Status of R&D for muon detector and study of SiPMs

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- Scintillation detector with WLS fiber
- High time resolution system
- Summary

Introduction

CEPC : FUTURE LEPTON COLLIDER

- Higgs/W/Z bosons, top, BSM searches, etc.
- Precision jet measurement.

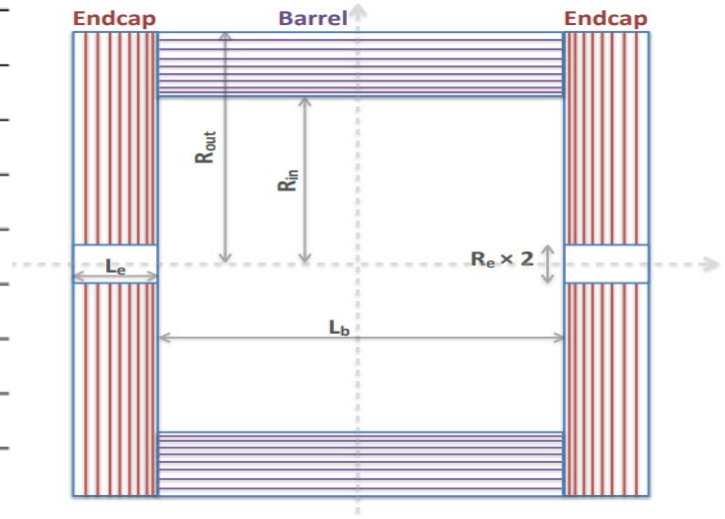
CEPC MUON SYSTEM

- **Muon identification.**
- **Standalone measurements of the muon momenta.**
- **Improve the identification of muons produced inside jets.**
- **Improve the jet energy resolution.**

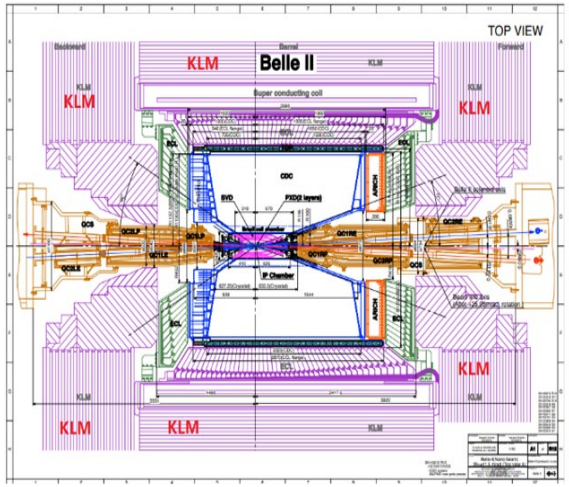
SCINTILLATION DETECTOR:

- Low costs
- High efficiency

Parameter	Baseline
$L_b/2$ [m]	4.14
R_{in} [m]	4.40
R_{out} [m]	6.08
L_e [m]	1.72
R_e [m]	0.50
Segmentation in ϕ	12
Number of layers	8
Total thickness of iron ($\lambda = 16.77$ cm)	6.7λ (112 cm) (8/8/12/12/16/16/20/20) cm
Solid angle coverage	$0.98 \times 4\pi$
Position resolution [cm]	$\sigma_{r\phi}$: 2 σ_z : 1.5
Time resolution [ns]	1 – 2
Detection efficiency ($P_\mu > 5$ GeV)	> 95%
Fake($\pi \to \mu$)@30GeV	< 1%
Rate capability [Hz/cm^2]	~60
Technology	RPC (super module, 1 layer readout, 2 layers of RPC)
Total area [m^2]	Barrel: ~4450 Endcap: ~4150 Total: ~8600



The structure of muon system at CEPC.



The K_L-muon detector(KLM) at Belle II.

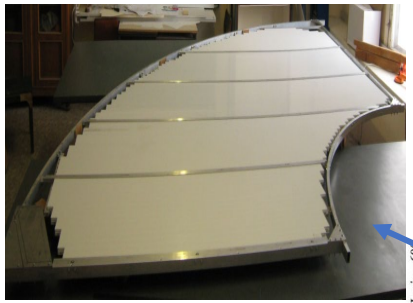
Structure of the current KLM detector

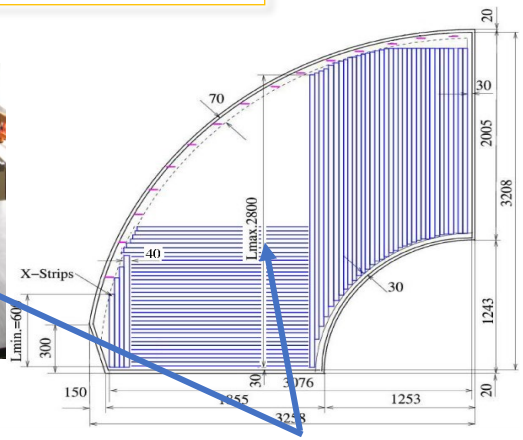
- Scintillator shape is flexible, easy to get good spatial resolution:

$$\sigma = {\text{width}}/{\sqrt{12}}$$

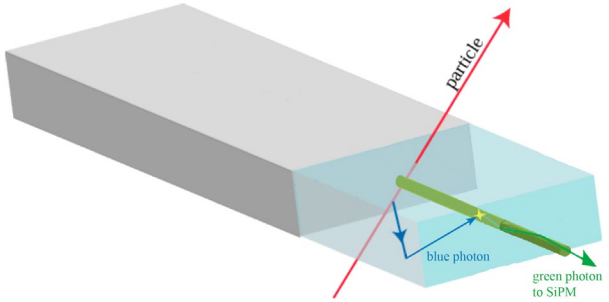
- Wave length shift (WLS) fiber inside scintillator to collect photons and guide them to SiPM.
- Use SiPM at one or both ends, small size, low cost, low operating voltage, high gain and can work at high magnetic field.

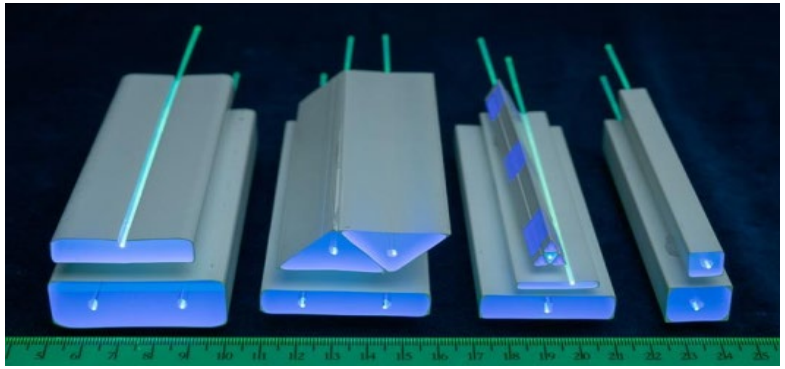
Belle II KLM

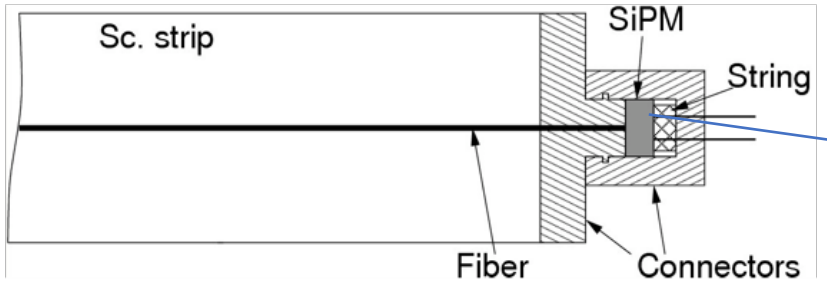


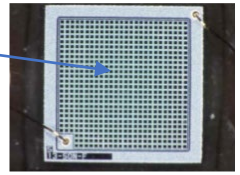


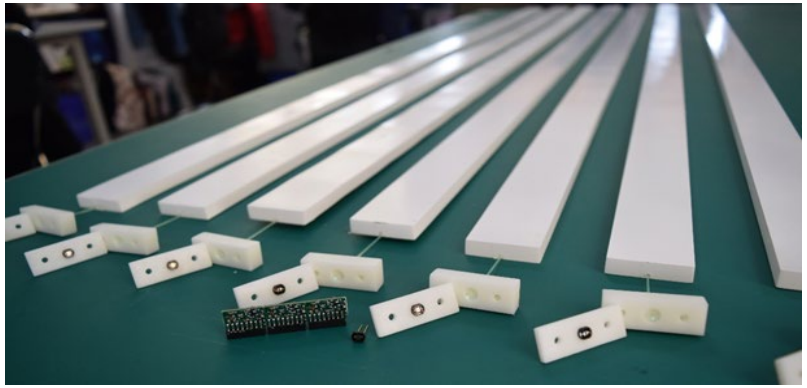
Superlayer for good 2-D resolution





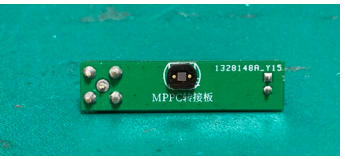


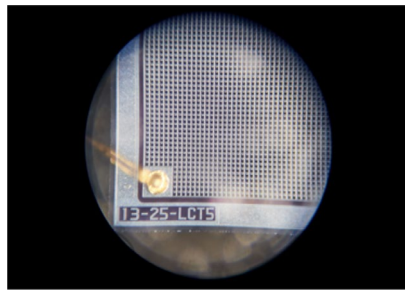




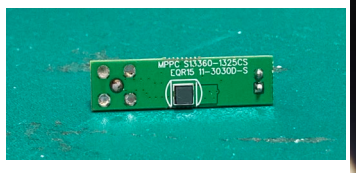
Scintillator + WLS fiber + SiPM

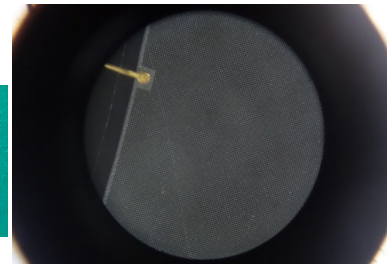
Photoelectron peak test of NDL & MPPC with laser



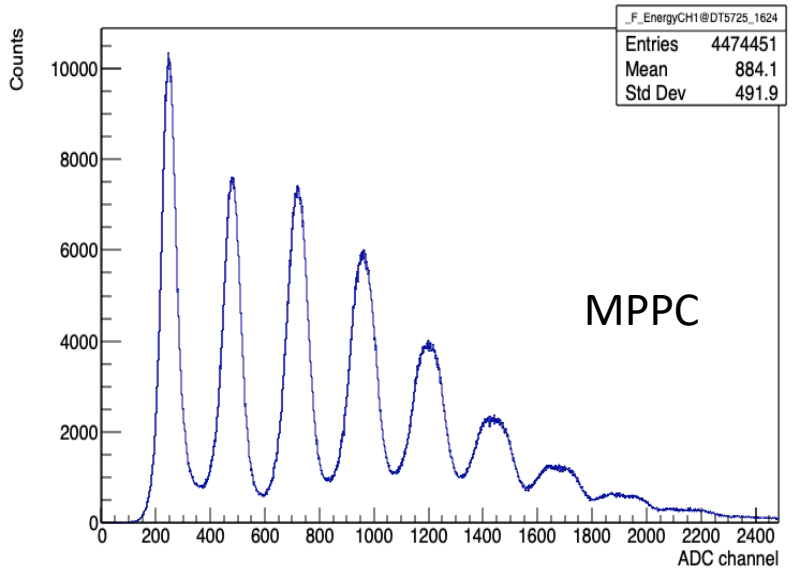


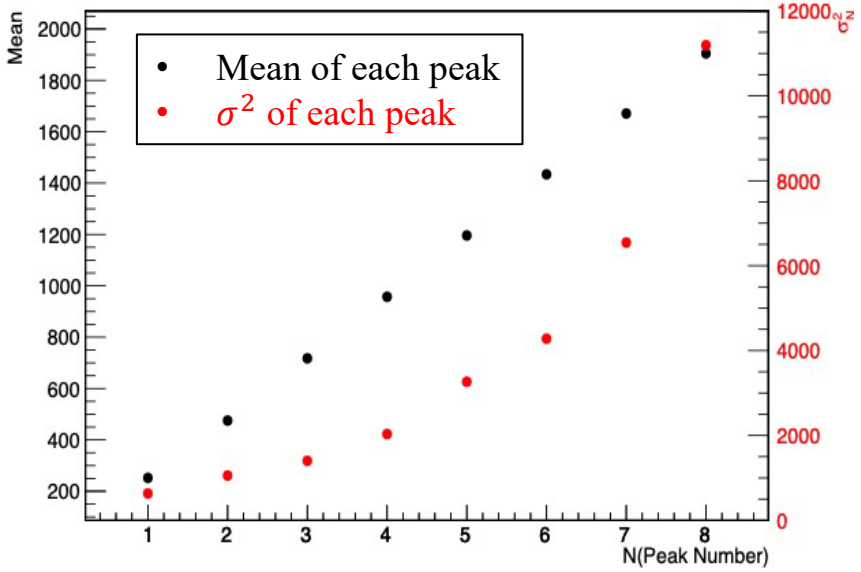
MPPC ($1.3 \times 1.3\ mm^2$)

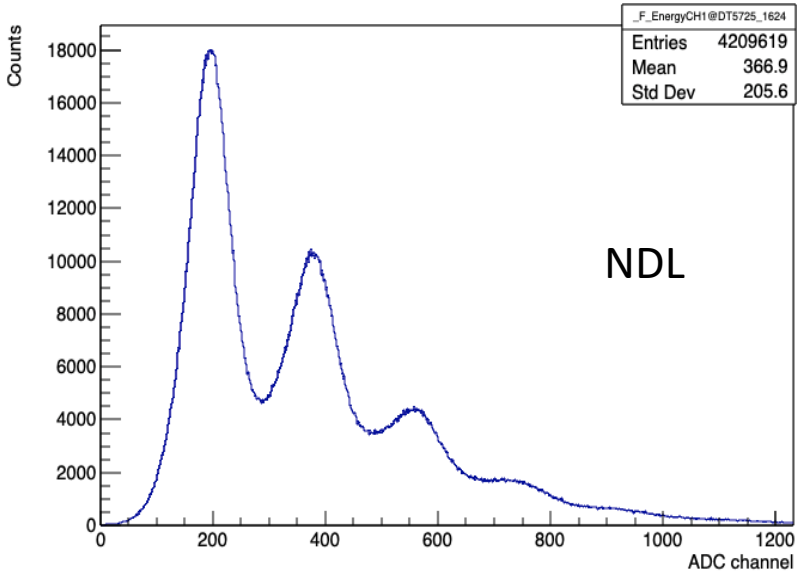


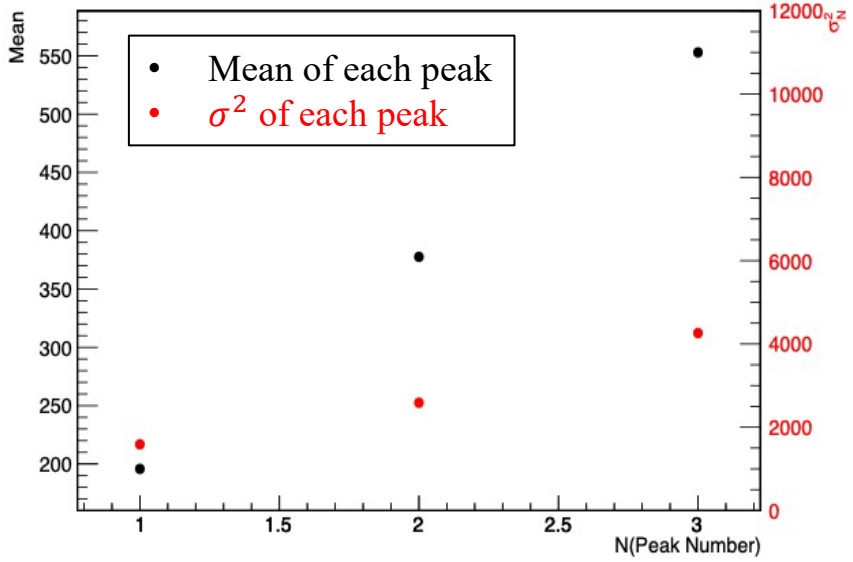


NDL ($3 \times 3\ mm^2$)



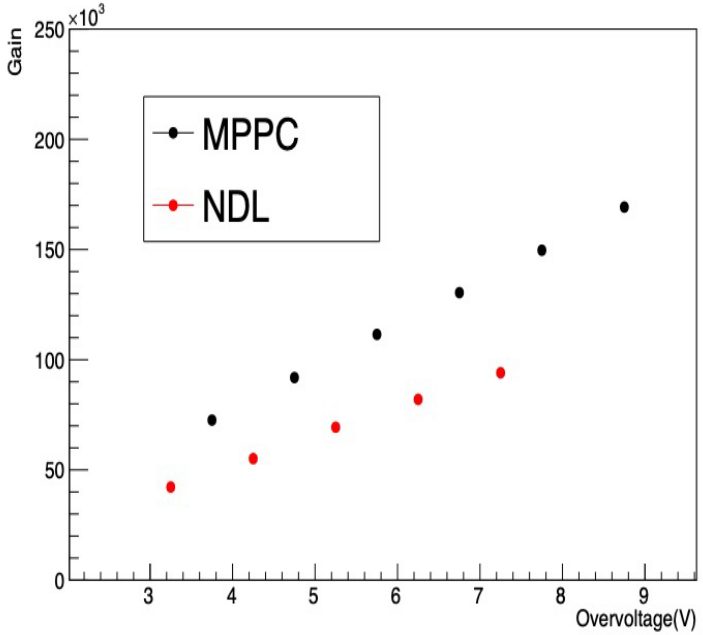




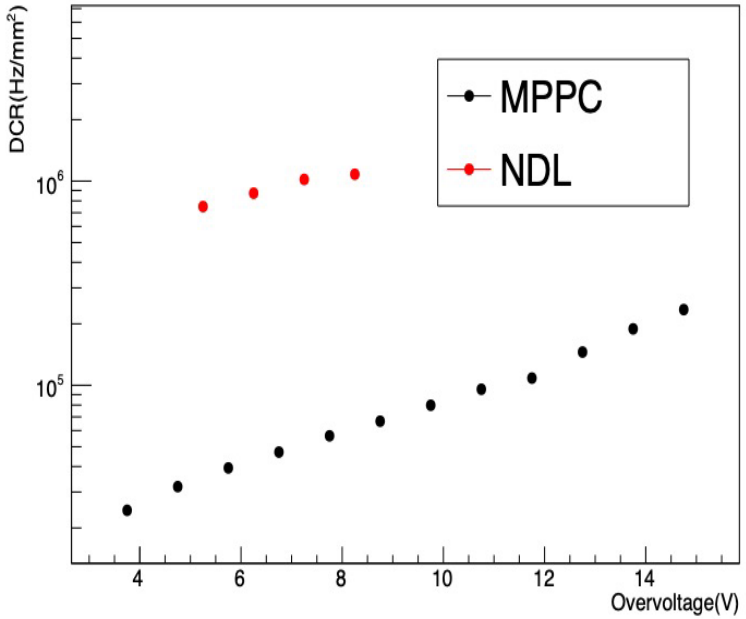


Test of NDL & MPPC

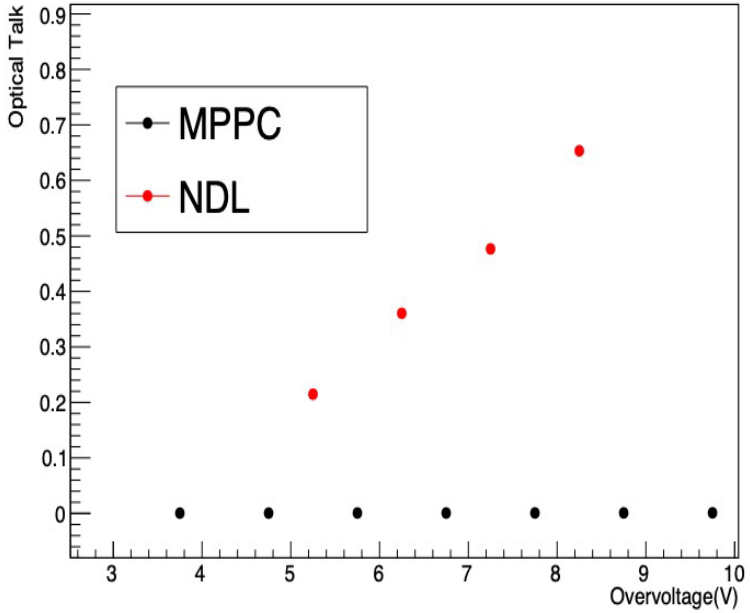
Gain



Dark count



Optical cross talk



NDL:

- Higher dark count rate
- Higher optical cross talk
- Lower Gain

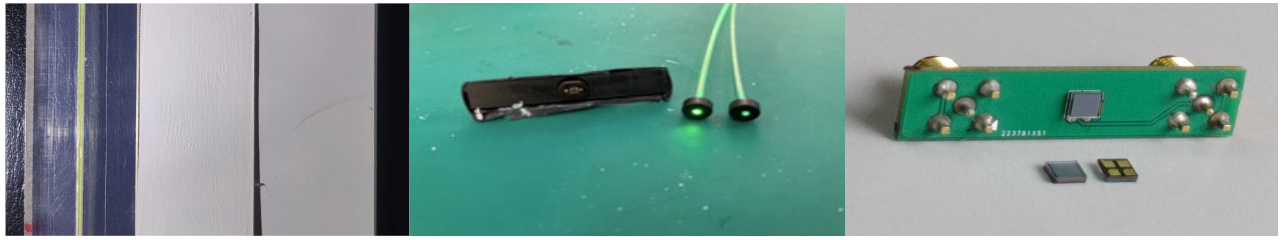
NDL is on developing ……

Test bench

Scintillator with Reflective layer

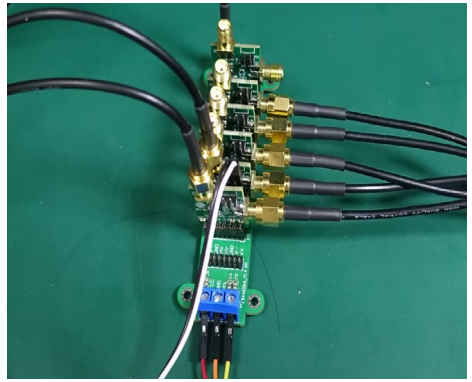
WLS fiber

SiPM

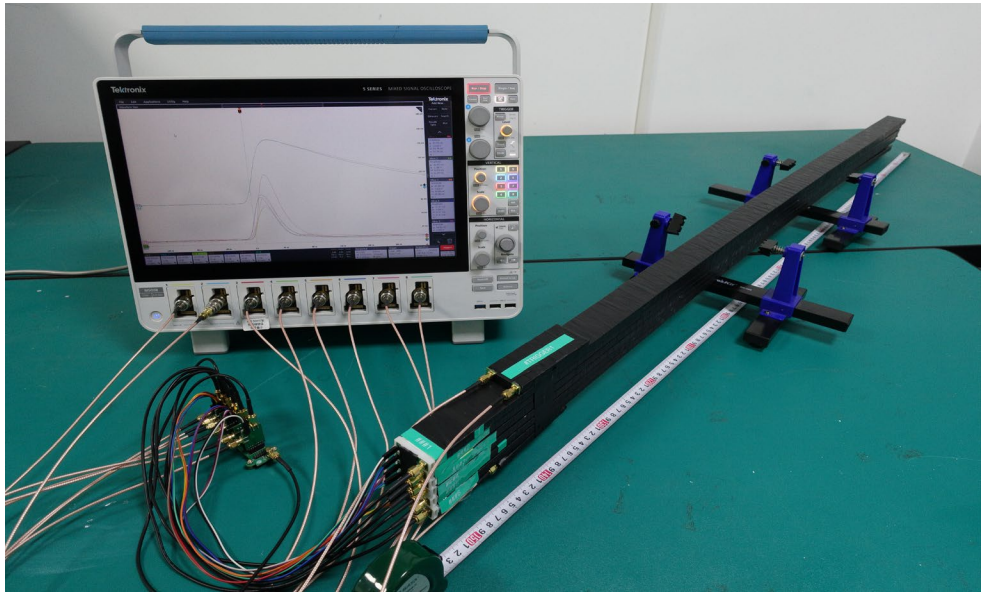


Dark box

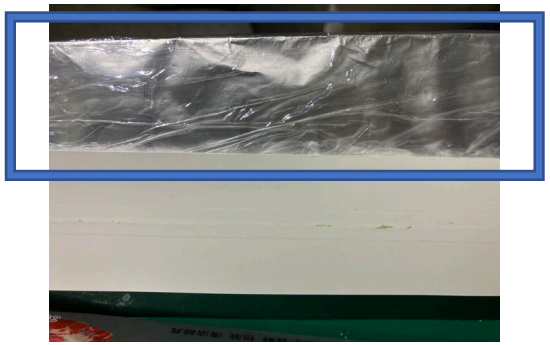
1.5 m scintillation detector



Preamplifier

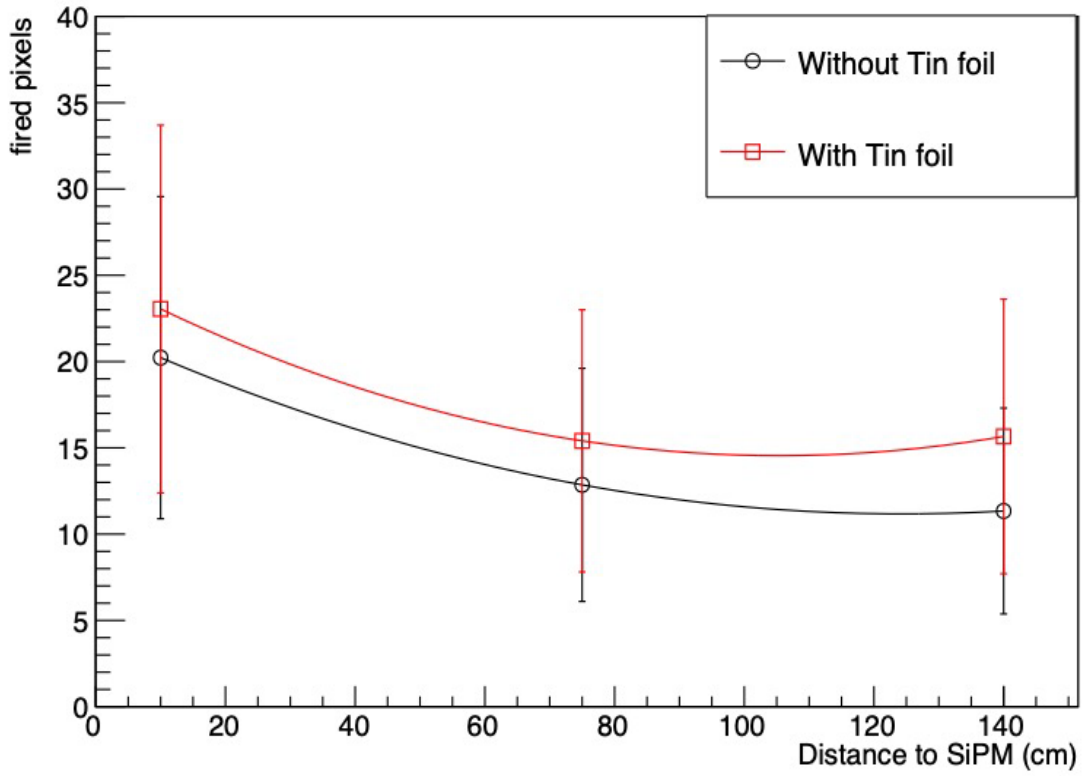


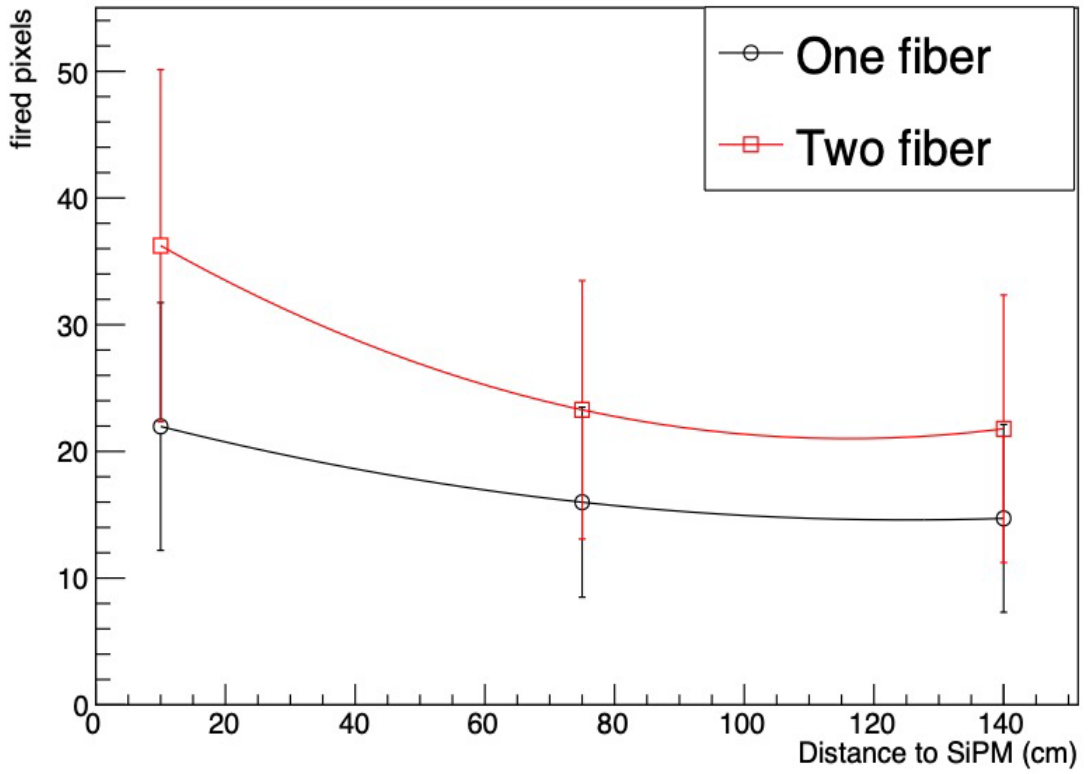
Light collection of scintillator detector



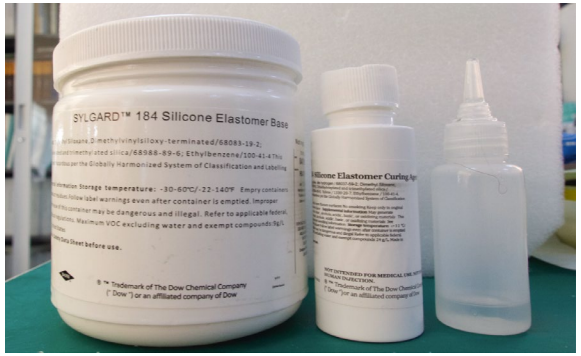
Light collection improved by Tin foil

Adding fiber to improve light collection

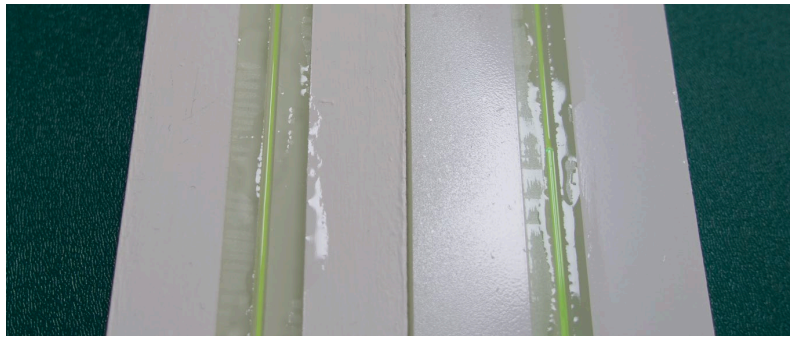




Light collection of scintillator detector

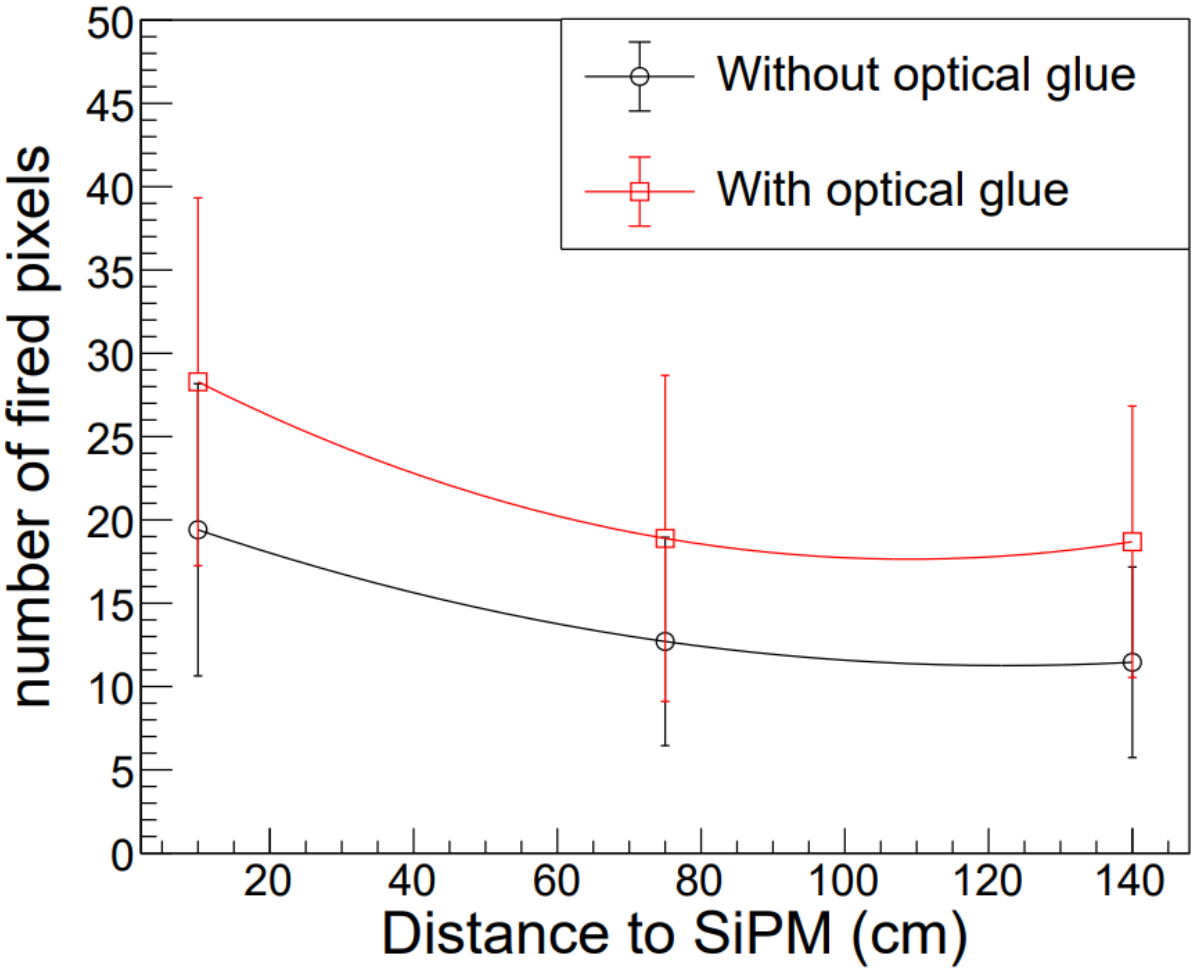


Optical glue： dowcorning 184
(Corrosion-free and light-transparent)

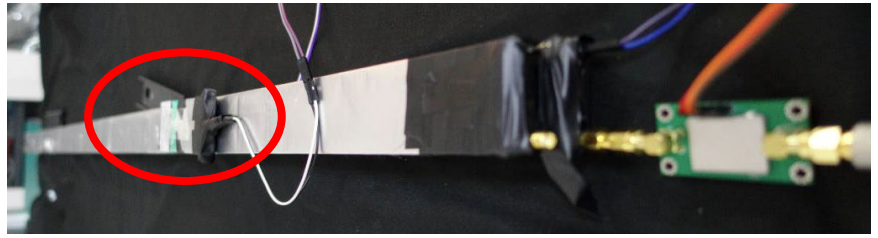


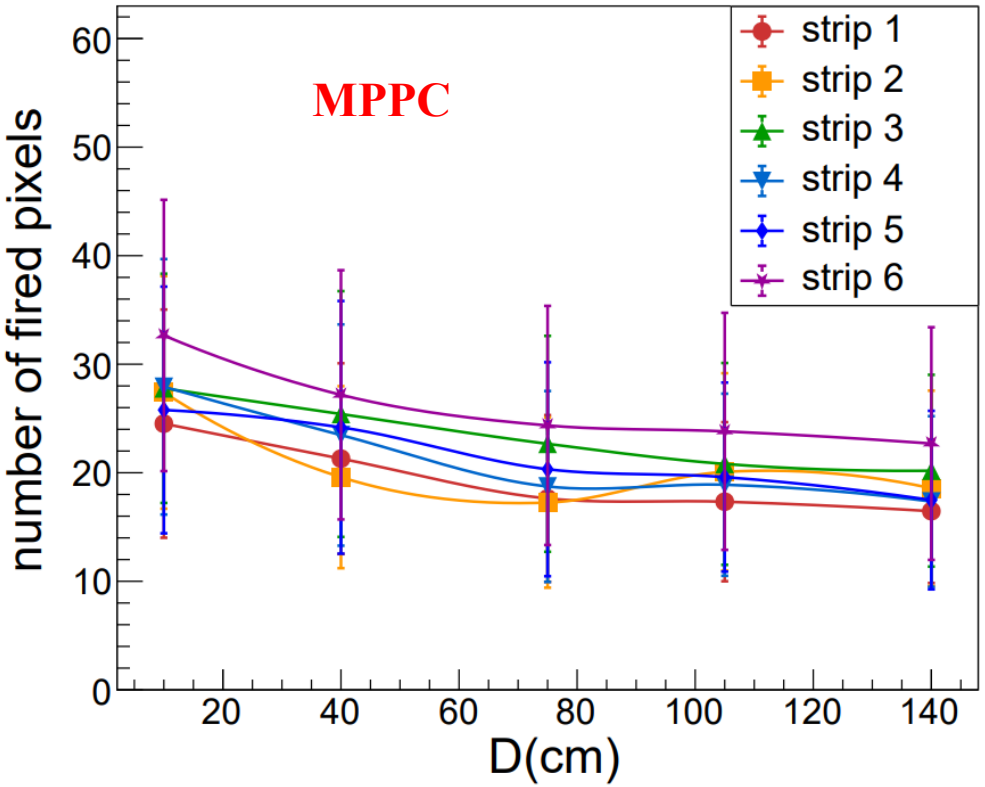
48h room temperature curing

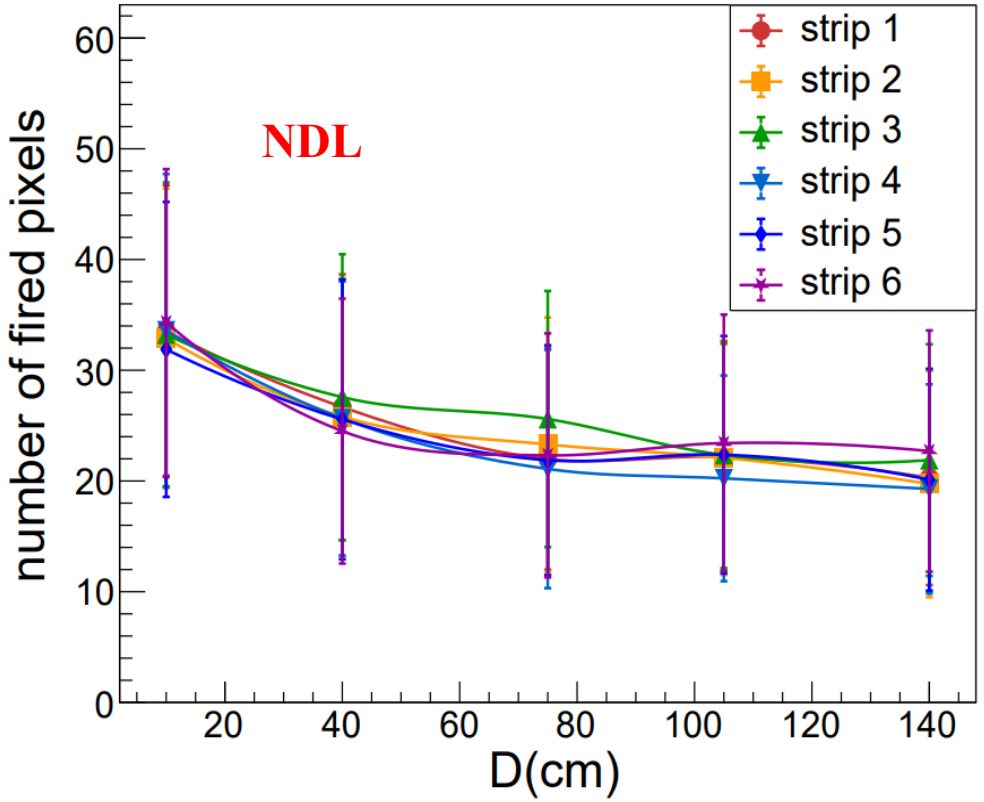
Completely wraps the scintillator to reduce light leakage



Light collection of scintillator detector



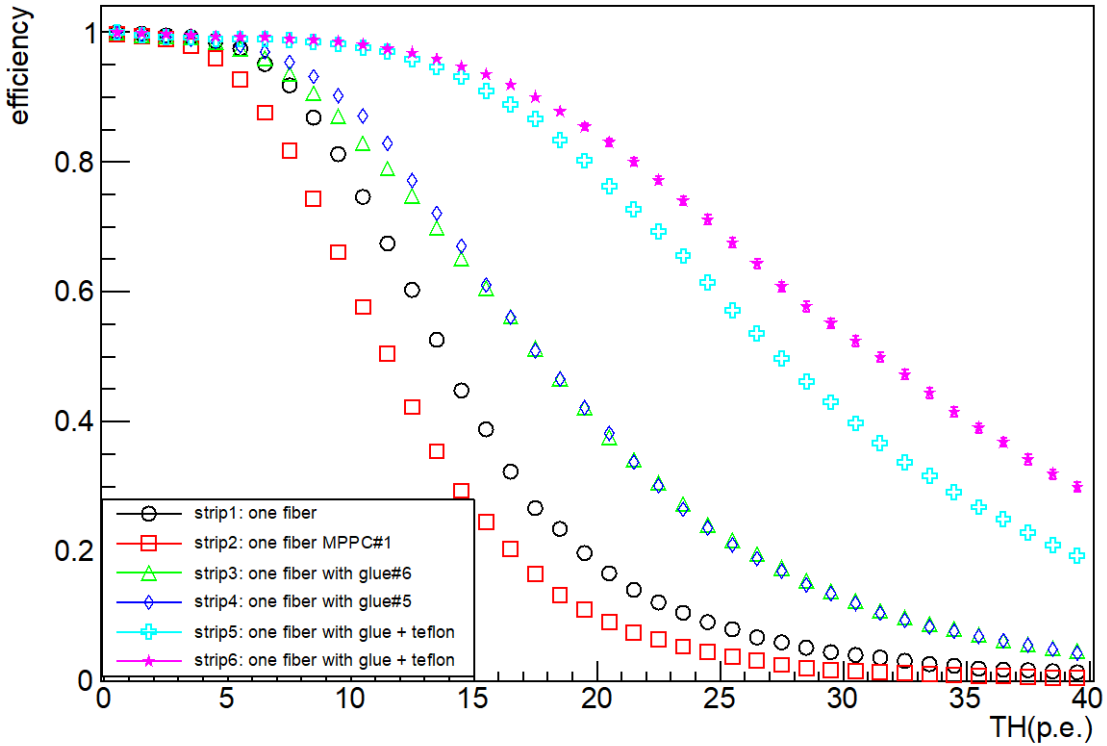


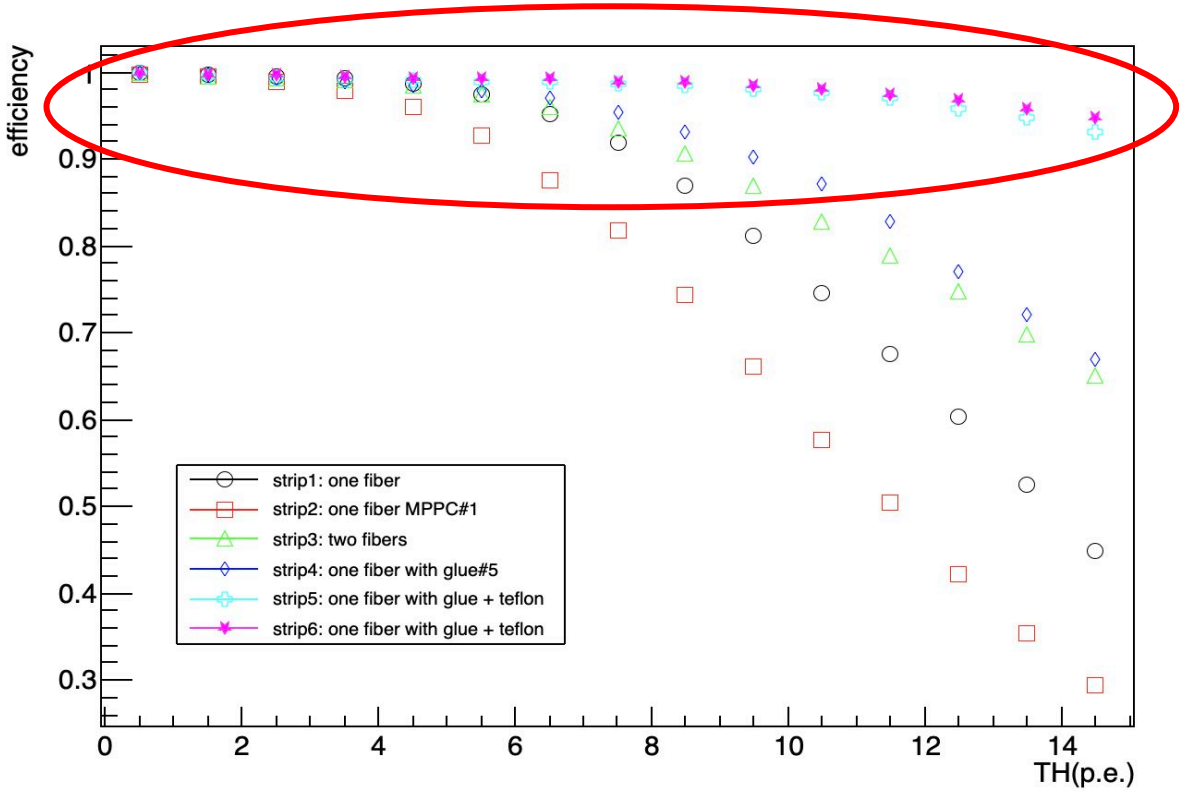


Wavelength-shifting fiber keeps good photon collection at long distance

Efficiency measurement

The efficiency of GNKD_150cm at far end.

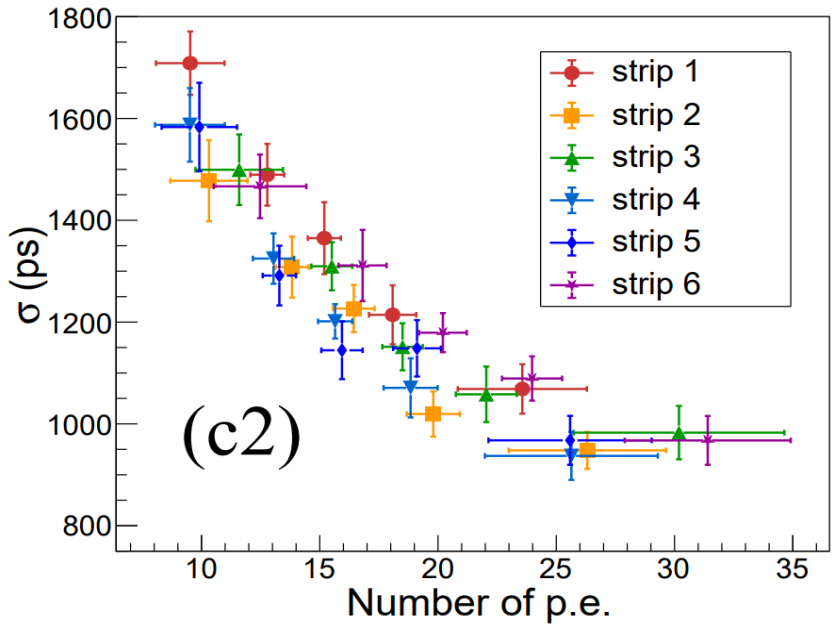


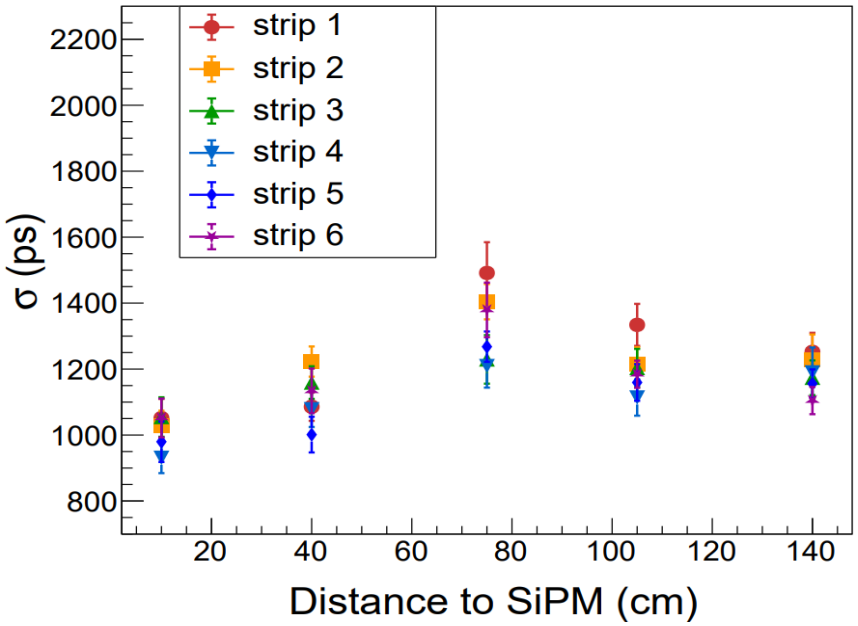


The strips with optical glue and Teflon have highest efficiency, keeping upon 98% at threshold of 10 p.e.

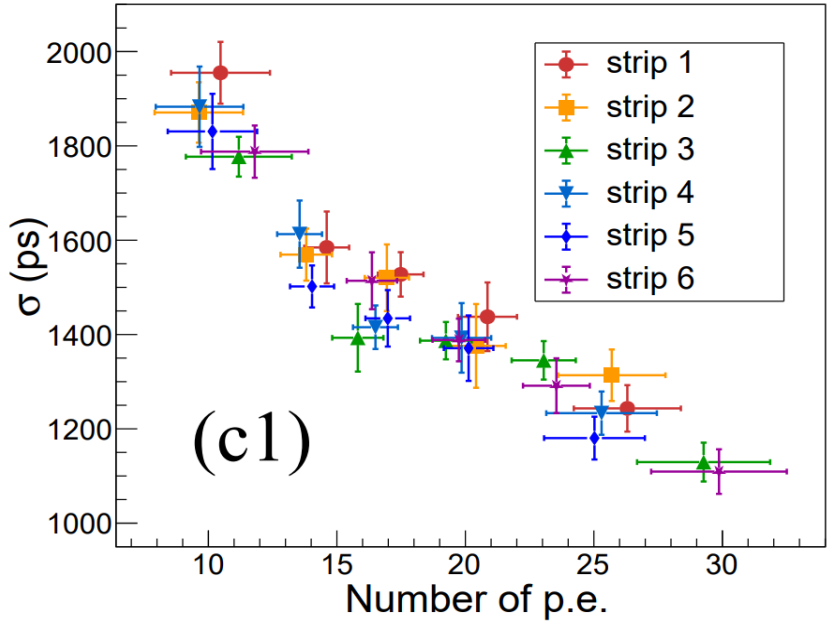
Time resolution test

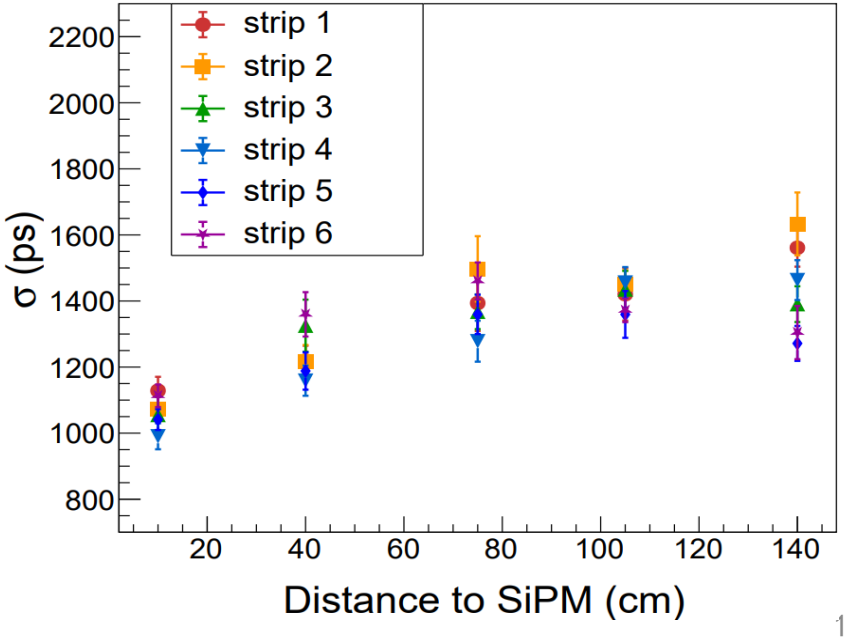
MPPC





NDL

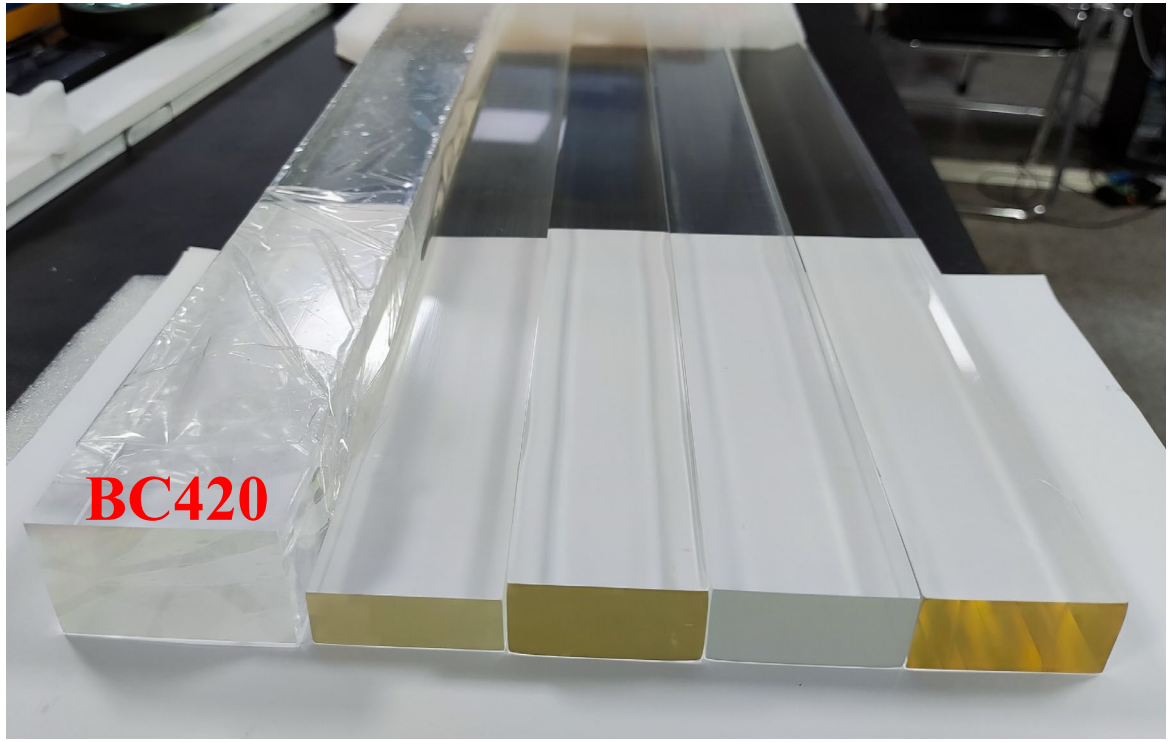




High time resolution scintillator system (TOF-like)

The scintillators and SiPMs

Solid scintillator (no WLS fiber)



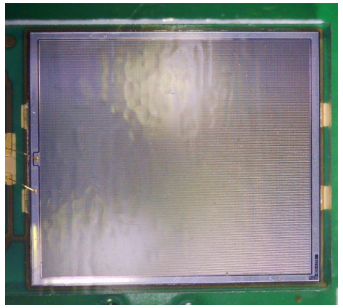
SAINT-GOBAIN

高能科迪 GAONENGKEDI

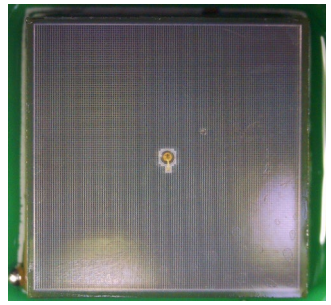
Multiple SiPMs

HAMAMATSU
PHOTON IS OUR BUSINESS

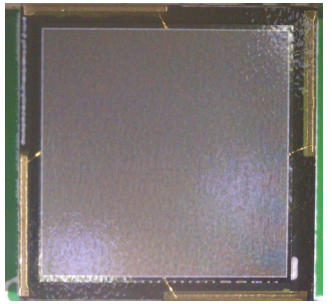
NDL



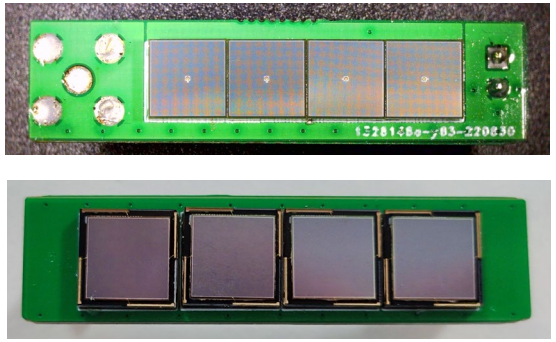
S13360-6025PE



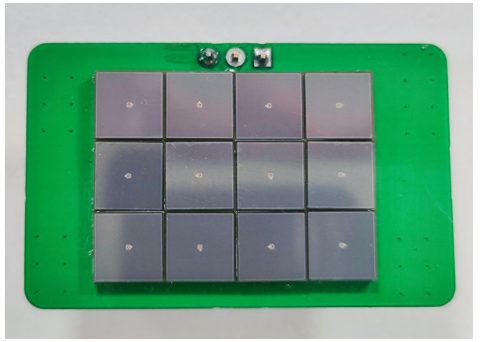
S14160-6050HS



EQR1511-6060D-S



4×SiPM



12×SiPM

➢ Thicker scintillators with longer attenuation lengths and large areas of SiPM can improve photon collection.

Influencing factors of time resolution

- Coincidence time resolution（CTR）

$$CTR \propto \sqrt{\tau_{d/n_p}}$$

τ_d: scintillation decay time

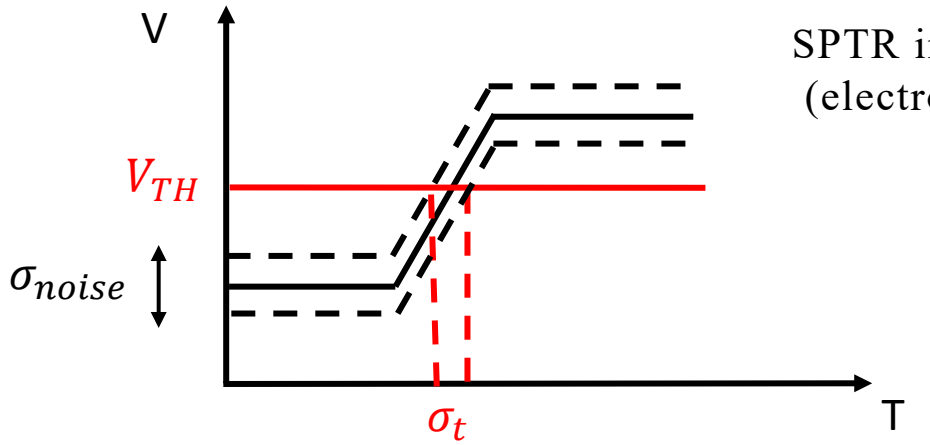
n_p: the number of photons detected

- the contribution of electronic noise on SPTR[2]:

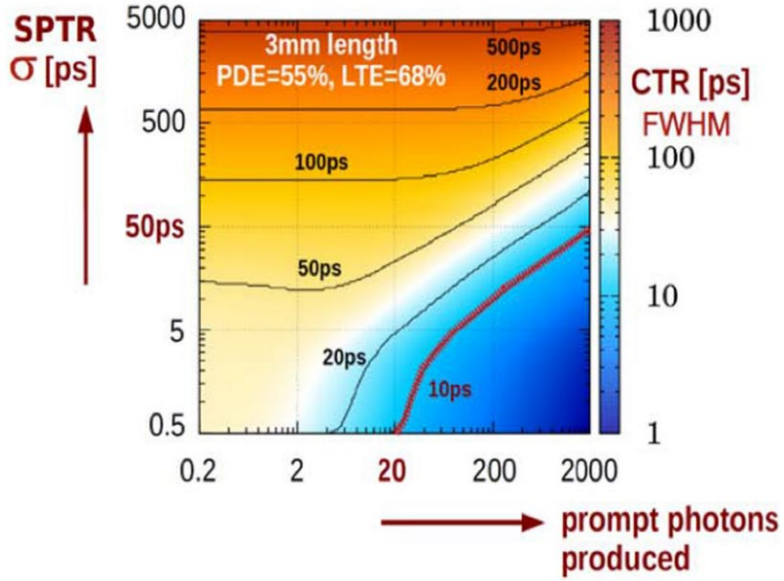
$$\sigma_t = \frac{\sigma_{noise}}{dV/dt}$$

σ_{noise} : the RMS of baseline noise

dV/dt : The slope of single photon waveforms



SPTR influenced by:
(electronics、SiPM)



single photon time resolution (SPTR)[1]

scintillator：3mm length LSO:Ce,Ca(0.4%) crystal

To improve CTR of scintillator:

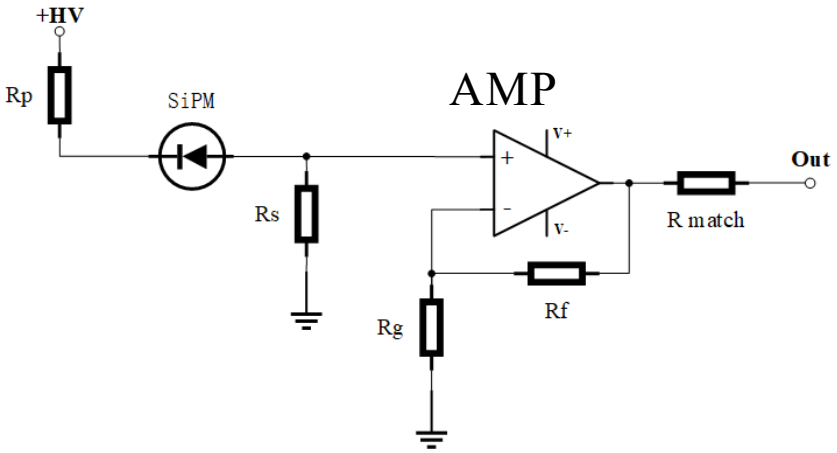
- Reduction of electronic noise
- Selection of scintillators --short decay time
- Increase photon number collection (high light yield)

- Improve the rise time → High bandwidth, high swing rate (>350MHz)
- Readout electronics noise reduction → Low-noise transistors, filter circuits* (<1mV)

[1]Stefan Gundacker, ect Measurement of intrinsic rise times for various L(Y)SO and LuAG scintillators with a general study of prompt photons to achieve 10 ps in TOF-PET[J],2016,61(7).

[2]Joshua W Cates,ect Improved single photon time resolution for analog SiPMs with front end readout that reduces influence of electronic noise[J],2018,63(18).

Design of preamplifier



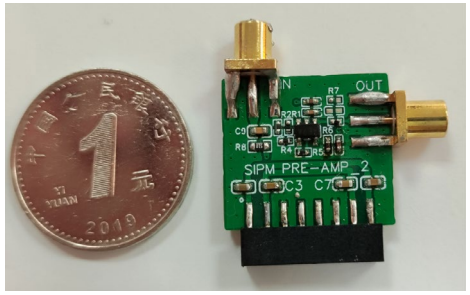
Gain：+20 V/V

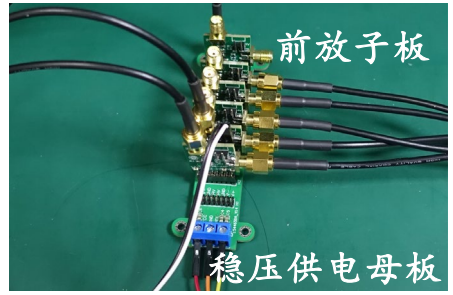
Bandwidth(-3dB)：400 MHz

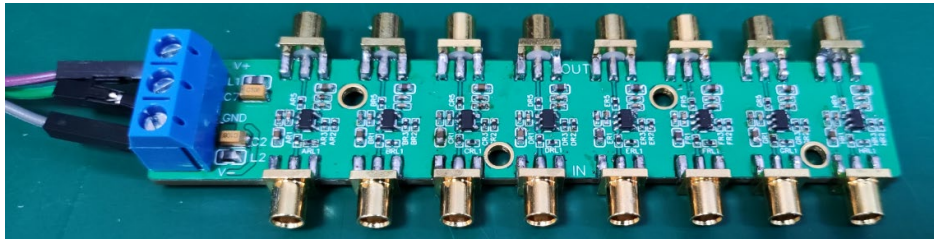
Baseline noise(RMS): 300uV

Input impedance: 50Ω

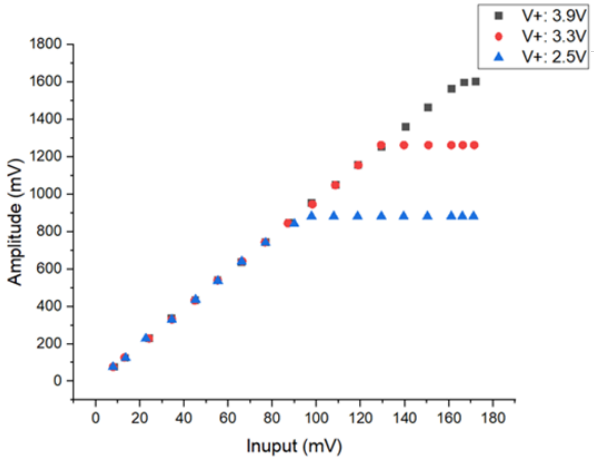
Cost :30 ¥/Ch

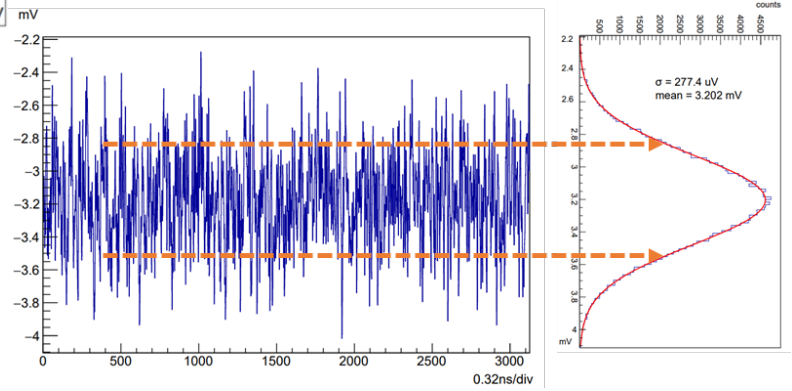


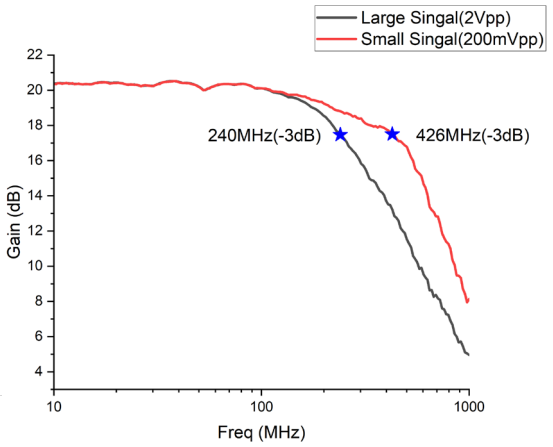


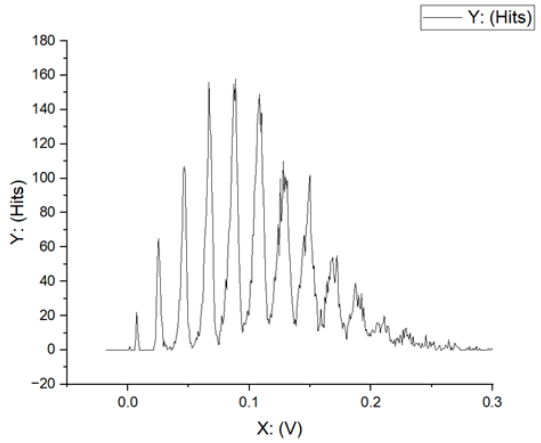


➢ Performance test of preamplifier



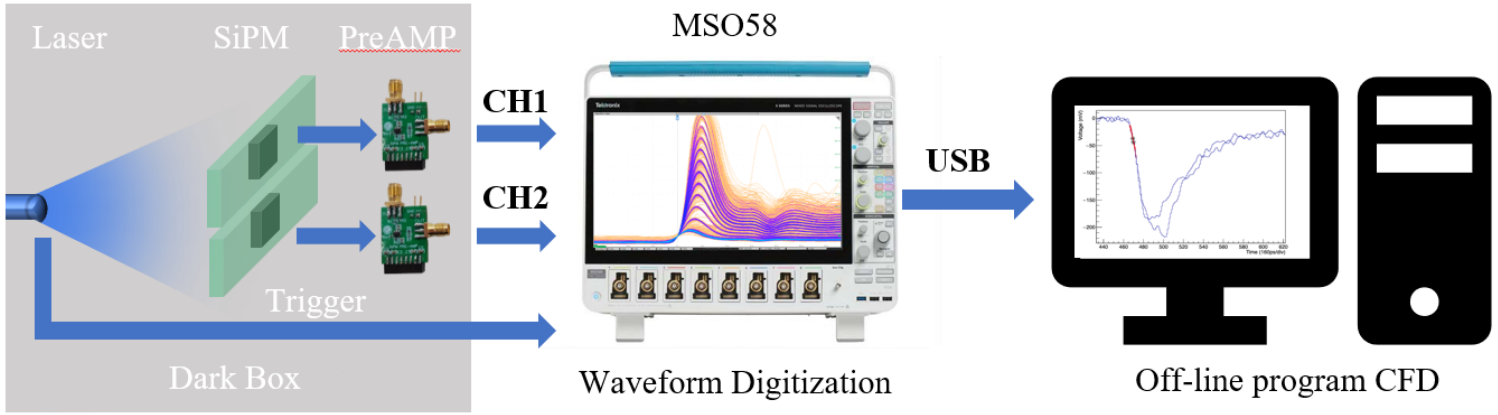


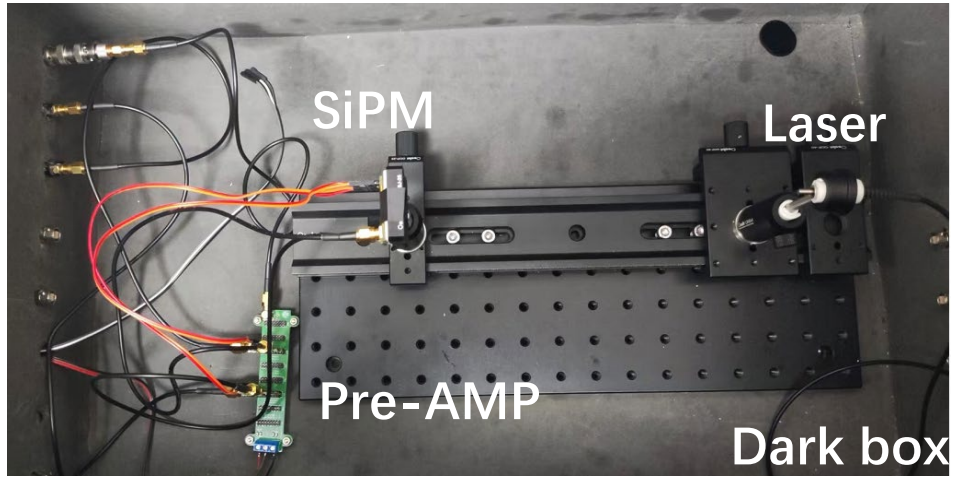




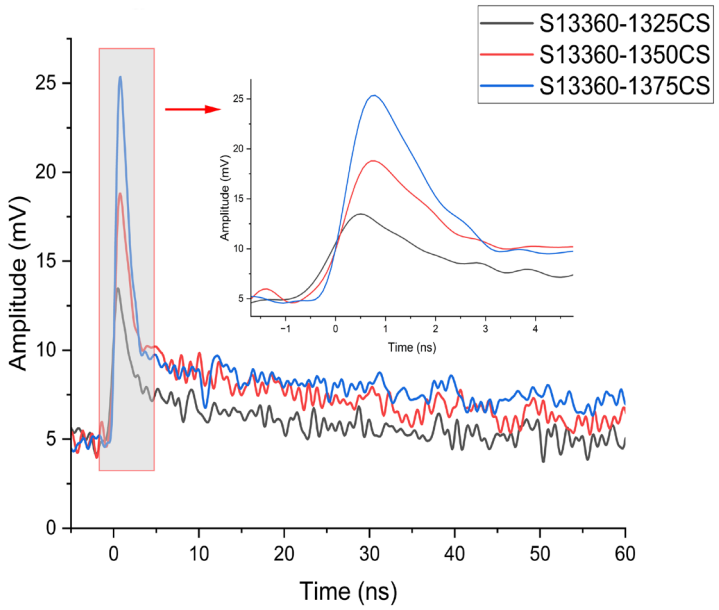
- Dynamic range testing
- Baseline noise test
- Bandwidth testing
- SiPM photoelectron peak

SiPM time resolution test

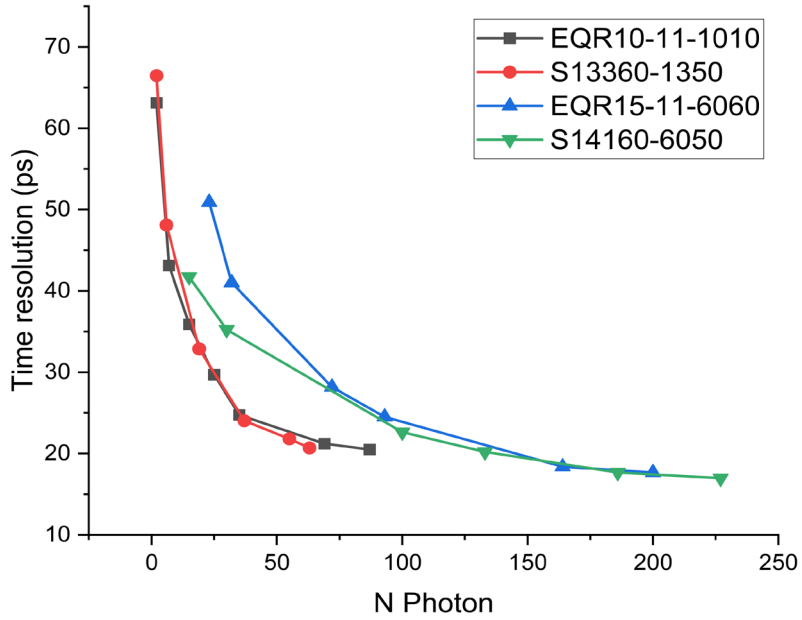




Time resolution test setup



Single photon signal of SiPMs

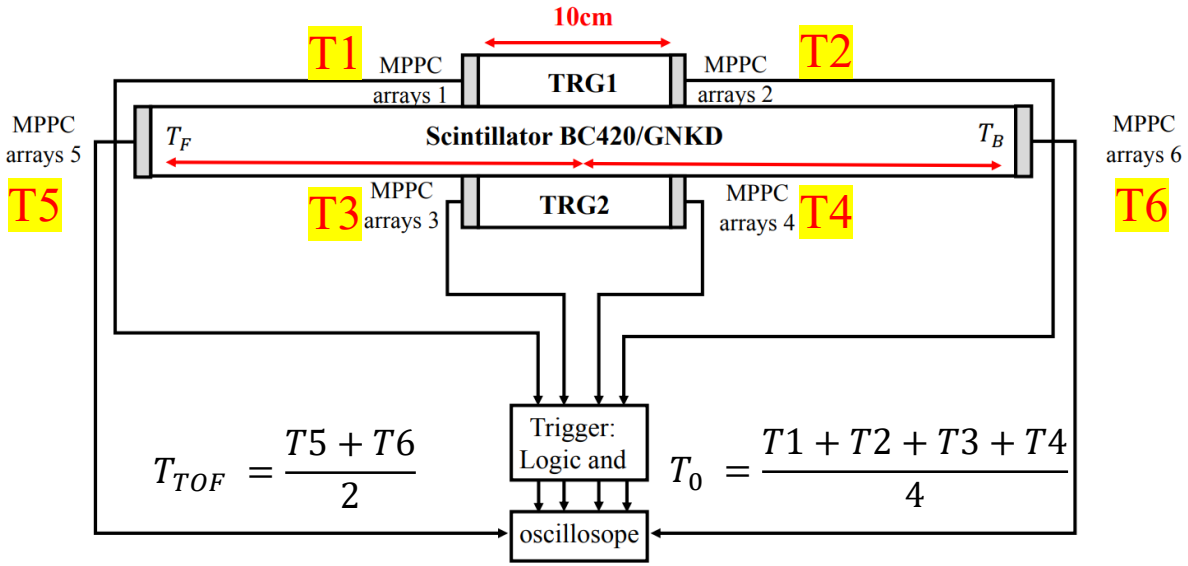


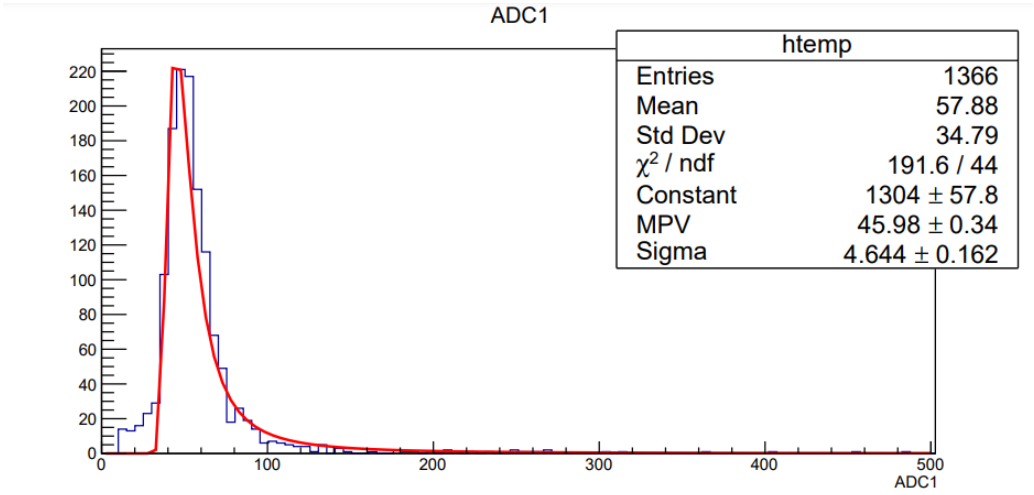
Time resolution varies with the number of photons

Small area: (1×1 mm^2 / 1.3×1.3 mm^2)
Photons > 5 , Time resolution < 50ps
Photons > 40 , Time resolution < 25ps

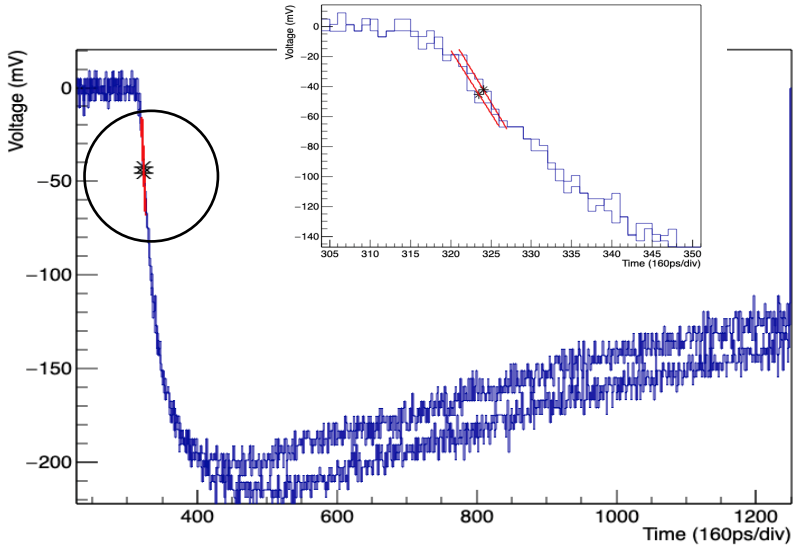
Large area: (6×6 mm^2)
Photons > 20 , Time resolution < 50ps
Photons > 70 , Time resolution < 25ps

Plastic scintillator test using cosmic rays



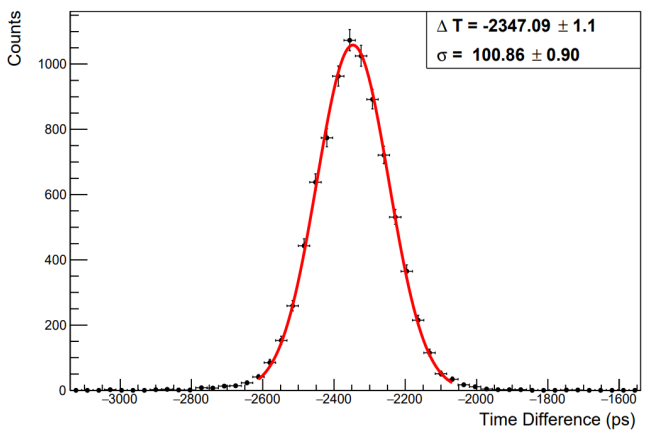


Energy spectrum of cosmic rays



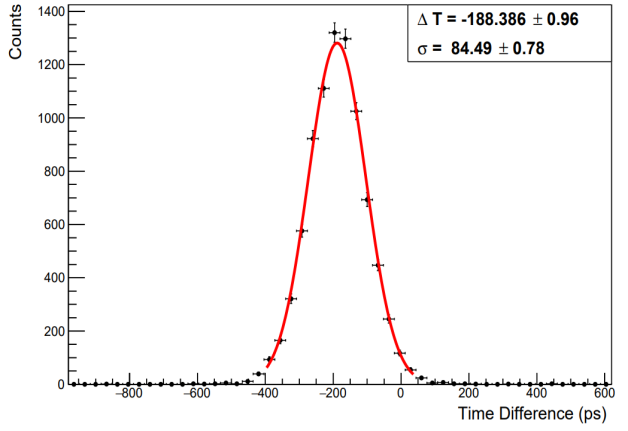
CFD timing of waveform

$$\frac{T1+T2}{2} - \frac{T3+T4}{2} \rightarrow \sigma_{TRG} \rightarrow \sigma_{T_0}$$



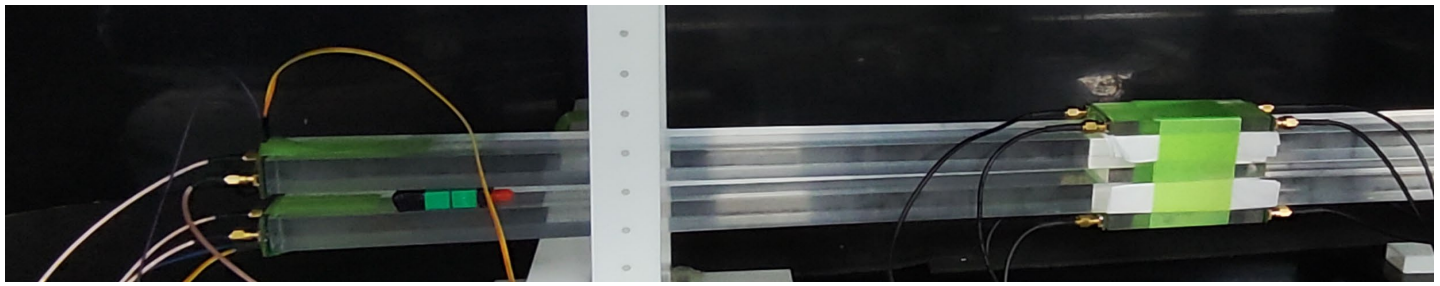
$\sigma_{TRG} = 100.8\text{ps}$ $\sigma_{T_0} = 50.4\text{ps}$

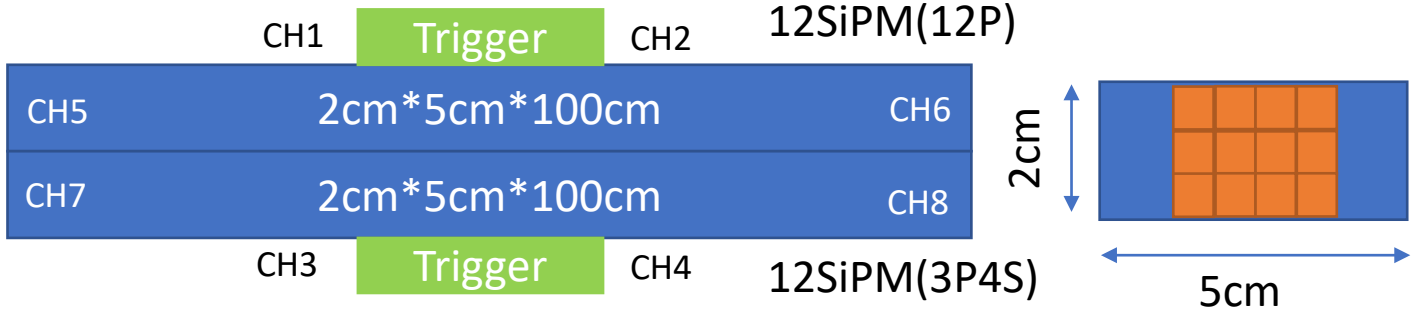
$$T_0 - T_{TOF} \rightarrow \sigma_{T_{TOF}}$$

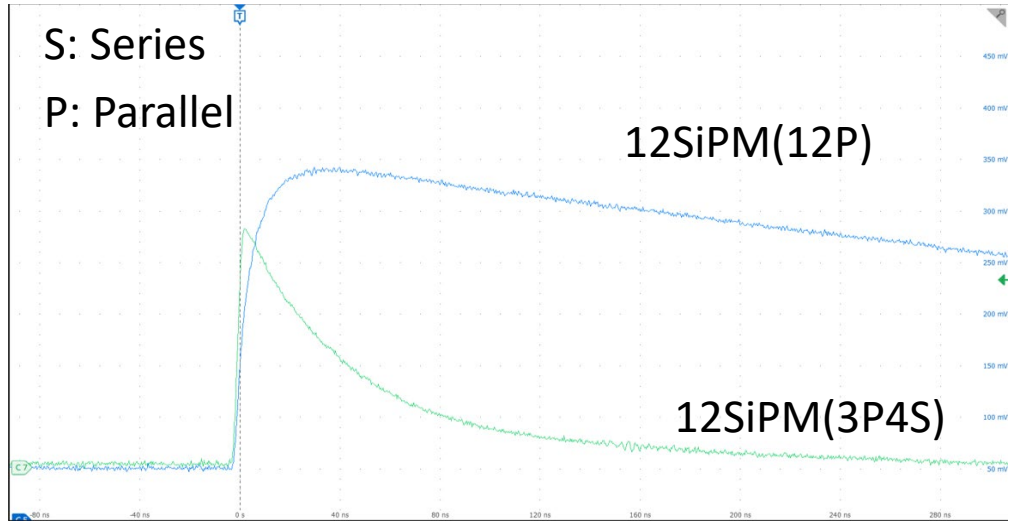


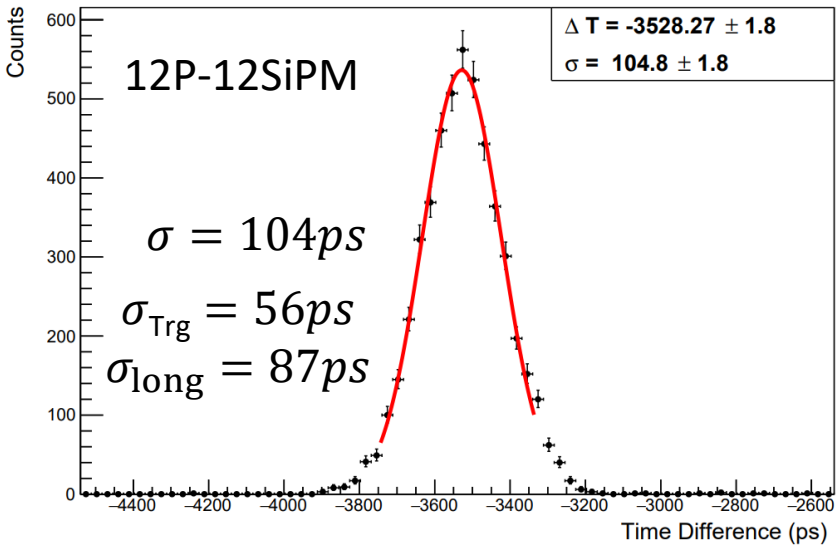
$\sigma_{T_{TOF}} = 67.5\text{ps}$

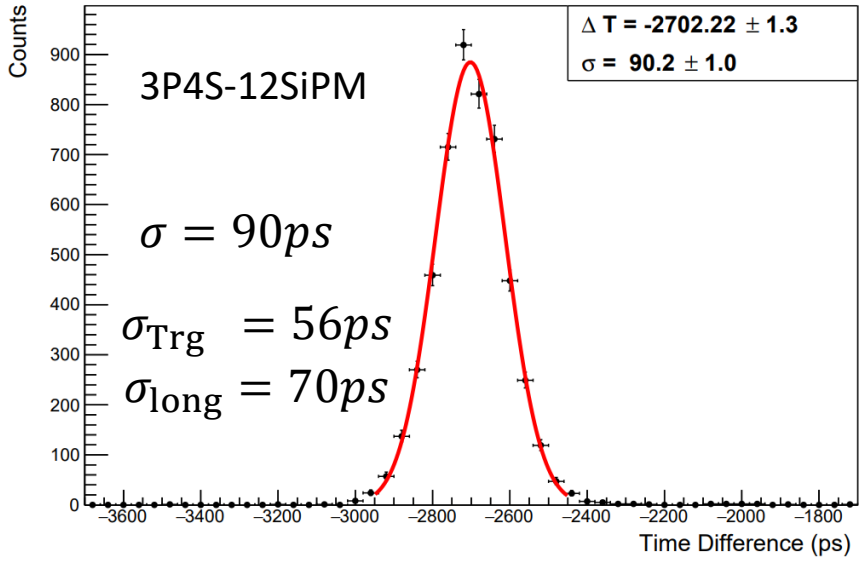
Time resolution of long strip: GNKD_new(2cm)

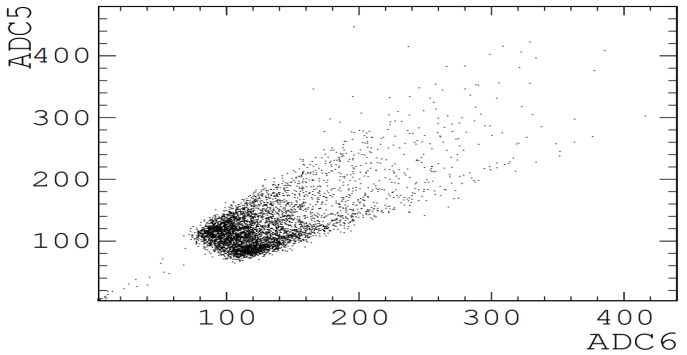


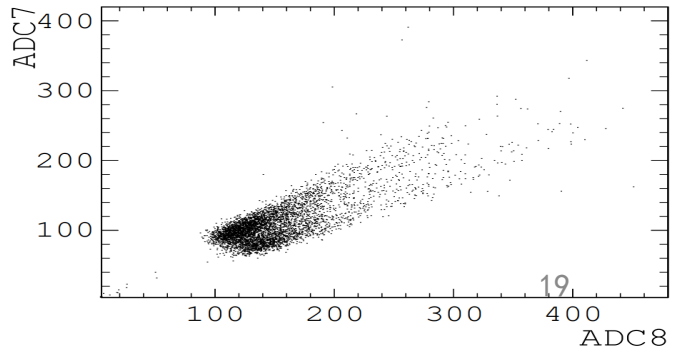




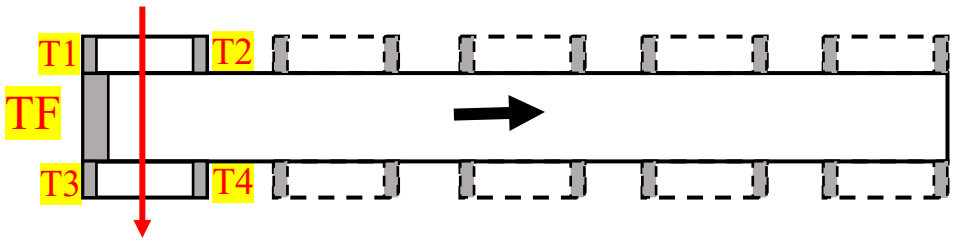




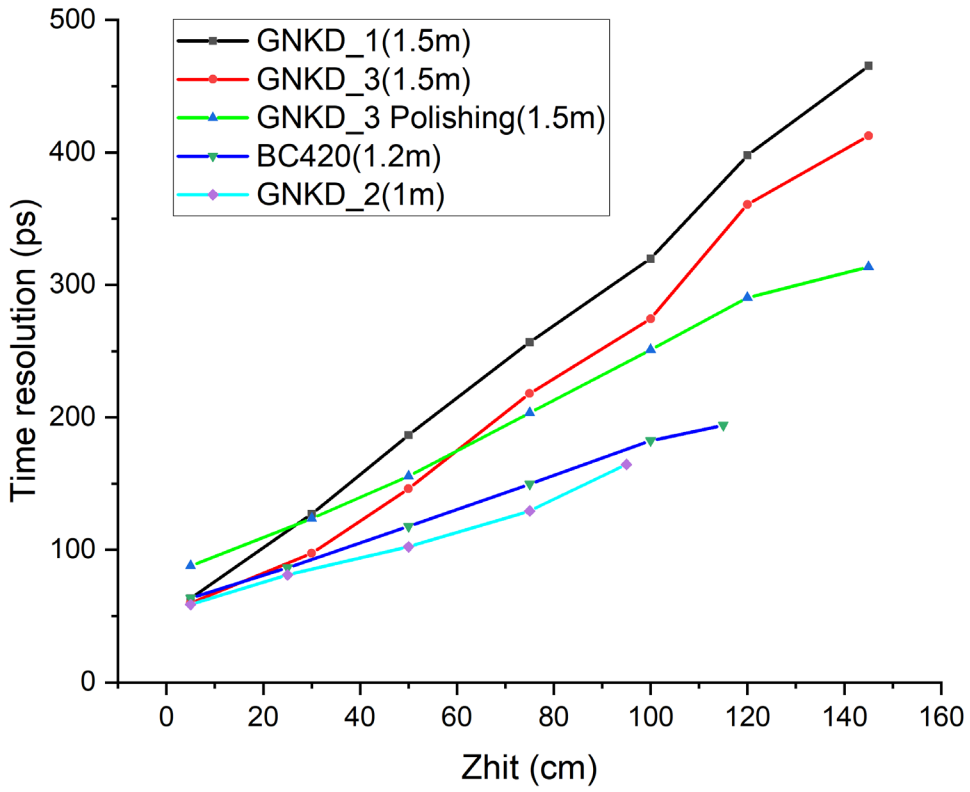




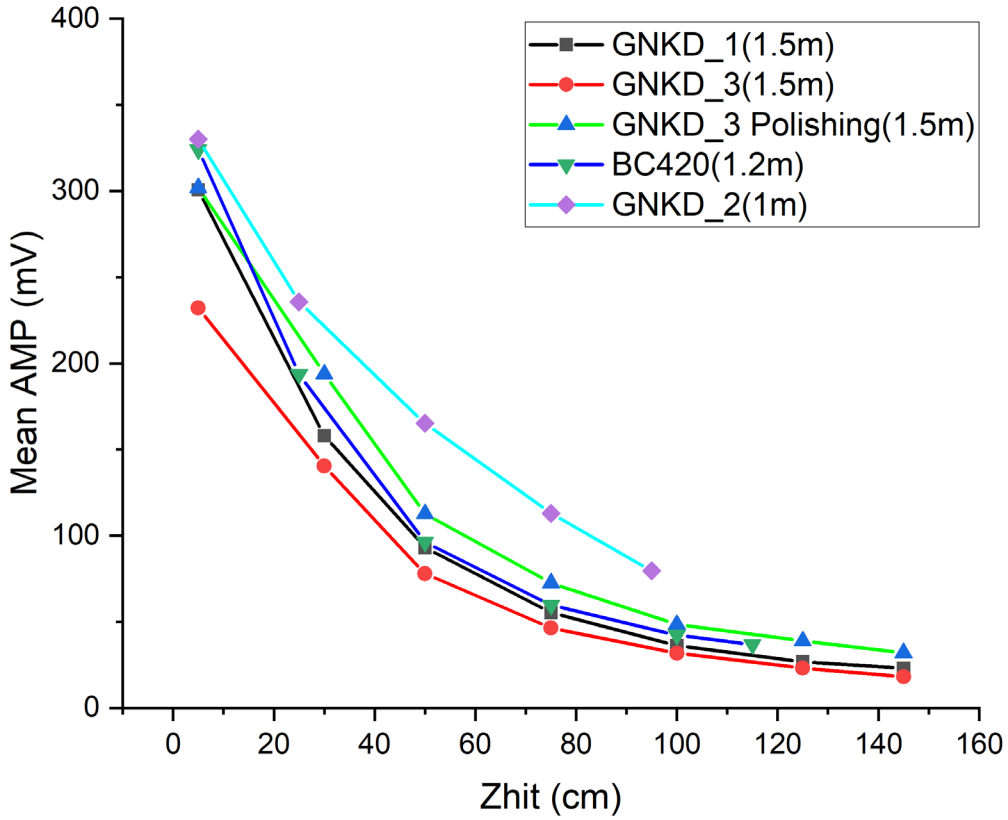
Time resolution test for different position(single-ended)



➢ Change the location of the trigger,
we can get the time resolution of different position.



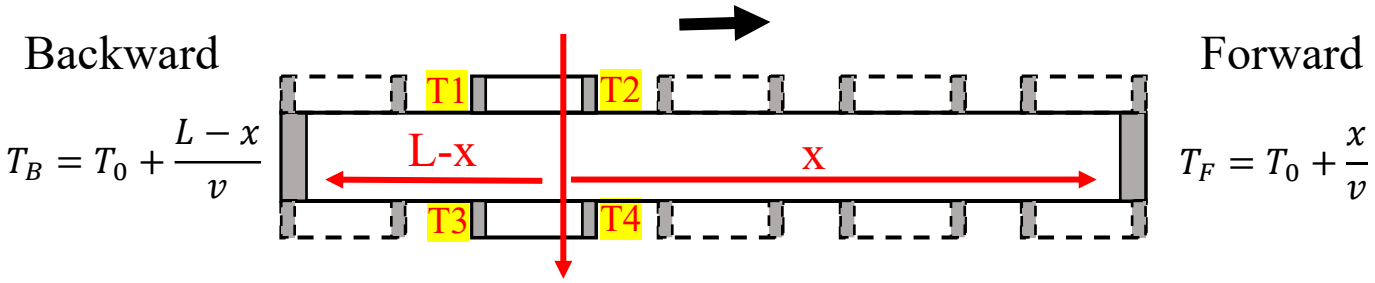
Time resolution of different positions of scintillator



Signal amplitude at different locations of the scintillator

➢ Less light collection at the far end makes the SNR smaller, resulting in worse time resolution.

Time resolution test for different position(both averaged)



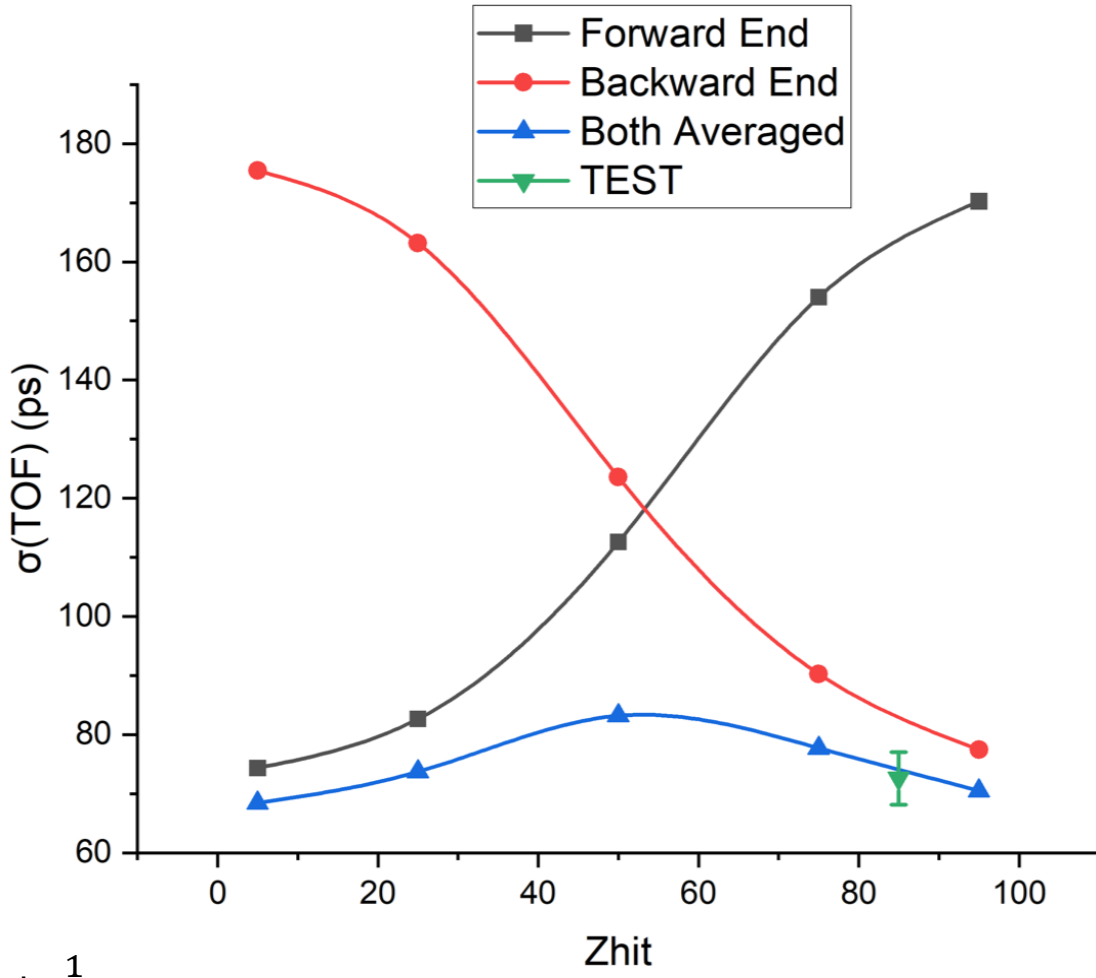
Unweighted:

$$T_{s.c.} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v} \qquad \sigma^2_{s.c.} = (\sigma_F^2 + \sigma_B^2)/4$$

Weighted average:

$$T_{s.c.} = \frac{T_F/\sigma_F^2 + T_B/\sigma_B^2}{1/\sigma_F^2 + 1/\sigma_B^2} \qquad \frac{1}{\sigma^2_{s.c.}} = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$$

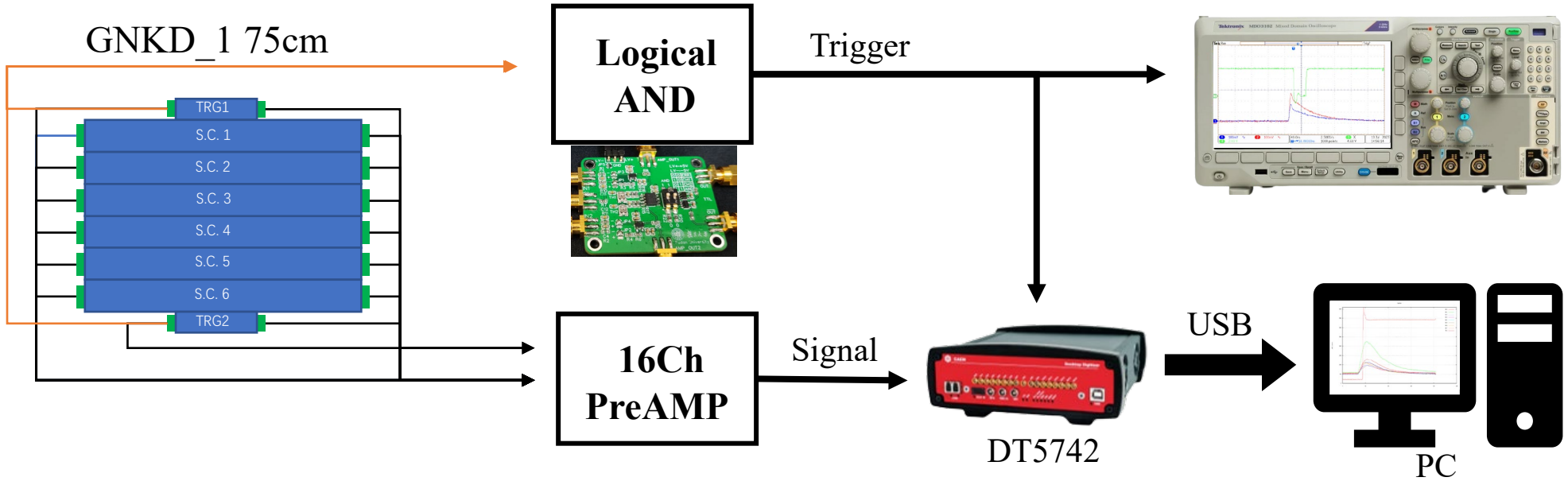
$T_{s.c.}$ related to hit position 'x'



Both Averaged Calculated by the error transfer formula $\frac{1}{\sigma^2_{s.c.}} = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$.

TEST Reduce the length of the Trigger (1cm) to reduce the 'x' uncertainty.

Prototype Test



DT5742

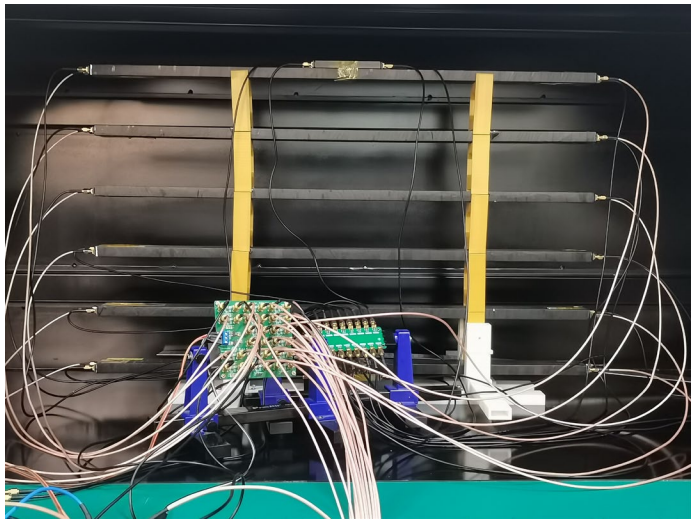
DRS4 chip

16 + 1 channel

12 bit @ 5 GS/s

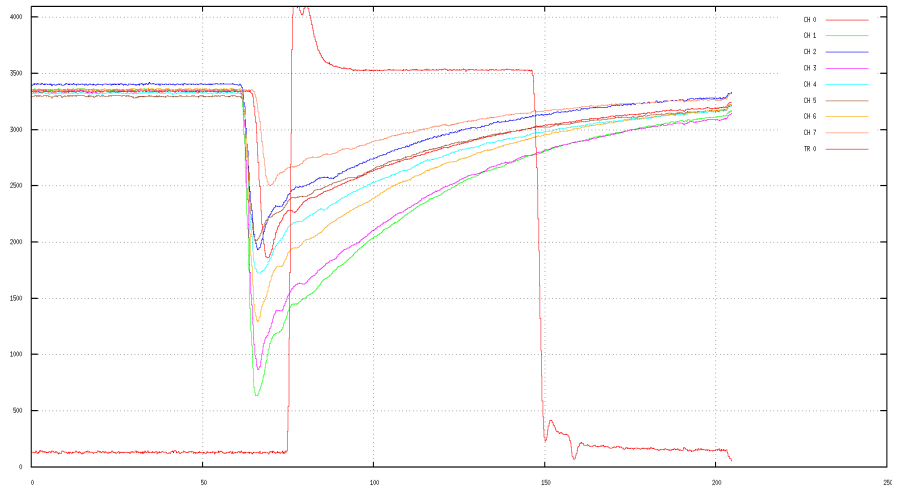
BW: 500 MHz

-1.5V ~ +1.5V



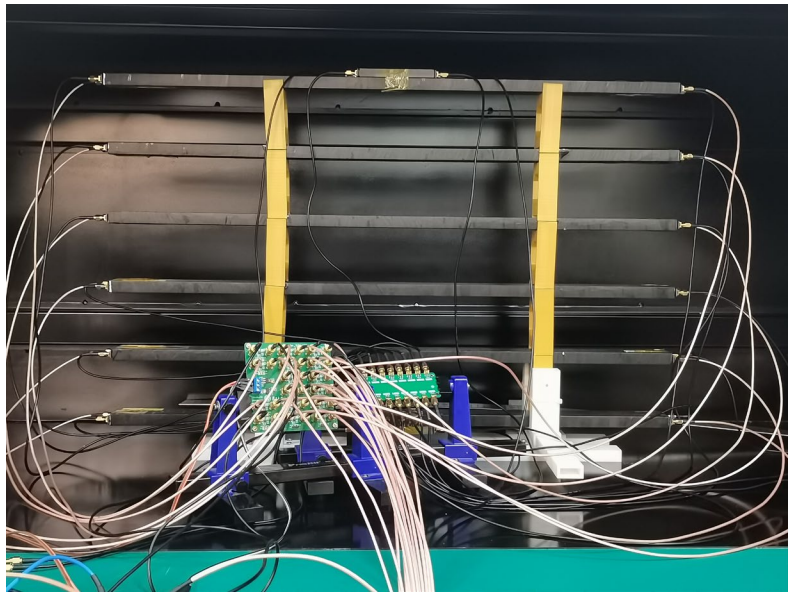
Prototype test setup

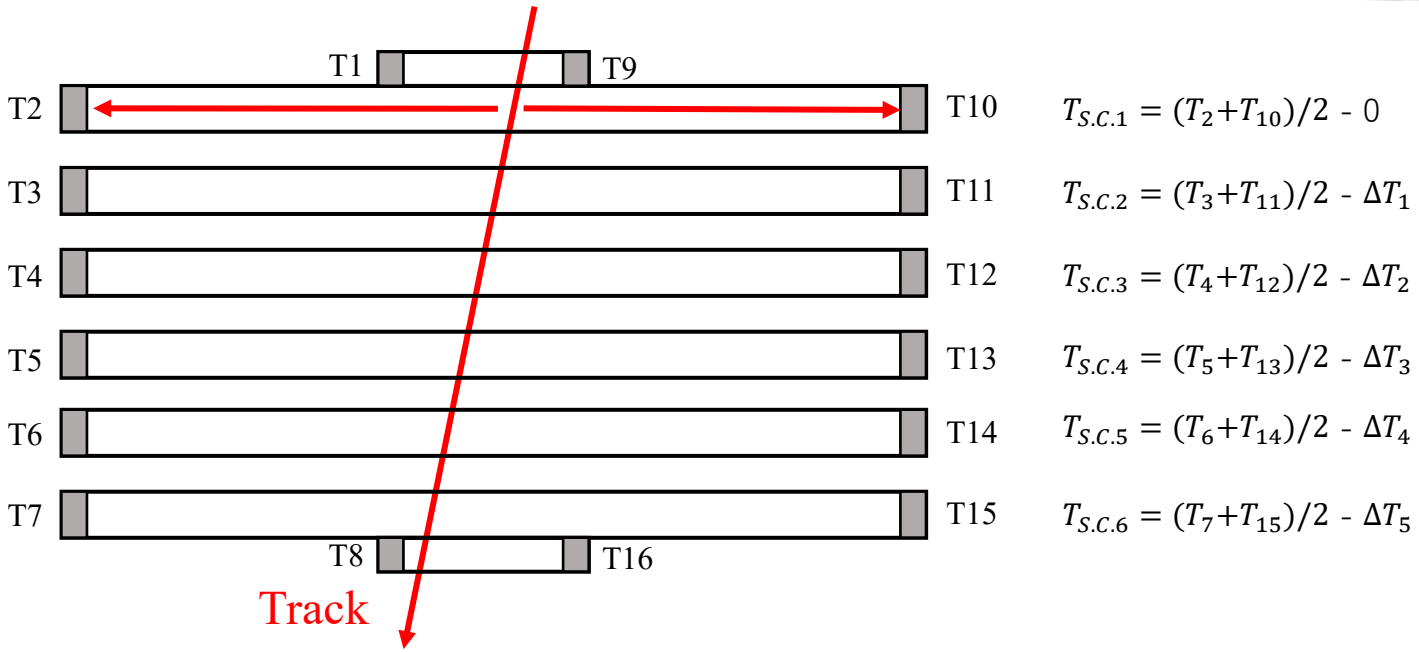
Time Calibration of prototype



DT5742 signal waveform

Prototype Test (Velocity of CR Muon)





$T_{S.C.1} = (T_2+T_{10})/2$ - 0

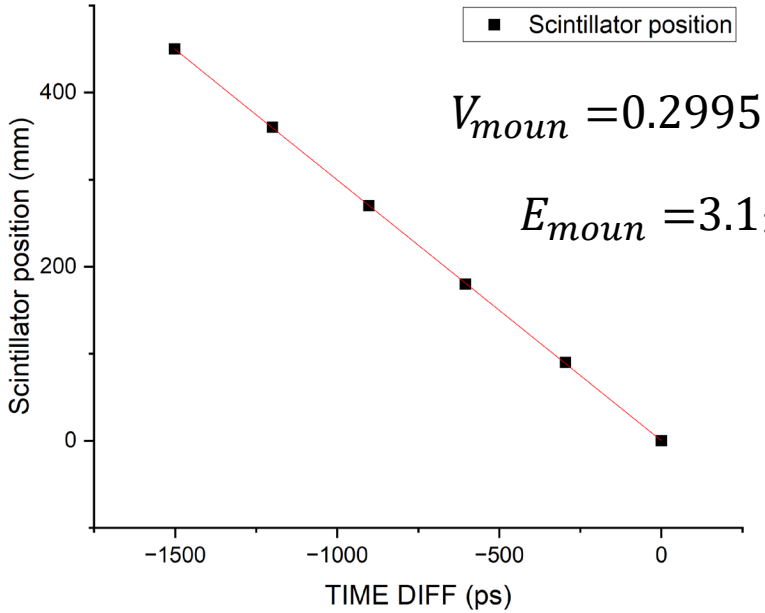
$T_{S.C.2} = (T_3+T_{11})/2$ - ΔT_1

$T_{S.C.3} = (T_4+T_{12})/2$ - ΔT_2

$T_{S.C.4} = (T_5+T_{13})/2$ - ΔT_3

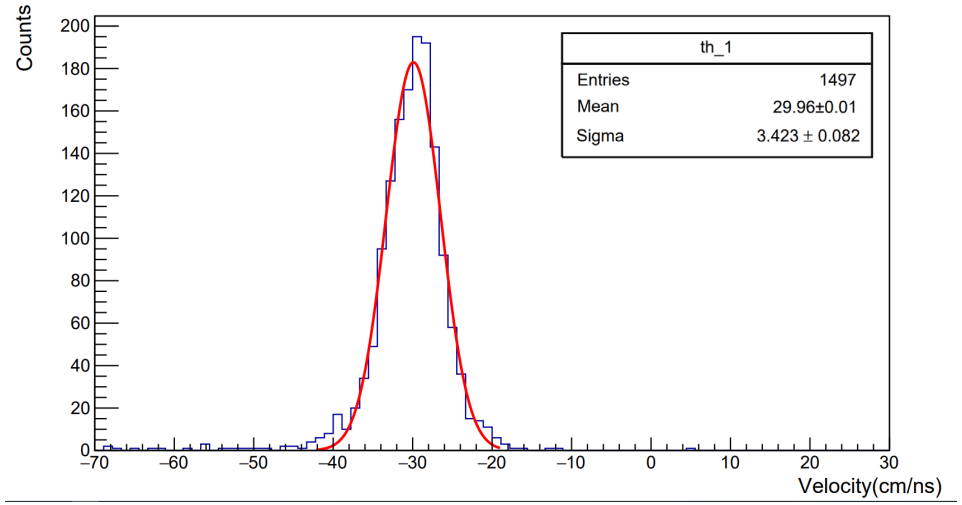
$T_{S.C.5} = (T_6+T_{14})/2$ - ΔT_4

$T_{S.C.6} = (T_7+T_{15})/2$ - ΔT_5



V_{moun} =0.299582±0.00011 mm/ps

E_{moun} =3.1±0.4 GeV/c^2



Muon velocity distribution of cosmic rays

Summary

- Good performance of the current design for efficiency.
- The time resolution is less than 1.5 ns for scintillator + WLS + SiPM system.

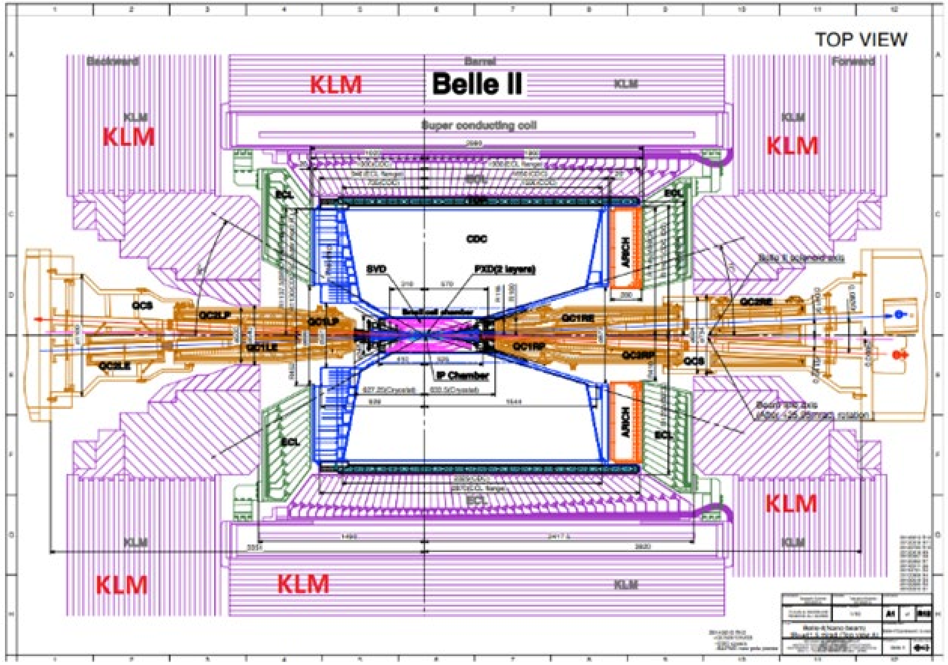
- A preamplifier with time resolution of 20ps is designed.
- The combination of series and parallel can improve the time resolution of multiple SiPM arrays.
- The GNKD plastic scintillator (1m) achieves a time resolution of 80ps.
- The prototype of scintillator realizes the energy measurement of cosmic ray Muon (3.1 ± 0.4 GeV/c^2).

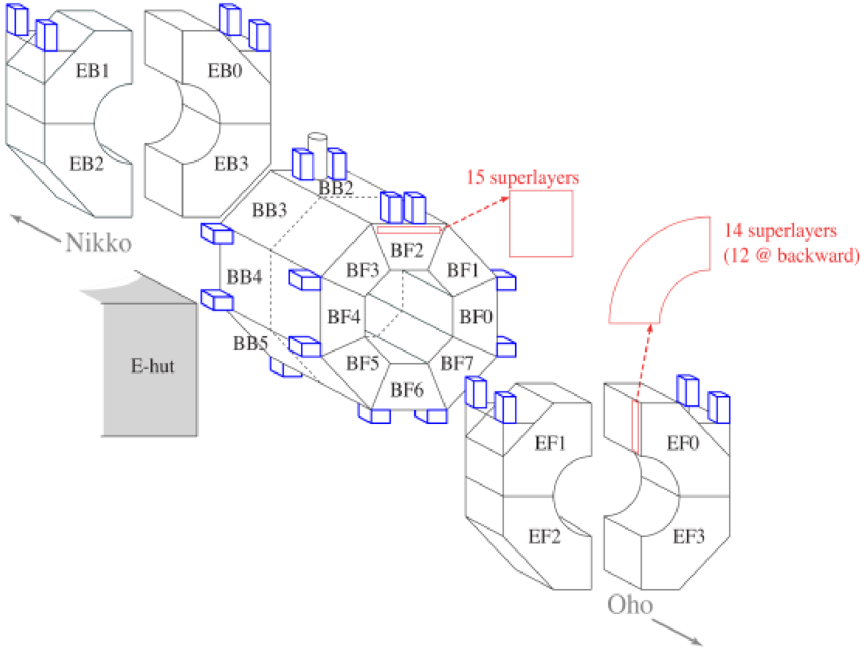
THANKS !

back up

K-long & Muon Detector upgrades

- ➢ Replace remaining RPCs in barrel with scintillator strips.
- ➢ Re-design electronics layout， high-resolution timing for K_L momentum via time of flight.

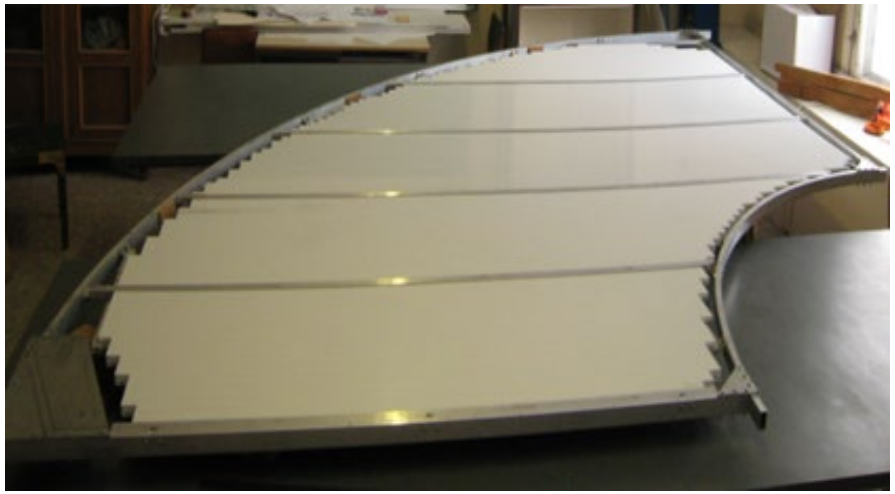




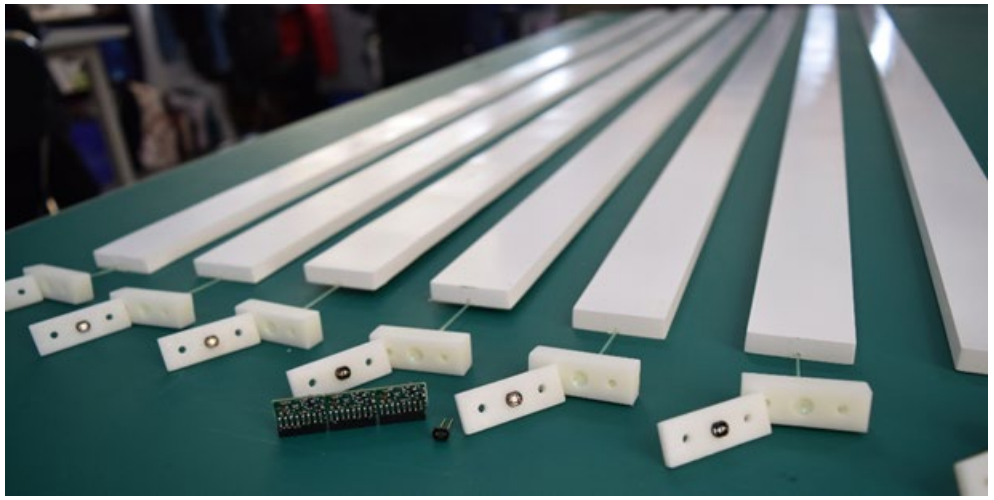
The structure of Belle II KLM

Snowmass whitepaper, arXiv: 2203.11349

K_L & muon detector in Belle



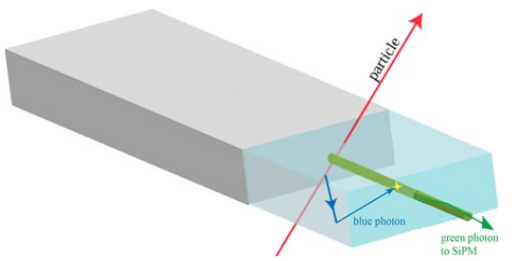
Scintillators of KLM end cap scintillators

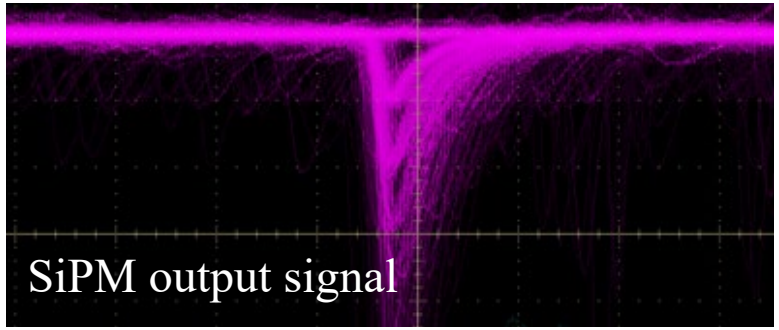


Scintillator + WLS fiber + SiPM

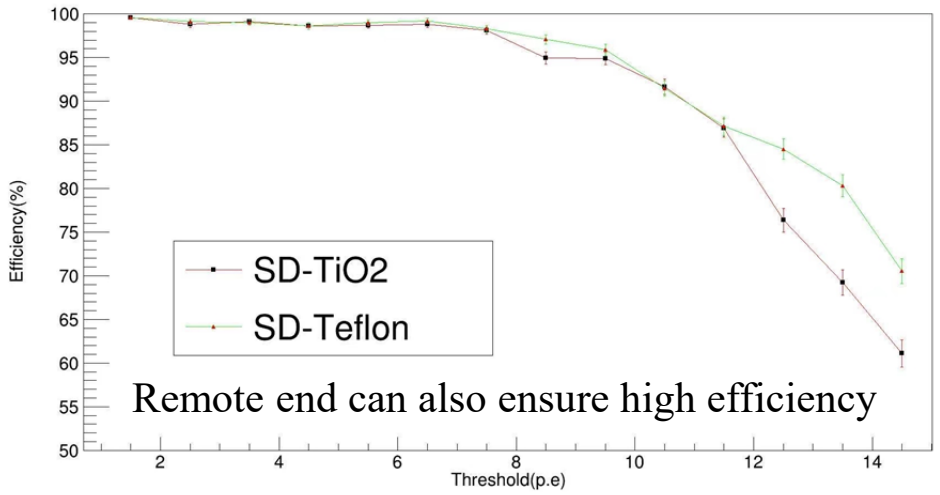
- CR testing with two strips
- High efficiency
- Time resolution: $< 1.5ns$

WLS fiber limits the improvement of time resolution

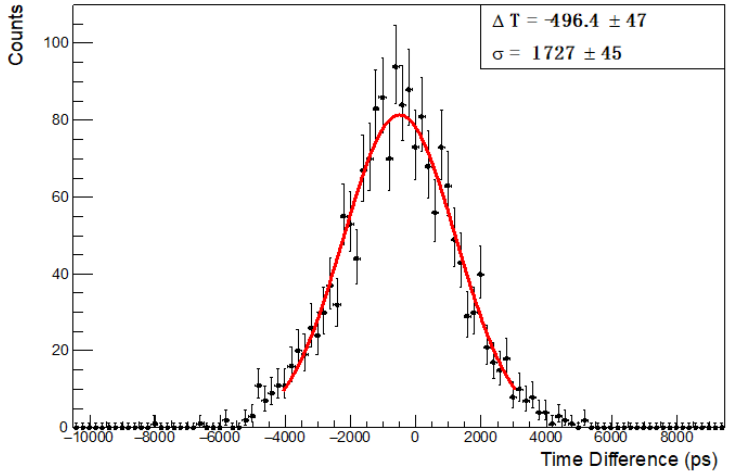




SiPM output signal



Keeping high efficiency at 10 p.e. threshold



Time difference of two channel

Time resolution upgrade

Scintillator for detection

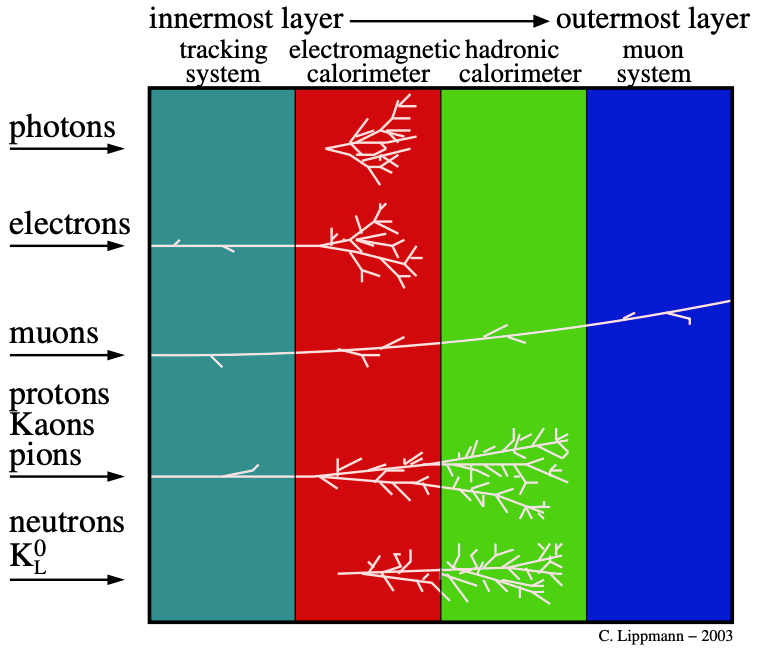
Precise measurement of the four-momentum of neutral hadrons

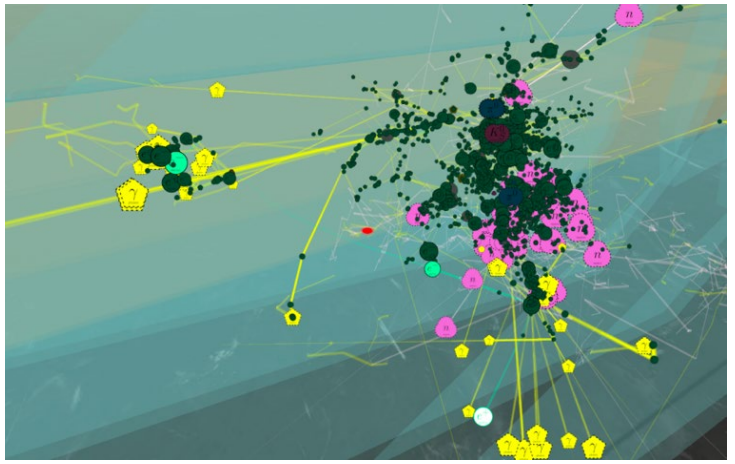
- Uncharged
- Complex hadron shower

Scintillator detector

- High time resolution
- Fast time response components in hadron showers
- Flight velocity： from the collision point to the KLM detector

  & solid angle and particle identification information





$$p = \gamma m v = \frac{mcL}{\sqrt{t^2c^2 - L^2}}$$

$$\frac{\delta t}{\delta p} = -\frac{m^2 L^2}{t \cdot p^3} = -\frac{m^2 L v}{p^3}$$

if L= 2 m, γ= 3, $p \approx 1.5$ GeV/c

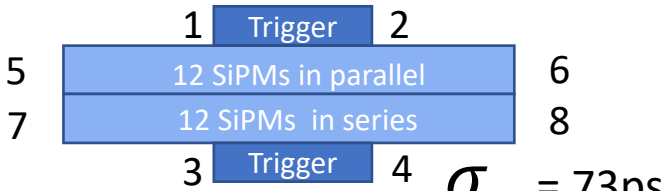
δt = 100 ps so δp = 0.19 GeV/c

Relative error ~ 13%

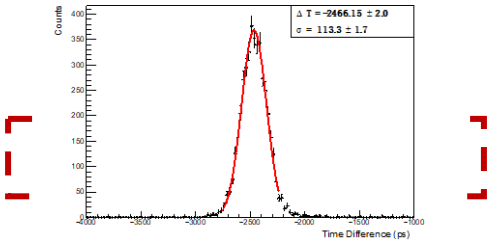
Time resolution of long strip: GNKD(3cm)

GNKD: $4 \times 3 \times 150\ cm^3$

Without polish and light guide



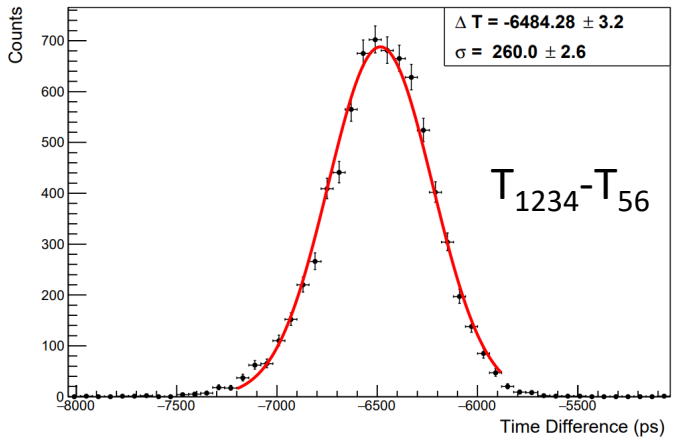
σ_{Trg} = 73ps



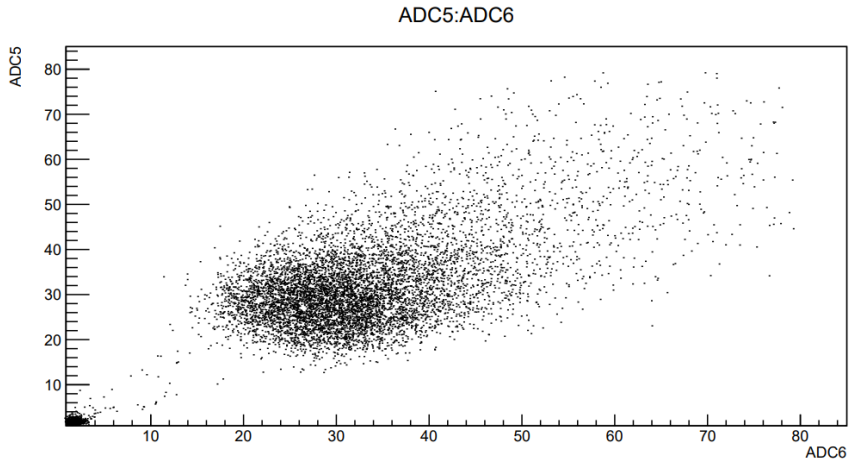
S-G σ_{long}=87 ps

GNKD

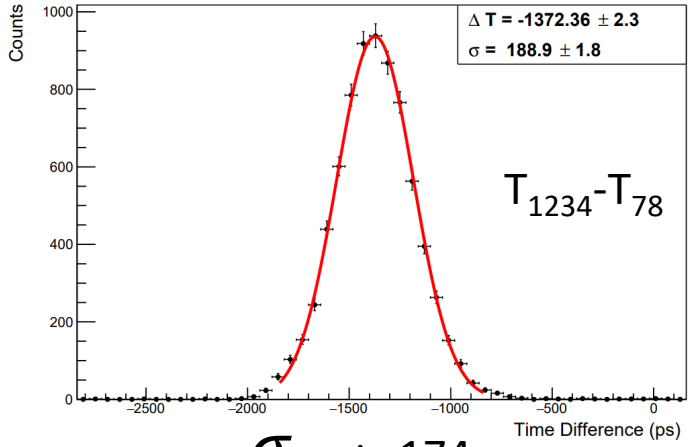
- Longer strip
- Shorter attenuation length



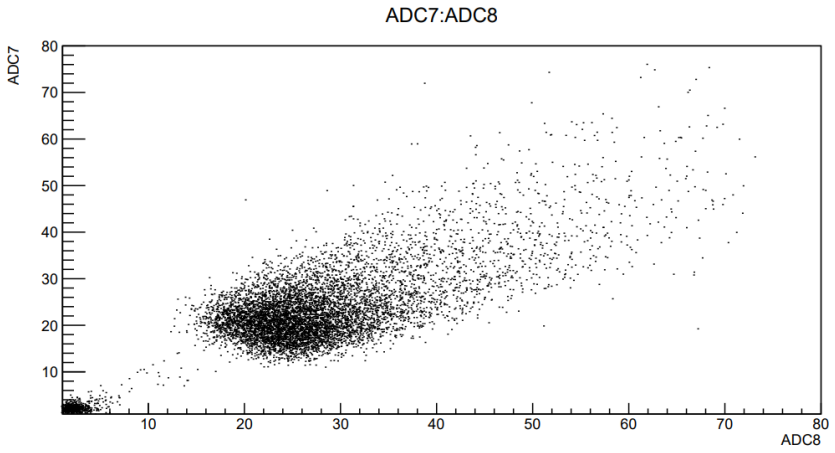
σ_{long}: 249ps



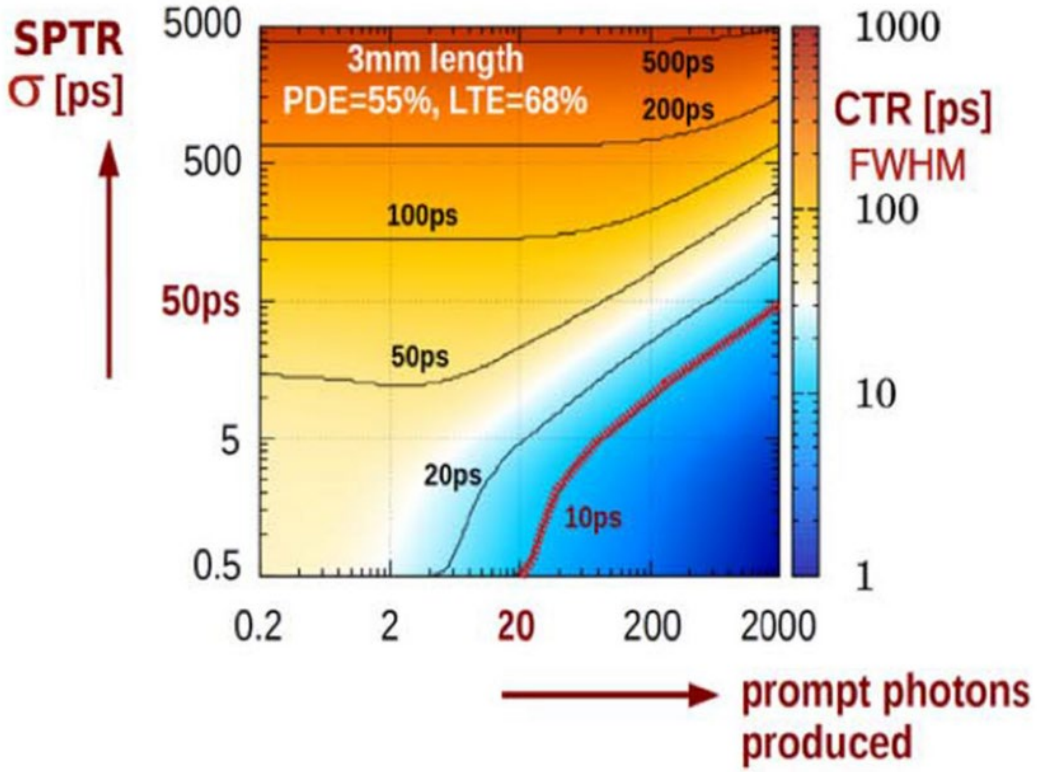
SiPM*12 in parallel



σ_{long}: 174ps

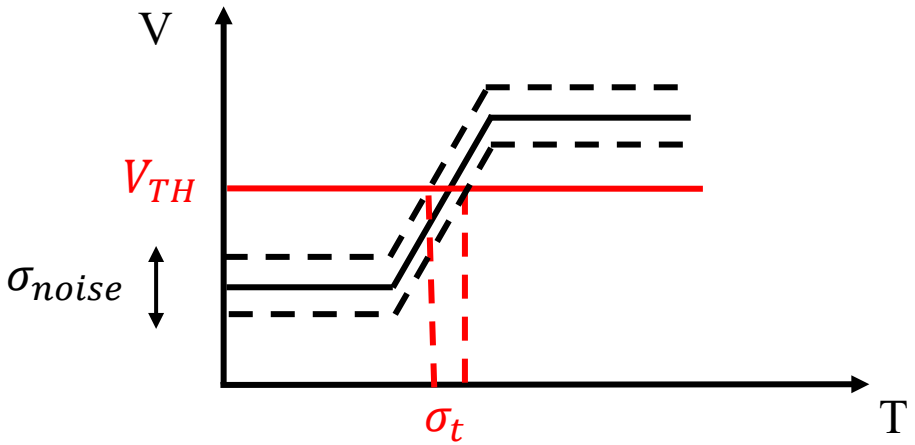


SiPM*12 in series

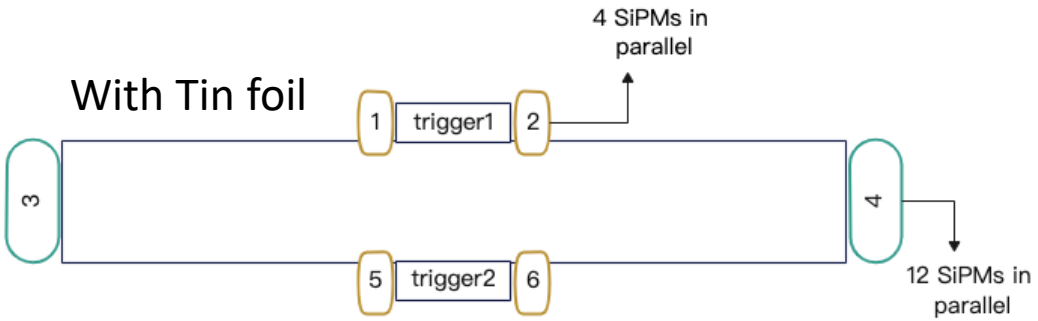


$$CTR \propto \sqrt{\tau_{d/n_p}}$$

$$\sigma_t = \frac{\sigma_v}{dv/dt}$$

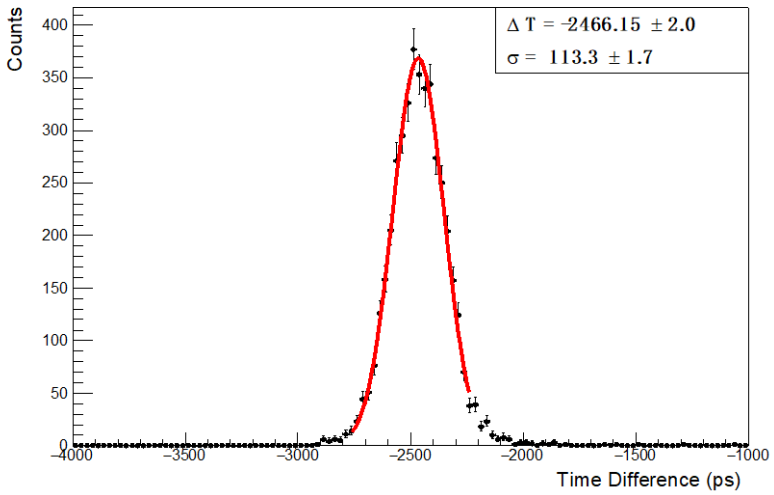


Time resolution of long strip： S-G + 12SiPMs

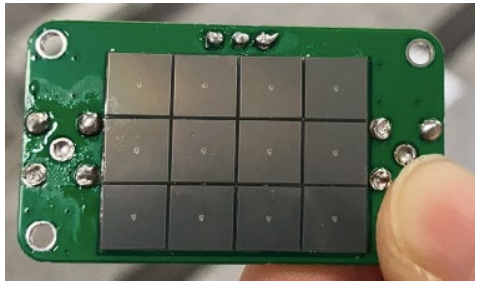


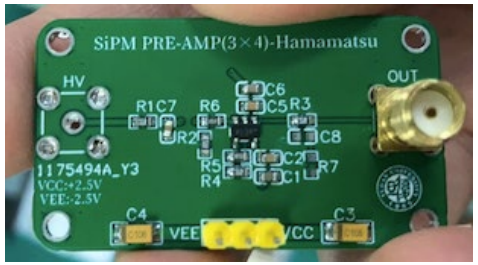
Saint-Gobain ($5 \times 3 \times 120\ cm^3$)

$\Delta T=(T1+T2+T5+T6)/4-(T3+T4)/2$

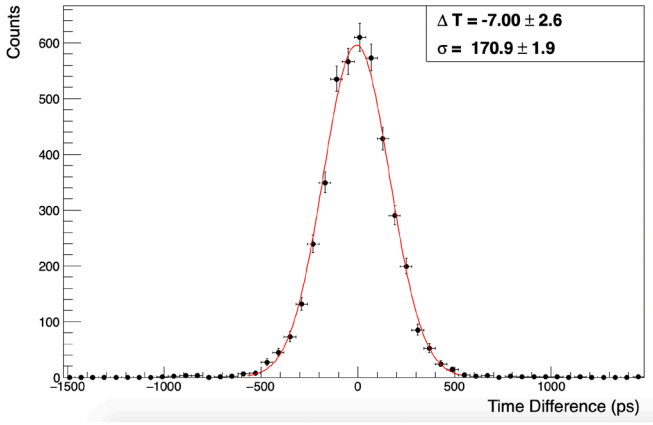


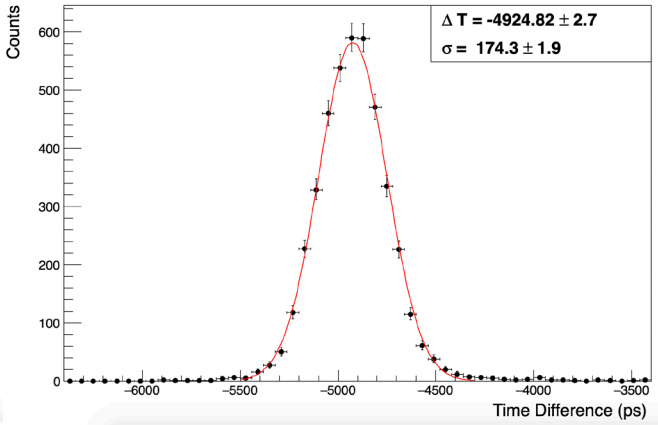
σ_{long}=87 ps





12 SiPMs in parallel

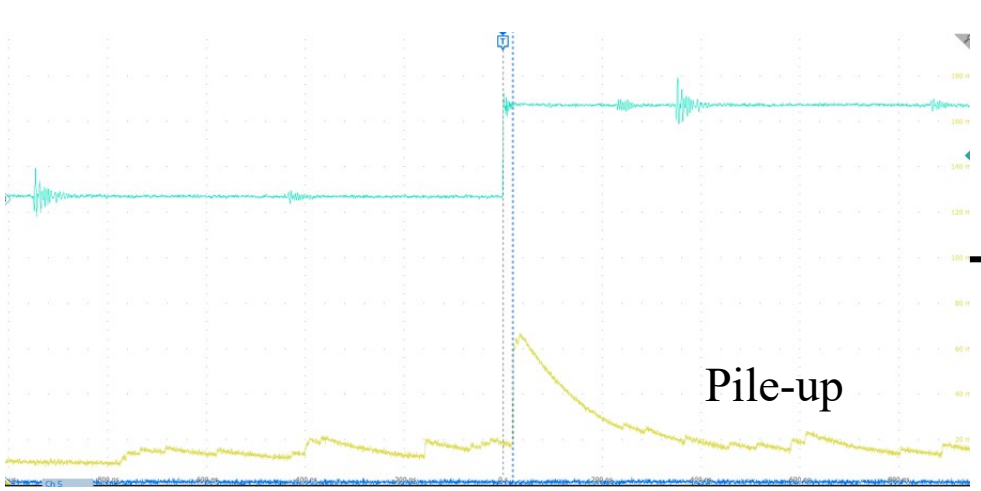




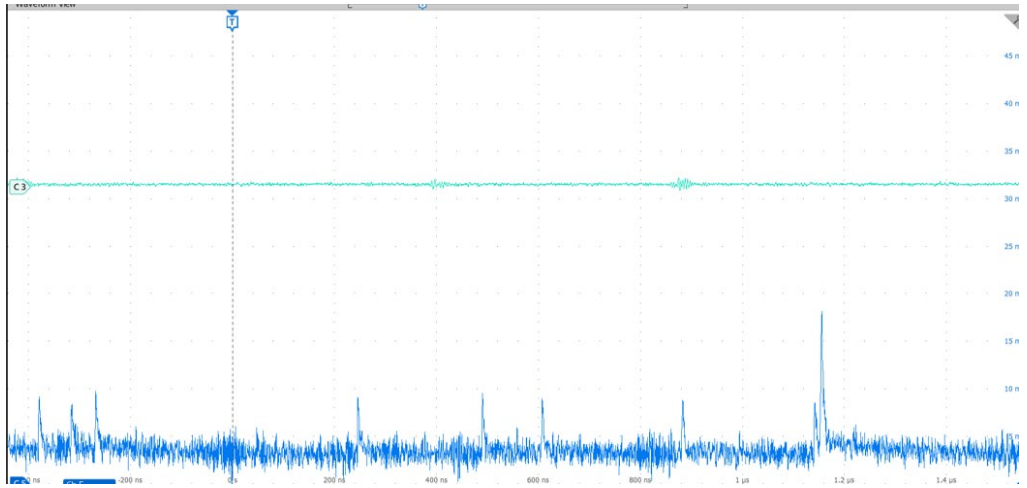
ΔT between 2+6 and 4 (left), or 1+5 and 3 (right)

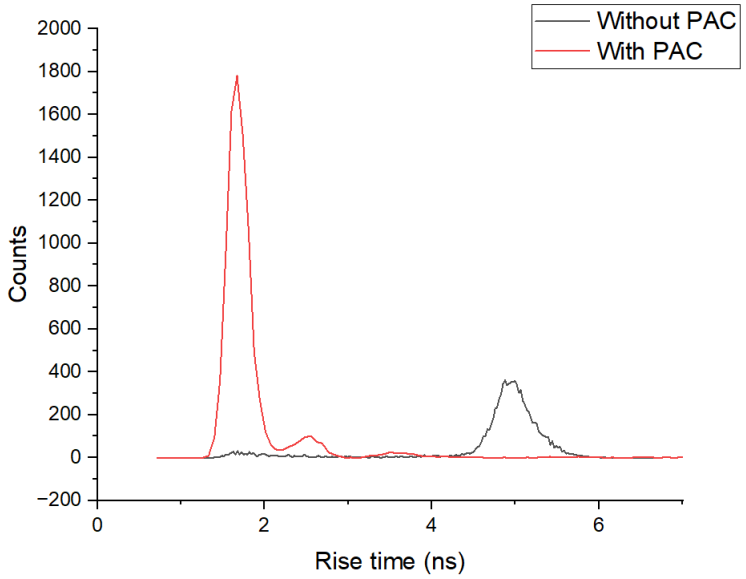
Spatial resolution according to ΔT between 3 and 4 should be $\sim 0.17 \times \frac{30}{n}\ cm$, which is 3.4cm

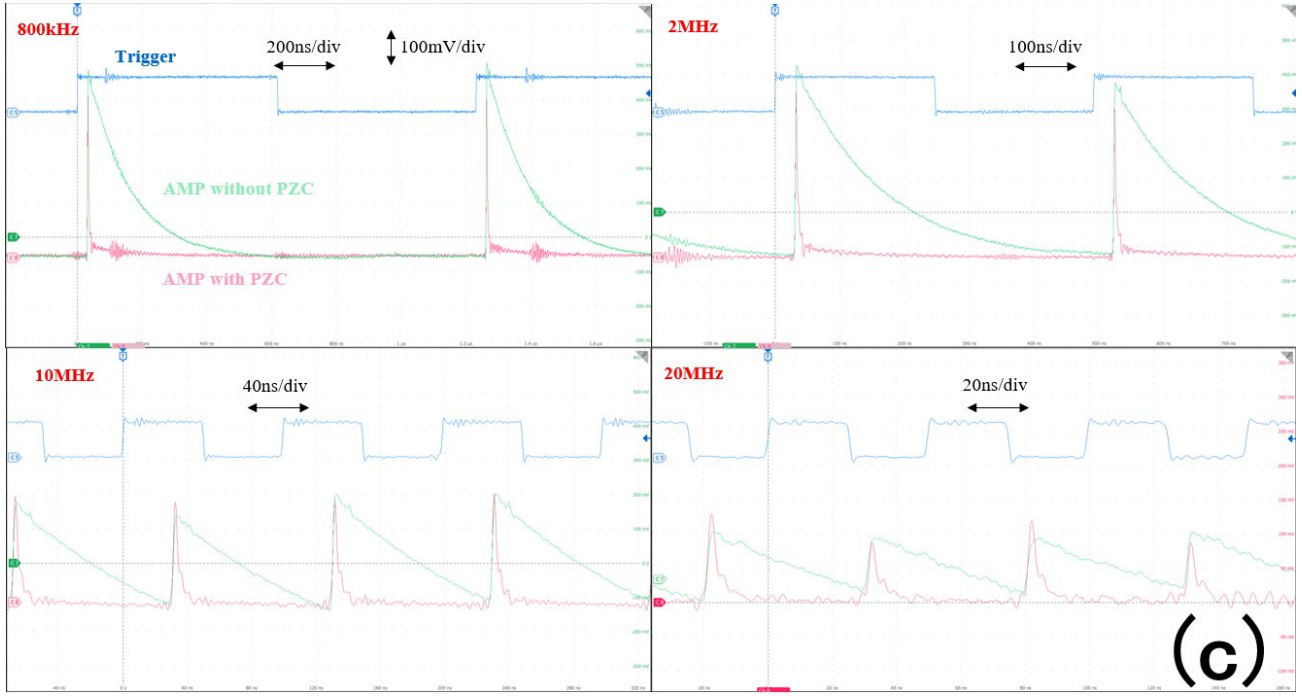
PZC


Pile-up

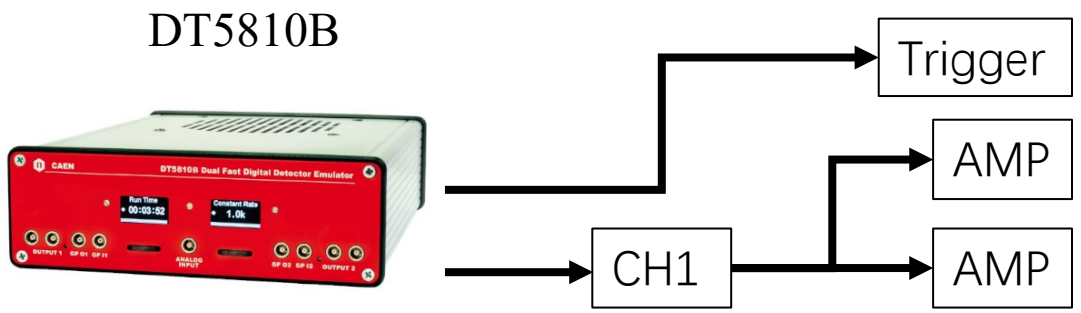
PZC

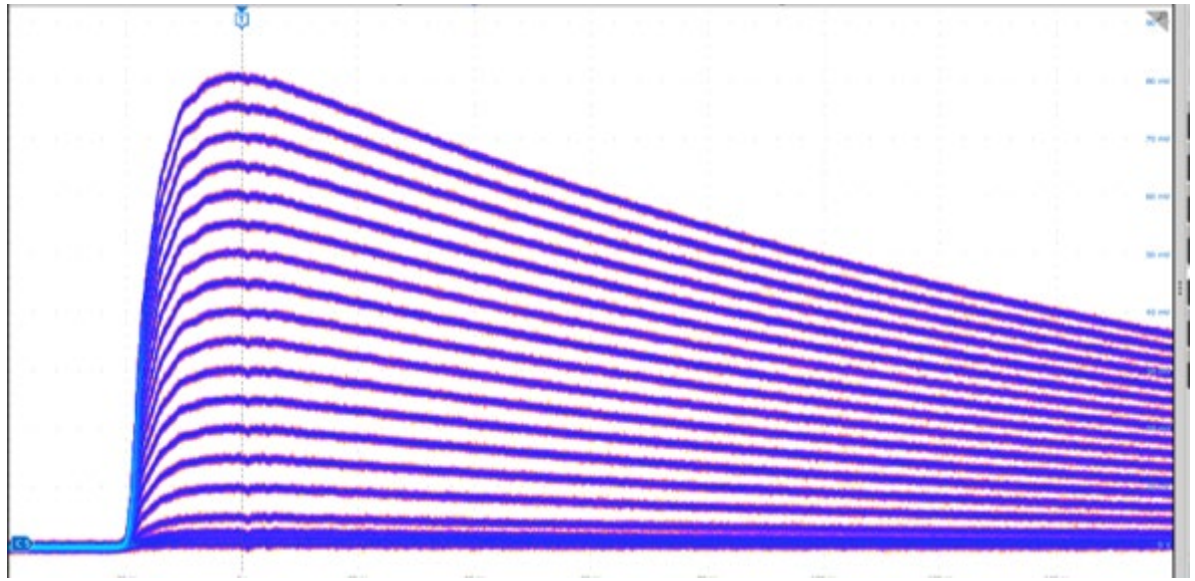


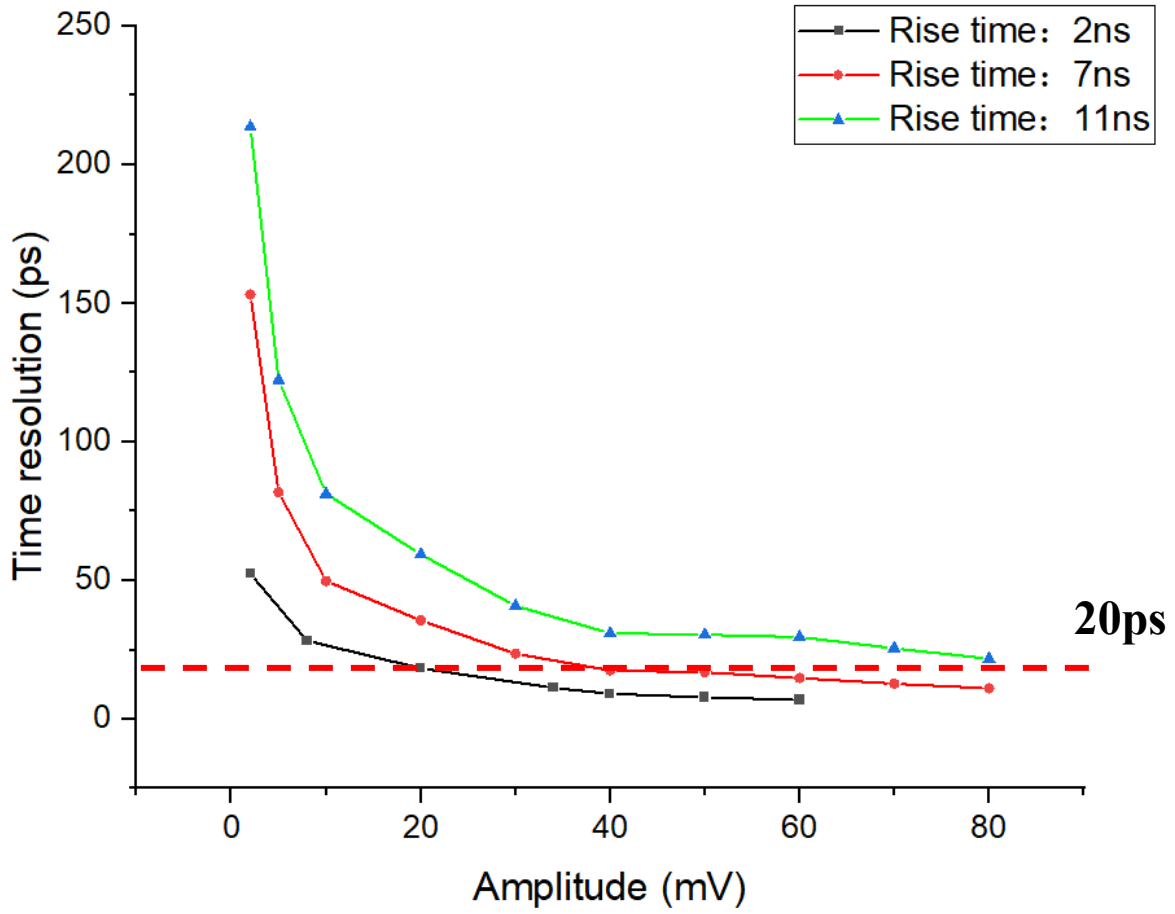

Without PAC
With PAC
Counts
Rise time (ns)


800kHz
Trigger
200ns/div
100mV/div
AMP without PZC
AMP with PZC
2MHz
100ns/div
10MHz
40ns/div
20MHz
20ns/div
(c)

SiPM readout electronics performance test





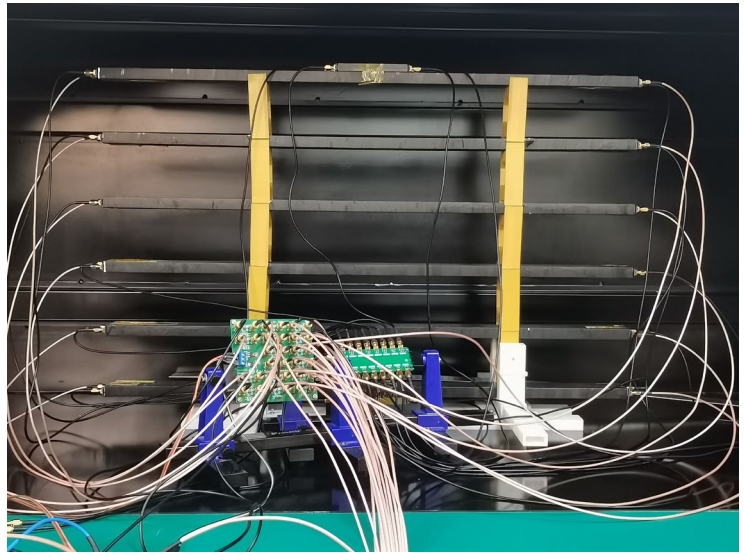


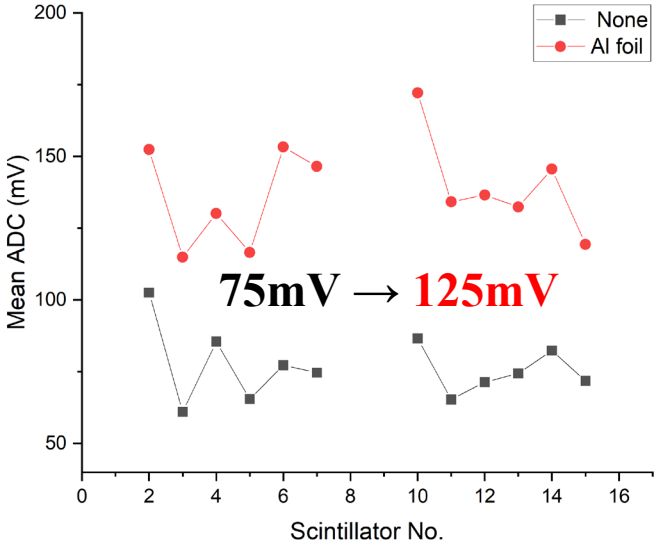
risetime： 1ns **fall time：** 100ns
signal amplitude: 2 – 80 mV

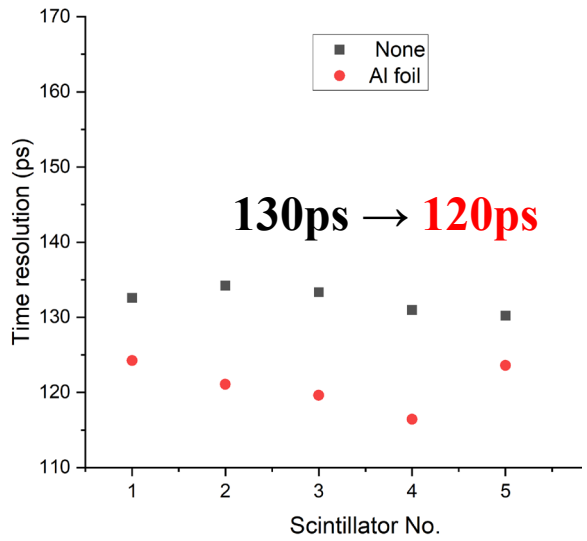
$$\sigma_t = \frac{\sigma_{noise}}{(dV/dt)_{MAX}}$$

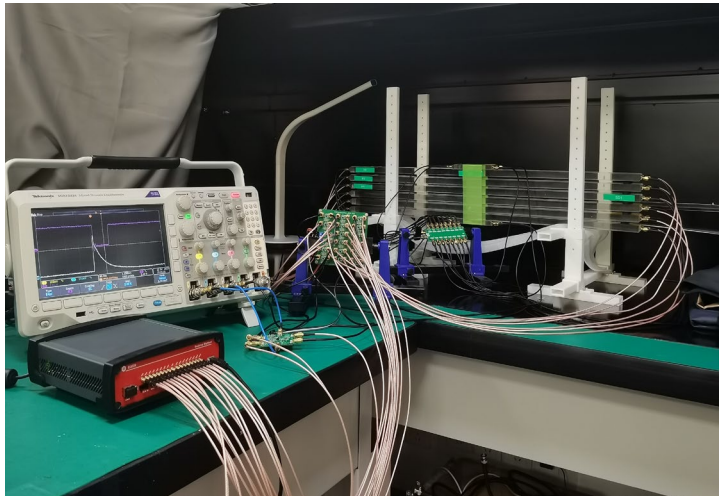
Prototype Test

- Using aluminum foil as the reflector can improve the signal amplitude, thus improve the time resolution.

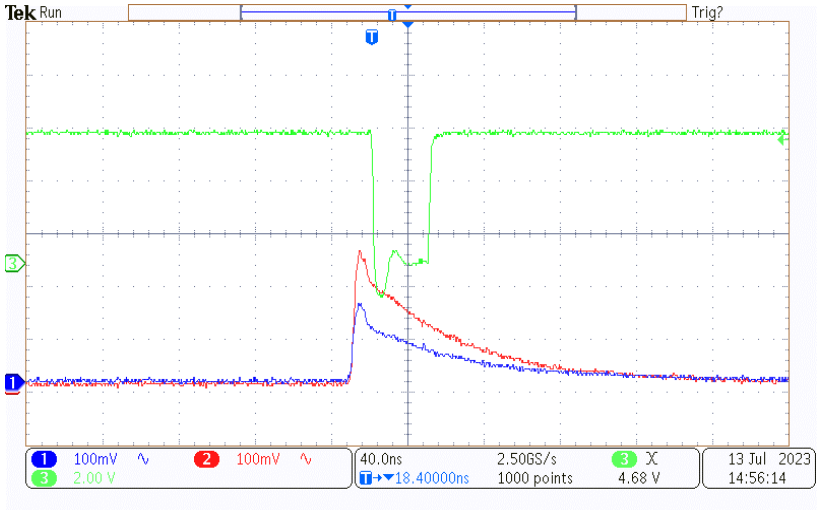




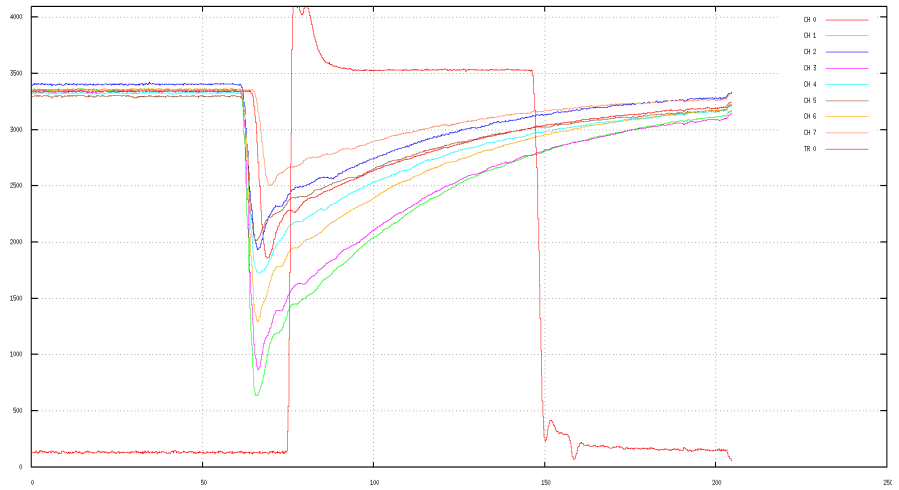




Prototype test setup



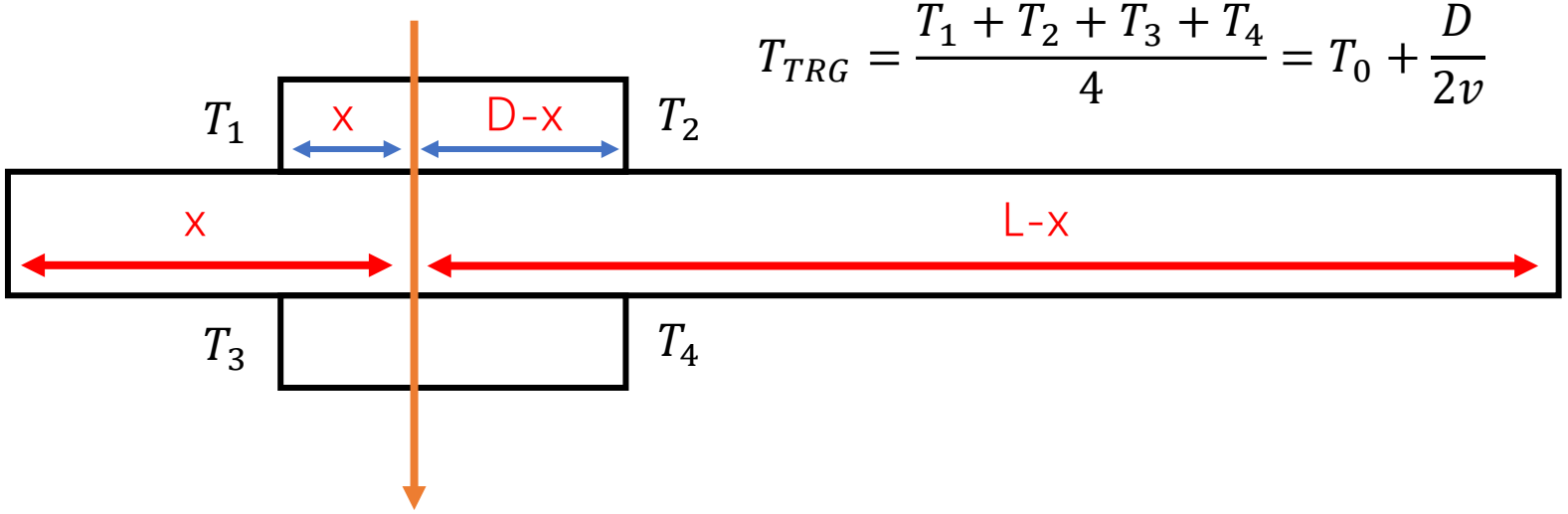
Trigger signal waveform



DT5742 signal waveform

$$T_{TRG} = \frac{T_1 + T_2 + T_3 + T_4}{4} = T_0 + \frac{D}{2v}$$

$$T_F = T_0 + \frac{x}{v}$$



$$T_B = T_0 + \frac{L - x}{v}$$

Unweighted:

$$T_{AVG} = \frac{T_F + T_B}{2} = T_0 + \frac{L}{2v}$$

$$\sigma_{AVG}^2 = (\sigma_F^2 + \sigma_B^2)/4$$

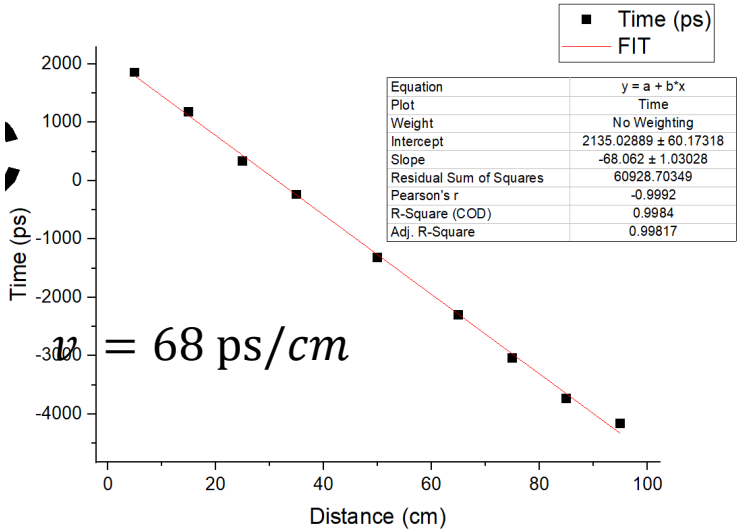
$$\Delta T = T_{TRG} - T_{AVG} = \frac{D - L}{2v}$$

$$\sigma_{\Delta T}^2 = \sigma_{TRG}^2 + \sigma_{AVG}^2$$

Weighted average:

$$T_{AVG} = \frac{(T_F - x/v)/\sigma_F^2 + (T_B - (l - x)/v)/\sigma_B^2}{1/\sigma_F^2 + 1/\sigma_B^2}$$

$$\sigma_{AVG}^2 = \frac{1}{\sigma_F^2} + \frac{1}{\sigma_B^2}$$



$u = 68\ \mathrm{ps/cm}$