PMT digitization in Hyper-Kamiokande

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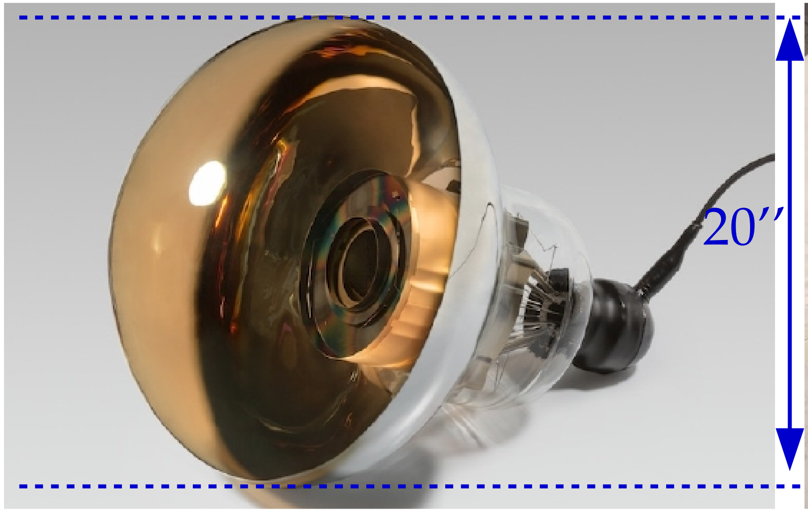
Workshop on the Evolution of Advanced Electronics and Instrumentation for Water Cherenkov Experiments, 2022/04/11

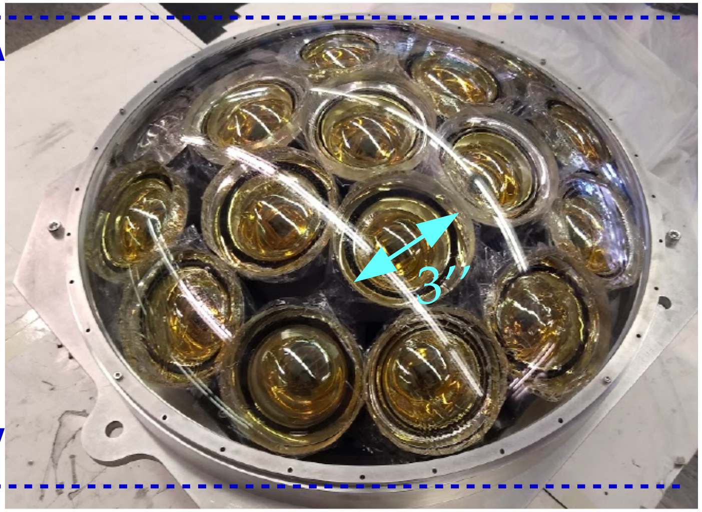
Sensor and electronics location

- World-leading ν program from low to high (MeV - TeV) energy.
  → Rely on three types of photosensors :

Inner Detector

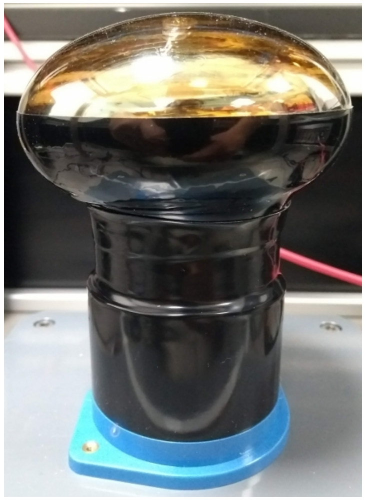


20″ Hamamatsu B&L R12860



Multi-PMTs

Outer Detector

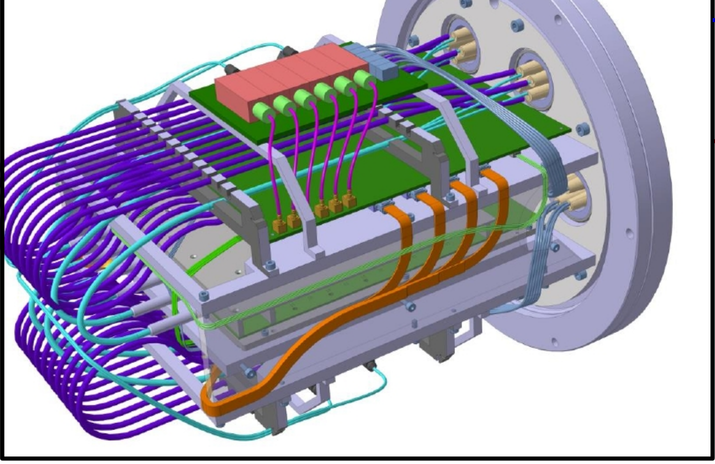


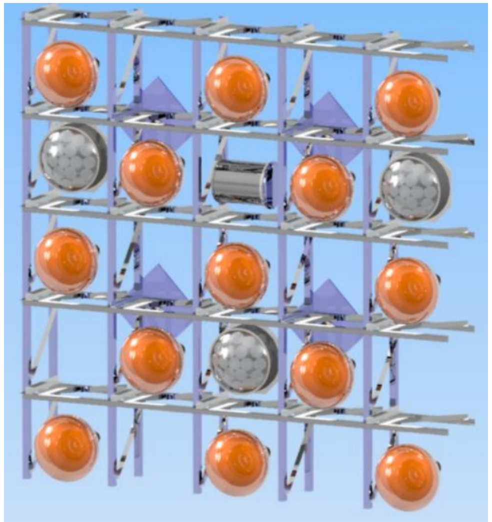
3″ PMTs

x 20

x 12

Under-water electronic box



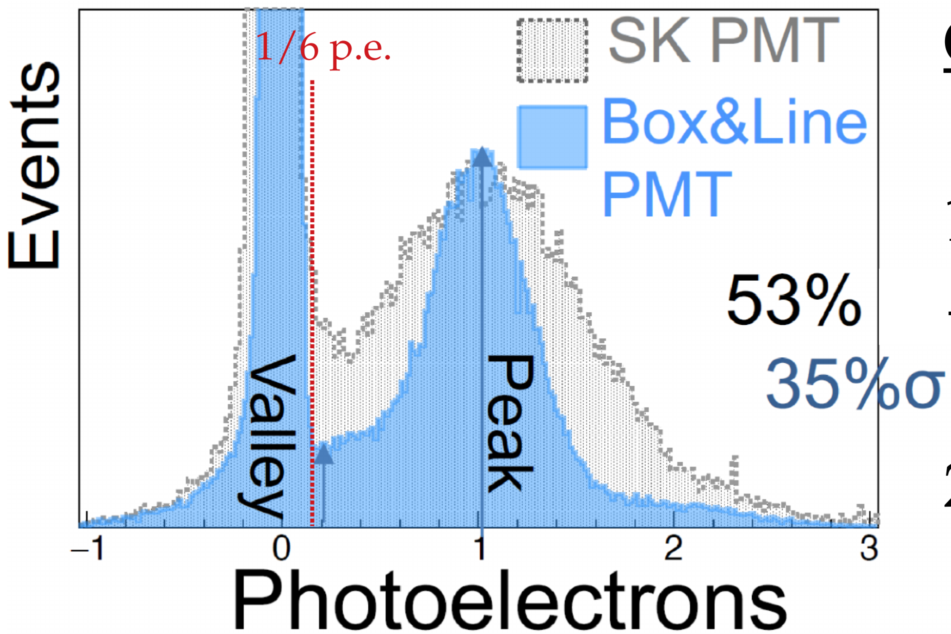


- Connected to a stainless steel electronic box under water.

Low energy sector

- PMTs receives almost exclusively 1 p.e. : 6 p.e / MeV for 20k PMTs.

  → Cherenkov ring not visible clearly in the background noise.



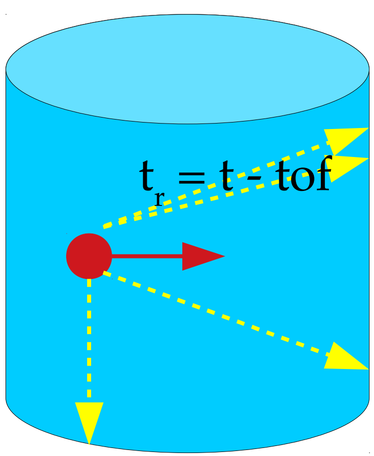
Our upgraded electronics aims to :

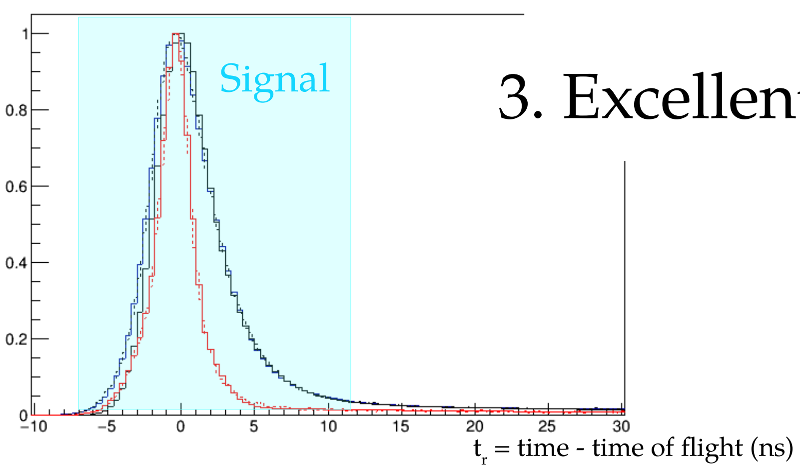
1. Maximize the signal efficiency

   → Low trigger threshold @ 1/6 p.e.

2. Minimize electronics noise.

→ Vertex finder based on time residual : t_r = time - time of flight



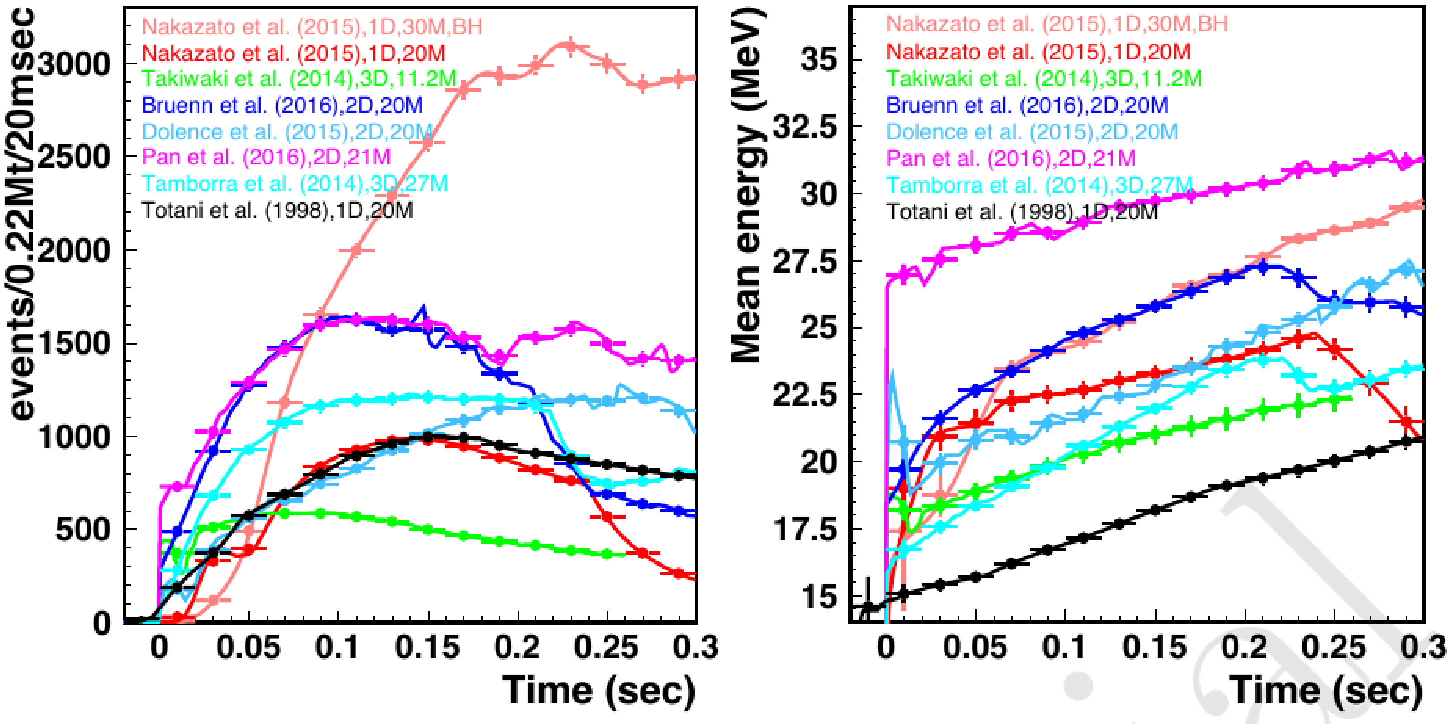


3. Excellent time resolution : ≤ 300 ps

Low energy : Supernovae detection.

If Supernovae happens (Beltegeuse):

- Max hit rate of 1 MHz during 300 ms.



- Hit loss is 50 % w/ a 1 μs deadtime, 36 % w/ 0.5 μs.

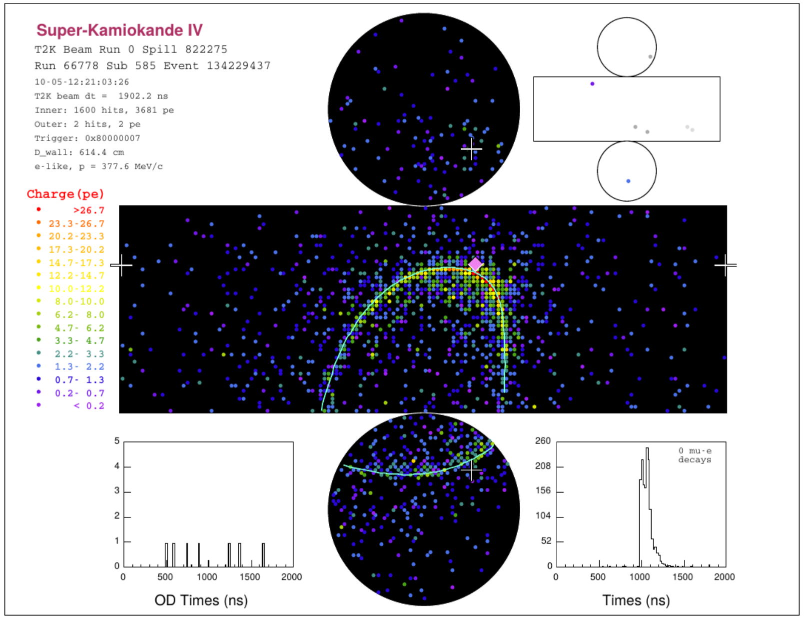
→ Inefficiency could lead to miss rate & energy variation wrt time i.e. reduce the constraint on the SN explosion mechanism.

→ Set our deadtime to be : ≤ 1 μs

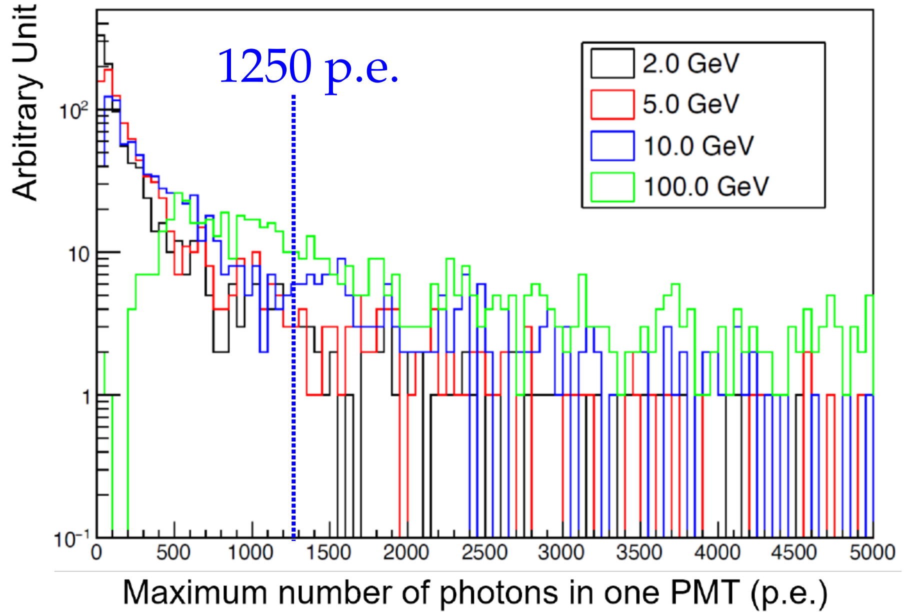
→ Need a deadtime as low as possible for Supernovae detection.

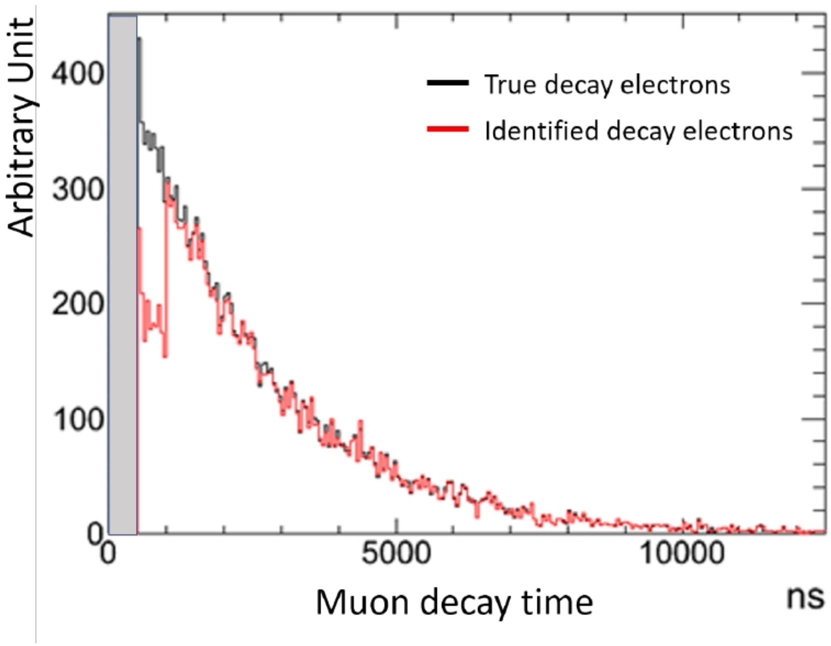
High-energy sector

- Particle momenta, type & vertex reconstructed with Q/T information.



→ PMTs receives 1→ ≥ 1000 p.e.





1. High linearity (≤ 1%) on whole dynamic range & high charge resolution (≤ 0.1 p.e).

2. High time resolution : ≤ 300 ps.

3. Low deadtime ≤ 1 μs : identify decay-e, separate scattered & reflected light etc.

Summary of digitizer requirements

Requirements	ID	OD
Discriminator threshold	1/6 p.e. (0.27 pC)	1/4 p.e.
Charge linearity	1 % for 1 p.e. to 1,250 p.e. (1.6 pC to 2,000 pC)	
Charge resolution	0.1 p.e. for < 10 p.e. (0.16 pC for < 16 pC) better than 1% for > 10 p.e. (1% for > 16 pC)	0.1 p.e. for < 10 p.e. better than 1% for > 10 p.e.
Signal reflection	0.1% (-60dB) with 25m 50ohm (reference) cable	0.1% (-60dB) with 25m 50ohm (reference) cable
Crosstalk	<1/1,000 when neighboring channel has 1,250 p.e. (2,000 pC)	<1/1,000 when neighboring channel has 100 p.e.
Maximum hit rate	> 1MHz/ch	> 1MHz (for combined 3 ch.)
Threshold stability	Must be stable if 1 p.e. (1.6pC) signal comes at 1 MHz.	Must be stable if 1 p.e. signal comes at 1 MHz.

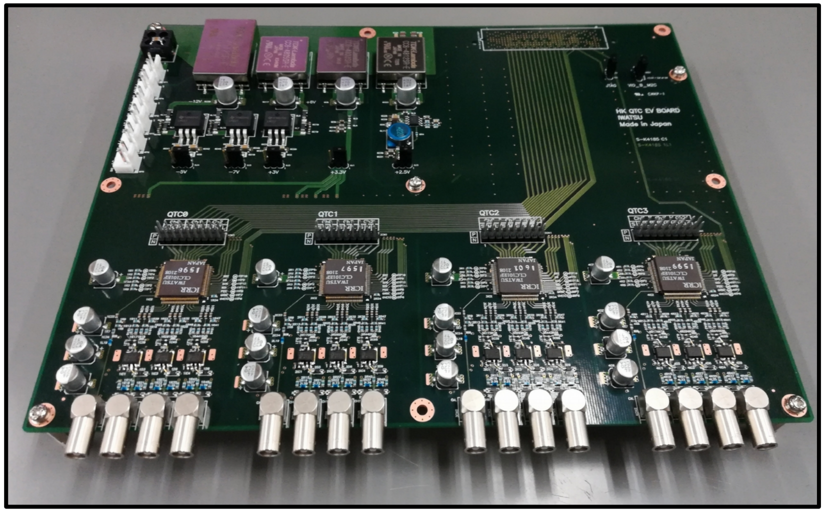
Summary of digitizer requirements

Requirements	ID	OD
Threshold stability for short interval pulses	Efficiency should be stable even if 1 p.e. (1.6pC) pulse comes 1 us after 1,250 p.e. (2,000 pC) pulse comes in.	Efficiency should be stable even if 1 p.e. pulse comes 1 us after 100 p.e. pulse comes in.
Timing LSB	shorter than 0.5 ns	shorter than 0.5 ns
Timing resolution	300 ps for 1 p.e. (1.6 pC) 200 ps for > 6 p.e. (8 pC)	3 ns for 1 p.e. 0.9 ns for > 5 p.e.
Temperature dependence of charge measurement	0.4%/degree without correction, 0.1%/degree with correction	0.4%/degree without correction, 0.1%/degree with correction
Temperature dependence of timing measurement	0.02 ns/degree from 10 to 40 degree C	0.02 ns/degree from 10 to 40 degree C
Operating Humidity	20% to 90%	20% to 90%
ESD tolerance	(under discussion)	(under discussion)
Power consumption	24W for 24 PMTs	24W for 72 PMTs
Failure rate	<0.1% / year	<0.1% / year

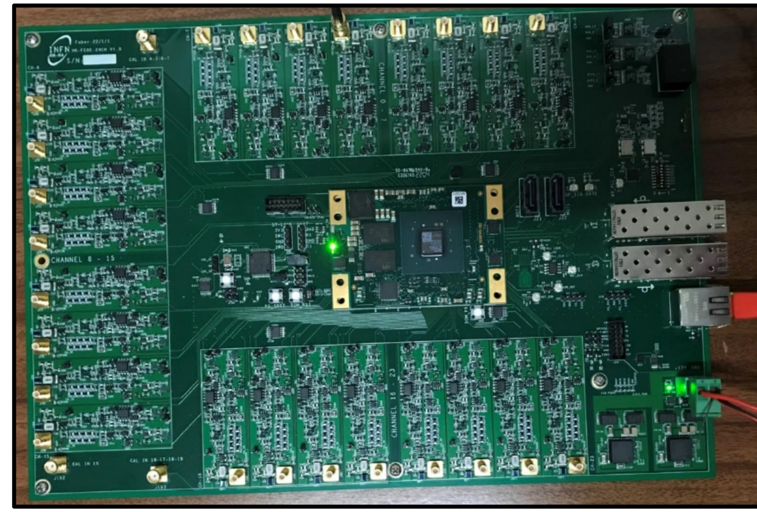
The Hyper-K candidate digitizers

- <u>3 digitizers considered :</u> all high-specs but explore ≠ digitization method

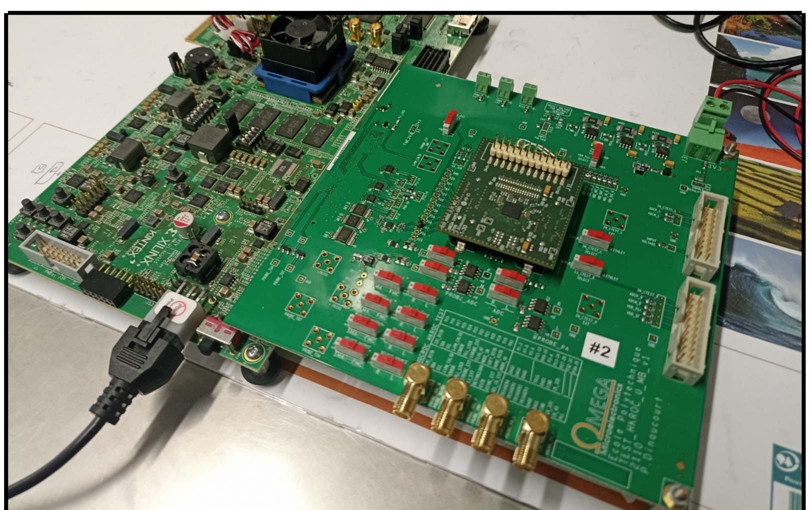
<u>QTC digitizer (Japan)</u>



<u>Discrete digitizer (Italy)</u>



<u>HKROC digitizer (France)</u>



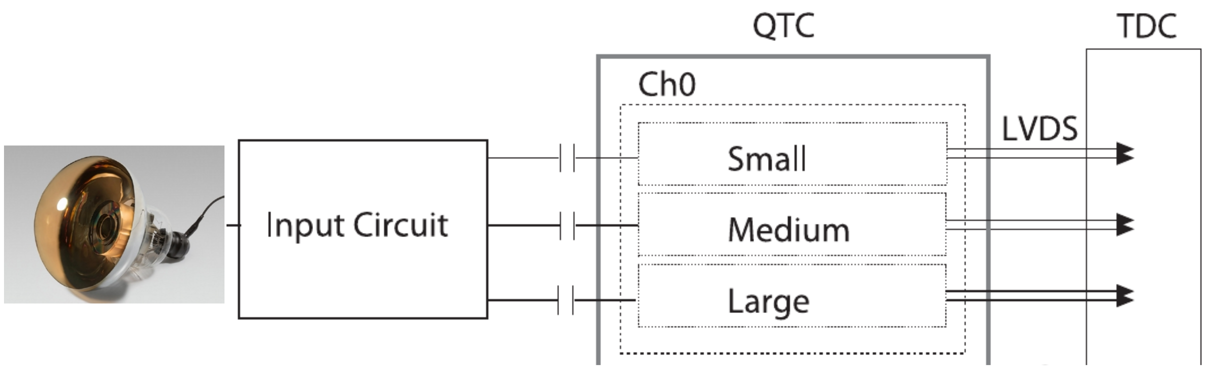
	QTC	Discrete	HKROC
Charge digitizer	ASIC (QTC)	Commercial ADC	ASIC (HKROC)
Digitization method	Charge integration	Charge integration	Waveform digitizer
TDC	On FPGA	Same as QTC	HKROC internal TDC

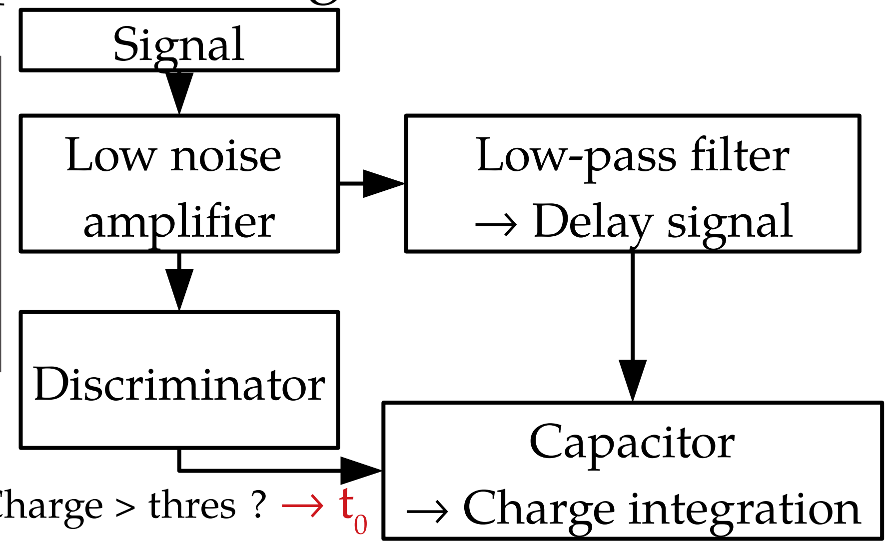
The QTC digitizer

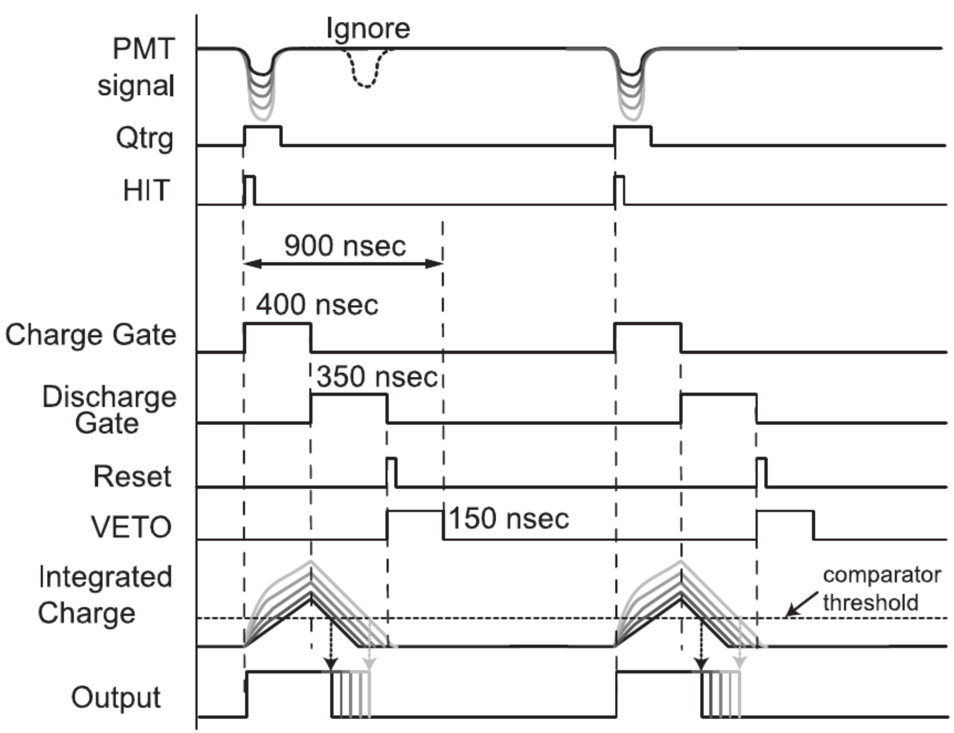
- Developed originally for SK : 1 QTC board ↔ 12 PMT channels.

→ 1 PMT : readout by 3 QTC channels : high, medium & low gain

→ Cover the whole dynamic range 0-1250 p.e. with high resolution.







- Discharge by a constant current

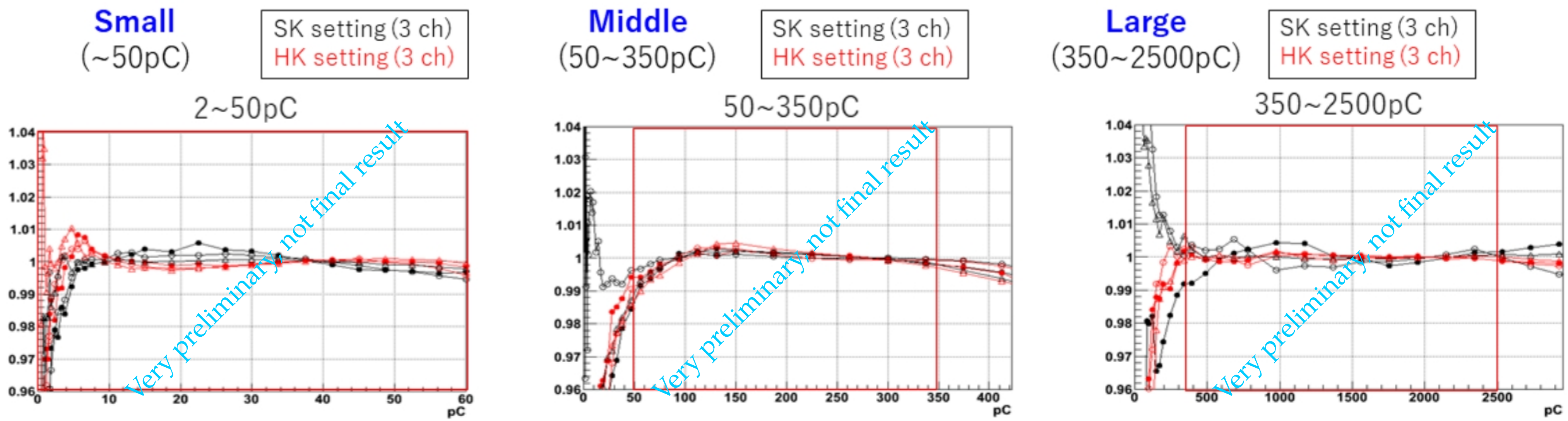
→ Discharge time proportional to integrated charge.

→ Convert charge to time (QTC).

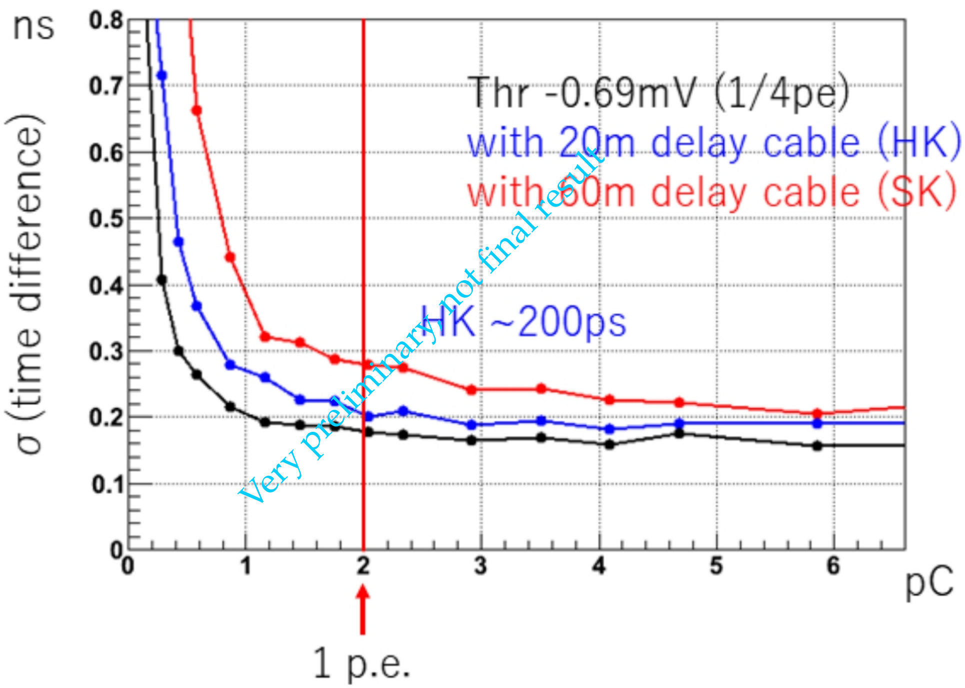
- TDC used to record the start (trigger time) and end (Δt provides charge).

QTC digitizer results

- Charge linearity : ≤ 1 %



- Time resolution ~ 200 ps.

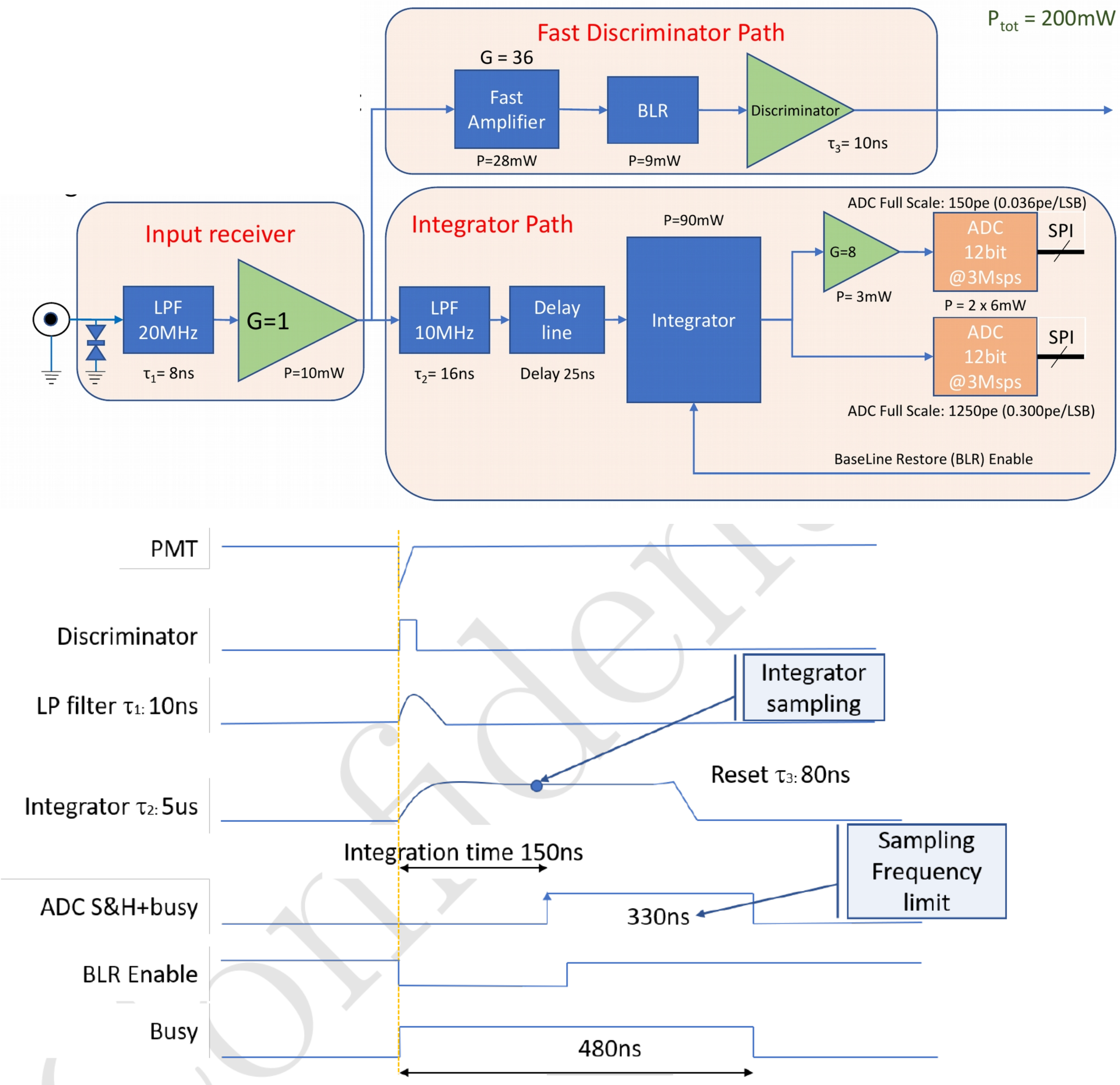


- Excellent charge resolution < 0.1 p.e.
- Deadtime tunable based on the integration gate (~500 ns).

Parameters	SK setting	HK setting
Integration time	393 ns (comp1=30)	192 ns (comp1=14)
Discharge time	366 ns (comp3=26)	156 ns (comp3=10)
Pedestal	(offset=50, i4=0)	(offset=50, i4=40)
Reset&Veto	225 ns (dveto=0)	180 ns (dveto=1)
Total dead time	984 ns	528 ns

The discrete digitizer

- Based on commercial discrete components.



- 1 PMT split into 2 channels to assess the whole dynamic range.

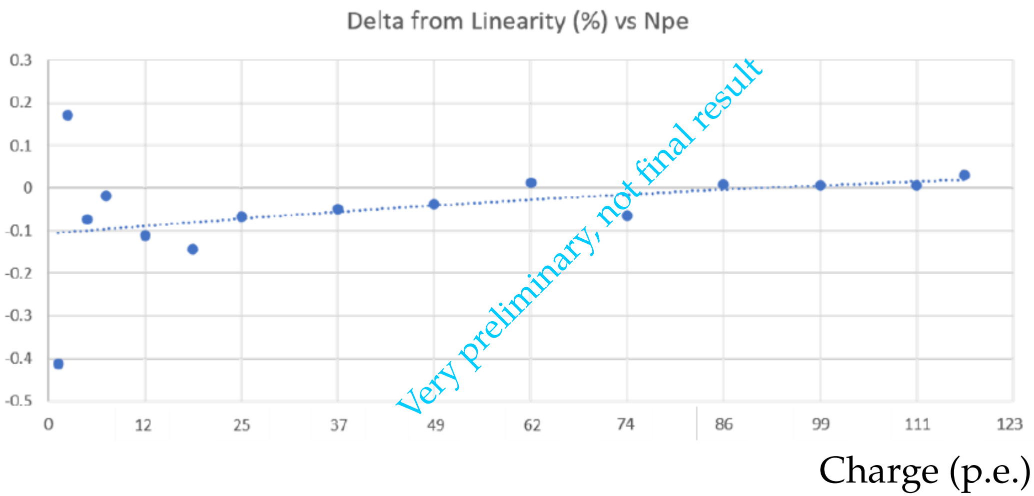
- PMT → 2 paths :

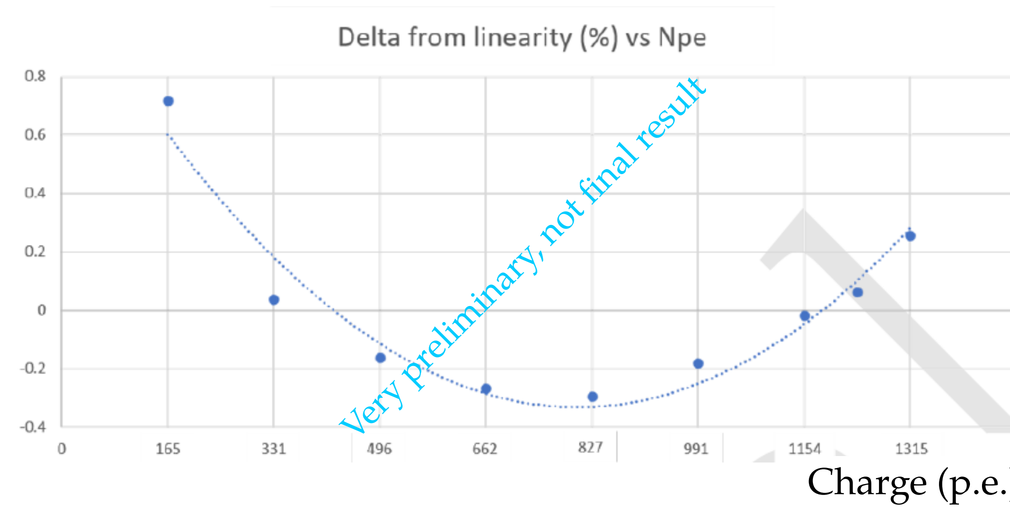
1. Fast shaper → Discri.
→ Time sent to TDC.

2. A LP filter (delay)
→ Charge integrator
→ Digitized / Wilkinson ADC conversion synchronized wrt 150 ns after the discriminator pulse.

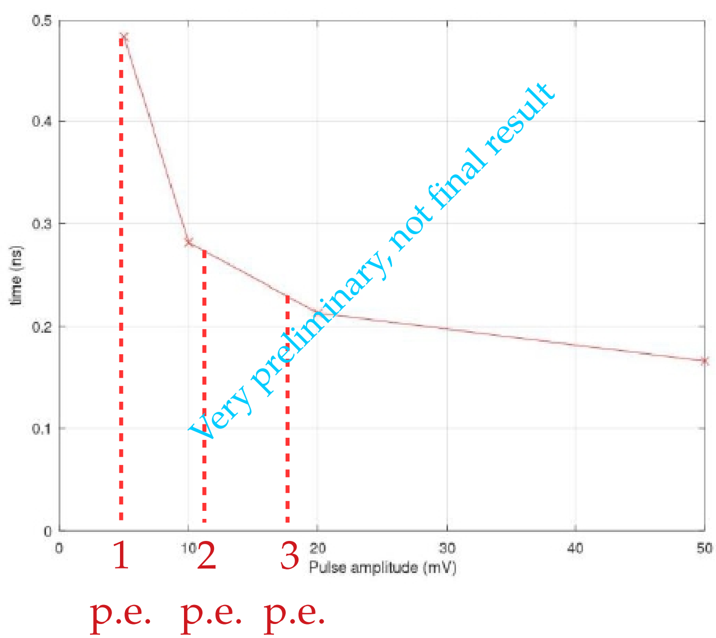
Discrete digitizer results

- Linearity ≤ 1 %





- Time resolution : 450 ps @1p.e., 260 ps @2 p.e., ≤ 200 ps > 3 p.e.



- Excellent charge resolution :

1. HG : resolution of 0.06 p.e.
2. LG : resolution of 0.16 p.e.

- Low deadtime ≤ 480 ns

(150 ns integration + 330 ns digitization).

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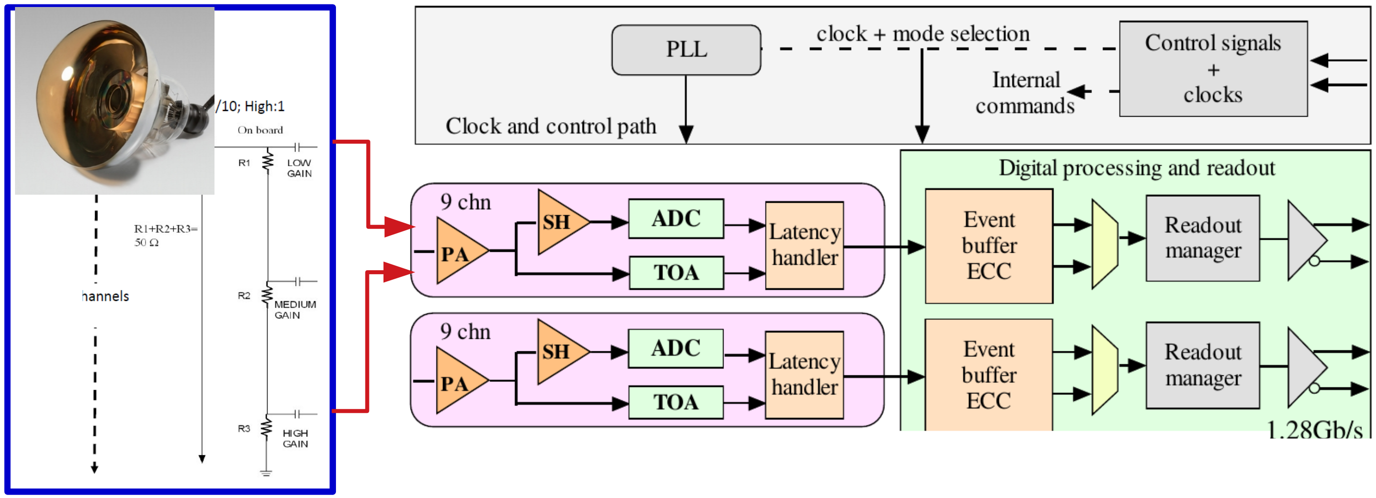
The HKROC digitizer

- Based CMS HGCROC ASIC : a waveform digitizer → Developed for HK.

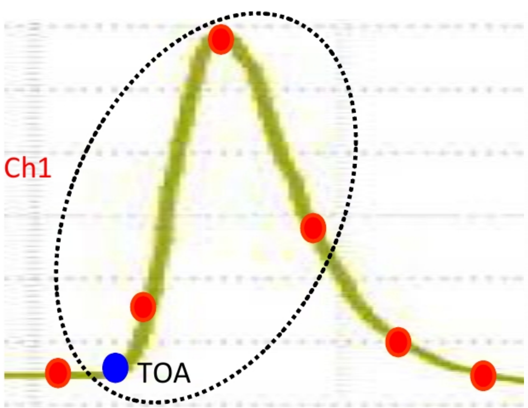


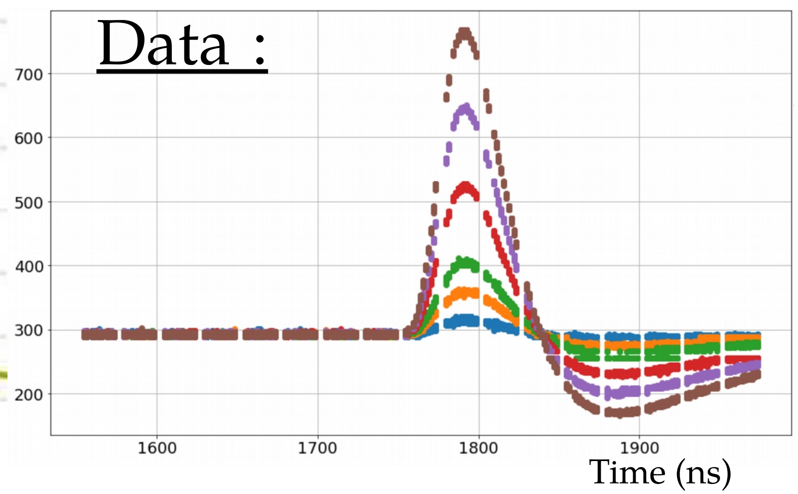
- 1 PMT readout by 3 channels (as QTC).
- 2 paths (as discrete) :

1. Fast shaper → Discri.
→ Time sent to TDC.

2. A slow shaper (delay)
→ Waveform digitization every 25 ns (tunable).
→ Take 1-7 points (tunable) using SAR ADC.

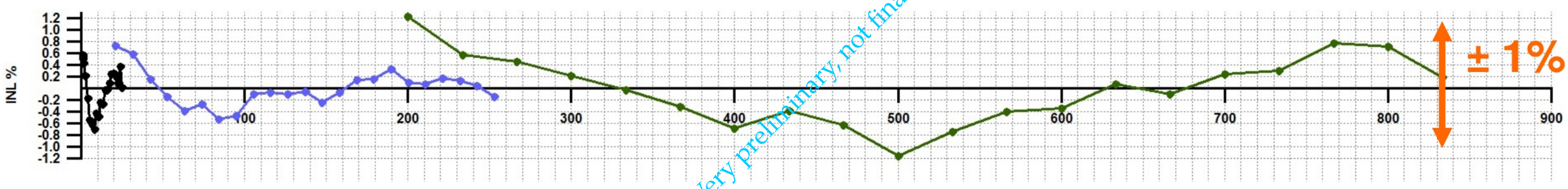
- Example of waveform digitization :



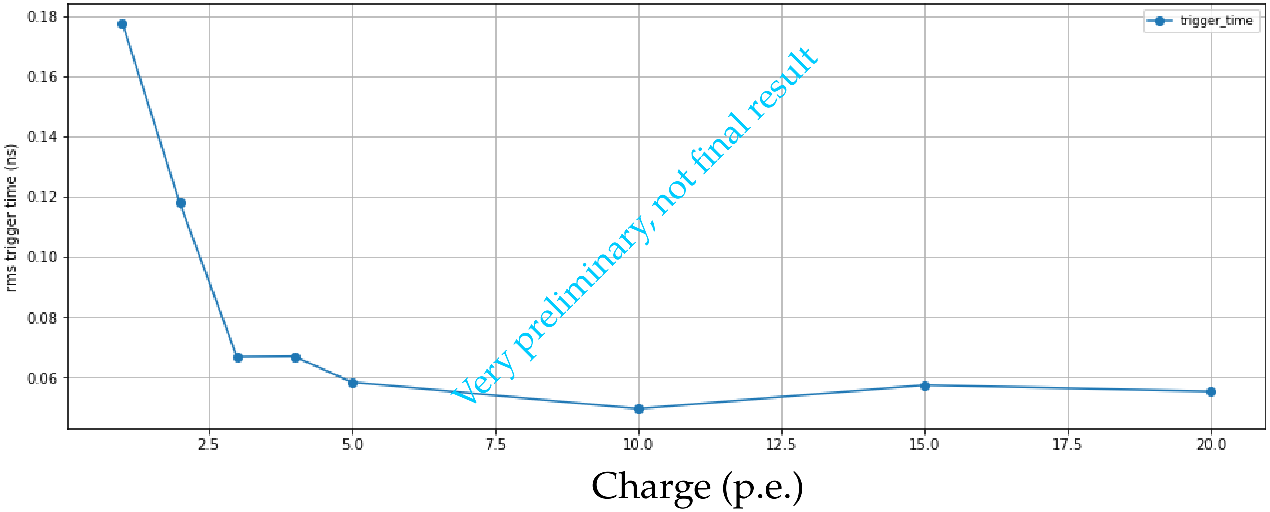


HKROC digitizer results

- Linearity ≤ 1 %.



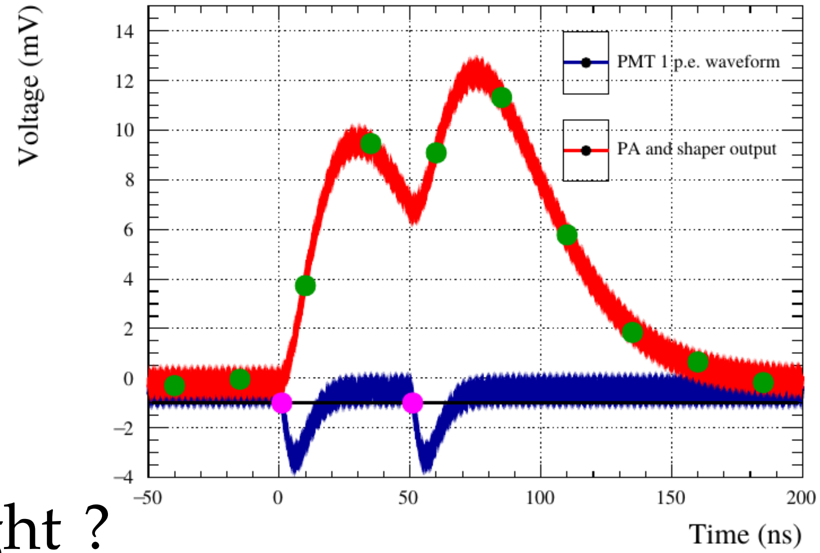
- Time resolution : 180 ps @ 1p.e., 120 ps @ 2 p.e, ≤ 60 ps ≥ 3 p.e.



- Charge resolution ≤ 0.08 p.e. ≤ 250 p.e.

- Very low theoretical deadtime (TBC) :

	≤ 5 p.e.	10 p.e.	100 p.e.	1000 p.e.
Deadtime	30 ns	80 ns	300 ns	500 ns



→ Disentangle direct/scattered/reflected light ?

Conclusions and schedule

- <u>HK will have a world-leading physics program from MeV-TeV.</u>
  → PMTs with enhanced timing resolution & S/N ratio.
  → Requires an upgraded electronics to match this ambitious programs.

- <u>3 solutions are considered by the collaboration :</u>
  → All with improved specs compared to SK.
  → Rely on ≠ methods : charge integration & waveform digitization, providing ≠ physics information.
  → Not discussed here but low failure rate (≤ 1% in 10 years) is crucial.
  → TDC highly synchronous between digitisers & w/ universal time : very reliable time generation & distribution → See Mathieu's talk

- <u>Decision to be taken this summer 2022 :</u>
  → Review started in April.
  → Complete design freeze by the end of 2023.
  → Mass production starts by the end of 2024.