Performance and commissioning of HAPDs in the Belle II Aerogel RICH counter

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10th International Workshop on Ring Imaging Cherenkov Detectors

Outline

- **Introduction**
  - Belle II / ARICH counter
  - Photon detector : HAPD
  - Peripheral of HAPD
- **Performance evaluation of HAPDs**
  - Quality of installed HAPDs
  - Performance evaluation
  - Temperature dependency
- **HAPDs in the commissioning of Belle II**
  - Performance during Phase II operation
- **Summary and plan**

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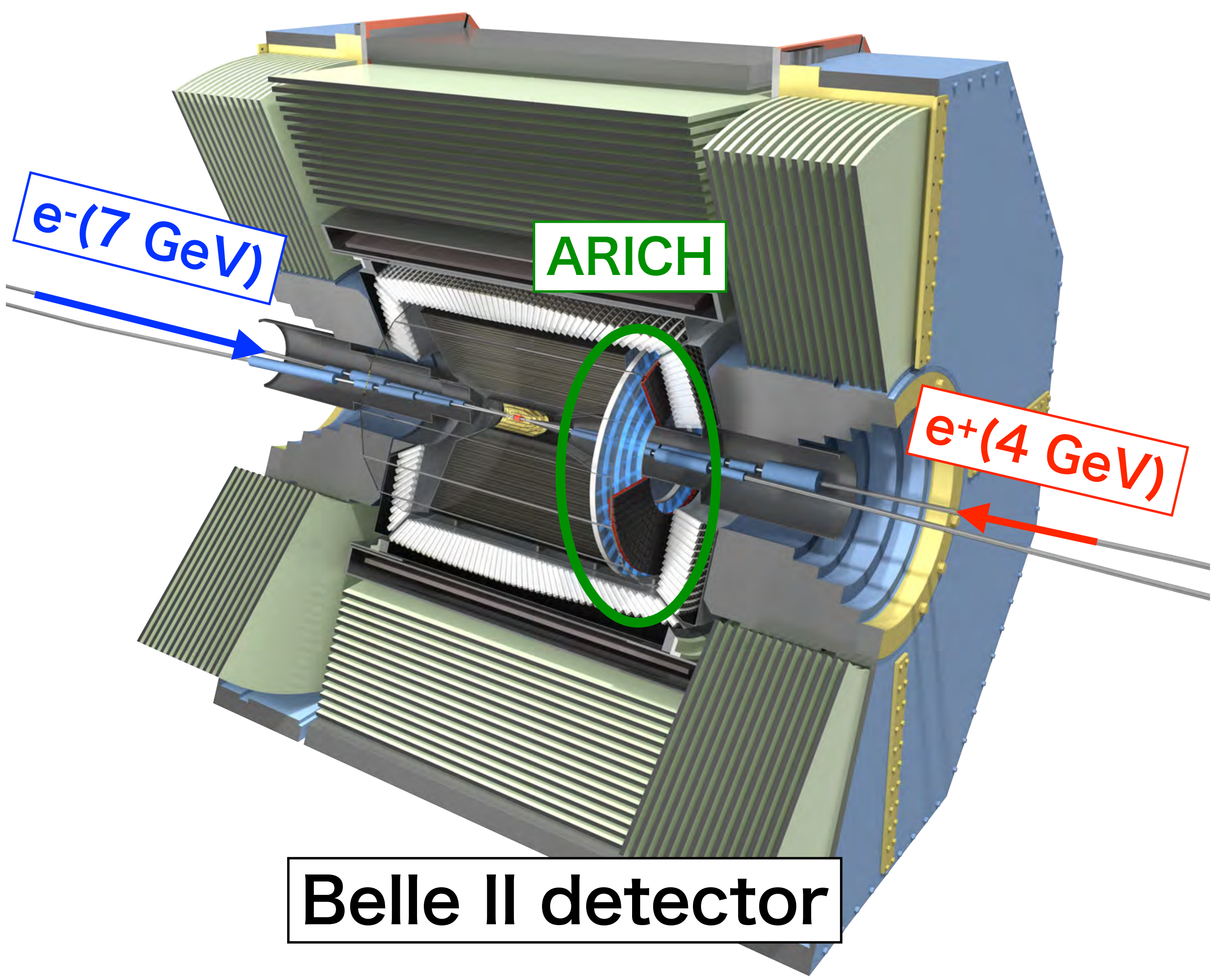
The Belle II experiment

The Belle II experiment at KEK aims to search for new physics beyond the Standard Model using 50 ab^{-1} integrated luminosity.



the Belle II experiment

the SuperKEKB accelerator

target luminosity : $8\times10^{35}[cm^{-2}s^{-1}]$

(luminosity at KEKB ×40)

the Belle II detector

4π acceptance

30 kHz readout

high background resistance

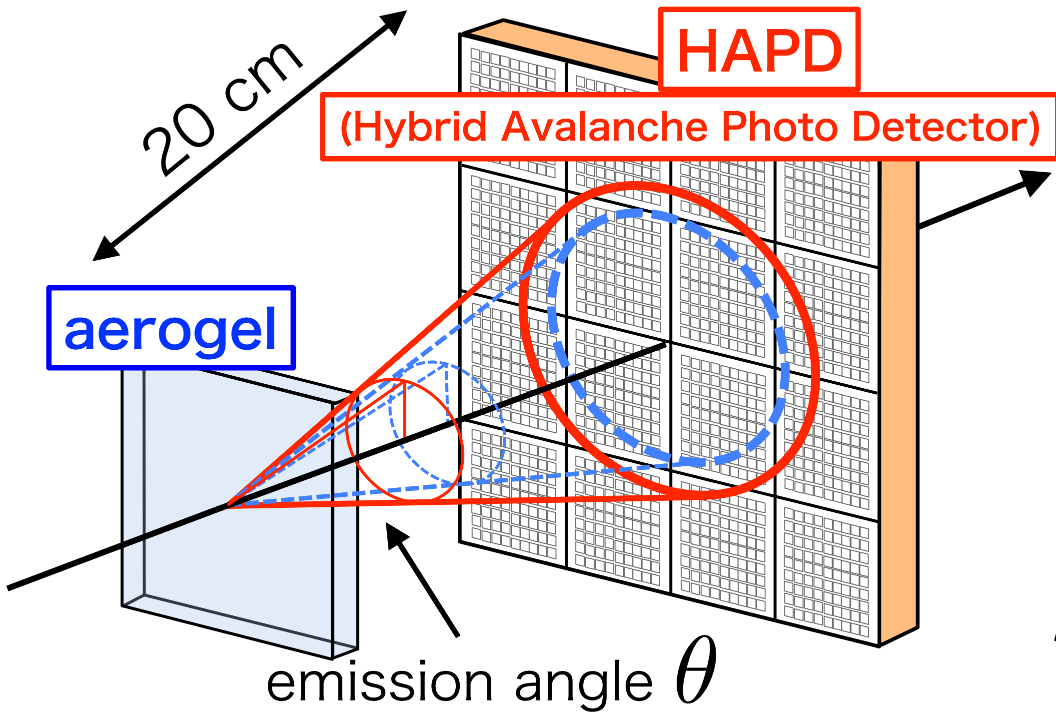
ARICH counter

Identify charged π/K

between 0.5 GeV/c and 4.0 GeV/c

at the endcap region

Particle identification in ARICH

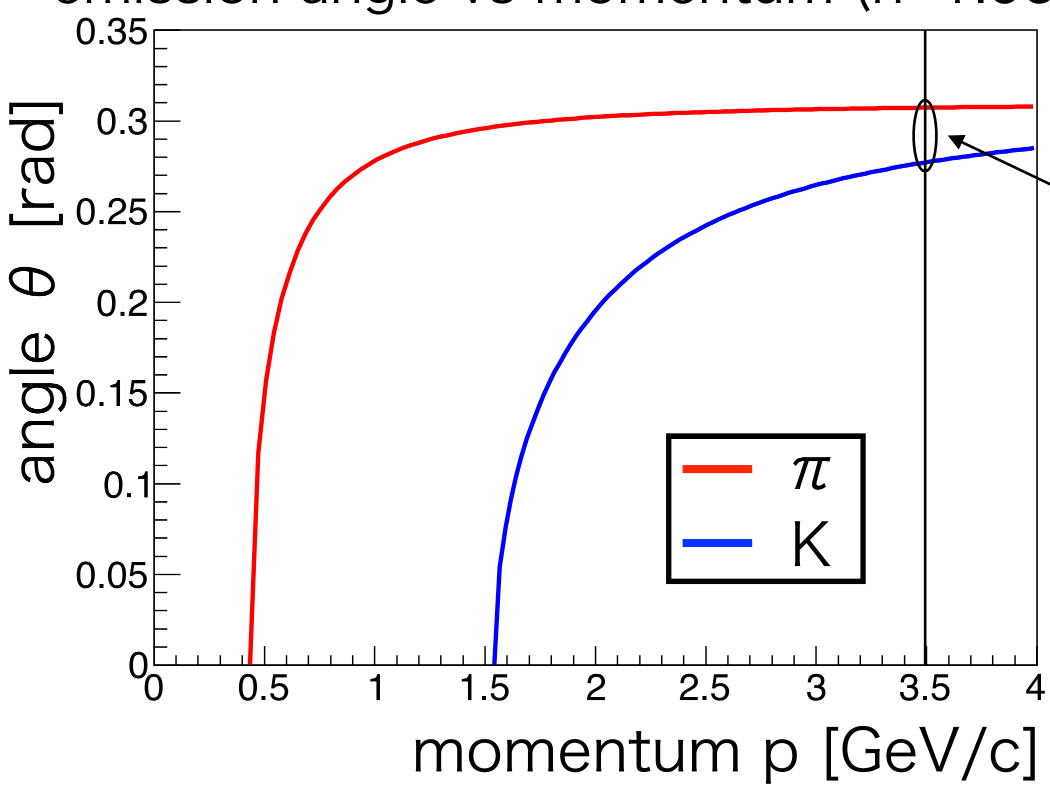


- Cherenkov photons emitted in aerogel are detected on the HAPD as 2D image.
- Measuring emission angle from 2D image ⇒perform particle identification.

$$m = p\sqrt{n^2\cos^2\theta - 1}$$

m : mass
n : refractive index
p : momentum

emission angle vs momentum (n=1.05)



radius of ring at p=3.5 GeV/c、n=1.05

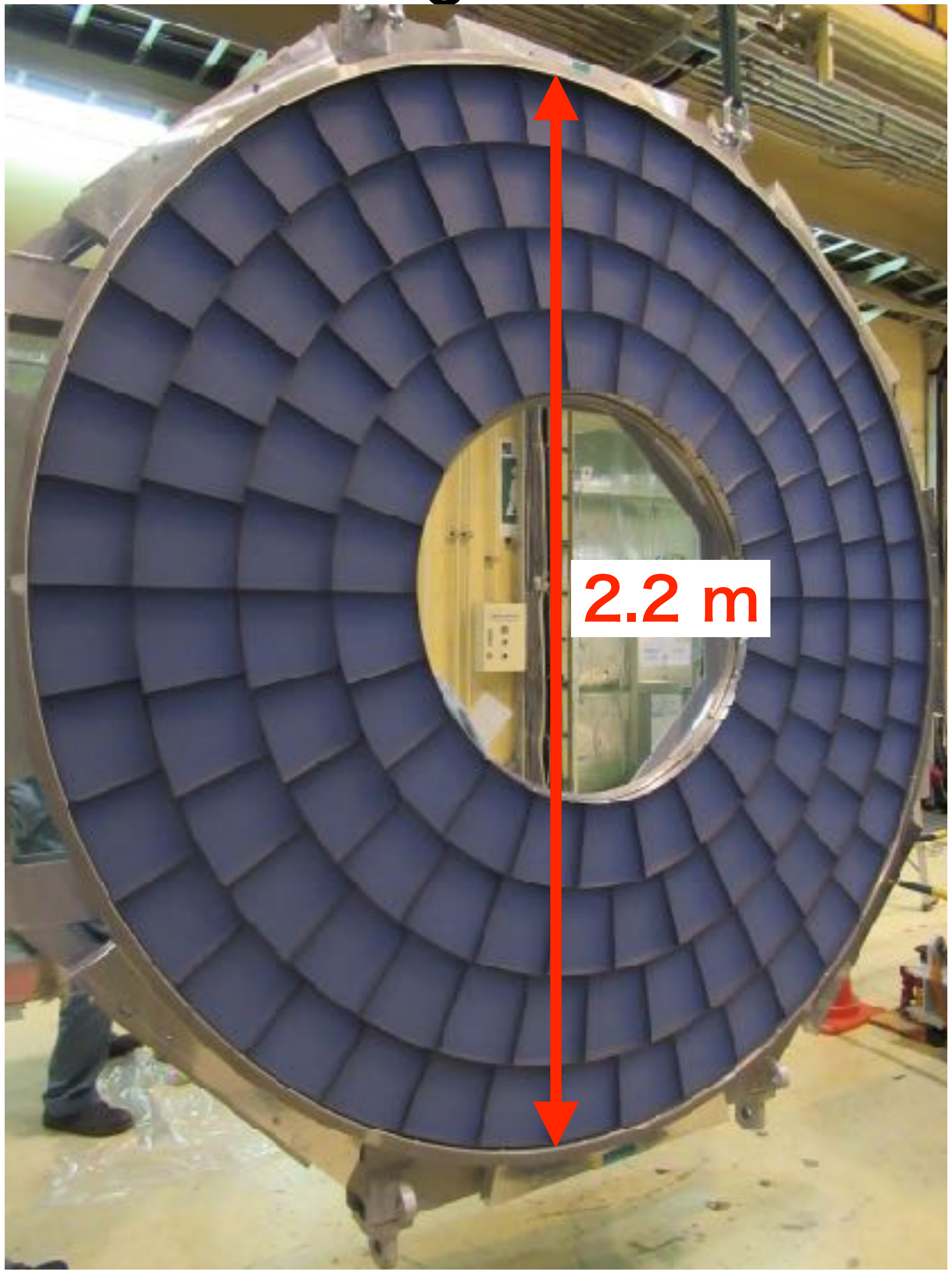
π : r=54 mm (307 mrad)
K : r=48 mm (277 mrad)

difference is 6 mm at 3.5 GeV/c

We have developed photon detector which has high position resolution

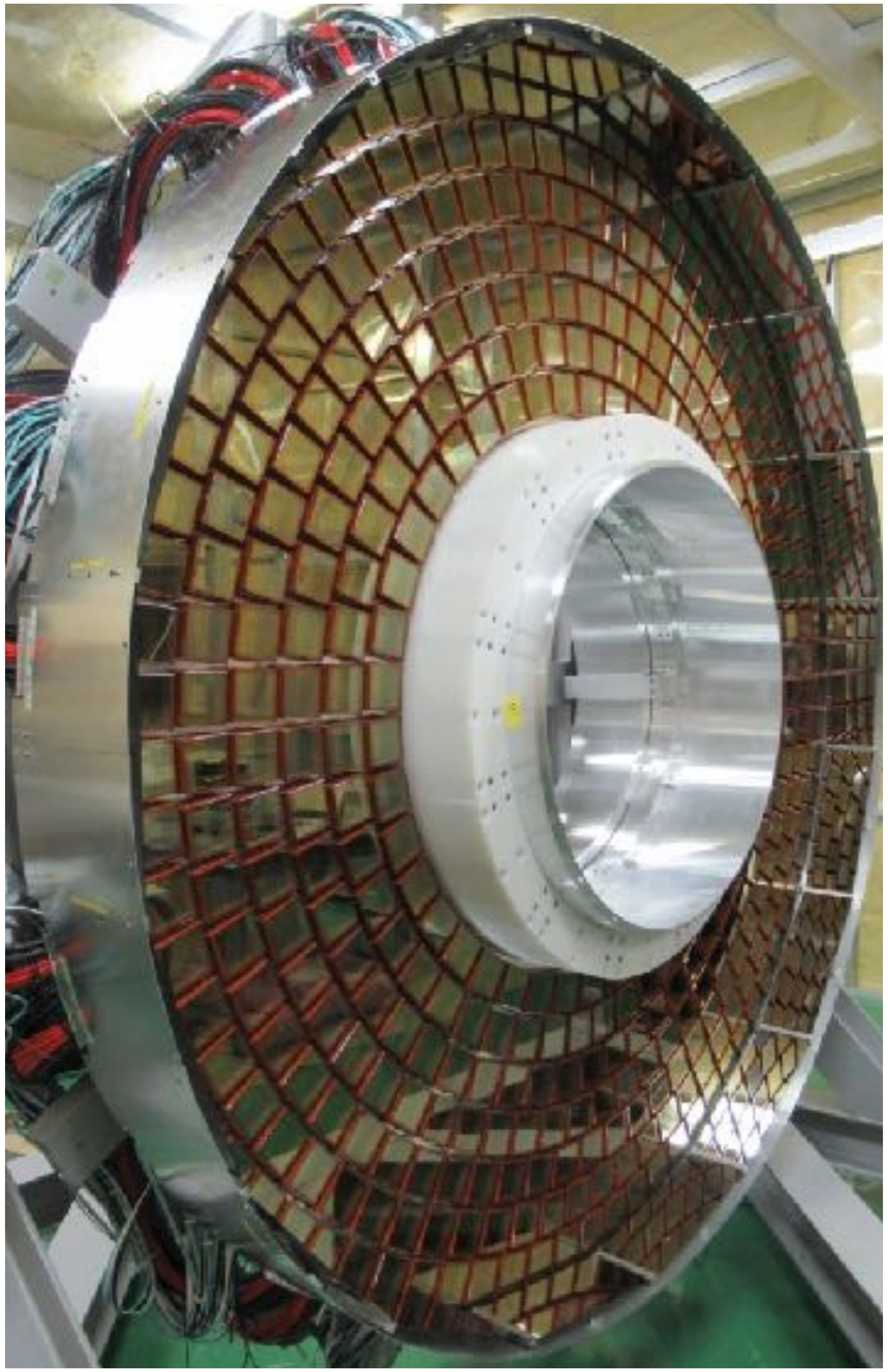
ARICH(Aerogel tiles and HAPDs)

aerogel side



aerogel : 248 tiles

HAPD side



HAPD : 420 sensors

History and schedule

2017/9/20 : ARICH was installed to Belle II

2018/3/19~7/17 : Phase II run (Belle II detector w/o VXD)

now

2018/9 : ARICH is extracted from Belle II

↕ preparation for Phase III

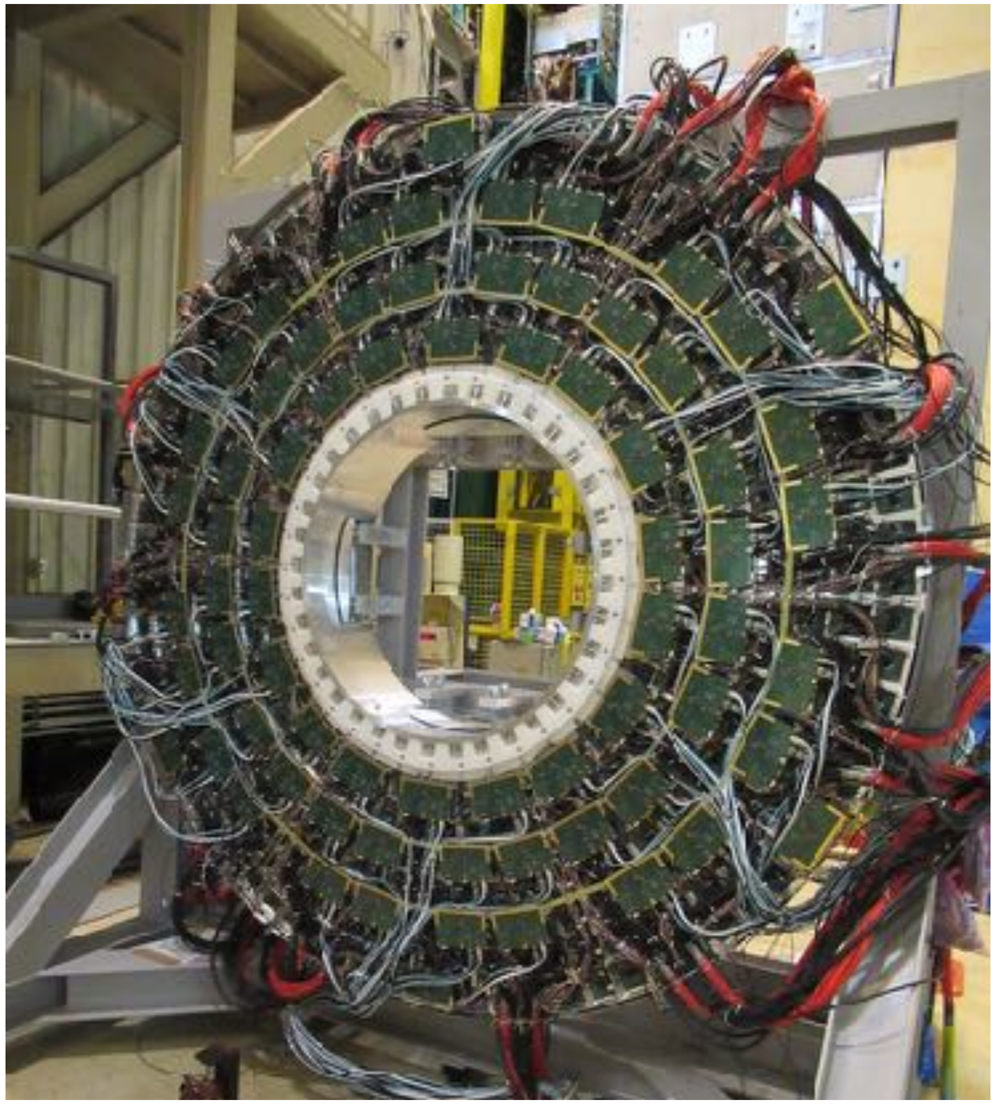
2019/2 : Phase III run start (full Belle II detector)

Phase II main purpose for ARICH

- Belle II integrated operation of ARICH
- Optimize ARICH parameters by integrated operation

Preparation for Phase III

- Extract ARICH and improve hardware

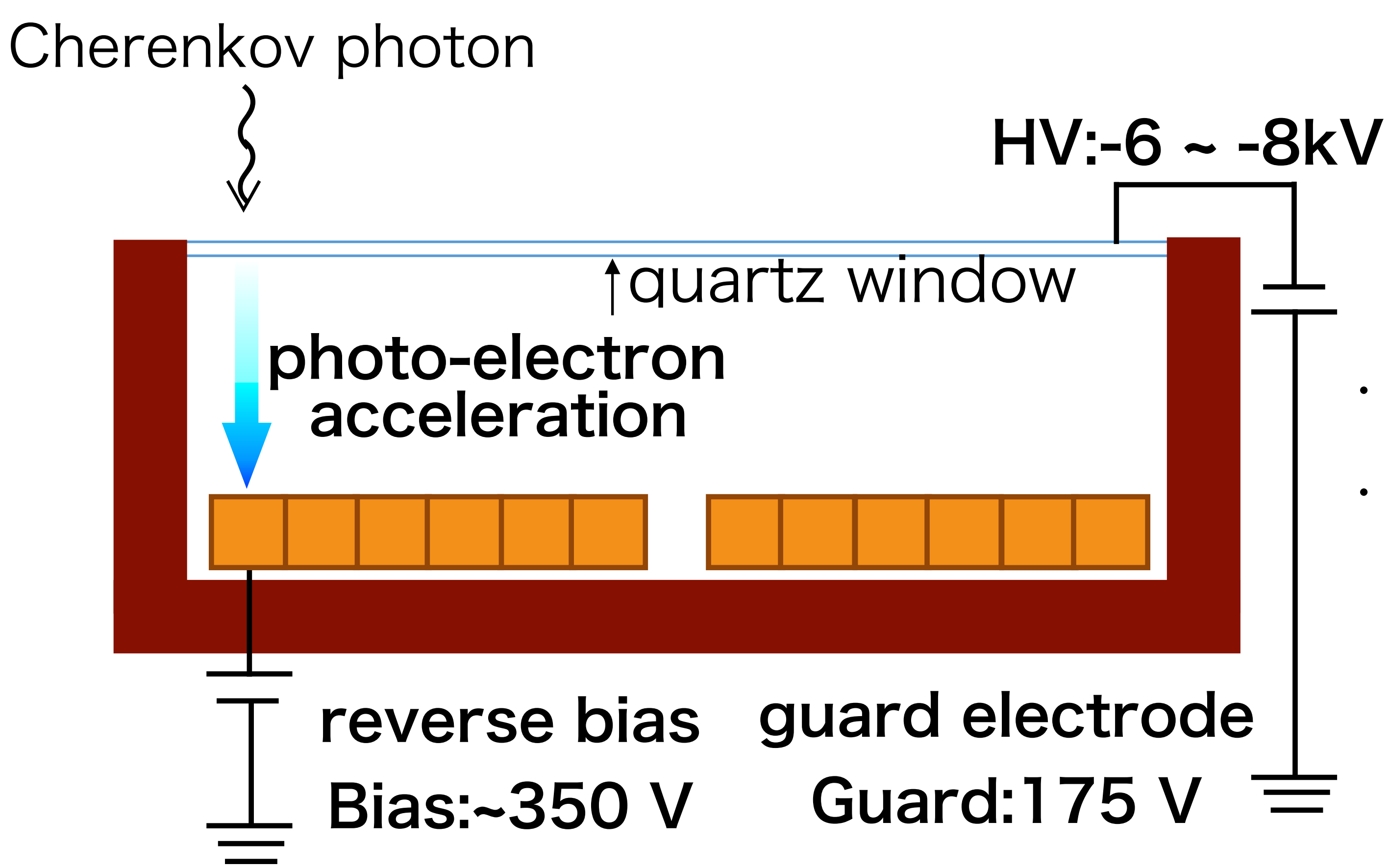


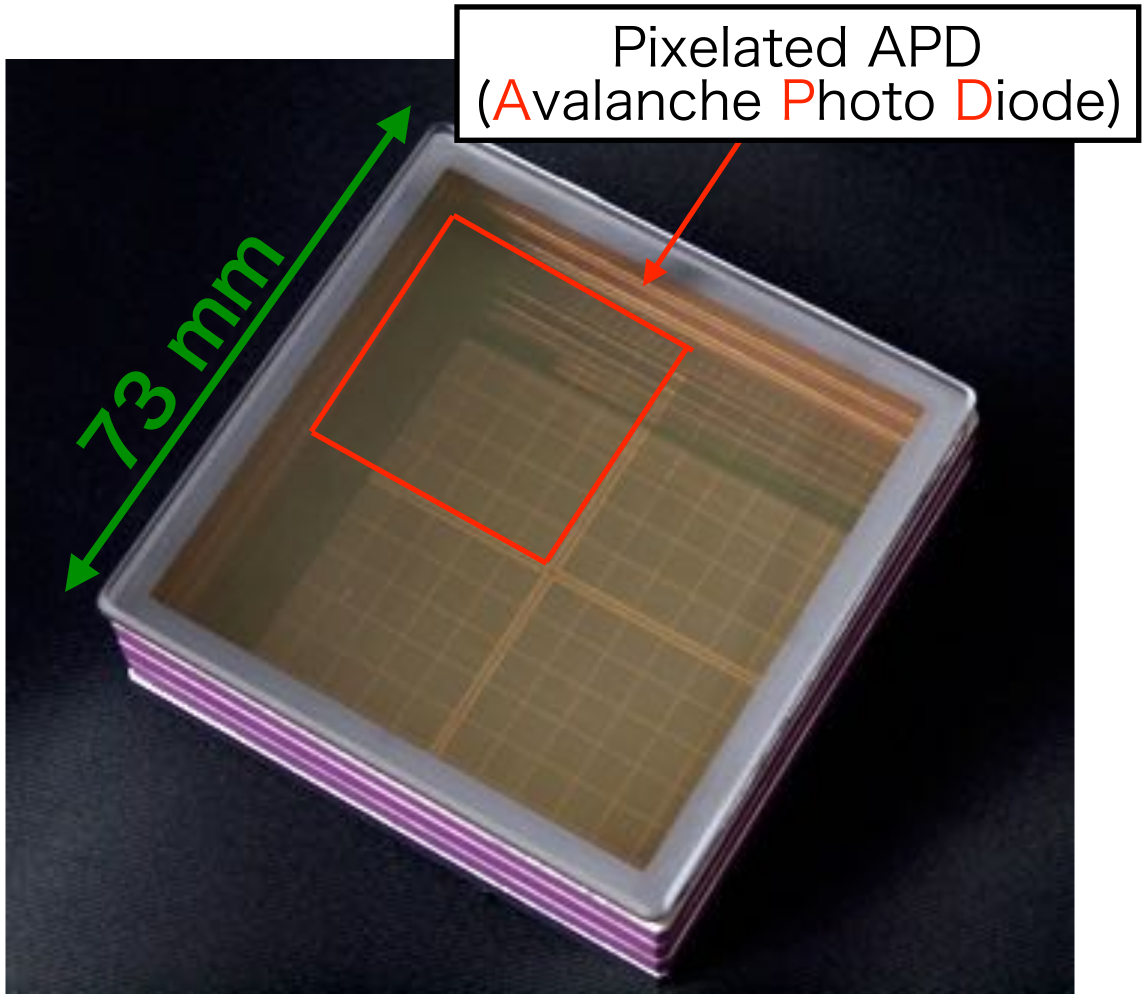
HAPD

Hybrid Avalanche Photo Detector

- Single photon detection
- Usable in high magnetic field (1.5 T)
- 4 APD chips
- 144ch multi-pixel
- 1 pixel : 4.9mm×4.9mm

ARICH use 420 HAPDs





Hamamatsu Photonics K.K.

- High QE : ~30%
- Two amplitude mechanism
  - bombardment gain : 1800
  - Avalanche gain : 40
  - ➡total gain : 72000

HAPD

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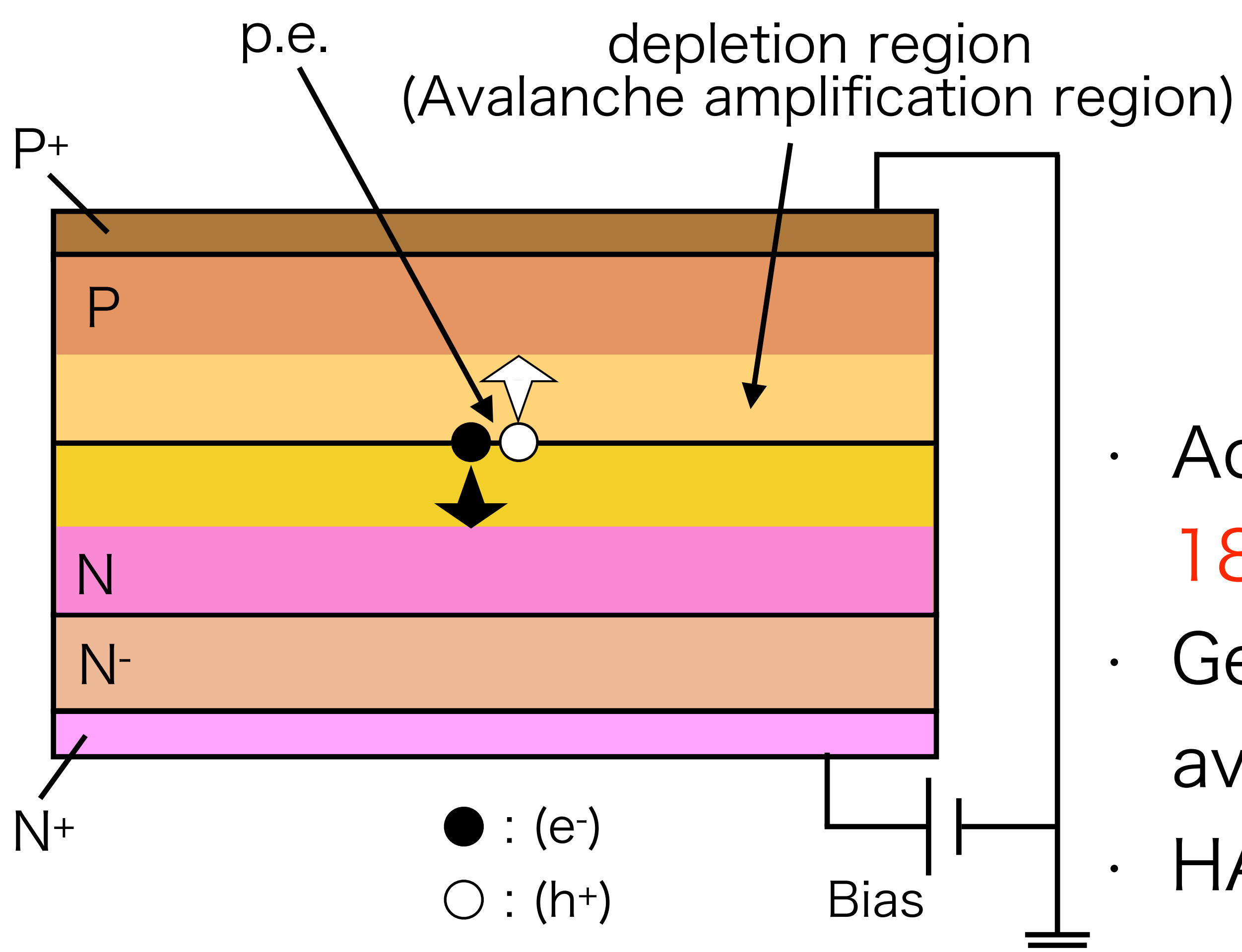
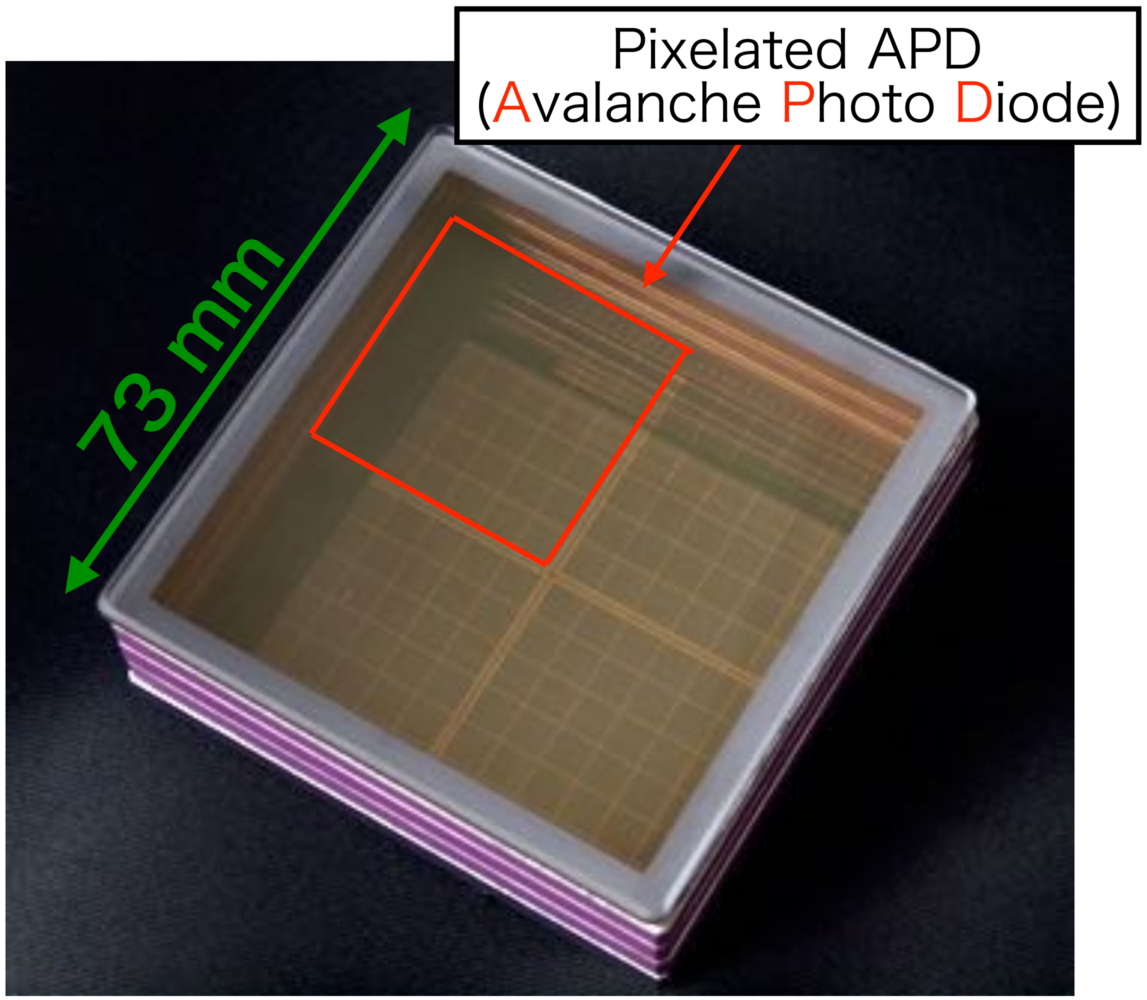
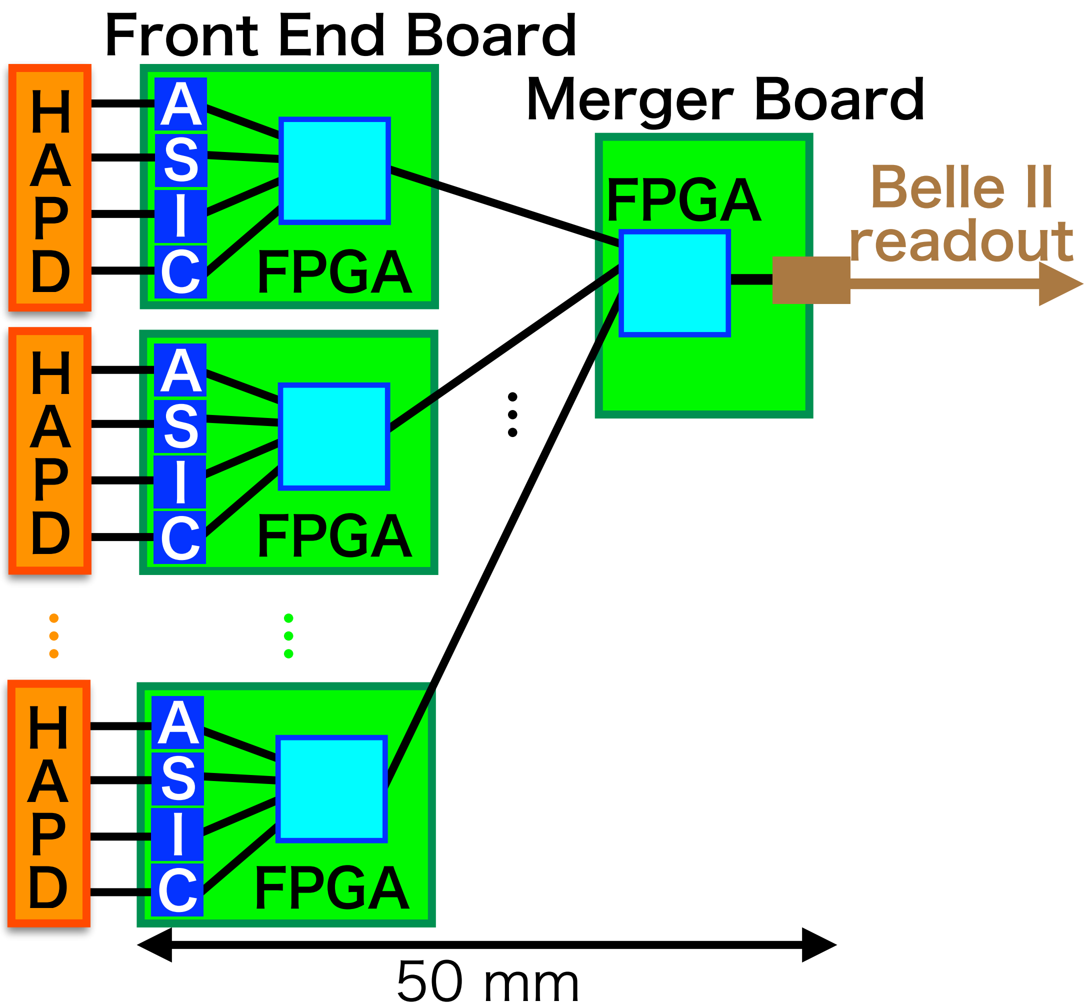




Hamamatsu Photonics K.K.

- Accelerated p.e. enters to APD and 1800 electron-hole pairs are generated.
- Generated electron is amplified (~40) at avalanche amplification region.
- HAPD has 72000 gain in total.

ARICH readout electronics



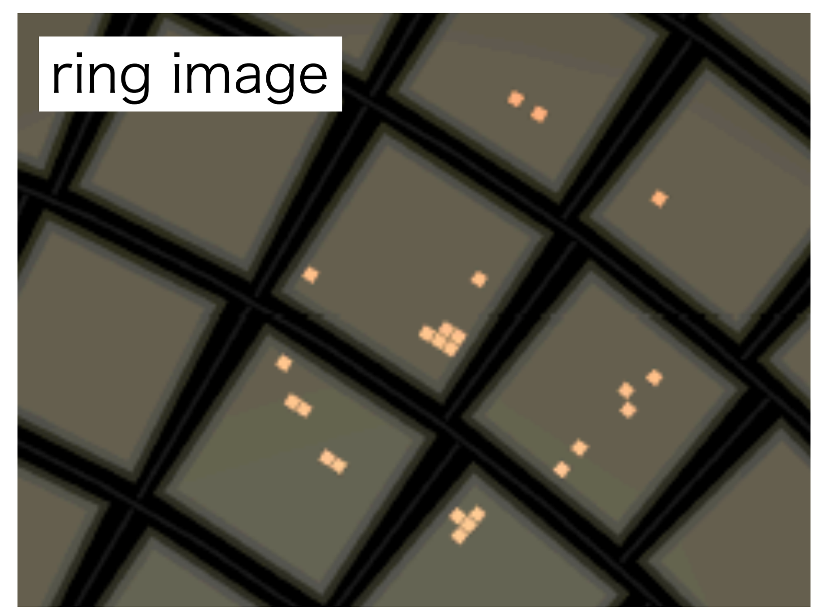
ARICH readout electronics consists of two components.

①Front End Board (FEB)

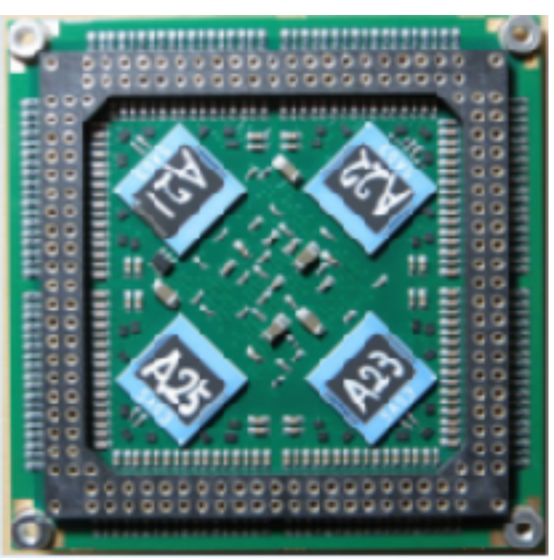
- Digitize analog signal from HAPD.

②Merger Board (Merger)

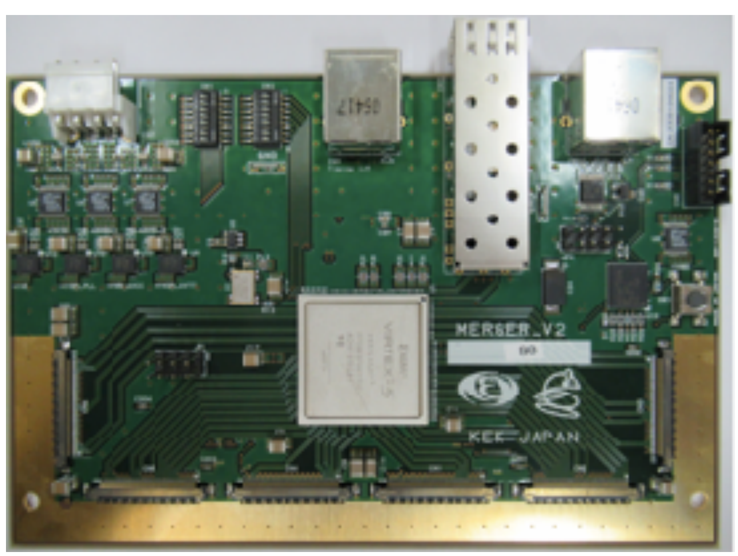
- Merge data from 5 or 6 FEBs.



ARICH sends only hit/no hit data.



Front End Board



Merger Board

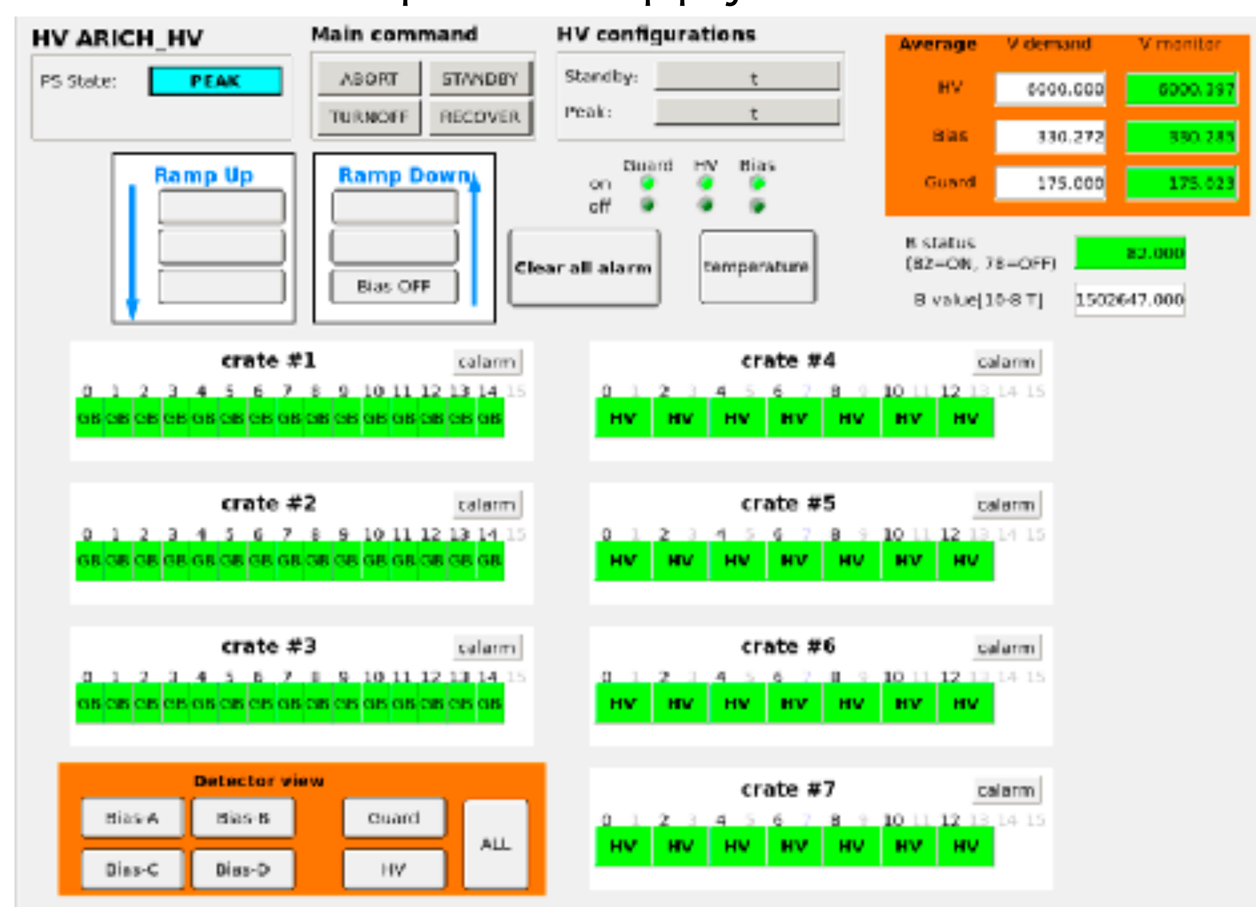
※hit is generated only raising edge

Power supplies for HAPDs

- Supply voltages to HAPDs using two types : HV and bias-guard

	HV	Bias-guard
model number	A1590	A7042A
Max voltage	-9000V	500 V
Max current	50 uA	500 uA
# of channels	16	48

HAPD power supply control GUI



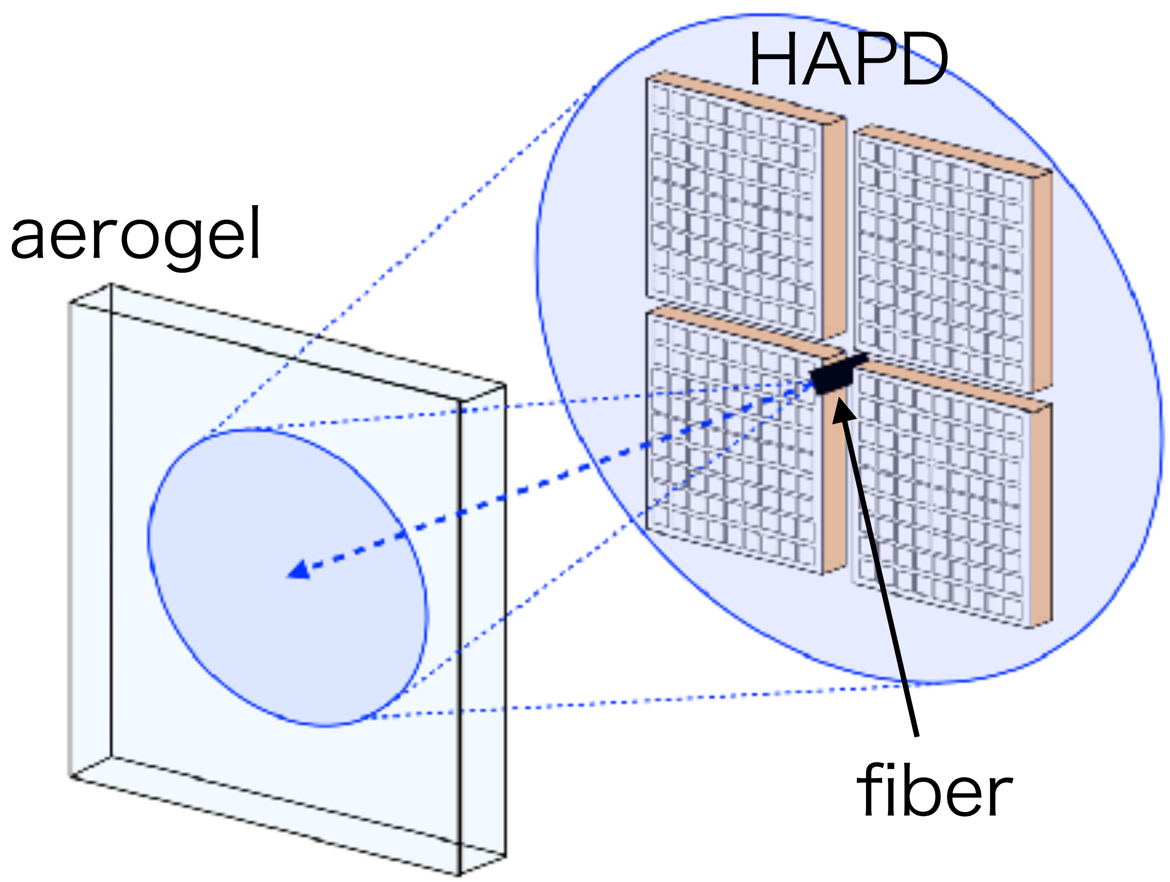
ARICH usage

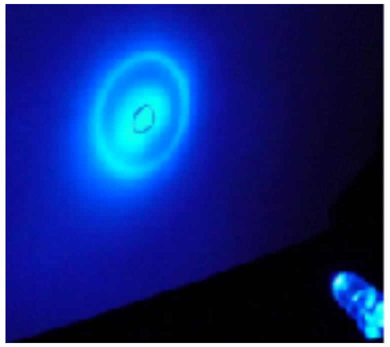
(to operate 420 HAPDs)

	HV	Bias-gaurd
# of crates	7	
# of modules	28	45
# of channels	448	2160
# of cables	24	48

LED monitor system

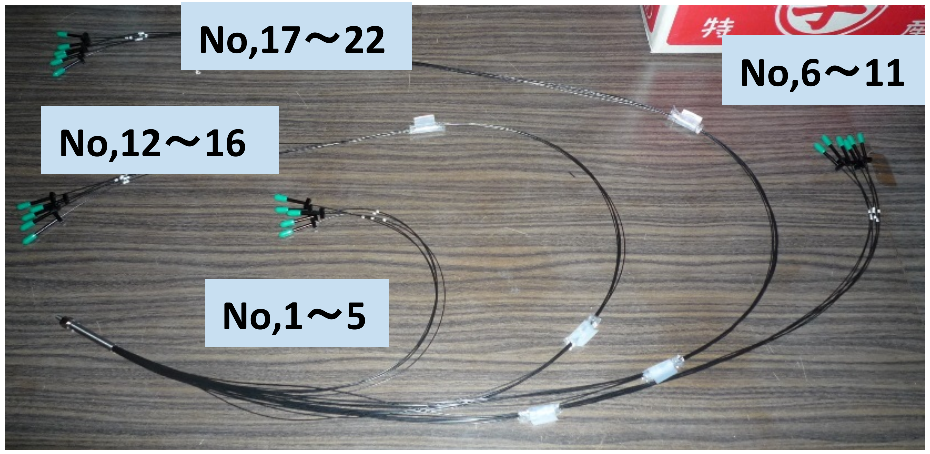
- To measure HAPD healthiness, we implement LED monitor system.
  - Transmit LED light via optical fiber.
  - Illuminate aerogel tiles direction from HAPD side.
  - Photons are scattered in aerogel tiles and go back to HAPD.
  - By detecting scattered photons, measure the HAPD healthiness.

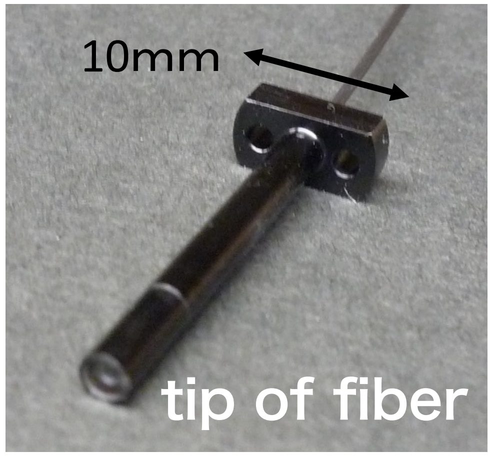




LED light
(λ=470nm)

optical fiber for LED monitor system





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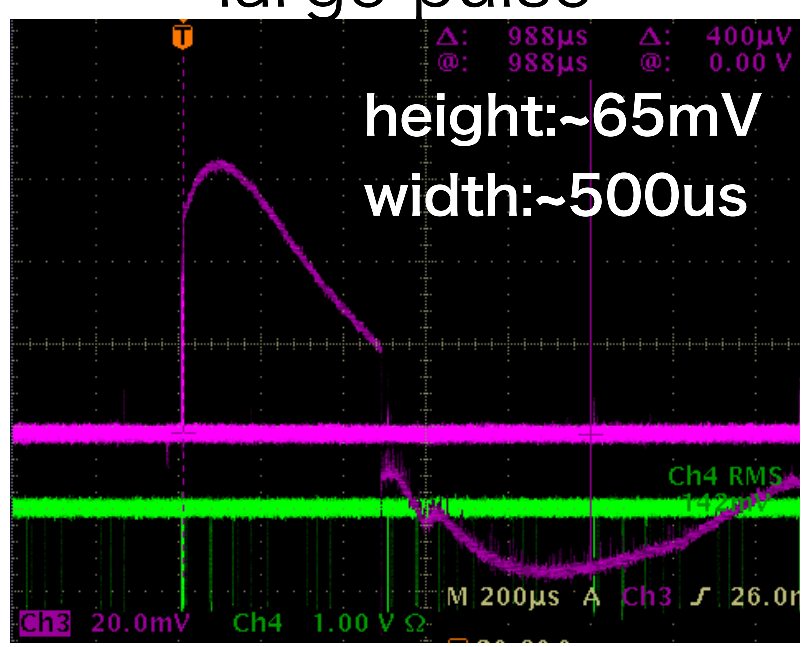
Issue: HAPD in magnetic field

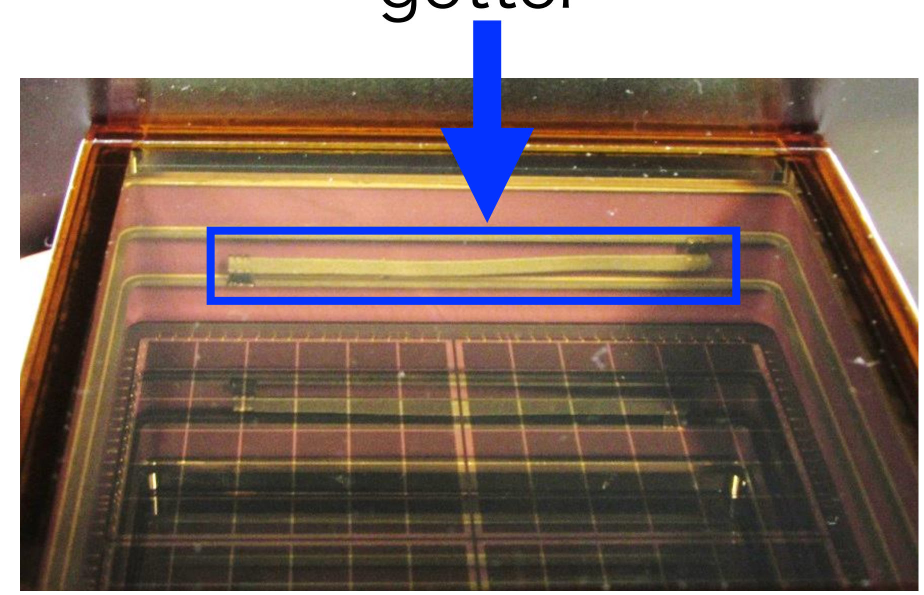
- Large pulse were observed when we operate in the magnetic field.
  - The frequency of large pulses varies HAPD by HAPD.
  - The frequency of large pulses ranges from 0 to 10Hz.
  - The frequency is stable in few hours.
- The large pulse makes dead time.
  - After large pulse, almost channels of readout don’t respond ~0.1s.
- Getter re-activation improves the dead time.
  - A small piece of gas absorbing metal to improve the vacuum within tube.

a few photons signal

large pulse



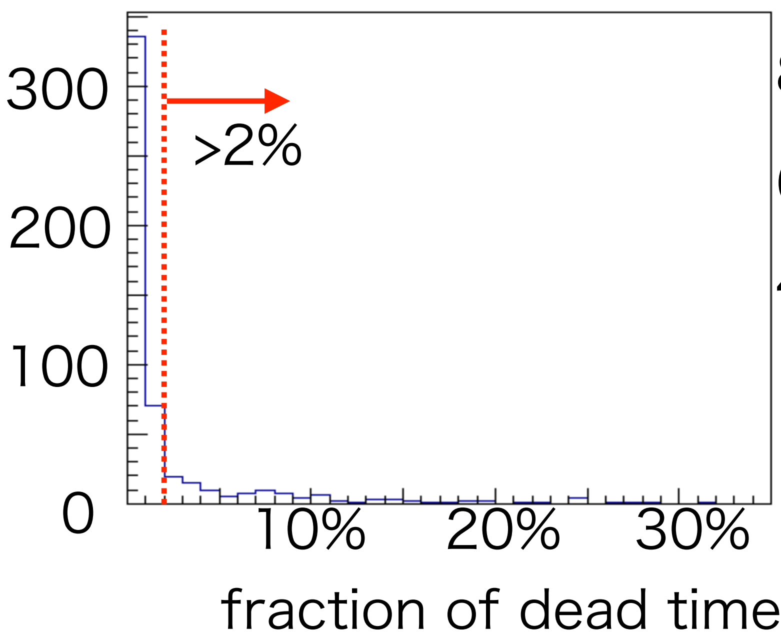
getter



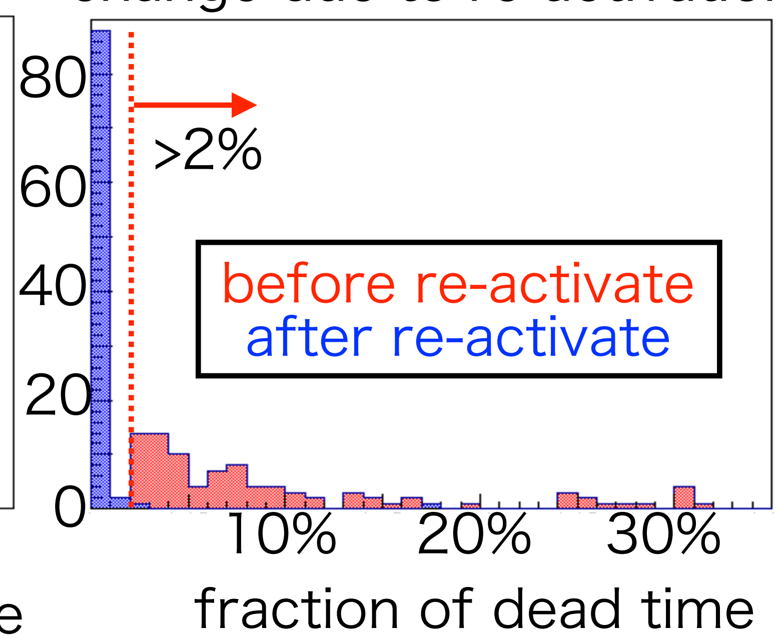
Quality of Installed HAPDs

- 92 out of 524 HAPDs have large dead time (≧2%).
- After the getter re-activation for HAPDs which has large dead time, dead time of 90 HAPDs are reduced to be less that 2%.
- As the result, we prepare more than 420 HAPDs.

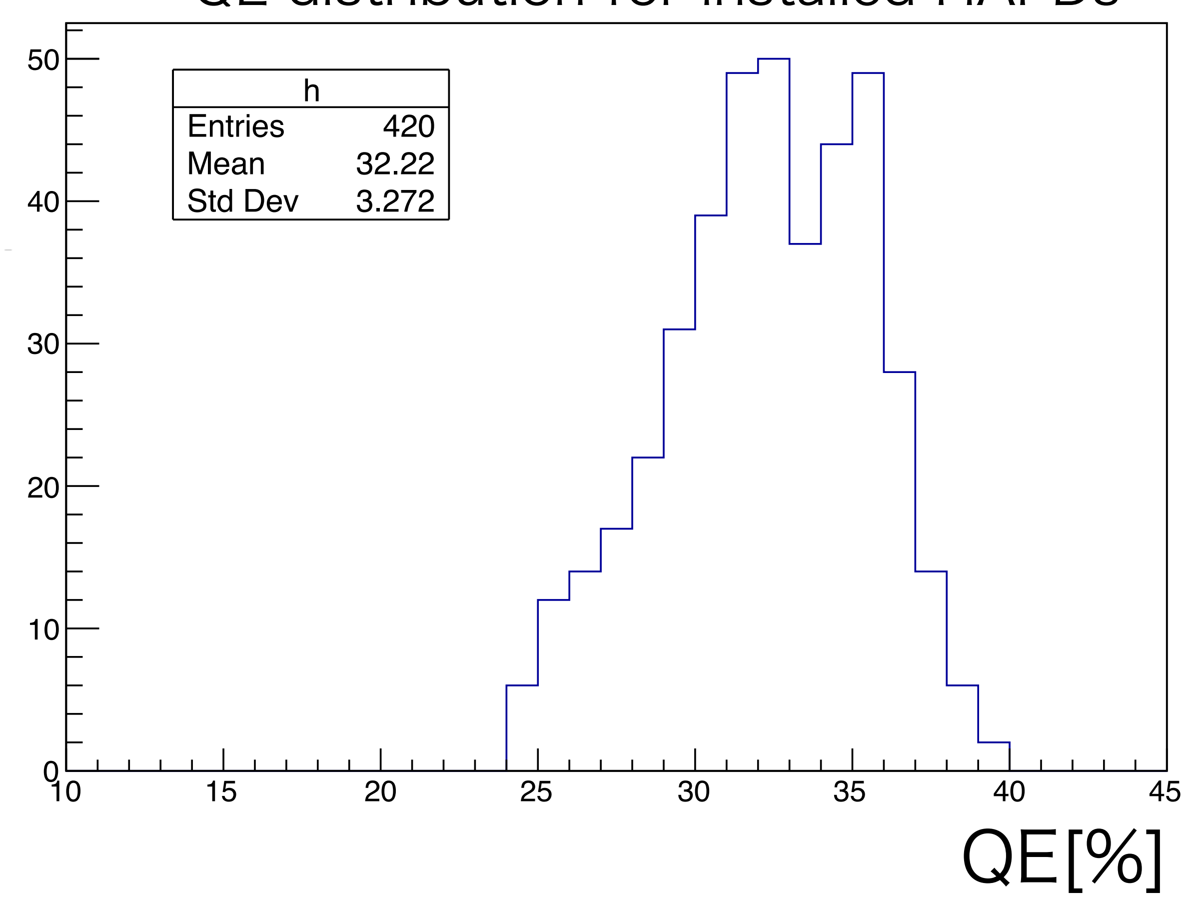
for all 524 HAPDs



change due to re-activation



QE distribution for installed HAPDs



- HAPDs are installed based on QE.
  - mean value of QE is 32.2%

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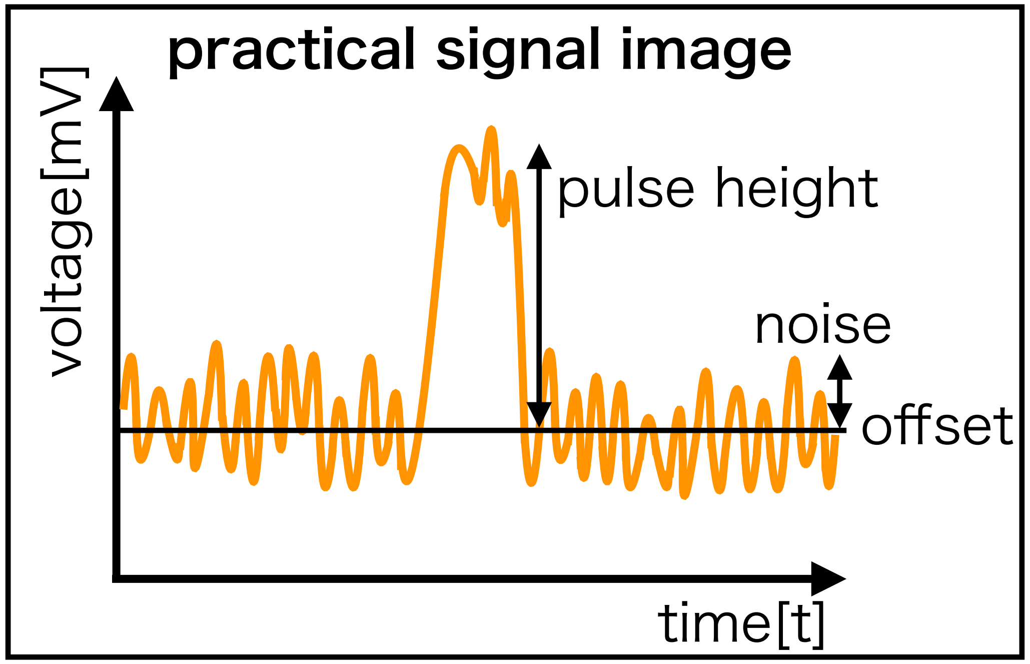
Measurement items

We have three main measurement items for HAPD.

Considering these three items, we evaluate HAPD performance.

- **offset**
  - Aligned since we use same threshold voltage for all channels.
- **noise**
  - Enough small value comparing with pulse height.
- **pulse height**
  - Enough large value comparing with noise.



We use two measuring conditions.

- **Noise measurement** : random trigger
- **Signal measurement** : monitor system

Results include all HAPDs data.

- except unusable HAPD (detail will be explained)

Signal using LED monitor system

Trigger : 1000 triggers

All voltages : on

Threshold voltage : operation value

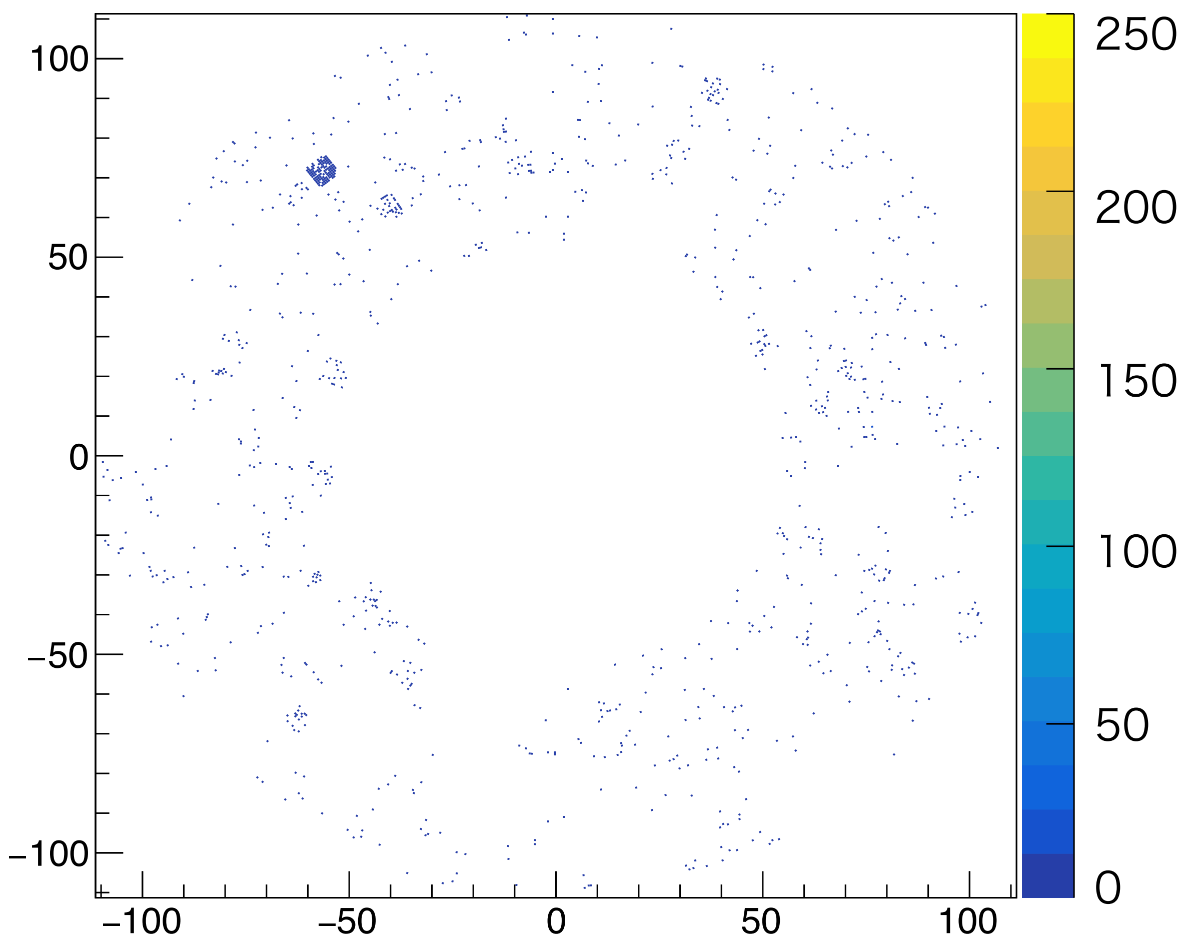
LED : ~0.1 p.e./channel/pulse

Number of hits

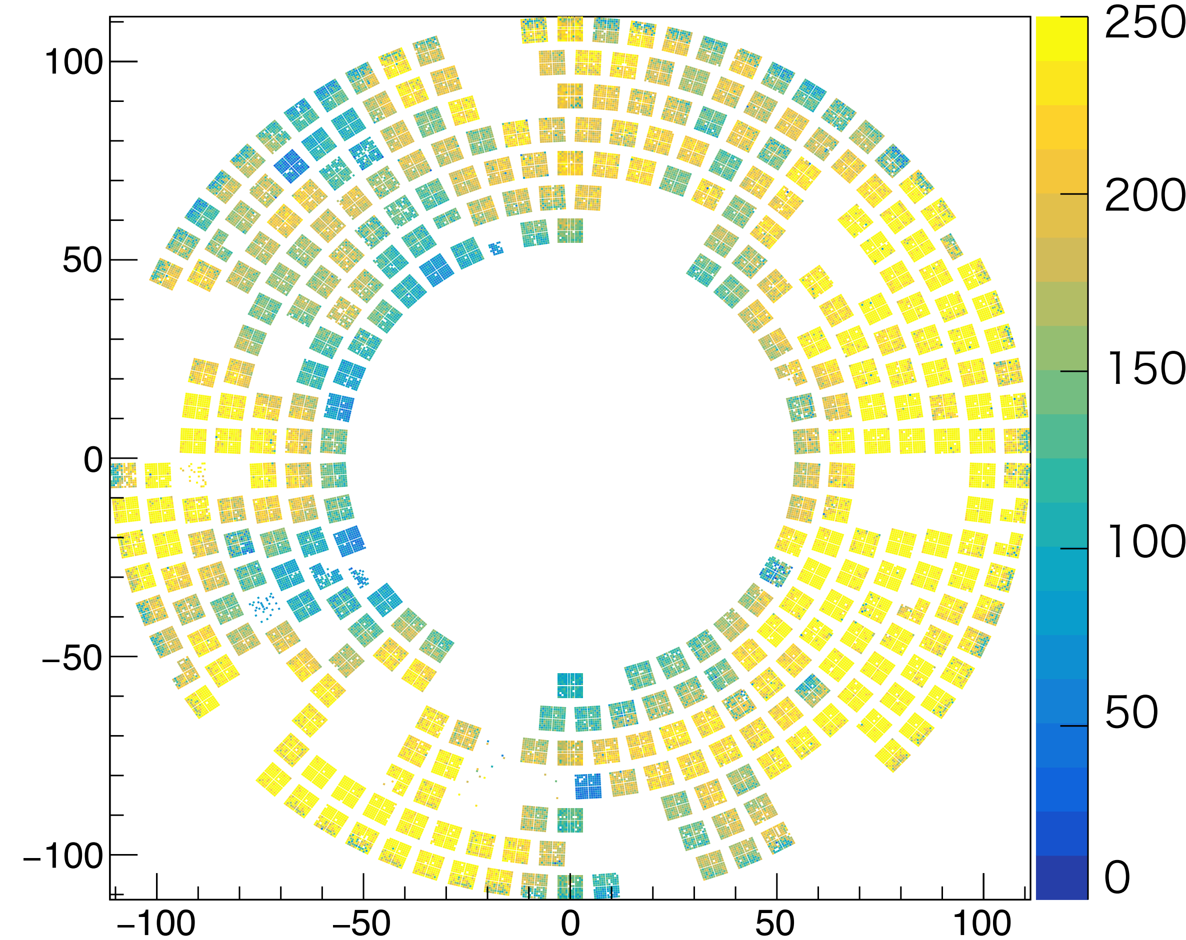
LED off : 2.7×10^{-5} hits/ch/triggers

LED on : 0.18 hits/ch/triggers

LED off (for noise)



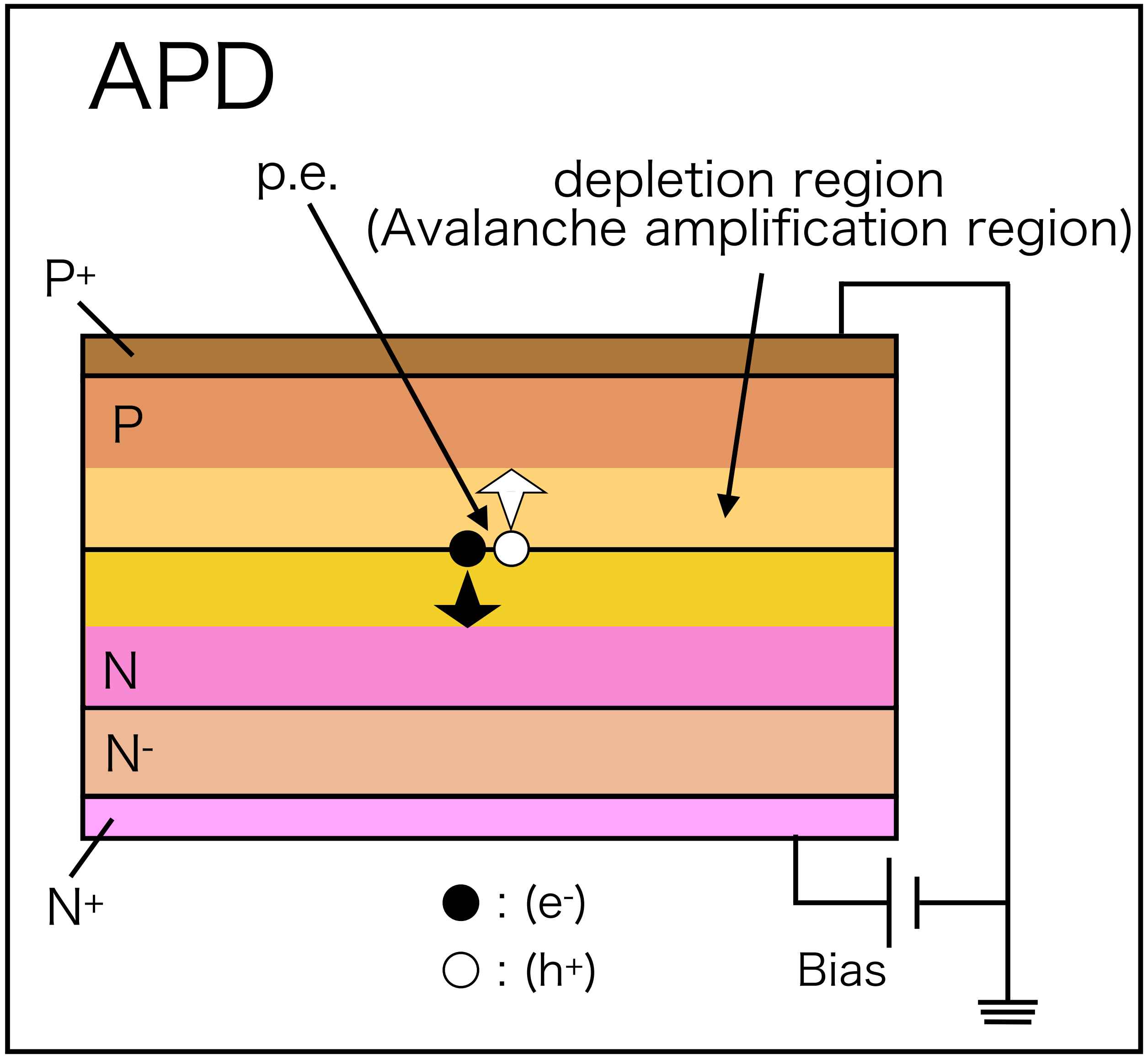
LED on (for signal)

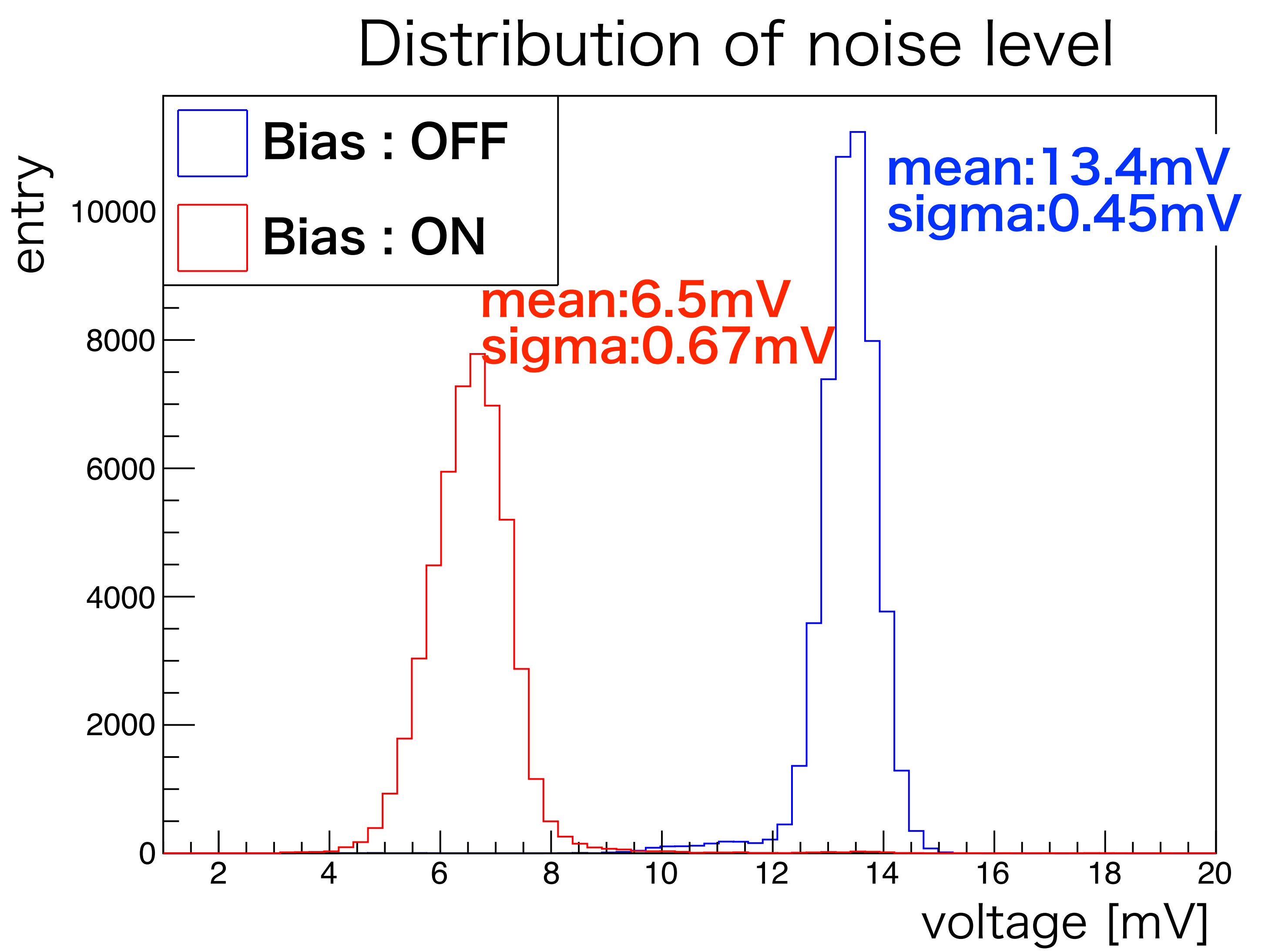


Using LED monitor system, we can check HAPD response.

Noise level with/without bias

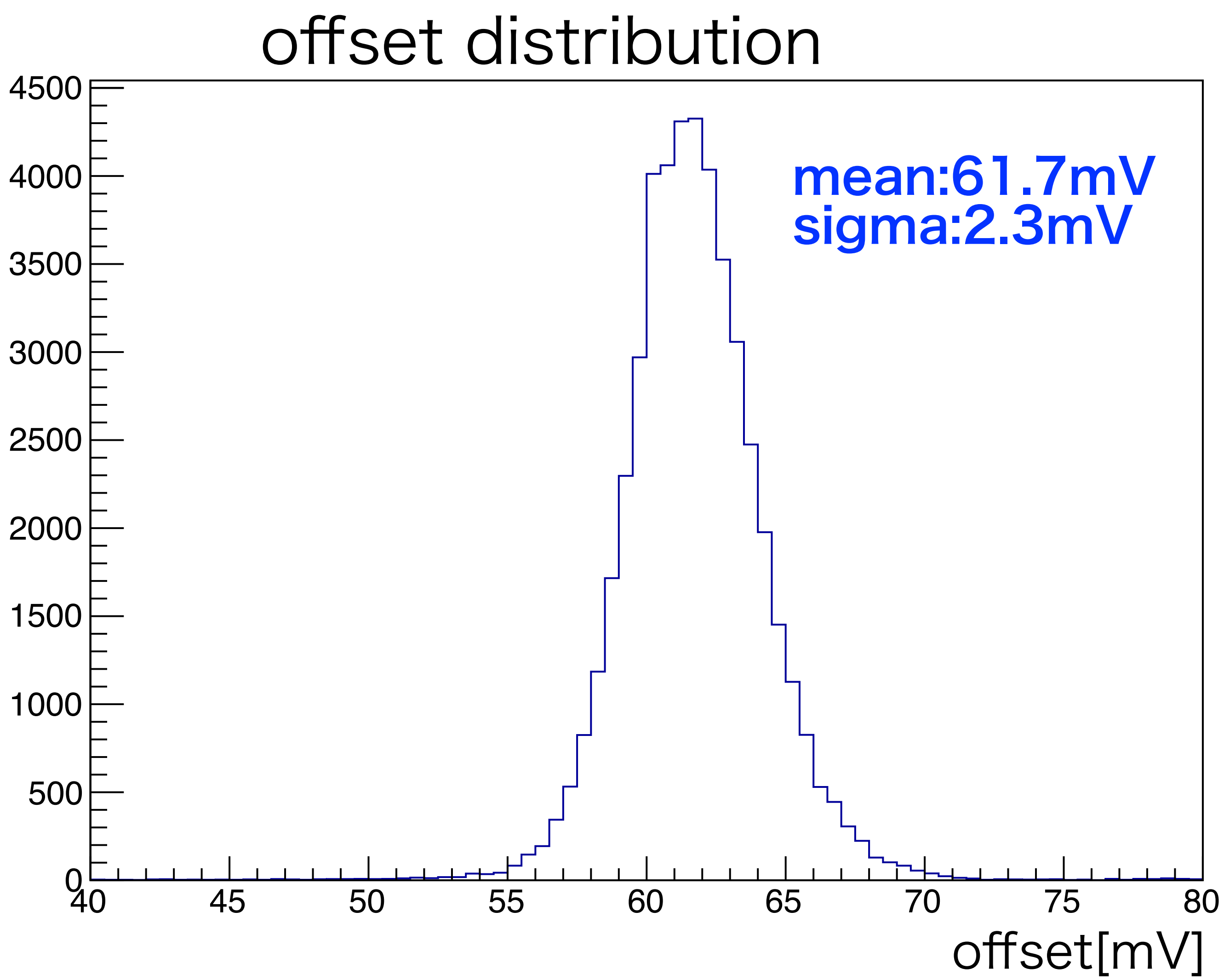
APD put on HAPD is applied bias voltages and depletion region is generated.
As the result, noise level is decrease while applying bias voltage.

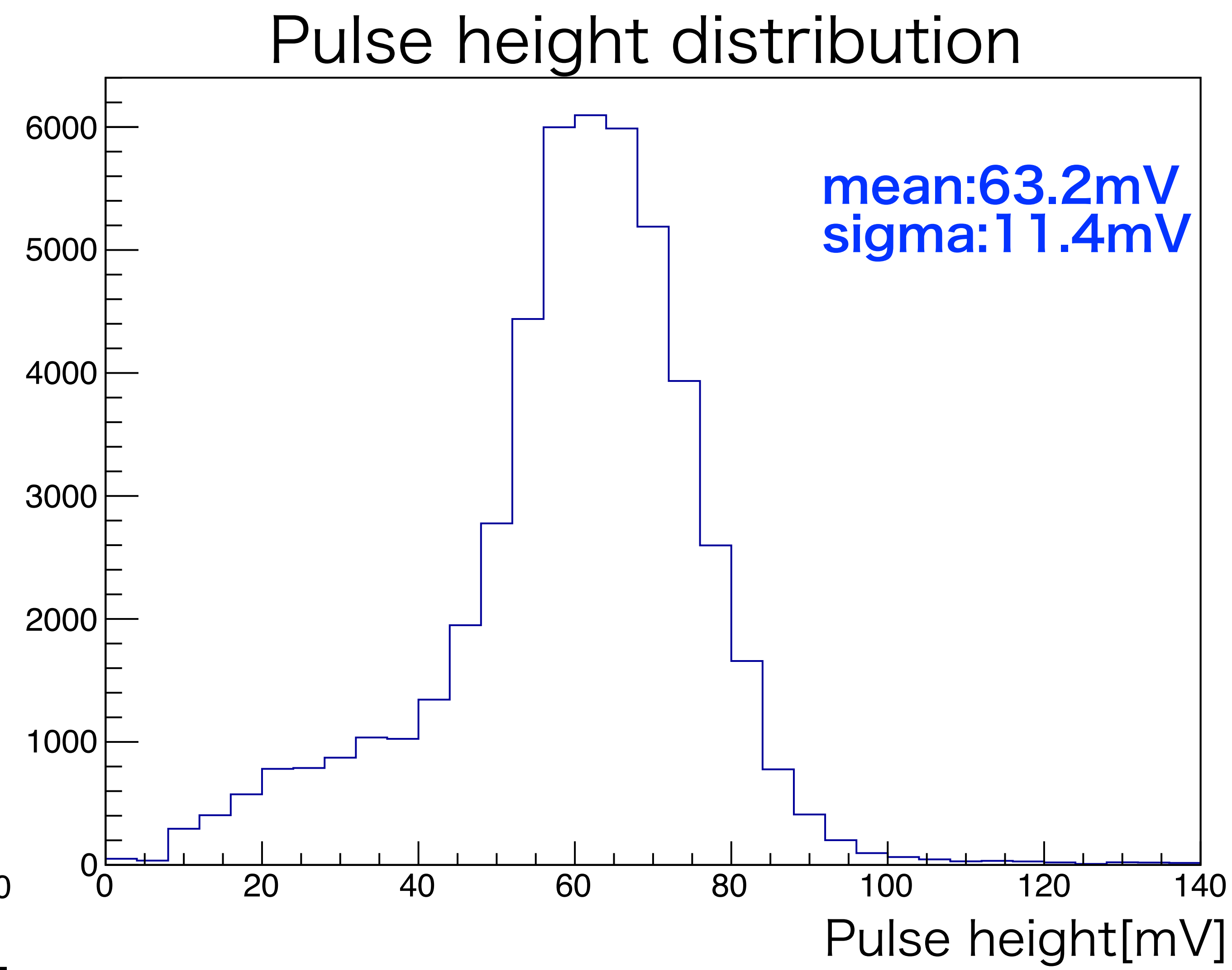




Noise reduction is clearly seen by applying bias.
Noise level is reduced by half.

Offset and pulse height





	mean[mV]	sigma[mV]
offset	61.7	2.3
noise	6.5	0.67
pulse height	63.2	11.4

We set

- 60 mV as offset
- 120mV as threshold voltage

Offset sigma(2.3mV) is less than noise mean(6.5mV).
Pulse height is sufficiently larger than noise.

Unusable HAPDs

- We can use not all HAPDs ascribed to three reasons :
  - Power supply : 3 HAPDs and 4 APDs
    - cables, patch panel etc.
  - Trouble in HAPD : 4 HAPDs and 10 APDs
    - broken APD, circuit etc.
  - Trouble in readout electronics : 59 HAPDs
    - 10 out of 72 merger boards are unusable
- Dead channels in used HAPDs are also measured.
  - Comparing number of hits LED on / off data
  - dead channels : 381 channels

Total unusable fraction (reason in HAPD)
1.5% of HAPDs due to applying voltage
0.8% of channels are dead

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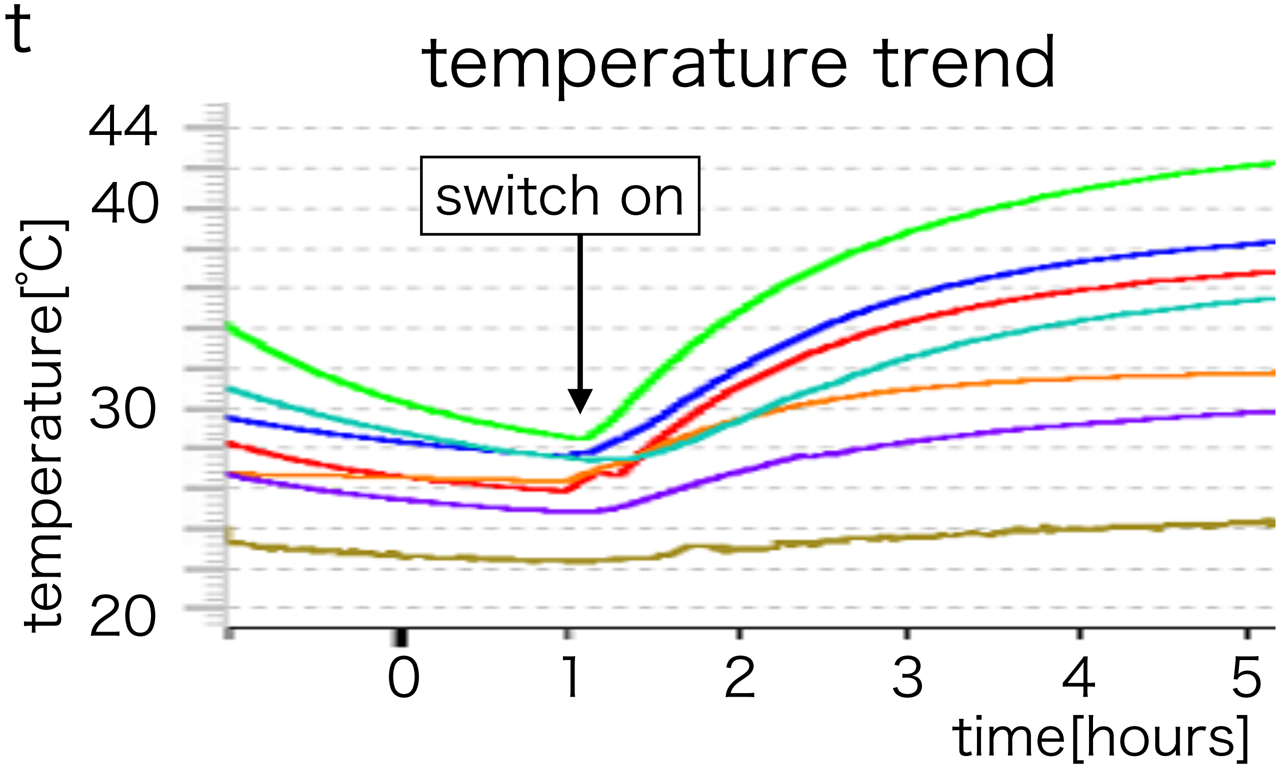
Noise and pulse height study

- Readout electronics has too high temperature than our expectation.
- Temperature of ARICH is closes to limitation, if all electronics are on.
  - We switch on only up to 4 out of 6 ARICH sectors at usual operation.
- We concern temperature effect especially noise level and pulse height.

Measurement of temperature effect

- Measuring at three different temperatures.
  - **1** (~30°C) : just after turned on electronics
  - **2** (~36°C) : stable temperature operating 4 out of 6 ARICH sectors
  - **3** (~41°C) : near the temperature limit
- The following parameters are checked.
  - offset
  - noise
  - pulse height



Temperature dependency

- Measuring with three different temperatures.
- Bias are NOT applied for offset and noise measurement
  - note : noise level is decreased by half while applying bias voltage.
- Voltages are applied for pulse height measurement

temperature dependency for offset/noise/pulse height

	offset	noise	pulse height
1	61.7	13.4	66.4
2	60.8	15.8	62.0
3	60.5	15.7	55.7

Offset : little change by changing temperature.
Noise : increased with higher temperature.
Pulse height : decreased with higher temperature.

Considering reduction of noise level by applying bias, pulse height is still sufficiently larger than noise level.

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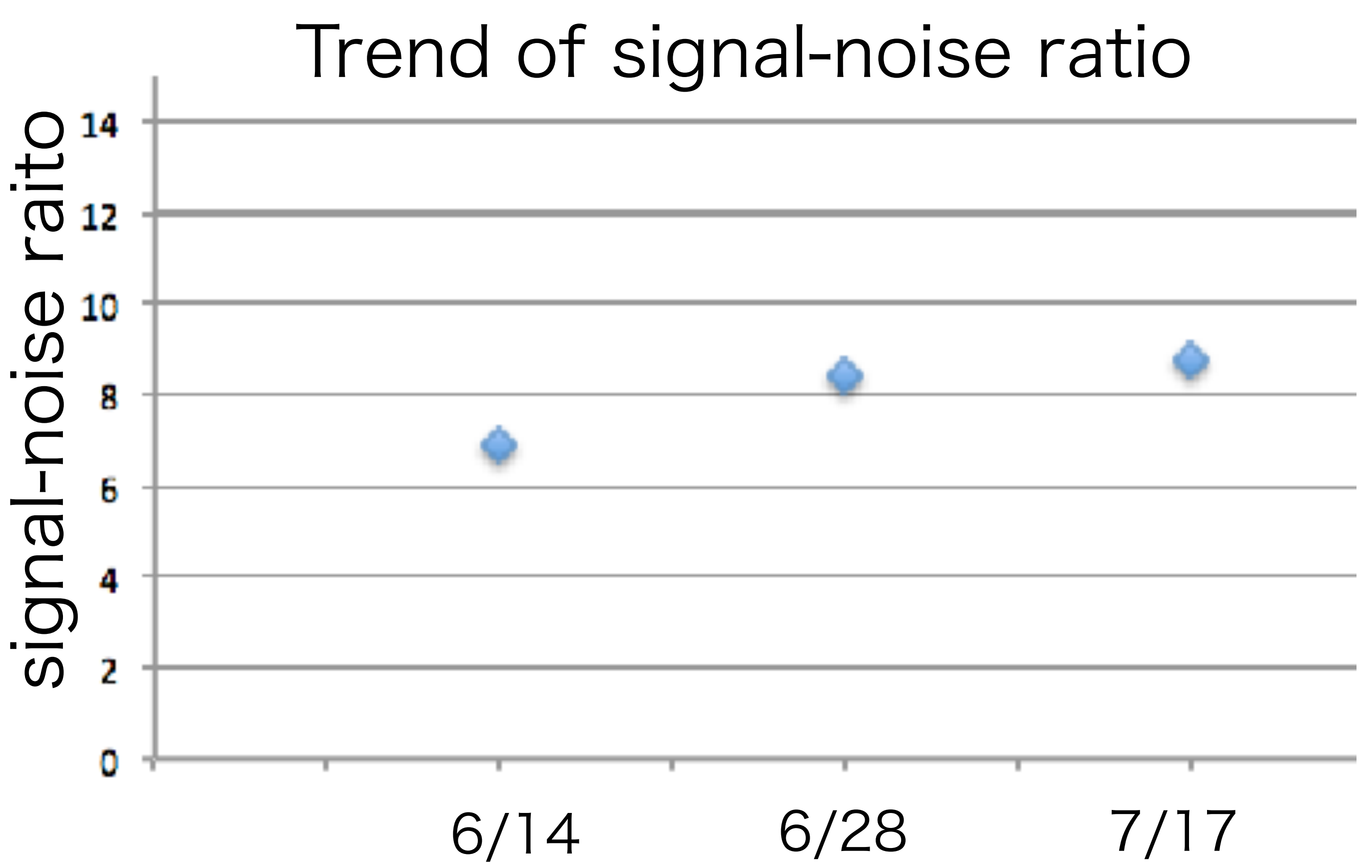
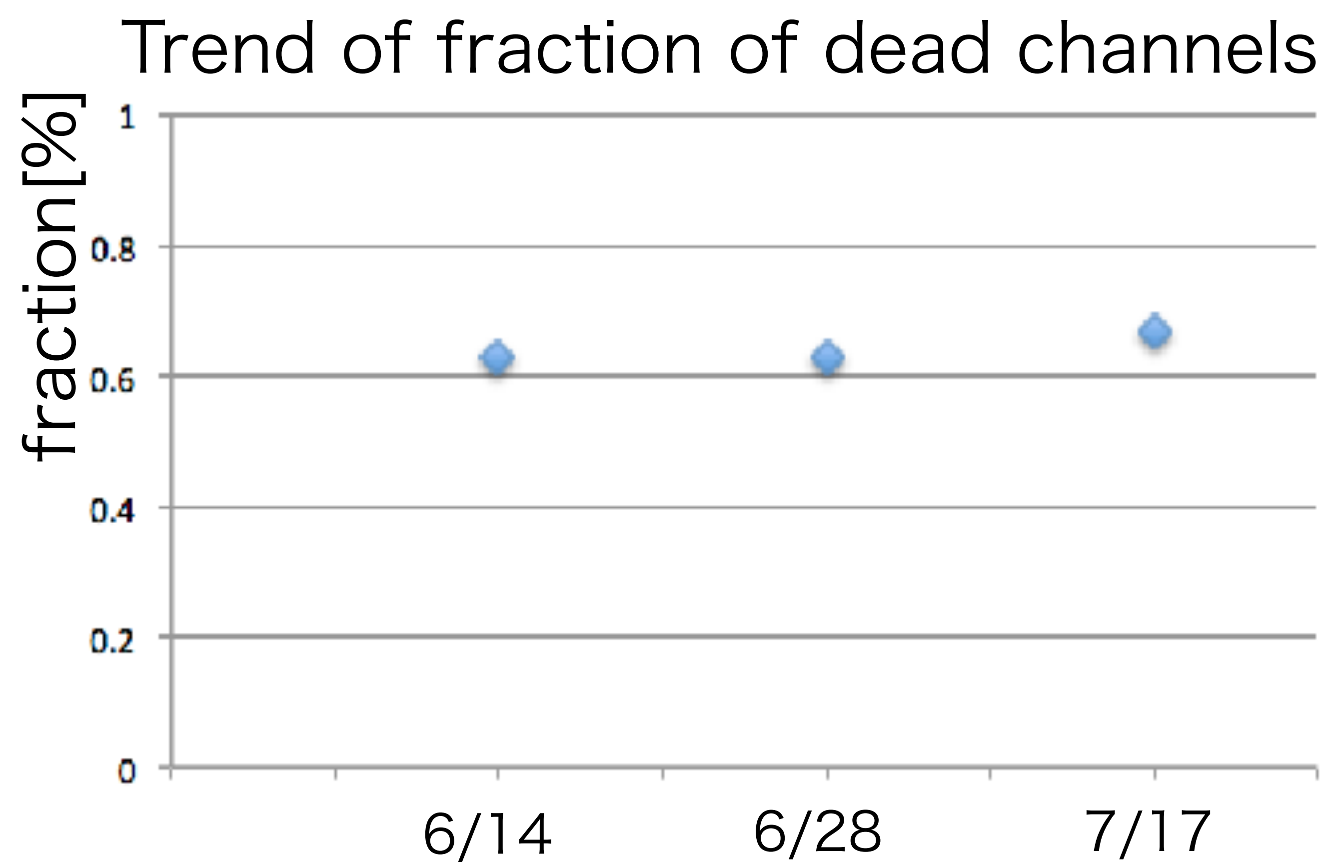
Long term stability in Phase II

Use only a sector that is used throughout the Phase II period.

Data taken at 6/14, 6/18, 7/17

Signal-noise ratio and fraction of dead channels are evaluated.





Signal-noise ratio is more than 6.
Fraction of dead channels is less than 1%.

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Summary and plan

- 420 HAPDs are used as photon detector for ARICH.
- Behavior of each HAPDs are as expected
- Temperature dependency is seen, but is acceptable.
- Photon detection is correctly working.

HAPDs in the ARICH counter are working in the Belle II Phase II operation.

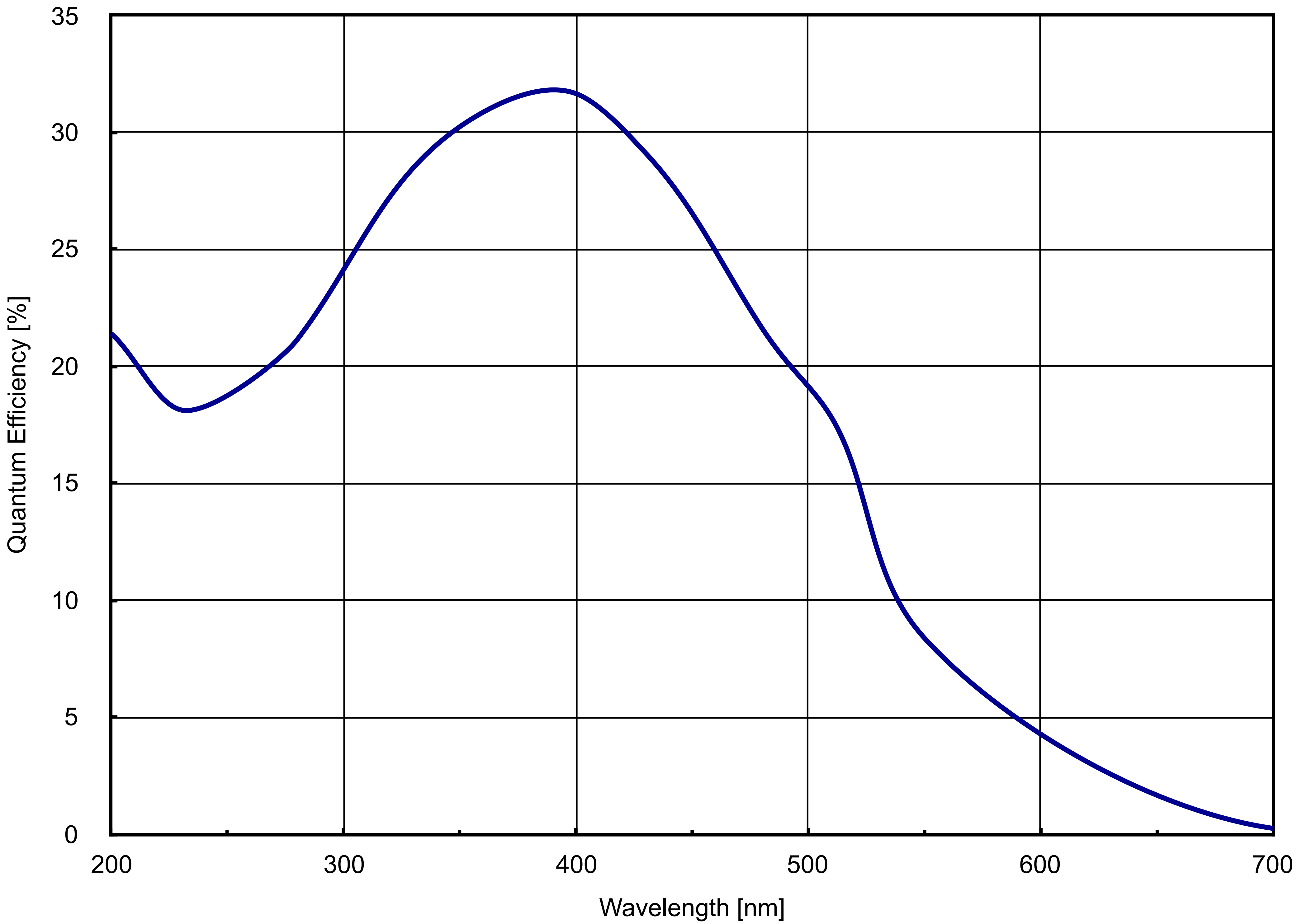
Plan

- Investigate problematic HAPDs
- Preparation for Phase III
  – Improve cooling system

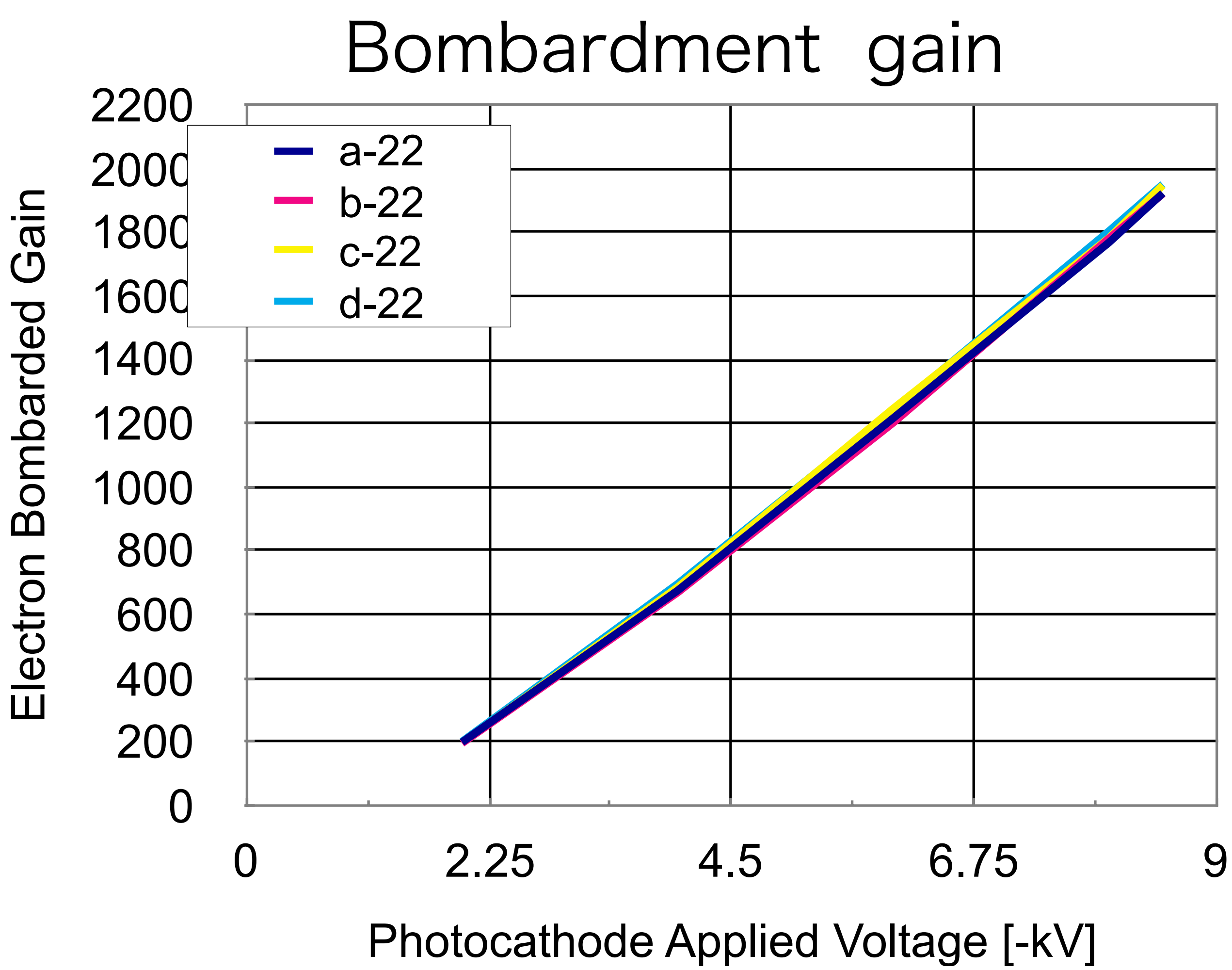
Thank you for your attention!

Back up

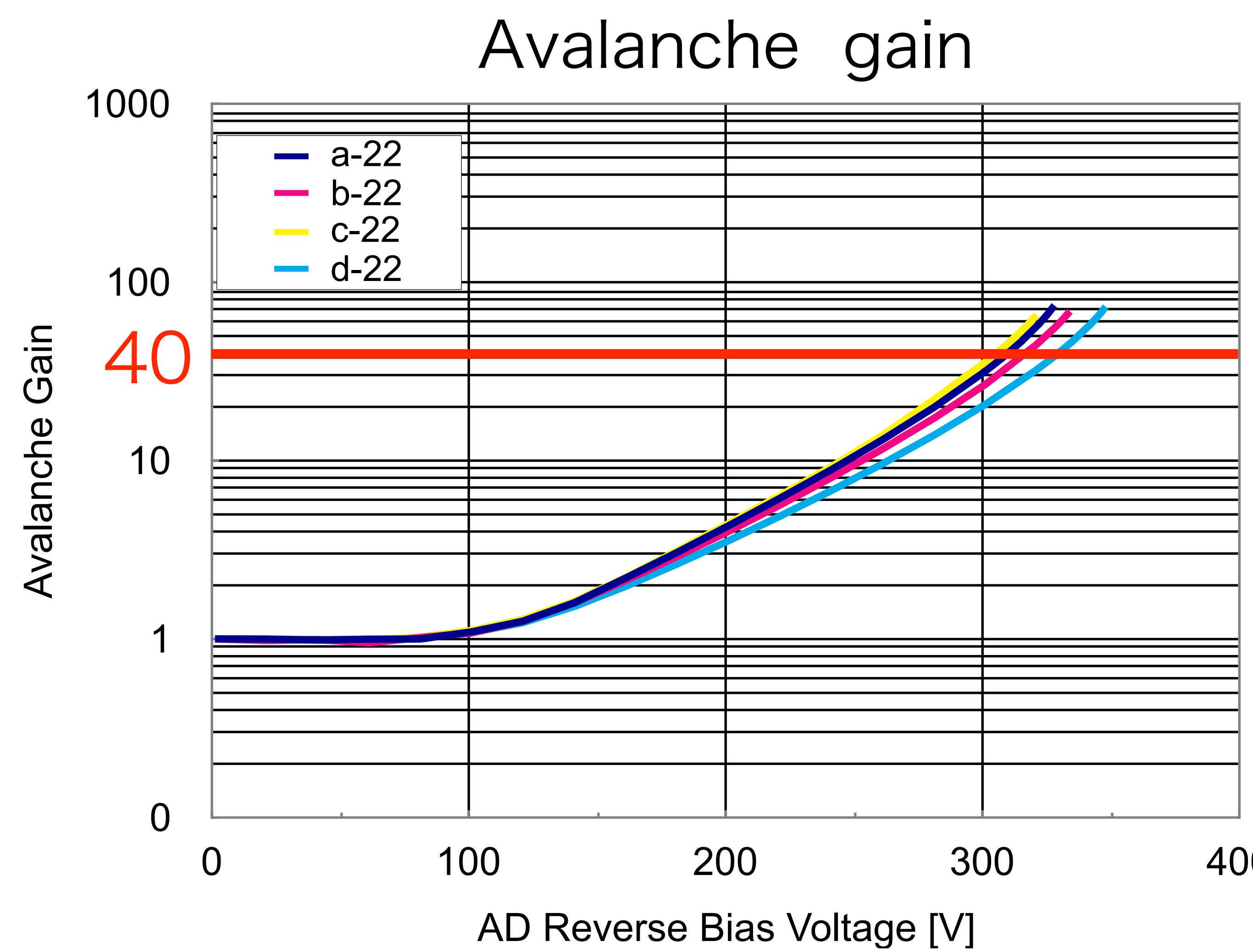
QE vs wavelength



HAPD gain

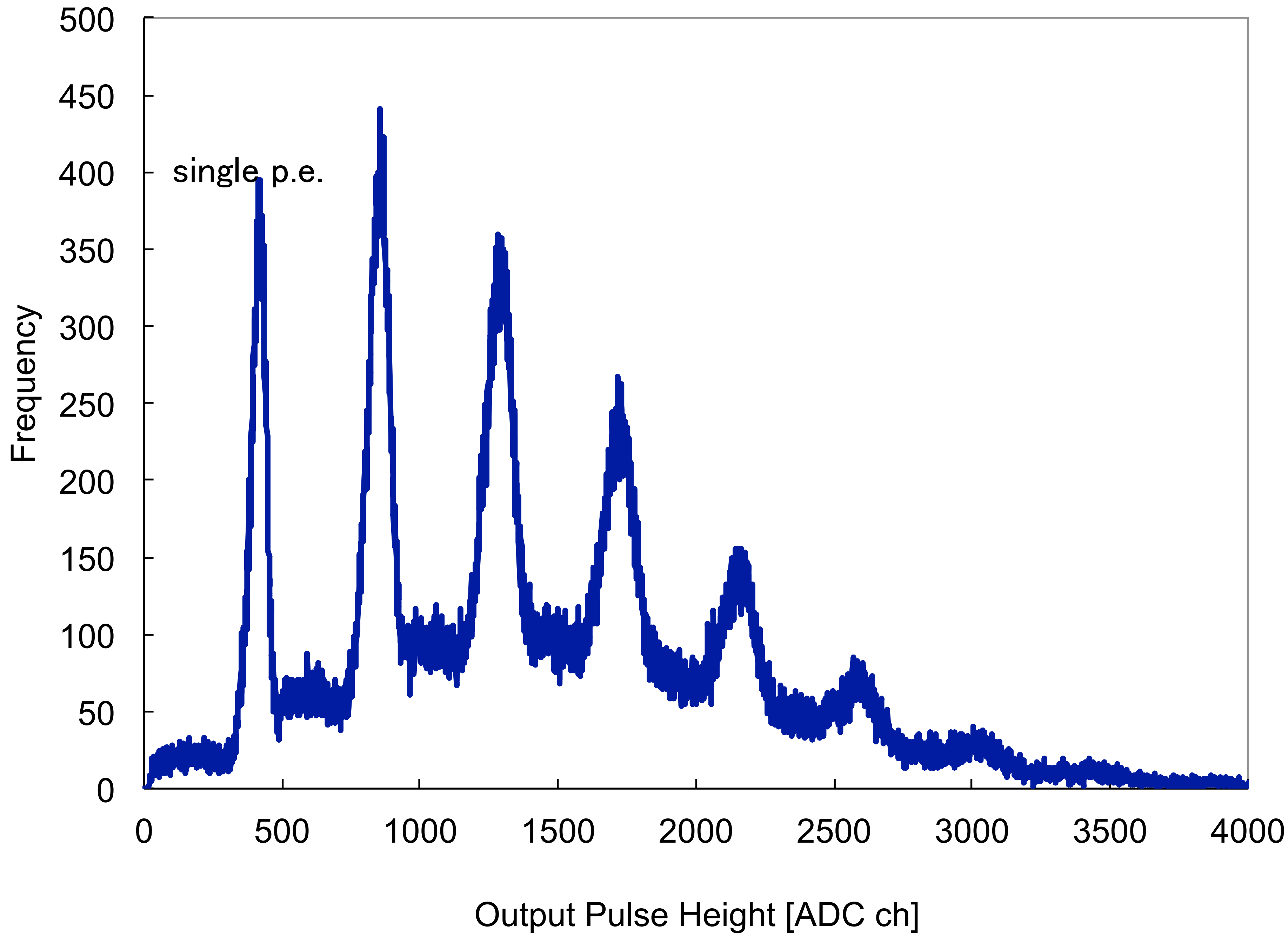


Bombardment gain
Electron Bombarded Gain
Photocathode Applied Voltage [-kV]
a-22
b-22
c-22
d-22
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0
2.25
4.5
6.75
9



Avalanche gain
Avalanche Gain
AD Reverse Bias Voltage [V]
a-22
b-22
c-22
d-22
40
0
1
10
100
1000
0
100
200
300
400

Single photon separation

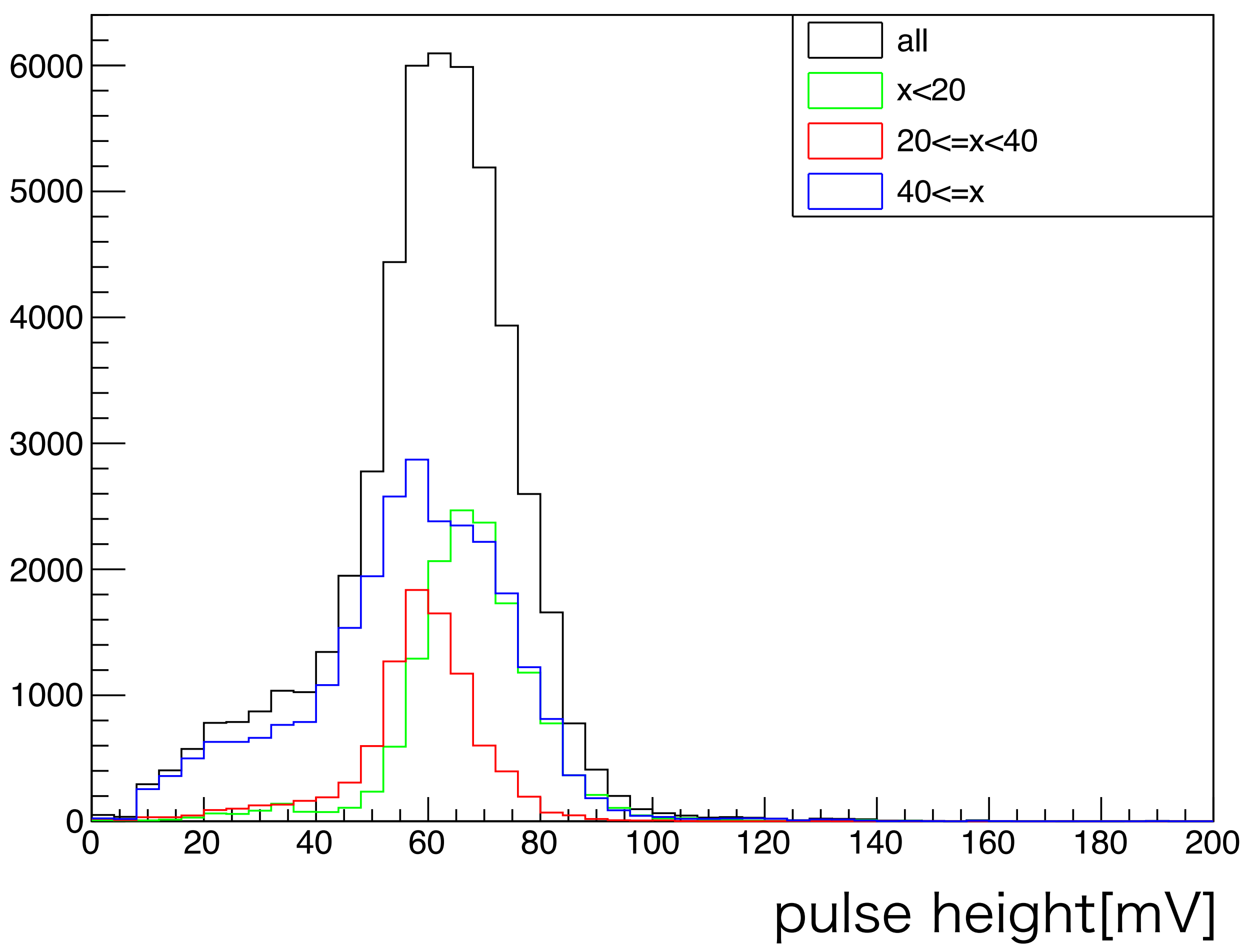


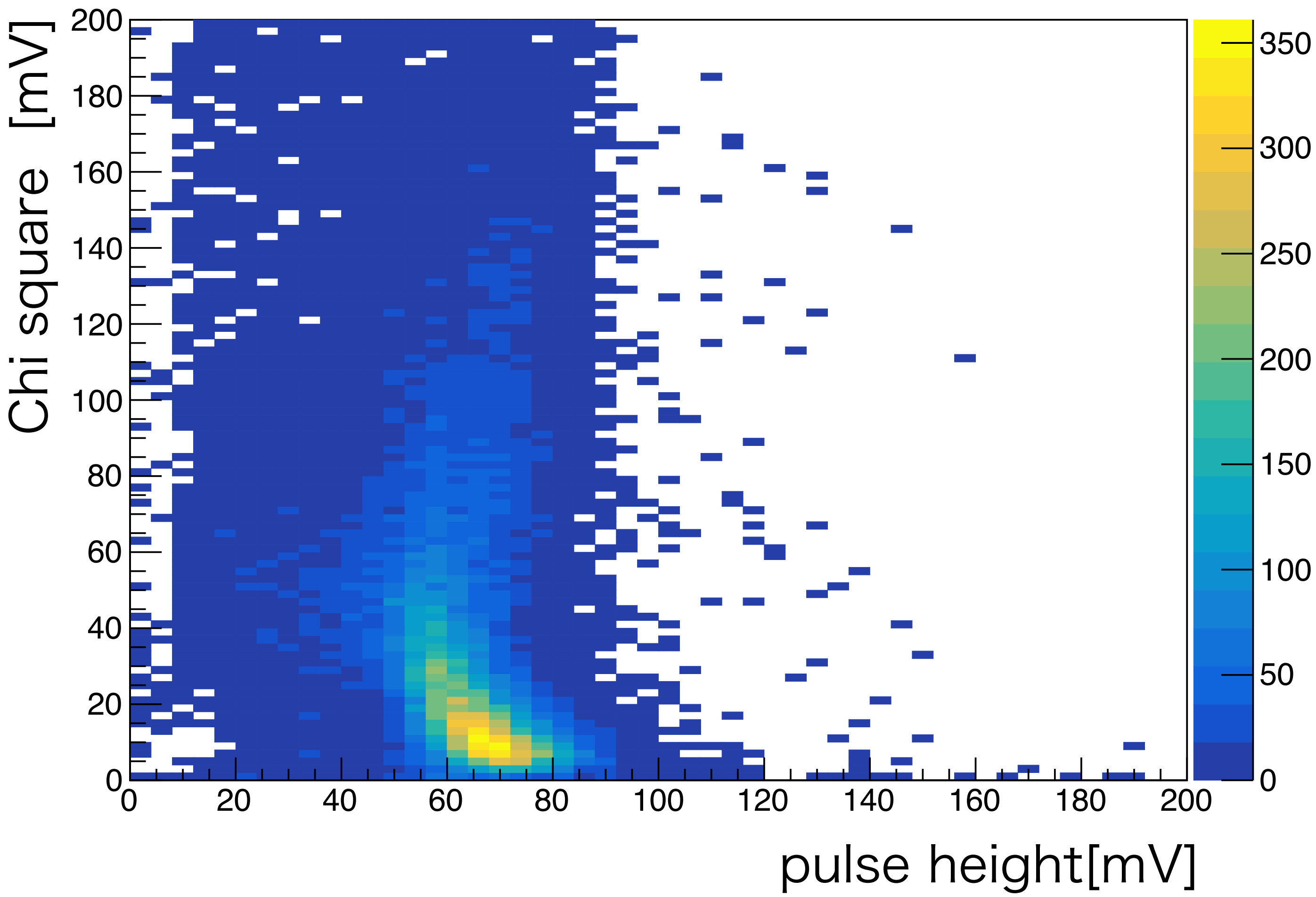
Pulse height distribution

Many lower pulse height.

It is due to fitting accuracy.

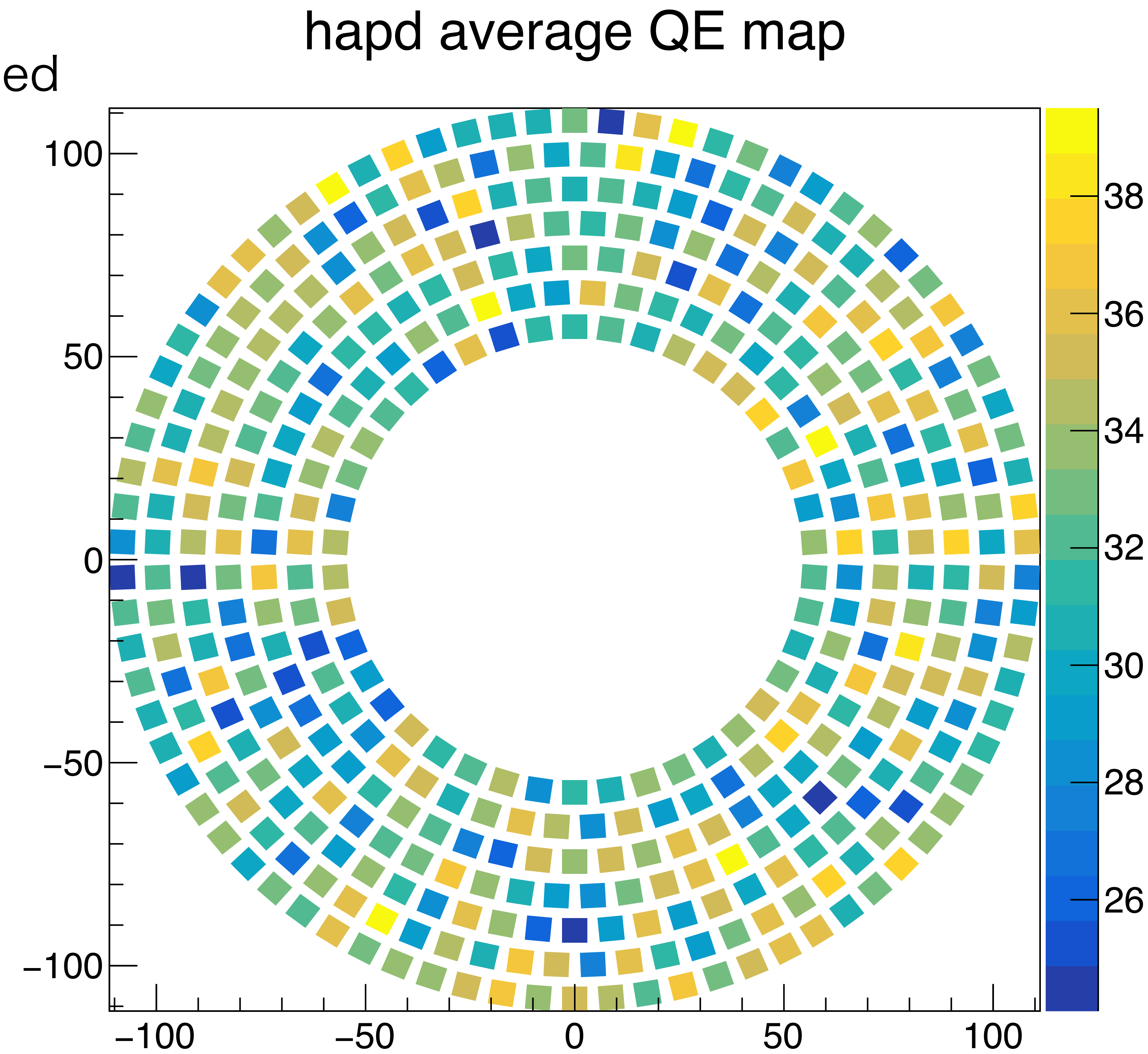
Improvement of fitting algorithm is needed.





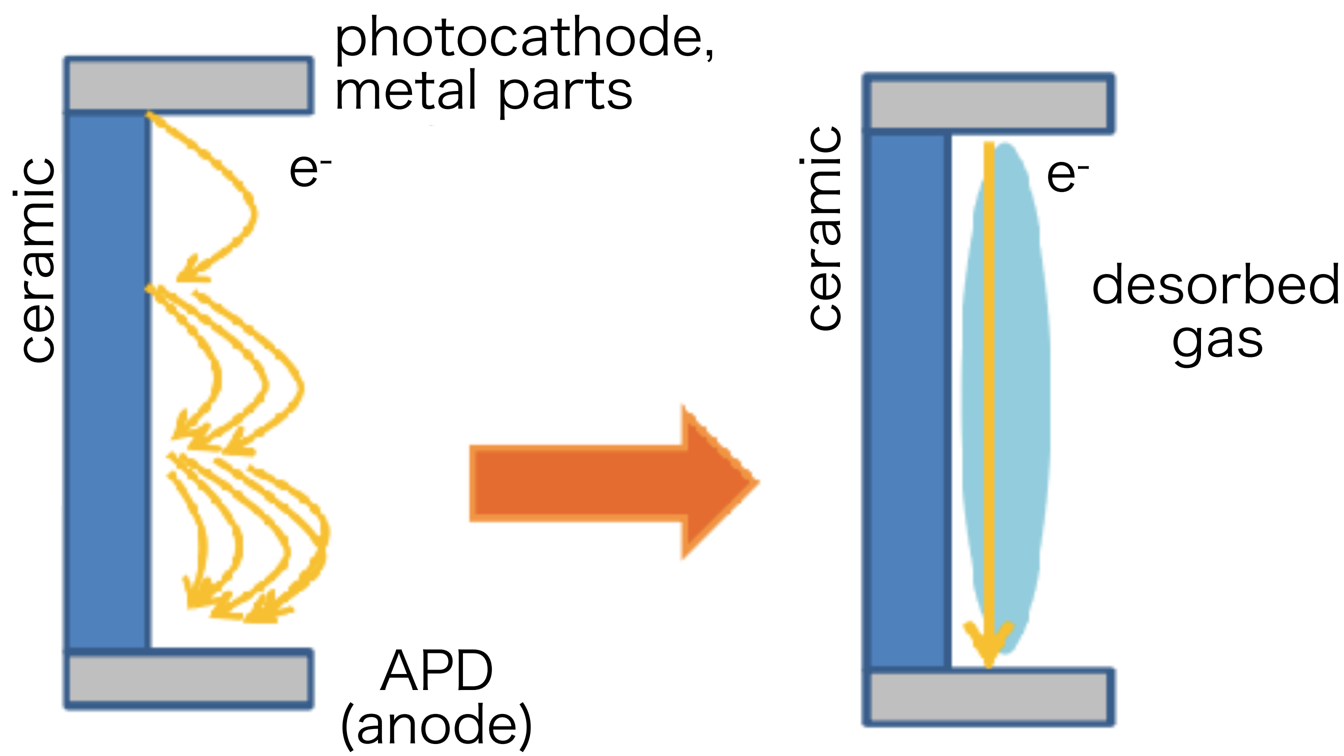
QE distribution

Using average QE of HAPD.
HAPD placement is sequenced for uniform about QE.



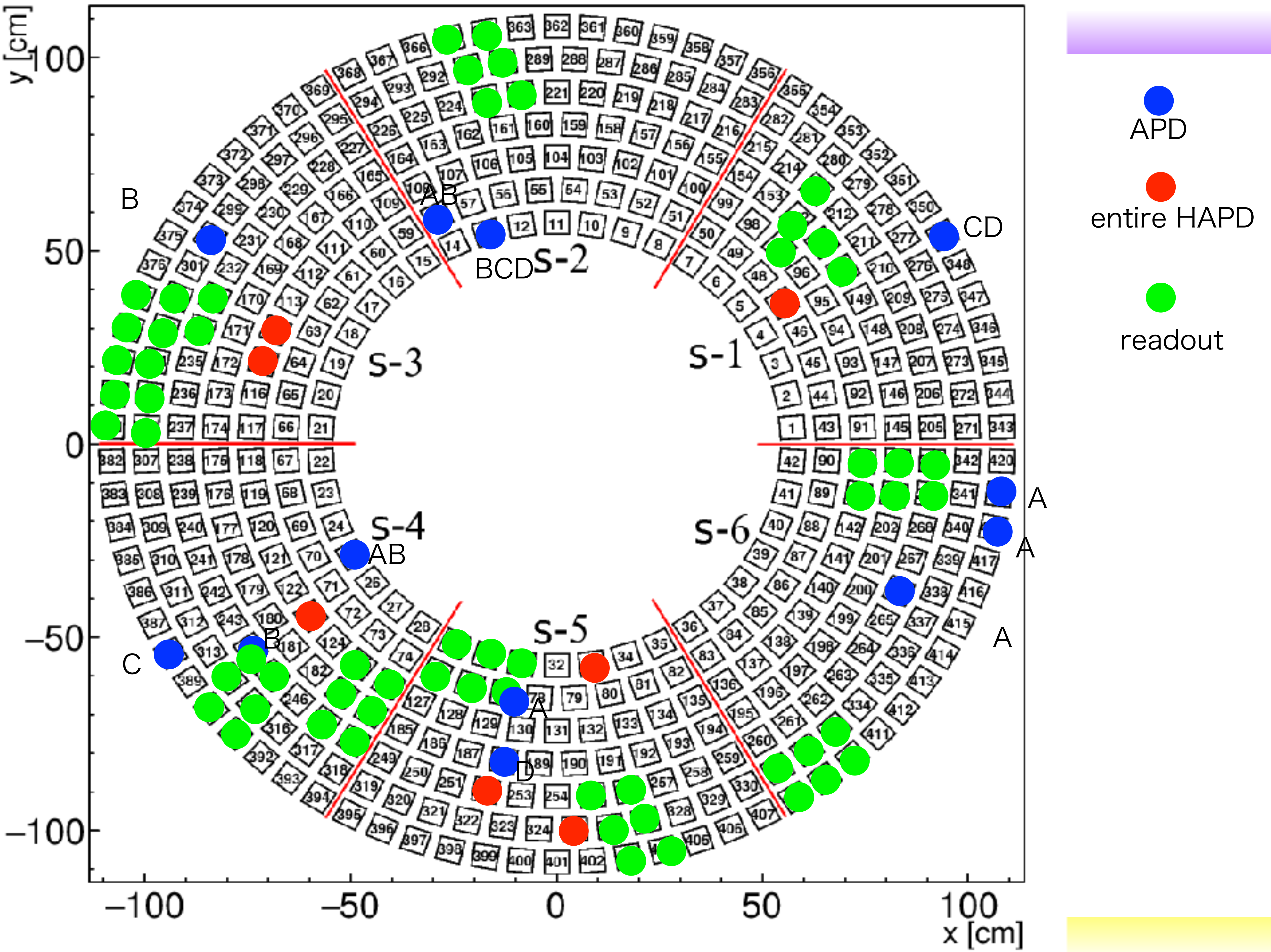
Flash over

- Electron emitted from photocathode hit the ceramic surface and cause secondary emission.
- By repeating the crashes and emissions, a gas is desorbed from ceramic surface.
- The gas is energized between the parts applied HV and APD →"large pulse"



HAPD has layer structure
stacked with ceramic and metal ring

unusable HAPDs



Masked HAPD

- Applying voltages is most basic way to check healthiness of HAPD.
- Some HAPDs are masked by two reasons
  - Power supply system → cable, patch panel, connector, power supply
  - HAPD problem → APD, circuit in HAPD, heavy noise

# of masked PS channels		before installation	beginning of Phase II	end of Phase II
PS side	HV channel	3	3	3
	Bias channel	2	4	4
HAPD side	Bias	1	5	14
	Guard	0	1	1
	HV	0	0	1
	Heavy noise	0	2	2
ratio of masked region	in total	0.9%	1.9%	2.7%
	HAPD issue	0.06%	1.0%	1.8%

# of channels
HV : 420
Bias : 1680
Guard : 420

- Problem in PS side will be repaired in this summer.
- Problem in HAPD side will be confirmed in this summer.
  - Replace the HAPD if needed.

Summary of unused HAPDs

10 out of 72 merger boards are masked by readout problem.

- not send data
- not receive trigger
- cannot download firmware
- connection fail

⇒59 HAPDs are masked by merger boards.

59/420=14.0% ↳ N(LED hits)<10

N(LED trigger)

<table>
<tr><th></th><th></th><th></th><th>ratio</th></tr>
<tr><td rowspan="3">unused HAPDs</td><td>PS issue</td><td>3 HAPDs and 4 APDs</td><td>0.9%</td></tr>
<tr><td>HAPD issue</td><td>4 HAPDs and 10 APDs</td><td>1.5%</td></tr>
<tr><td>readout issue</td><td>59 HAPDs</td><td>14.0%</td></tr>
<tr><td colspan="2">dead channel in used HAPDs</td><td>470 channels</td><td>0.9%</td></tr>
<tr><td>total</td><td>caused by HAPD</td><td>-</td><td>2.4%</td></tr>
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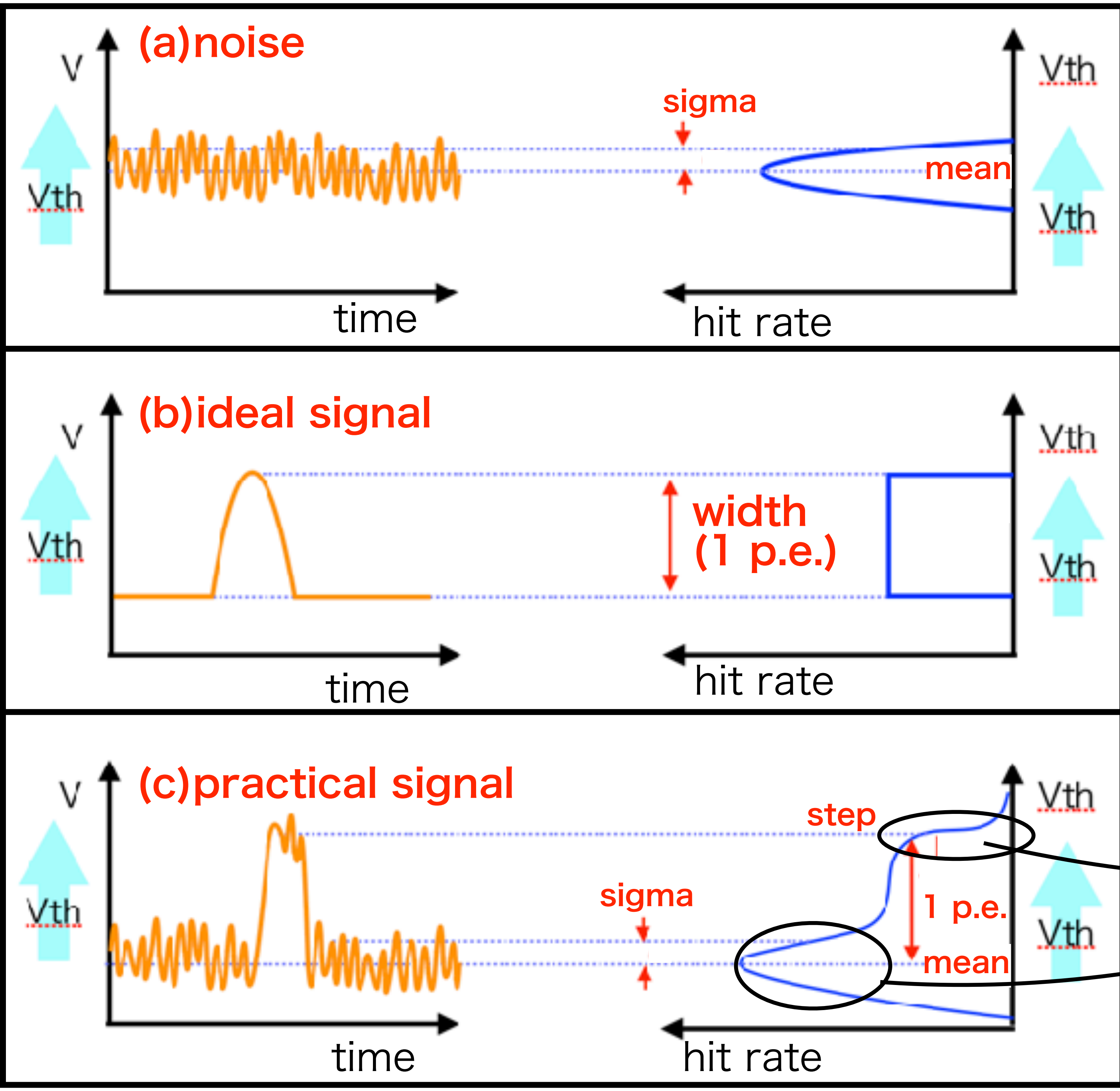
Threshold scan

Getting analog information from data (hit/no hit).

⇒Measure the hit rate while changing threshold voltage.



noise

shape : gaussian

- mean : offset
- sigma : noise level

ideal signal

shape : rectangle

- width : pulse height

practical signal

shape : error function for shoulder

gaussian for peak

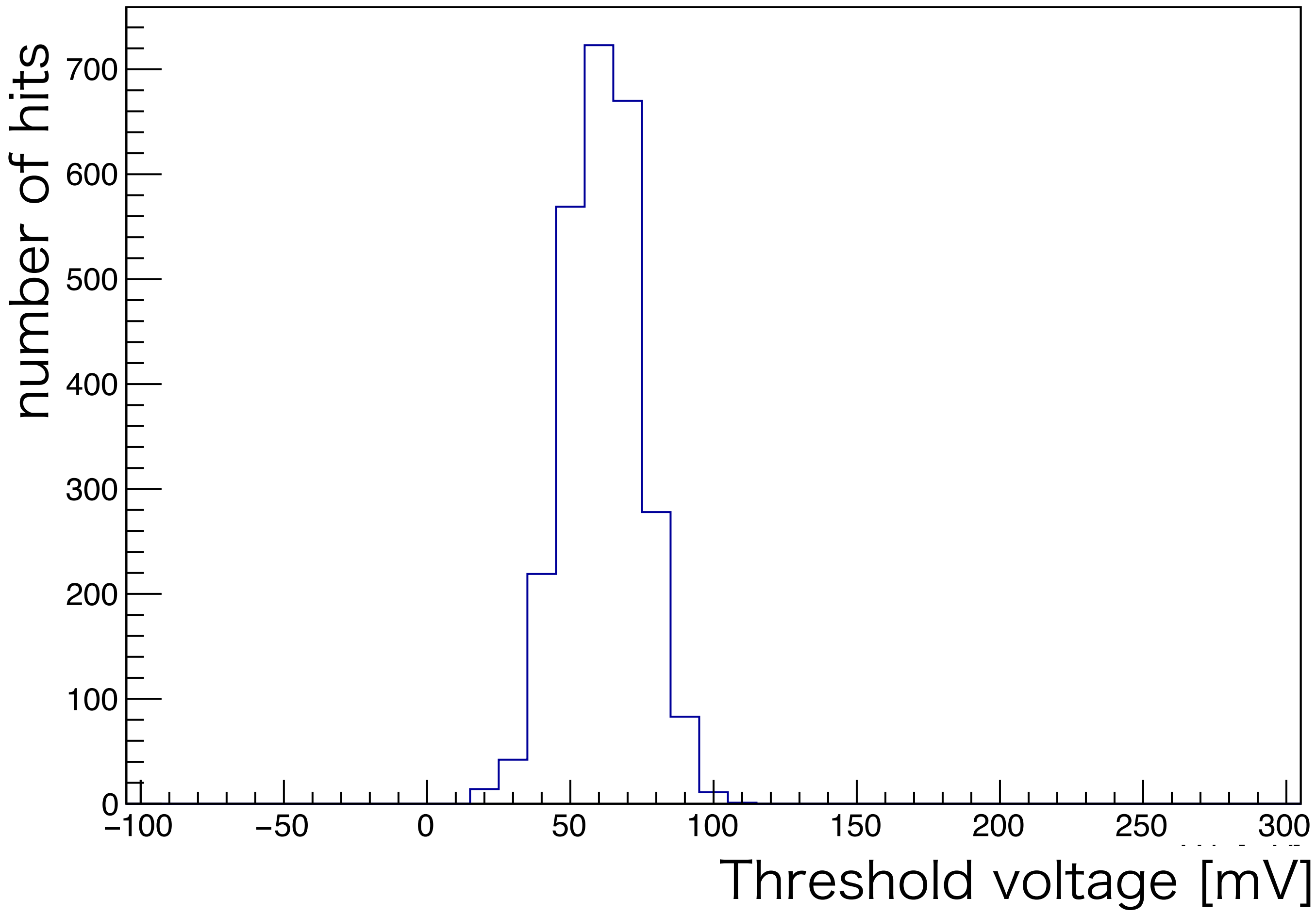
- difference between step and mean is 1 p.e. pulse height.

Measurement examples

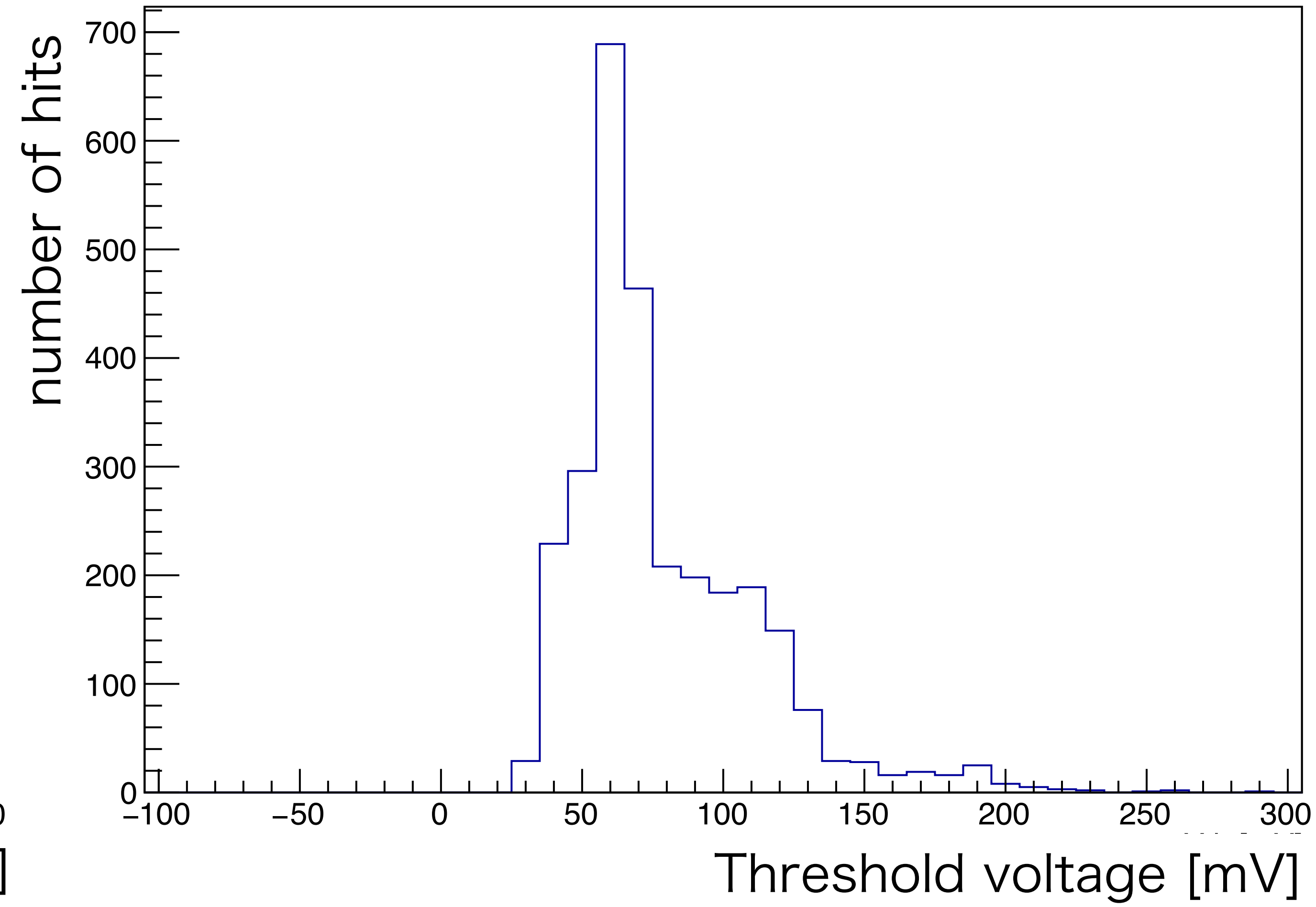
Results of threshold scan for one channel is shown.

- left : no voltages and random trigger
- right : all voltages are applied and LED monitor system

threshold scan for noise



threshold scan for LED signal



Threshold scan method is used to evaluate HAPD performance.

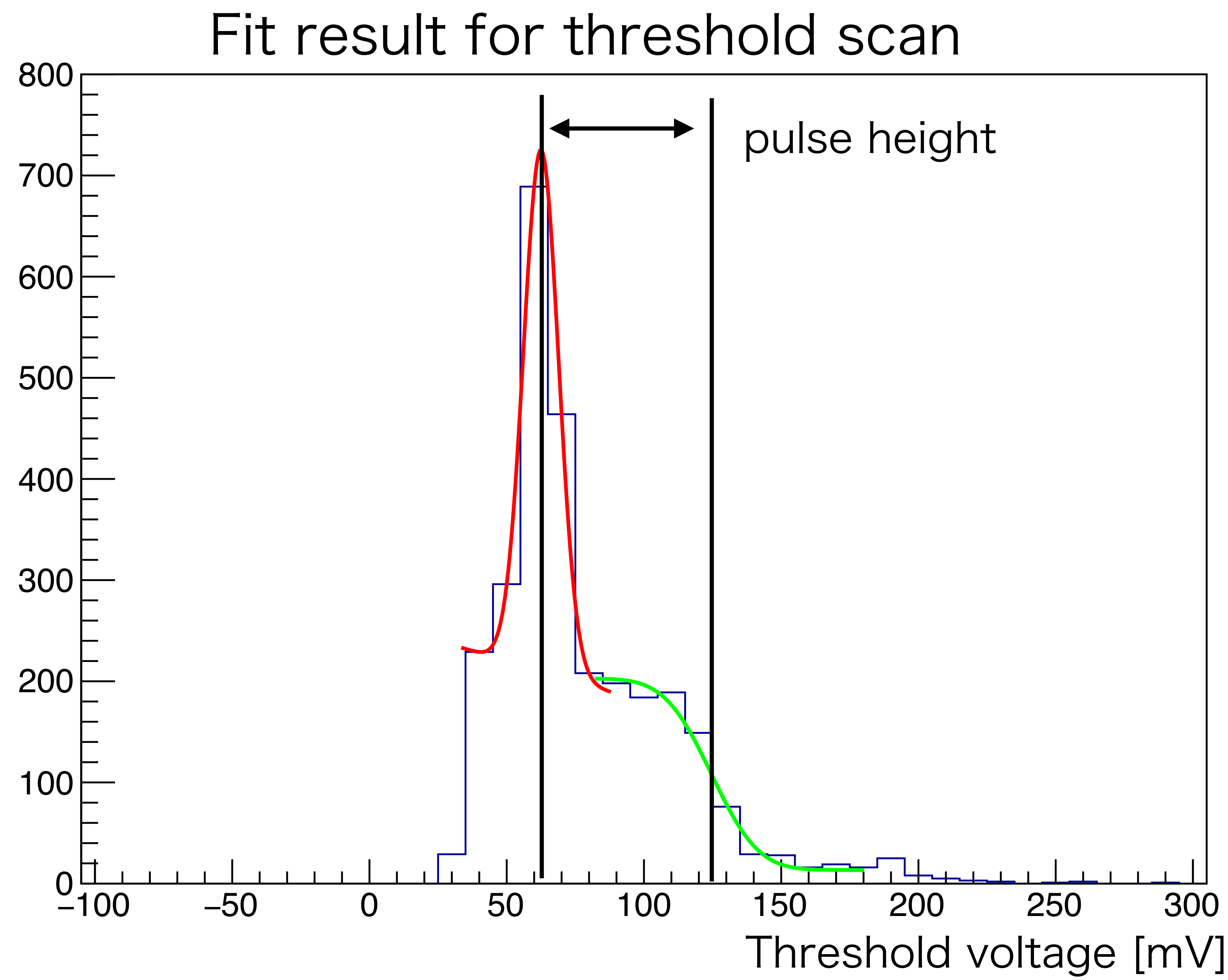
Fitting for threshold scan

Threshold scan result with LED monitor system.

Fitting

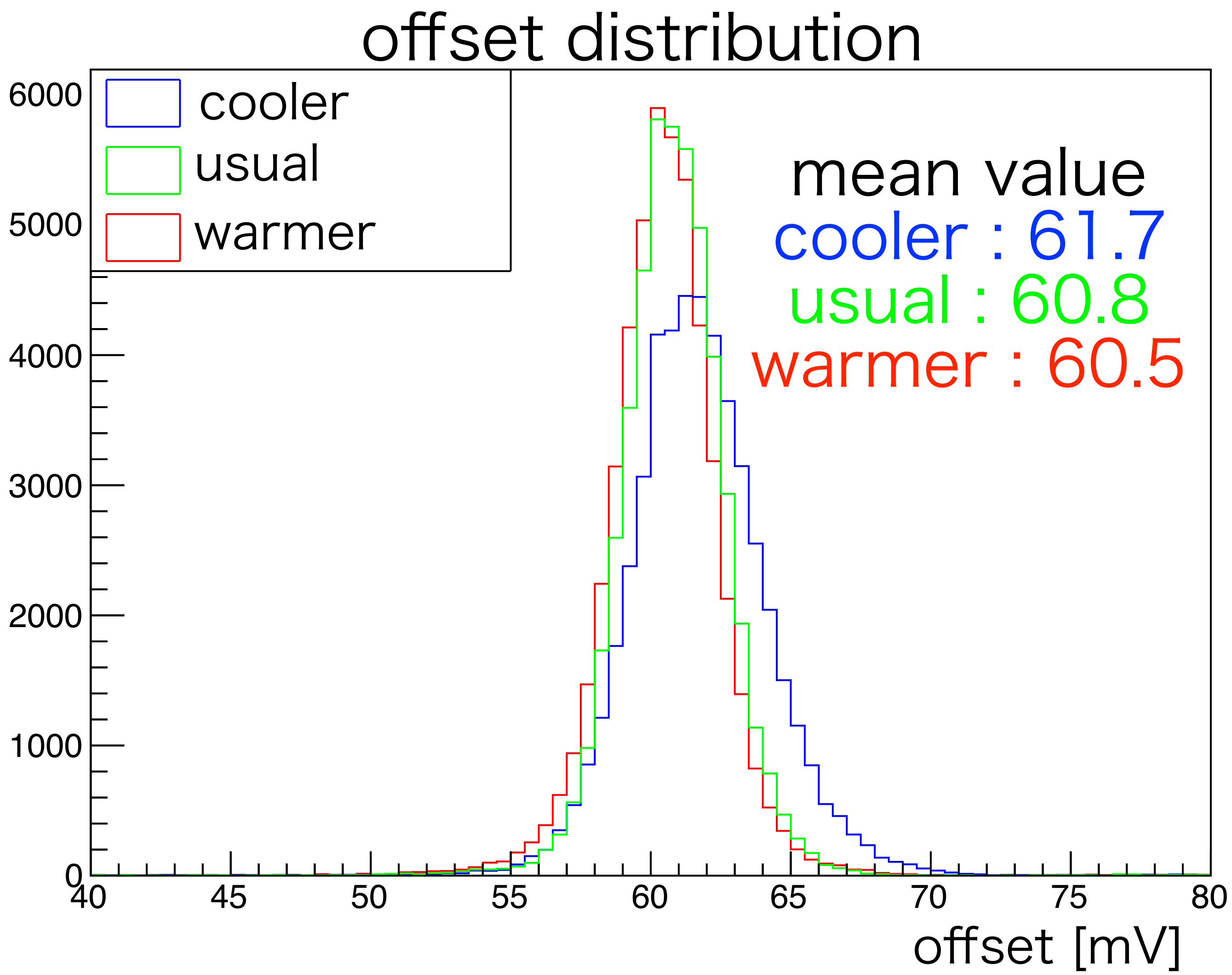
peak : gaussian

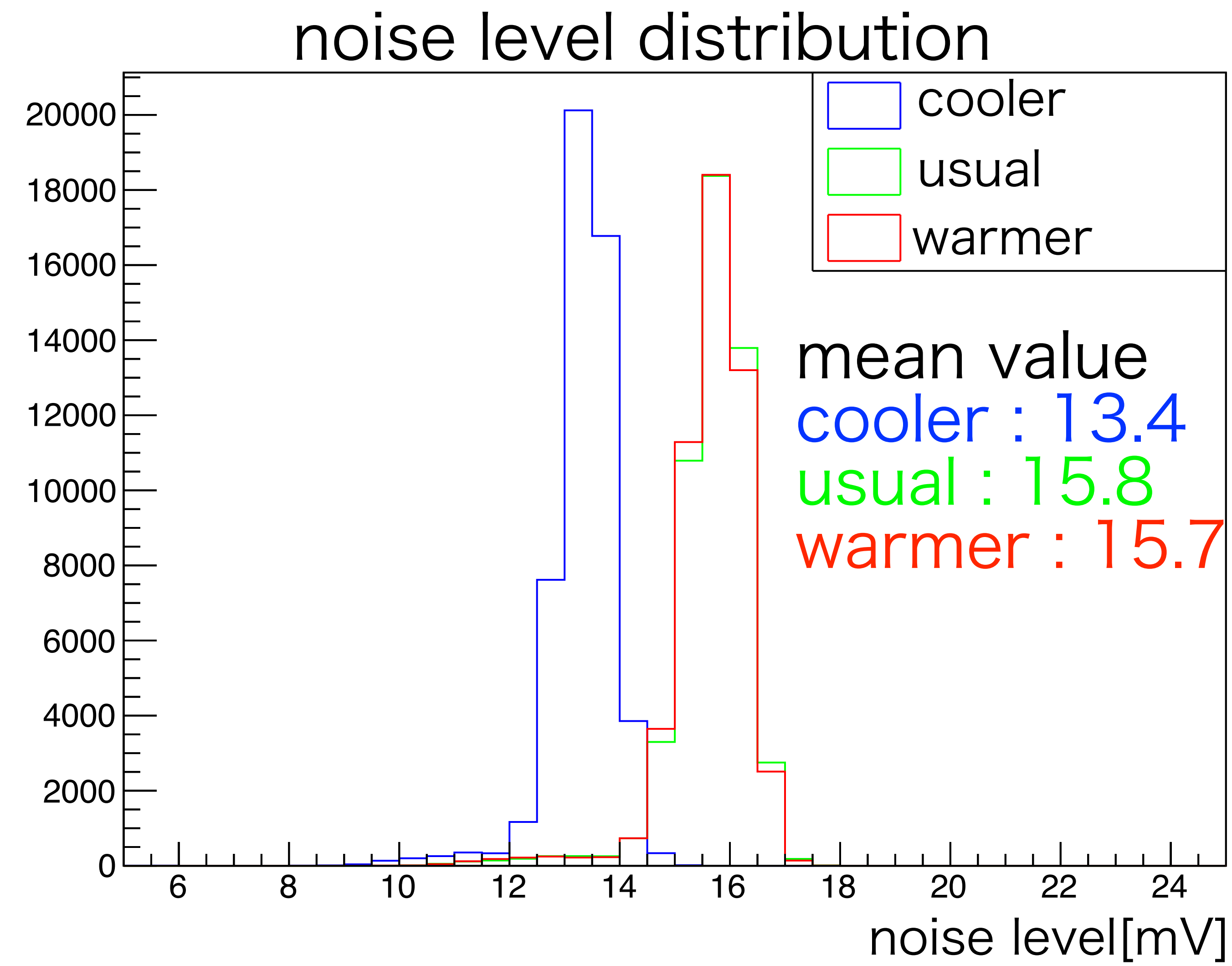
shoulder : error function



Temp. dependency offset

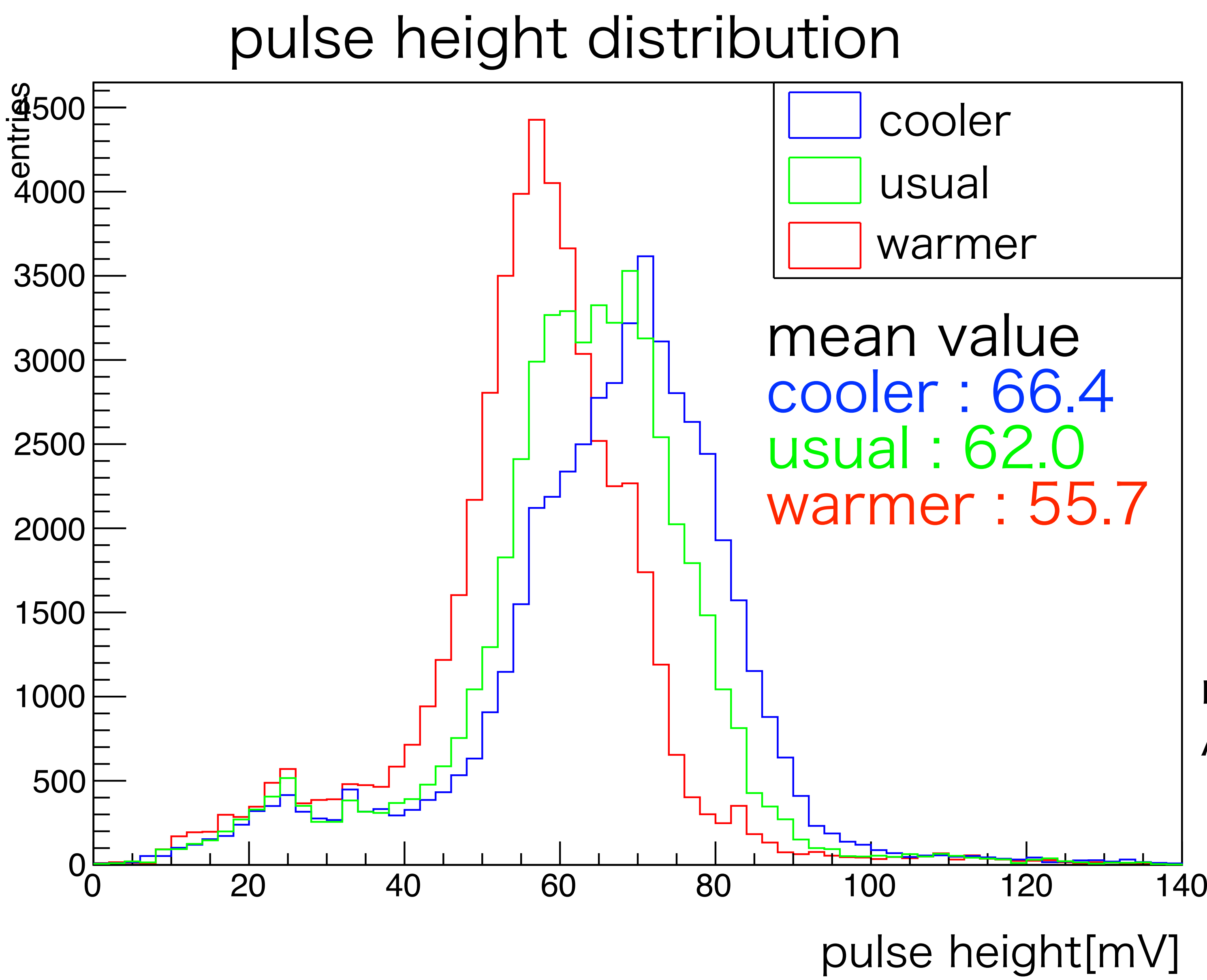
- Threshold scan with three different temperatures.
  - cooler, usual, warmer
- All voltages are not applied to see noise level.





Offset has little change by changing temperature.
Noise level is increased with higher temperature.

Compering pulse height with noise



Pulse height is decreased with higher temperature.

	noise	pulse height
cooler	13.4	66.4
usual	15.8	62.0
warmer	15.7	55.7

note :
Applying Bias noise level is decreased by half.

Pulse height is enough larger than noise level .
⇒We can use same threshold voltage at every temperature.