Development of high-speed multi-channel data acquisition system for large-area Compton camera (LACC)

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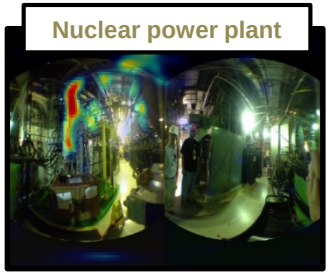
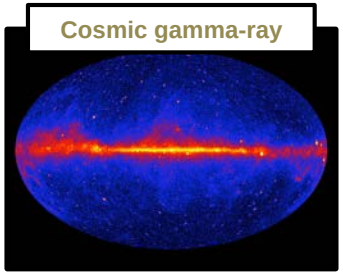
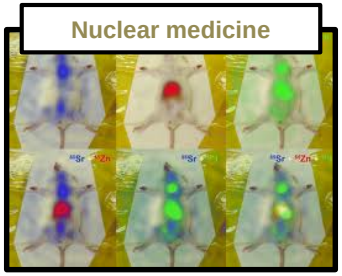
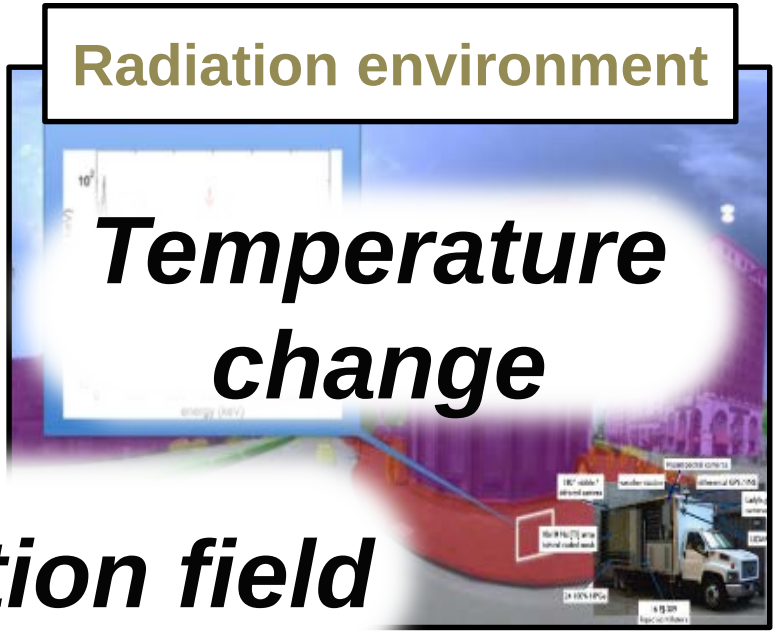
Introduction

Gamma imaging applications and requirements









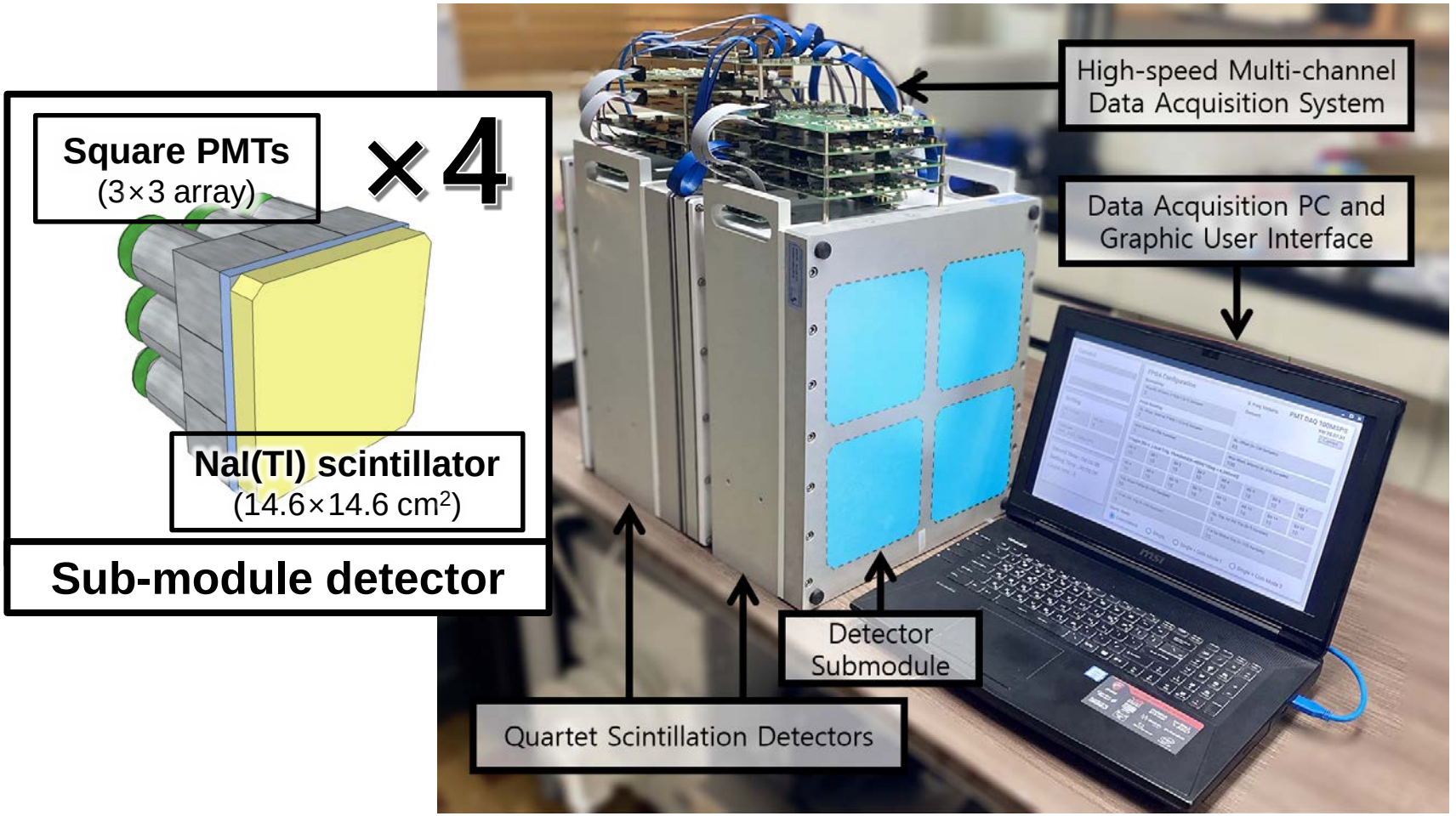
High radiation field

Requirement of imaging system for field applications

High performance (Sensitivity / resolution)

Durability (Mechanical / electronical)

Large-area Compton Camera (LACC)



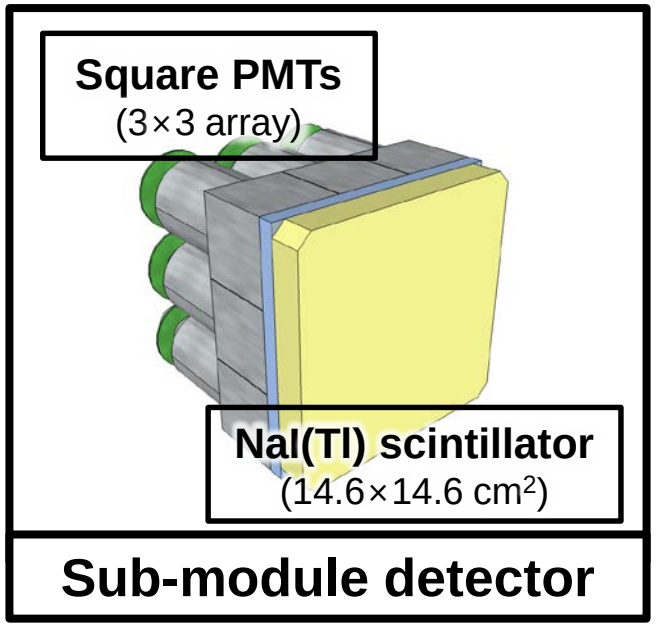
Large-area Compton Camera (LACC)

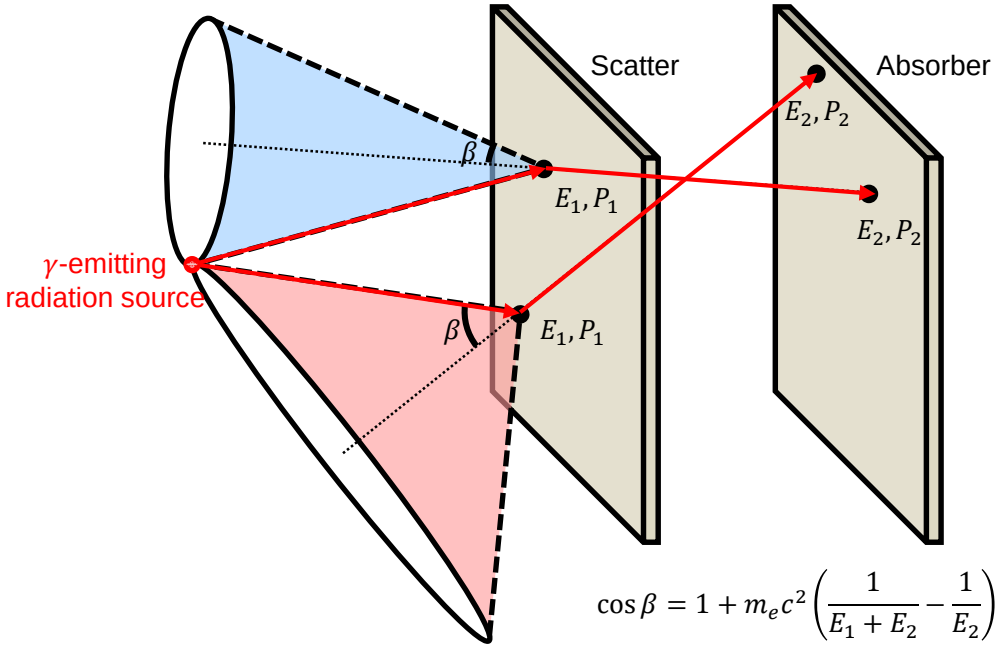
- **High sensitivity**: 7.2×10^{-5} (@662 keV)
- **Image resolution**: 5.9° (@662 keV)
- **3D image** reconstruction

Quartet scintillation detector

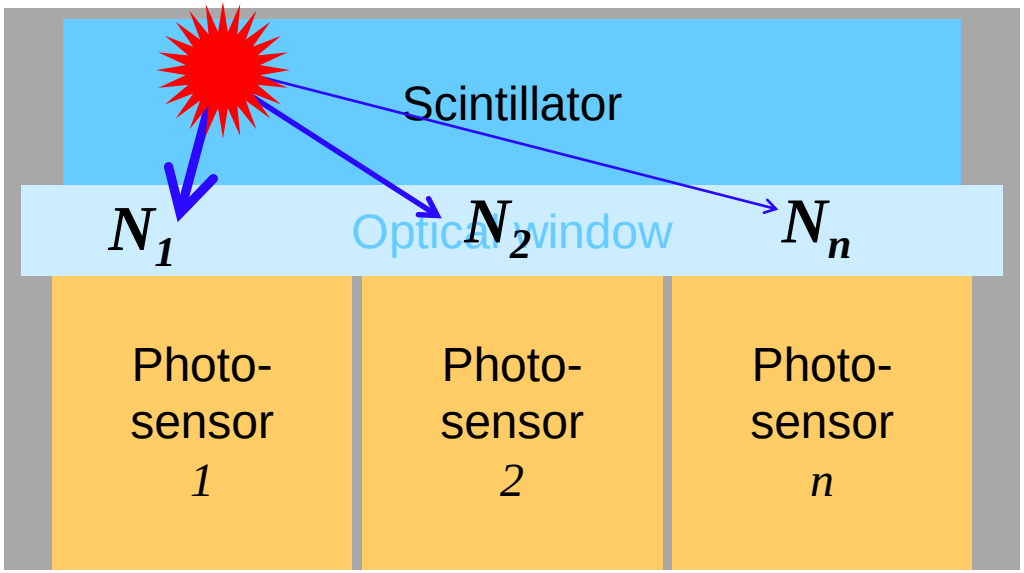
- **High sensitivity**: $>7.2\times10^{-5}$ (@662 keV)
- **Image resolution**: ~5.9° (@662 keV)
- **3D image** reconstruction
- High **immunity** to external **shock** and **vibration**

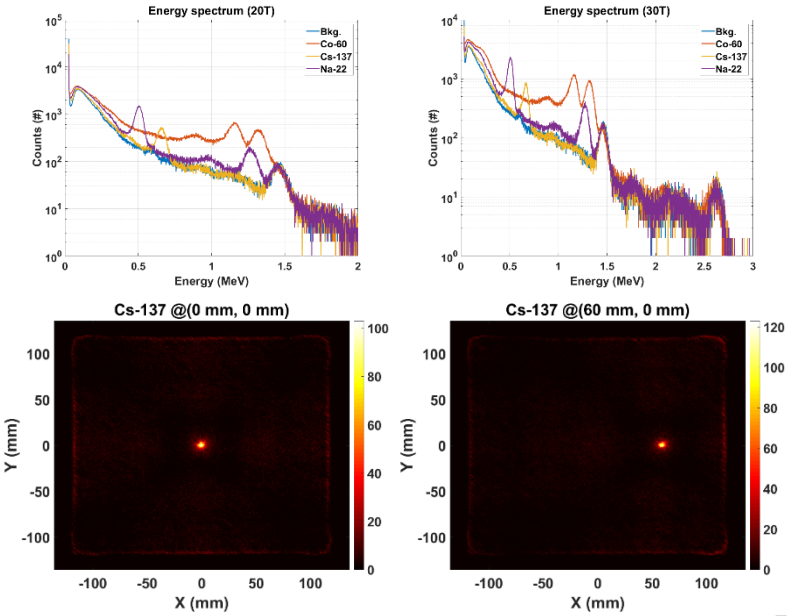
Quartet scintillation detector



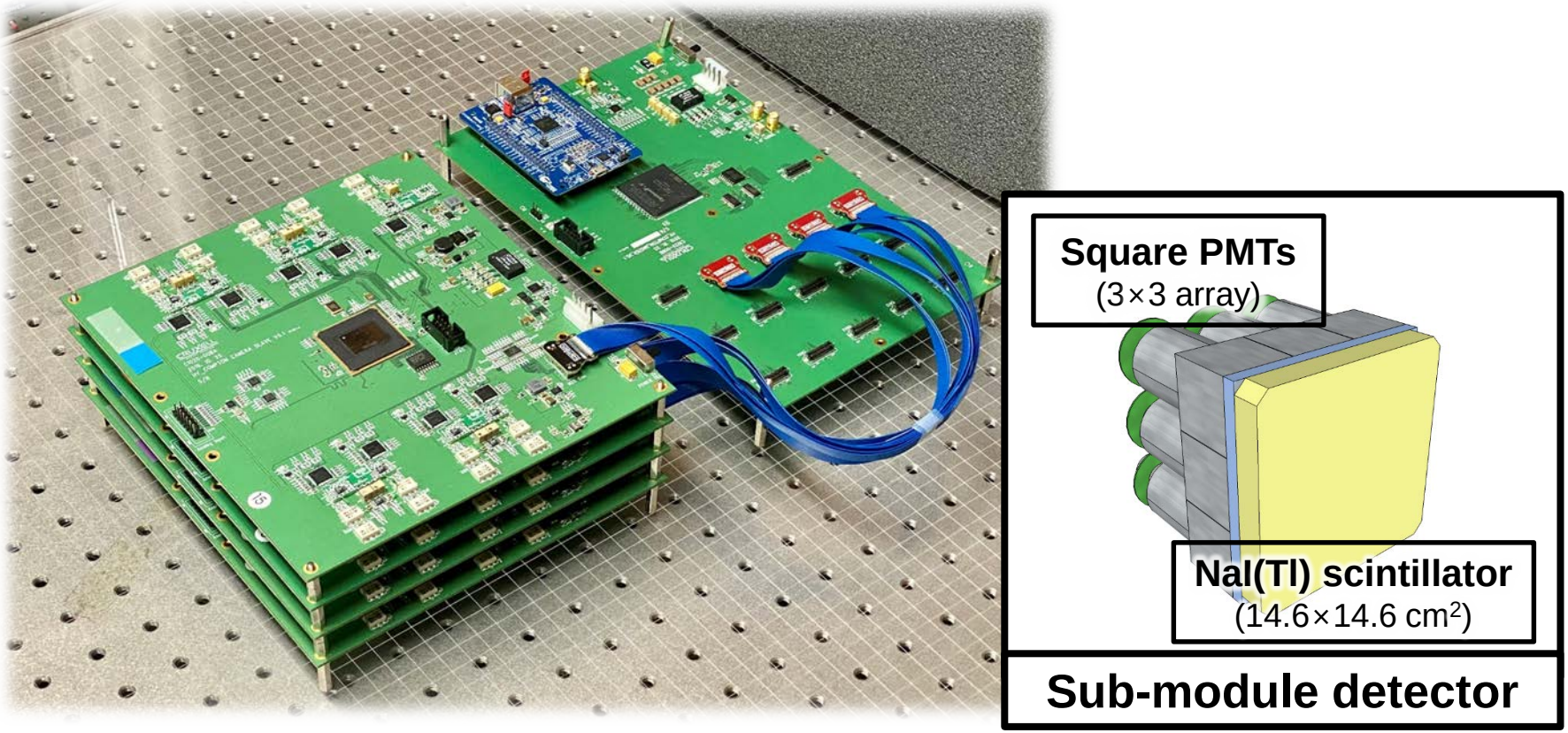


$E_0 \rightarrow N_0$





Research objectives

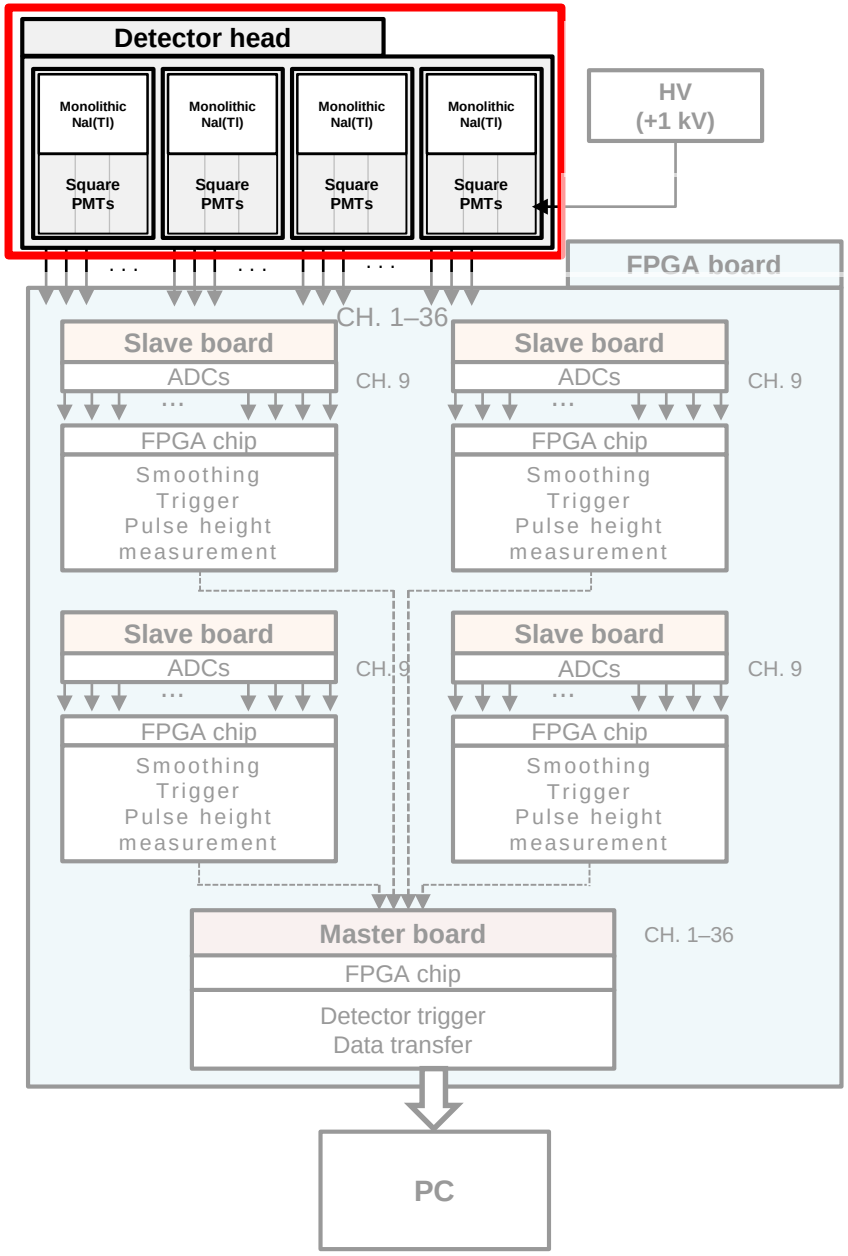


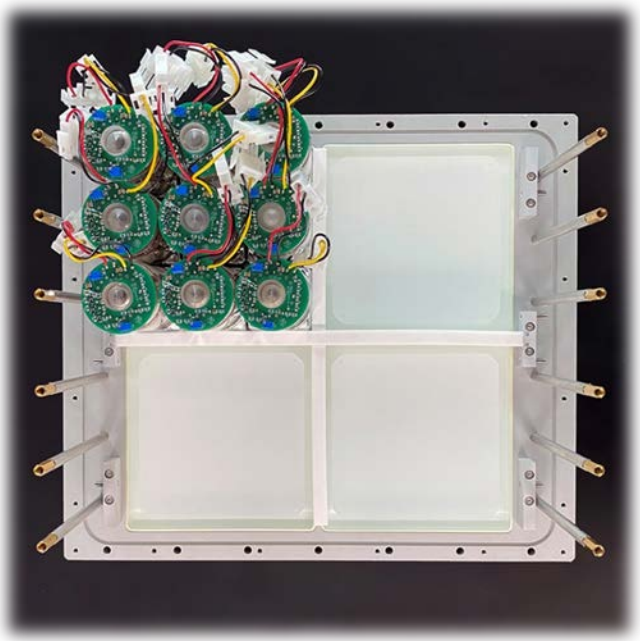
FPGA-based high-speed multi-channel data acquisition (DAQ) system

- Digital signal processing
  - Good energy resolution & minimum pulse pile up
  - Flexibility in the choice of parameters
- Optimization concerns:
  - Good energy resolution
  - Low triggering from noise
  - Lower limit of energy measurement

FPGA based high-speed multi-channel DAQ system

Component detector: detector head





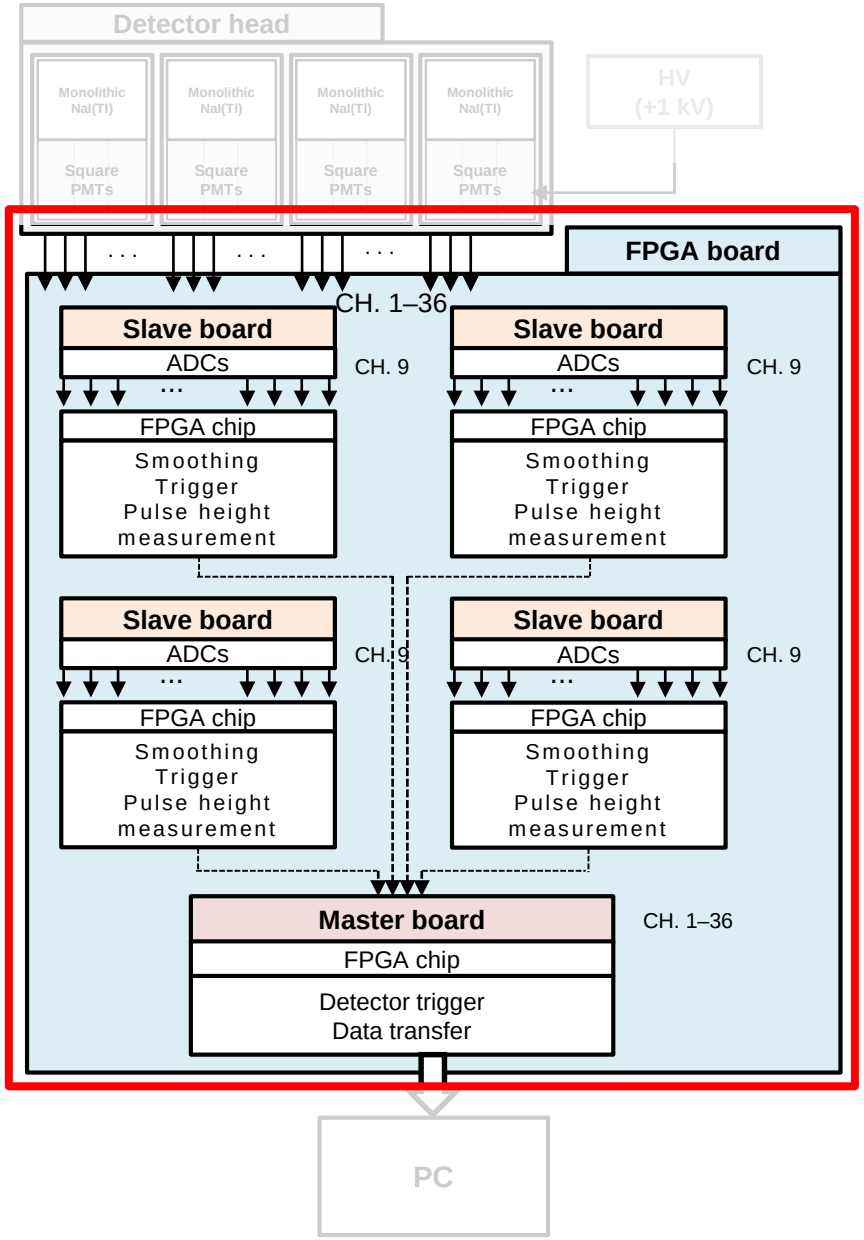
Quartet scintillation detector

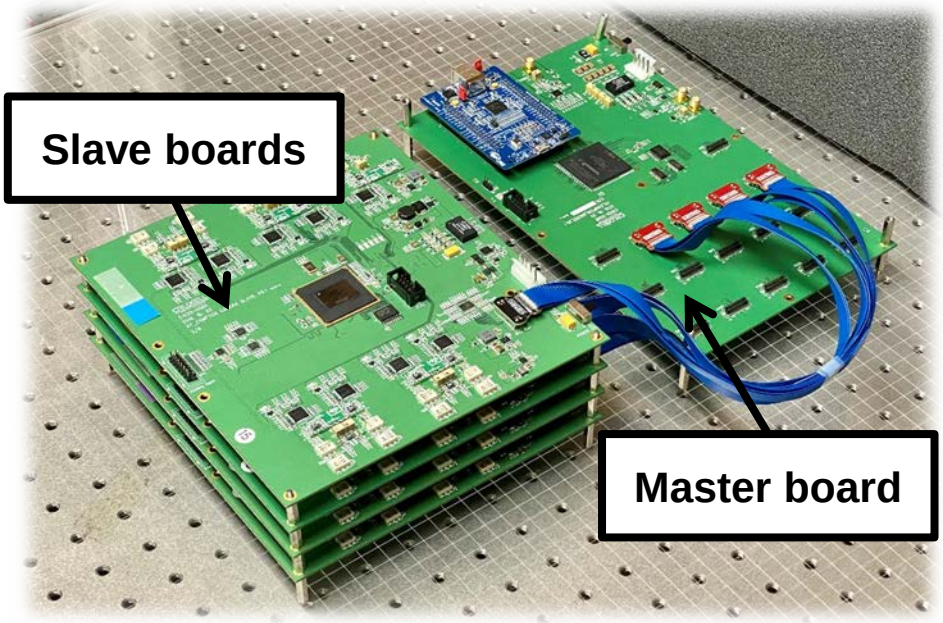
(order-made; Scintitech, MA, USA)

- **Crystal:** NaI(Tl) (14.6 cm × 14.6 cm)
- **PMT:** XP3290; Photonis, France
- **Nine PMT** in one module
- **Four modules** in one detector head
- **Two detector head** in on Compton camera

→ 9 PMTs ×4 modules×2 detector = 72 channels

FPGA based high-speed multi-channel DAQ system

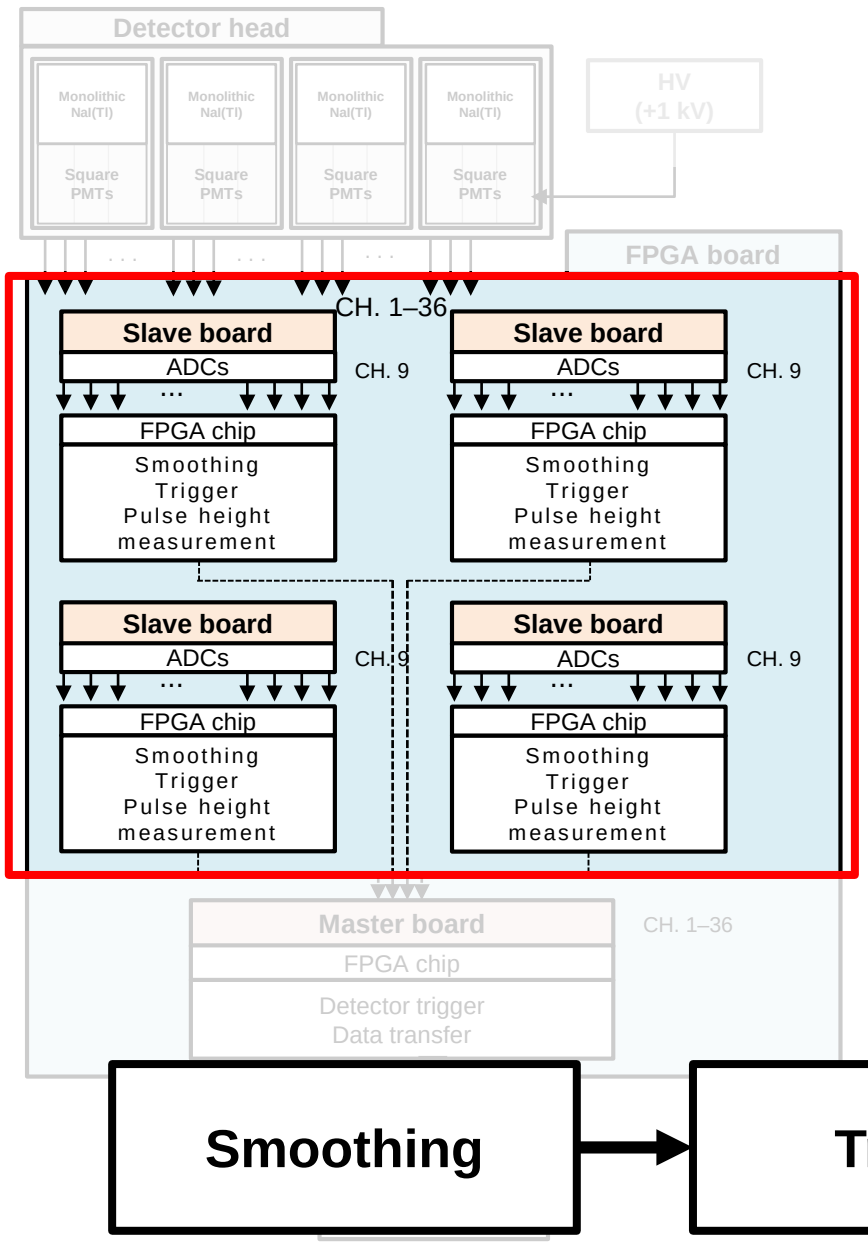


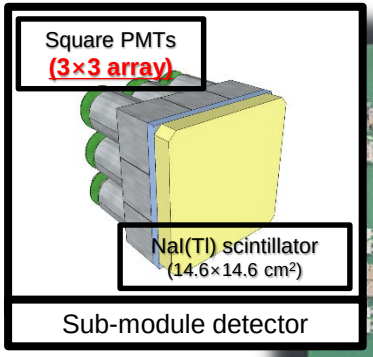


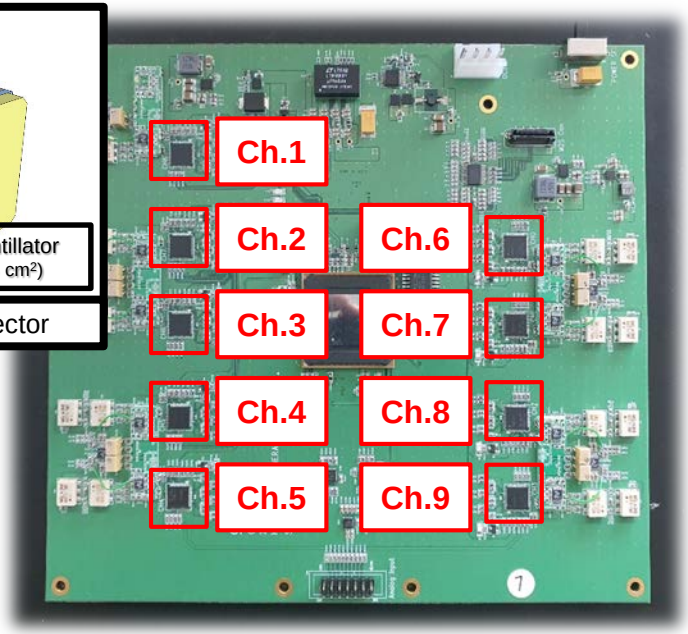
FPGA board (order-made; CRUXELL, Korea)

- **Master-slave integrated system**
  Master board: control/transfer pulse height
  Slave board: smoothing/trigger/pulse height measurement
- **Input/output signals**
  Input: PMT voltage signals from the detector
  Output: PMT voltage pulse height (USB3.0)

FPGA based high-speed multi-channel DAQ system





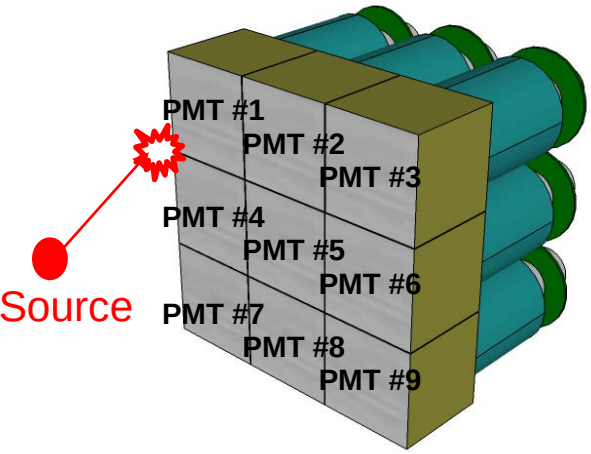


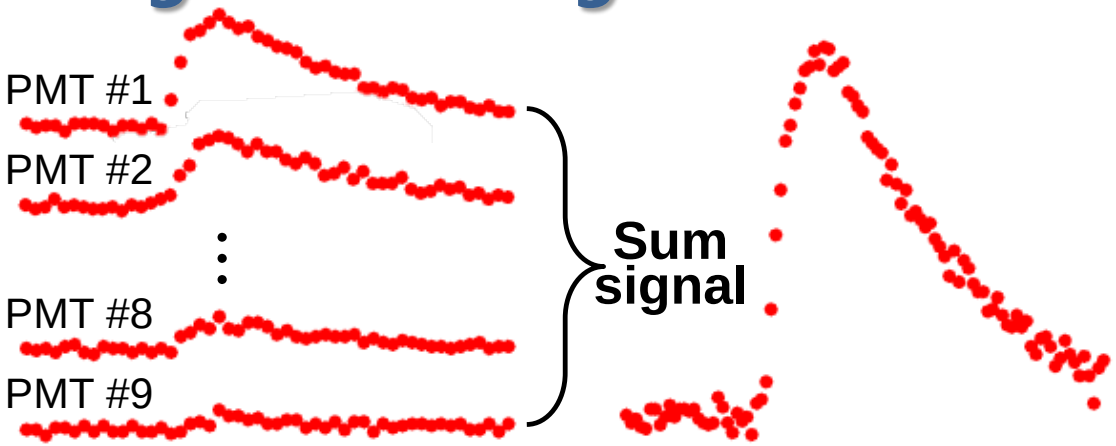
Slave board

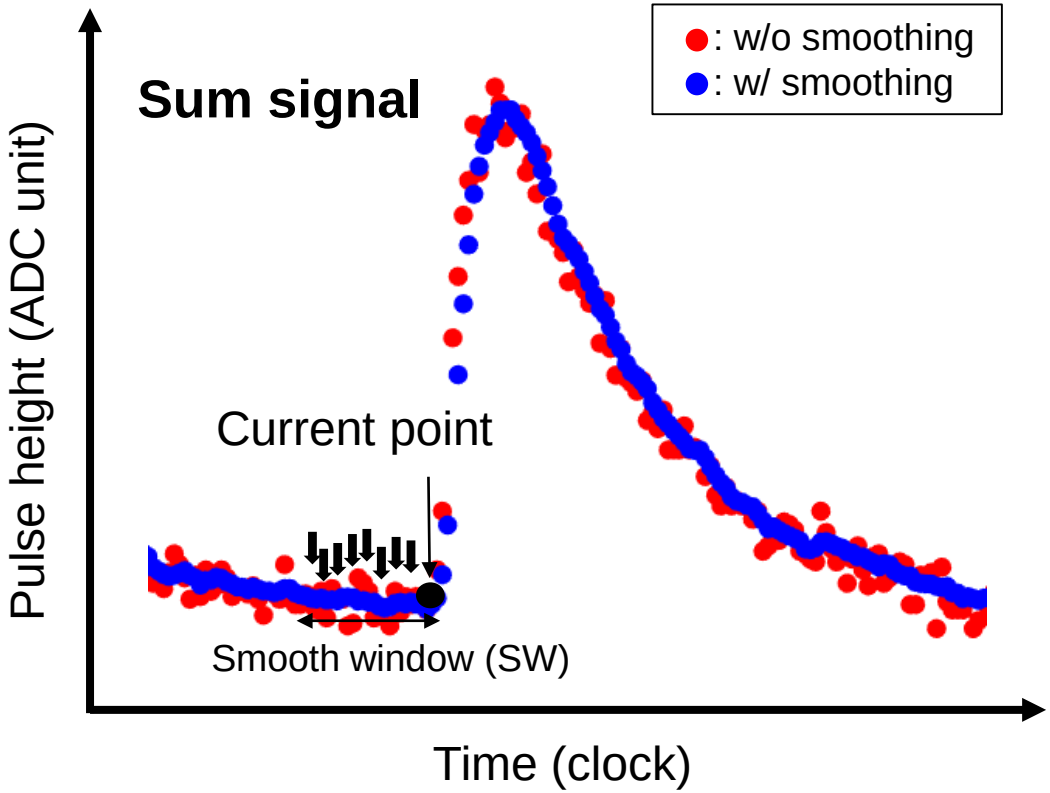
- The **14-bit ADC** (TI, USA) samples and digitizes the **9 PMT signals** per slave board at **100 MHz clock rate**.
- The digital signal processing with **Cyclone 5 FPGA** (Altera, USA)

Smoothing → **Trigger** → **Pulse height measurement**

Digital signal processing: smoothing







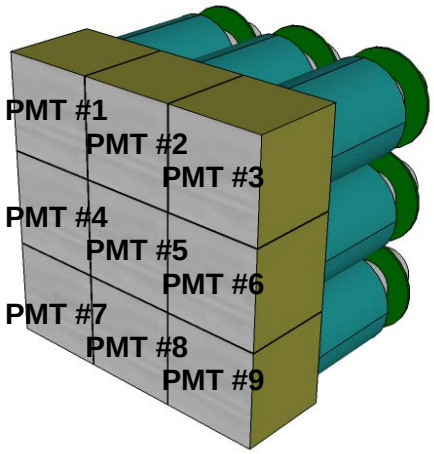
Smoothing

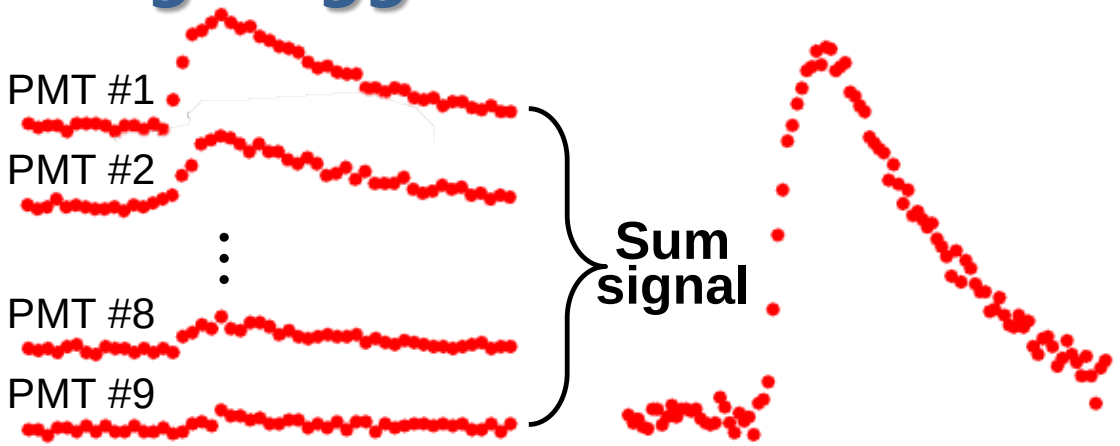
- Moving average
- The average of the previous 2^N points from current point
- Smooth window:
  2^0, 2^1, 2^2, 2^3 clock (=10 ns)

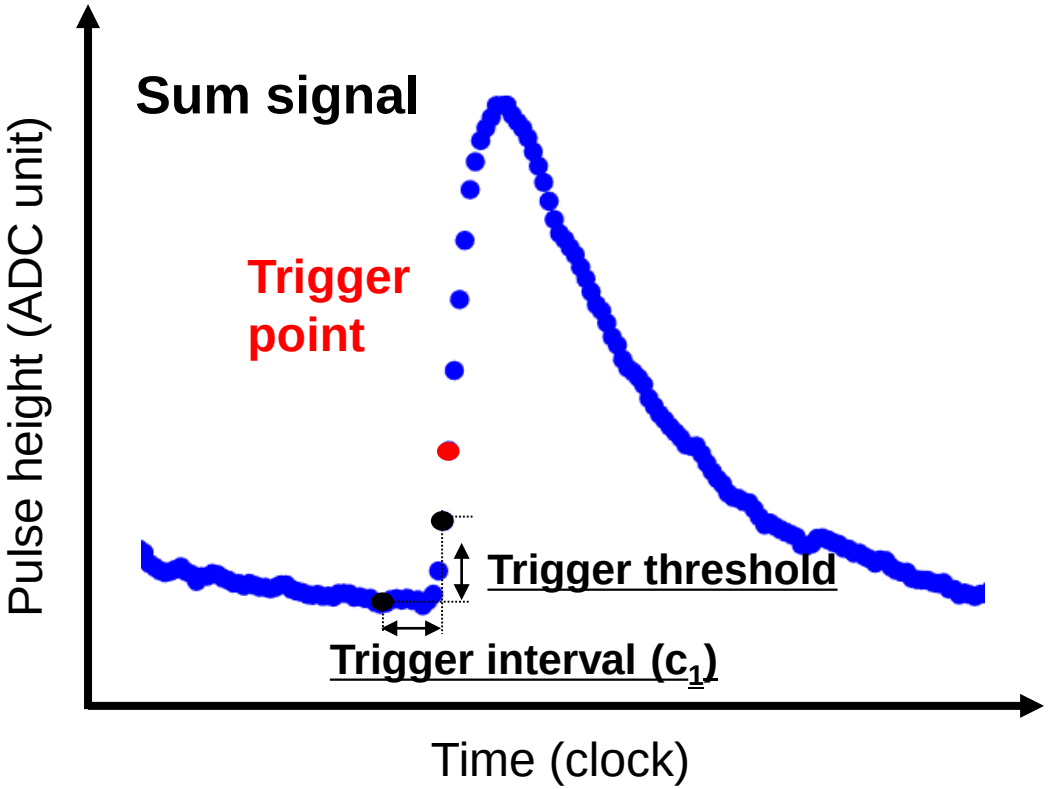
Smoothing on **sum signal**
→ stable triggering

Smoothing on **each channel**
→ stable pulse height measurement

Digital signal processing: trigger



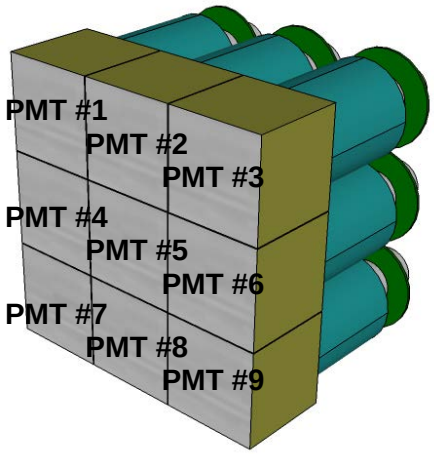


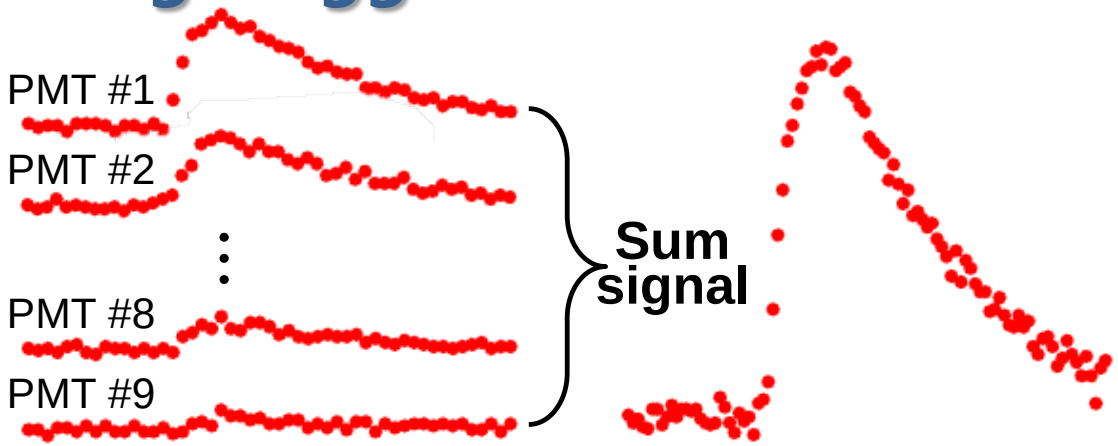


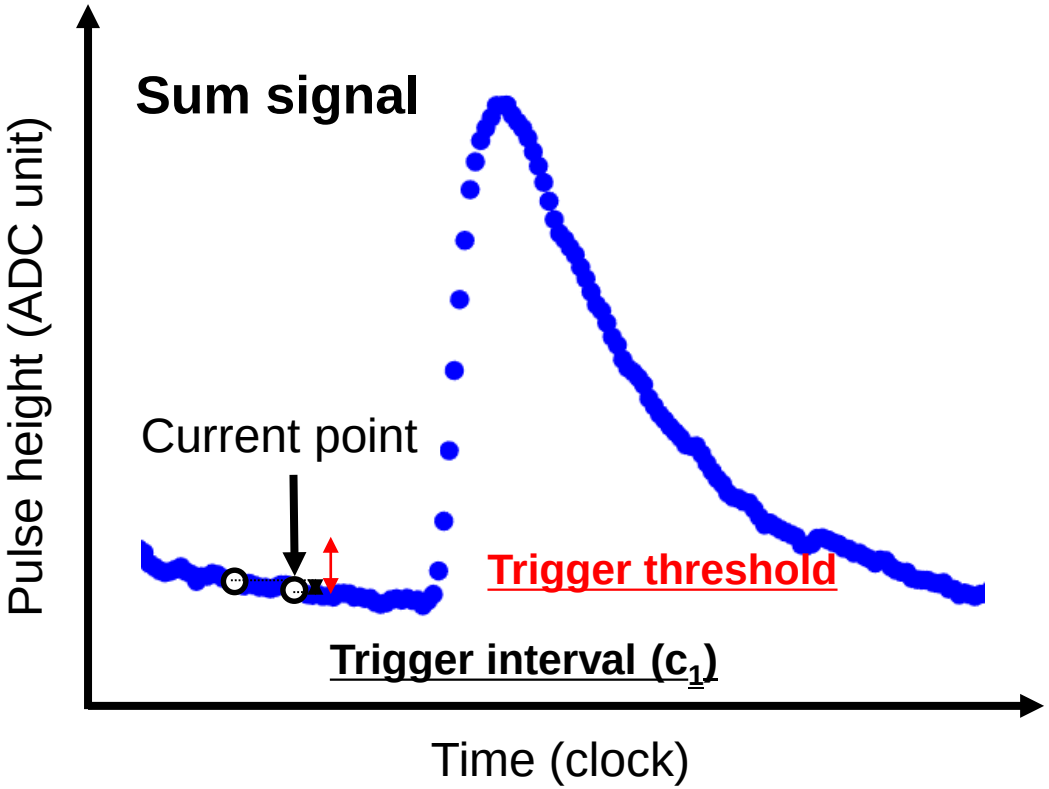
Triggering

- Trigger interval (c_1): **100, 200, 300, …, 900, 990 ns**
- Trigger threshold: **9, 18, …, 126, 135 ADC unit**
- The generation of trigger, based the difference between the current point and the previous (c_1) point

Digital signal processing: trigger







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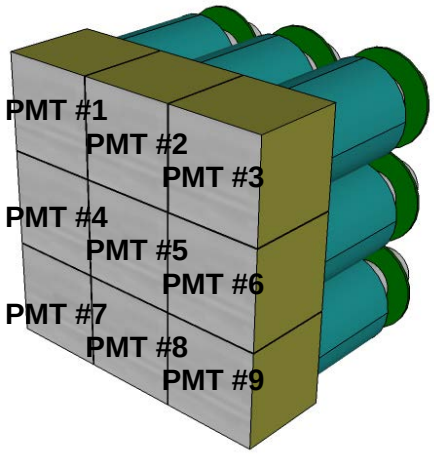

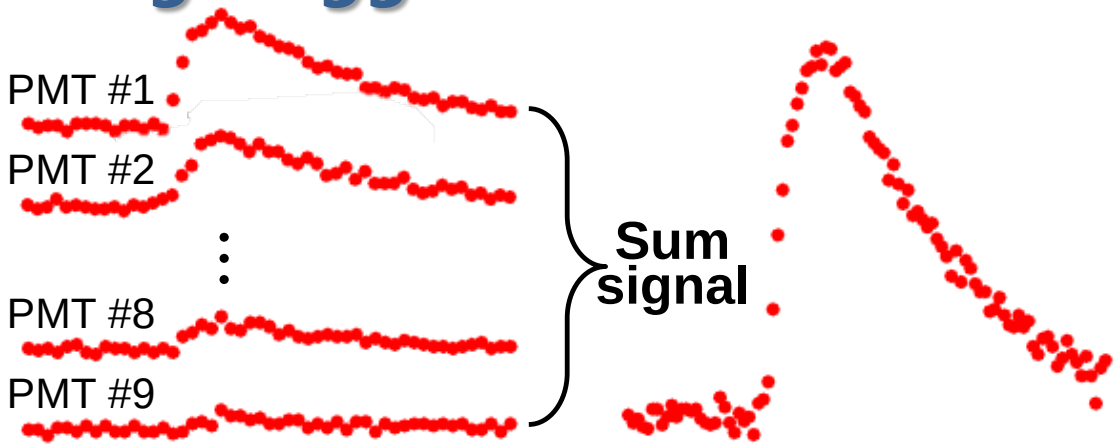

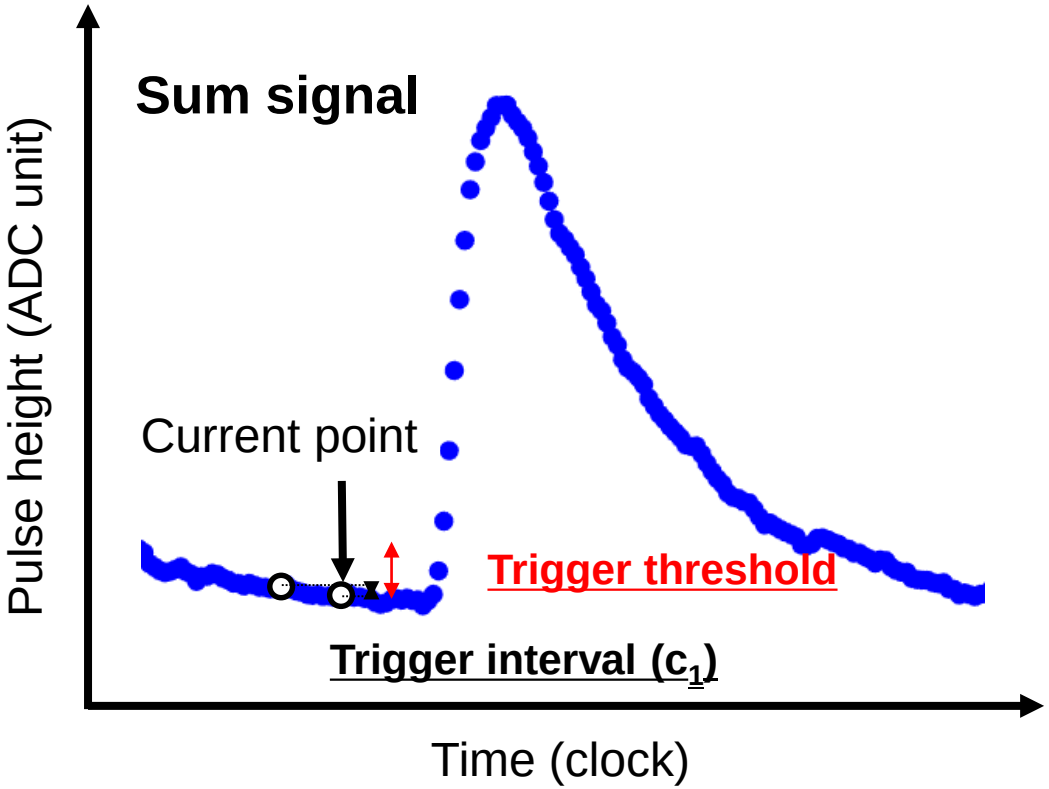

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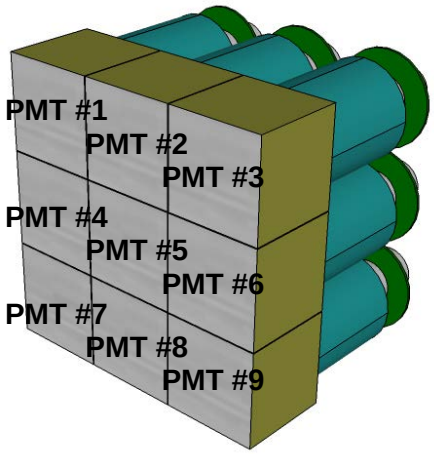

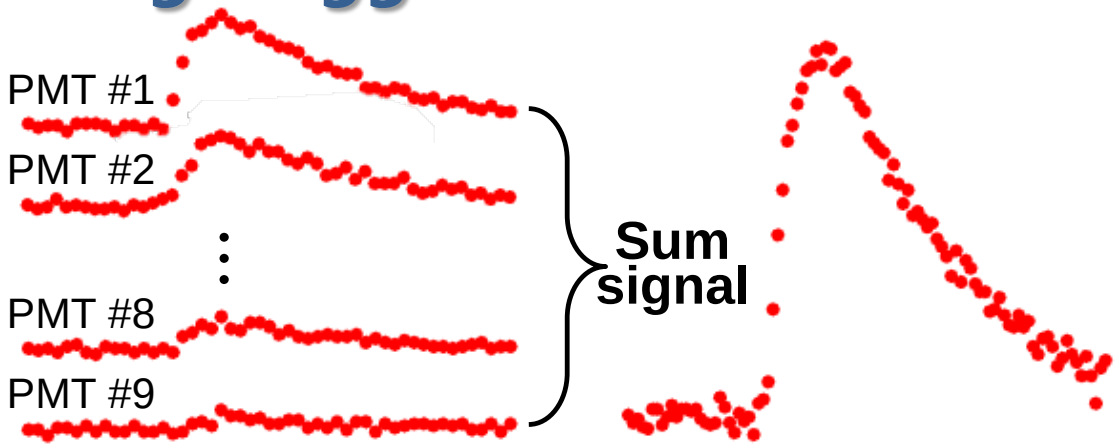

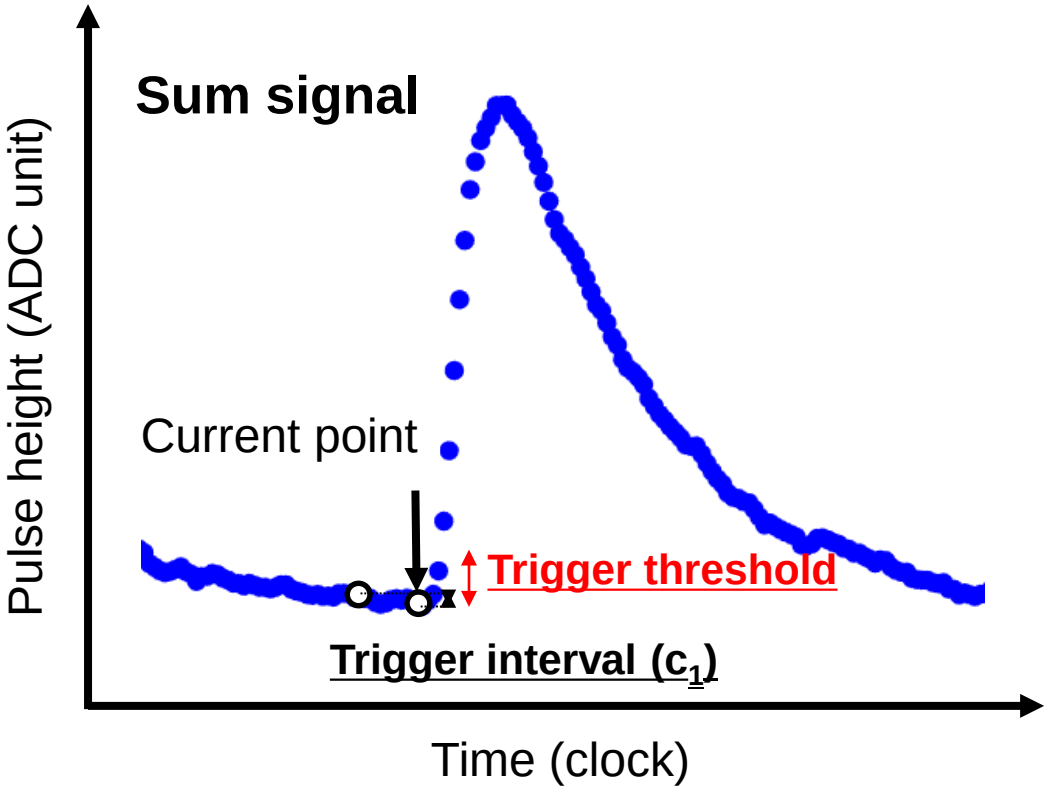

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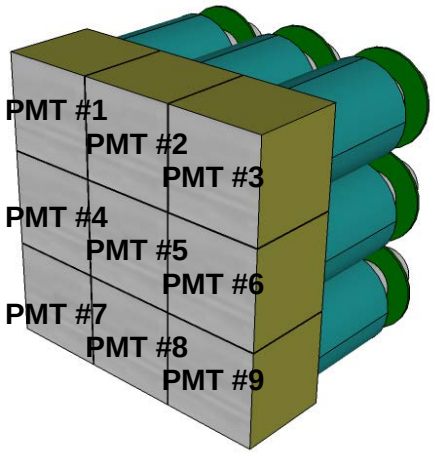

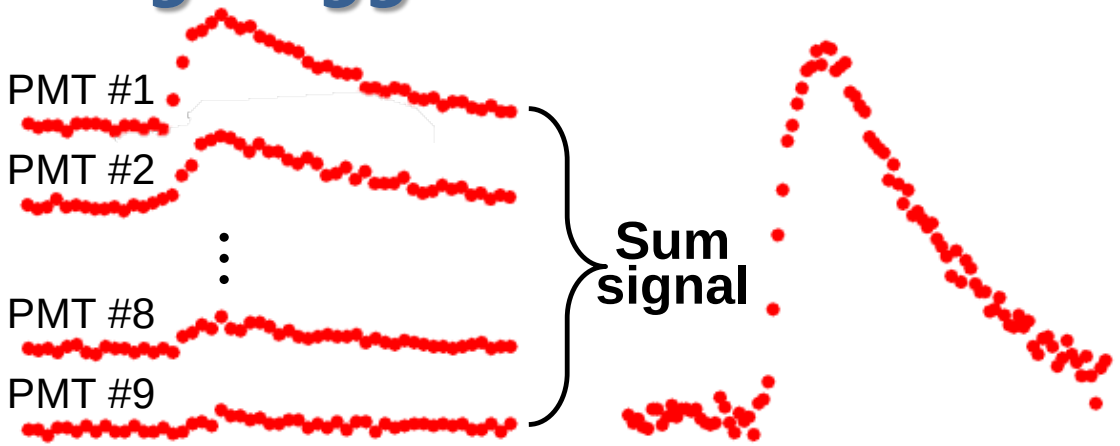

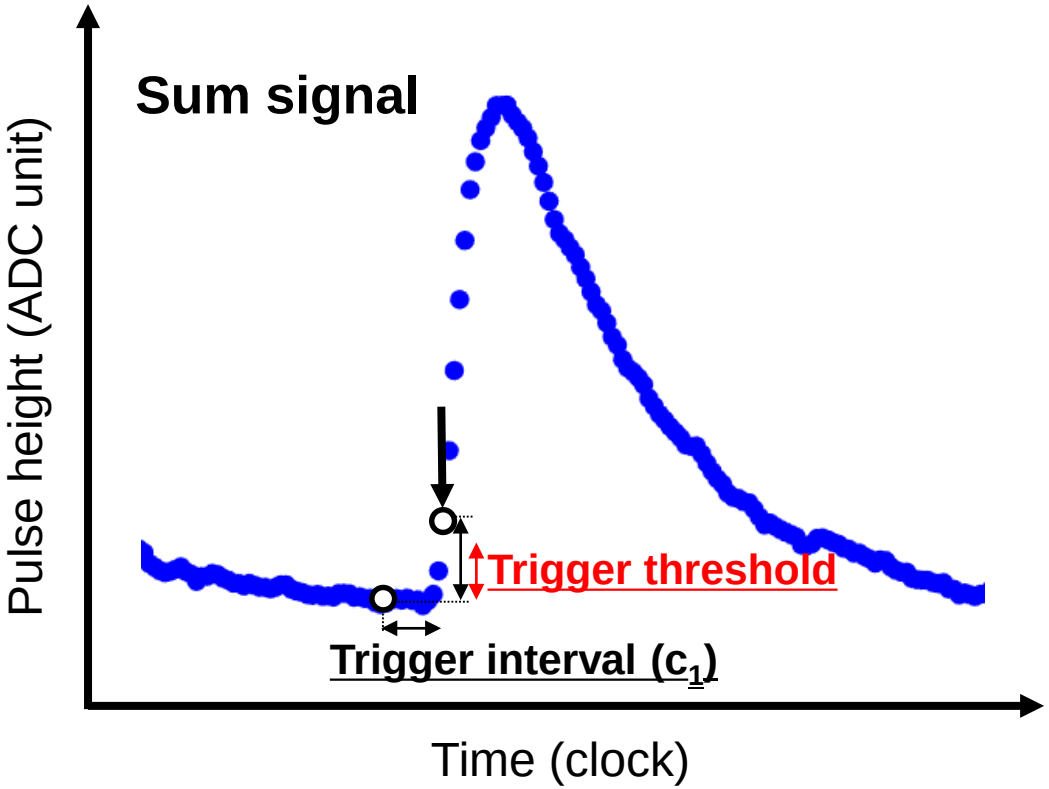

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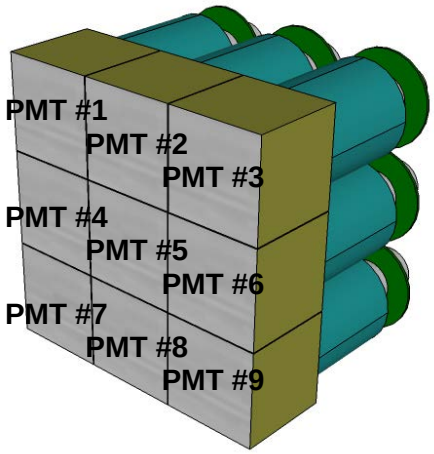

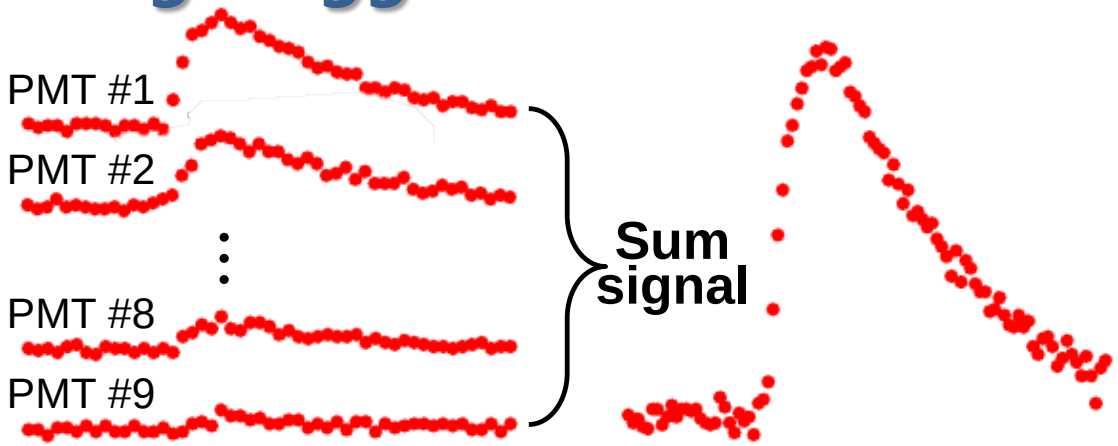

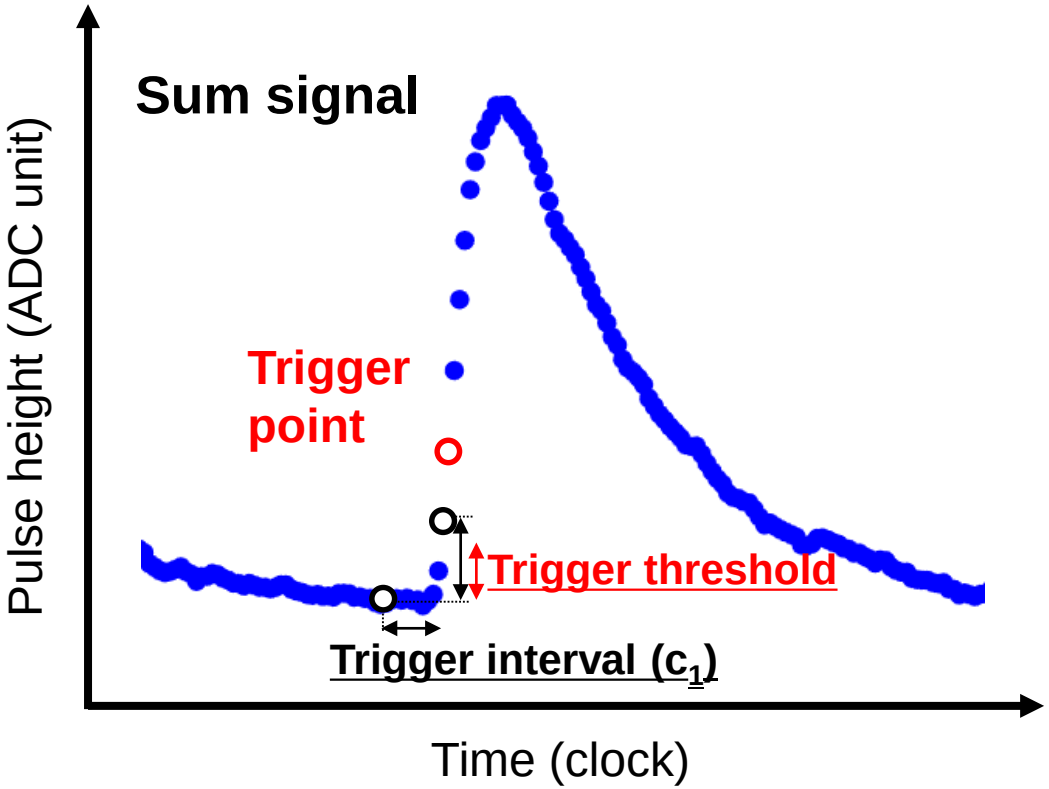

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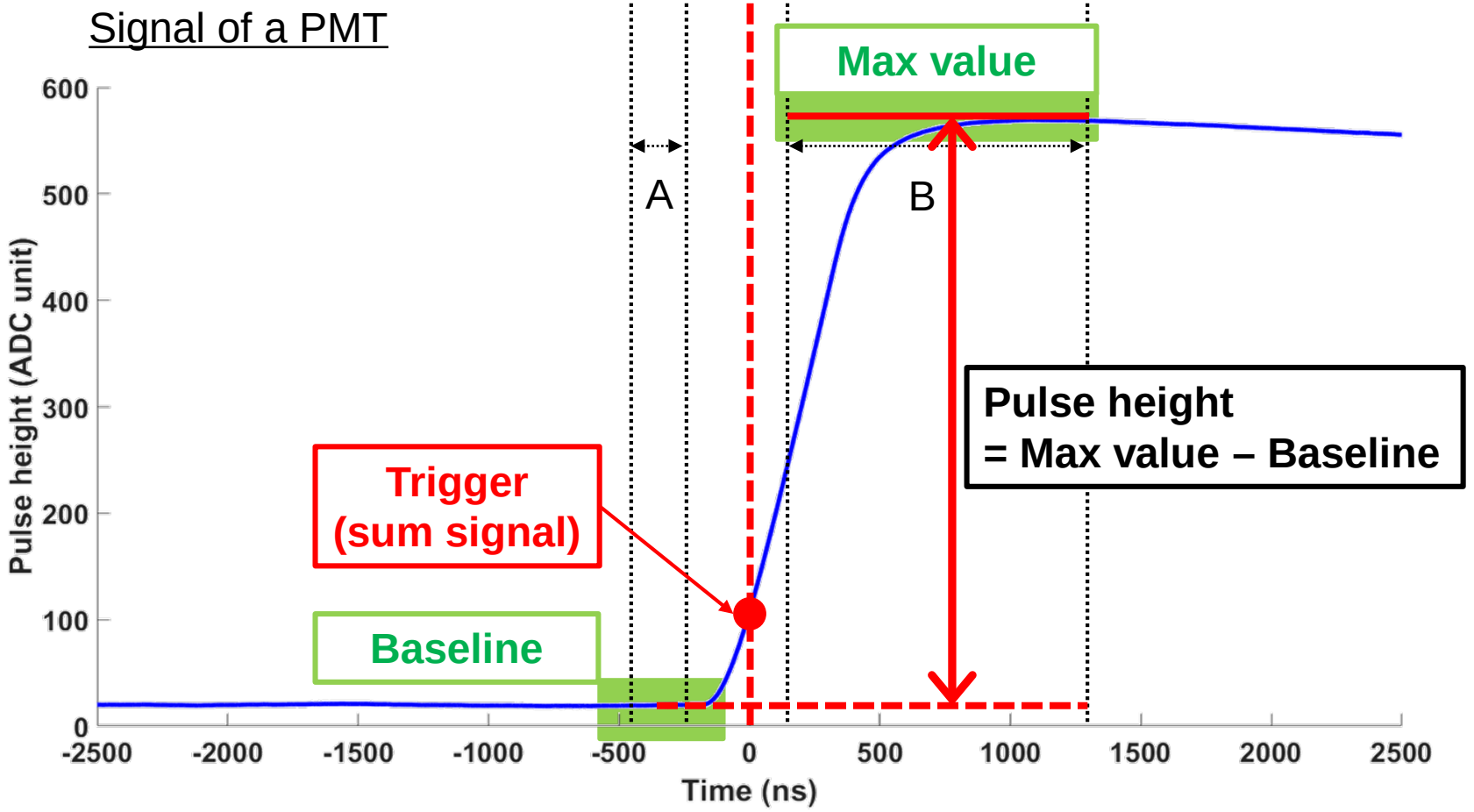
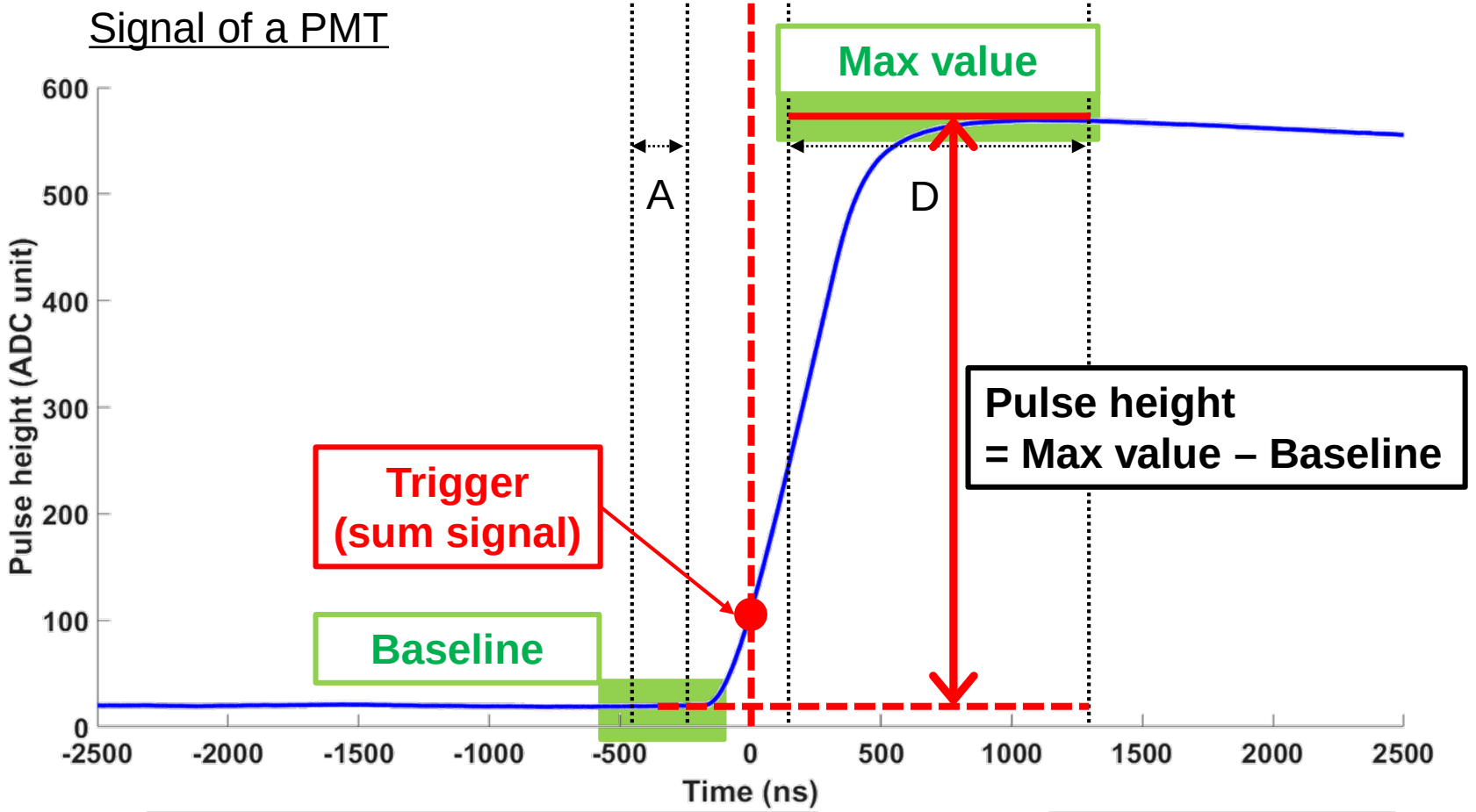
Digital signal processing: pulse height of PMT signal



A. Baseline measurement interval (c_2): **2^0, 2^1, 2^2, 2^3, 2^4 clock**

B. Maximum measurement interval (c_4): 100 clock

Digital signal processing configuration optimization



Low energy & noise performance

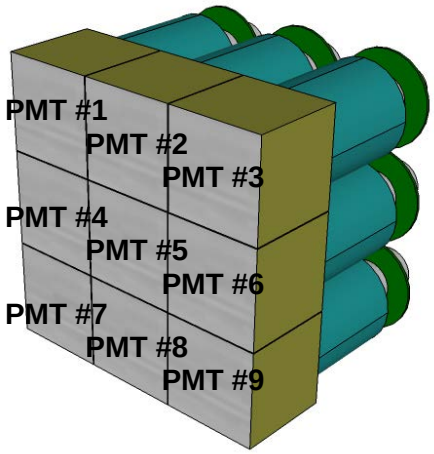
- Smooth window
- Trigger interval
  Trigger threshold

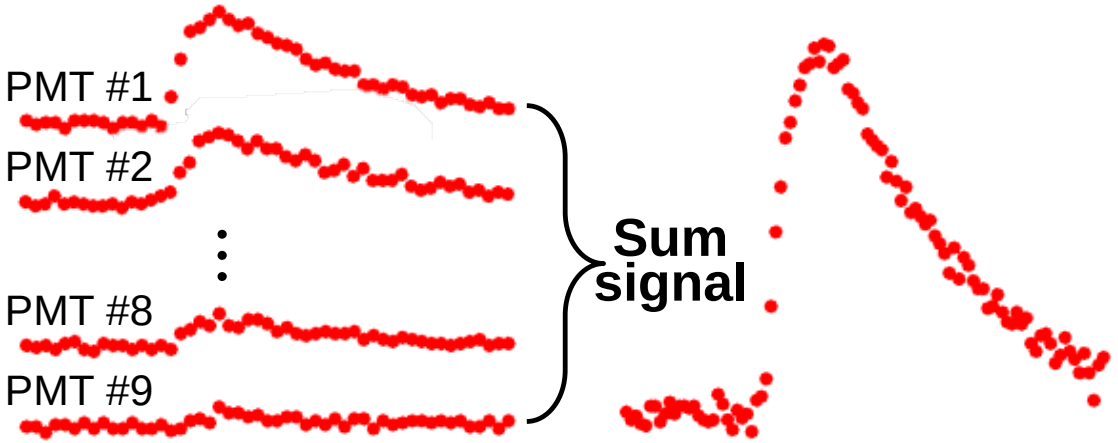
Measurement stability

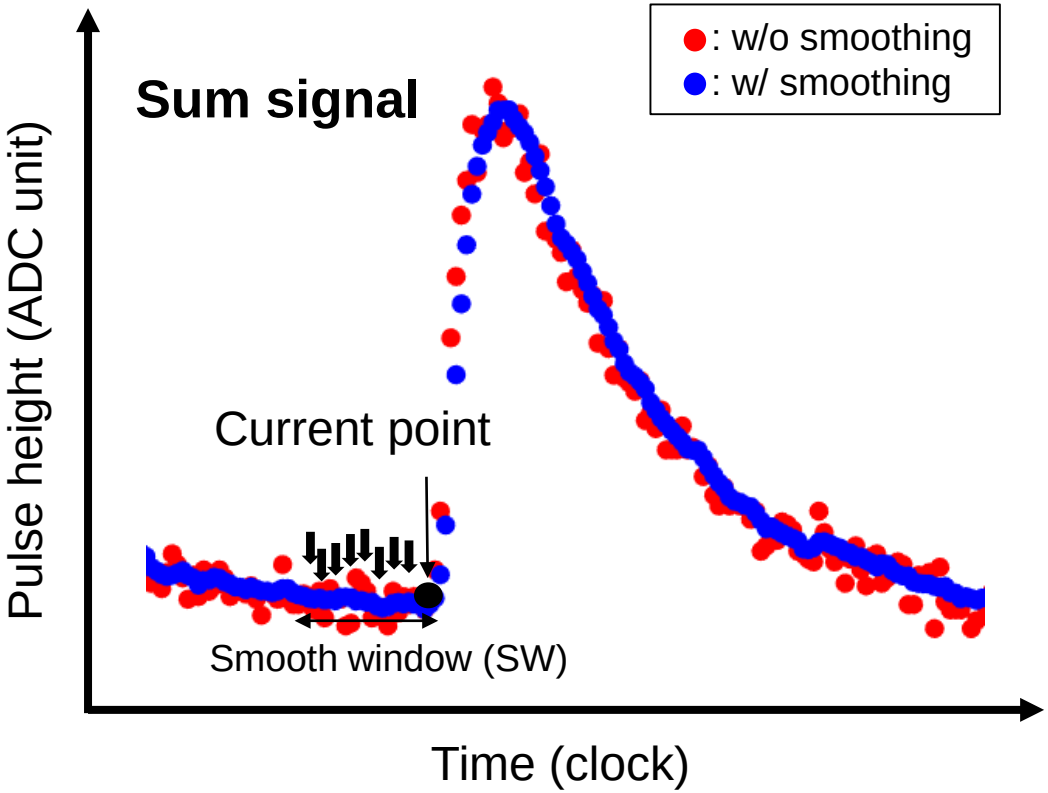
- Baseline measurement interval

Optimization of signal processing parameters

Optimization: smooth window







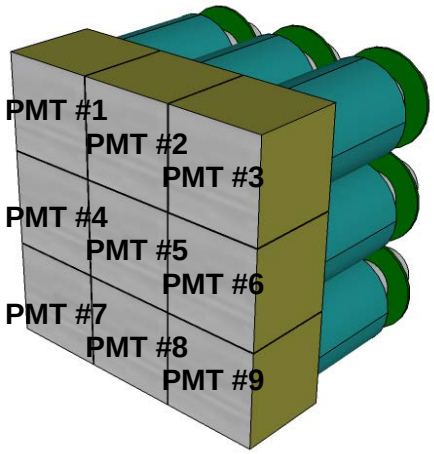
Smoothing

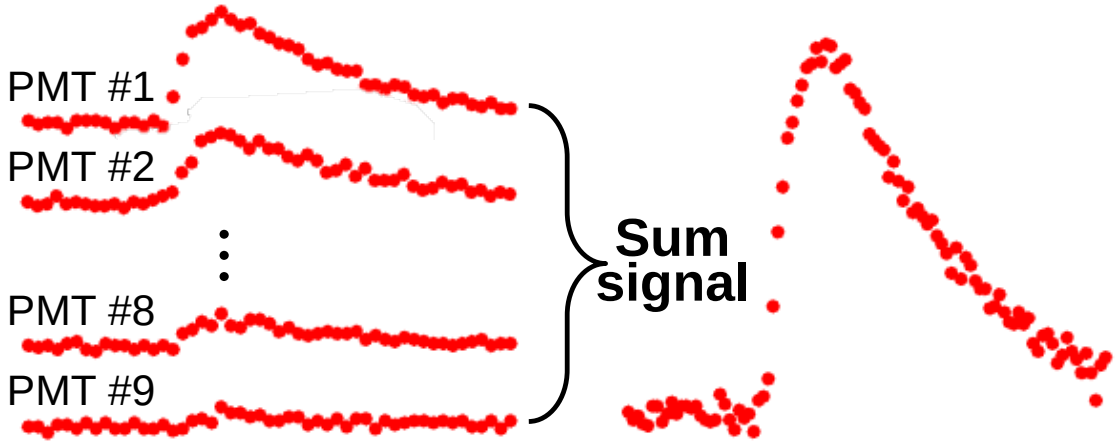
- Moving average
- The average of the previous 2^N points from current point
- Smooth window:
  2^0, 2^1, 2^2, **2^3** clock (=10 ns)

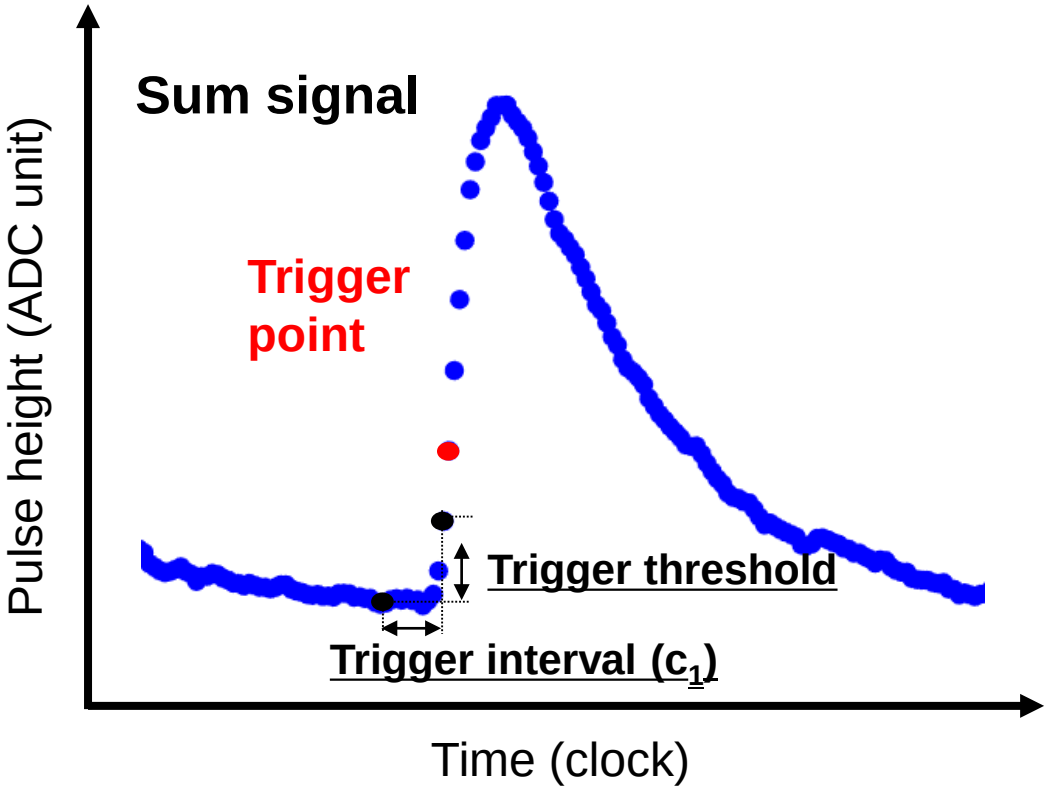
Smoothing on **sum signal**
→ stable triggering

Smoothing on **each channel**
→ stable pulse height measurement

Optimization: trigger







Trigger

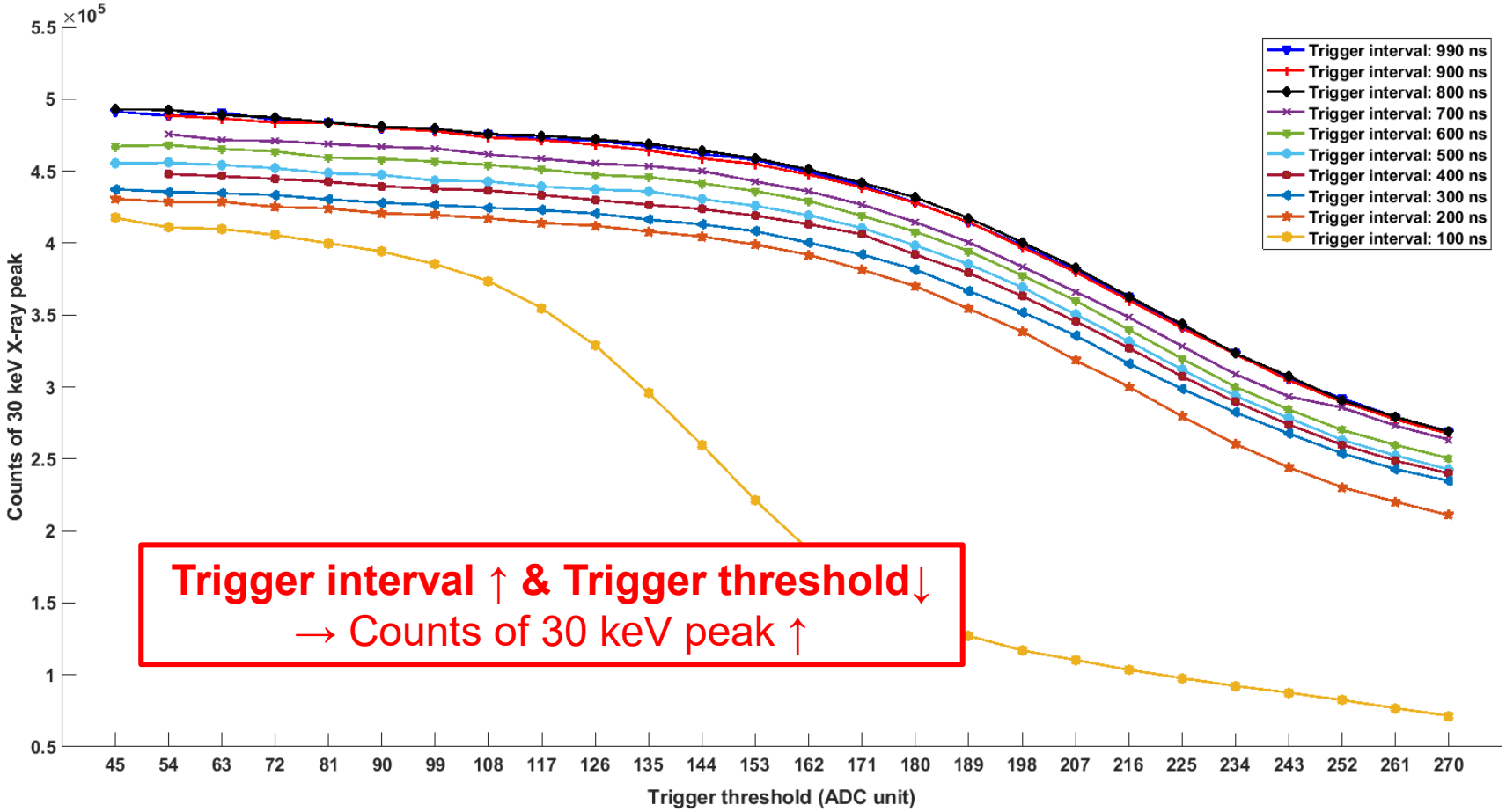
- Trigger interval (c_1):
  100, 200, 300, …, 900, 990 ns
- Trigger threshold:
  9, 18, …, 126, 135 ADC unit

Lower limit of energy measurement

→ high efficiency (~15%)

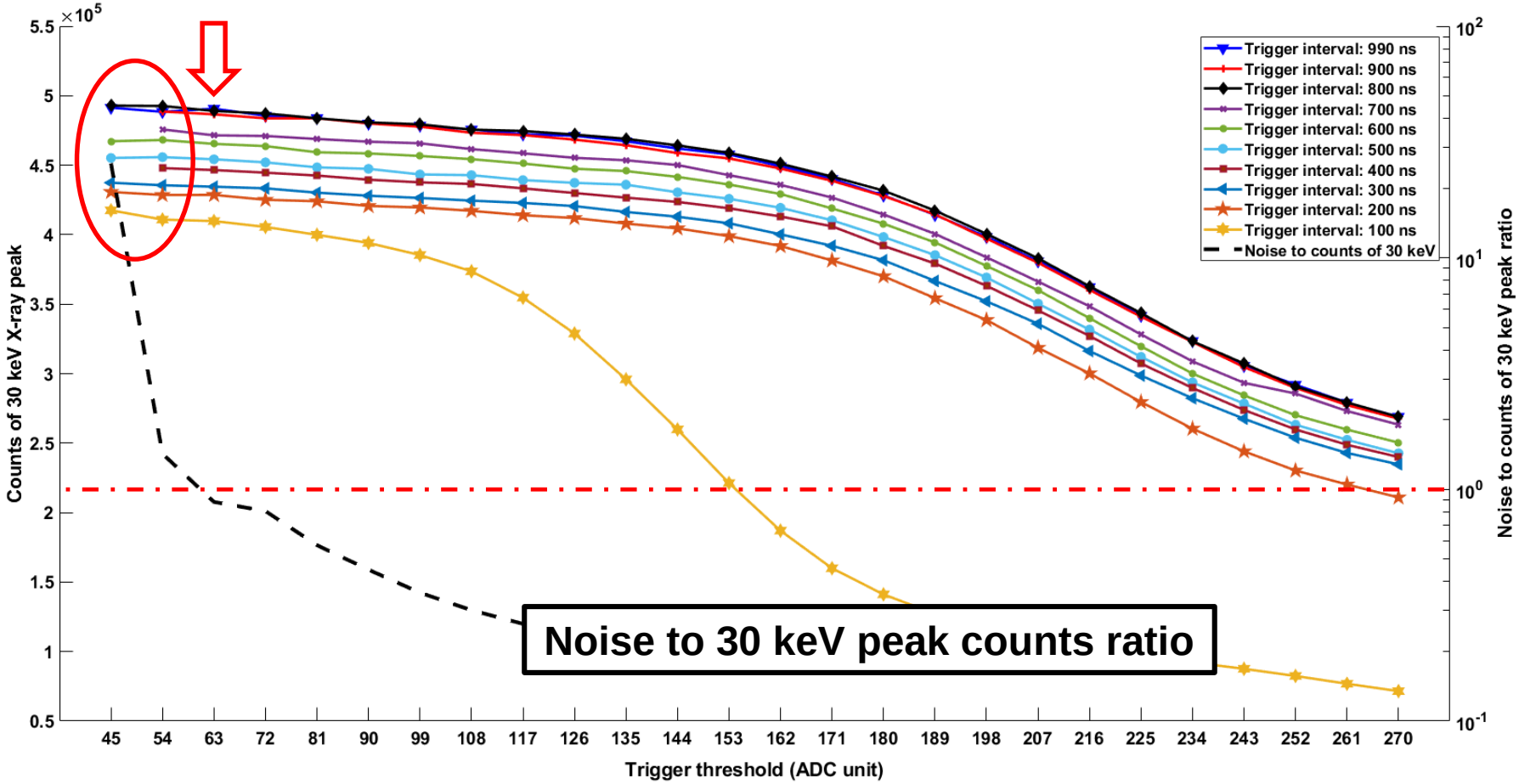
→ improved image resolution

Trigger threshold & trigger interval



Source: ^{137}Cs (80 μCi)
Position: @(0, 0, 50 cm)
Measurement time: 10 min
Trigger threshold (ADC unit): 45, 54, 63, 72, 81, 90, 108, 117, … , 252, 261, 270
Trigger interval (ns): 100, 200, 300, 400, 500, 600, 700, **800**, 900, 990

Trigger threshold & trigger interval



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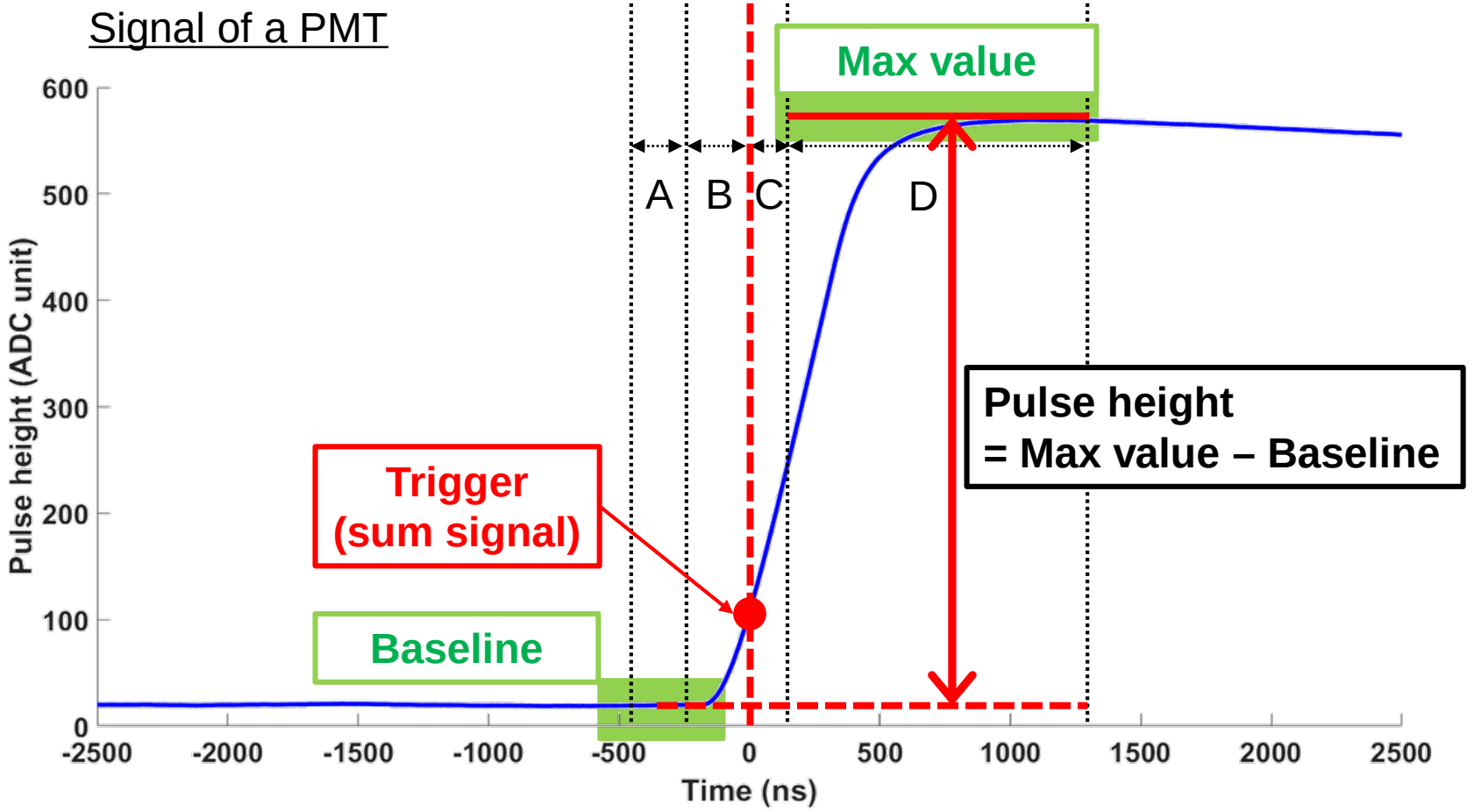
Optimization: baseline measurement interval



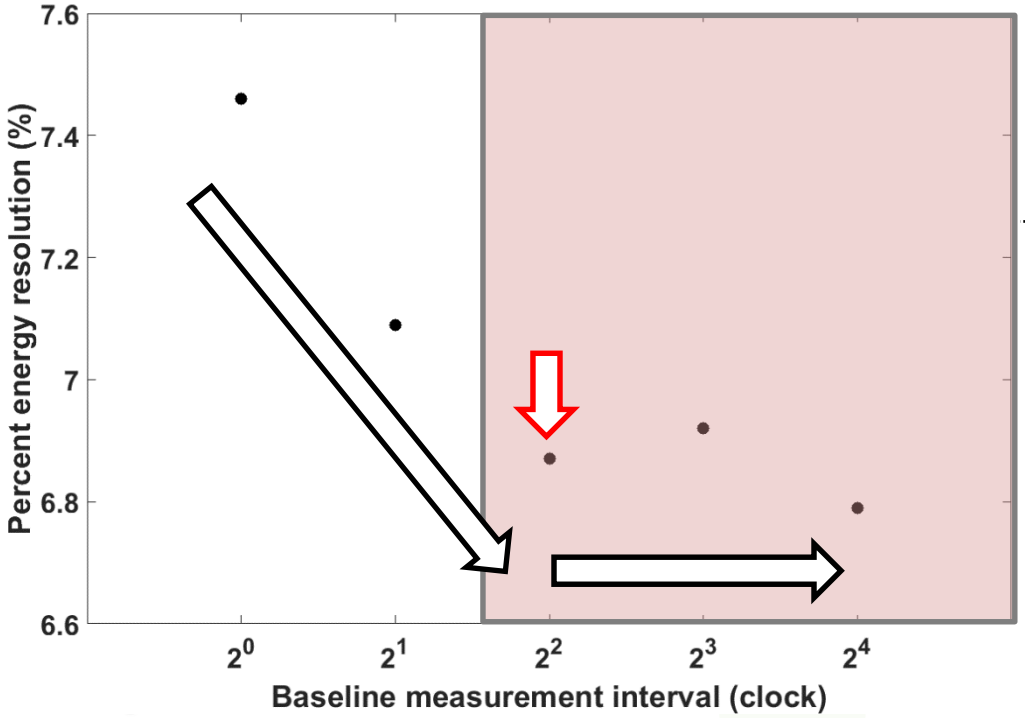
A. Baseline measurement interval (c_2): **2^0, 2^1, 2^2, 2^3, 2^4 clock**

B. Baseline side offset (c_3): (c_1)+1 clock

C. Maximum side offset: 1 clock

D. Maximum measurement interval (c_4): 100 clock

Optimization: baseline measurement interval



Baseline measurement interval	Energy resolution (%)
2^0	7.46
2^1	7.09
2^2	**6.87**
2^3	6.92
2^4	6.79

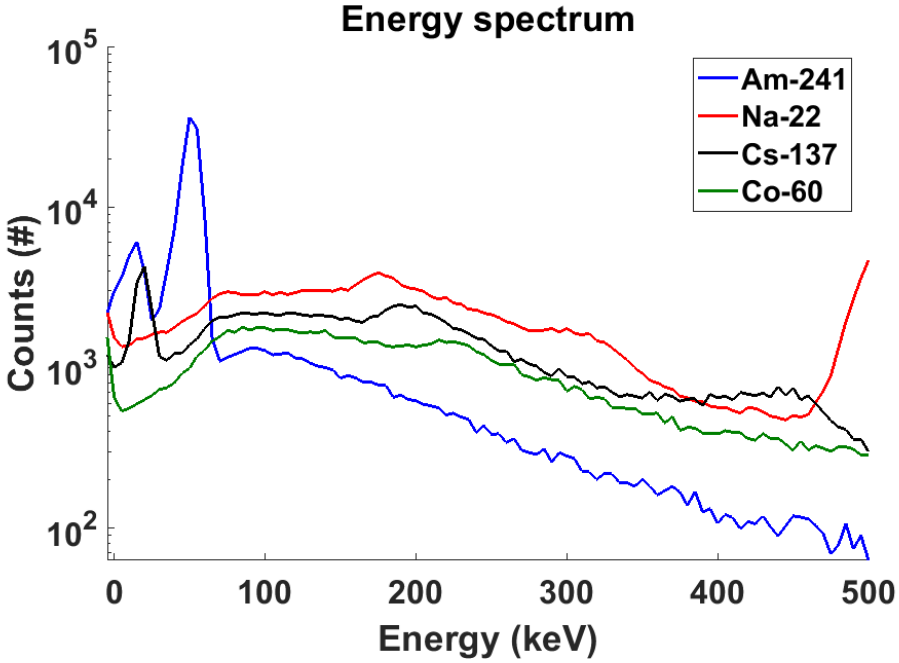
A. Baseline measurement interval (c_2): 2^0, 2^1, **2^2**, 2^3, 2^4 clock

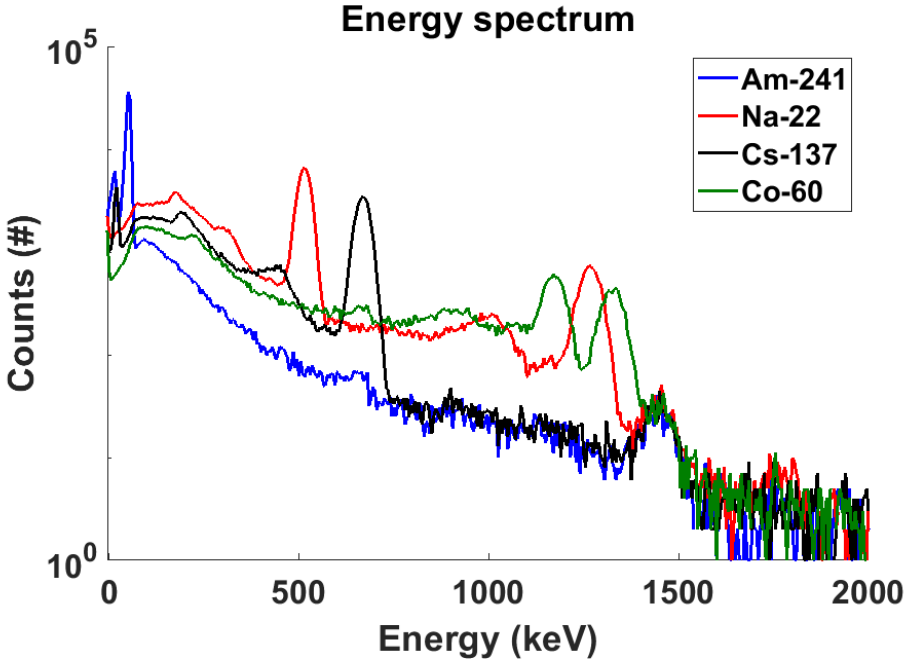
B. Baseline side offset (c_3): (c_1)+1 clock

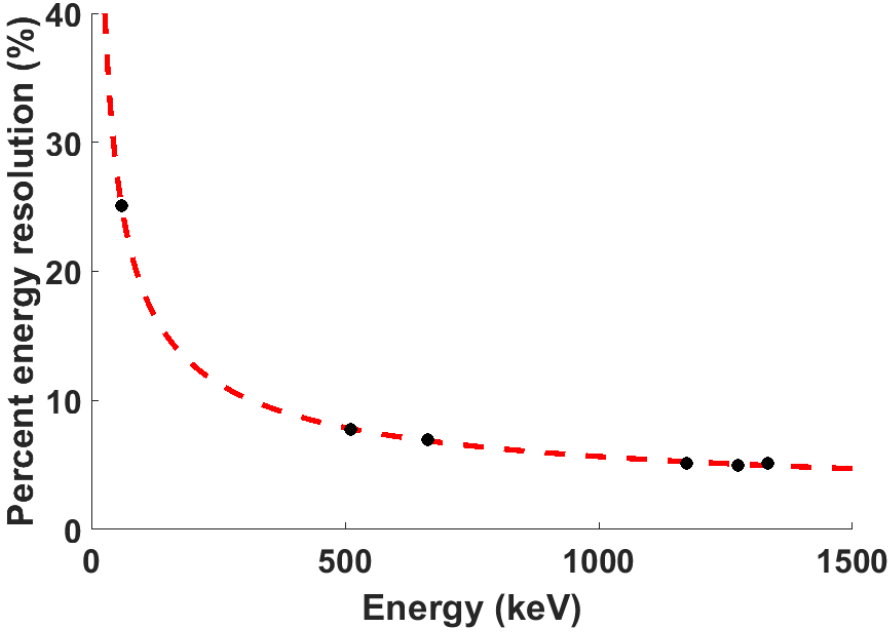
C. Maximum side offset: 1 clock

D. Maximum measurement interval (c_4): 100 clock

Performance evaluation with optimized parameters

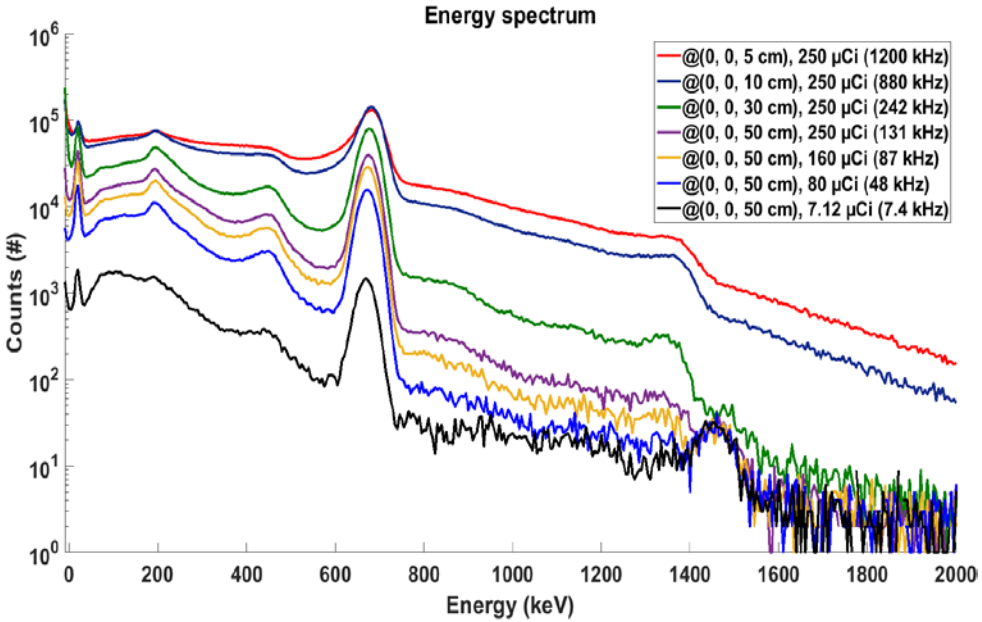


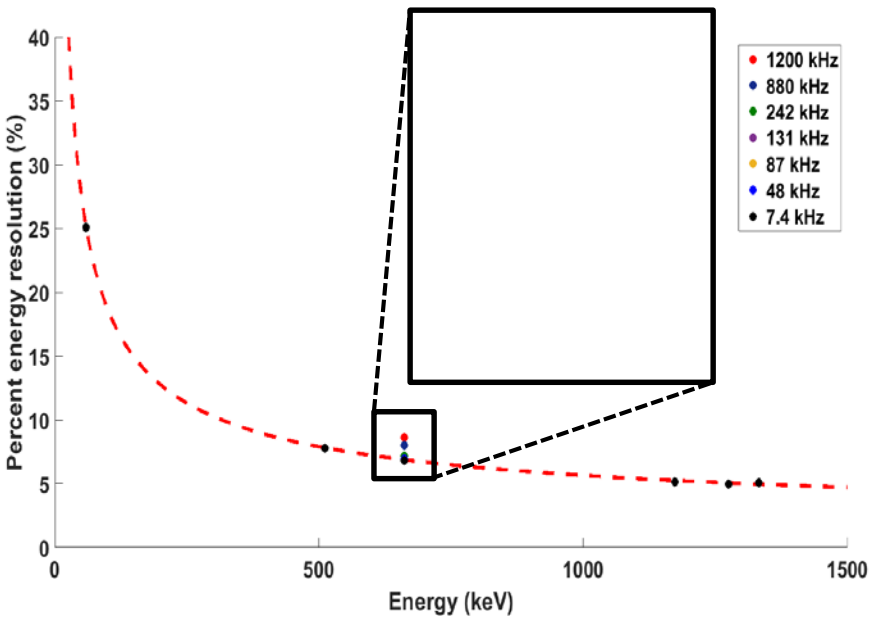




Energy (MeV)	Energy resolution (%)
0.060	25.1
0.511	7.79
0.662	**6.87**
1.173	5.16
1.275	4.98
1.332	5.11

Energy resolutions as count rates





Energy (MeV)	Activity (μCi)	Position	Count rate (kHz)	Energy resolution (%)
	7.12	@(0, 0, 50 cm)	7.4	6.83
	80	@(0, 0, 50 cm)	48	6.96
	160	@(0, 0, 50 cm)	87	6.89
0.662	250	@(0, 0, 50 cm)	131	6.94
	250	@(0, 0, 30 cm)	242	7.19
	250	@(0, 0, 10 cm)	880	7.99
	250	**@(0, 0, 5 cm)**	**1200**	**8.60**

Conclusion

Conclusion

- In the present research, the **high-speed multi-channel data acquisition system**, directly digitizing PMT signals, was developed and the optimization of the parameters was conducted.

- The developed FPGA based high-speed multi-channel DAQ system includes **smoothing**, **triggering**, and **pulse height measurement.**

- Considering the stable performance and characteristic of the noise, each parameter was optimized.

- The Optimized system not only performed **energy resolution of 6.9%** for the **^{137}Cs source** without significant peak shifting, but also maximized the performance **lower limit of energy measurement (~30keV).**

Thank you!