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Hyper-Kamiokande

Multi-Photomultiplier Detectors in the Water Cherenkov Test Experiment

Krzysztof Dygnarowicz

Warsaw University of Technology

On behalf of the Water Cherenkov Test Experiment and the Hyper-Kamiokande Collaboration

NuFACT 2025

Liverpool 2.09.2025

NuFact 2025

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Multi-PMT detectors

Key features:

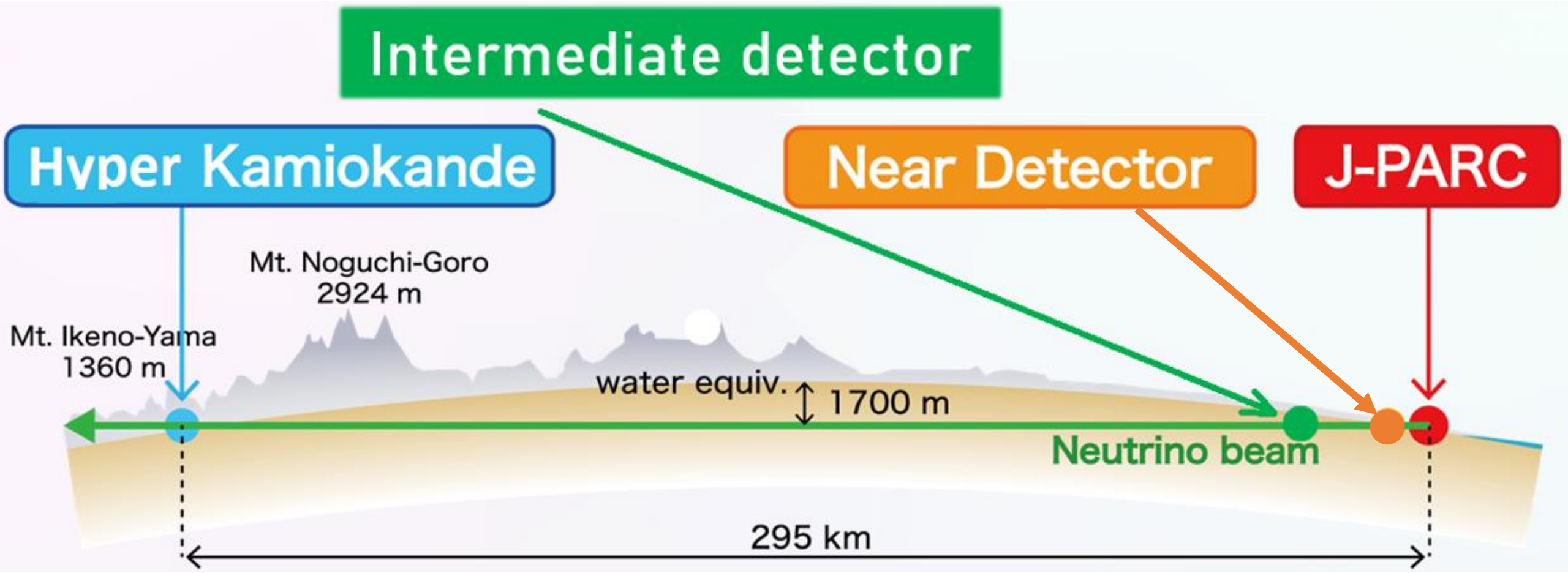
- Composite detector built from 19 PMTs (Hamamatsu R14374)
- Sealed in a waterproof container
- Gel to improve optical contact between PMT and acrylic dome
- Weight approximately 50 kg, diameter 0.5 m
- Integrated HV (Cockcroft-Walton base) & readout electronics

mPMT benefits compared to 50 cm PMTs:

- Better time and charge resolution
- Directionality
- Increased granularity
- Low dark rate per channel

Hamamatsu R14374 PMT
Spectral response: 300 to 660 nm
Maximum response: 420 nm
Photocathode: Bialkali
Typical gain: 5×10^6
TTS: 600 ps (sigma)
Dark rate: 200-300 Hz

Where will we use mPMTs?



Where will we use mPMTs?

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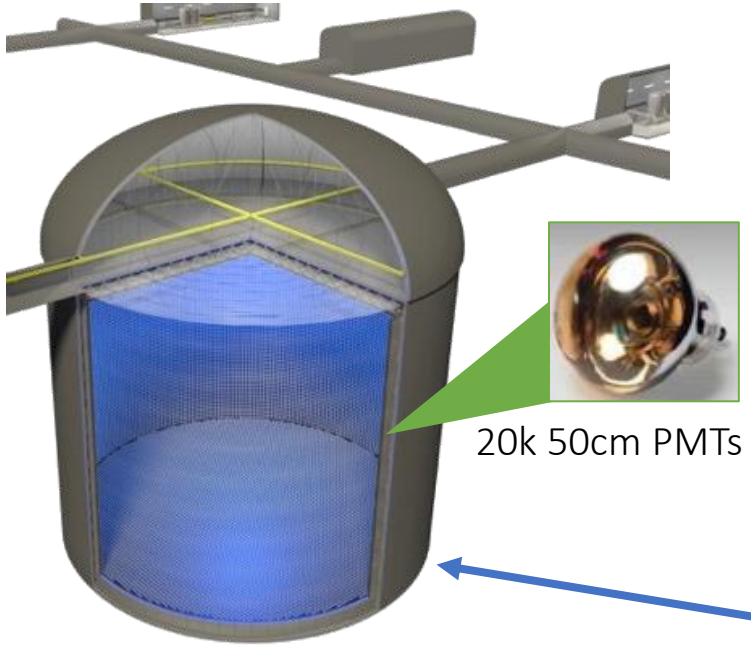
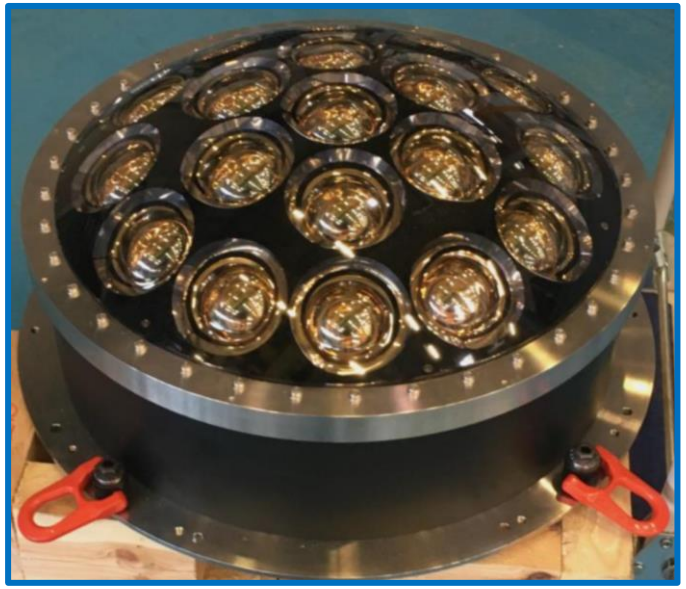
Hyper-Kamiokande Far Detector



Far detector:

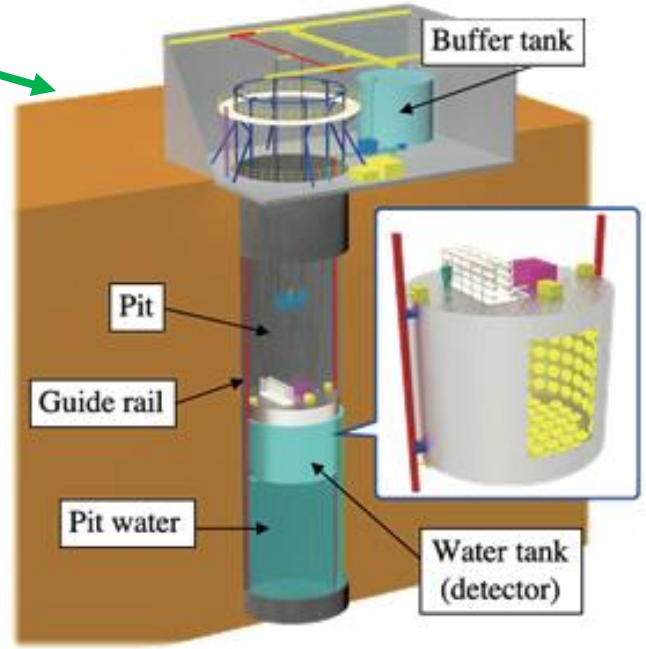
- Complementary detectors for calibration
- Optimised for low power
- Need high reliability
  (at least 10 years of operation)
- High-pressure working conditions (~1 MPa)
- Only Charge and Time
- Expecting 800 mPMTs

Intermediate Water Cherenkov Detector (IWCD)



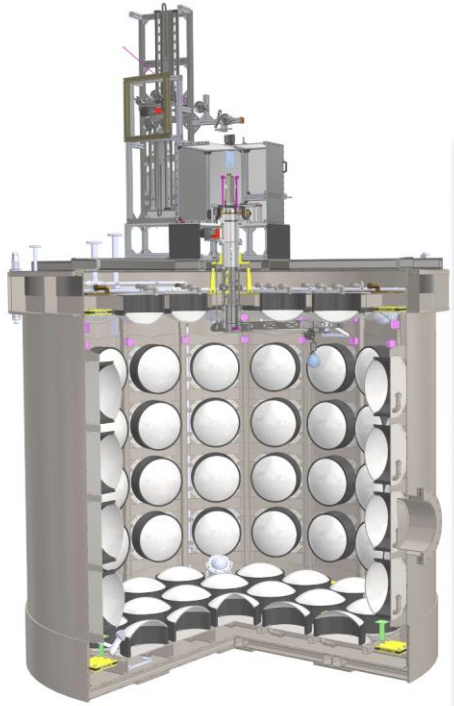
Intermediate detector:

- Main photosensors
- Optimised for high rate
- Flash ADCs with full waveforms readout
- Less strict reliability requirements
- Relaxed restriction on power consumption
- Around 360 mPMTs

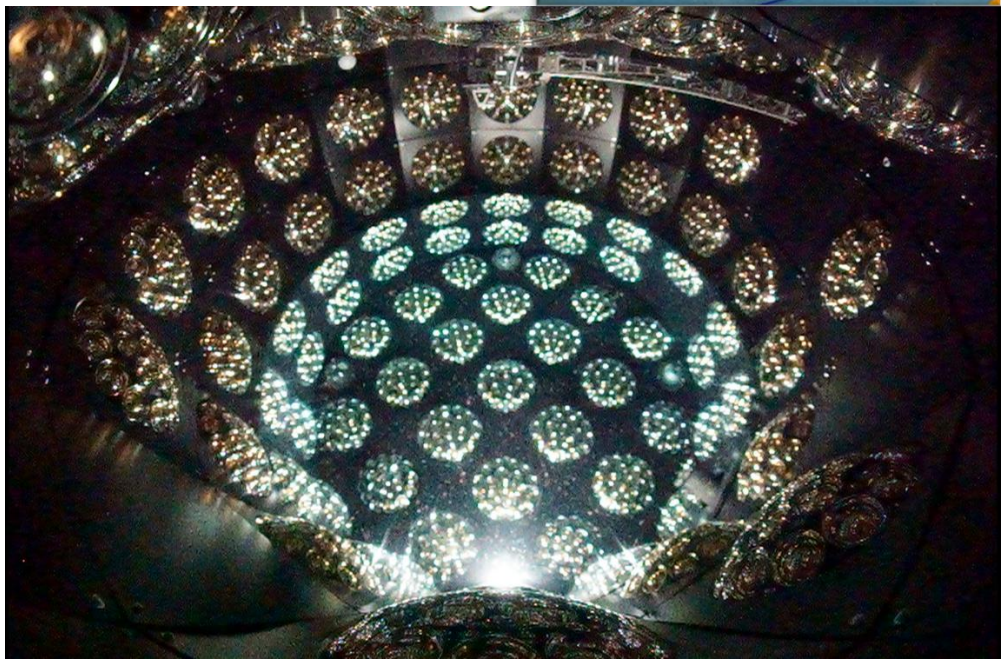


Water Cherenkov Test Experiment

- Beam line experiment at T9 in CERN
- Water tank of 3.8 m diameter × 3.6 m height, 41 t.
- Consists of 97 mPMTs
  - 93 IWCD style
  - 4 Far Detector variant
- Working period 10.2024 – 06.2025



- WCTE delivers beam-based control samples to constrain detector & interaction systematics relevant for Hyper-K CP violation sensitivity.
- Key physics studies: e/μ separation, π^0-related e/γ discrimination, water-target response; path to ν/ν̄ tagging (with Gd).
- Prototype for IWCD: tests mPMT granularity, reconstruction, and calibration under beam-like conditions.
- Outcome: better near→far extrapolation and smaller non-Gaussian uncertainties.



IWCD Multi-PMT assembly variants

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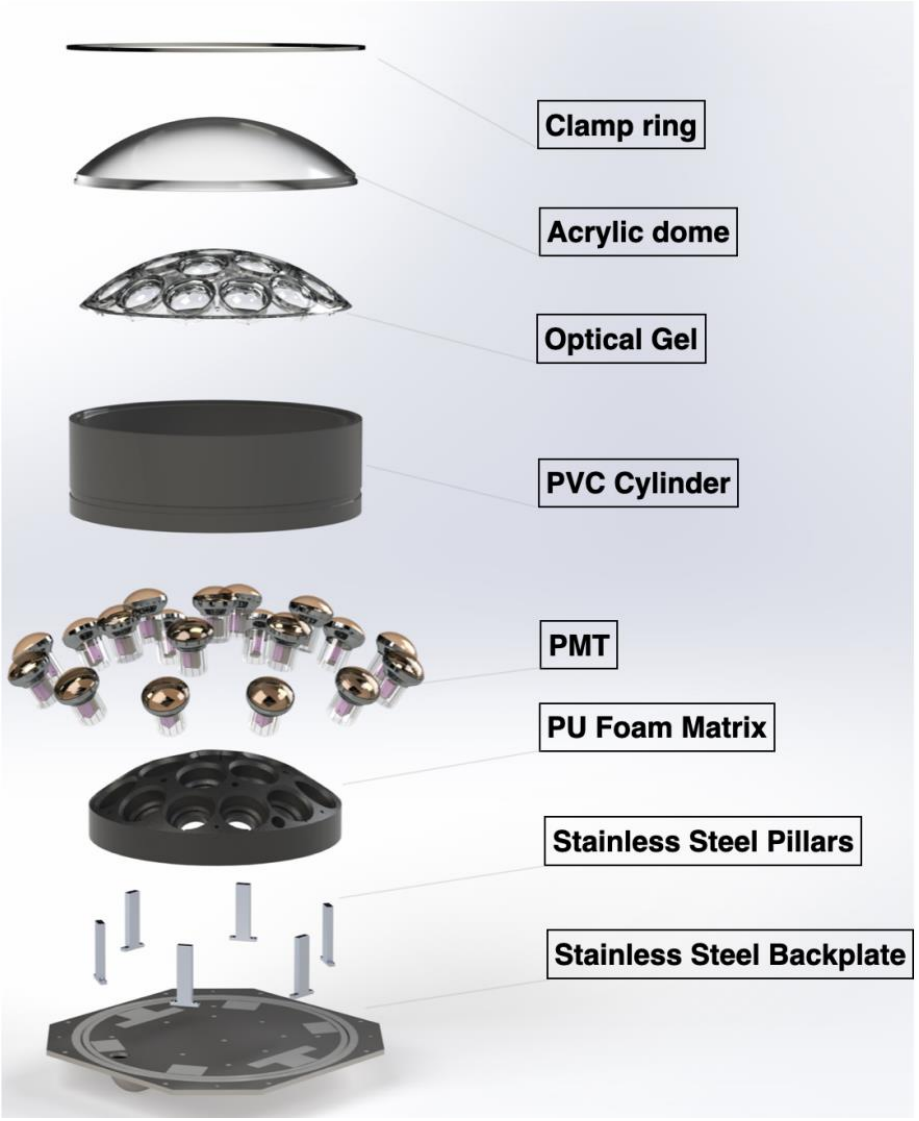
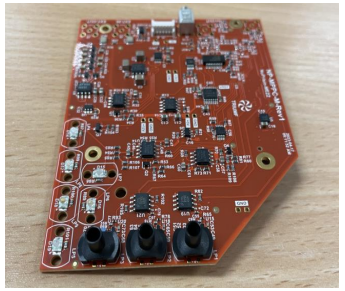
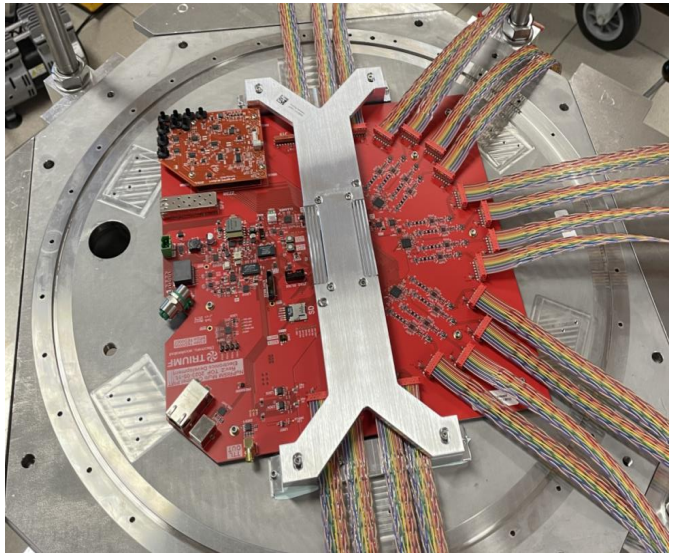
Ex-situ

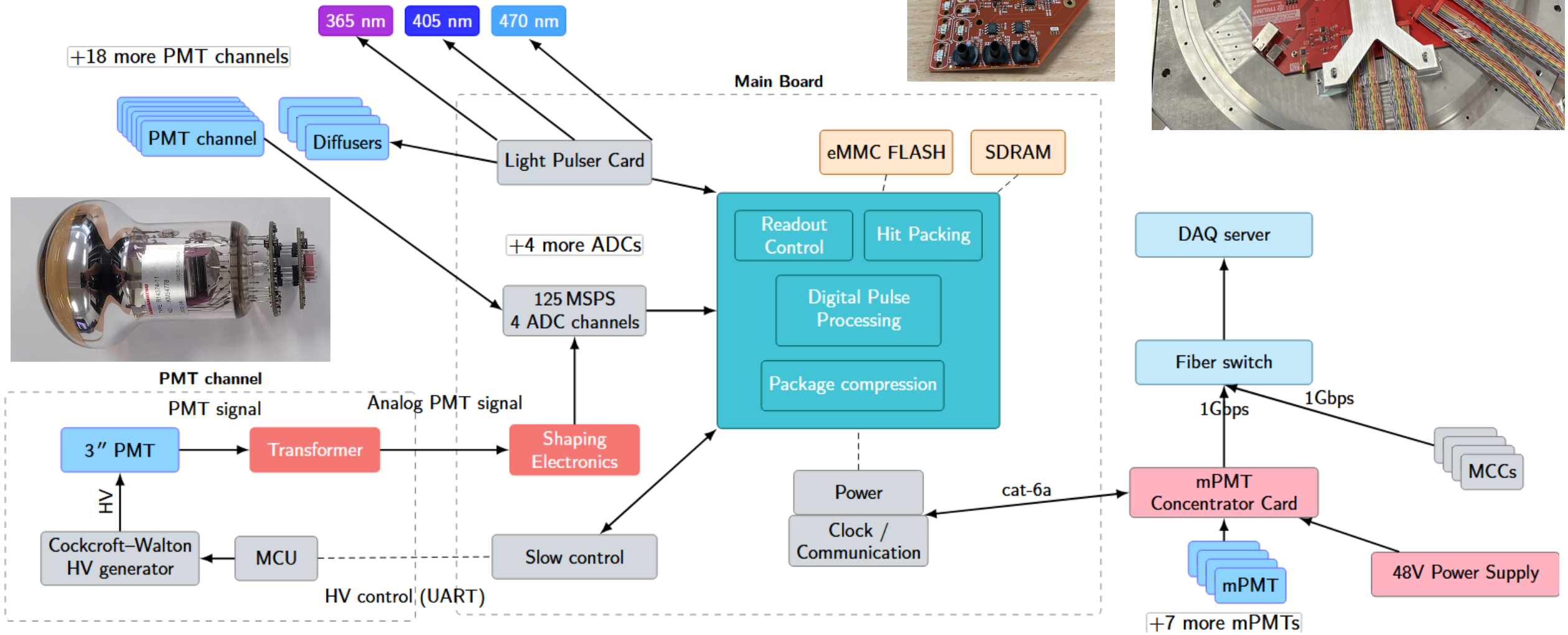
In-situ



IWCD Multi-PMT modules electronics







Multi-PMT assembly steps

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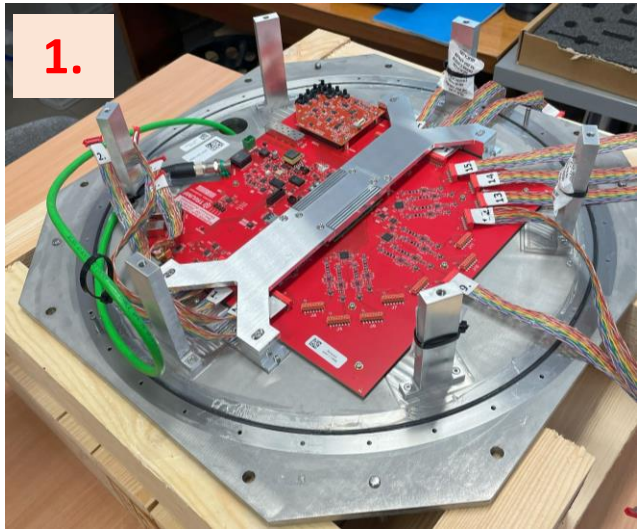
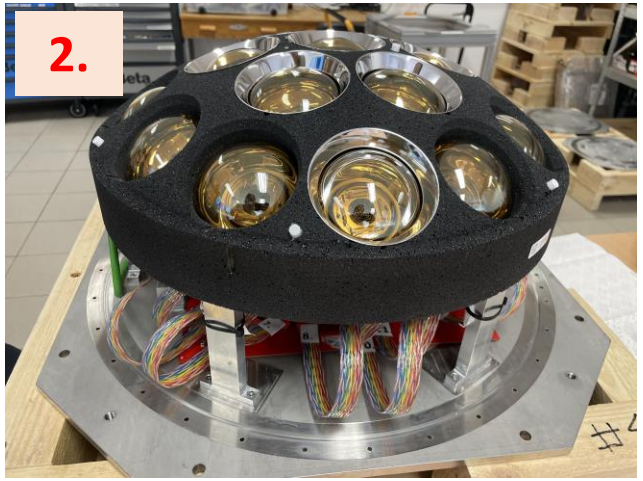
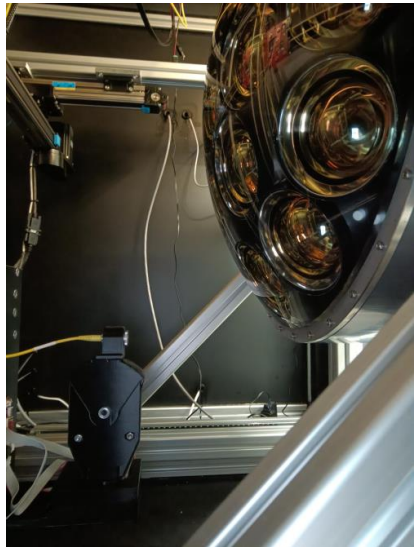
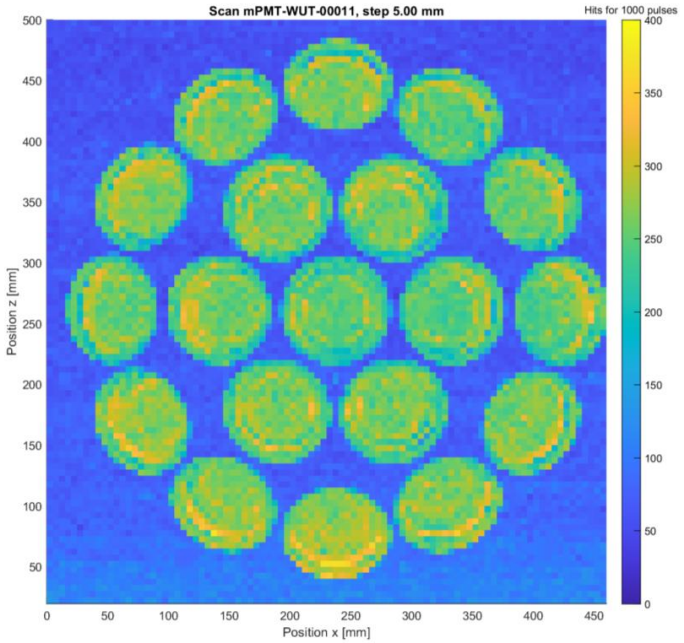




Quality assurance

- HV+FE testing:
  - 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 gelling and mounting in the mPMT modules
  - A set of 20 PMTs is tested in parallel
  - Checks: gain, dark rate
- mPMT modules:
  - Check operation in dark box using final DAQ
  - Selected mPMTs checked in XYZ test stand using a picosecond laser





WCTE mPMT Production

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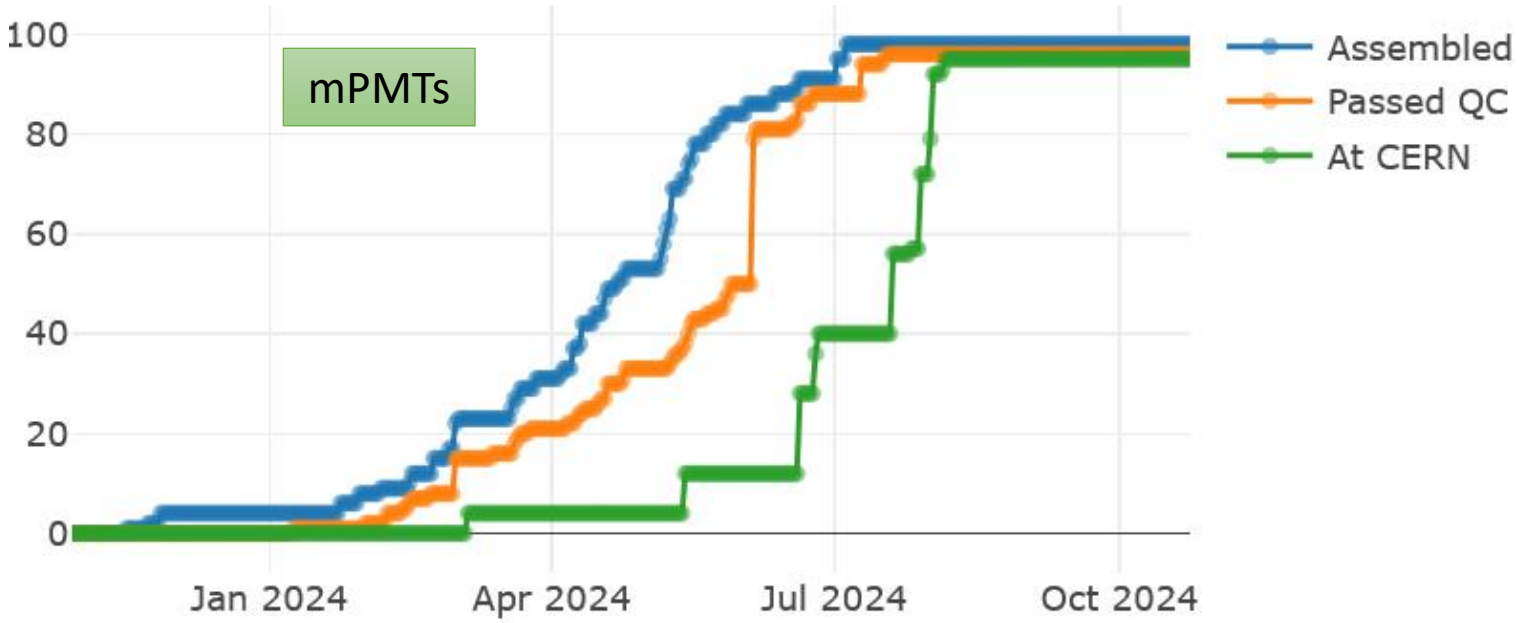
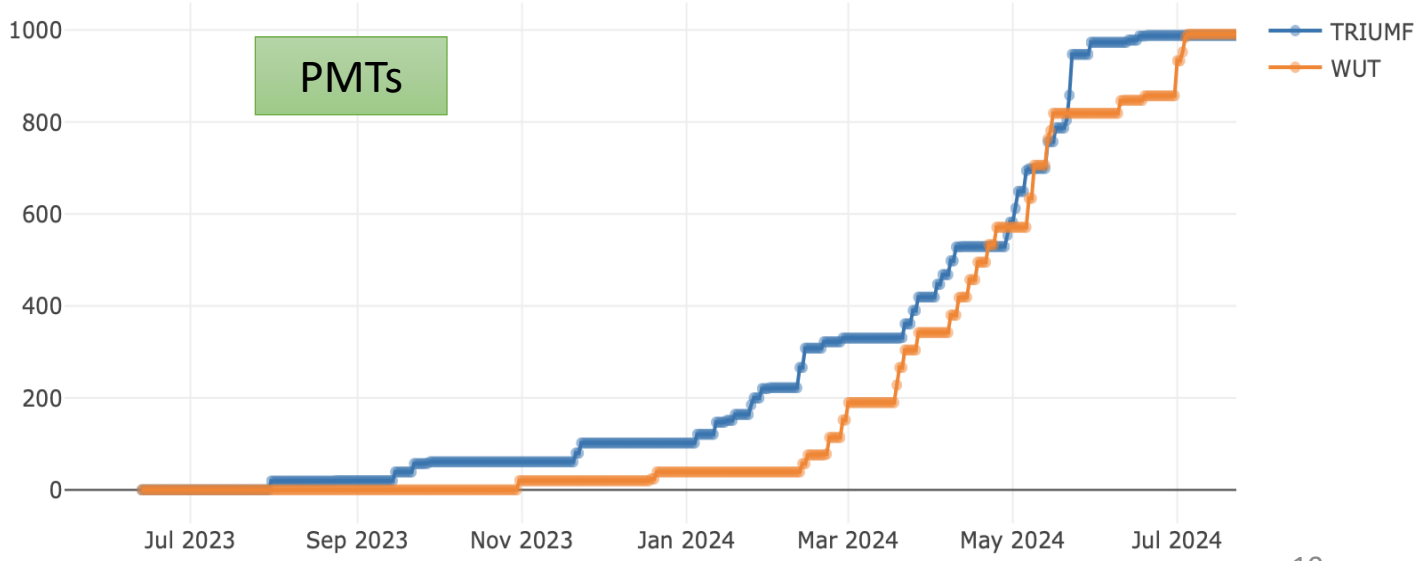
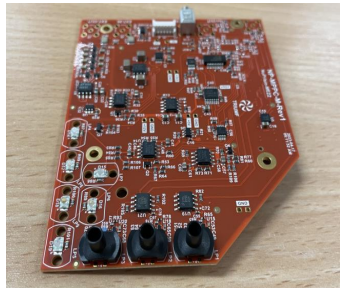
- Totally assembled 100 IWDC-style mPMTs in Canada and Poland
- Full production started in January of 2024 and was finished in June 2024 with a production rate of 5 mPMT modules per week
- A total of ¬2000 3-inch PMTs were used in Poland and Canada
- Produced 38 Ex-situ and 62 In-situ mPMTs
- More details:
  "Assembly, testing, and installation of mPMT photosensor for the Water Cherenkov Test Experiment"

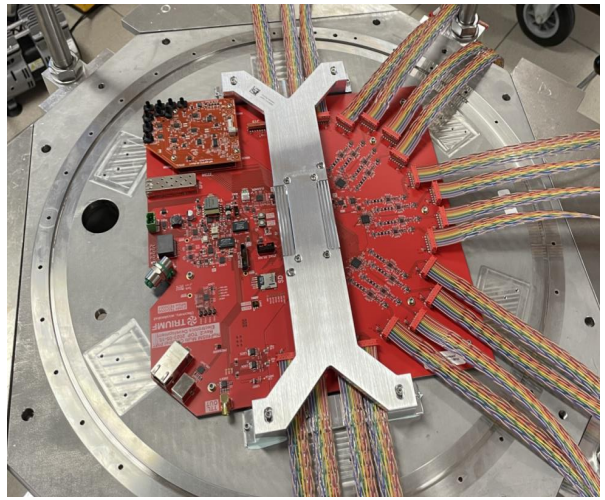
  https://arxiv.org/abs/2504.07216

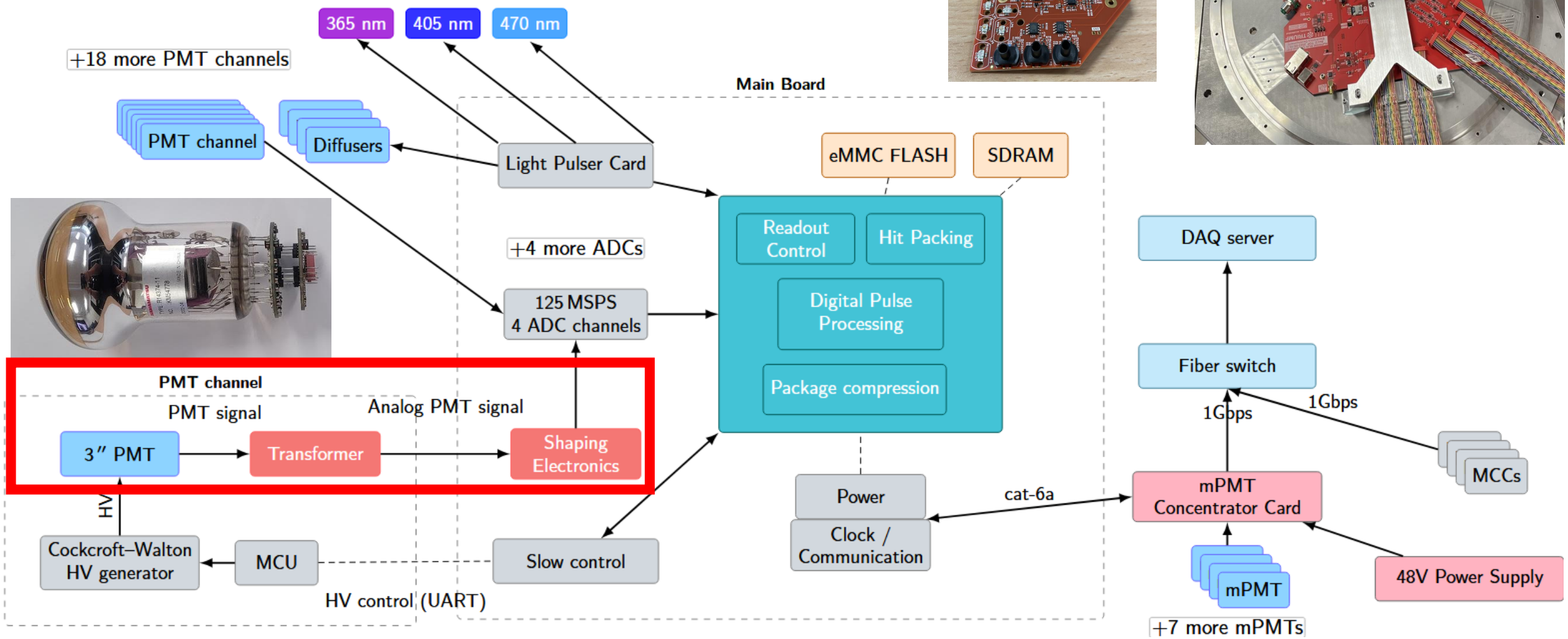




IWCD Multi-PMT Signal shaping







Signal shaping

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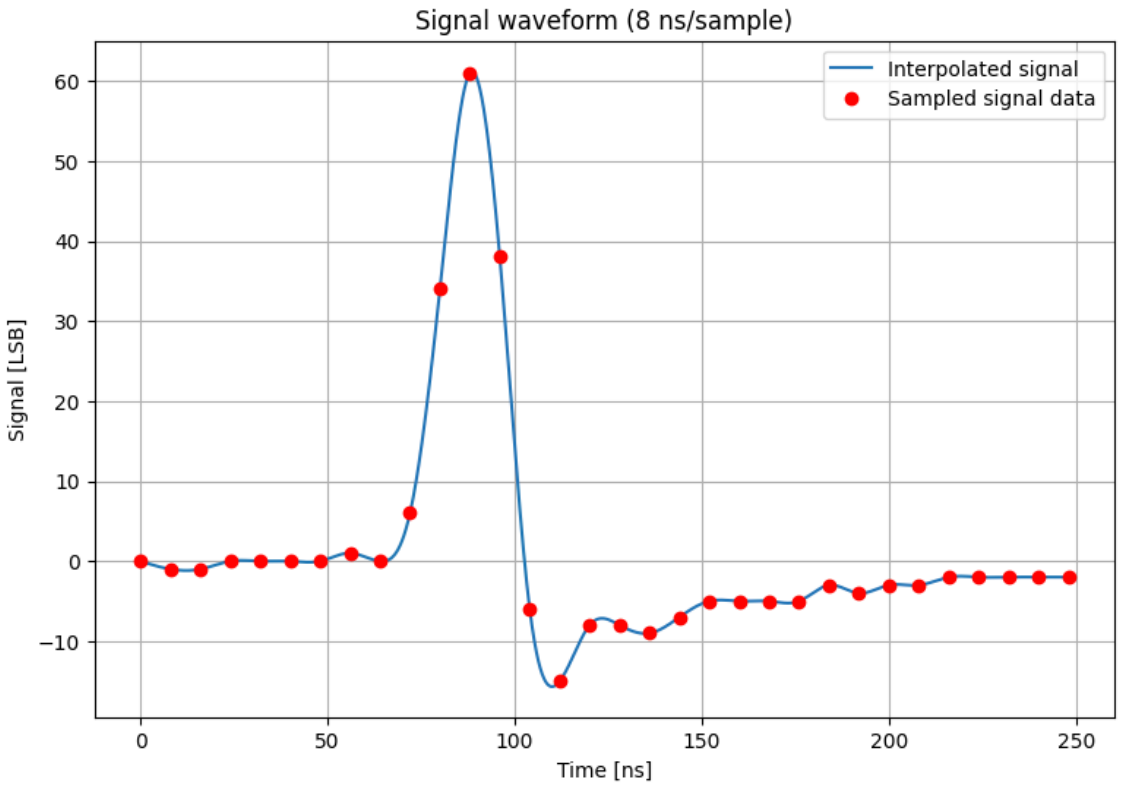
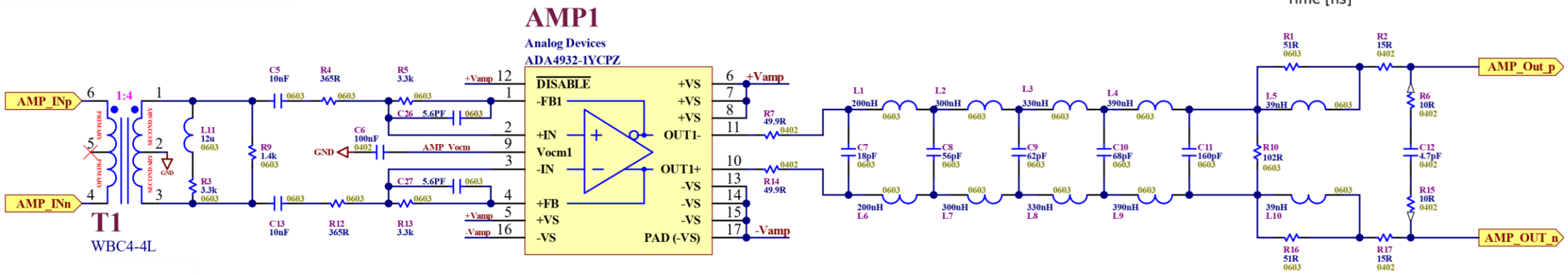
- Photomultiplier gain set to 5×10^6, which corresponds to 60 LSB (least significant bit) for one photoelectron
- Low-pass 9th-order Gaussian filter ($f_c \approx 21.7$ MHz)
- 12-bit 125 MSPS ADC
- Shaped signal parameters:
  - Rising time = 13.0 ns
  - Falling time = 9.2 ns
  - FWHM = 18.1 ns
- Approximately 4 samples per pulse
- With a known signal shape and with a proper signal-to-noise ratio, we can calculate time and charge with high accuracy





PMT signal shaping circuit

IWCD Multi-PMT FPGA

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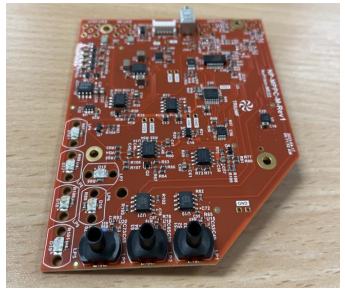
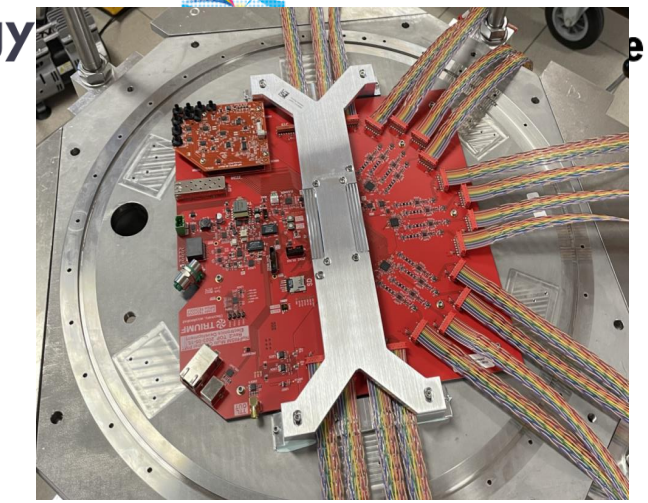
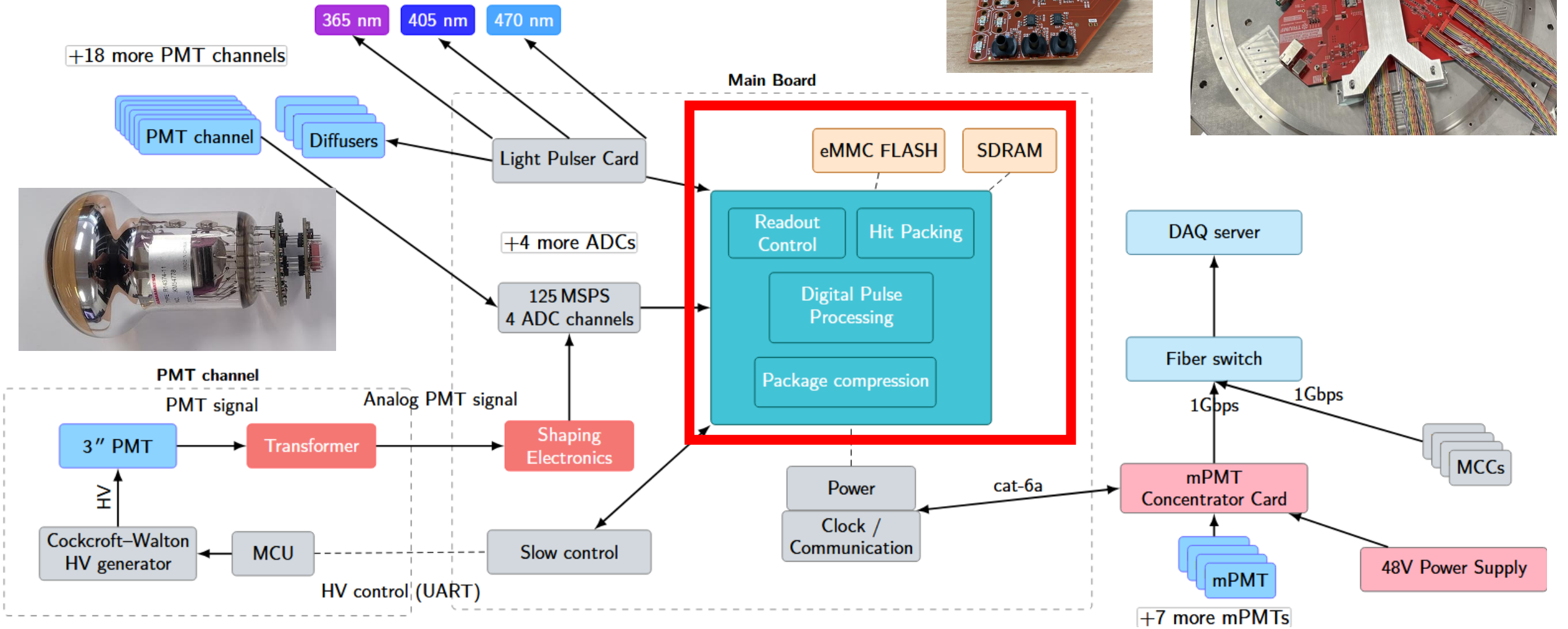


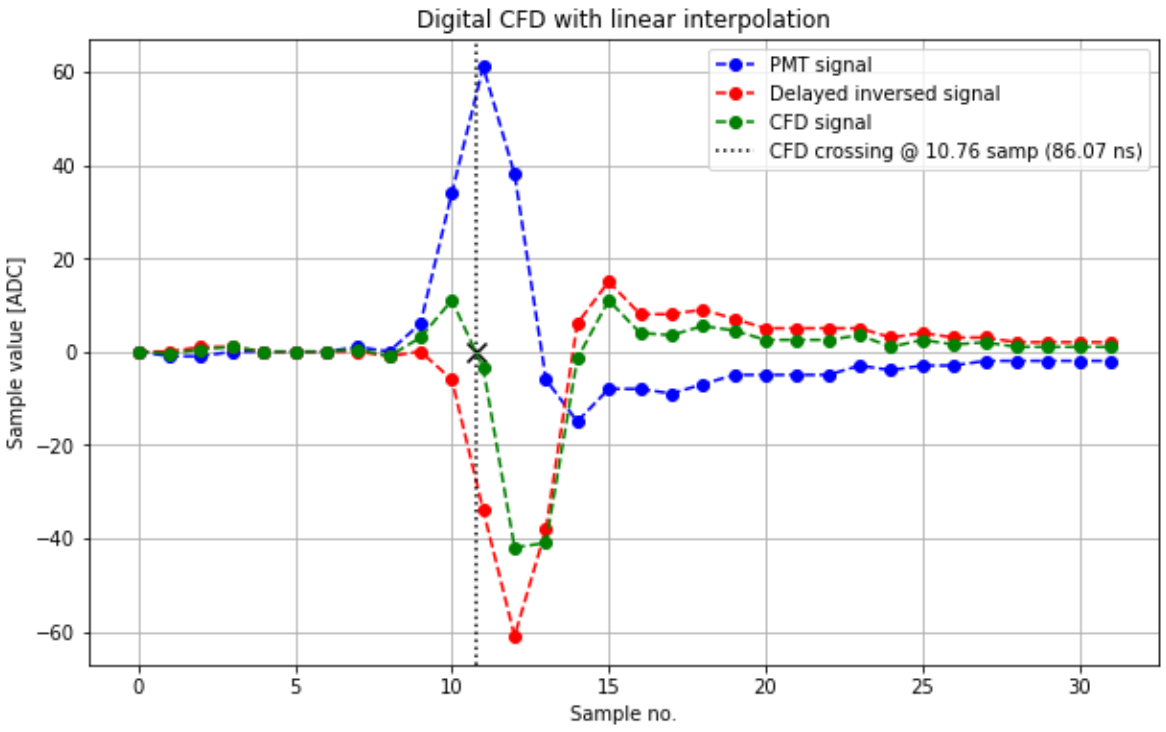


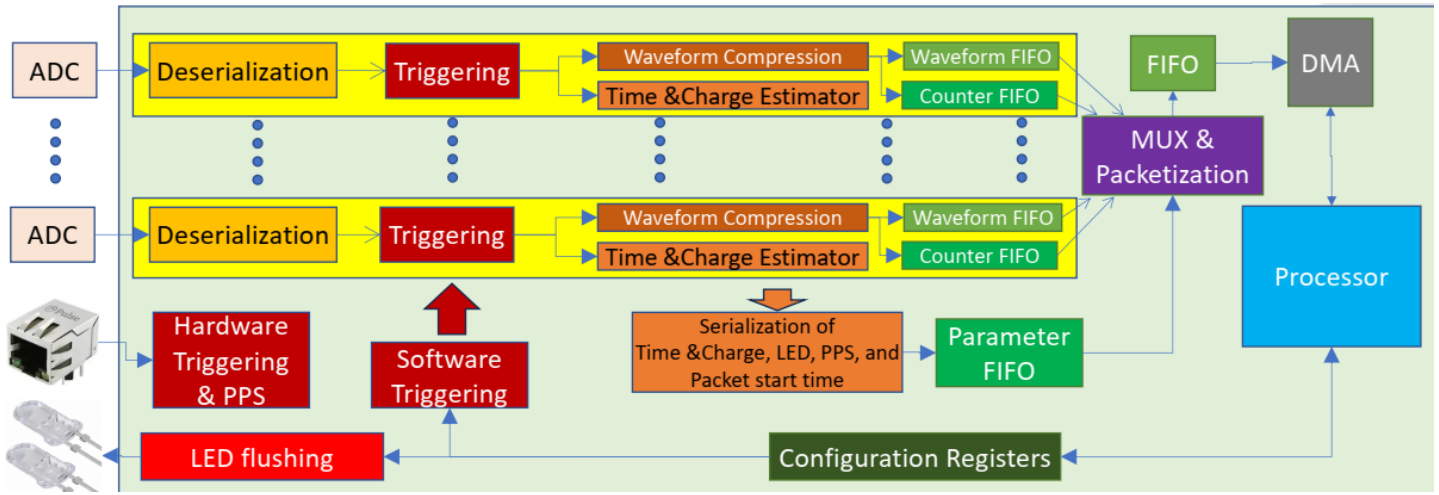


Multi-PMT FPGA algorithms

FPGA implementation algorithms on :

- Triggering:
  - Self based on pulse height and charge
  - Hardware trigger
  - Software trigger at the designed time
- Pulse time calculation:
  - Digital CFD (constant fraction discriminator) with linear interpolation and correction
- Pulse quality factor (0-best, 255-worst), computed as the Sum of Absolute Differences (SAD) between the signal with a hit and the selected waveform model
- Lossless waveform compression reduces waveform size up to 60%





IWCD Multi-PMT Fast LEDs

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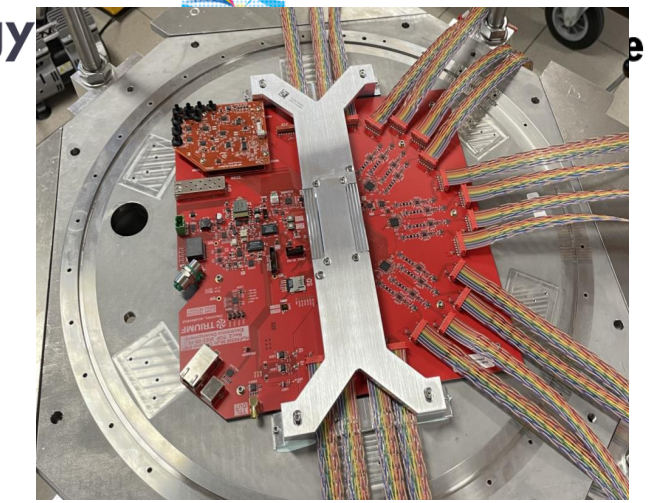

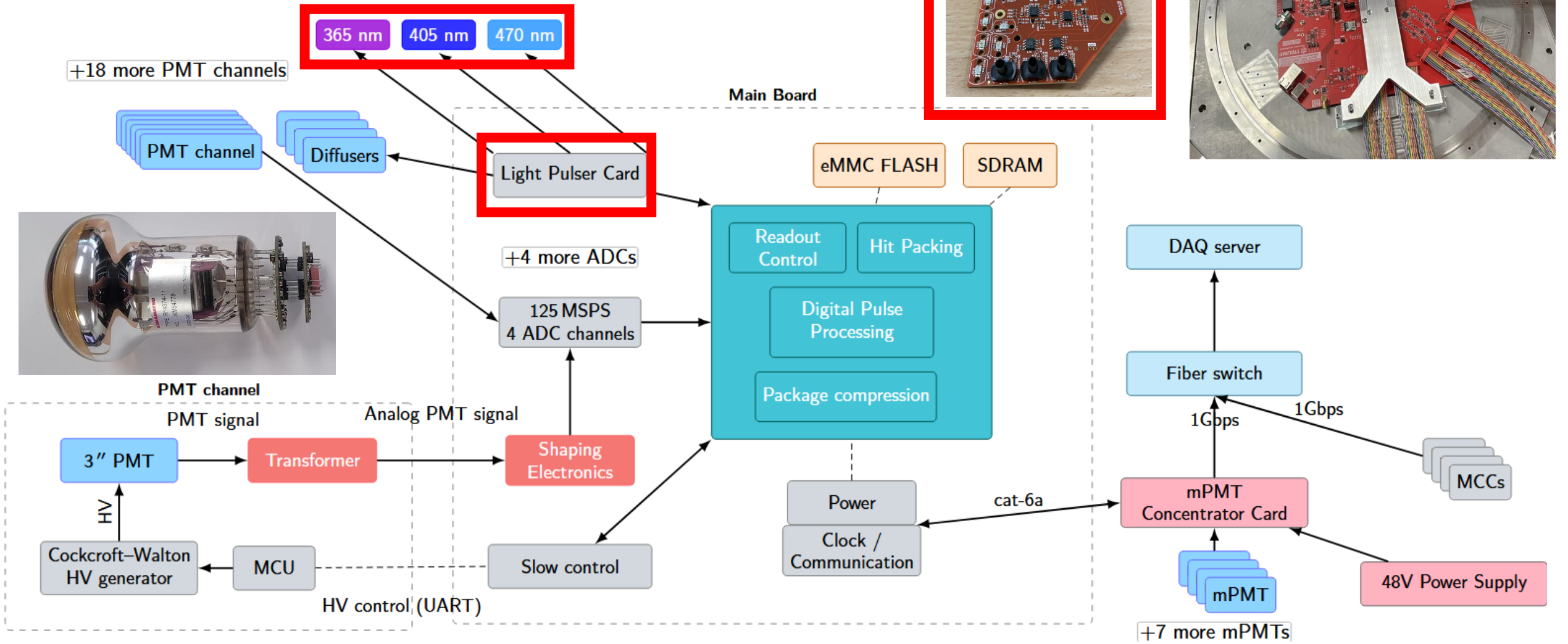

Assembled Multi-PMT – Fast LEDs

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- Each mPMT has **three fast LEDs** (wavelengths **365/405/470 nm**) used for **timing calibration, gain equalisation, and monitoring**; ex-situ optics: **two 15° collimated + one diffuse**; in-situ: **two 30° collimated + one diffuse**.

6 slow LEDs fibres output with diffusers

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

Anodized aluminium reflectors around each PMT

Calibration procedures in WCTE

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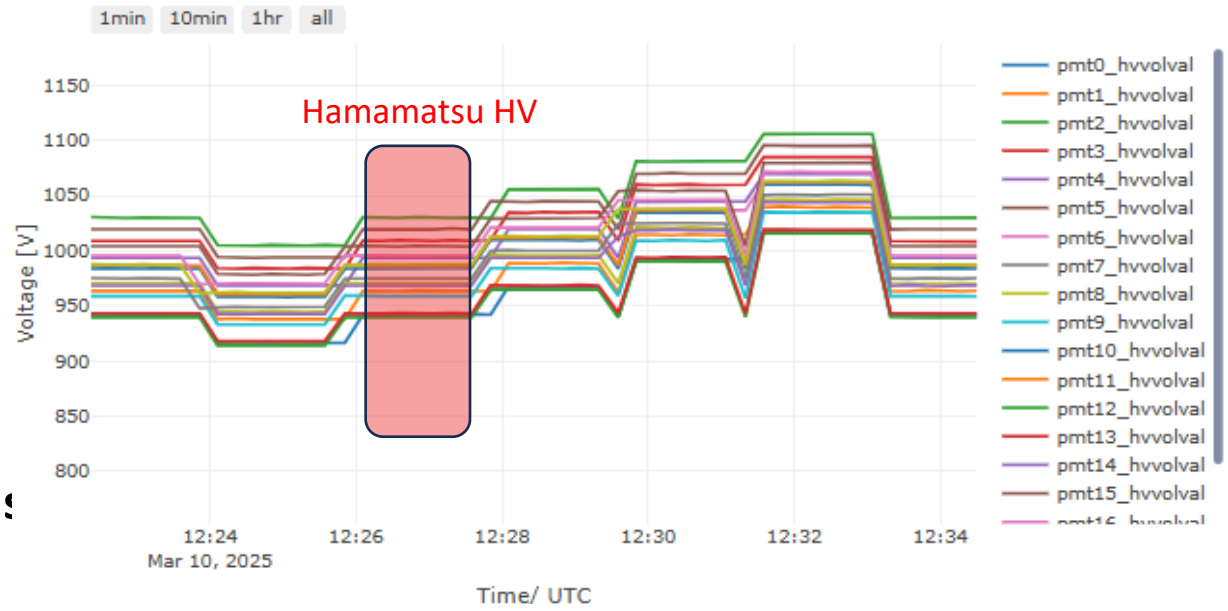
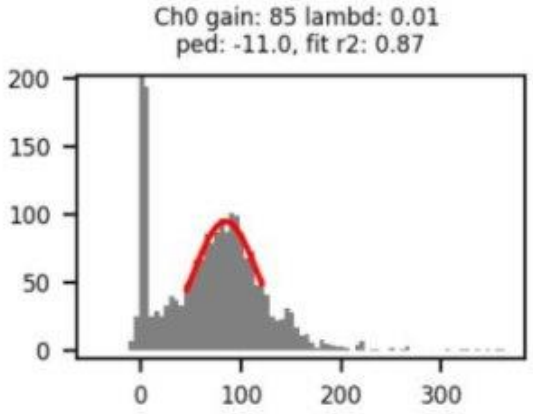
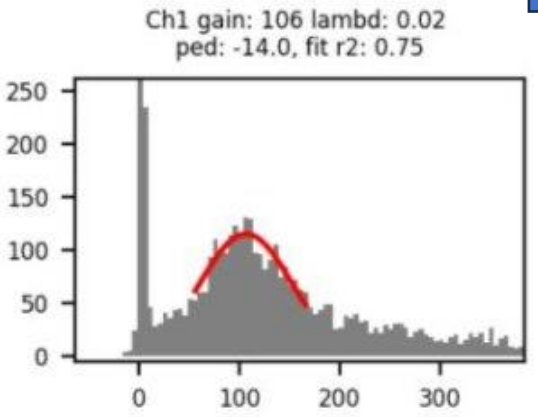
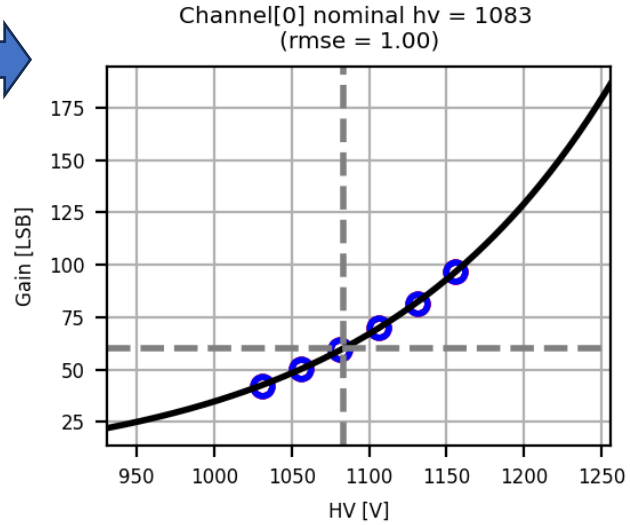
Procedure steps :

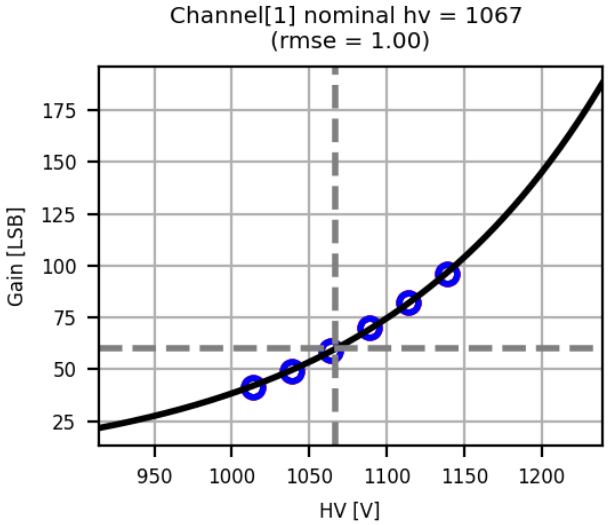
- Set fixed HV for all PMTs
- Flash all diffused LEDs in sequence and record waveforms
- Calculate amplitudes -> histograms -> Gaussian fit
- Fit mean values with an exponential function
- Calculate nominal HV for gain = 60 LSB
- **Achieved a dynamic range from 1 to 34 Photoelectrons**





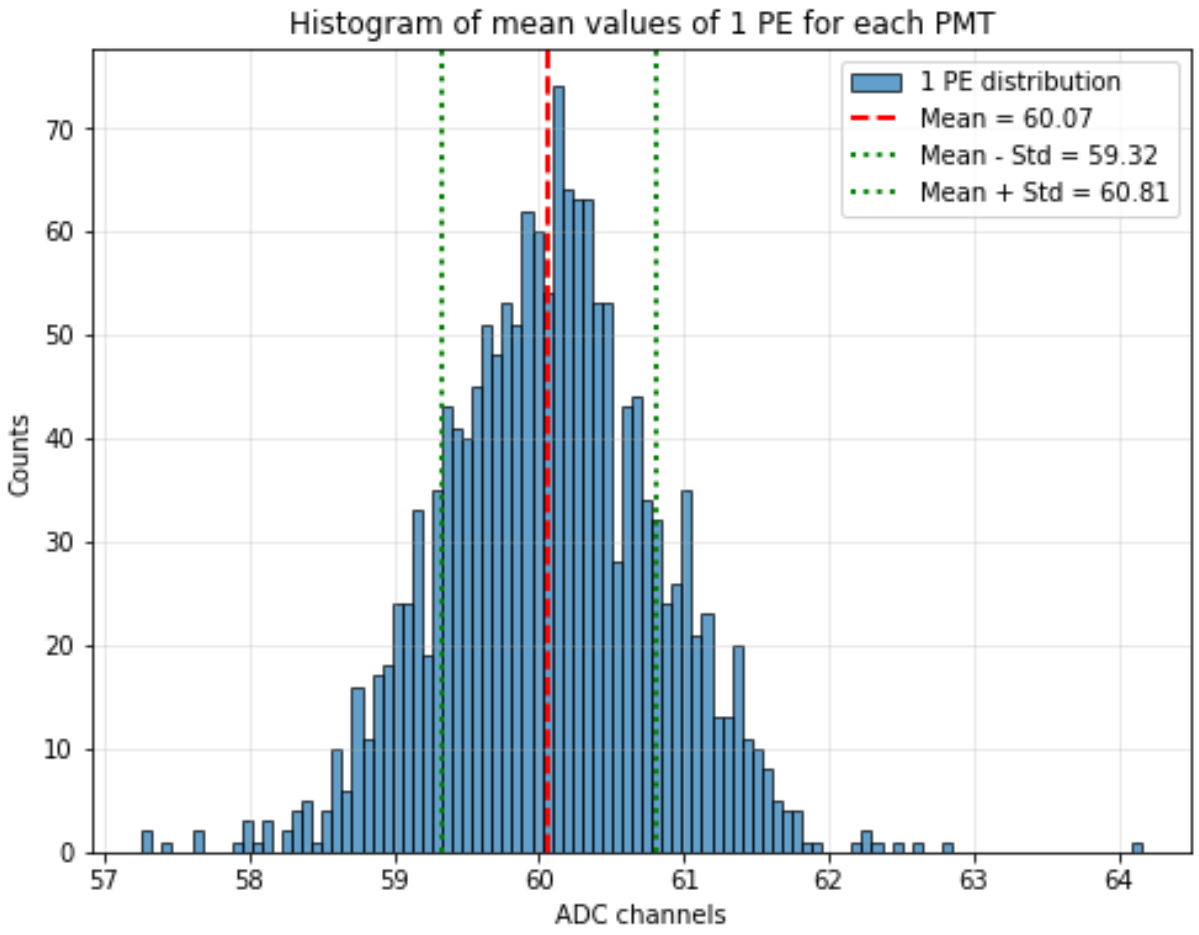


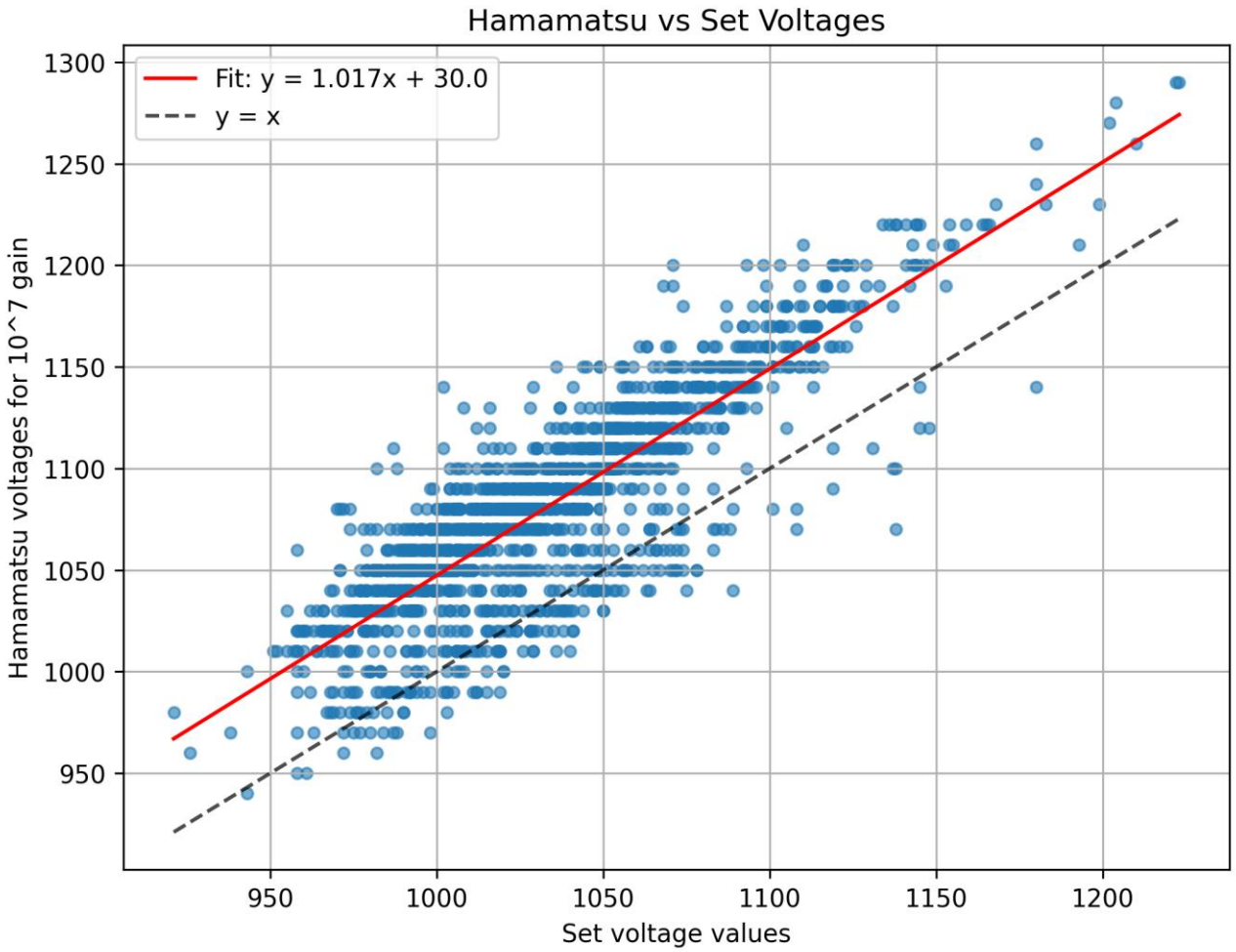




HV EQ results

- All 1 PE amplitudes values centred around 60 LSB
- Mean: **60.07 LSB**
- Standard Deviation: **0.74 LSB**





Timing calibration

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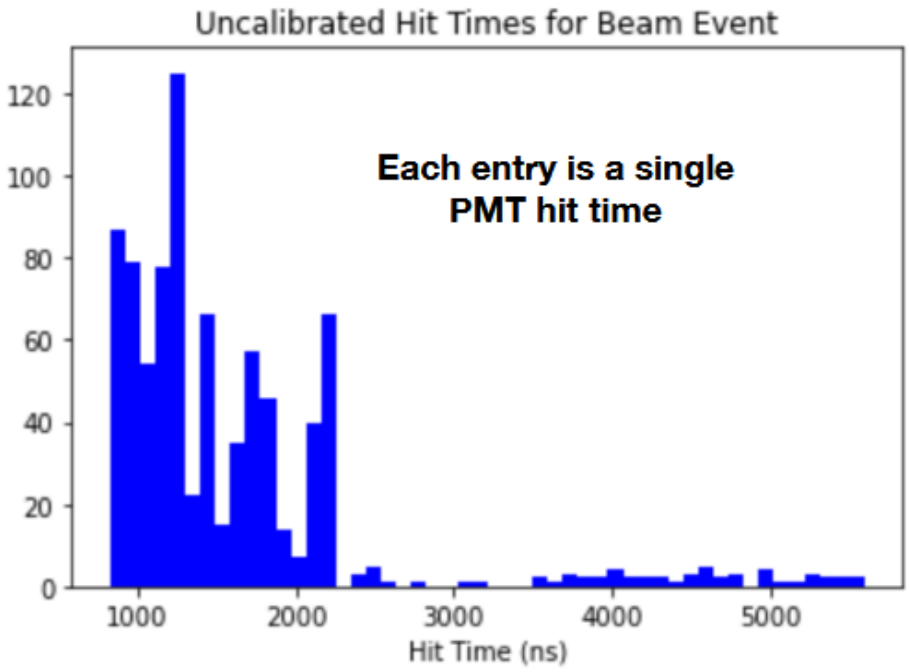
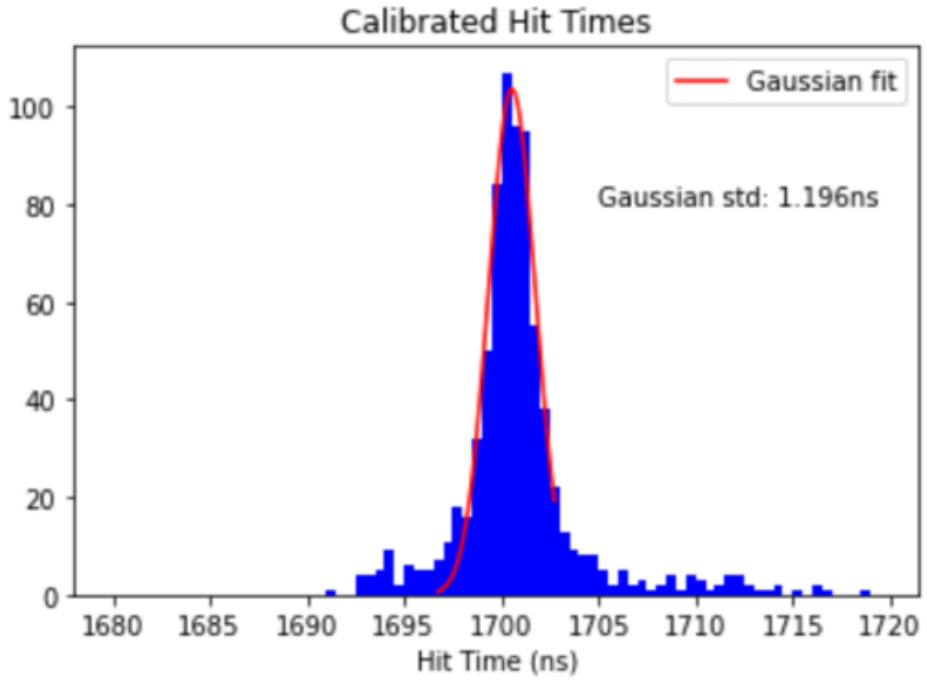
- Data from the LED is also used to apply timing calibration
- We use a digital constant fraction discriminator to get PMT hit times; build a linear system to solve for PMT/electronics delays and produce timing constants for each channel
- After applying constants, the event hit-time is around σ ≈ 1 ns
- **Timing constants are stable to < 1 ns** over days/weeks

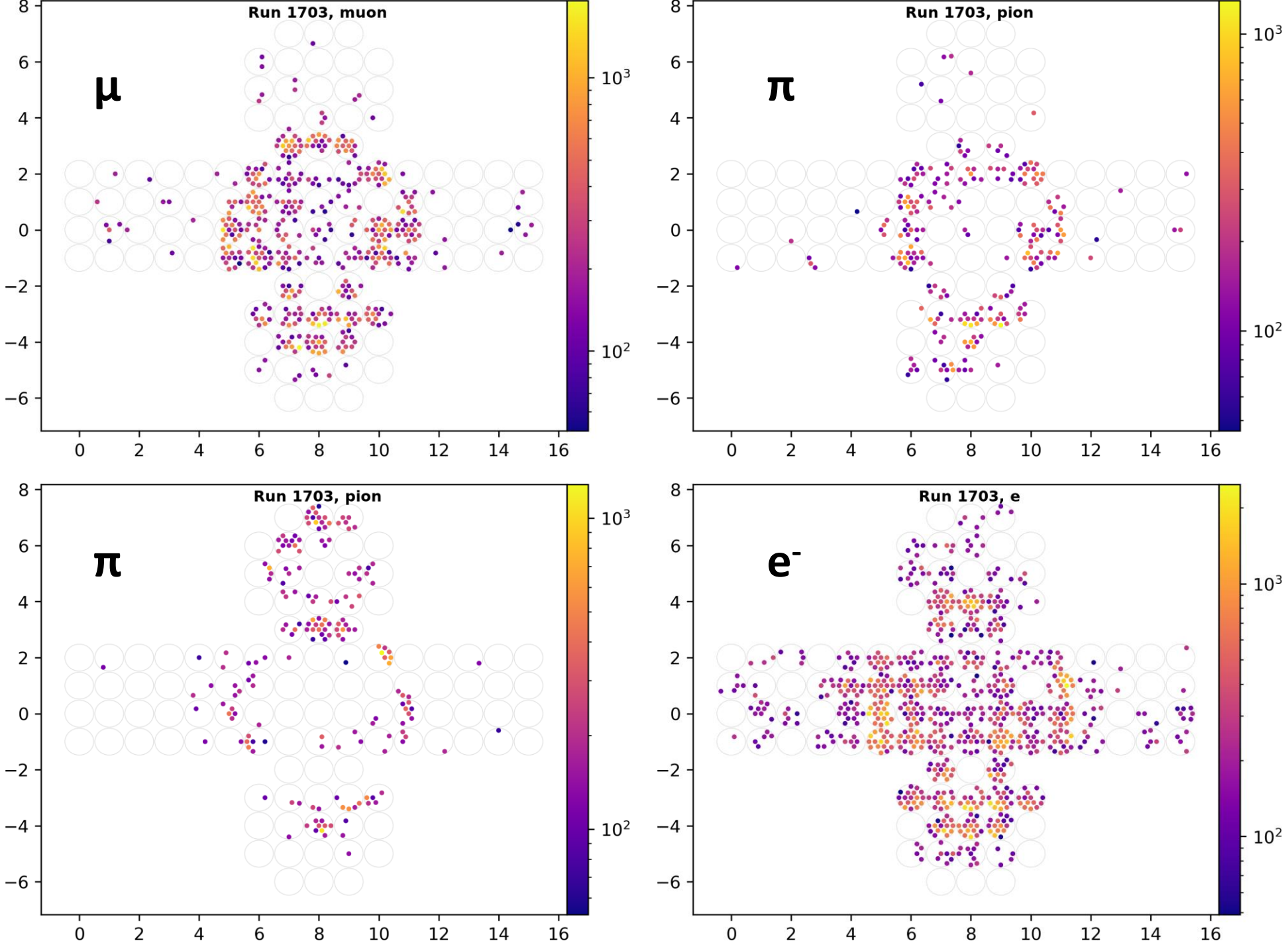


Calibration constants applied



WCTE results

- Examples of events after gain and time calibration
- Plots are the accumulated number of counts for each channel in the event



Summary

- WCTE was the opportunity to test mPMTs in real experiment conditions
  - Validated mPMTs under beam running conditions
  - Self-equalised gains and achieve ~1 ns timing
  - Made a significant step forward in the development of DAQ for IWCD

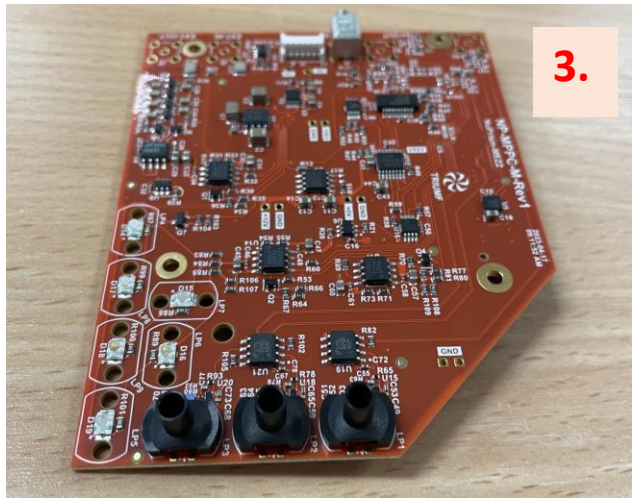
- Construction of IWCD has already started. Full production of mPMTs will begin in 2026.

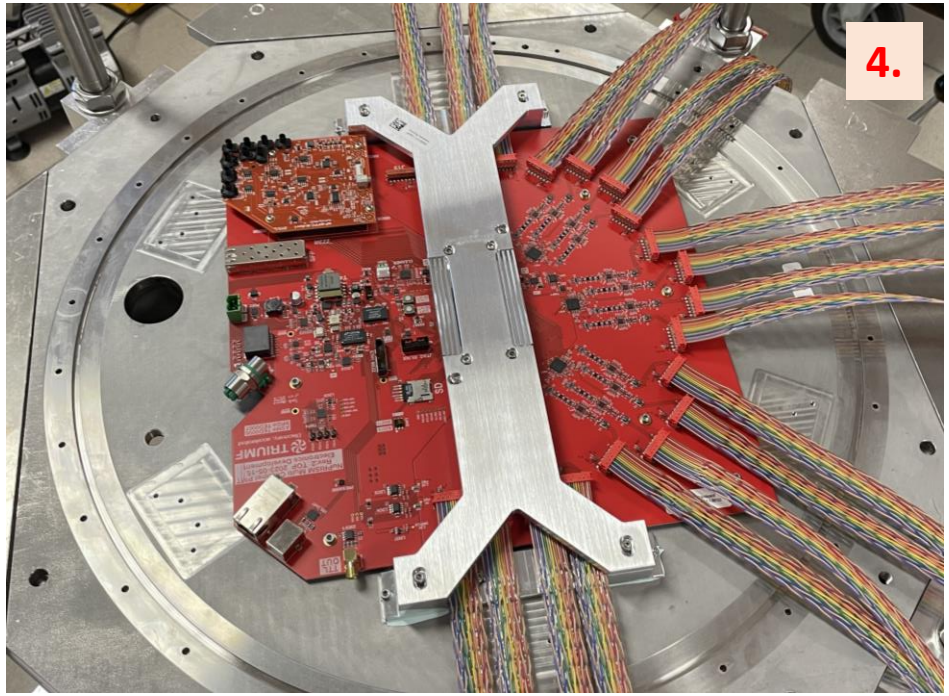
Thank You for Your attention

BACKUP

mPMT 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





Hamamatsu R14374 PMT
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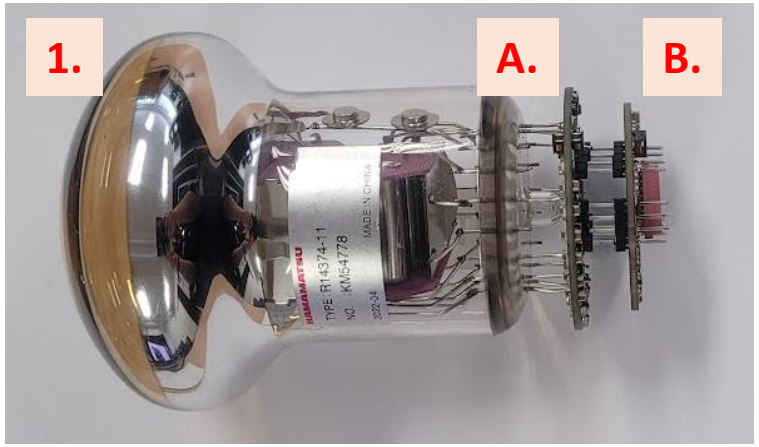
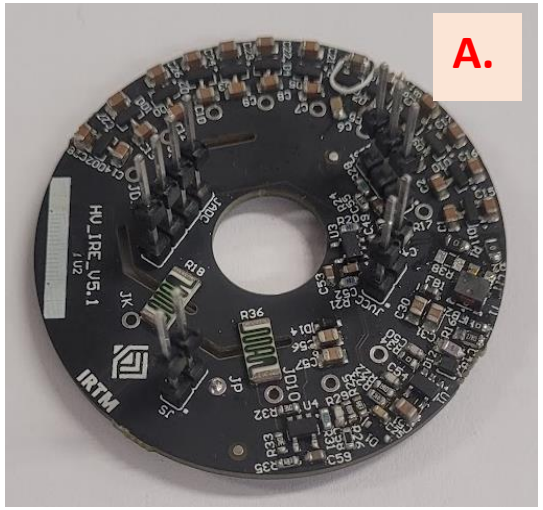
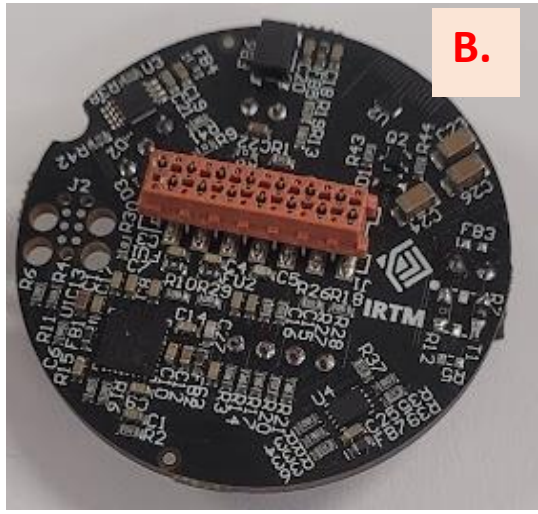


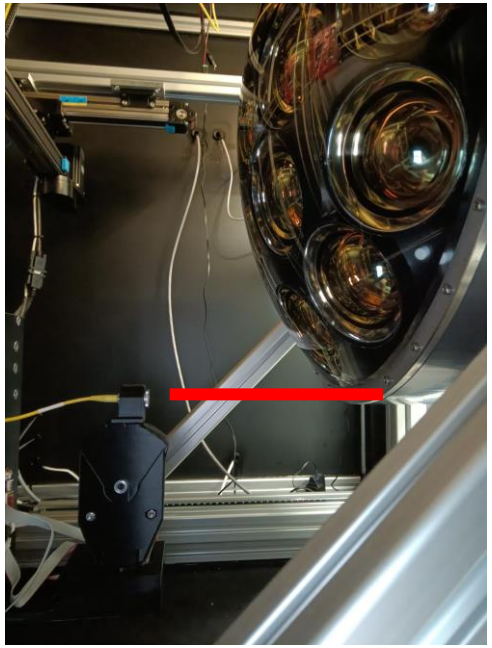


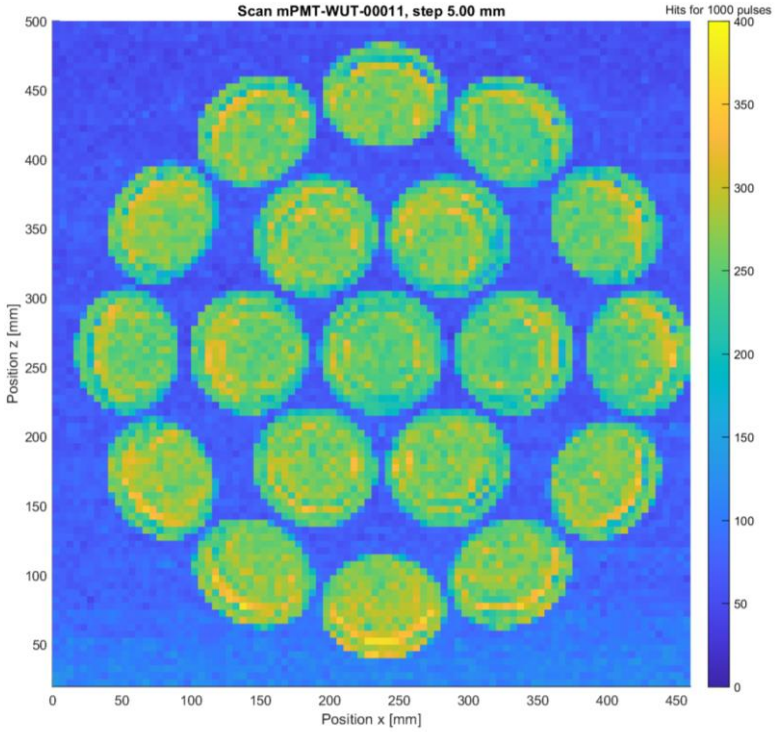


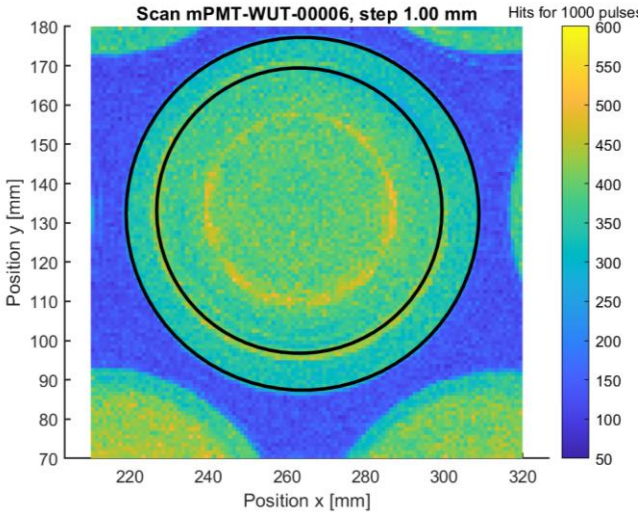
Multi-PMT scanning

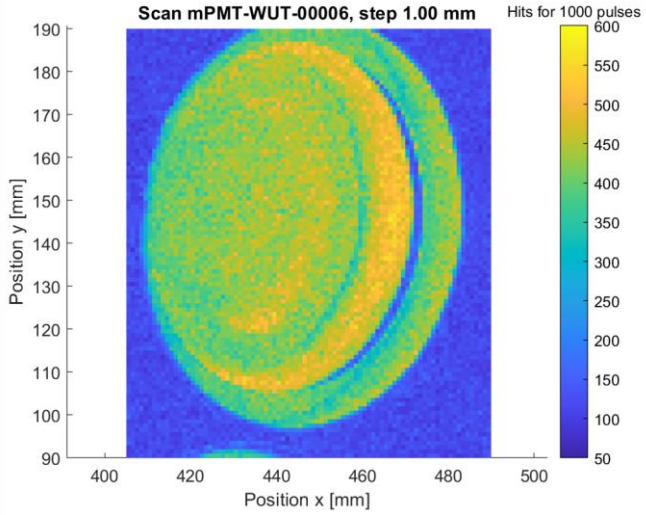
Tester for Multi-PMT with 3-axis robot:

- Laser scans with programable step size
- Picosecond laser 405 nm
- Collimation < 1mm spot
- 1000 waveforms/position
- Scan speed 7 steps/minute
- Full scan time: 23 hours









LED DAC for HV scan

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Hyper-Kamiokande

- To calculate 1PE response, we need to set LED power at correct value, not too low (need proper statistics), not too high (multi-PE response)

For $\lambda = 0.05$, the probabilities are:

- $P(X=0) \approx 0.9512$
- $P(X=1) \approx 0.0476$
- $P(X=2) \approx 0.00119$

The ratio $\frac{P(X=2)}{P(X=1)} \times 100$ is 2.5%.

```
%%%                          %%%
%                            %
%   mPMT5 LED2   LED1        %
%                mPMT4       %
%            LED3            %
%                mPMT37      %
%                            %
%%%                          %%%
```

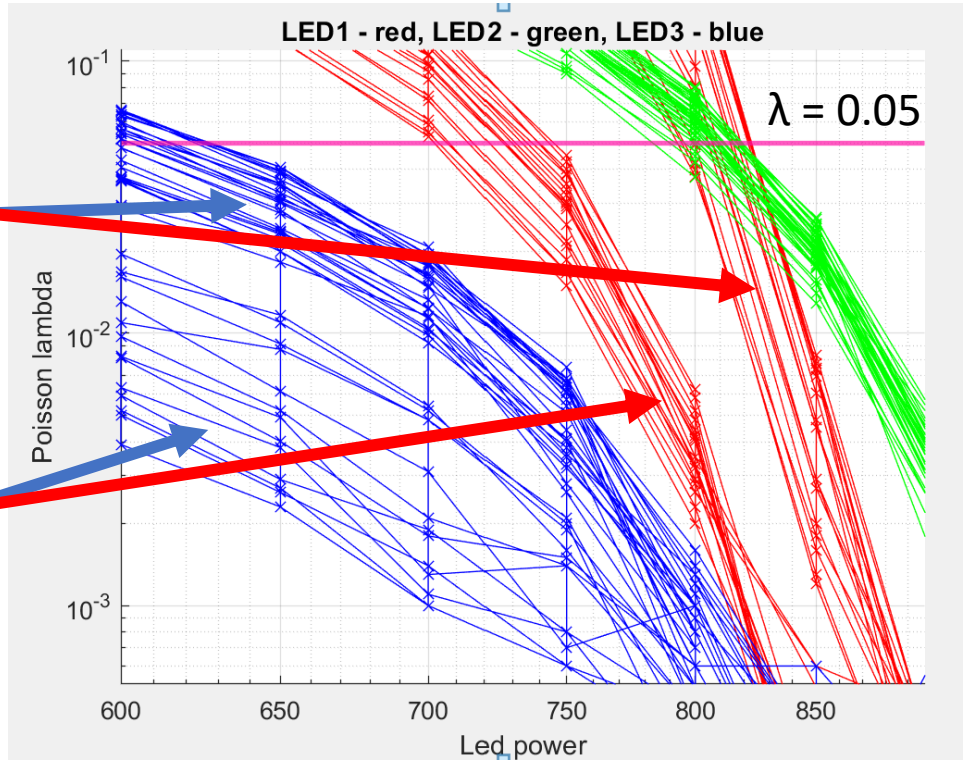
LED 1 (470nm)
Coordinate id: 0
Collimator type: 30deg

LED 2 (405nm)
Coordinate id: 1
Collimator type: 30deg

LED 3 (365nm)
Coordinate id: 2
Collimator type: Diffuser

Direct photons

Non-direct photons



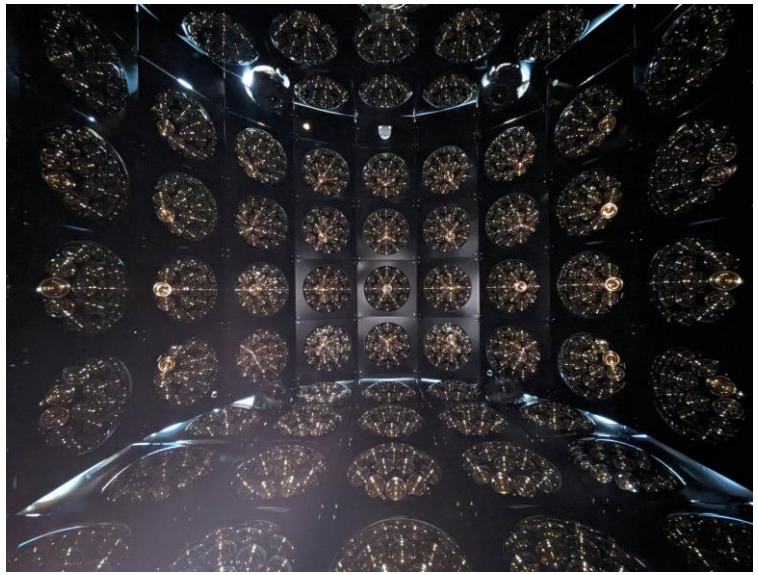
- Procedure
  - Flash diffused LEDs on mPMT-4, mPMT-5 and mPMT-37
  - LED power 600:50:900
  - Calculate Poisson λ
  - Determine DAC for LEDs for λ < 0.05
- Result: DAC 850 for LED 1 and 2, DAC 700 for LED 3 (UV)

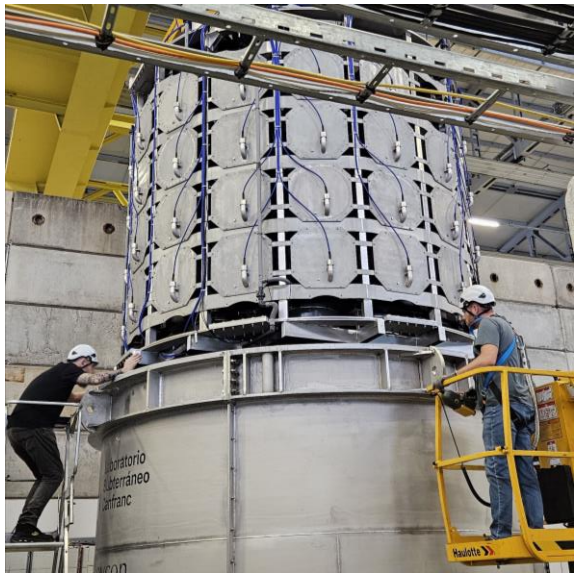
LED flashing legend:
mPMT-4 LED1 (470 nm) red
mPMT-5 LED2 (405 nm) green
mPMT-37 LED3 (365 nm) blue

WCTE assembly

Warsaw University of Technology

Hyper-Kamiokande





WCTE Beamline monitor

Suite of beamline monitor detectors:

Aerogel Cherenkov

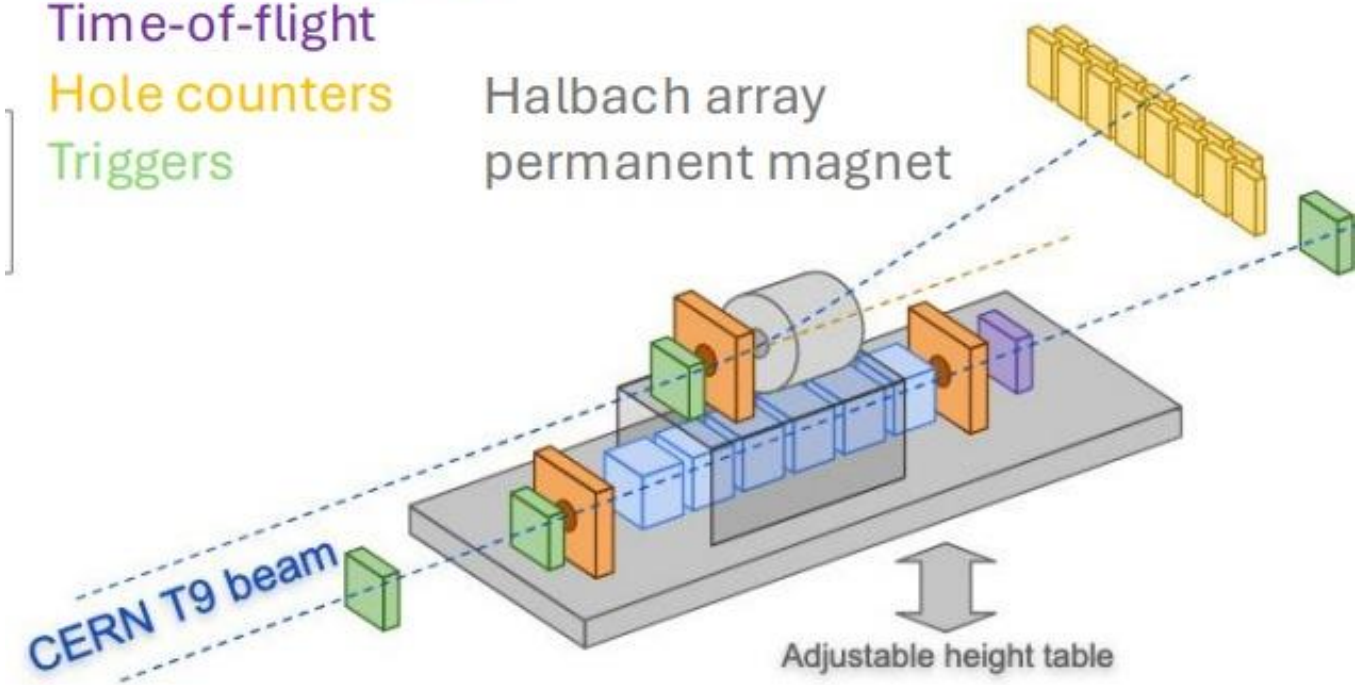
Time-of-flight

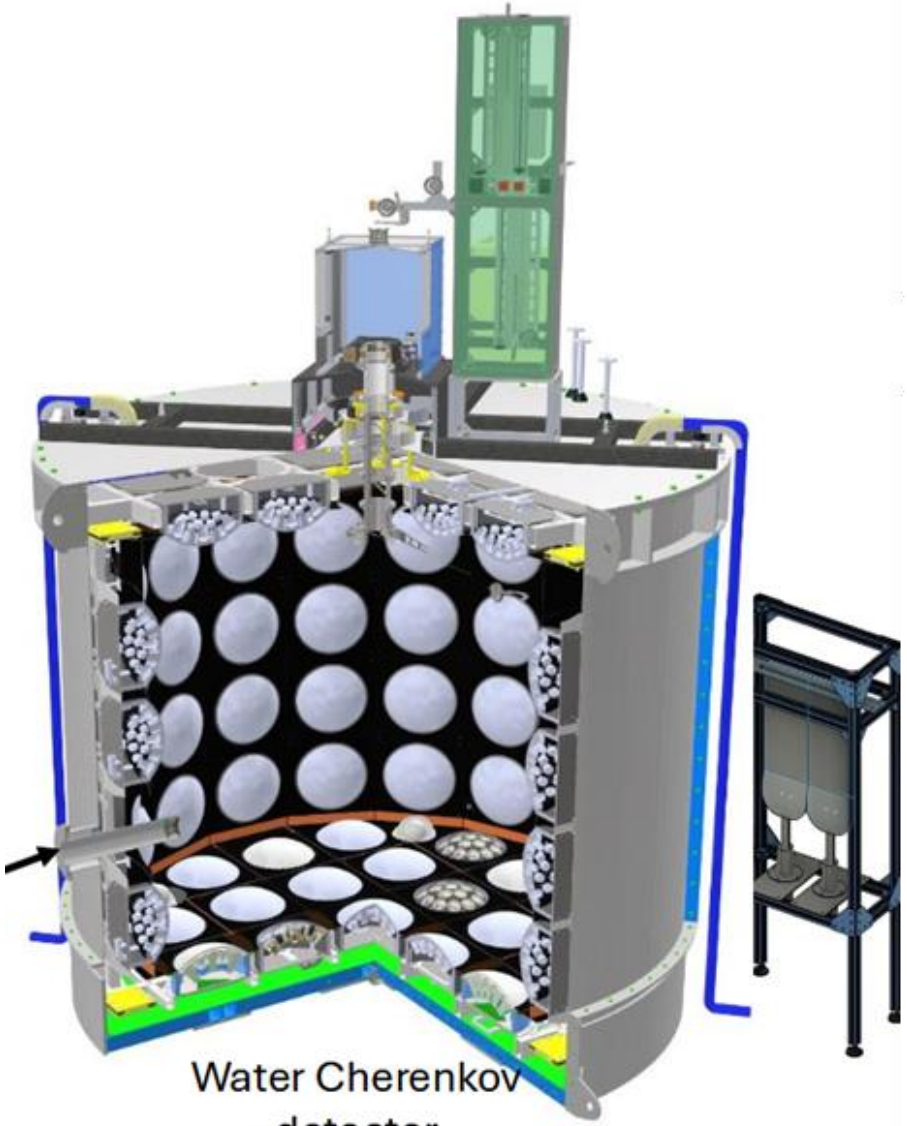
Hole counters

Triggers

Hodoscope

Halbach array permanent magnet





Water Cherenkov detector

Hardware trigger SYNC and MCC

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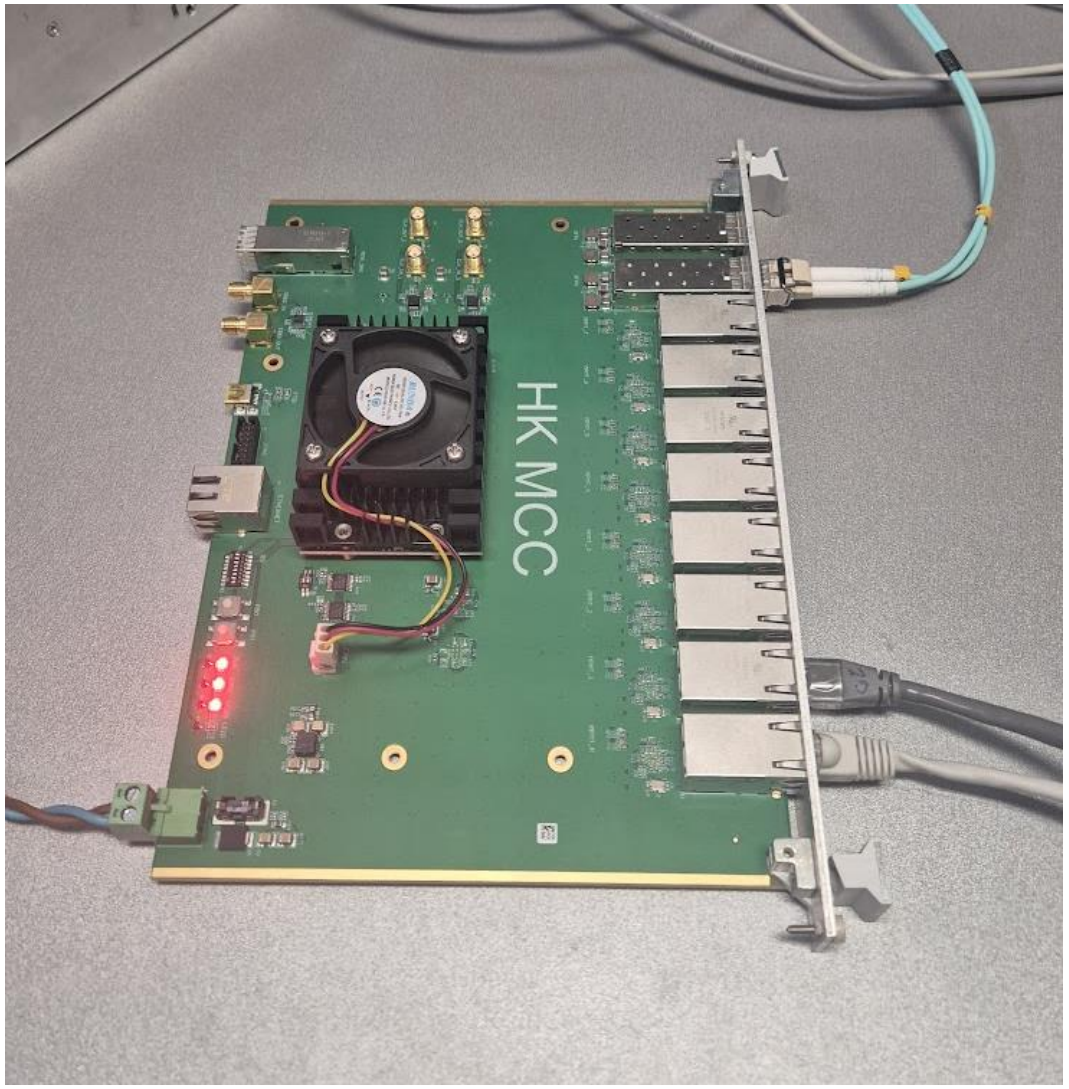
Hyper-Kamiokande



MCC layout

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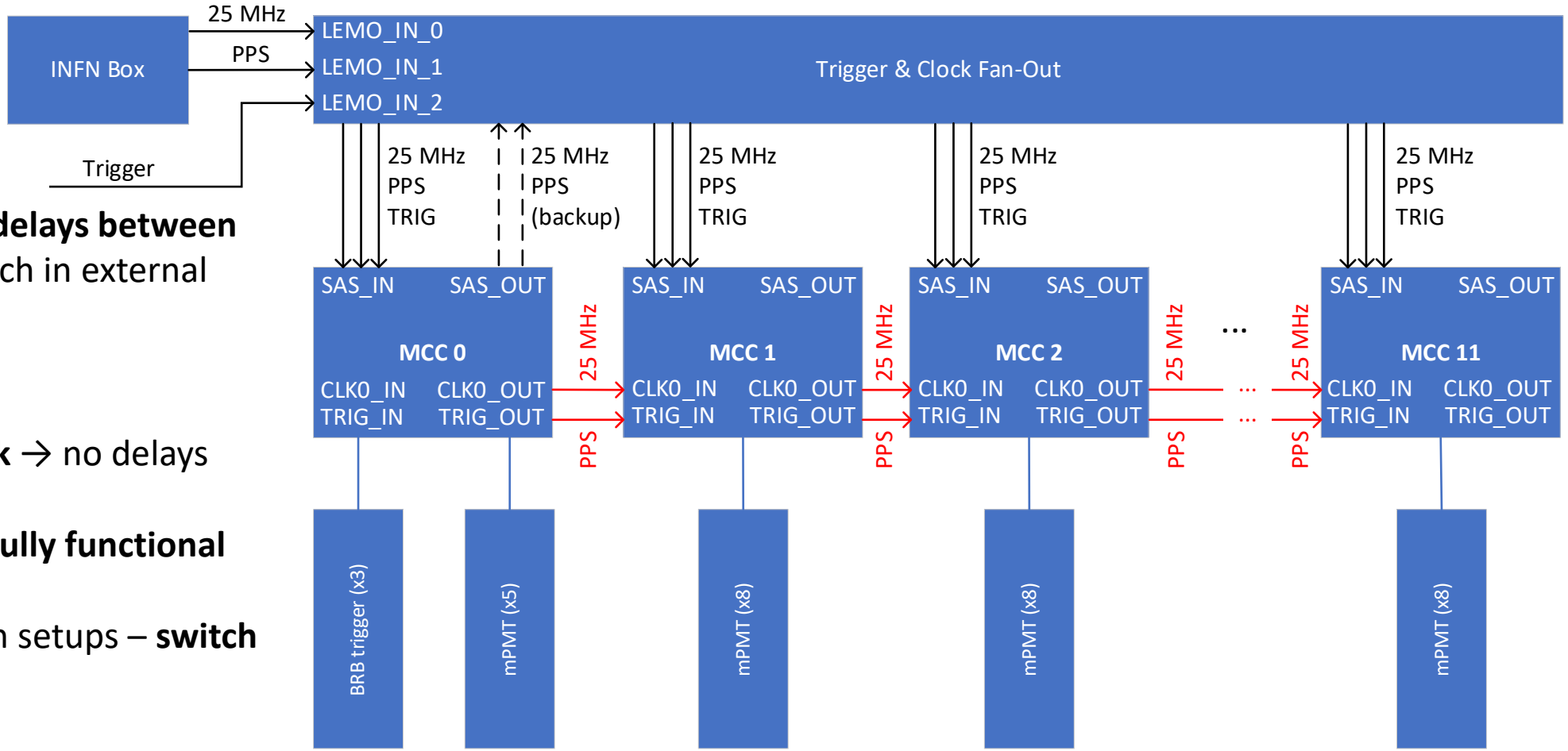
Hyper-Kamiokande

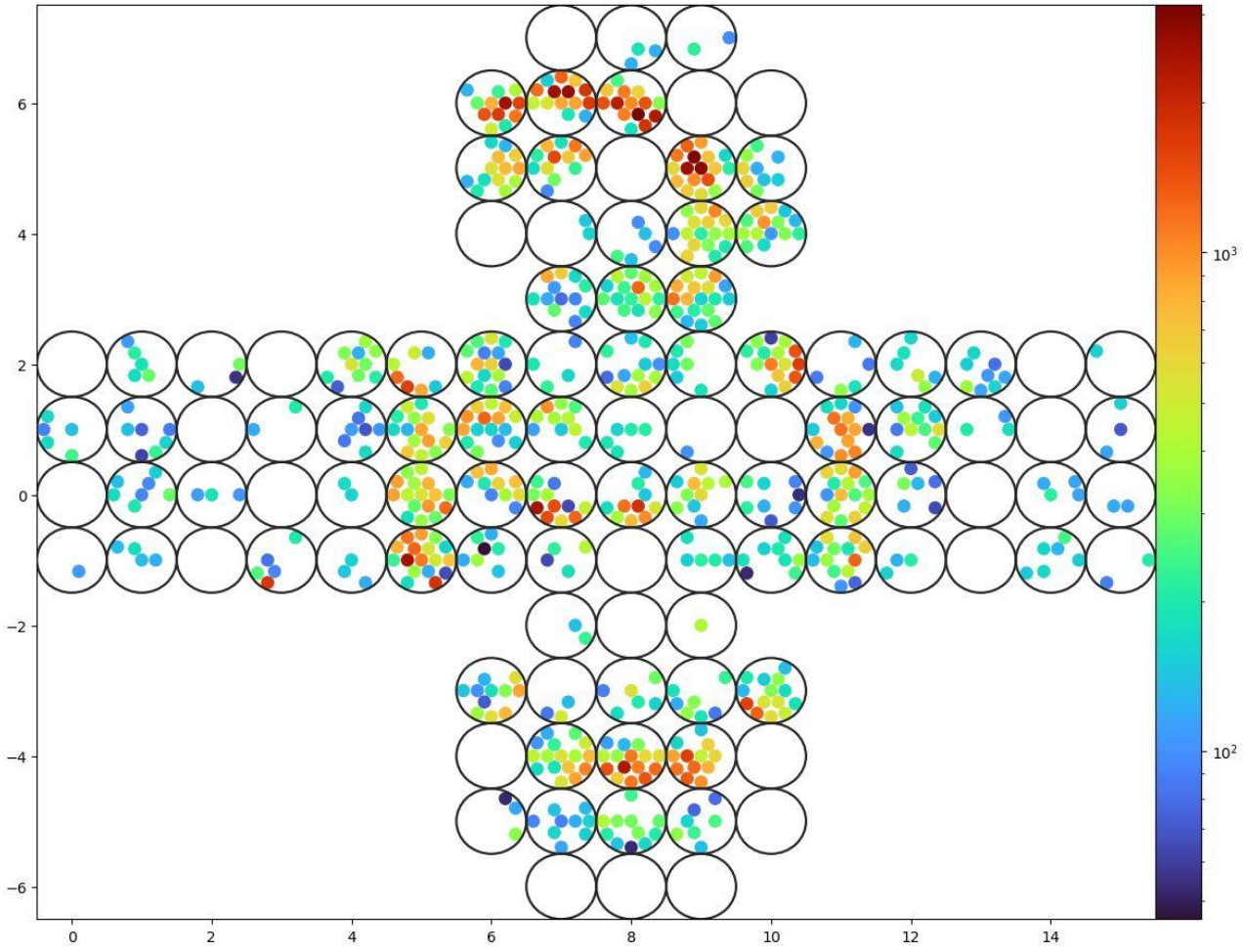
- **Red** = previous setup
- **Black** = updated setup

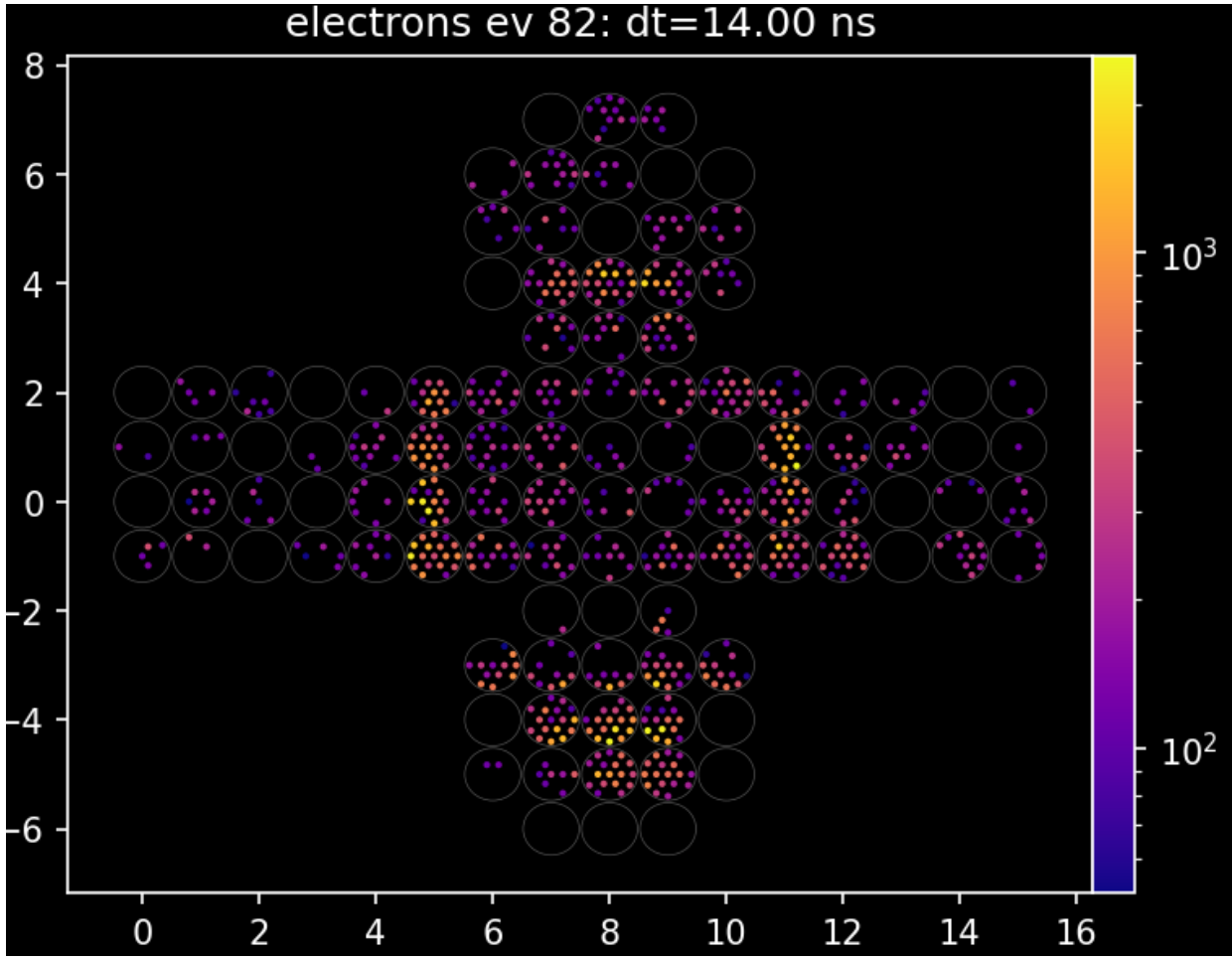


- Previous setup caused **delays between MCCs** → timing mismatch in external trigger mode
- New setup uses **trigger board** with **shared clock** → no delays
- **External trigger mode fully functional**
- Firmware supports both setups – **switch via flag**
- **All connections remain in place**

2 TON
COFFING
KIMTECH

Pions scattering and electrons

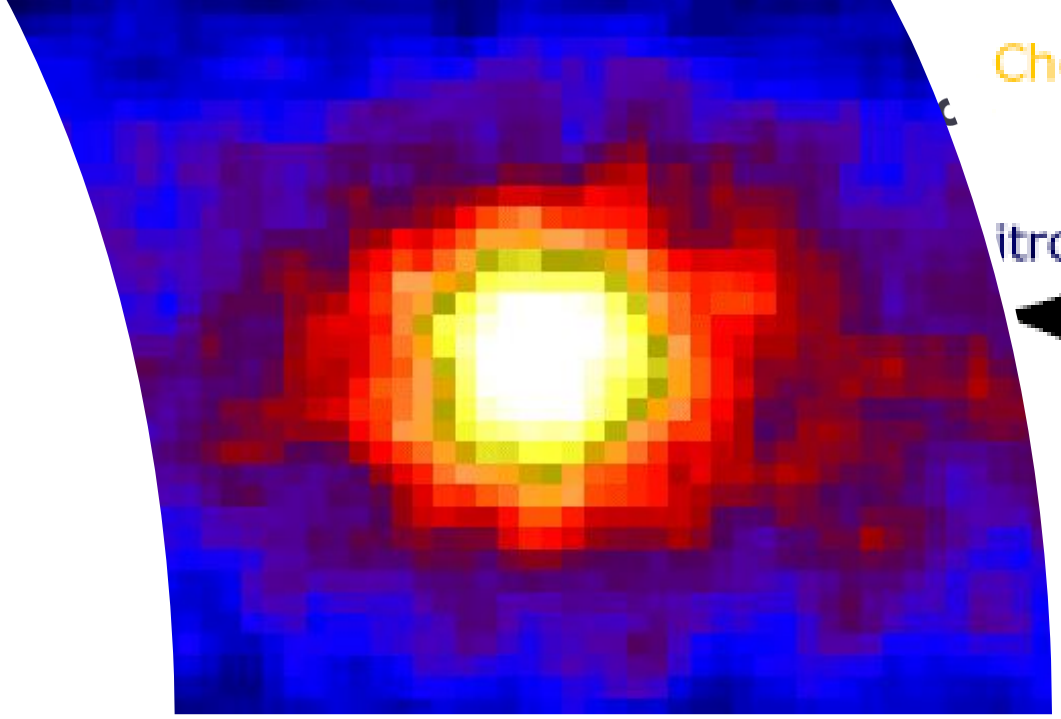


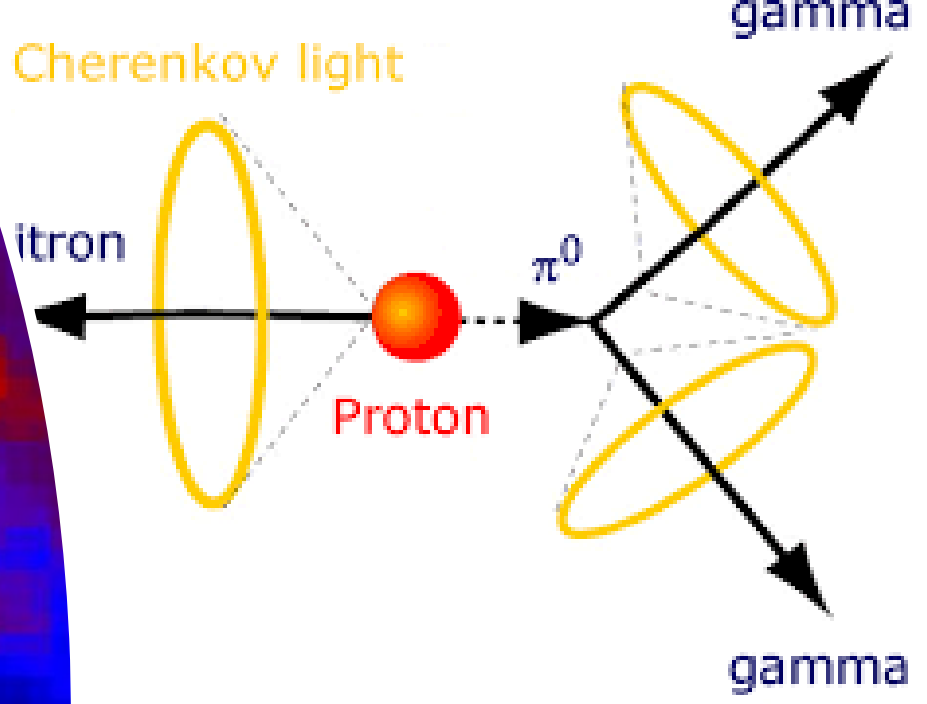


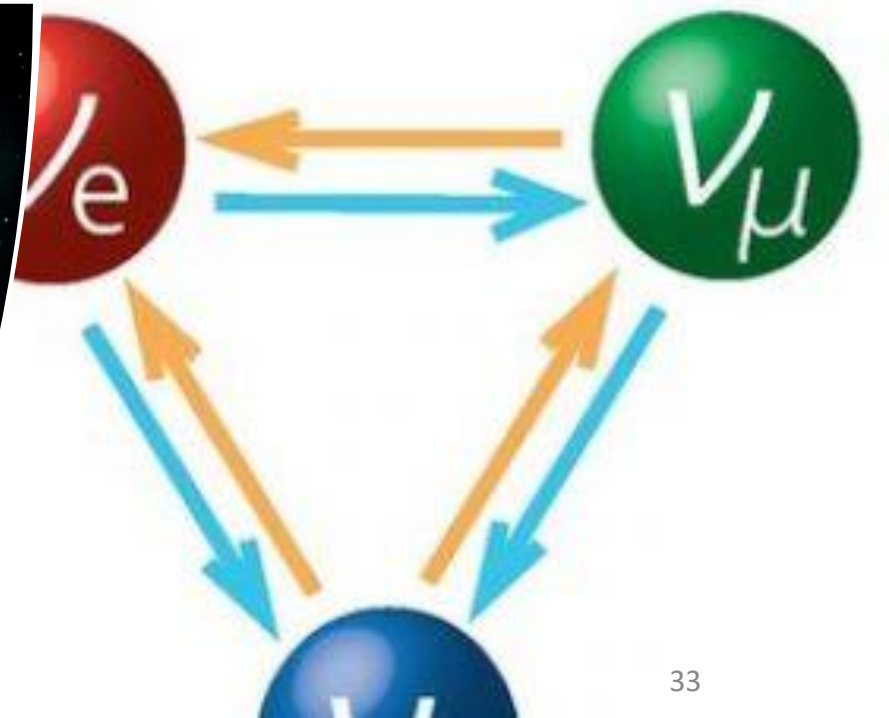
Why Hyper-Kamiokande

Main research tasks of Hyper-Kamiokande:

- Neutrino oscillation
- Study of CP-violation
- Study of cosmic neutrinos
- Proton decay search
- Dark matter search







Source:
https://www-sk.icrr.u-tokyo.ac.jp/sk/sk/pdecay-e.html
NASA, ESA, J. Hester, A. Loll (ASU)
http://www.hyper-k.org/en/