×23mm	High
MCP-PMT(LAPPD)[3]	$\sigma = 39$ ps	192×192 mm^2	Middle (volume cost)

※SiPM: Silicon Photo Multiplier
※MCP-PMT: Micro Channel Plate Photo-Multiplier Tube
※LAPPD: Large Area Picosecond Photo-Detectors

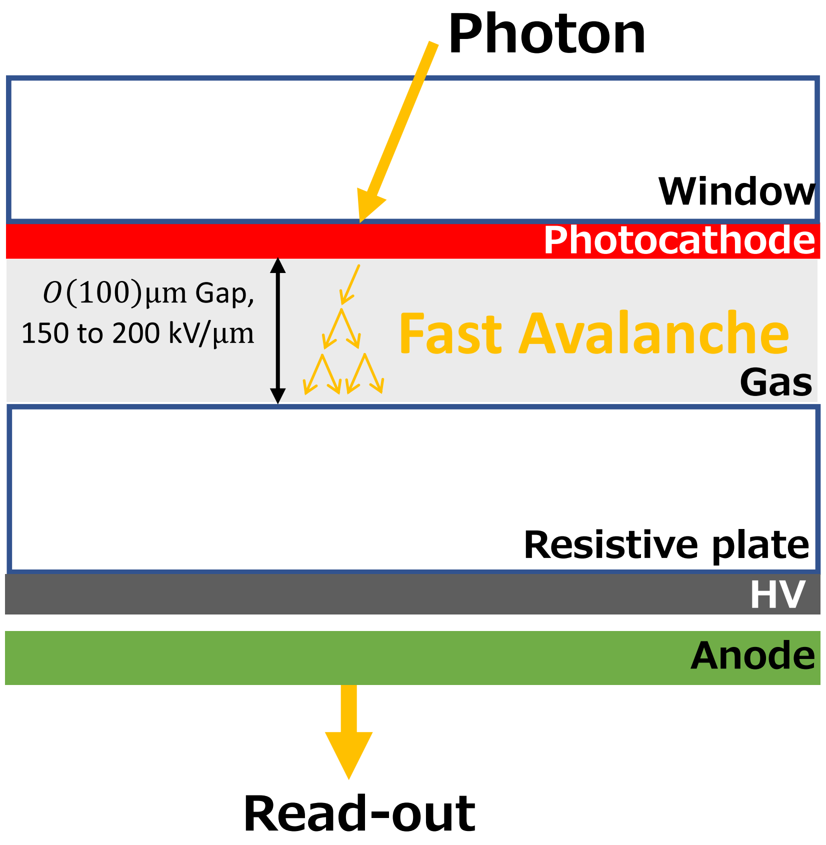
[1] https://doi.org/10.1088/1748-0221/11/10/P10016
[2] https://journals.jps.jp/doi/abs/10.7566/JPSCP.27.011020
[3] https://arxiv.org/abs/2309.15011

We aim to realize a photodetector with a better time resolution, larger area, and lower cost.

GasPM

How to realize a photodetector with a high time resolution, large area, and low cost?

Conceptual diagram of GasPM



Gaseous detectors

→ Advantages in scale and cost

How to achieve high-time resolution

1.Uniform structure

2.High electric field and narrow gap

→ **RPC–based photodetector with a narrow gap**

1st prototype of GasPM

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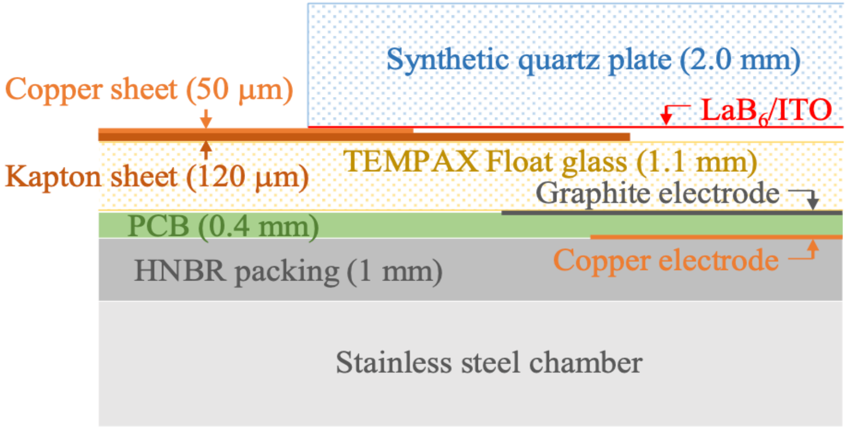
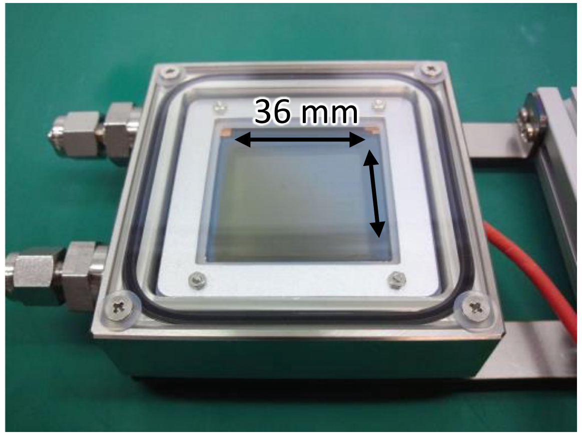
Aim of the first prototype: Demonstration of the high-time resolution

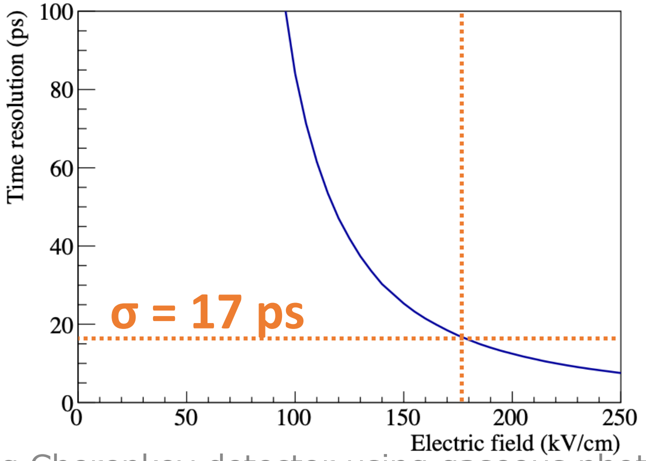
Prototype design



Prototype



Expected time resolution



LaB6 photocathode

Low QE , but stable performance in gas and the air.
→ Easy assembly

TEMPAX resistive plate

High resistivity $(10^{15}\Omega \cdot \mathrm{cm})$
→ To concentrate on the timing performance without being disturbed by discharge in the gap at all.

Prototype parameters

- Gap width 170 μm
- Gas: R134a 90%, SF_6 10%
- Applied voltage: 3 kV (176 kV/cm)
- Sensitive area: 36 mm×36 mm

Time resolution of GasPM

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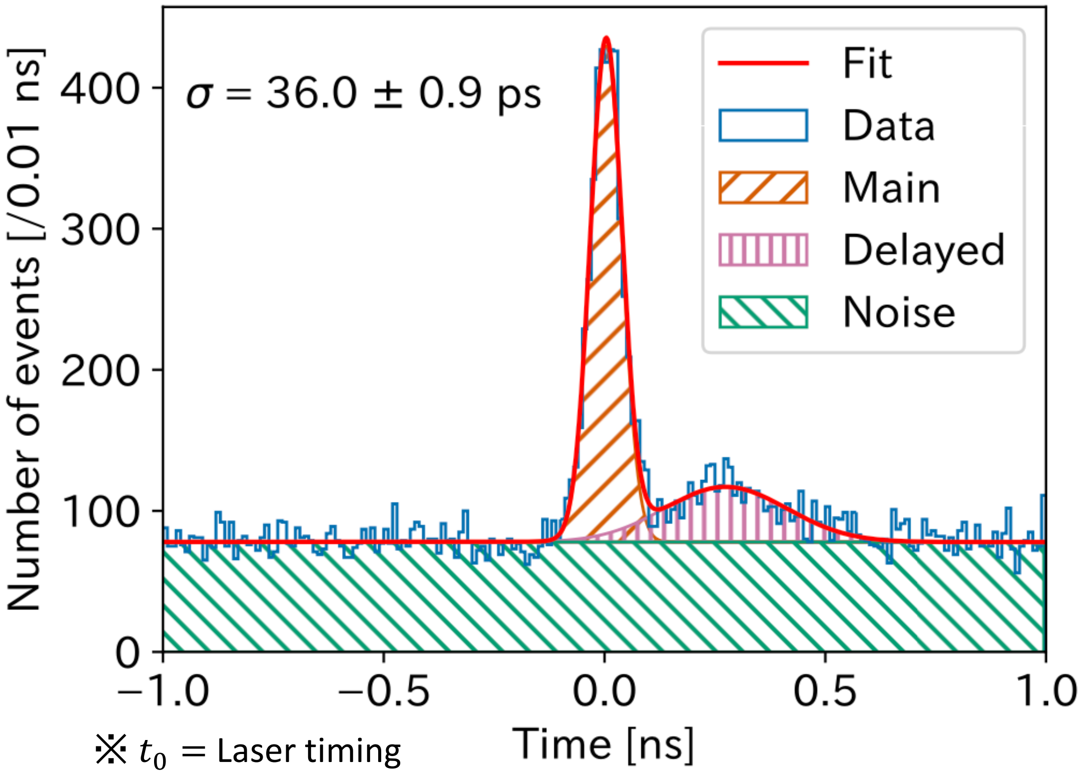
Demonstrated the high time resolution of GasPM!



※ t_0 = Laser timing

Time resolution

$\sigma = 36.0 \pm 0.9$ ps at the main peak.

Laser width: 21.8 ± 0.5 ps

(Measured by a streak camera)

Read out time resolution: 14.0 ± 0.3 ps

→**25.0 ± 1.1ps** w/o laser width and read-out resolution

Better than MCP-PMT

($\boldsymbol{\sigma = 30}$ **ps** (Channel diameter =10 μm))

Delayed timing signals

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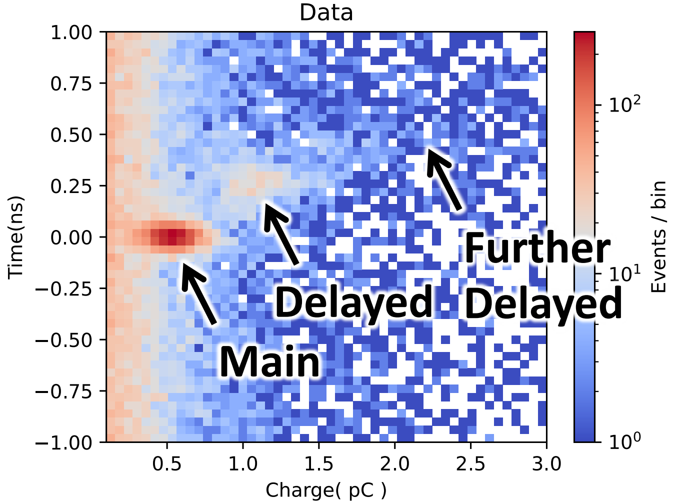
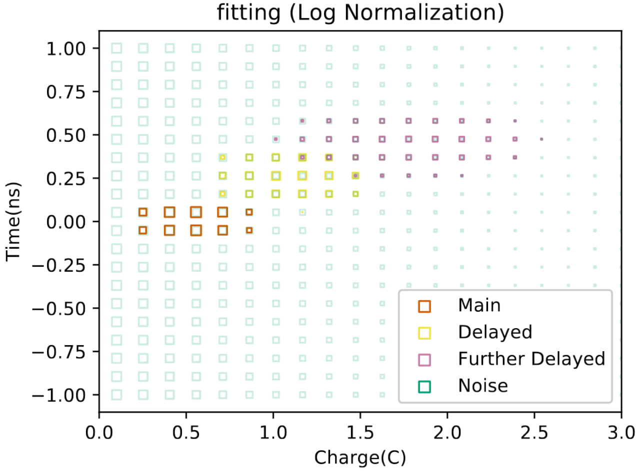
Charge and timing distributions

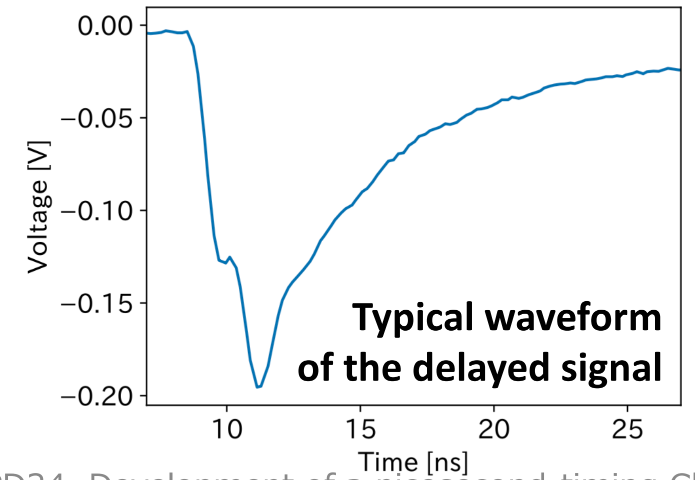


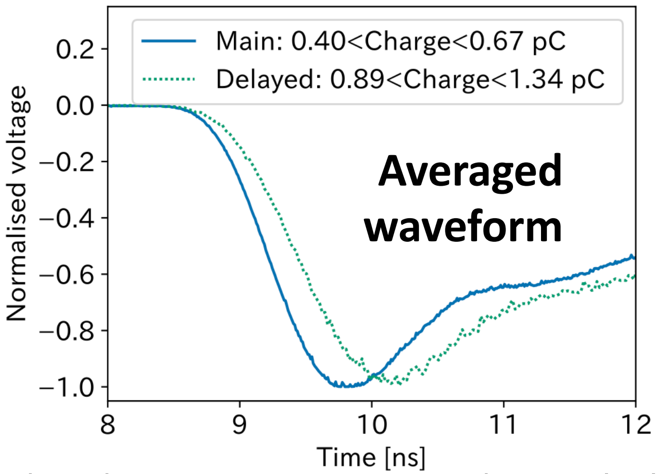


Delayed signal

- Larger signal charge than the main signal
- Slower rising edge on average
- Observed 2-3 overlapping peaks for each pulse in some events

Waveform





Signal Yields

	Yield	Ratio of the signal component
Main	3224 ± 64	1
delayed	752 ± 48	0.23 ± 0.02
Further-delayed	394 ± 47	0.12 ± 0.01

Photon feedback

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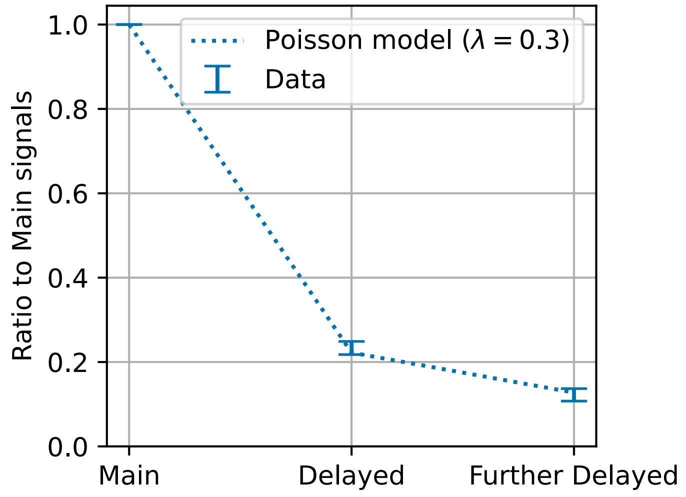
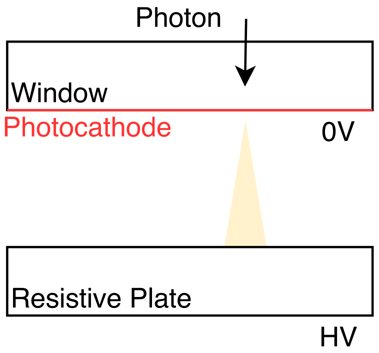
Secondary avalanche from UV light due to the gas excitation and deexcitation.

Photon feedback occurrence under the assumption of a Poisson model using the ratio of the signal component: **0.30 ± 0.02**.

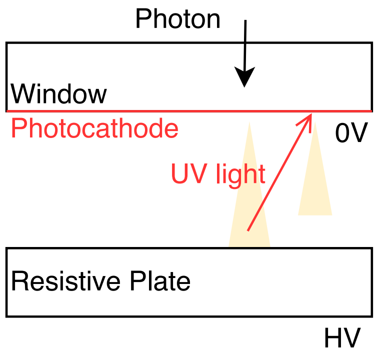


Main



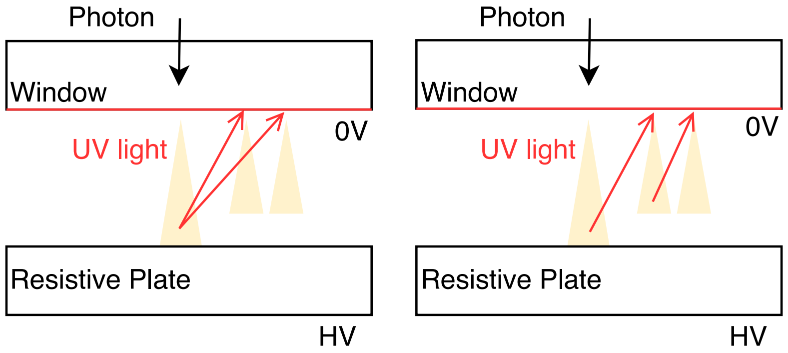
Delayed

1 photon feedback

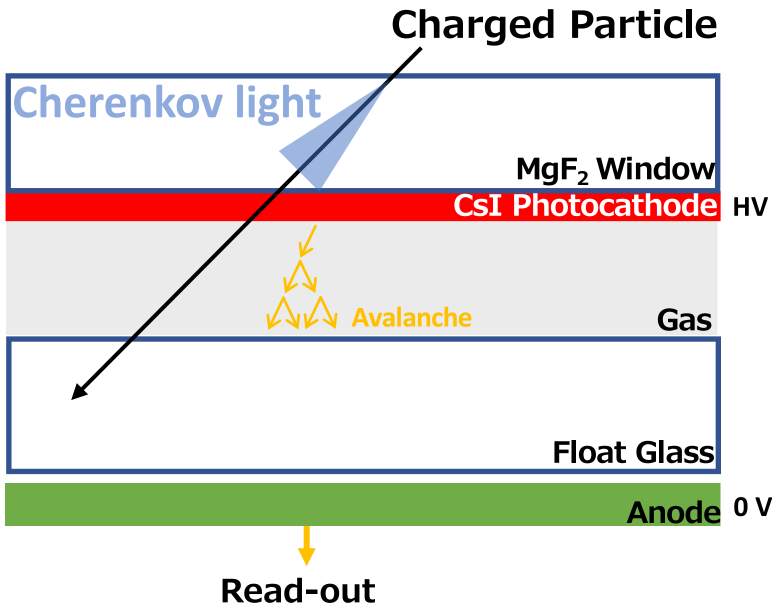


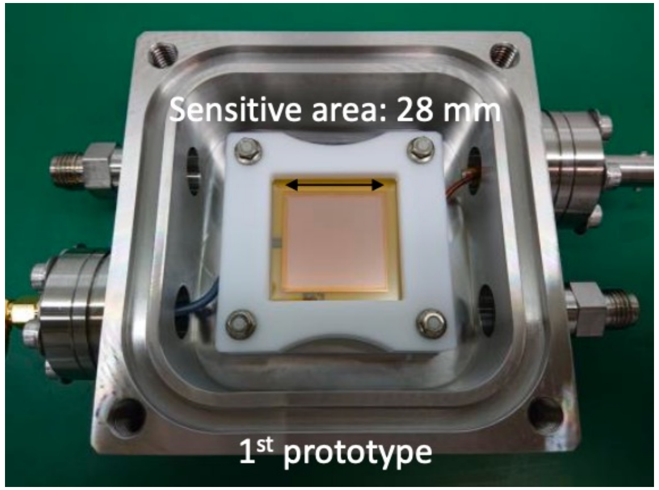
Further Delayed

2 photon feedback



Application of GasPM as a Cherenkov timing detector





Detect Cherenkov light with **CsI photocathode**

Design of the prototype

2 mm MgF_2 window

CsI photocathode: High gas resistance, Sensitive to UV light

→ Suitable for Cherenkov light detection.

Expected performance

7 photons/ track (with 2 mm MgF_2, QE(CsI)=20% at 160 nm)

→

Detection efficiency : **100%**

Time resolution : $\sigma = \frac{25}{\sqrt{N}}$ ps (**9 ps** w/ 7 photons)

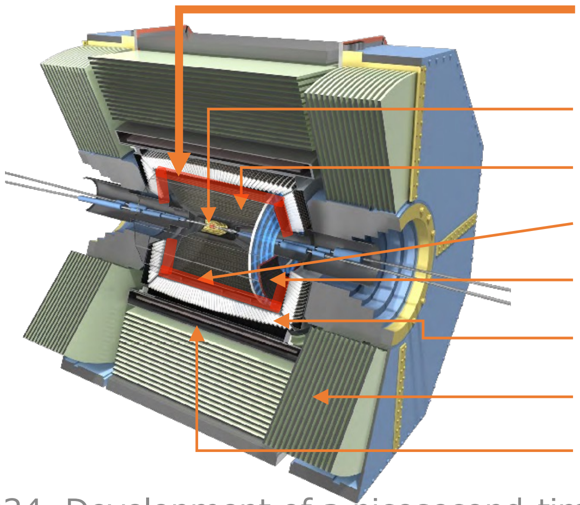
Possible application of GasPM: A picosecond timing TOF and γ timing measurements

GasPM can measure the timing of charged particles and low-energy γ with a picosecond resolution.

Possible application at Belle II

Belle II experiment

- High-luminosity e^+e^- collider at c.m. energy of 10.58 GeV.
- Located KEK, Japan
- Aim indirect BSM searches via precise measurement of B, D, τ



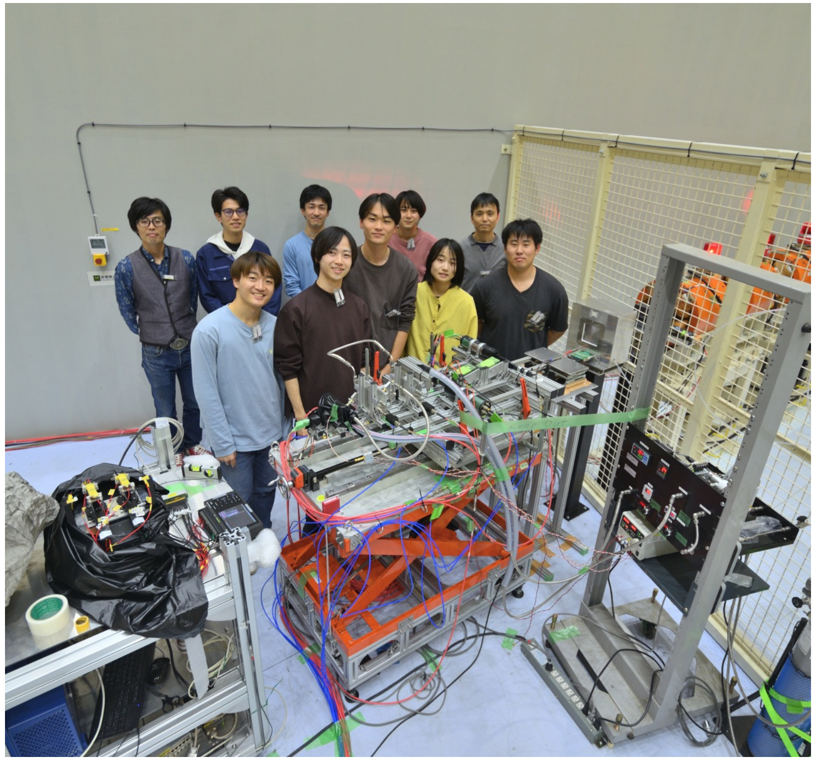
PID by TOF with high-resolution

- Improve K-π identification by measuring **TOF** with σ=20 ps with 100% efficiency.
  → K ID eff. 99.7% and π-misID 0.4% (2 GeV)

γ timing measurement with high-resolution

- Detect **γ timing** with $\sigma = 20$ ps and 90% efficiency
- Identify fake γ from beam background
- **Reduce fake calorimeter clusters to 10%**

Beam test



Target

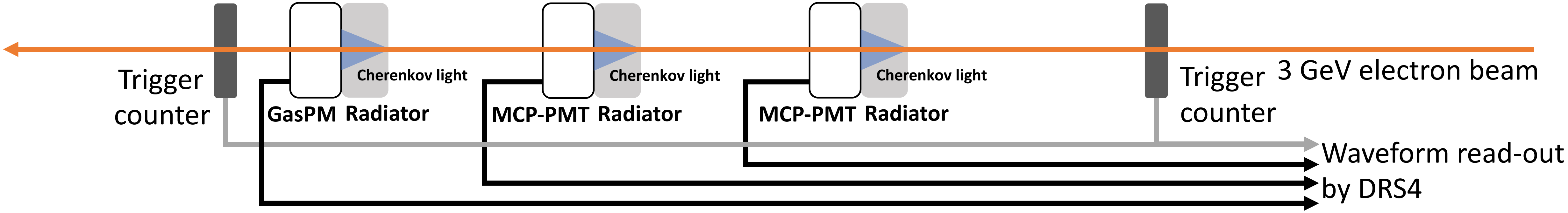
- Demonstrate the Cherenkov timing detection using GasPM
- Time resolution measurement of GasPM
  (We expect $\sigma = 50\text{-}70$ ps with this configuration.)

Location

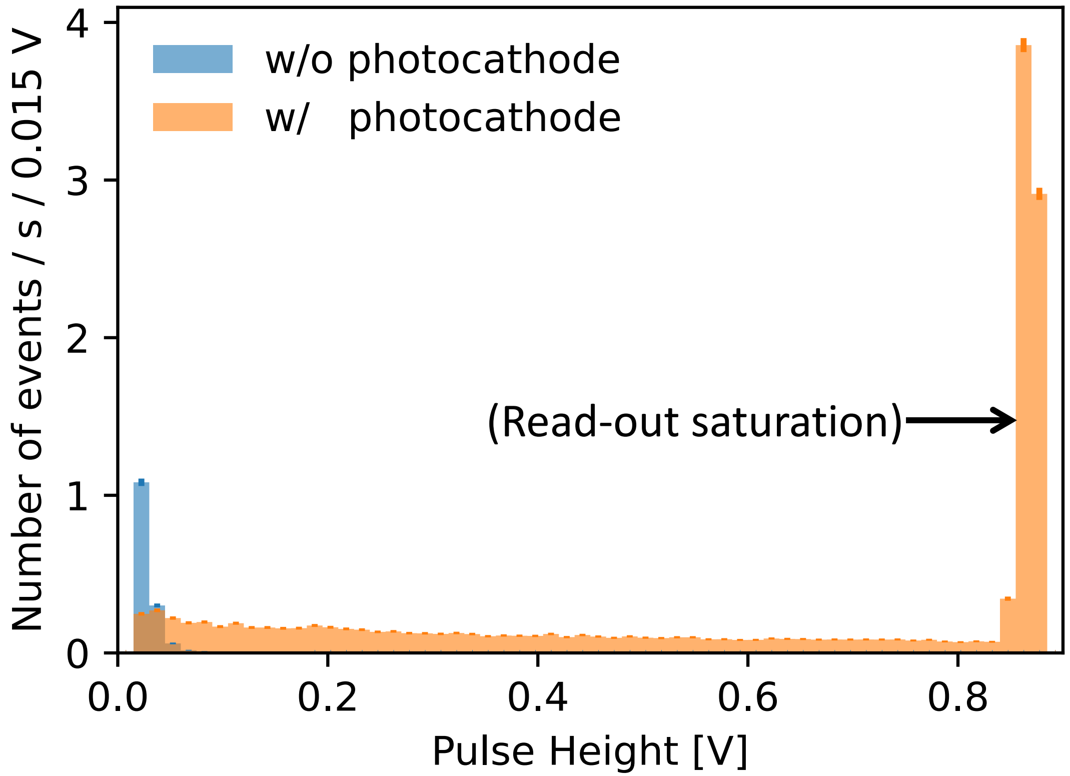
PF-AR test beam line at KEK (Japan)

Setup

- GasPM with a Cherenkov radiator (Gap voltage $= 2.8\ \mathrm{kV}/200\ \mu\mathrm{m}$
  (lower than before just to be safe
  because we observed noises with an extremely large pulse height)
- MCP-PMT for beam timing measurement ($\sigma = 30$ ps)
- Waveform read-out by DRS4 digitizer (5GSPS, $\sigma = 8.4$ ps)



The first Cherenkov light detection with GasPM

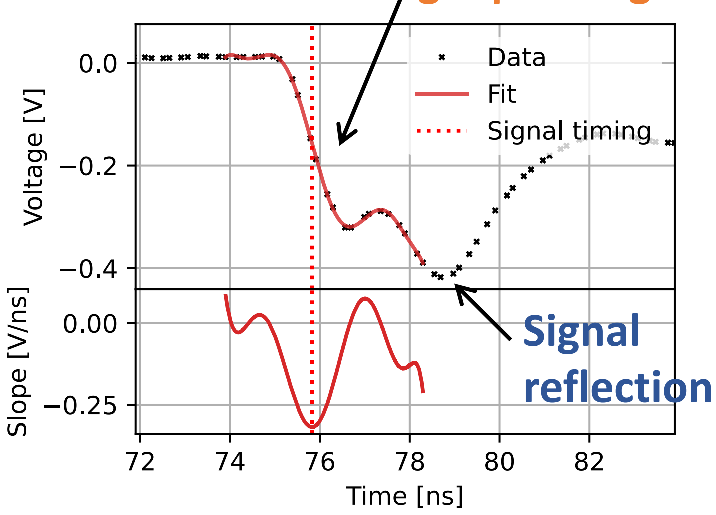


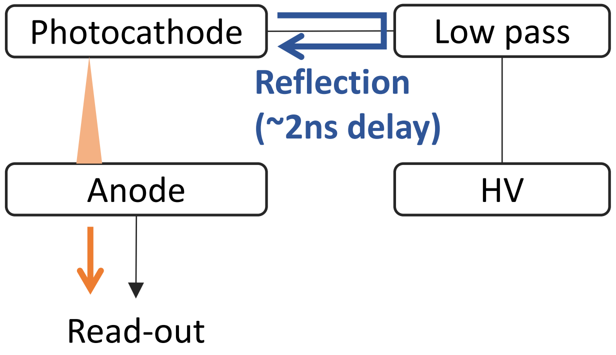
	Expected signal composition	Observed signal
w/ photocathode	Gas ionization + Cherenkov light	13.8 Hz
w/o photocathode	Gas ionization	1.5 Hz

→ Demonstrated Cherenkov light detection

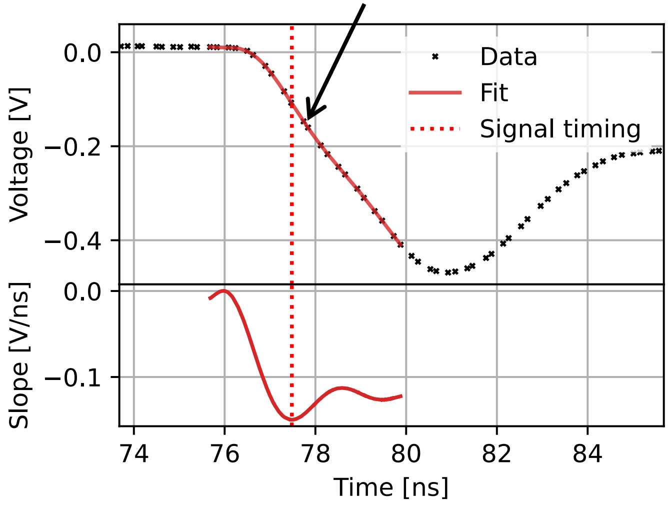
Signal timing extraction

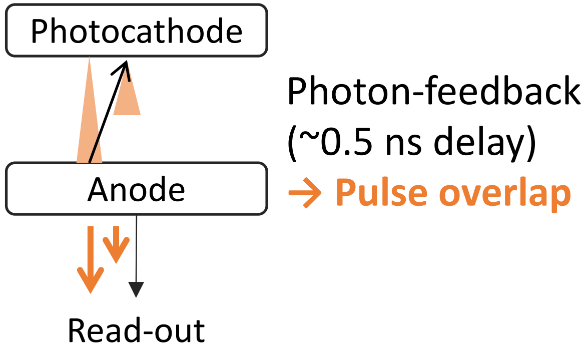
Single-peak signal





Signal with photon feed back





Challenges

- Pulse overlap due to photon feedback
- The probability of the photon feedback increased because of the improved quantum efficiency
  → Developed a fitting with the **first pulse detection**.

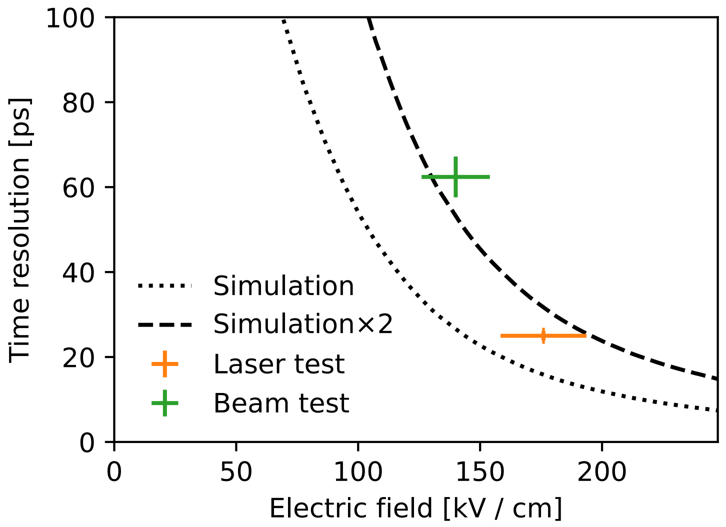
Fit procedure

1. Fit waveform with a polynomial
2. Measure the slope of the fitted curve
3. Extract the timing at the maximum slope

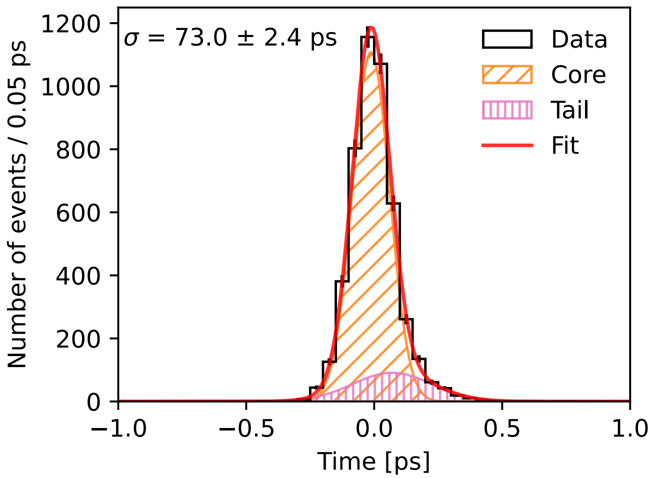
Time resolution

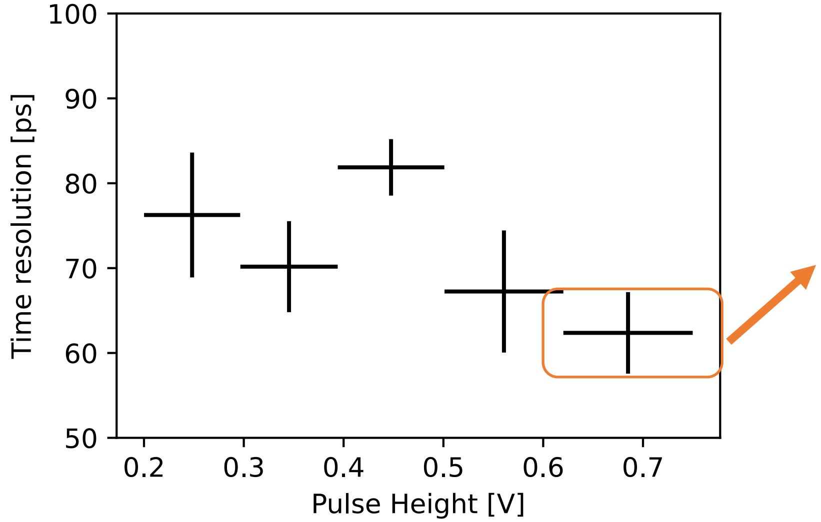
- 73.0 ± 2.4 ps (all), **62.3 ± 4.8 ps** (Large pulse height)
- Expected time resolution by the simulation: $22 - 33$ ps
  → Data/Simulation ratio =1.9 – 2.3
  which is consistent with the first test with the laser
  (Data/Simulation ratio = 1.2 – 2.1)

→ Achieved the expected time resolution with a Cherenkov light detection using GasPM.

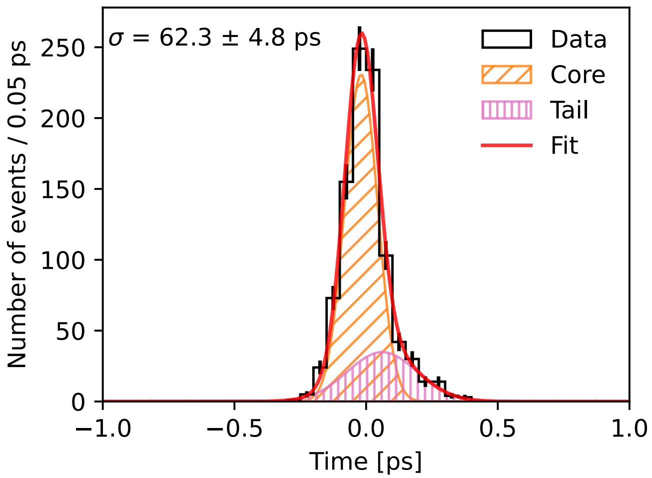


Time resolution (all)





Time resolution (Large pulse height)



Future development plan

How to achieve the 10 ps resolution as designed?

- Increase the read-out sampling rate from 5GSPS to 10GSPS for better separation for the photon feedback signals.
- Increase the gap voltage from 2.8 kV to 3.5 kV
  → Factor 2 improvement in the single photon resolution
- Increase the number of the detected photons with a thicker radiator and the new CsI photocathode
  → If the detected photons/event will be about 1 to 10, time resolution will be improved by factor 3.

→ We can improve the time resolution from 62.4 to about 10 ps with this assumption.

Summary

Gaseous photomultiplier is a photodetector that has three advantages, high time resolution, large-area, and low cost.

Single photon response of GasPM

- Demonstrated that GasPM has an excellent single photon time resolution of **25.0 ± 1.1ps.**
- Some of the signals have a delayed timing and a large charge due to photon feedback.

Application of the GasPM as a charged particle detector

- Performed beam test at PF-AR test beamline at KEK, Japan
- Time resolution 73.0 ± 2.4 ps (all), **62.4 ± 4.8 ps** (Large pulse height) which agrees to the expectation

Next

- Plan to increase the gap voltage and increase the number of the detected photons.
  → **Aim to reach $\sigma \simeq 10$ ps resolution!**

K. Matsuoka, R. Okubo, Y. Adachi,
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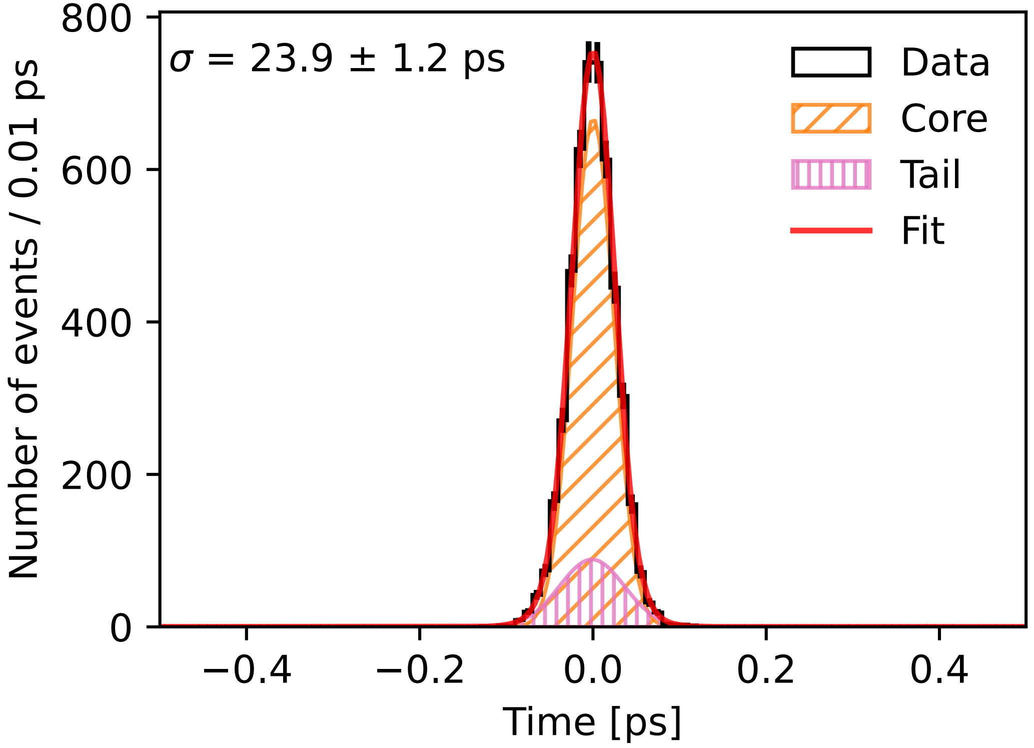
Time resolution of the MCP-PMT



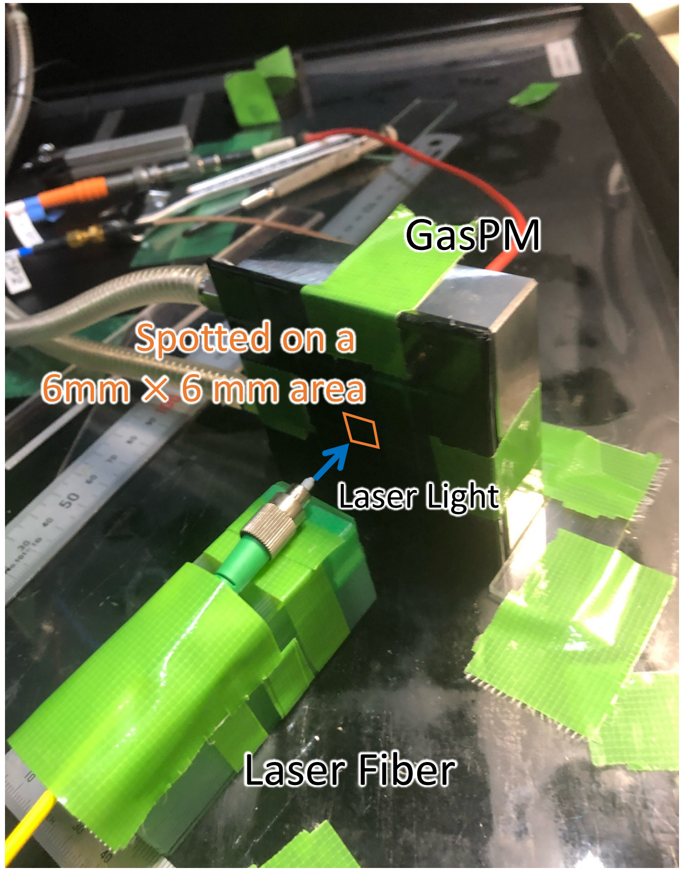
$\sigma = 23.9 \pm 1.2$ ps for two MCP-PMTs.

Read-out resolution: $\sigma = 8.4$ ps

→ Time resolution of each MCP-PMT:
$\sigma = 15.8 \pm 1.1$ ps

Time resolution measurement

Set up



Laser

Picosecond pulse laser with short wavelength and large intensity that is suitable for this measurement

- **Wavelength**: 375 nm
- **Average Power**: 1 mW
- **Pulse width**: 21.8 ±0.5 ps
- **Repetition rate** : 100 MHz

  Laser signal detection rate: 0.02 Hz
  → Single photon
  Random noise rate : 0.3 – 1 Hz

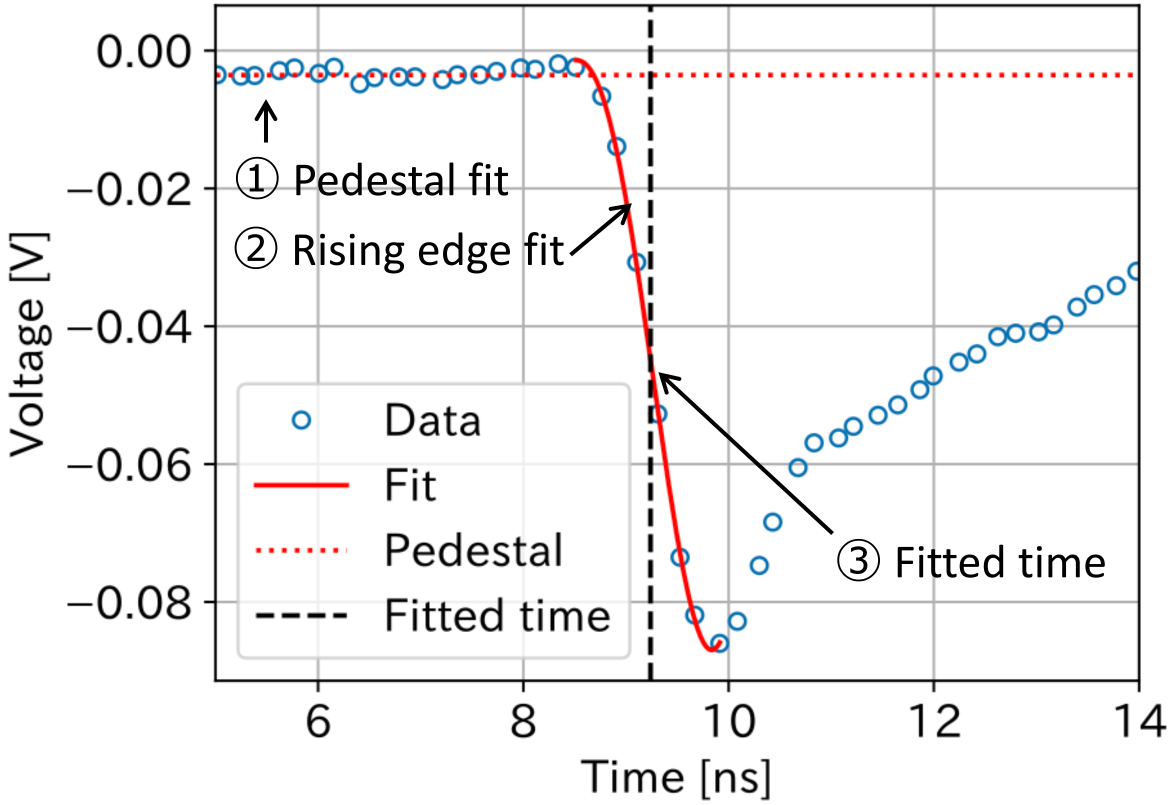
DRS4 evaluation board

Wave form readout with a good time resolution.

- Sampling rate: 5 G samples / sec
- Analog bandwidth: 700 MHz
- Measured time resolution in this setup: 14.0 ± 0.3 ps

GasPM waveform

Typical waveform (amplified by 27dB)



Response to single photons

Gain	3.3×10^{6}
Rise time	1 ns

Signal timing determination by fitting

Determine the signal timing as the time when the rising edge reaches half of the maximum voltage