Performance Evaluation for Hyper-Kamiokande Digitizer

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Hyper-Kamiokande Collaboration

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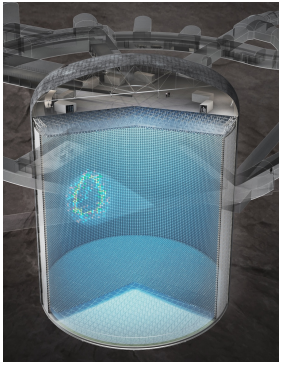
Hyper-Kamiokande Experiment

What is HK

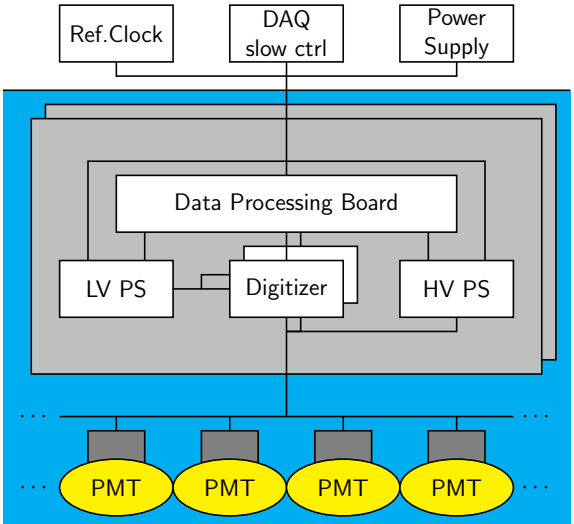
- The next-generation water Cherenkov detector in Japan.
- Fiducial volume is $190\,\mathrm{kton}$ (8 times bigger than SK)
- Planned to start data taking in 2028.

Physics Goals	Signal Characteristics
Proton Decay	$30\,\mathrm{MeV}$–$1\,\mathrm{GeV}+2.2\,\mathrm{MeV}\gamma$
Accelerator Neutrino	$100\,\mathrm{MeV}$–$30\,\mathrm{GeV}+2.2\,\mathrm{MeV}\gamma$
Atmospheric Neutrino	$100\,\mathrm{MeV}$– a few$\mathrm{TeV}+2.2\,\mathrm{MeV}\gamma$
Solar Neutrino	3.5–$15\,\mathrm{MeV}$
Galactic Supernova Neutrino	Typically $<30\,\mathrm{MeV}$ 30k events in 1s
Nearby Supernova Neutrino	Typically $<30\,\mathrm{MeV}$ 75M events in 1s



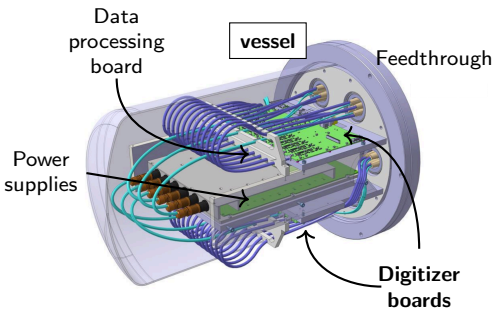
Artist's rendering of HK

HK Data Acquisition System



- PMT signals are processed directly by electronics inside the underwater vessels.
- Filling and draining the tank takes more than one year in total.
- Replacement and repair are difficult once they are installed.
- Long-term stable operation (> 10 years) is required.

HK Electronics in Vessels

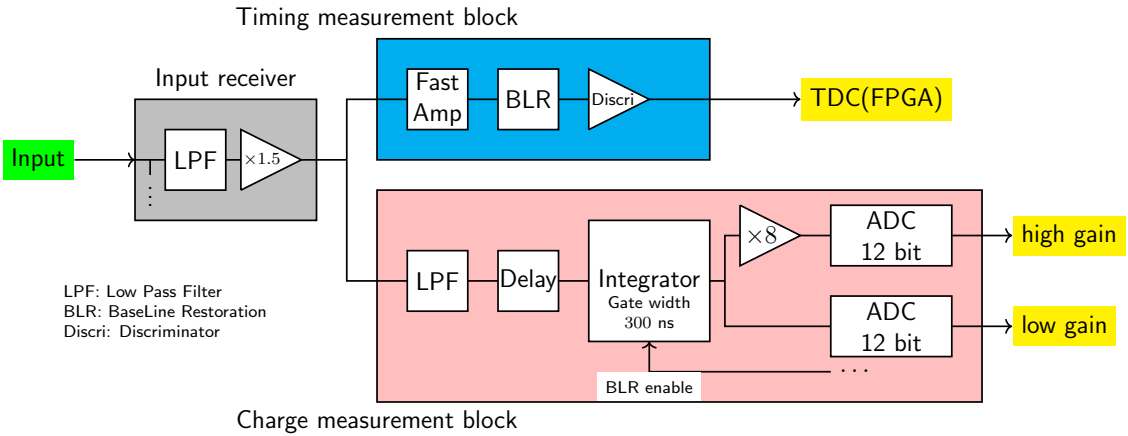


Underwater vessel

- **Digitizer board** $\times$ 2
  - To integrate PMT pulses and measure their timing.
  - Each board handles 12 PMTs.
- Data processing board $\times$ 1
  - To readout data from digitizer, slow control, communicate with electric hat and distribute the timing clock.
- Power supplies
  - For PMTs and electronics

- Integration of the electronics will take place at CERN from autumn 2026.
  - Nearly 1000 of vessels will be integrated.
- Quality assurance will be performed in Japan(Toyama) before installation.

Schematic View of the HK Digitizer



- The gain of PMT is $\mathcal{O}(10^7)$, with a dynamic range of $1\,\mathrm{p.e.} - 1250\,\mathrm{p.e.}$.
- The pulse height of a $1\,\mathrm{p.e.}$ PMT signal is about $-6\,\mathrm{mV}$ ($\sim 1.9\,\mathrm{pC}$).

HK Digitizer Performance Requirements

These requirements are driven by the physics goals.

Items	Requirements (with FG)
Noise rate	$< 1\,\mathrm{Hz}$(threshold $-1\,\mathrm{mV}$)
Dynamic range	$1.9\,\mathrm{pC}$ – $2350\,\mathrm{pC}$
Charge linearity	$< \pm 1\,\%$
Charge resolution	$< 1.9\,\mathrm{pC}(< 19\,\mathrm{pC})$ $< 1\,\%(> 19\,\mathrm{pC})$
Timing resolution	$< 300\,\mathrm{ps}(1.9\,\mathrm{pC})$ $< 200\,\mathrm{ps}(> 9.5\,\mathrm{pC})$
High rate tolerance	stabel $> 1\,\mathrm{MHz}$
Hit cross-talk	$< 0.1\,\%(2350\,\mathrm{pC})$

- A function generator (FG) is used to understand the performance of the electronics themselves.

Motivation

Motivation

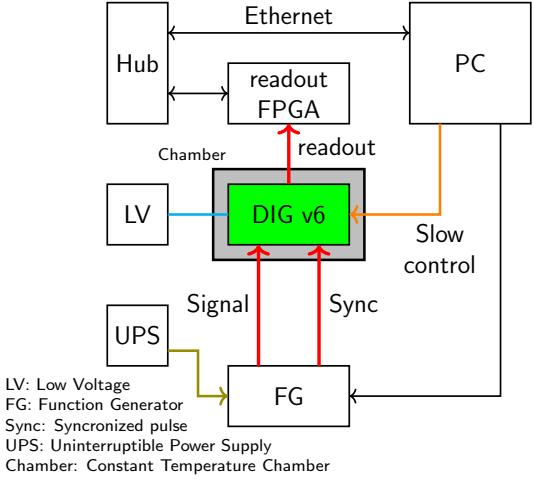
- The latest version of digitizer board has not yet been evaluated.
  - We need to re-evaluate the performance because the charge integration circuit has been modified.
- Mass production is planned to start in summer 2026, so we need to confirm that the performance meets the requirements as soon as possible.
- Channel dependence on the performance also should be confirmed to be small before the mass production.

What we did in this research

- We evaluated the performance of four channels of the HK digitizer v6 and verified that they pass the requirements.

Setup

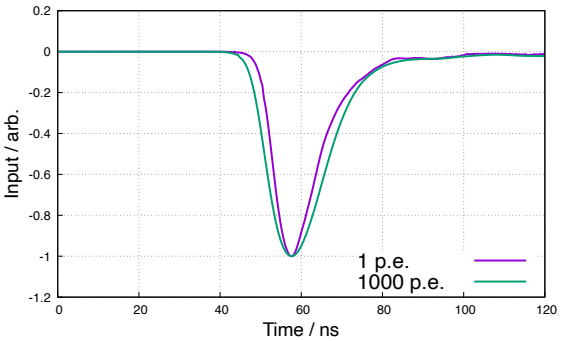
Temperature is kept at $10\,^{\circ}$C.
CH1,5,8 and 11 are evaluated.



Only the digitizer is used in the actual HK operation.

Input Signal

- We emulate PMT signals by FG and vary the amplitude to scan the charge range.
- Signals with a large number of p.e. have a wider pulse shape, so we adjust the signal shape depending on the charge range.



A PMT-like signal is sampled and used as the input.

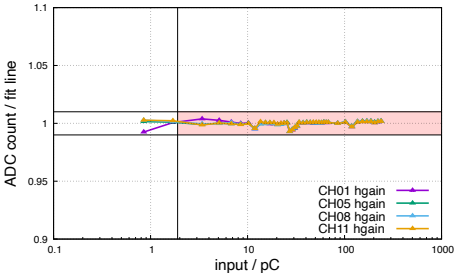
$1\,\mathrm{p.e.}$ signal:

- pulse height $-6\,\mathrm{mV}$ corresponds to $1.7\,\mathrm{pC}$ approximately.
- Used for high gain

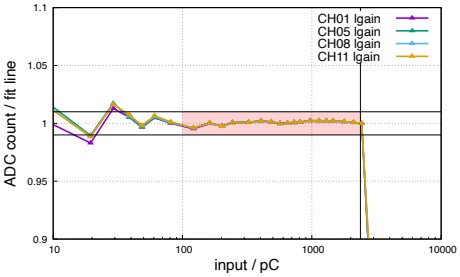
$1000\,\mathrm{p.e.}$ signal:

- pulse height $-6\,\mathrm{mV}$ corresponds to $2.4\,\mathrm{pC}$ approximately.
- Used for low gain (above $\sim 100\,\mathrm{pC}$)
- An amplifier($\times 2.6$) is used to cover the upper range.

Charge Linearity

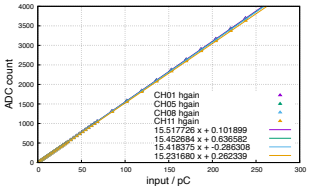


High gain linearity



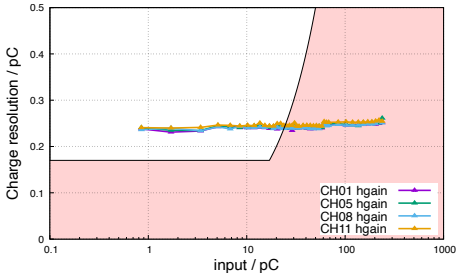
Low gain linearity

- Requirement: $< \pm 1\,\%$ for 1.9 –$2350\,\mathrm{pC}$
- The linearity of the digitizer is crucial because PMT non-linearity must be corrected through calibration, which requires a linear readout response.
- **The requirement is satisfied.**

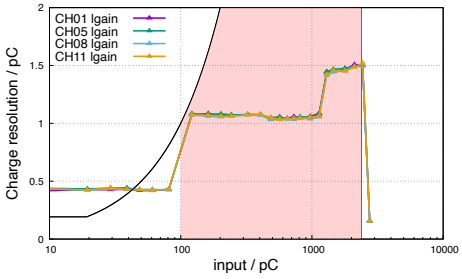


input vs ADC value

Charge Resolution



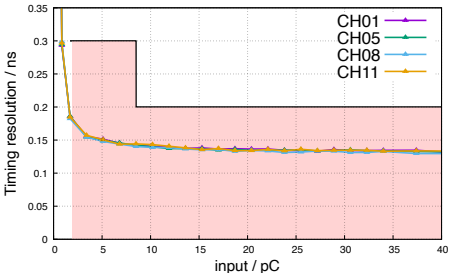
High gain charge resolution



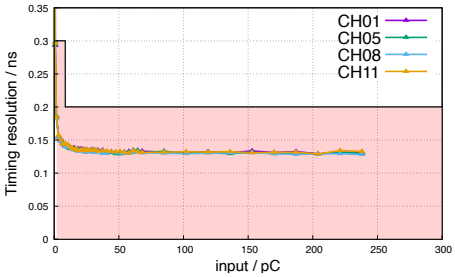
Low gain charge resolution

- Requirement: $\begin{cases} < 0.19\,\mathrm{pC} (\text{for inputs below } 19\,\mathrm{pC}) \\ < 1\,\% (\text{for inputs above } 19\,\mathrm{pC}) \end{cases}$
- **The requirement is not satisfied in the low pulse height region.**
- The PMT pulse fluctuations are much larger than this resolution.
- The requirement was originally defined for the integration gate width $200\,\mathrm{ns}$, but we use $300\,\mathrm{ns}$ for HK to collect the reflected PMT signals. Therefore the criterion needs to be updated.
- Noise from the setup should be taken into account.

Timing Resolution



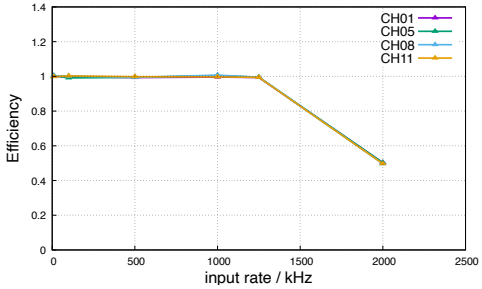
Timing resolution in small input range



Timing resolution

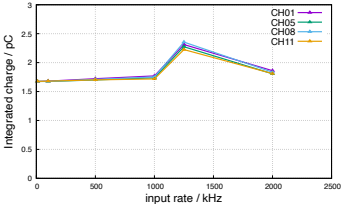
- Requirement: $\begin{cases} < 0.3\,\mathrm{ns} (\text{for inputs between } 1.9\,\mathrm{pC} \text{ and } 9.5\,\mathrm{pC}) \\ < 0.2\,\mathrm{ns} (\text{for inputs above } 9.5\,\mathrm{pC}) \end{cases}$
- **The requirement is satisfied.**

High Rate Tolerance

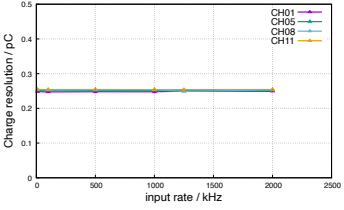


Efficiency as a function of input rate.

- Requirement: stable performance above $1\,\mathrm{MHz}$
  - Efficiency decreases around $2\,\mathrm{MHz}$ due to the integration dead time.
  - It is known that the baseline fluctuates approximately $800\,\mathrm{ns}$ after the input pulse. As a result, the integrated charge at $1.25\,\mathrm{MHz}$ is slightly overestimated.
- **The requirement is satisfied.**



Integrated charge



Charge resolution

Summary of Performance Evaluation

Items	Requirements (with FG)	Satisfied
Noise rate	$< 1\,\mathrm{Hz}(\mathrm{threshold} - 1\,\mathrm{mV})$	✓
Dynamic range	$1.9\,\mathrm{pC} - 2350\,\mathrm{pC}$	✓
Charge linearity	$< \pm 1\,\%$	✓
Charge resolution	$< 1.9\,\mathrm{pC}(< 19\,\mathrm{pC})$	×
	$< 1\,\%(> 19\,\mathrm{pC})$	✓
Timing resolution	$< 300\,\mathrm{ps}(1.9\,\mathrm{pC})$	✓
	$< 200\,\mathrm{ps}(> 9.5\,\mathrm{pC})$	
High rate tolerance	$> 1\,\mathrm{MHz}$	✓

- ×: The criterion needs to be updated to reflect actual operating conditions.
  - PMT uncertainties are dominant in this region.

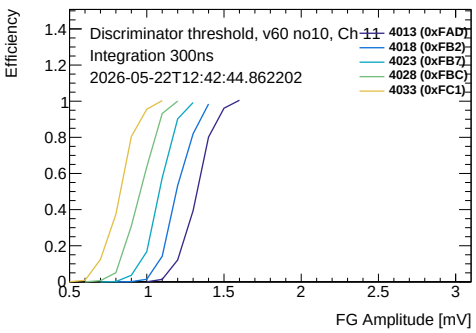
No significant variation is observed between channels.

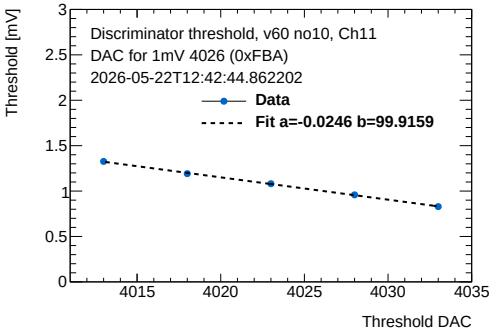
Future Plan

- Combining the digitizer with actual HK PMT.
- Developing a new feature of HK digitizer.
  - Acquiring Time-Over-Threshold (TOT) information during the integration dead time will improve the detection efficiency.
  - A nearby supernova is expected to produce hit rates of a few MHz per PMT. In this case, TOT can also help minimize the effect of the integration dead time.
- Mass production of HK digitizer will begin in summer 2026.

BACK UP

Threshold Calibration

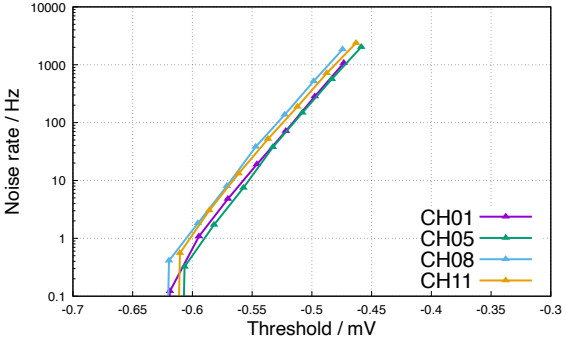




- The threshold value is set by the DAC value via slow control.
- The threshold is defined as the pulse height at which a PMT-like signal is detected with $50,\%$ efficiency.

1. Fix the DAC value and scan the amplitude of the PMT-like pulse.
2. Find the pulse height corresponding to $50\,\%$ efficiency by interpolation.
3. Repeat this procedure for different DAC values and perform a linear fit.

Noise Rate



Noise rate as a function of threshold

- Requirement:$< 1\,\mathrm{Hz}$ at a threshold of $-1\,\mathrm{mV}(1/6\,\mathrm{p.e.})$
- **The requirement is satisfied.**

Hit Caused by Cross-talk (v5+)

A 10.5 V signal is injected at 50 kHz for 20 seconds.

Input CH	Response in other CHs
CH01	One trigger observed in CH05 after $2\,\mu\mathrm{s}$
CH05	None
CH08	None
CH11	None

- Requirement: Hit probability in other channels $< 0.1\,\%$ for $1250\,\mathrm{p.e.}$ input signal.
- **The requirement is satisfied.**
- The difference between v6 and v5+ is not so significant.

HK Digitizer Performance Requirements with HK-PMT

These requirements are driven by the physics goals.

Items	Requirements (with PMT)
Noise rate	$< 1\,\mathrm{Hz}$(threshold $-1\,\mathrm{mV}$)
Charge linearity	$< \pm 1\,\%$ for $200\,\mathrm{pC}$
Charge resolution	$< 40\,\%(1.9\,\mathrm{pC})$
Timing resolution	$< 1.5\,\mathrm{ns}(1.9\,\mathrm{pC})$
High rate tolerance	stabel $> 1\,\mathrm{MHz}$
Hit cross-talk	$< 0.1\,\%(2350\,\mathrm{pC})$