Characterization of the Hyper-Kamiokande 50-cm Photomultiplier Tubes

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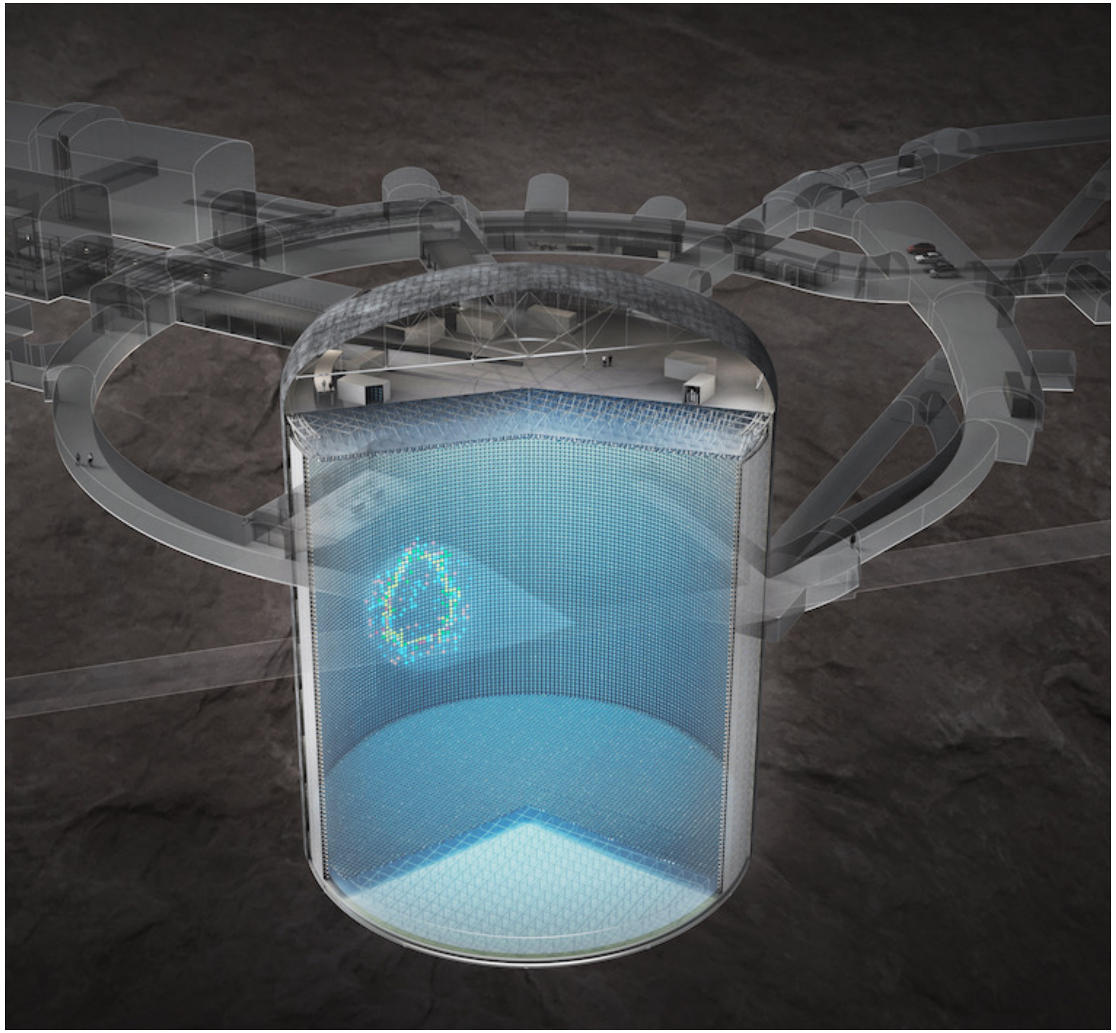
Hyper-Kamiokande (HK)

- Gigantic water Cherenkov detector
- Successor to the Super-Kamiokande (SK)
  - ×8.4 fiducial mass (190 kt) of SK
  - 20k 50-cm PMTs
- Physics motivation
  - Neutrino CP violation
  - Neutrino mass ordering
  - Cosmic neutrino
  - Nucleon decay

  etc.

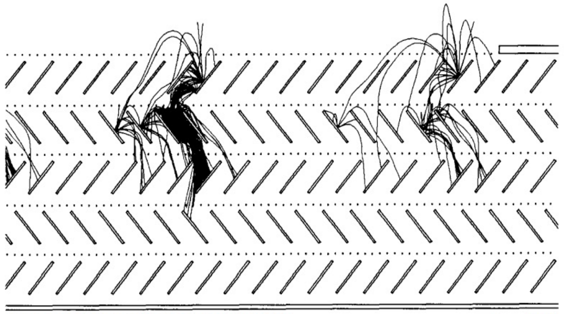
→ Start operation in 2027



50-cm PMT for HK (HKPMT)

- 20k 50-cm PMTs (R12860 by Hamamatsu-photonics) will be used in HK to detect Cherenkov light.
- HKPMT is improved from 50-cm PMT used in SK (R3600).
  - **“Box & Line”** dynode (changed from “Venetian blind” dynode of SKPMT)
  - Higher quantum efficiency photocathode, higher collection efficiency
  - **x2 in detection efficiency, x2 in charge resolution, more than x2 in timing resolution**
- Mass production is in progress, ~12000 PMTs have been delivered so far.

SKPMT (R3600)

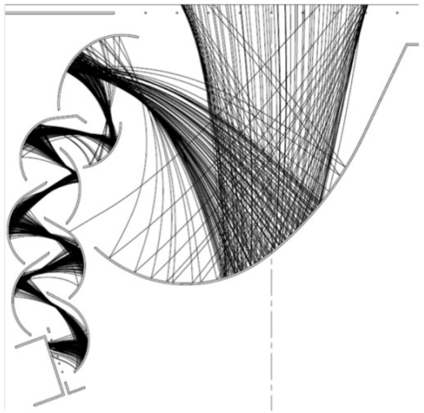


NIM A329 (1993) 299-313 (一部)

Venetian blind dynode

Improved

HKPMT(R12860)



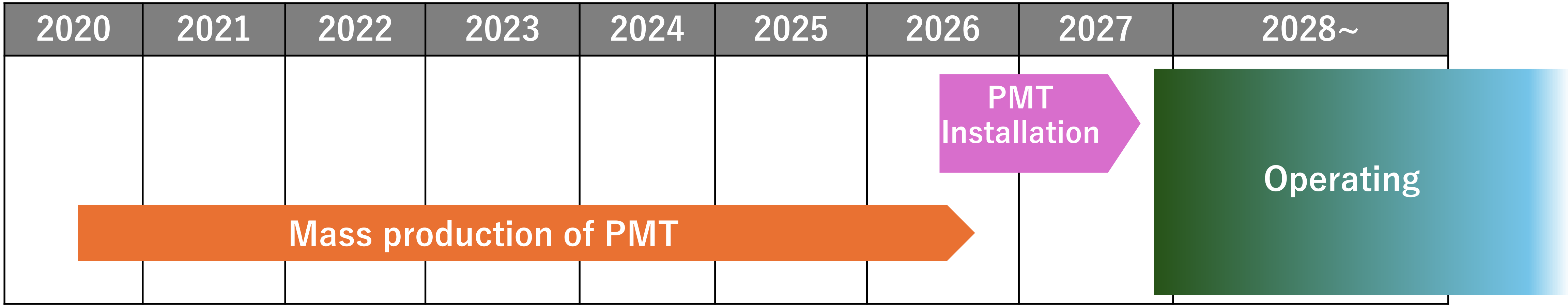
Box & Line dynode

Motivation of HKPMT measurement

- Mass production of PMT will continue until 2026.
- PMT performance is directly related to the HK's performance, and PMT stability is important for HK's long period operation.

→Need to check if quality of PMT is maintained throughout mass production and if PMTs work stably for long-term.

→ Several types of PMT measurements are now ongoing <u>to understand quality</u> <u>**from multiple angles.**</u>



Purpose of each measurement

- Common purpose : to see stability and manufacturing quality

- Precise measurement :

→ Variations in **basic performance** (charge resolution, timing resolution, after pulse, etc.)

- Mass measurement :

→ Measurement of **stability for large numbers**

- Long-term measurement :

→ Demonstration of **long-term use**

Ensure the low uncertainty and high durability of HK detector.

1. Precise measurement

- Precise measurement :

→ Variations in **basic performance** (charge resolution, timing resolution, after pulse, etc.)

- Mass measurement :

→ Measurement of stability for **large numbers**

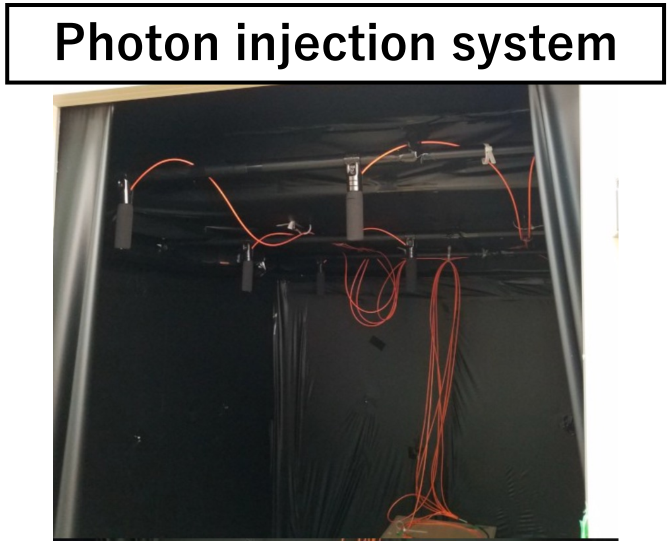
- Long-term measurement :

→ Demonstration of **long-term use**

1. Precise measurement

- Regular measurement of various basic performance of HKPMT
  - Measurement of 16 PMTs (8 PMTs × 2) every month
  - Magnetic field shielding with mu-metal
  - Light source for 1 p.e. spectrum and timing response
  - Charge resolution, After pulse*, Timing resolution, etc.

*After pulse : Signal that occurs with a delay of 2~40 μs from the main signal due to collision of electron & residual gas, etc. Here, counting the number of after pulse, not charge.



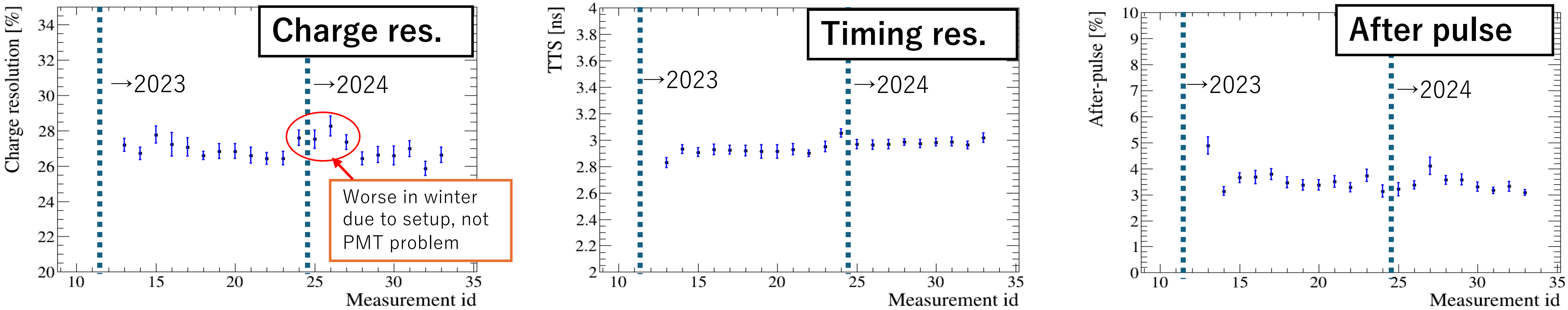
Basic performance of HKPMT

- Results obtained in measurements since 2023 (More than 280 PMTs)

	Charge resolution*1	Timing resolution*2	After pulse	Gain stability*3
Average	**26.9 %**	**2.95 ns**	**3.47 %**	**0.51 %**
RMS	**1.8 %**	**0.14 ns**	**0.81 %**	**0.11 %**

*1 : σ of 1 p.e. peak / *2 : FWHM of transit time / *3 : RMS of gain over each measurement period (~1month)

→Small individual differences with expected high performance.



- Mean (point) and RMS (error bar) over measured PMTs in each period.

→Quality is stable throughout production.

"Measurement id" indicates measurement for different delivery

2. Mass measurement

- Precise measurement :

→ Variations in **basic performance** (charge resolution, timing resolution , after pulse, etc.)

- Mass measurement :

→ Measurement of **stability for large numbers**

- Long-term measurement :

→ Demonstration of **long-term use**

2. Mass measurement

Inside the dark room

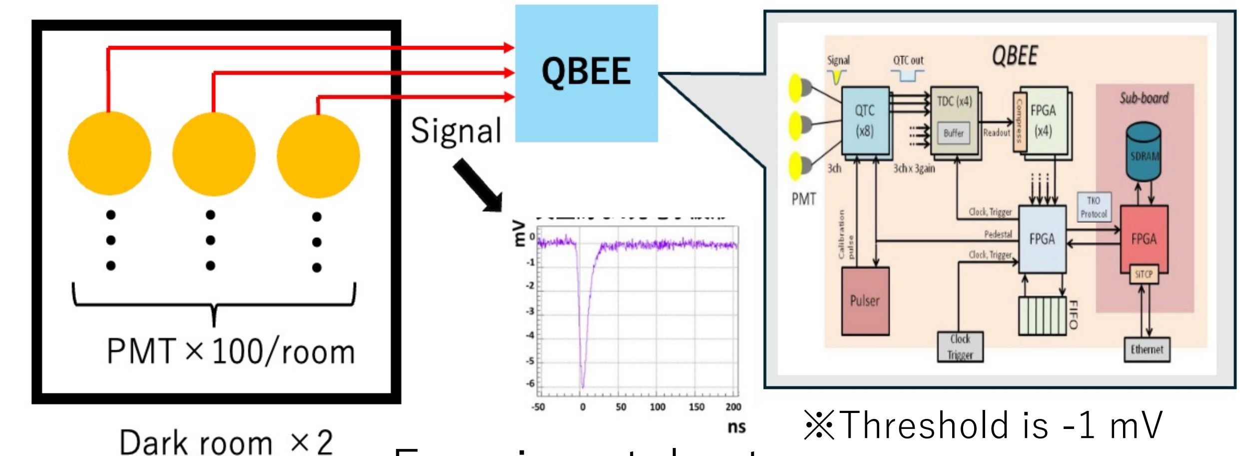
- 200 PMTs measurement (2 rooms, 100 PMTs/room)
  - 1-month measurement for 100 PMTs every month
  - 3-month measurement for 100 PMTs every 3 months

  (※Several hundred PMTs delivered every month)
- Measure charge and time of dark count*

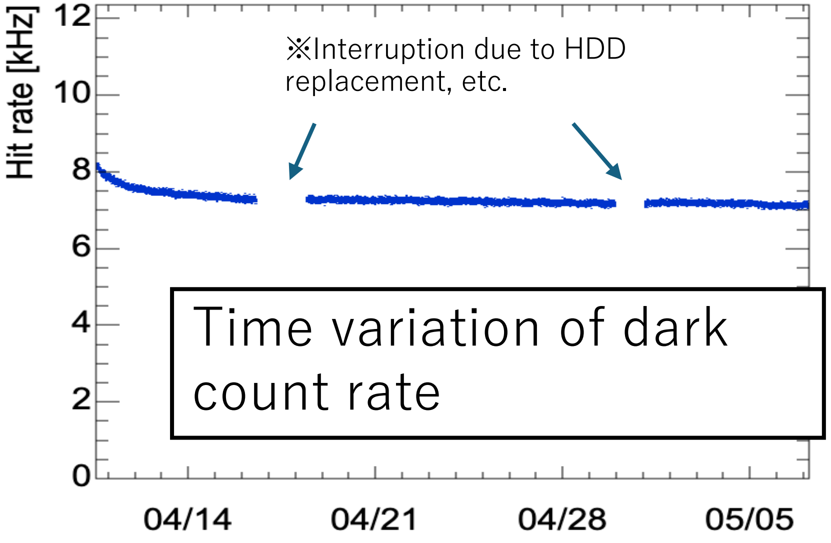
→Evaluate dark count rate per a minute and its stability, as those are critical for HK performance.

*Dark count :Signals without external light. Due to thermal electron, RI in glass of PMT, environmental radiation, etc.

- I focus on 3-month measurements with about 300 PMTs.



Experimental set up



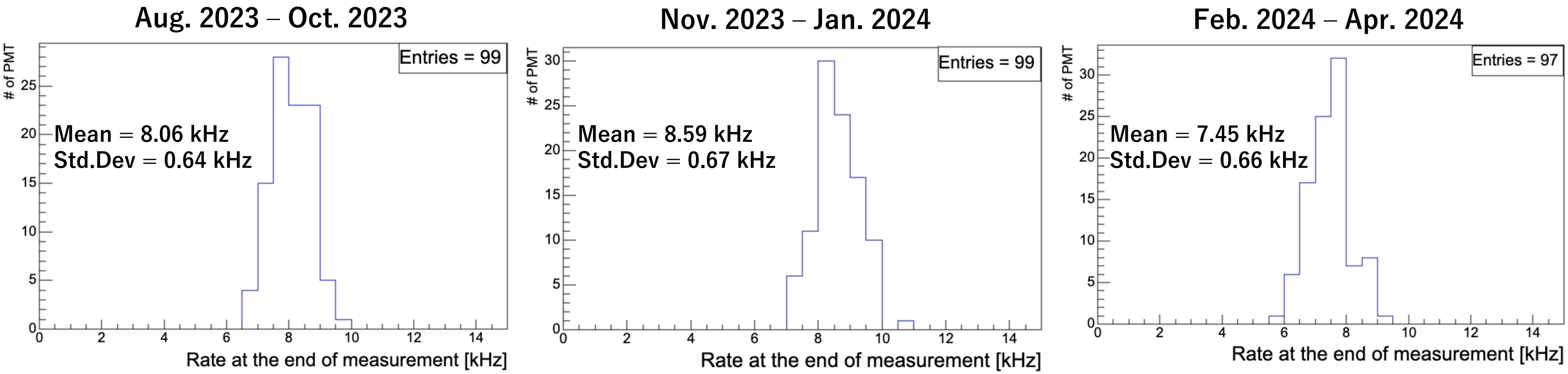
Time variation of dark count rate

Distribution of dark count rate

About 100-PMT distributions of dark count rates at the end of each 3-month measurement.

- Average is about 7~9 kHz, standard deviation is about 0.6~0.7 kHz.

  ※Actual value of rates should be ~4 kHz lower due to environmental radiation

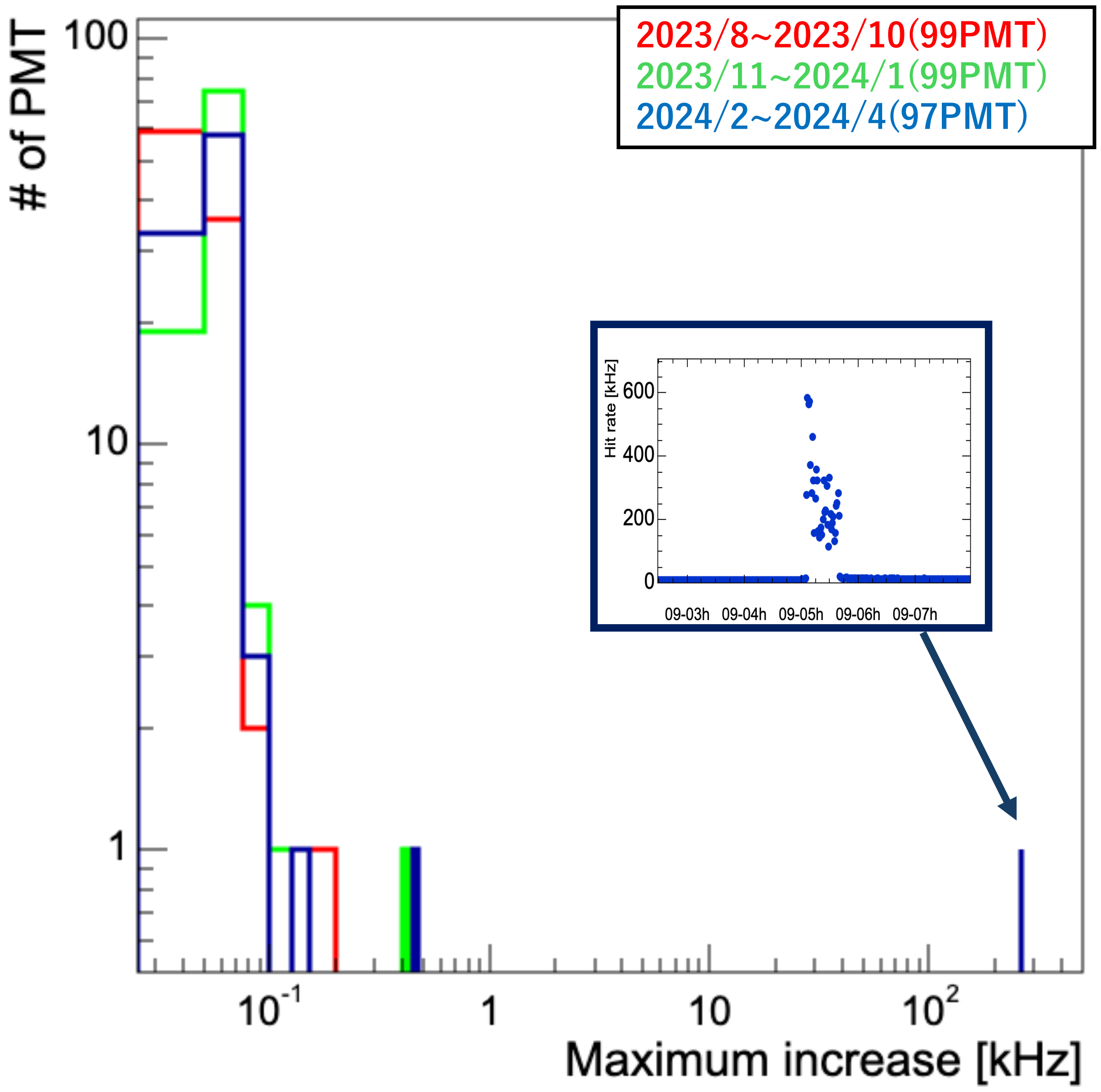


Stability of dark count rate

- Dark count rate can rapidly increase due to PMT's problem such as insulation failure.
- We check such rapid rate increase and monitor if unstable PMTs exist or not.

→Distribution of the maximum rate increase compared with previous 5 min in each PMT

→ Though a very few showed clear instability, **most PMTs were stable for as long as three months.**



3. Long-term measurement

- Precise measurement :

→ Variations in **Basic performance** (charge resolution, timing resolution , after pulse, etc.)

- Mass measurement :

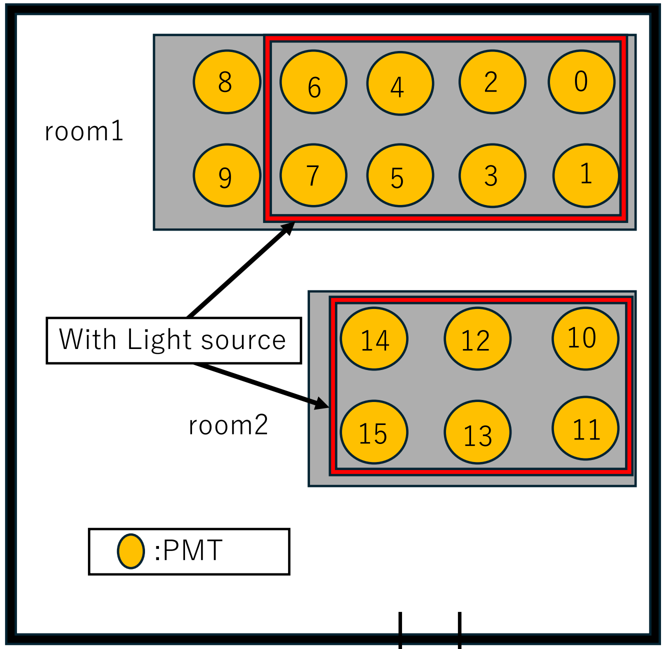
→ Measurement of **stability for large numbers**

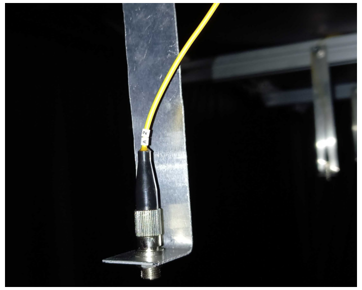
- Long-term measurement :

→ Demonstration of **long-term use**

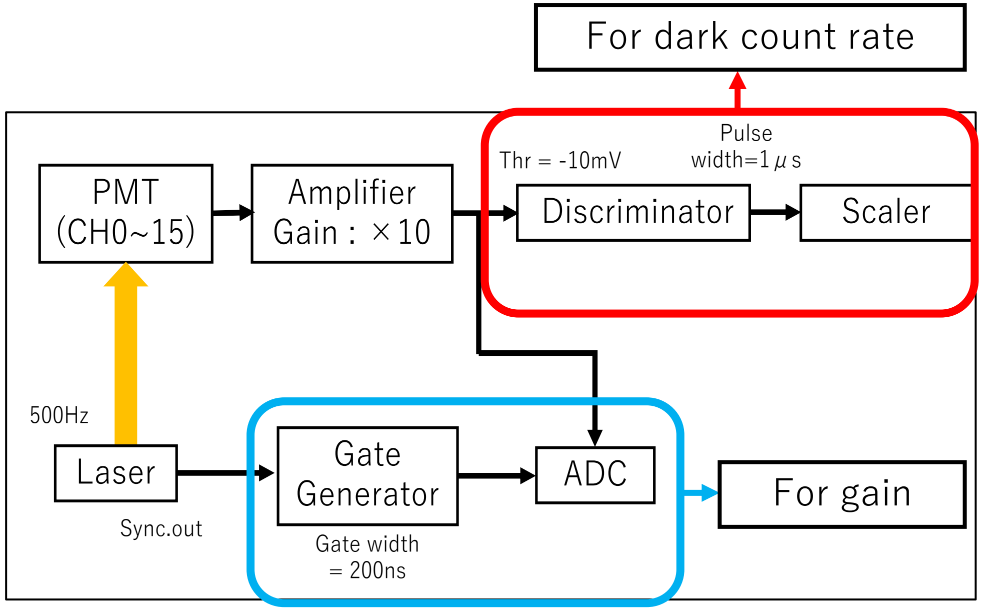
3. Long-term measurement

- Measurement of 16 PMTs for more than 1 year in the Kamioka mine
  - Compensation of the earth magnetic field using coils
  - Photon injection system for 1 p.e. spectrum
- Check the long-term stability of HKPMT :
  - **Dark count rate**
  - **Gain (for 14 PMTs)**



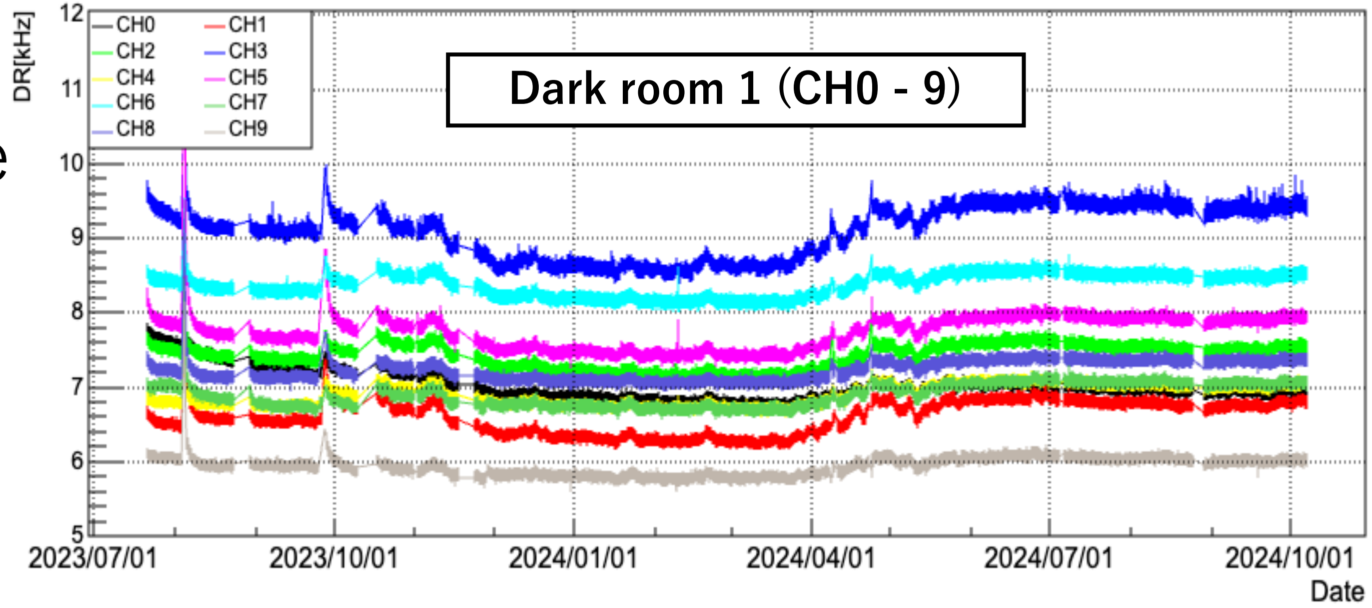


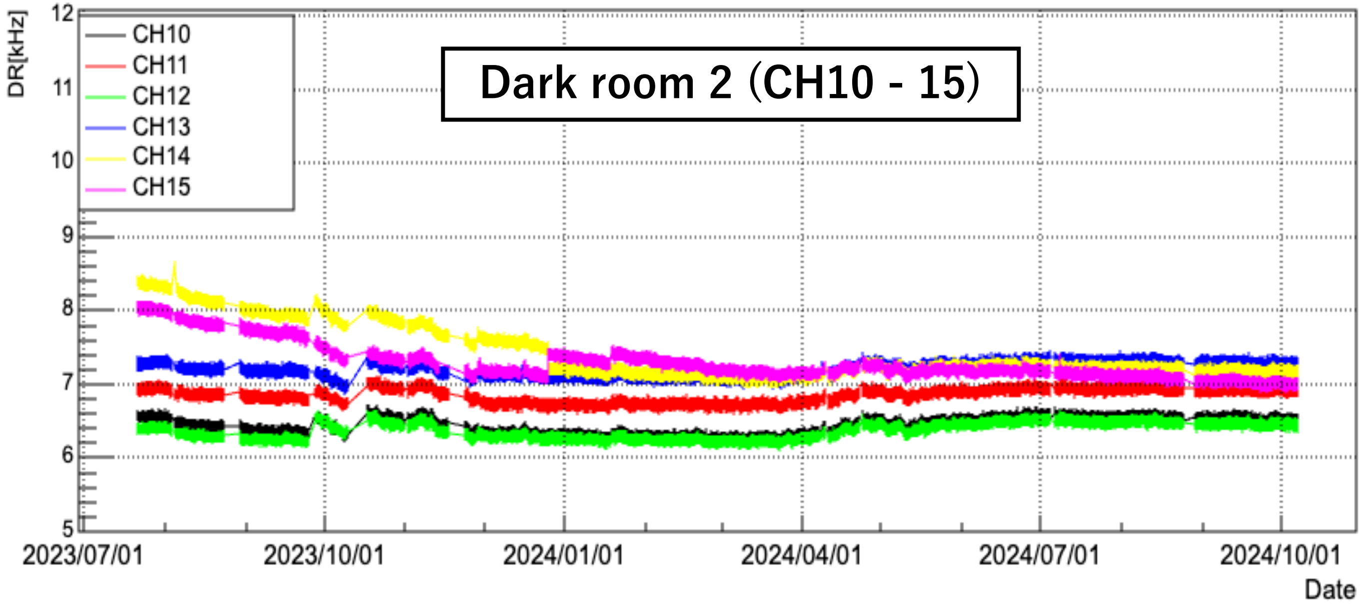
←Optical fiber for gain measurement



Monitoring dark count rate over a year

- Time variation of dark count rate since July 2023 (over a year)
- **PMTs work stably for more than 1 year.**
- **No strange variations of dark count rates** except for variations due to external factors such as seasonal change of Rn concentration.





Measurement of Gain

- Gain of HKPMT ~ 1×10^7
- Charge distribution is fitted with a function as below

Fitting function

$$\equiv p_0 \exp\left\{-\left(\frac{x-p_1}{\sqrt{2}p_2}\right)^2\right\} : \textit{Pedestal peak}$$

$$+ p_3 \exp\left\{-\left(\frac{x-p_4}{\sqrt{2}p_5}\right)^2\right\} : \textit{1 p.e peak}$$

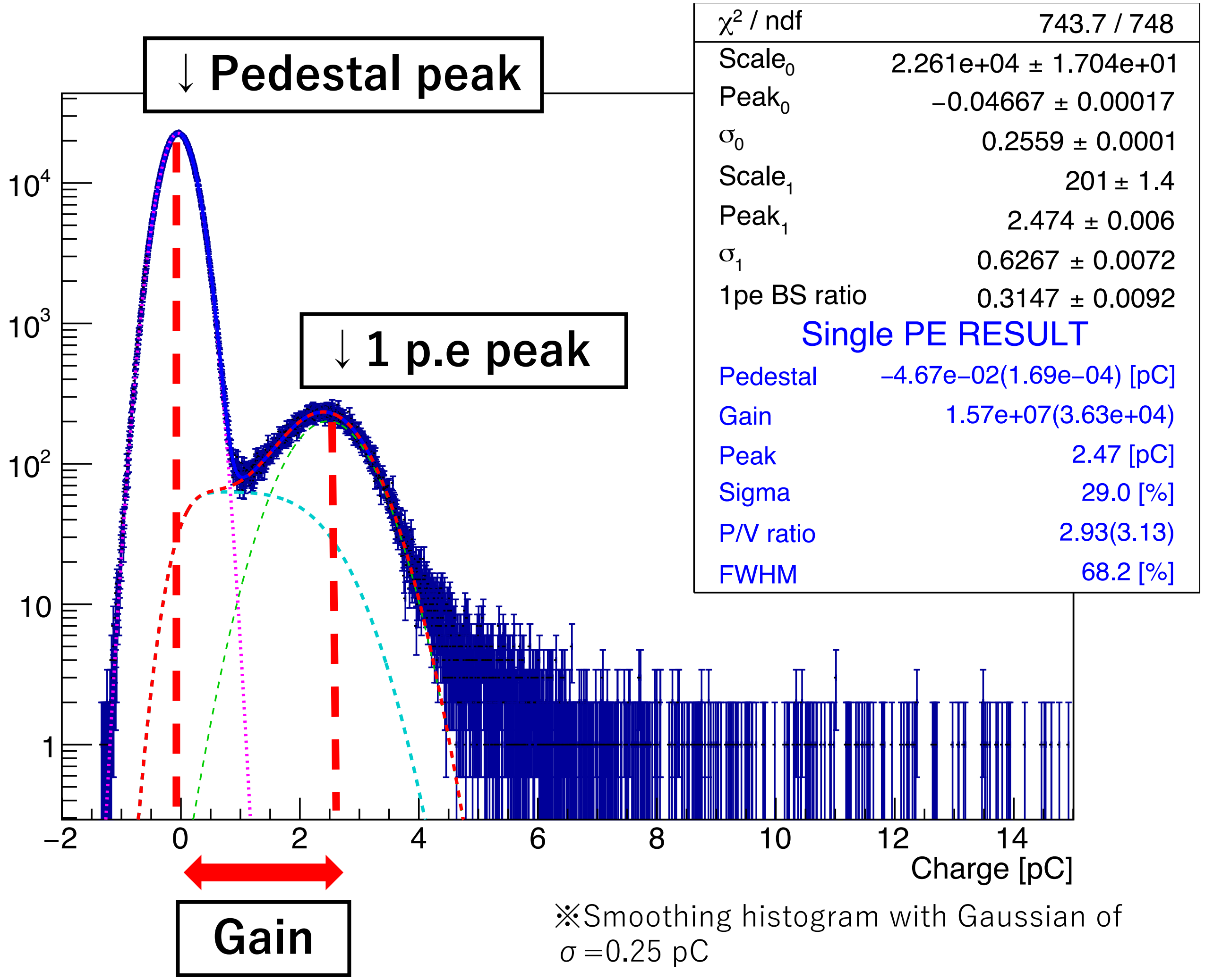
$$+ \frac{p_6 p_3}{2}\left\{\mathrm{erf}\left(\frac{x-p_1}{\sqrt{2}p_2}\right) - \mathrm{erf}\left(\frac{x-p_4}{\sqrt{2}p_5}\right)\right\}$$

: *for inelastic scattering, etc.*

$$Gain \equiv \frac{p_4 - p_1}{elementary\ charge}$$: 1 p.e peak – pedestal peak

→ Monitor gain of each PMT.

Example of Charge distribution



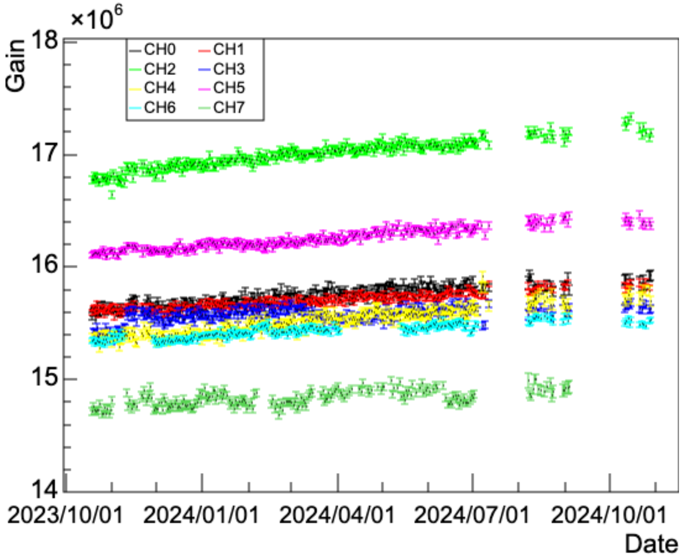
※Smoothing histogram with Gaussian of σ =0.25 pC

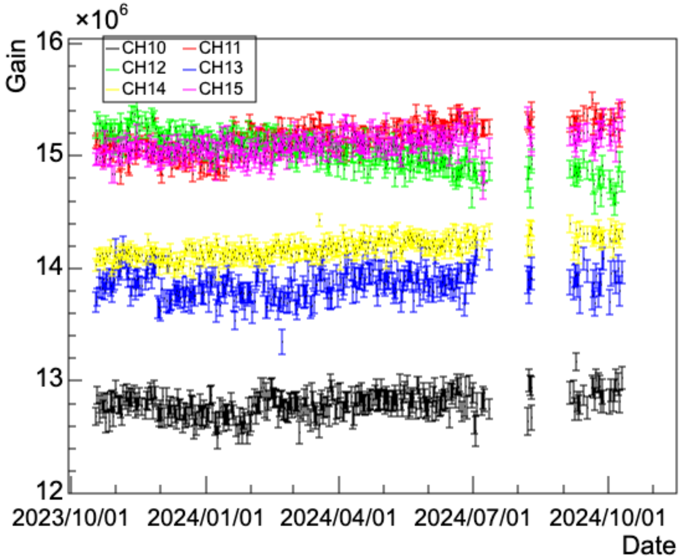
Monitoring gain over a year

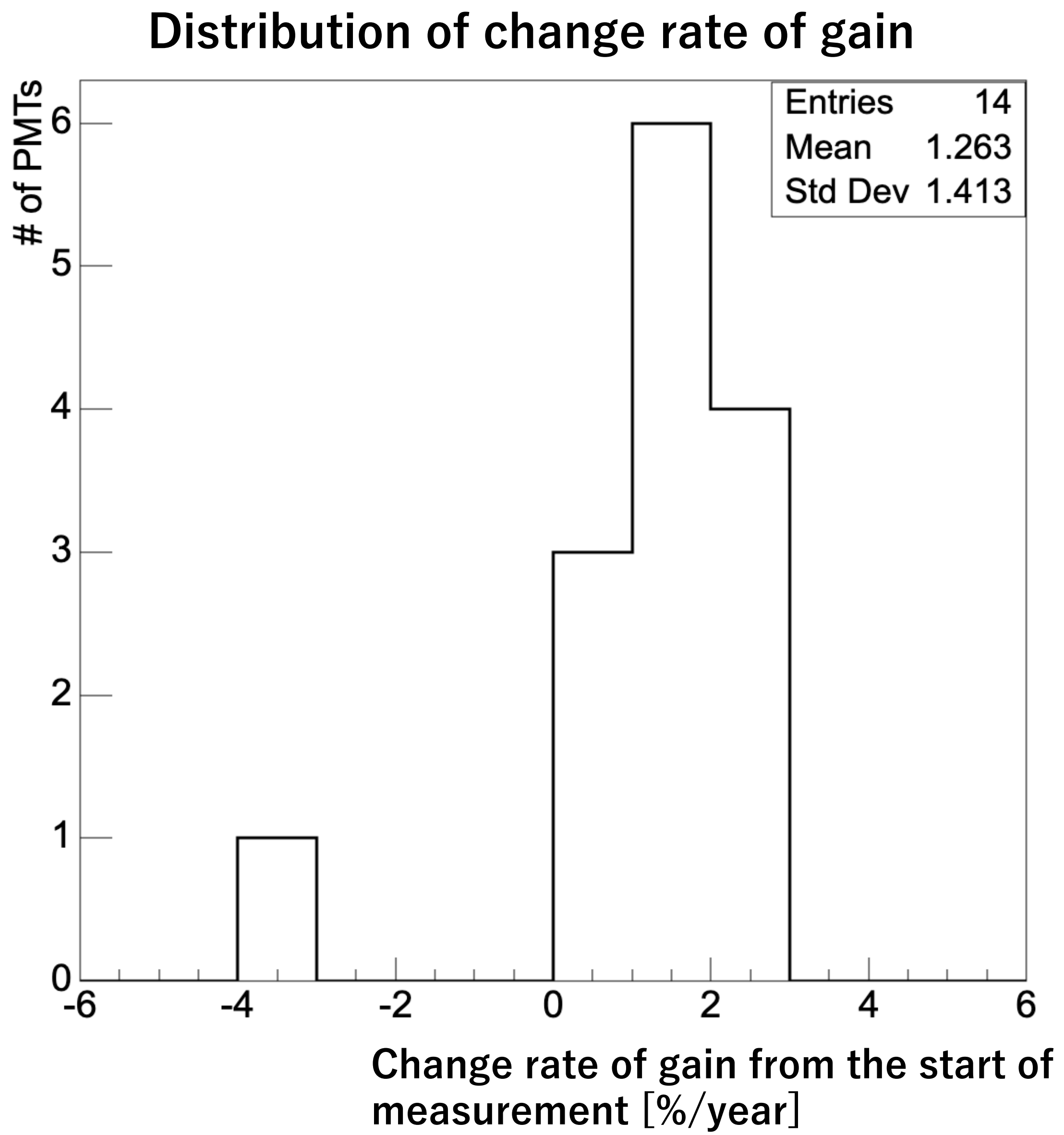
- Since Oct. 2023 (over a year)
- **Increase tendency** of gain appears.
  - Average of gain change : **1.3** ± **0.4 [%/year]**
- In SKPMT, increasing tendency has been observed (~ 2 %/year), too.

→ **Similar trend with SKPMT**

Time variation of gain since Oct. 2023







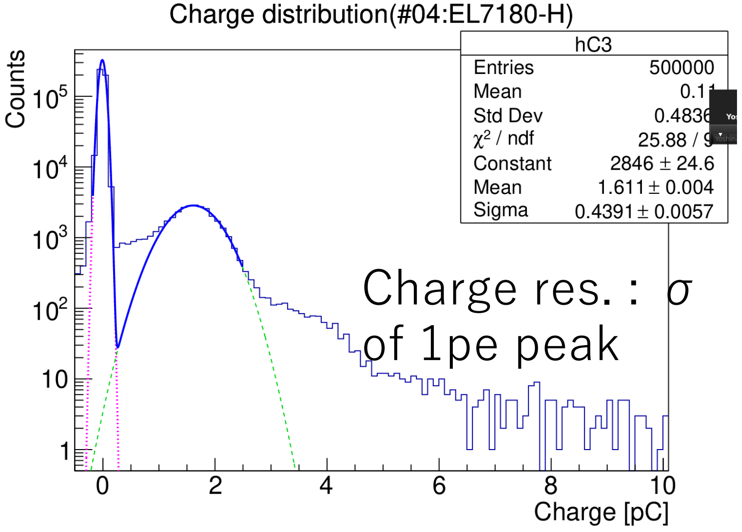
Summary

- Mass production of 50-cm PMTs for HK is in progress.
- We are monitoring the quality and stability of HKPMTs from multiple angles :
  - Precise measurement
    - Basic performance of more than 280 PMTs for about 1 month
    - Small individual differences with high performance and stable quality
  - Mass measurement
    - Dark count rate stability of ~300 PMTs for 3 months
    - Most PMTs worked stably
  - Long-term measurement
    - Dark count rate and gain of 16 PMTs over a year
    - Work stably with known increase tendency in gain

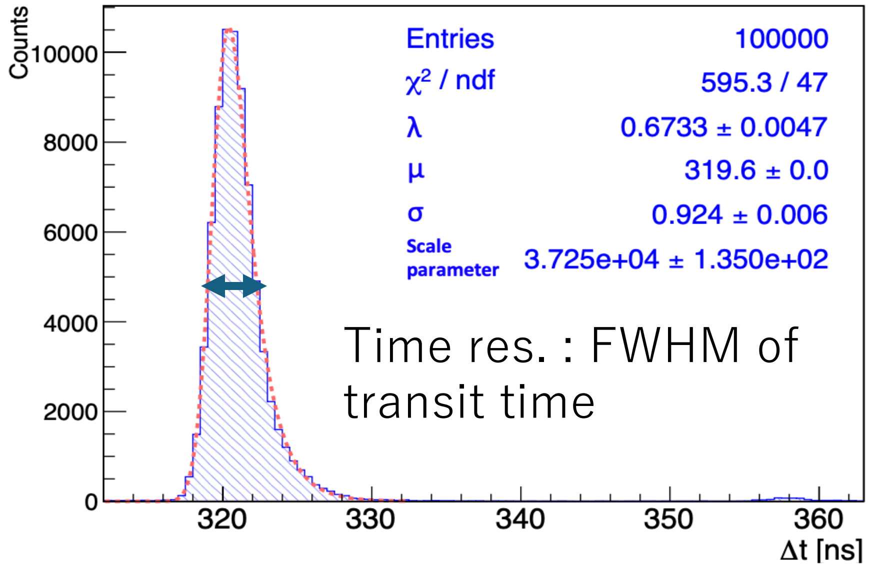
→ **Confirm stable quality throughout production.**

Back up

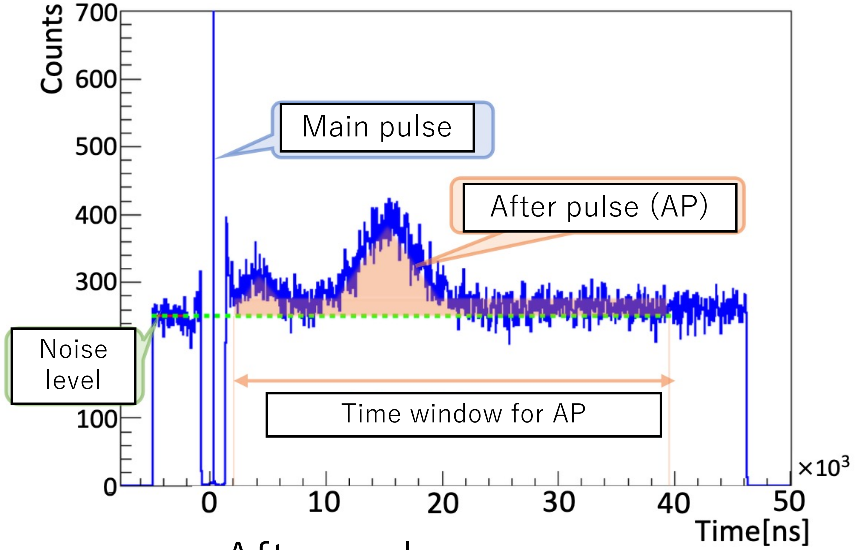
Measurement of Charge res., Time res., AP



Charge res. : σ of 1pe peak

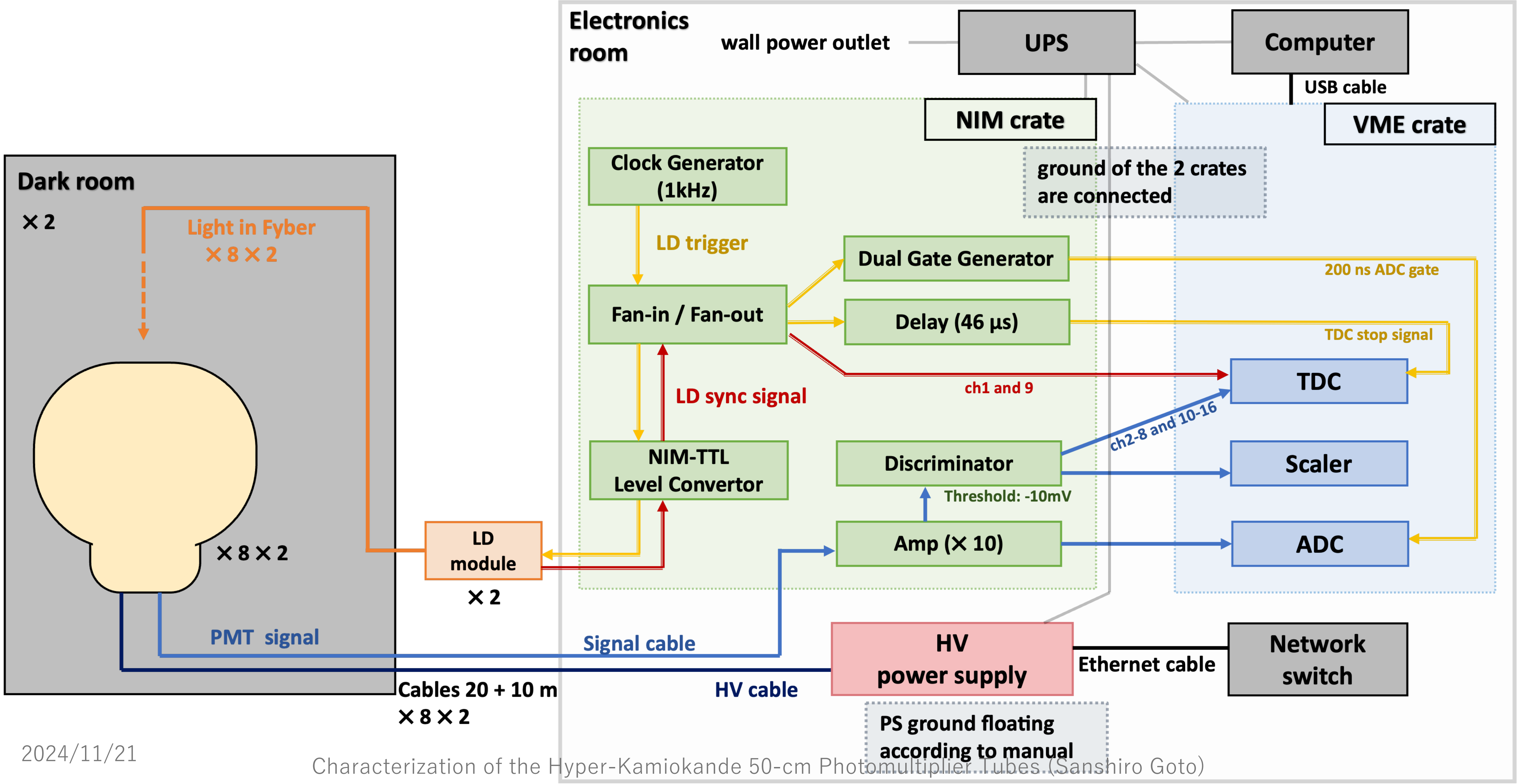


Time res. : FWHM of transit time



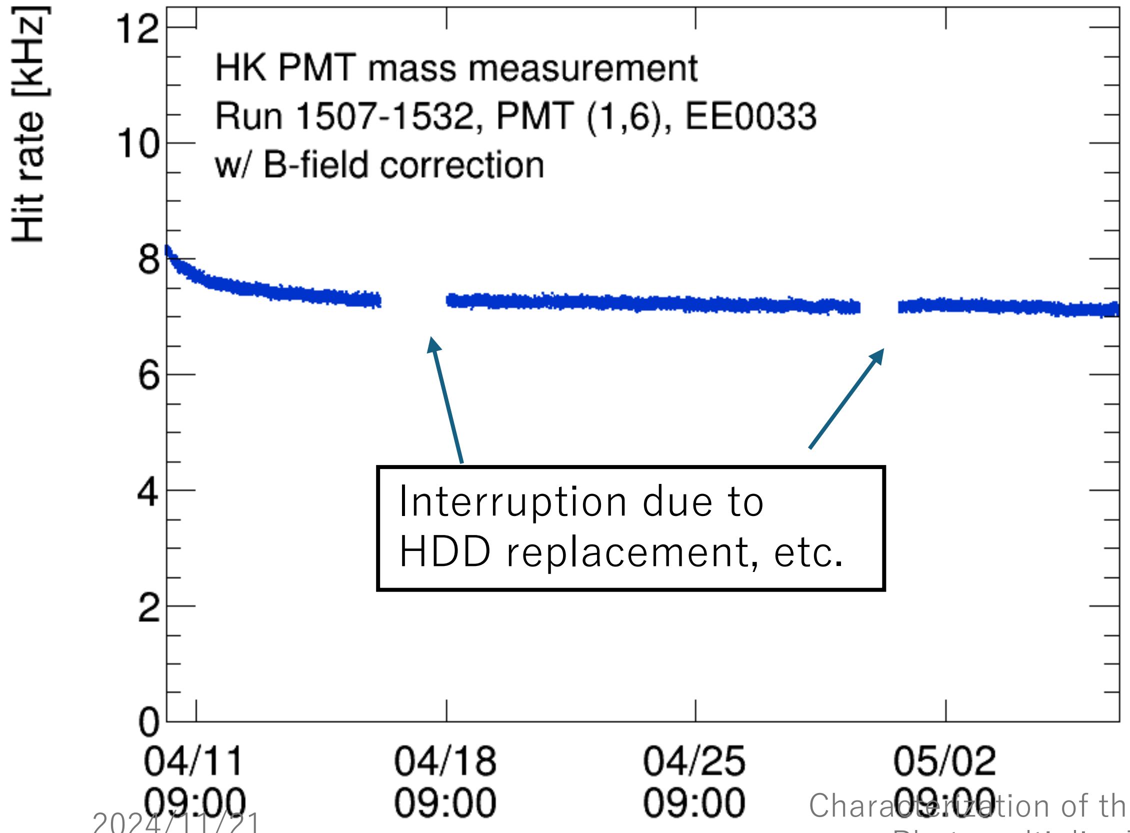
After pulse :
# of pulse in 2~40us /# of Main pulse

Set up of precise measurement



Mass measurement of dark count rate

- Calculate dark count rate as an average of the number of signals every 60 sec
- Threshold is -1 mV (~ 1/6 of typical hight of 1 p.e signal)



←An example of dark count rate transition

The rate is high immediately after PMT installation in the dark room and gradually decreases and stabilizes.

Why dark count rate?

- Dark count → Back ground of true signal (Cherenkov light)
- Amount of dark count rate is used to estimate the true number of PMT which detect the Cherenkov light when physics event occurs

→Instability of dark count rate can be uncertainty of HK

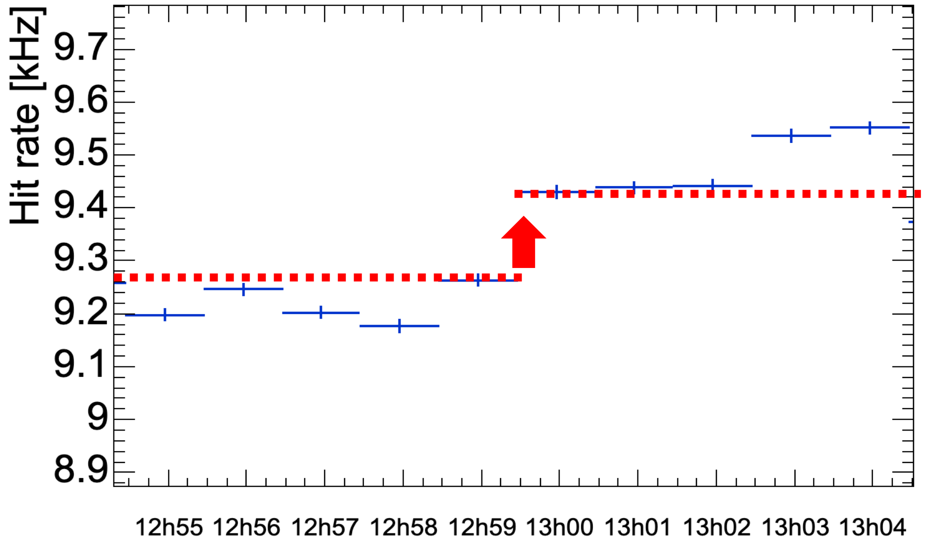
- Too much dark count rate makes data transmission difficult
- Instability of dark count rate may be a sign of PMT breakdown

Stability of dark count rate

- 2 types of rate variation

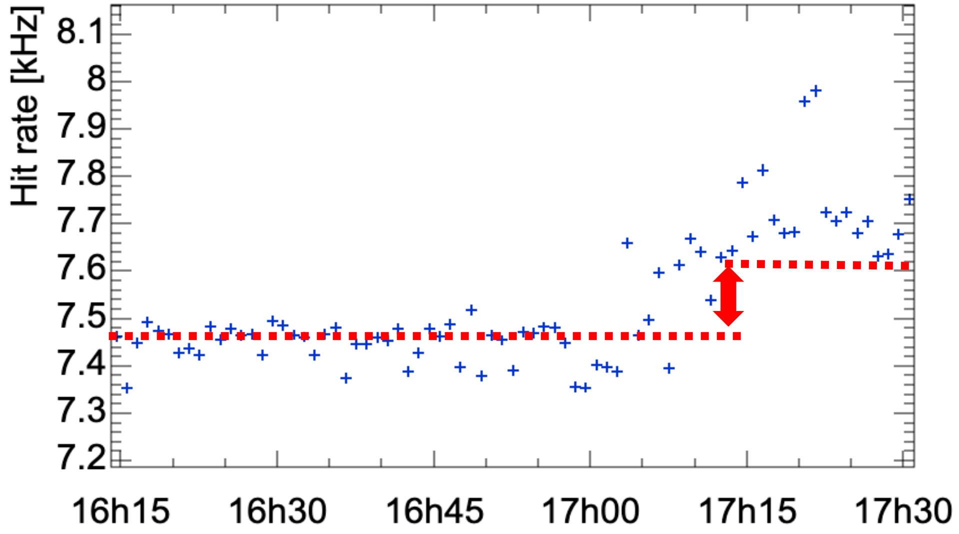
➢ **Rapid rate increase**

  - Related to insulation failure, etc.
  - Check the distribution of the maximum rate increase (lasting more than 5 minutes*) at each PMT from the rate in the previous 5 minutes



➢ **Moderate rate fluctuations**

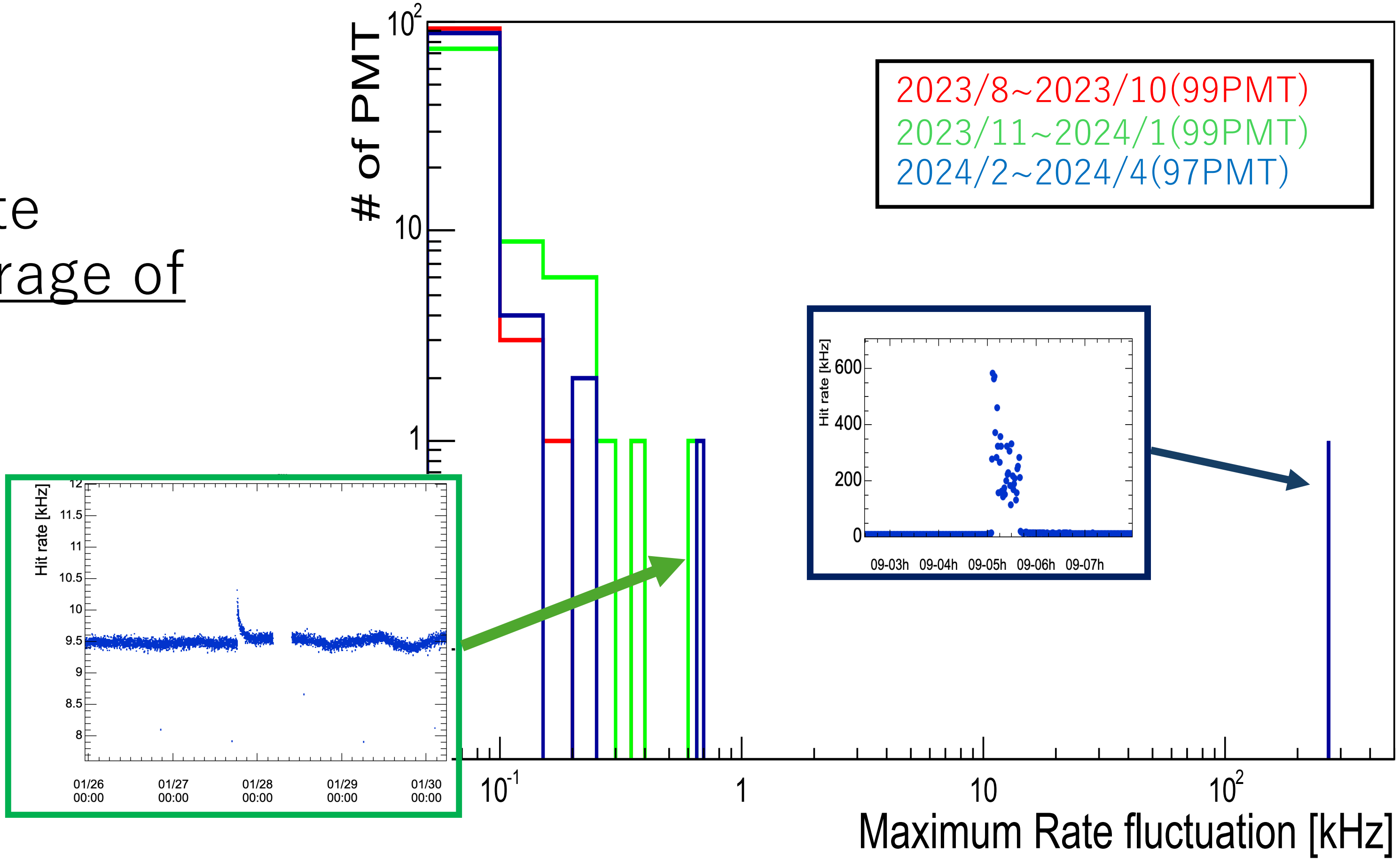
  - More general PMT instability
  - Check the distribution of the maximum rate fluctuation (lasting more than 5 minutes) from the average of the previous hour's rates at each PMT.



*Only increase and fluctuation "which last longer than 5 minutes" are recorded because of the existence of very short-time (about 1 minute) fluctuations due to external noise, DAQ slowdowns, etc.

Rate fluctuation including decrease or gradual change

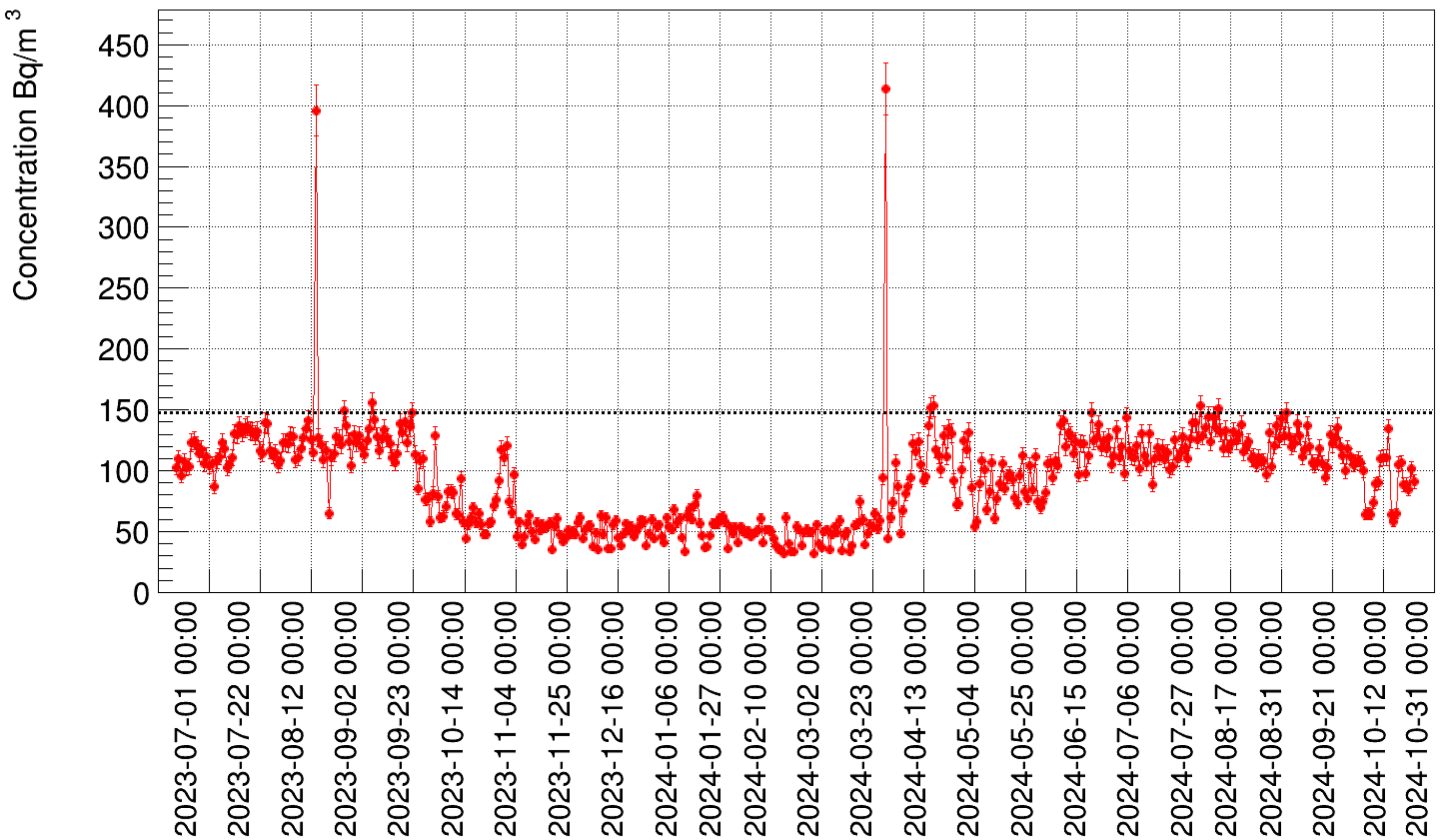
- **Moderate rate fluctuations**
  - More general PMT instability
  - Distribution of the maximum rate fluctuation* compared with <u>average of previous 1 hour</u>



*Select ones last for > 5 min only

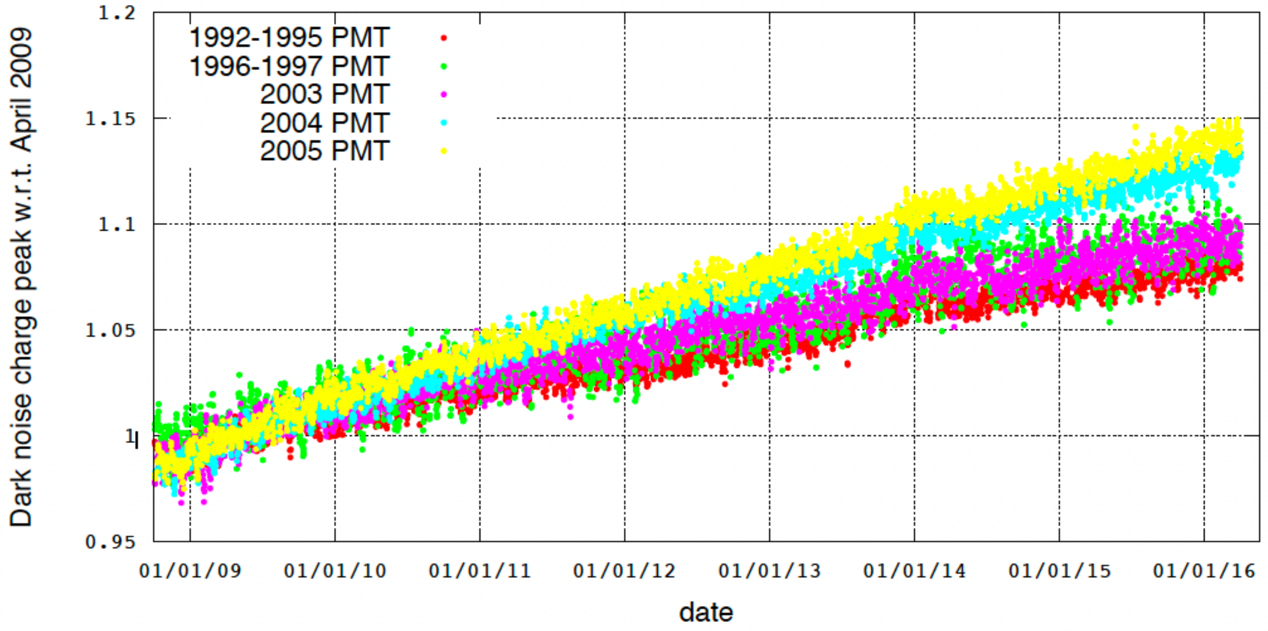
Rn concentration in the laboratory (long-term measurement)

- Rn concentration in the laboratory
- Seasonal change due to the wind direction inside the mine



Gain increase of SKPMT

- In SKPMT, increasing tendency of gain has been observed (~2%/year)



← Yusuke Suda. "Search for Proton Decay Using an Improved Event Reconstruction Algorithm in Super-Kamiokande." PhD thesis, University of Tokyo, 2017.

- It is speculated that the cause of this change is that the amount of Cs in the dynode changes during operation.