The Design and Performance of Multi-PMT Modules for the Hyper-Kamiokande Experiment

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for the WCTE and Hyper-Kamiokande Collaborations

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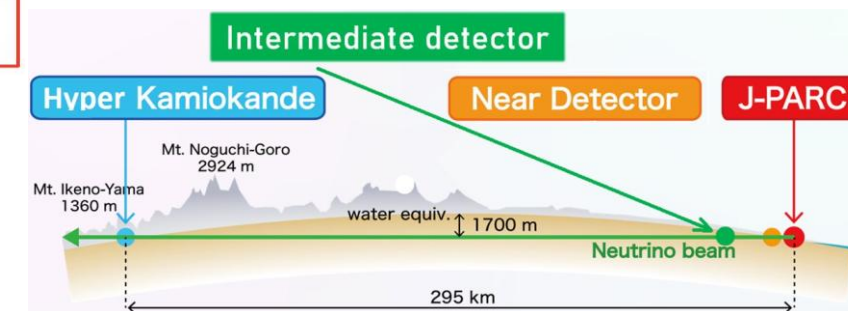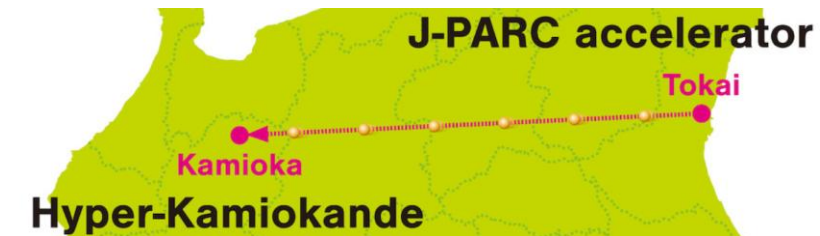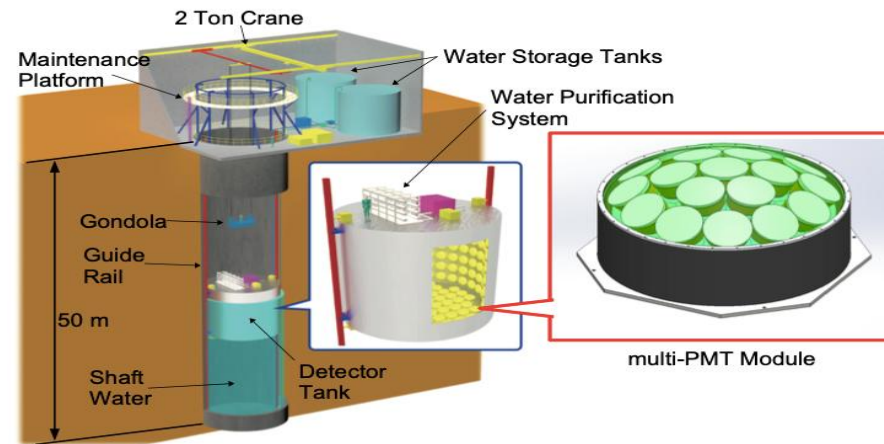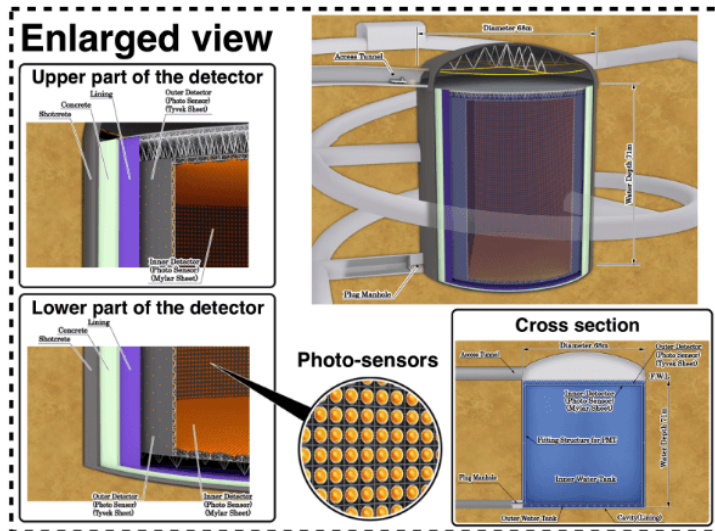
Experiments

Hyper-Kamiokande experiment

- A multipurpose experiment under construction in Japan
- Next generation underground water Cherenkov detector
- Uses two types of photosensors - 20-inch PMTs and multi-PMT modules

Intermediate Water Cherenkov Detector (IWCD)

- Near detector for long-baseline neutrino program
- 500-ton water Cherenkov detector ~1 km from the beam production point
- Moveable 6 m tall x 8 m diameter detector in ~50 m tall pit

### International collaboration

The Water Cherenkov Test Experiment

The Water Cherenkov Test Experiment (WCTE)

- 40-ton water Cherenkov detector was operated in CERN (T9 beam line)
- Sever as a technology demonstrator for new water Cherenkov detector technologies
- Photon detection system - multi-PMT modules
- 97 multi-PMT modules in total:
  - 93 IWCD mPMT variant
  - 4 Hyper-Kamiokande mPMT variant
- Time of operation:
  - Assembly – summer of 2024
  - Disassembly – summer of 2025
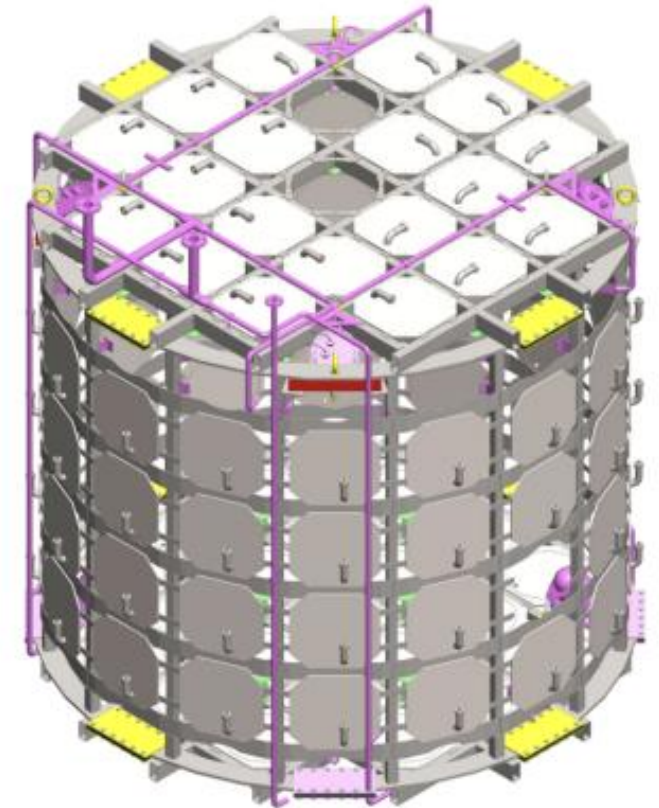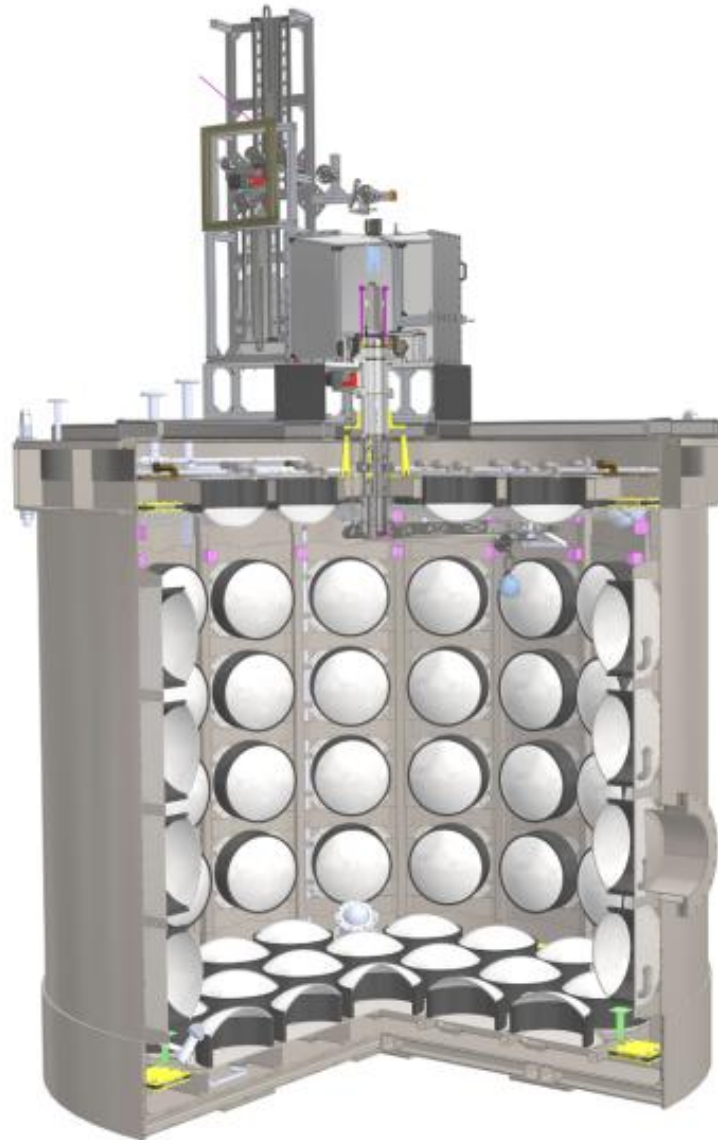
Multi-PMT module variants

Multi-PMT for Hyper-Kamiokande

- Nineteen 3" PMTs oriented towards center of water tank

- PMTs will image the flash of Cherenkov light from neutrino interactions, as well as from other sources

- Electronics inside multi-PMT: feed-through in backplate for power/communication cable

- 2 variants with different front-end electronics:
  - Hyper-Kamiokande far detector (FD):
    - Robust - withstand 0.7 MPa pressure
    - Electronics designed for low power consumption (and low rate)
    - ~800 will complement 20'' PMTs in Hyper-Kamiokande
  - IWCD multi-PMT:
    - Optimized for higher event rates
    - Lighter - withstand 0.2 MPa pressure
    - ~360 will fully equip IWCD (the only photodetector)
   - 93 equipped WCTE experiment in CERN


Multi-PMT for Hyper-Kamiokande
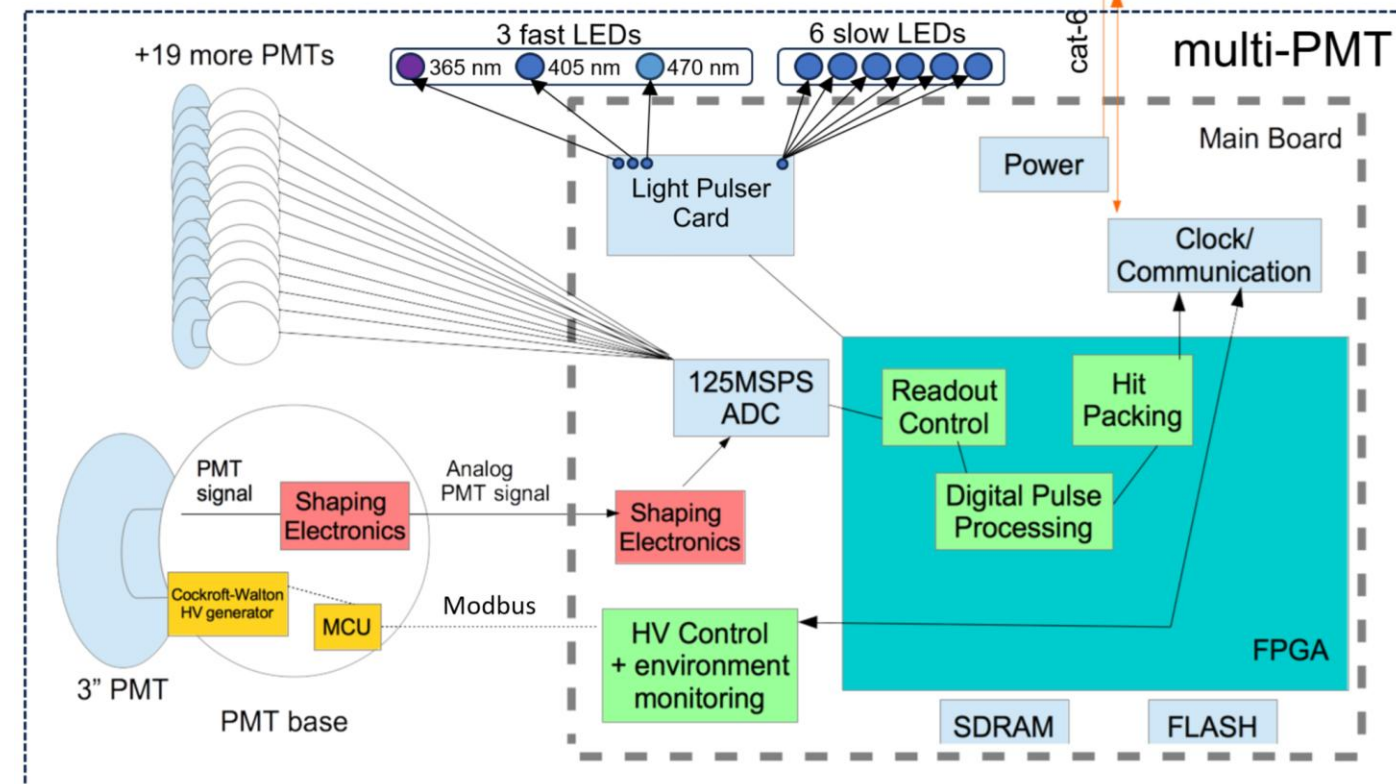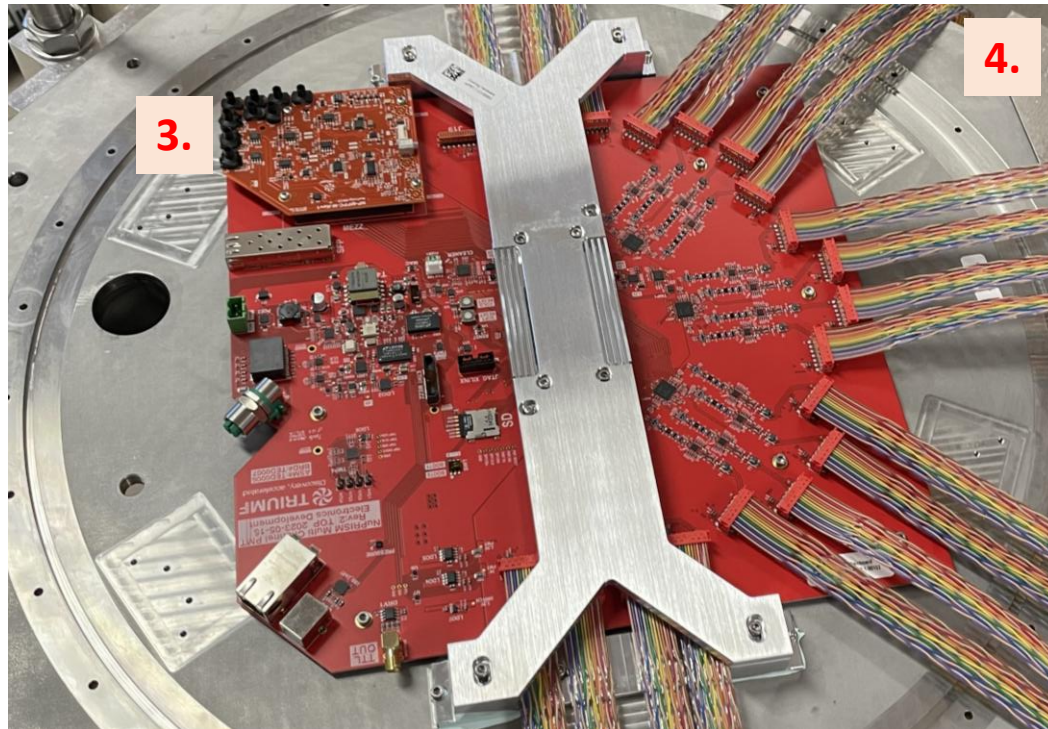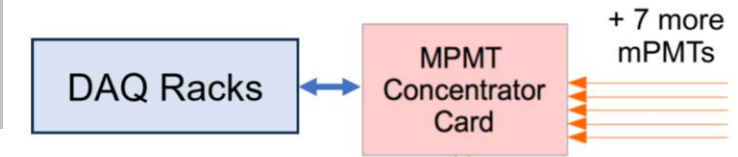

Multi-PMT for IWCD

IWCD Multi-PMT module

- Front-end electronics close to PMTs
- Each PMT has individual HV power supply (Cockcroft-Walton base)
- Optical gel used to couple PMTs to transparent, acrylic dome
- Twisted-pair cable to connect power supply and transmit data, clock (100 Mbit PoE Ethernet) and trigger signal
- Takes advantage of directionality of PMTs
- Very good time resolution of 3'' PMTs (TTS (FWHM) ~ 1.3 ns)
- Includes fast LEDs for calibration

PVC vessel

Stainless steel backplate

Stainless steel clamp ring

Reflector
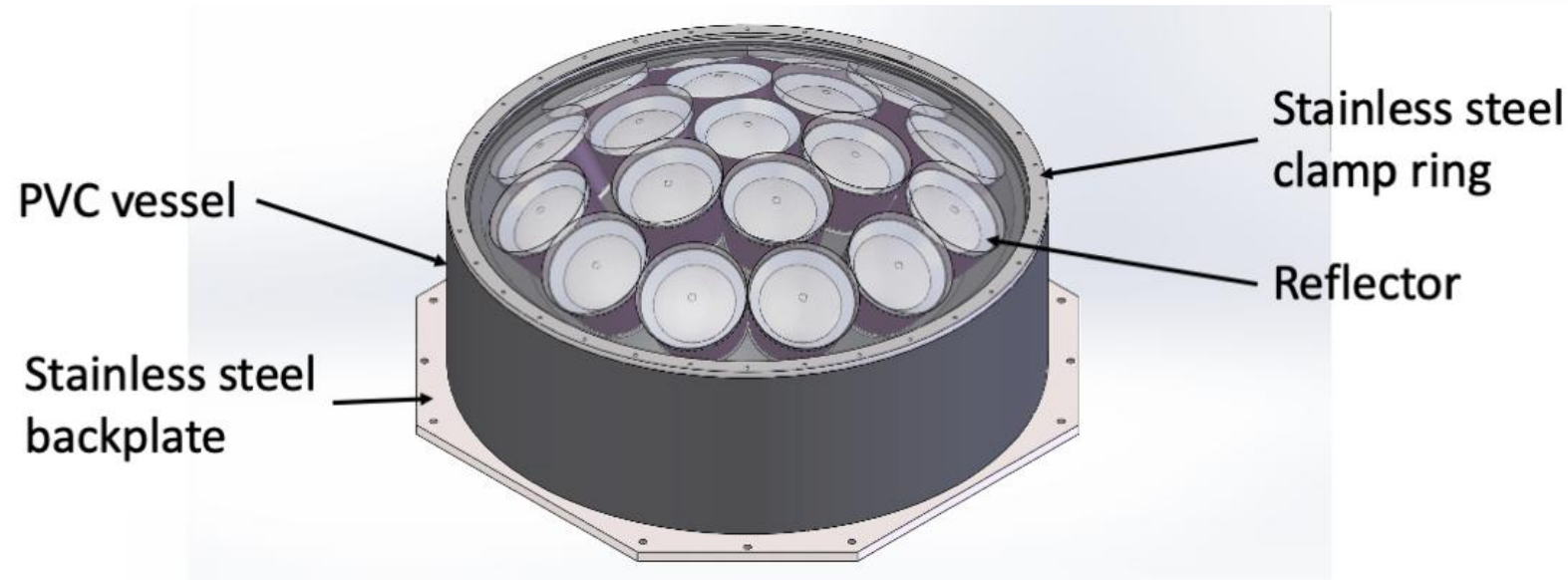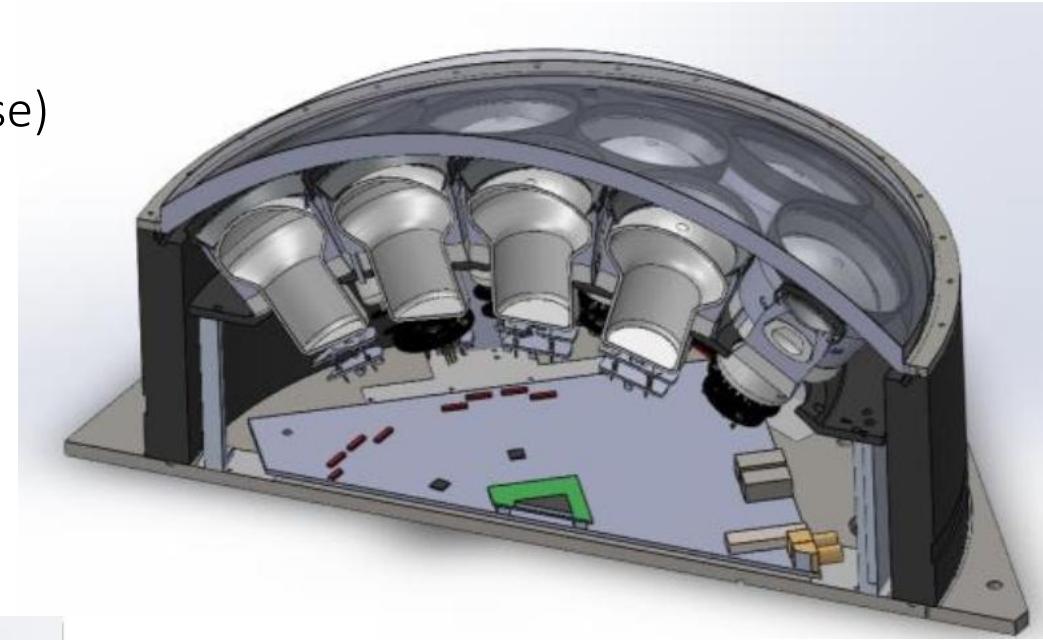
Multi-PMT electronic components

1. Photodetector R14374 PMT
2. HV Cockcroft-Walton generator:
   A. High Voltage supply board (HV)
   B. Front End board (FE)
3. Light Pulser Card
4. Mainboard - Big Red Board (BRB) mounted on backplate with twisted pair ribbon cables terminated with micro-match connectors
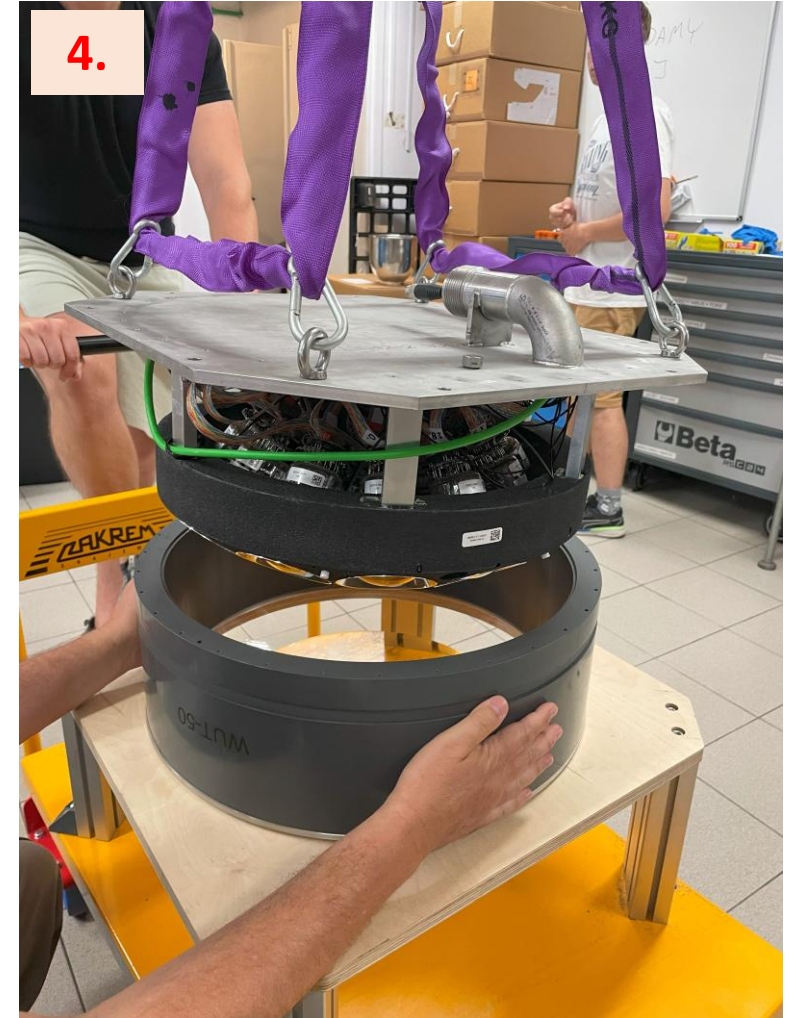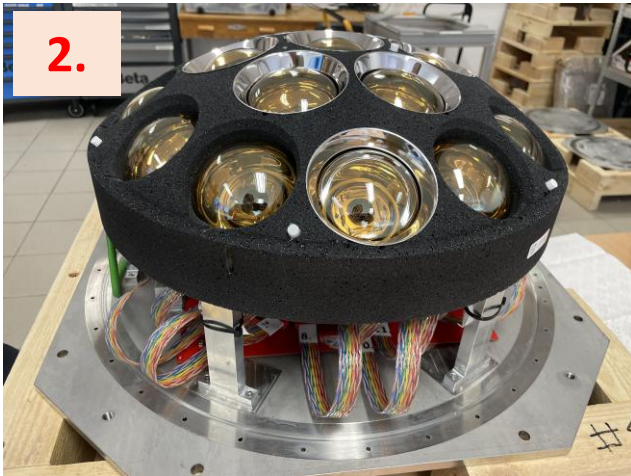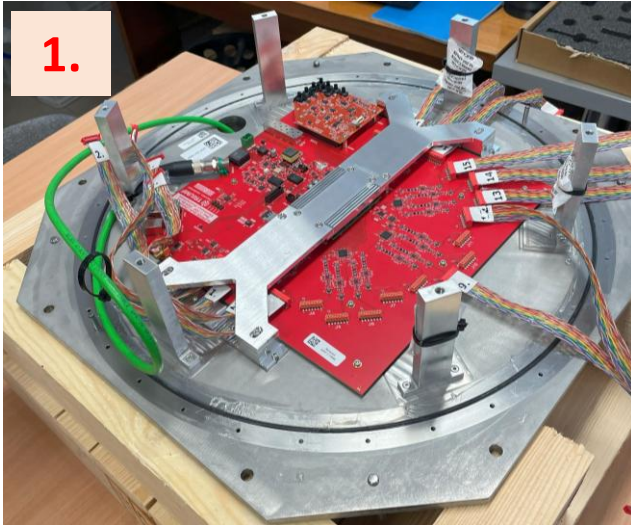
Multi-PMT assembly variants

Ex-situ

Clamp ring
Acrylic dome
PVC Cylinder
Optical Gel
3D Printed Cup
PMT
3D Printed Matrix
Stainless Steel Pillars
Stainless Steel Backplate

In-situ

Clamp ring
Acrylic dome
Optical Gel
PVC Cylinder
PMT
PU Foam Matrix
Stainless Steel Pillars
Stainless Steel Backplate

Multi-PMT assembly steps

Assembled Multi-PMT

6 slow LEDs fibers output with diffusers

3 fast LEDs fibers output: diffuser, 15 or 30 deg collimators

Anodized aluminum reflectors around each PMT

PMT signal shaping and readout

- Photomultiplier gain set to 5×10^6 (60 LSB - least significant bit)
- Shaping circuit: low pass 9th order Gaussian filter (fc = 21.7 MHz)
- 12 bit 125 Msps ADC
- Shaped signal parameters:
  - Rising time = 13.2 ns
  - Falling time = 9.2 ns
  - FWHM = 18.5 ns
- Approximately 4 samples per pulse
- With known signal shape and with proper signal to noise ratio we can calculate time and charge with high accuracy


Example of a waveform


PMT signal shaping circuit
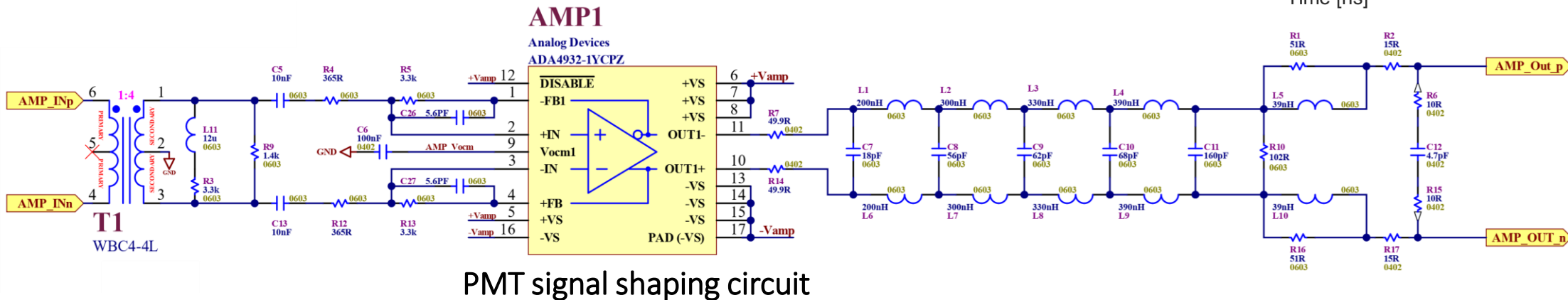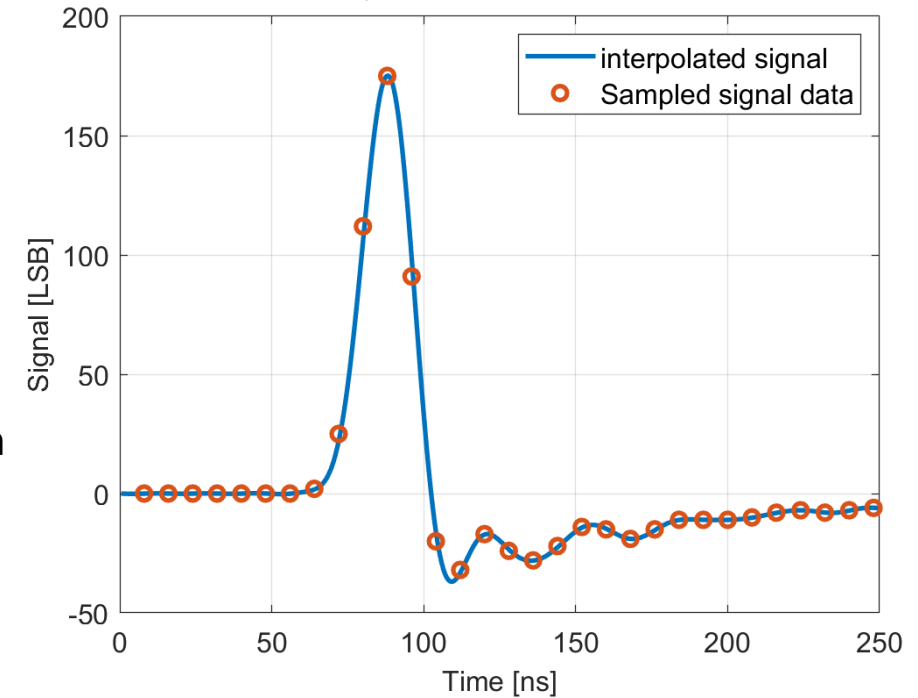
Multi-PMT FPGA algorithms

FPGA implementation algorithms:

- Triggering:
    - Self/autotrigger based on pulse height and charge
    - Hardware trigger on Ethernet connection
    - Software/programmable trigger on timer
- Pulse time calculation:
    - Digital constant fraction discriminator with linear interpolation and correction
- Pulse quality factor (0-best, 255-worst), computed as Sum of Absolute Differences (SAD) between the signal with a hit and the selected waveform model
- Waveform lossless compression up to 60%
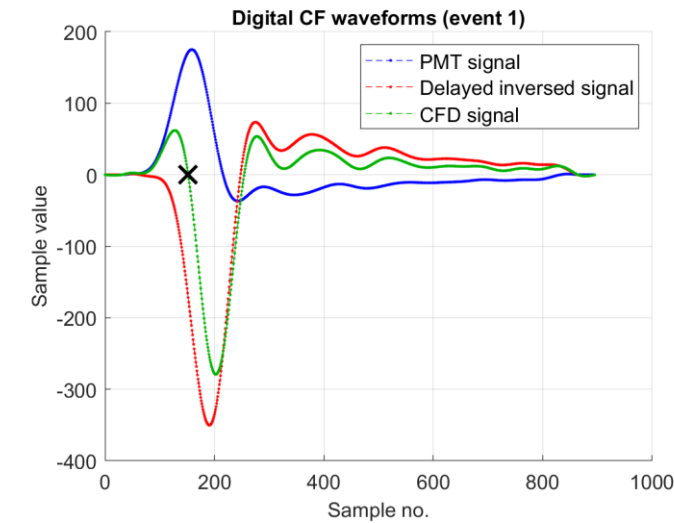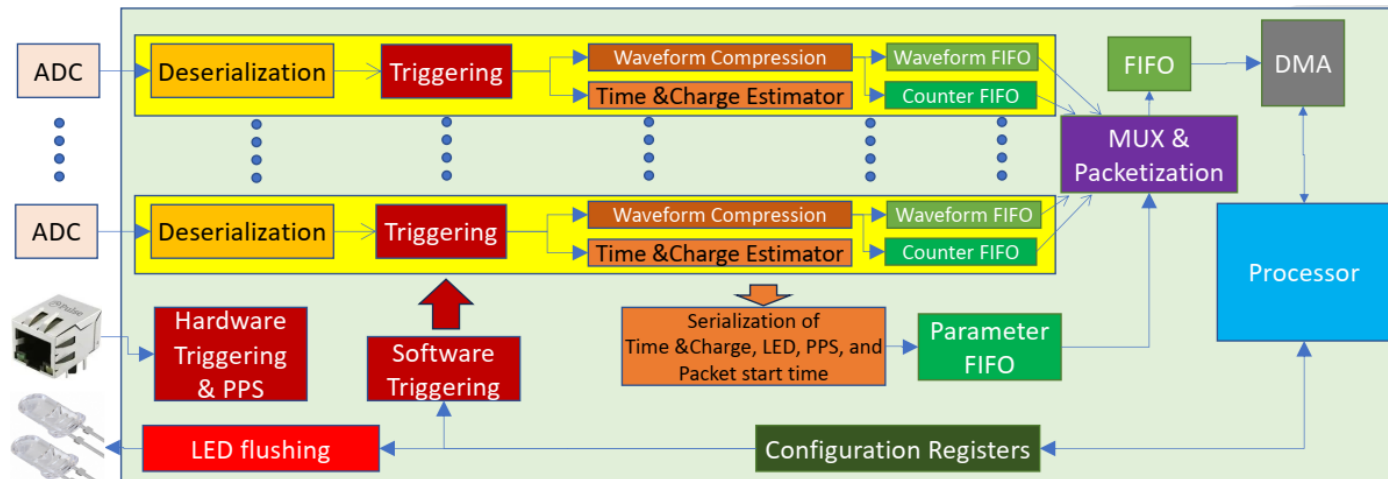
Linear interpolation + correction
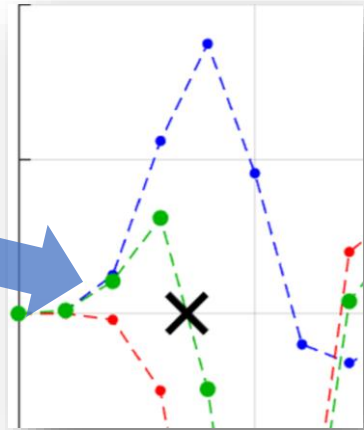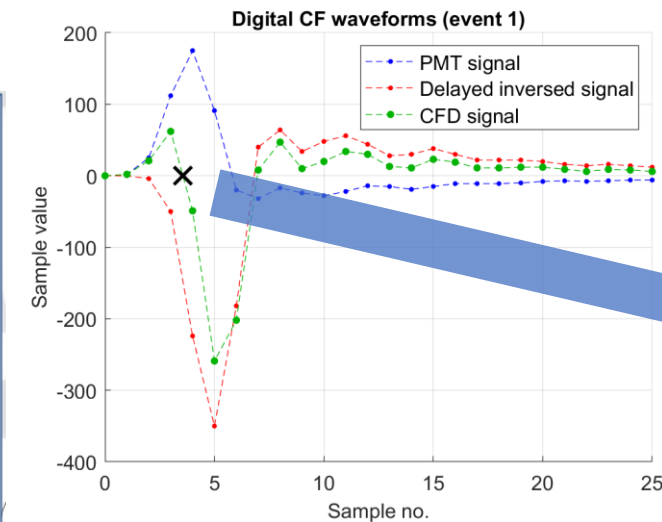
Quality assurance

- Front-end electronics (HV + FE):
  - Dedicated test device
  - µC programming, HV calibration, signal check
- Mainboard testing:
  - Analog path, acquisition, clocks, power supply
- 3" PMT assemblies:
  - Assembly = PMT + HV + FE card
  - Verification before mounting in the multi-PMT modules
  - A set of 20 PMTs is tested in parallel
  - Checks: gain, dark count
- Multi-PMT modules:
  - Check operation in dark box using final DAQ
  - Selected mPMTs checked in test stand using a picosecond laser
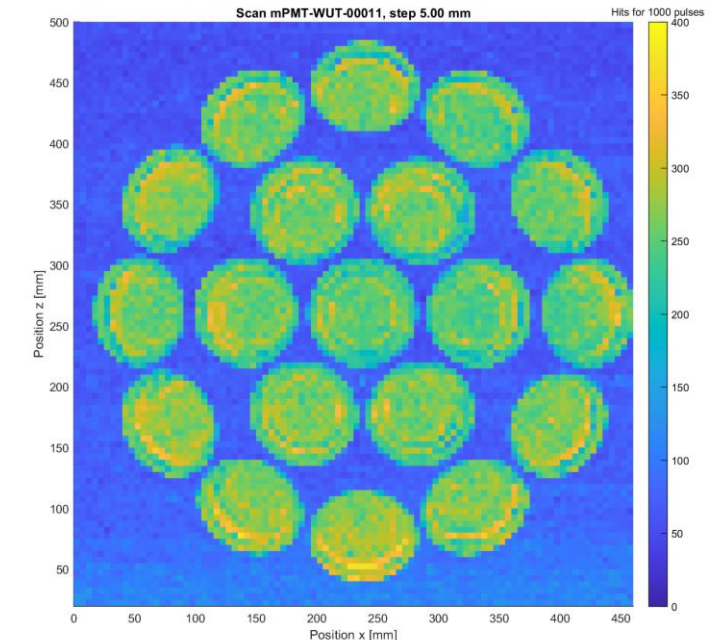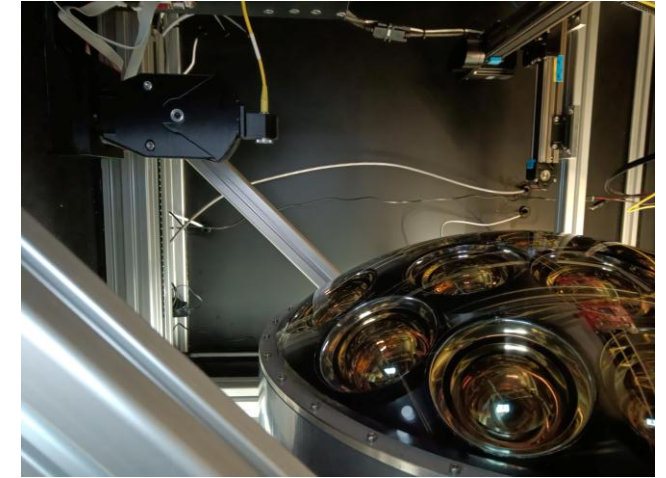
Multi-PMT in WCTE

WCTE detector in CERN assembled in summer 2024
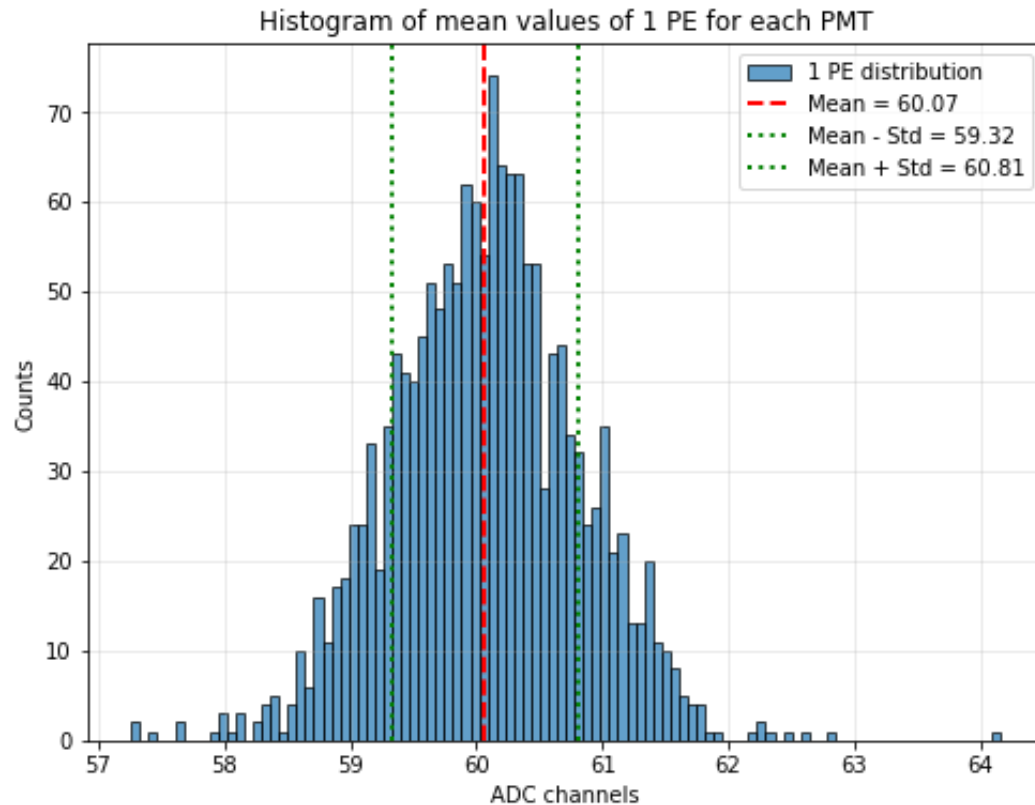
Two runs with T9 beam:

- October - November 2024

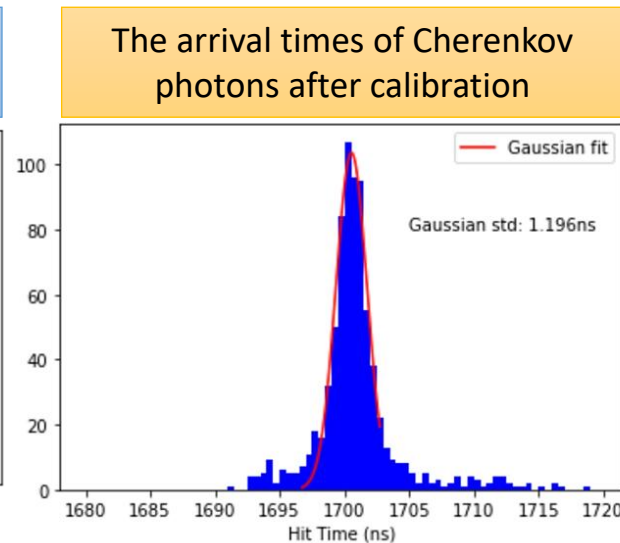- February - June 2025
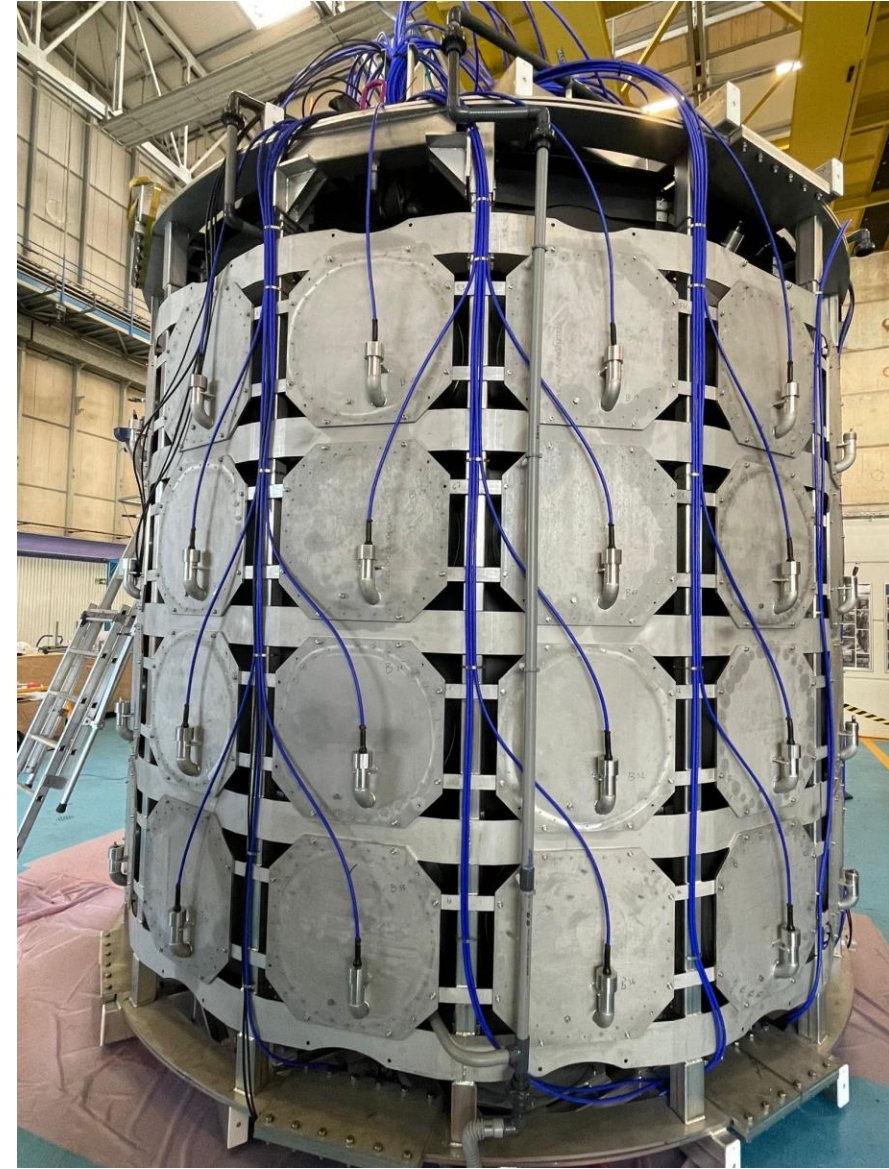
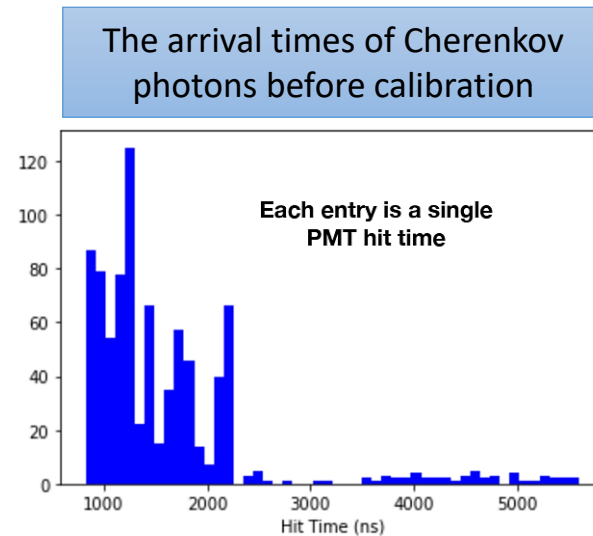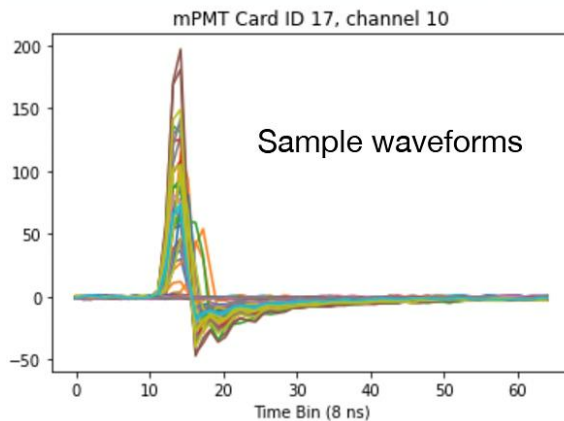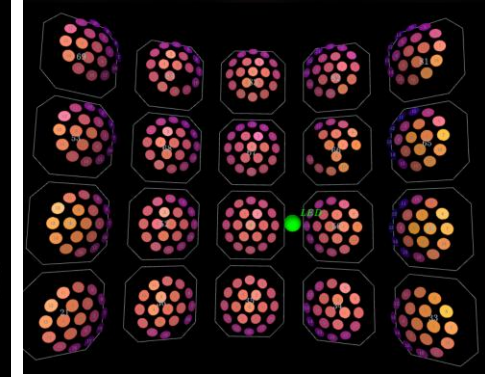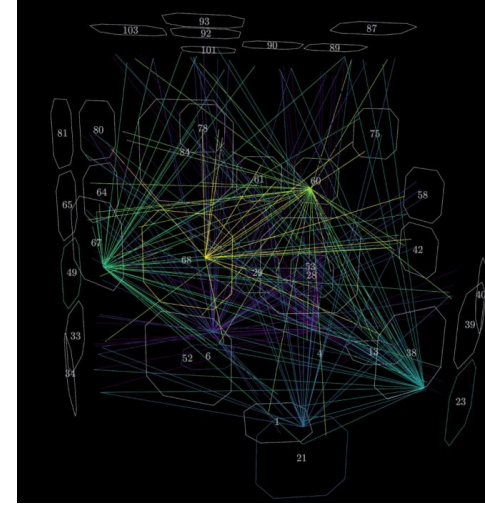# Results of 1PE response equalization

- Fully automated procedure for single PE response equalization

- Fast LEDs used as the light source

- All 1PE amplitude values centered around 60 LSB

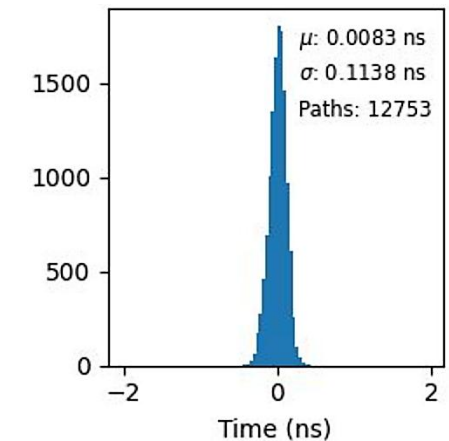- Mean: 60.07 LSB, Standard Deviation: 0.74 LSB
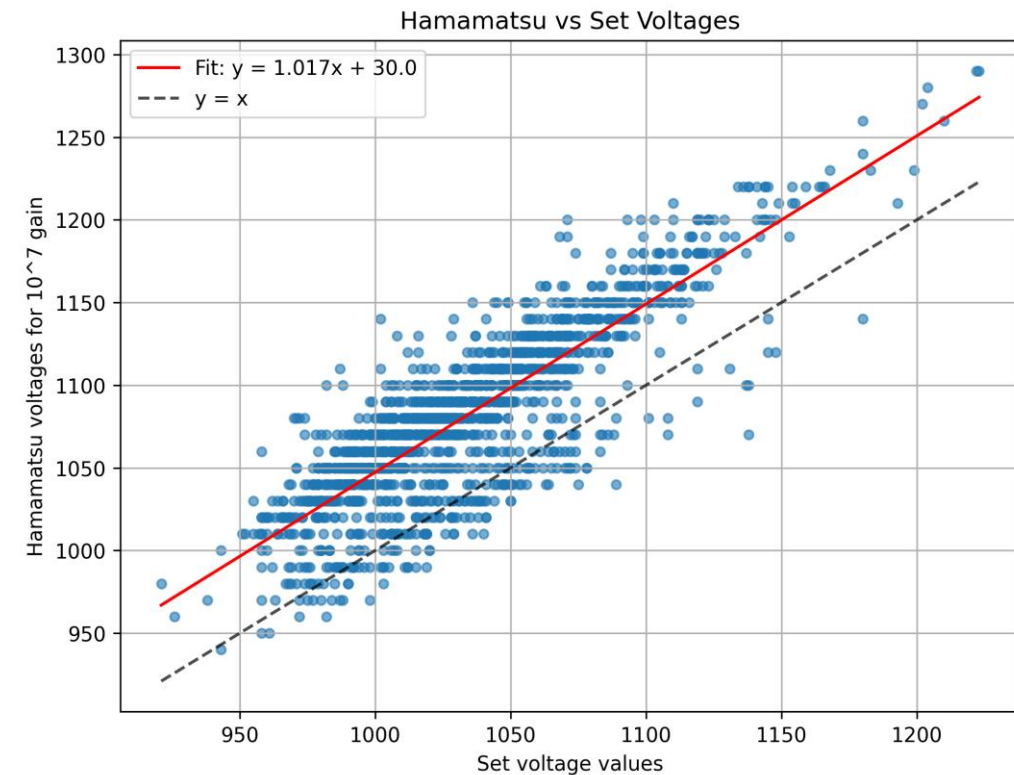
Timing calibration

- The WCTE used diffuse LED light sources embedded in mPMTs to perform timing calibration

- Procedure: pulse a given LED, record the time at which this happens, and record the time at which a signal is seen in a PMT receiving the light

- A set of 15 LEDs was chosen for the calibration

- Approximately 3-4 LED runs were taken each day

- The resulting timing constants were stable over the course of the WCTE run, with fluctuations of < 1 ns over the course of days/weeks


The arrival times of Cherenkov photons before calibration

The arrival times of Cherenkov photons after calibration

The differences between the calibrated LED flight times and the expected flight times

Sample waveforms

Each entry is a single PMT hit time

Gaussian fit

Gaussian std: 1.196ns

μ: 0.0083 ns
σ: 0.1138 ns
Paths: 12753

Showcase of events in WCTE

- Full physics run completed in Spring/Summer 2025

- Examples of events after gain and time calibration

- Map of number of hits in each PMT

- The WCTE data analysis is in progress

Andrzej Rychter – Warsaw University of Technology
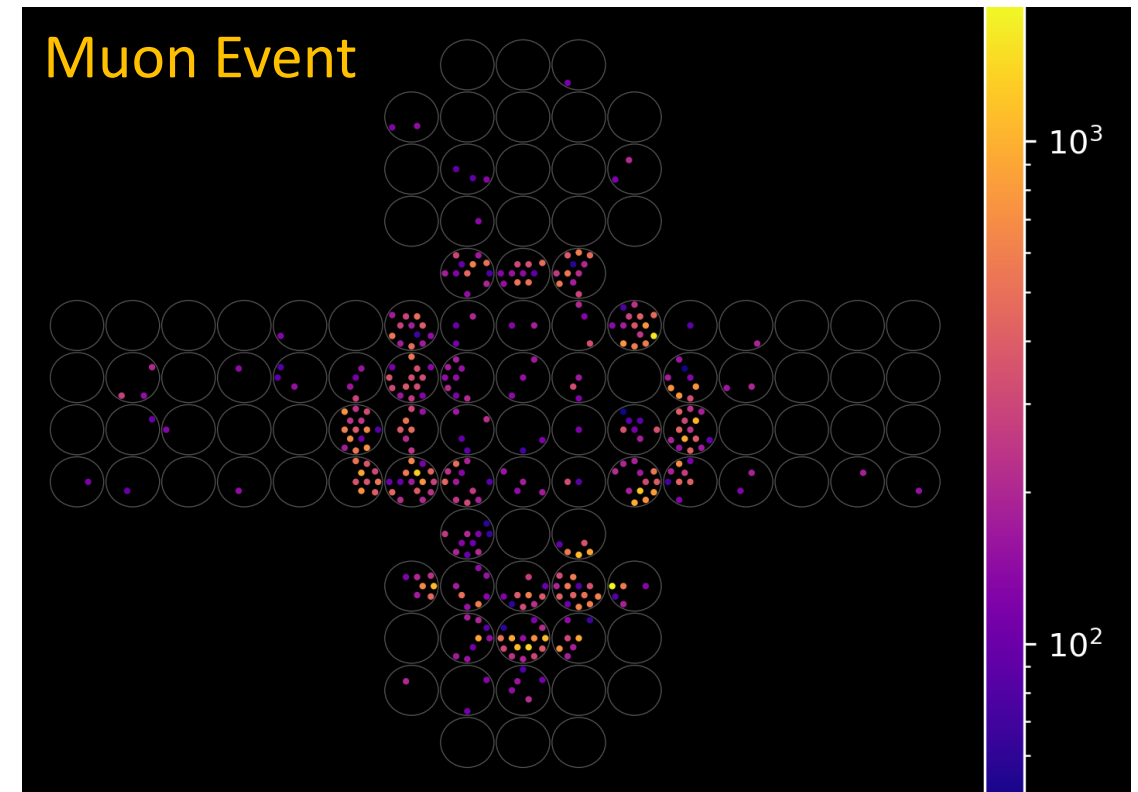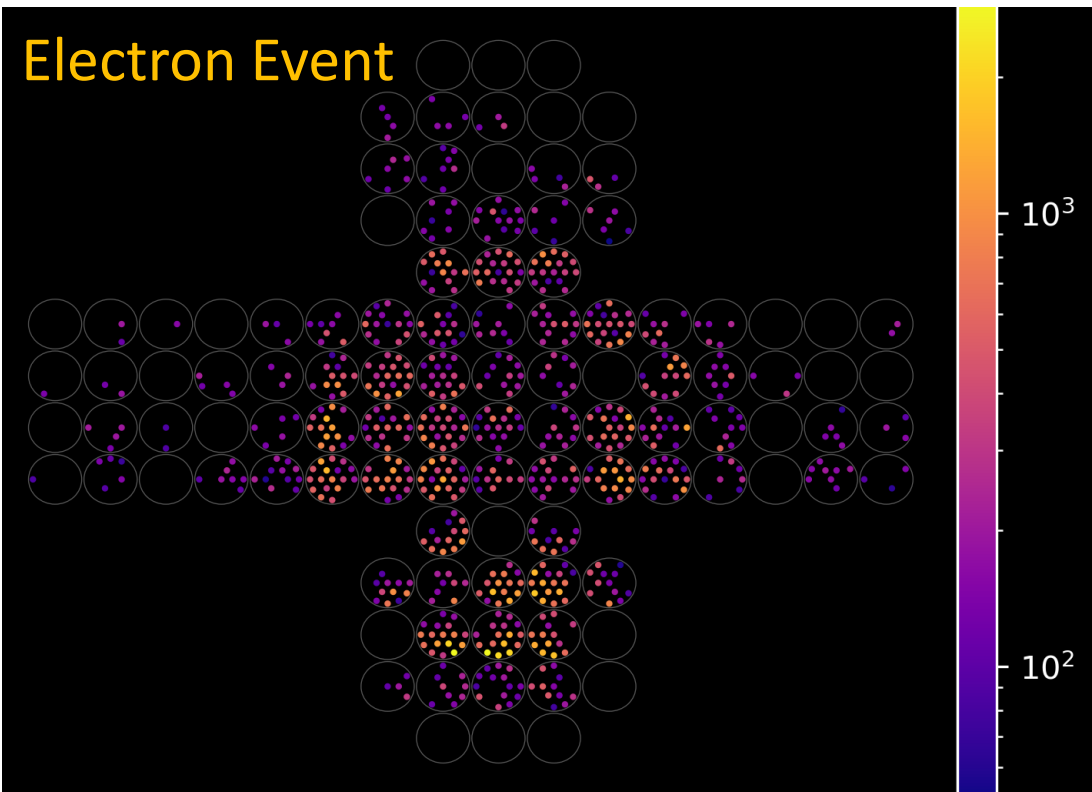
Summary

- Hyper-Kamiokande FD and its near detector IWCD will feature novel light detection multi-PMT modules
- WCTE was the opportunity to test multi-PMTs in real experiment conditions
    - Validated multi-PMTs under beam running conditions
    - Self-equalised gains and achieve ~1 ns timing
    - Made a significant step forward in the development of DAQ for IWCD and Hyper-Kamiokande detectors

- Construction of Hyper-Kamiokande and IWCD has already started
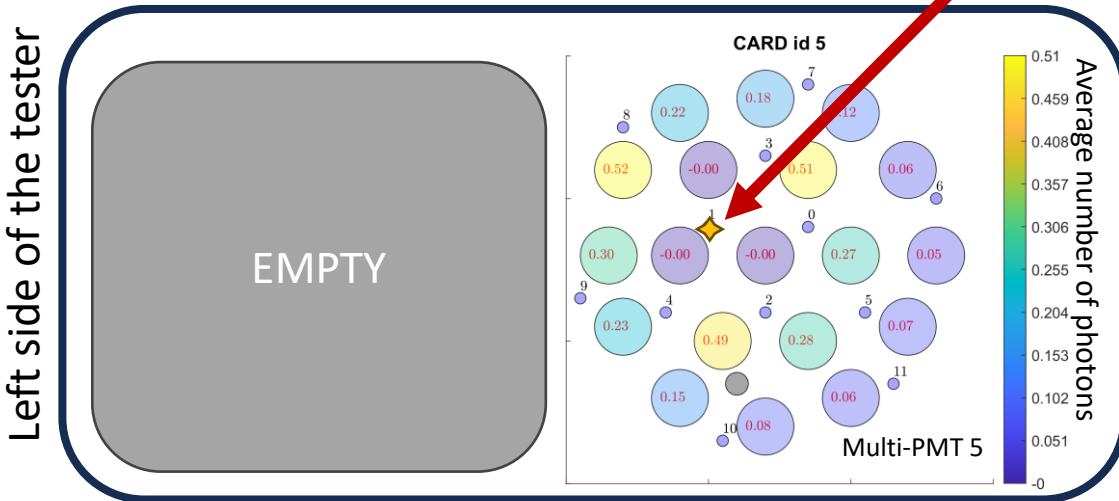- Full production of multi-PMTs for Hyper-Kamiokande FD and IWCD will begin in 2026

Thank you

Multi-PMT testing (backup)

1. Multi-PMT 5 generates fast light pulses
2. Using LED 405 nm with diffuser
3. Gain scan with software trigger
   I. 1PE amplitudes histogram fit
   II. 1PE vs HV plot and fit with exponential function
   III. Calculate HV for nominal gain = 5×10^6 (60 LSB)
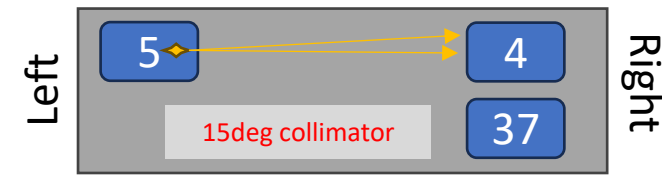

Example histogram

Nominal HV calculation

Left · Right
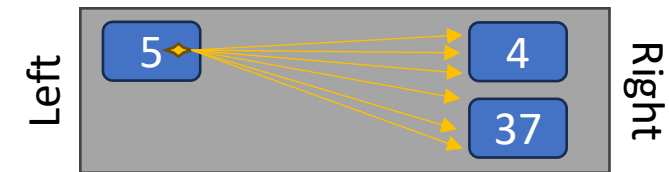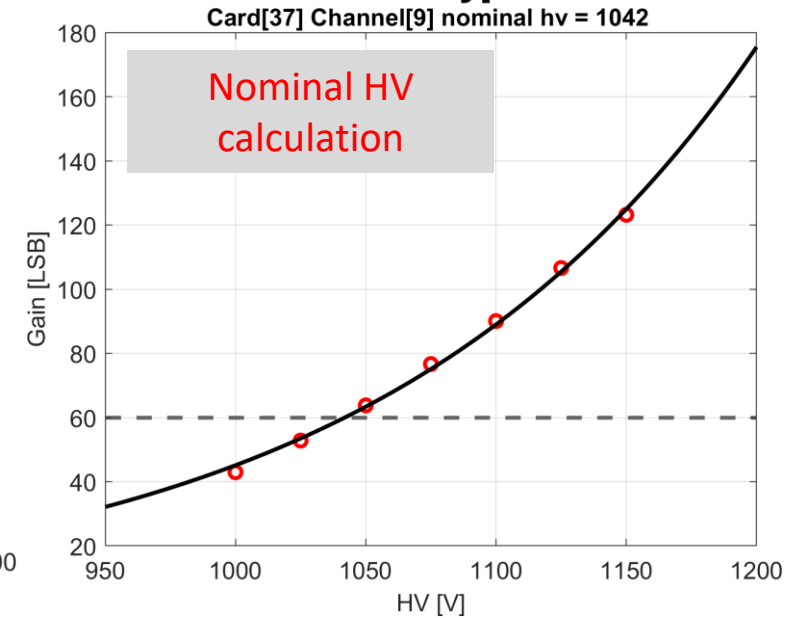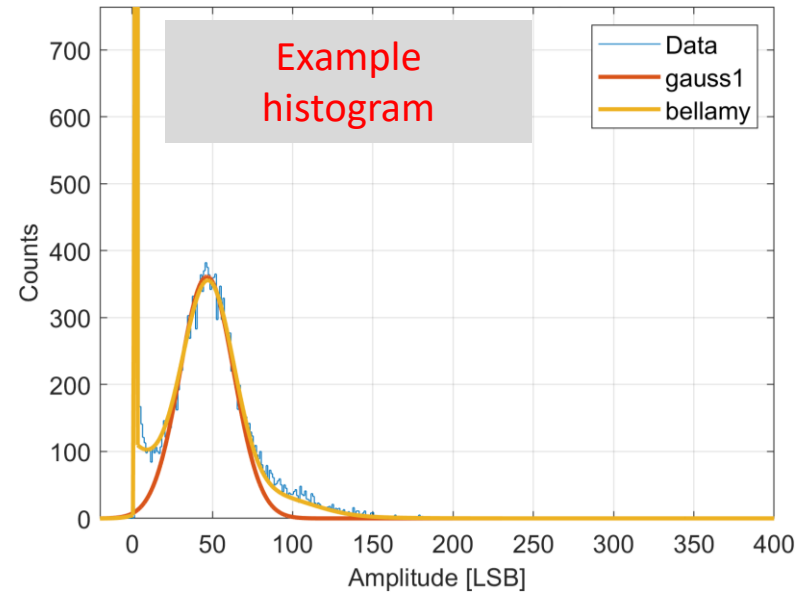
Firing LED with diffuser

Uniform number of photons

Left side of the tester

EMPTY

Multi-PMT 5

Right side of the tester

Multi-PMT 4 · Multi-PMT 37
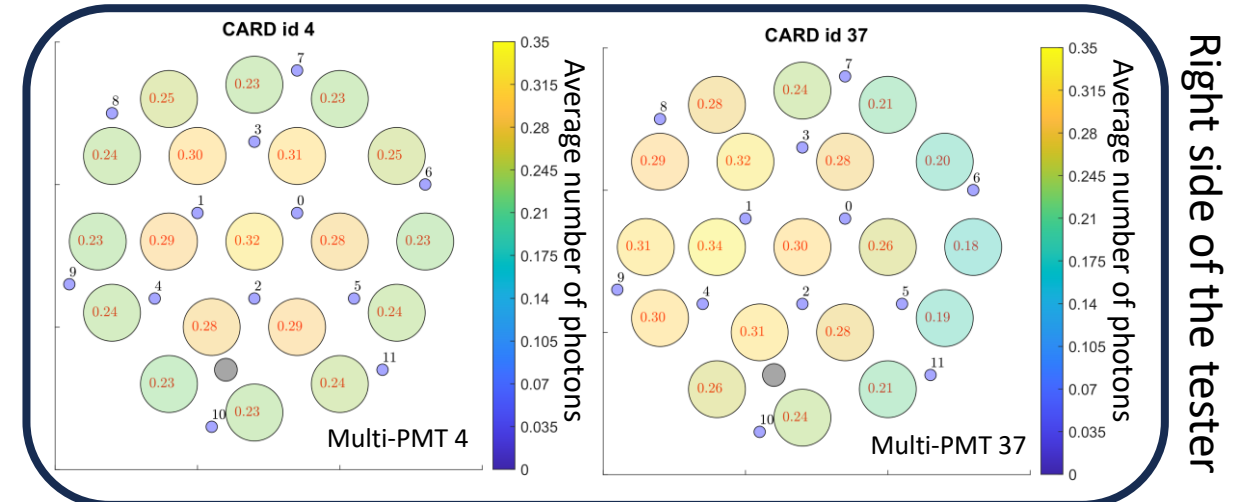
Timing resolution software trigger (backup)
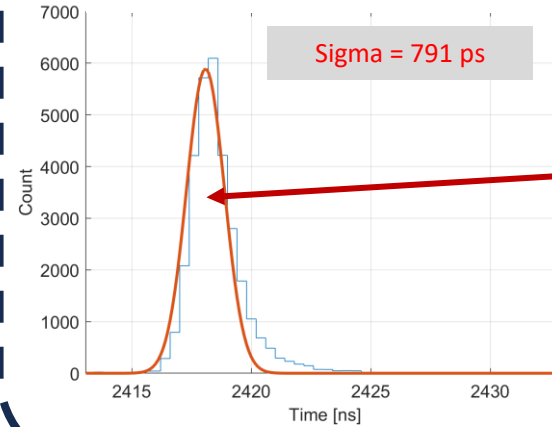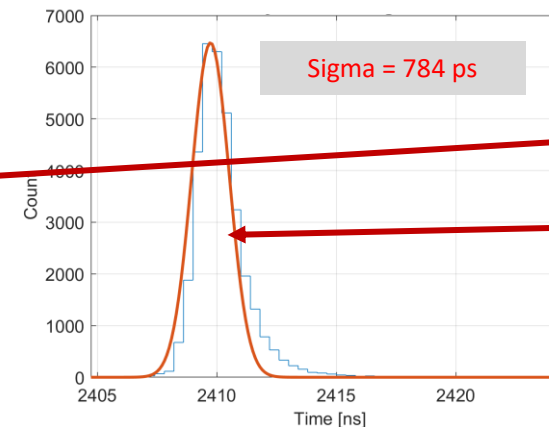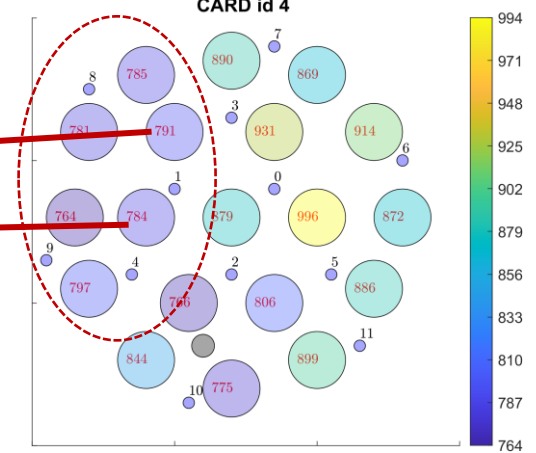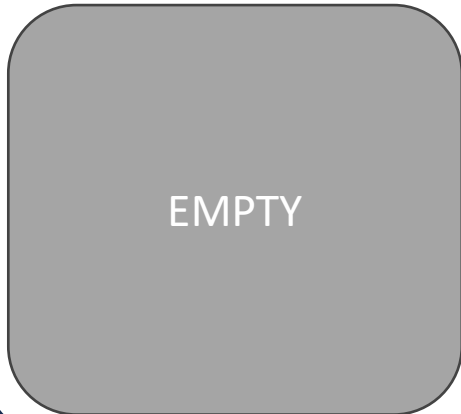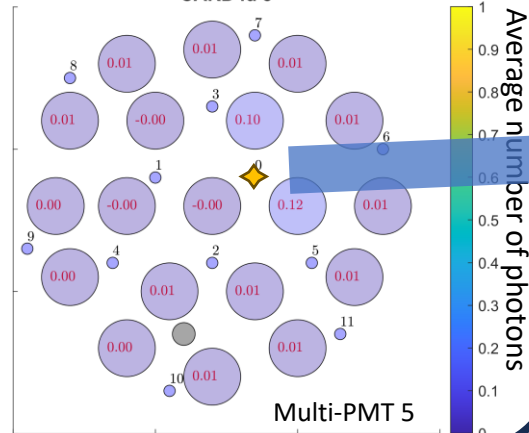

1. Set HV for nominal gain.
2. Program 65000 fast LED light pulses.
3. Using LED 470nm with **15°** **collimator**
4. Signal amplitude = 1PE
5. Analyze waveforms and calculate time.
6. Timing resolution = 800 ps