mPMT electronics and DAQ system in WCTE operation

Michał Nurek
Warsaw University of Technology
For the WCTE and Hyper-Kamiokande Collaborations

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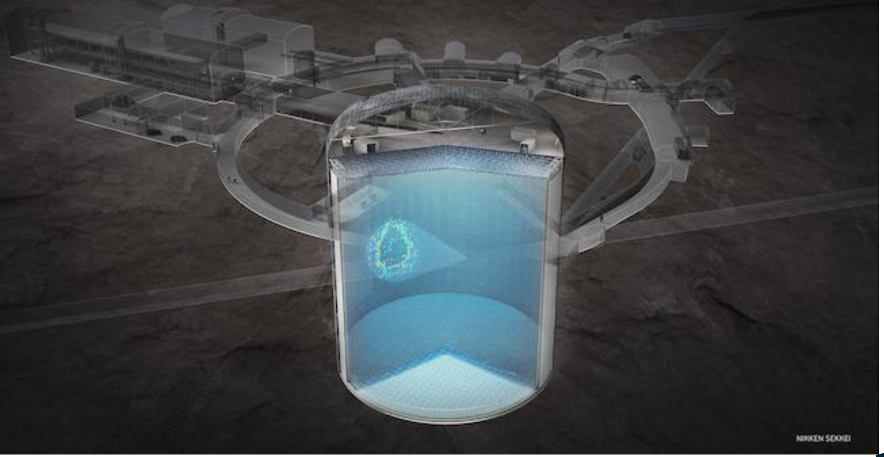
Hyper-Kamiokande experiment

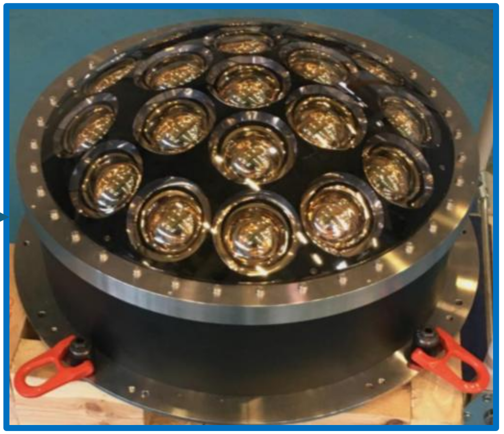


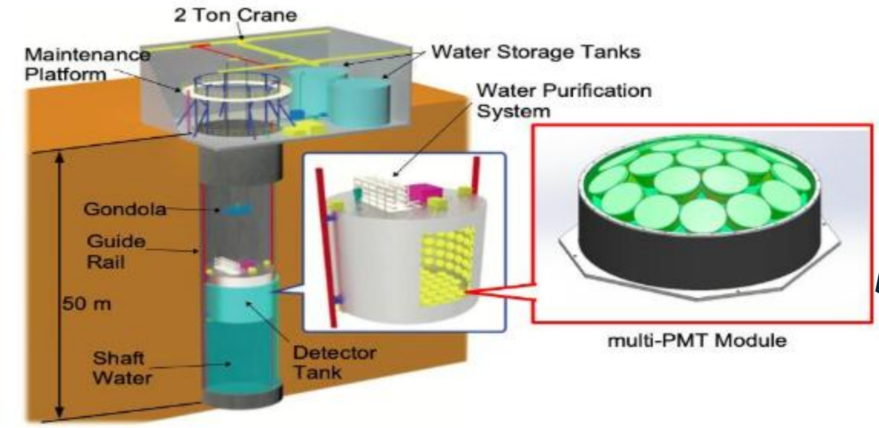
Next-generation underground water Cherenkov long baseline neutrino experiment

- Long-baseline neutrino program
  - J-PARC neutrino beam
    -> Near detectors (ND280)
    -> Intermediate Water Cherenkov Detector (IWCD)
    -> Hyper-Kamiokande far detector

Hyper-Kamiokande far detector

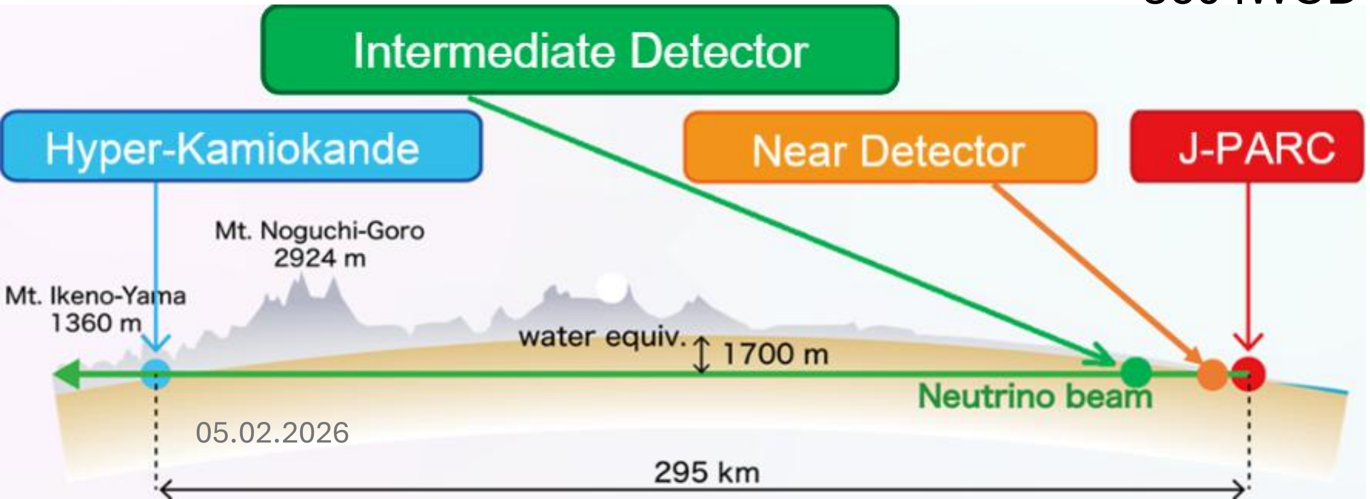
- 71 m height, 68 m diameter, ~258 kt
- 20k 20” photomultipliers
- ~800 far detector style mPMTs





Intermediate Water Cherenkov Detector (IWCD)

- Movable 10 m height, 8.8 m diameter, ~600 t
- ~360 IWCD style mPMTs



PROPER TEST FOR IWCD MULTI-PMT BASED SYSTEM

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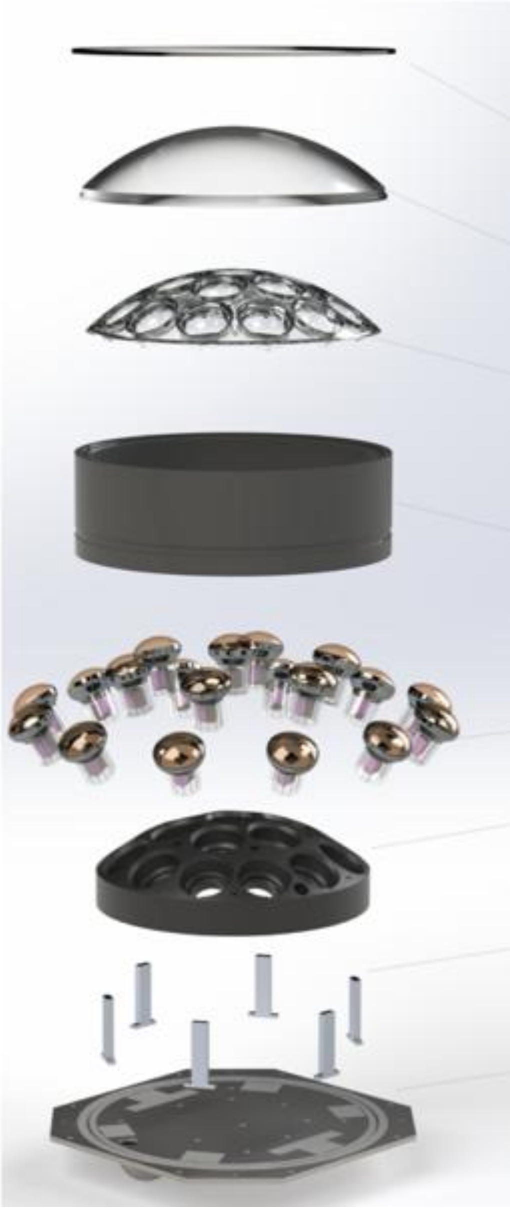
WATER CHERENKOV TEST EXPERIMENT

Water Cherenkov Test Experiment (WCTE)



IWCD style mPMT

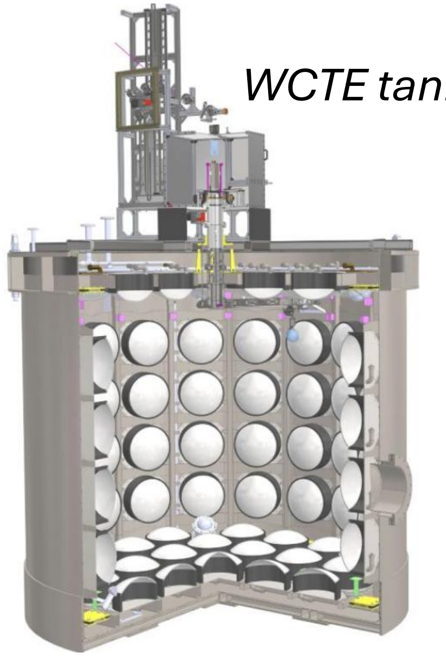
Specs

- Beam line experiment at T9 area – CERN
- 3.6 m height, 3.8 m diameter, ~41 t
- 97 mPMT modules
  - 93 IWCD style mPMTs
  - 4 far detector style mPMTs
- ~1700 channels in total
- DAQ developed for the entire Hyper-K experiment
- Operation: 10.2024 – 06.2025

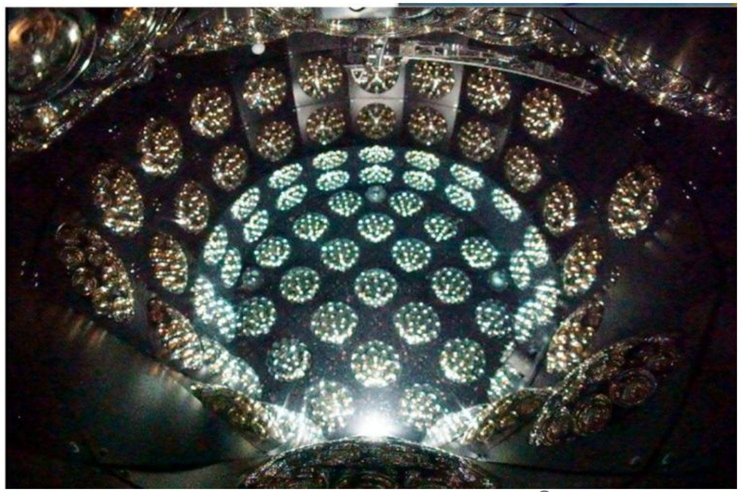
Goals

- IWCD **photodetection**, **calibration**, **water** (also Gd compatibility), **DAQ** system prototype
  - Tests mPMT granularity, event reconstruction, and calibration under beam-like conditions
  - WCTE delivers beam-based control samples to constrain detector & interaction systematics relevant for Hyper-K CP violation sensitivity
- Physics studies
  - e/μ separation, π^0-related e/γ discrimination, water-target response; path to ν/ν̄ tagging (with Gd)
- Outcome
  - Better near -> far extrapolation and smaller Gaussian uncertainties

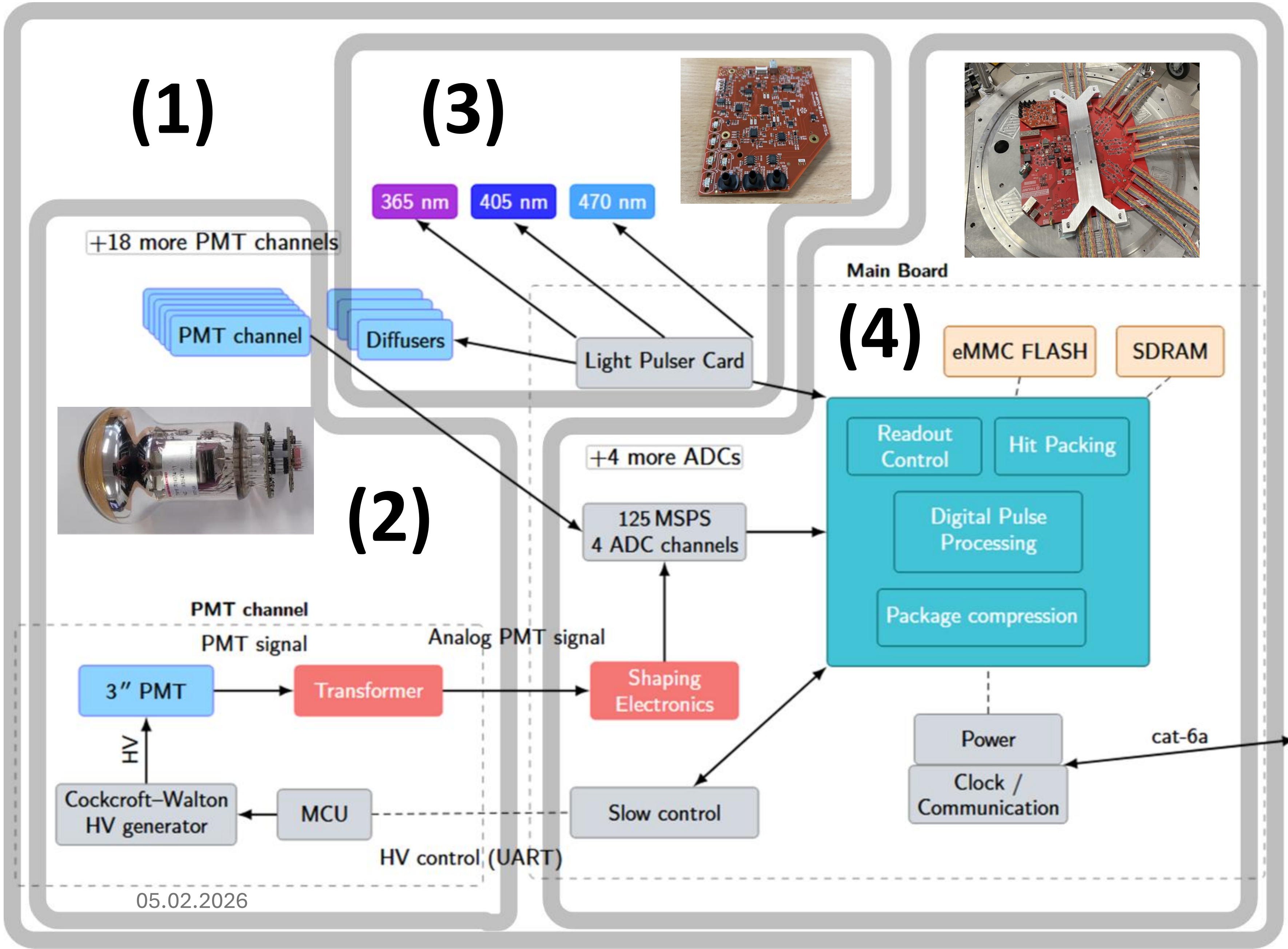
WCTE tank



WCTE tank inside



WCTE photodetection system

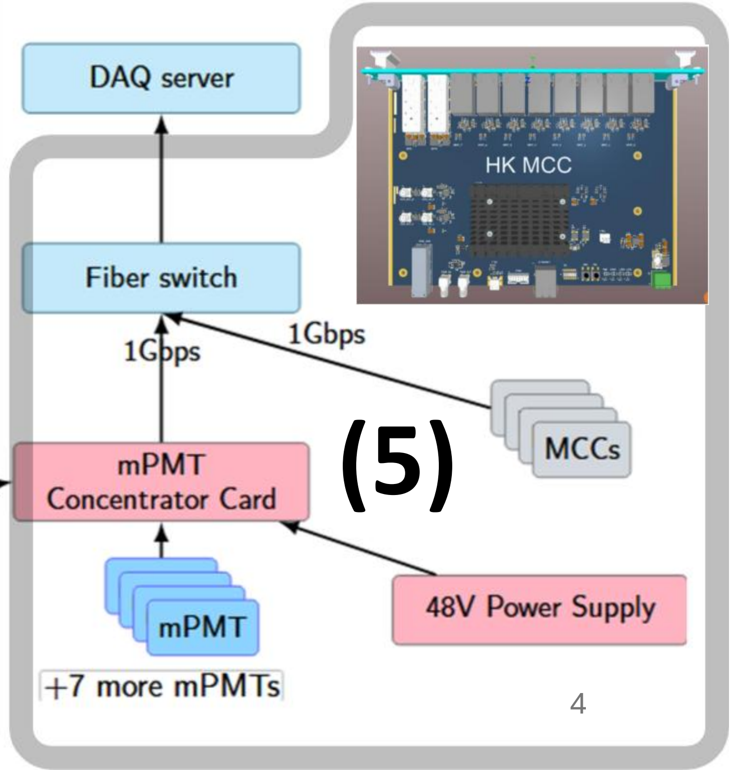


MAIN COMPONENTS

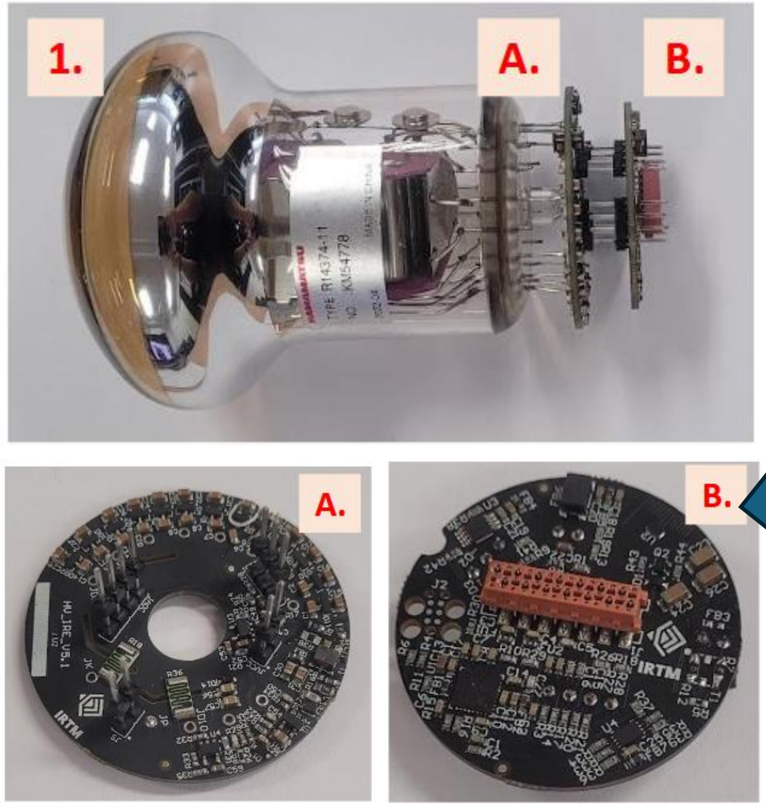
(1) mPMT module

- **(2) PMT + HV board + front-end board**
- **(3) Light Pulser Card board**
- **(4) Mainboard**

(5) mPMT Concentrator Card



mPMT module
PMT + HV + front-end board

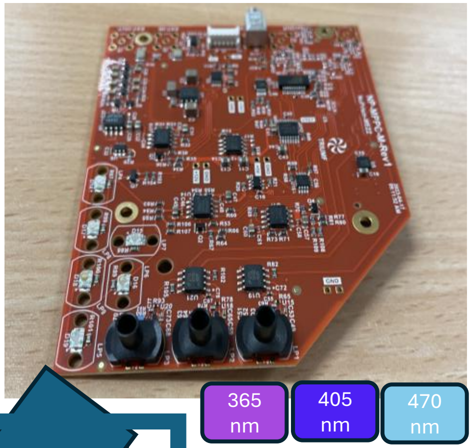


1. PMT A. HV board B. front-end board

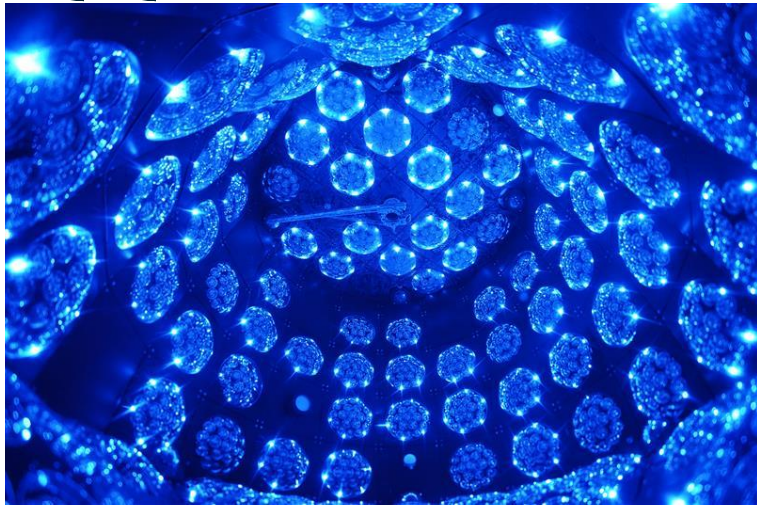
Hamamatsu R14374 PMT

- 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 1/s

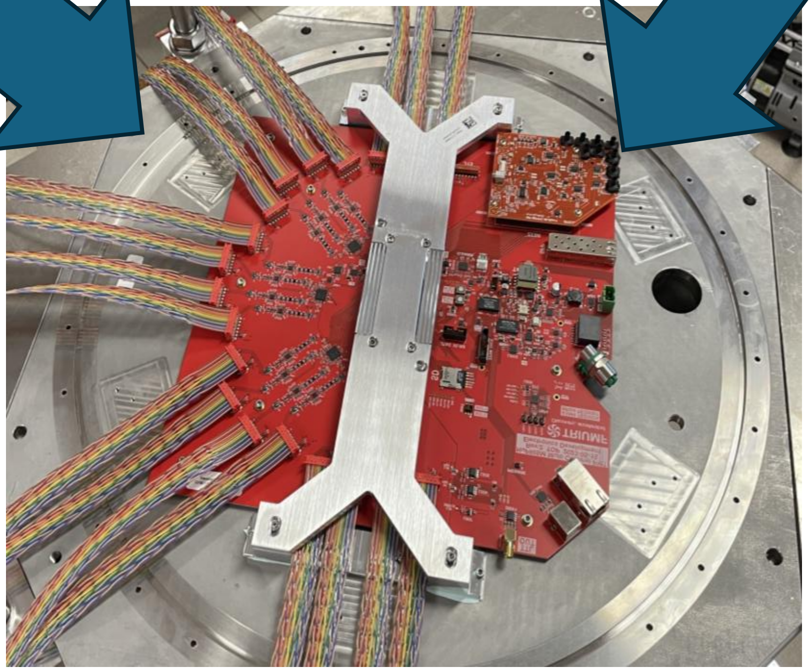
mPMT module
Light Pulser Card (LPC)



- 3 fast LEDs (365/405/470 nm)
  - 2 colimated, 1 diffused
  - Timing calibration
  - Gain equalisation,
  - Monitoring
- 6 slow LEDs
  - All diffused
- MCX connectors
  - Clock/trigger input/output for debugging purposes

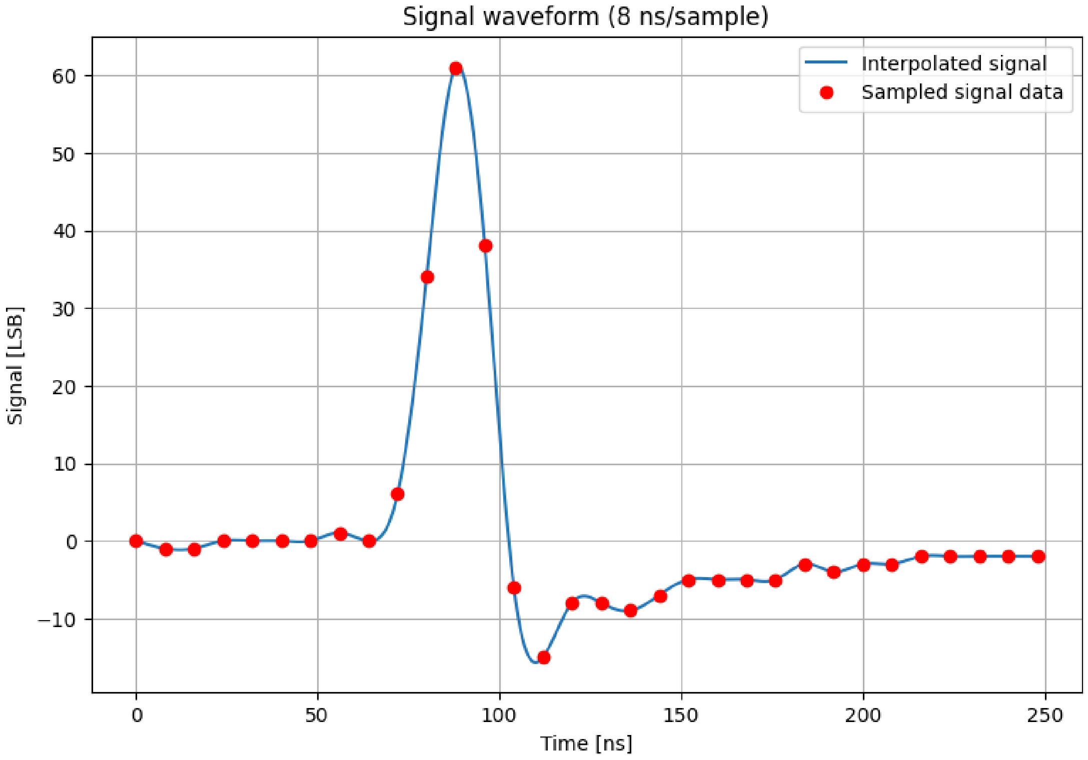


mPMT module
mainboard

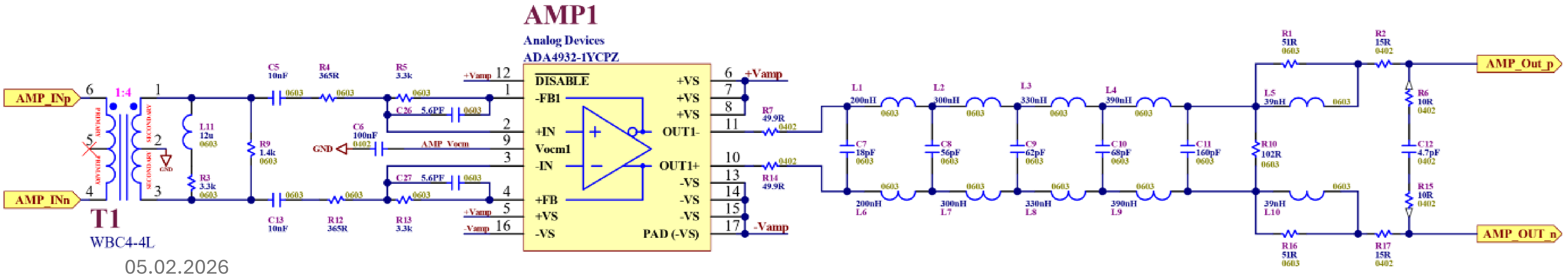


mPMT mainboard - analog processing (shaping circuit)

- 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

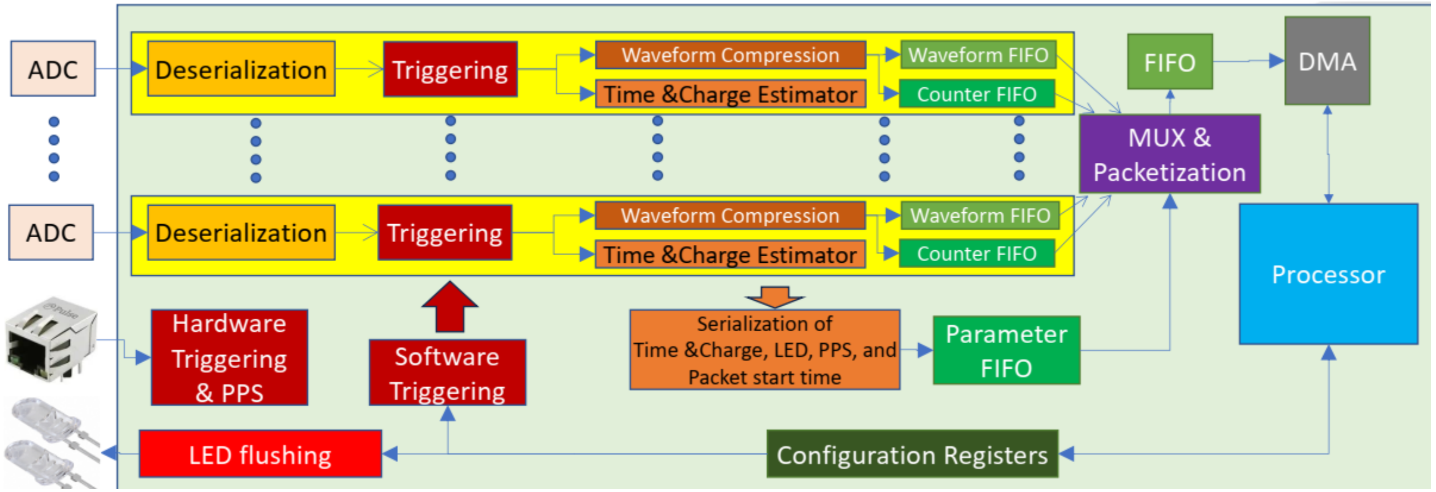


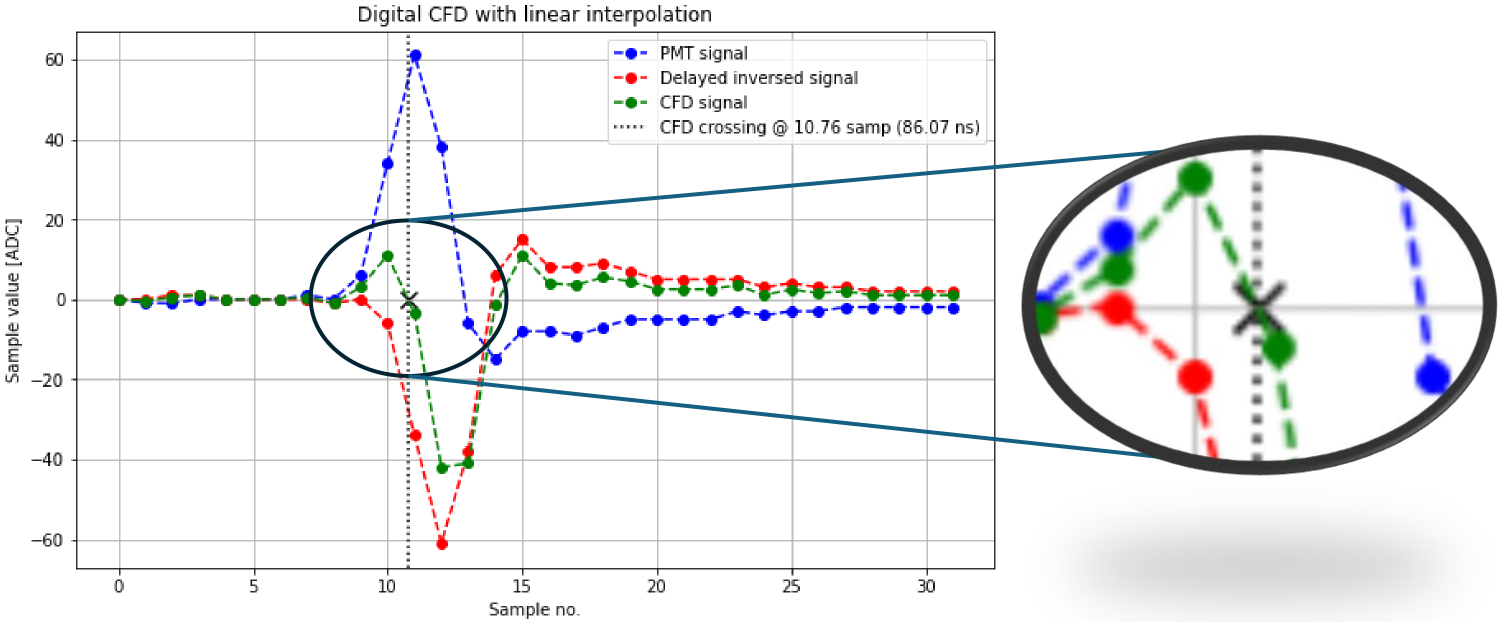
PMT signal shaping circuit



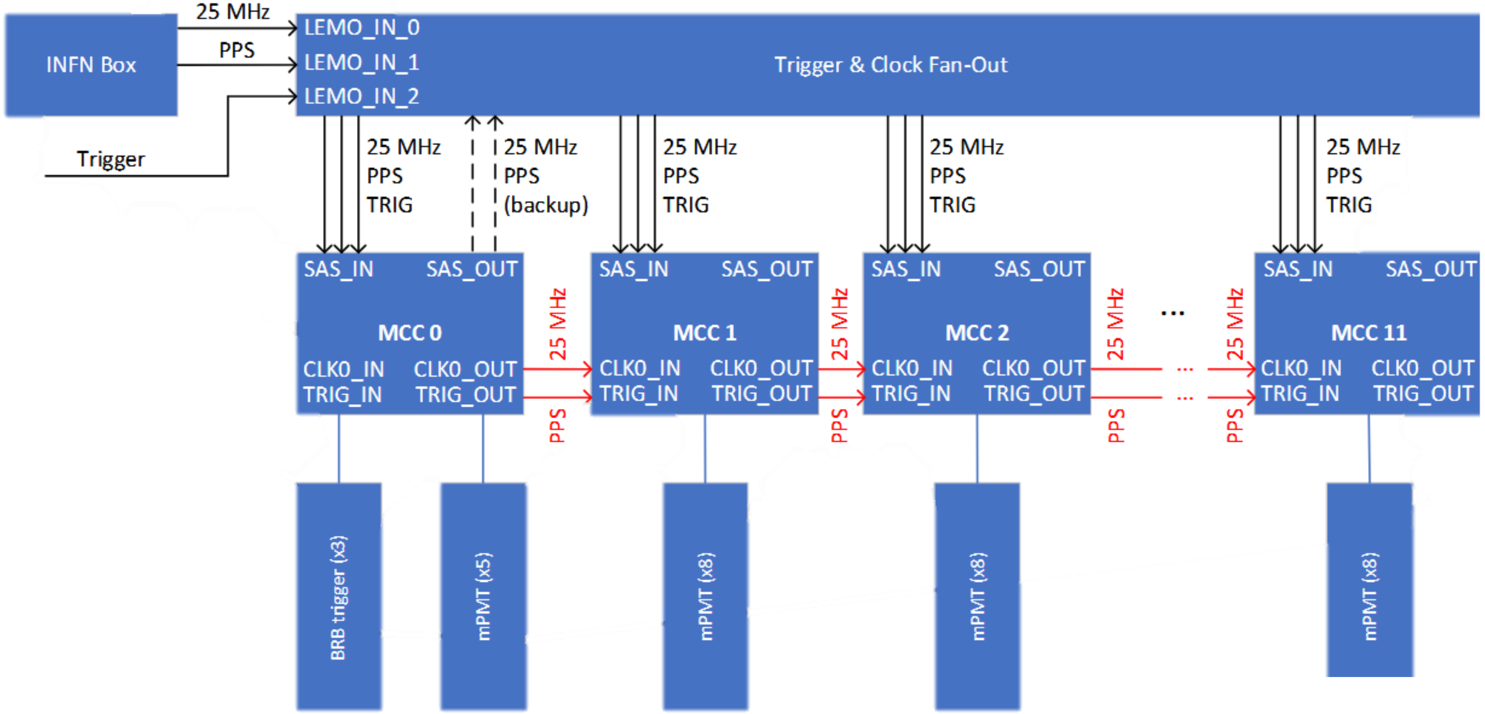
mPMT mainboard - digital signal processing (FPGA algorithms)

- AMD Zynq Ultrascale+ MPSoC
- ADC – 125 MSPS 4 channels
- Triggering modes
  - Software trigger
  - External trigger
  - Self trigger
    - Amplitude exceeds threshold
    - Integral of seven samples exceeds 2x threshold
    - Local peak identified
    - Sufficient interval after previous pulse
- Parameter extraction
  - Time
    - Constant Fraction Discriminator + correction
  - Charge
    - Integral of the pulse signal
  - Quality factor
    - Sum of absolute differences (8 samples) (signal – reference)





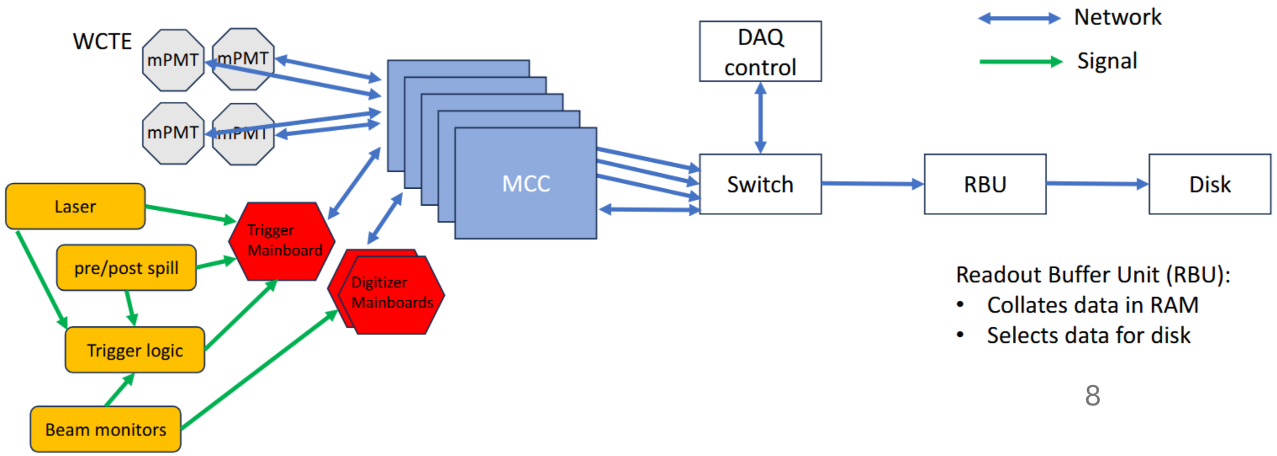
mPMT Concentrator Card (MCC) - clock, trigger & synchronization



100 Mbit/s Ethernet

- mPMT-MCC data transmission
- 2x twisted pairs used for clock/trigger distribution
- PPS signal encoded in the clock signal for experiment synchronization

- Multi-PMT Concentrator Card (MCC)
  - One MCC serves max 8 mPMT modules
  - Clock
    - Internal source - distributed by daisy chaining MCCs
    - External source – uniform clock delay
  - Trigger
    - Trigger signal from trigger mainboard or digitizer mainboards processed by the special Trigger Board and then fed to the MCC
  - Synchronization
    - PPS signal (Pulse Per Second)



Data Aquisition System (DAQ) - ToolDAQ

ToolDAQ

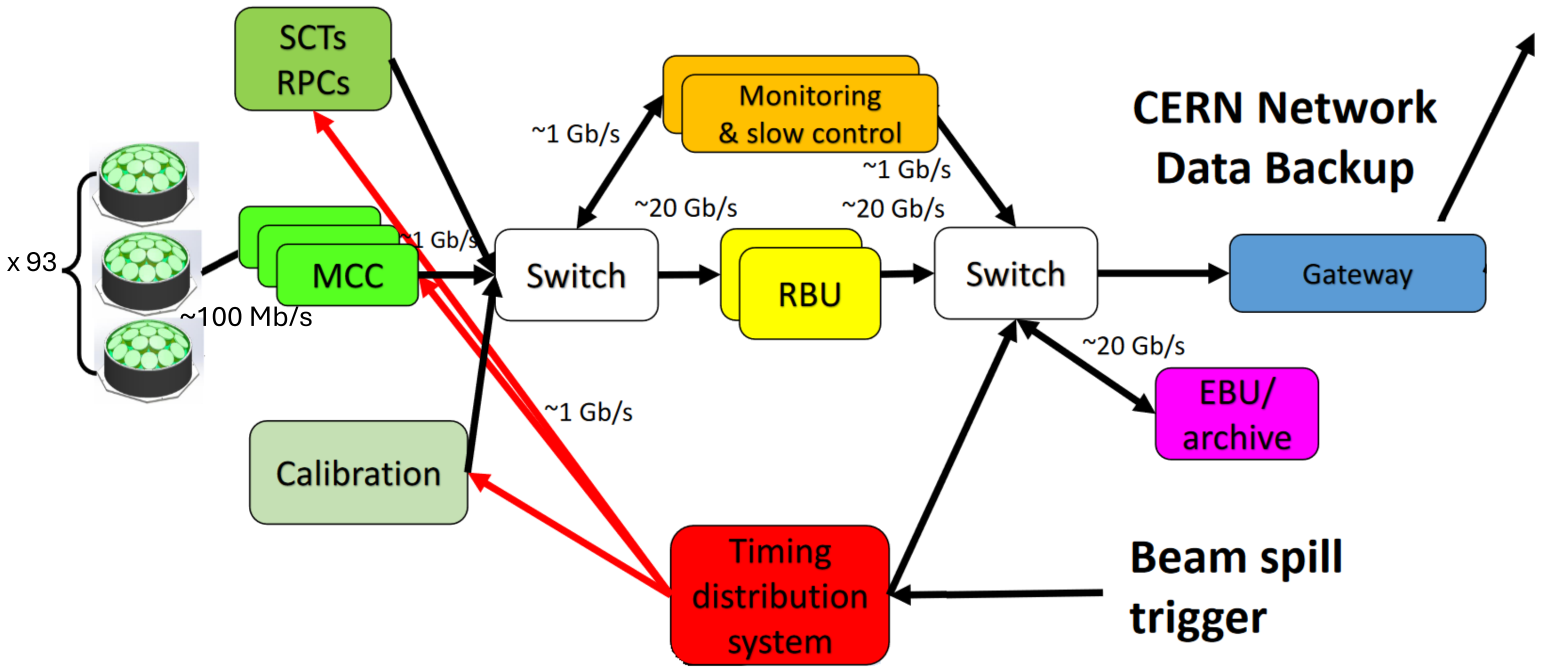
- Pure C++
- Fast Development
- Very lightweight
- Modular
- Highly Customisable
- Scalable (built in service discovery and control)
- Fault tolerant (dynamic connectivity, discovery, message caching)
- Underlying transport mechanisms ZMQ (Multilanguage Bindings)
- JSON formatted message passing
- Few external dependencies (Boost, ZMQ)

ToolDAQ process executes seqeunce (ToolChain) of classes (Tools) using a Boost-based dynamic data storage (DataModel), may interact internally and with other processes (Node) using ZeroMQ message queuing

Subsystems organised in nodes running ToolDAQ-based app, e.g.:

- RBU – Readout Buffer Unit
- EBU – Event Builder Unit
- Monitoring & slow control
- Calibration

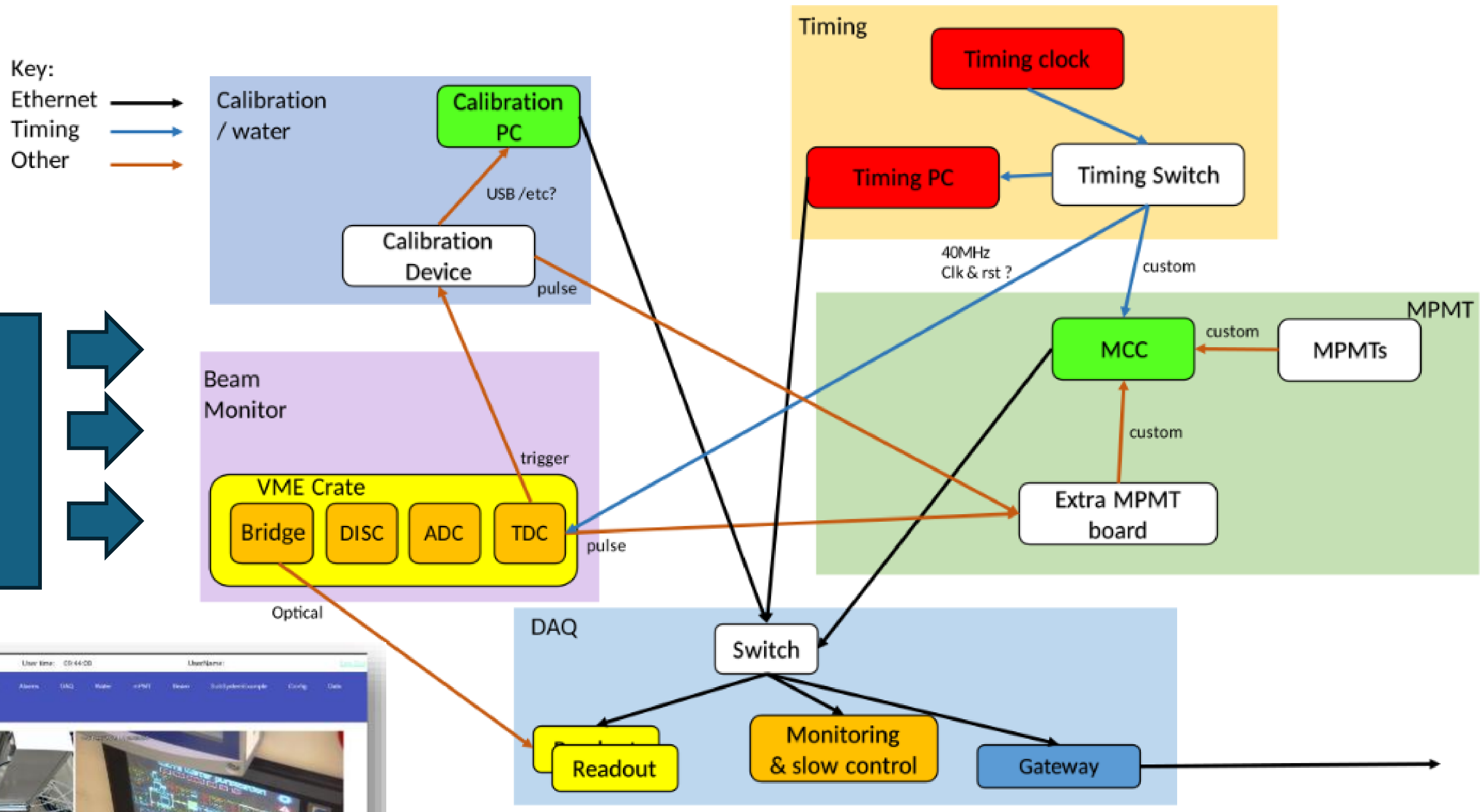
Dynamic reconnectivity allows for keeping fault tolerance even if the hardware of one node fails

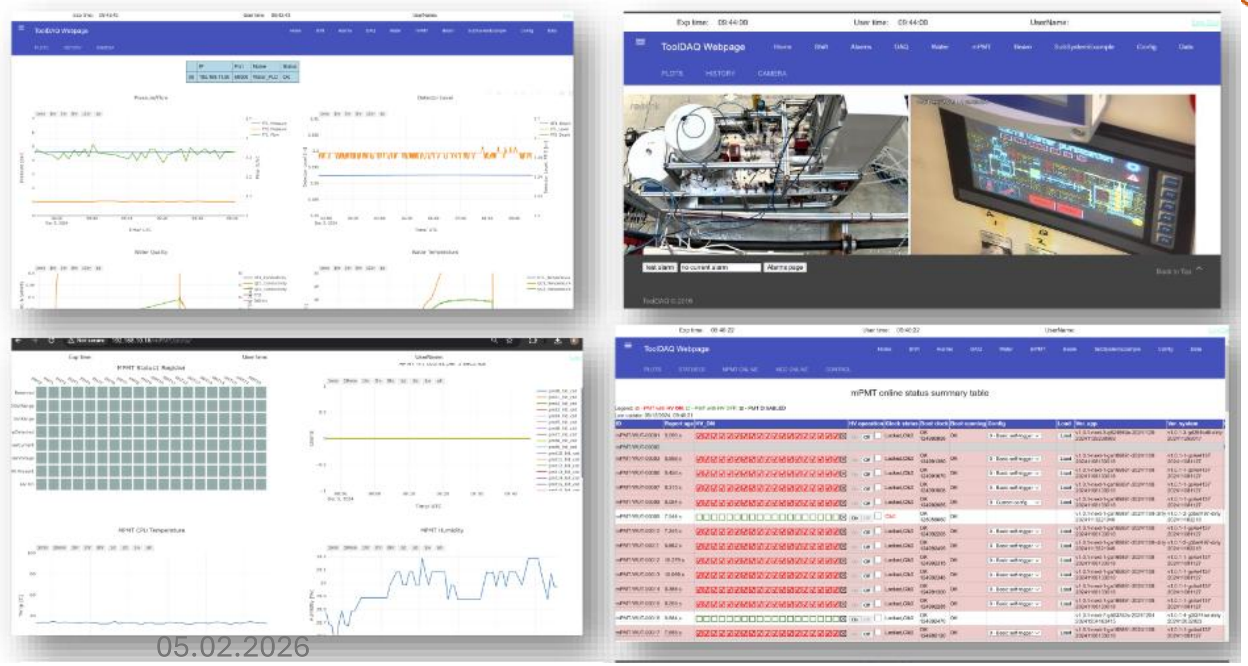


Developed in the UK, for Hyper-K and WCTE collaboration development supervised by dr Benjamin Richards, University of Warwick

Data Aquisition System (DAQ) - WCTE

WCTE allowed to test the performance and throughput of ToolDAQ-based system
~1700 PMT channels
WCTE sub-systems: mPMT, Timing, Calibration, Water, Beam Monitor, DAQ





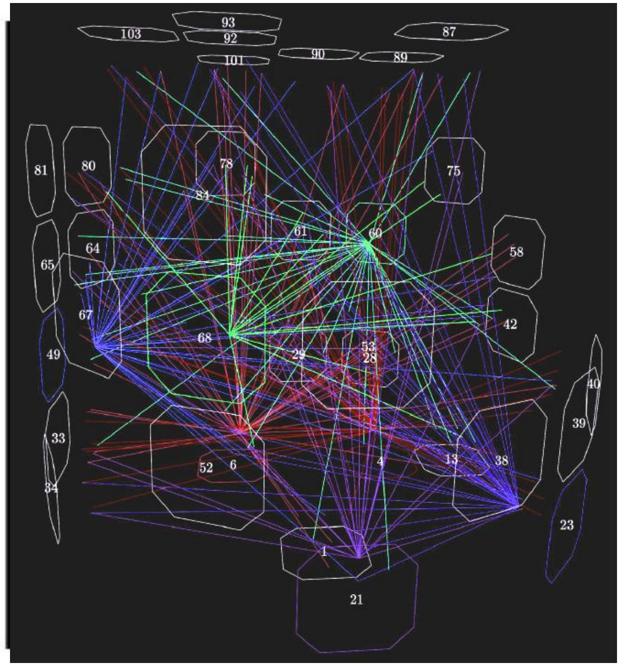
JSON configuration for each node,created, distributed from the ToolDAQ front-end web app (Webserver)

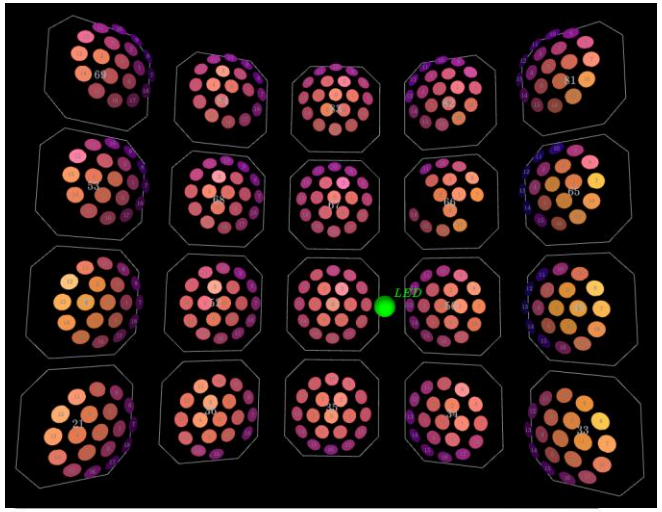
Webserver maintain

- slow control (experiment run start/stop, sending JSON configuration files to experiment nodes)
- monitoring (plots, alarms)

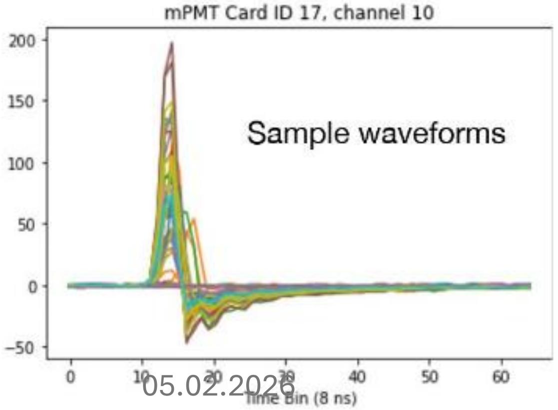
mPMT reliabilty – timing constraints

- 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 operation of the WCTE run, with fluctuations of <1 ns over the course of days/weeks

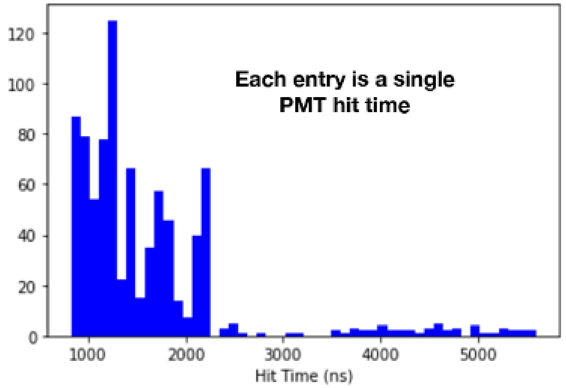




The differences between the calibrated LED flight times and the expected flight times



The arrival times of Cherenkov photons before calibration



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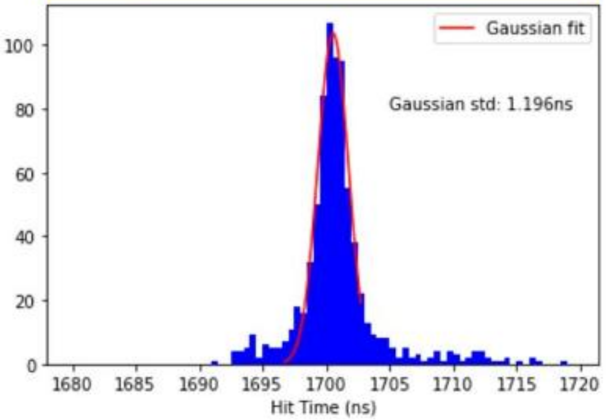

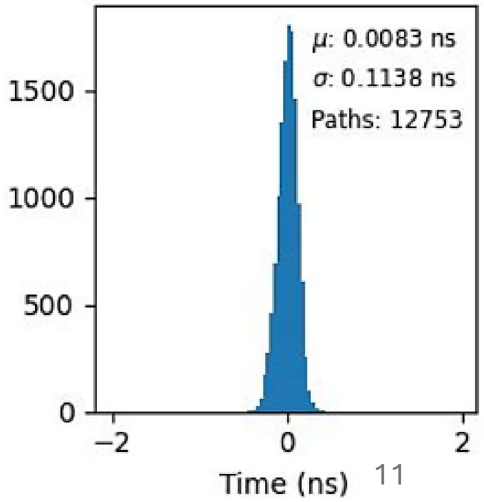

Thank you for your attention