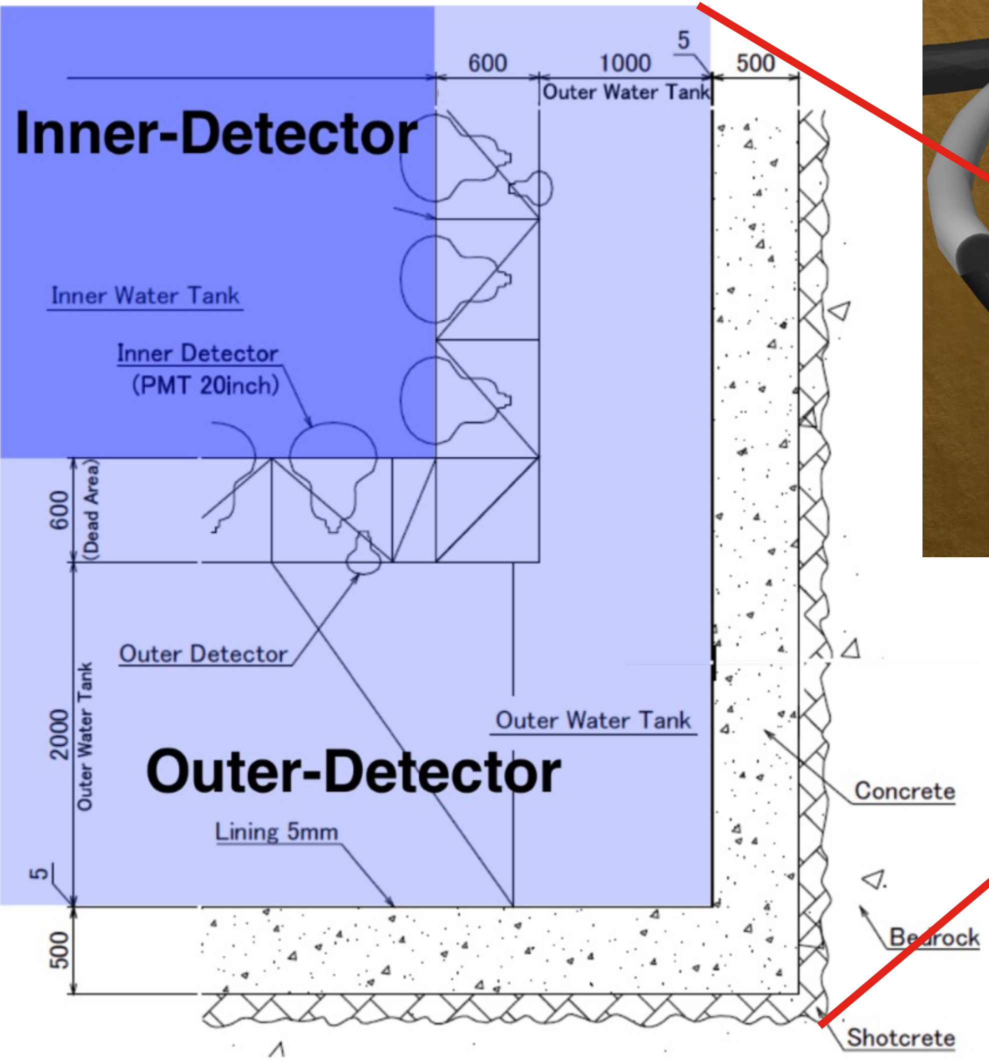
Quality Assurance of the Hyper-Kamiokande Outer Detector Photomultiplier Tubes

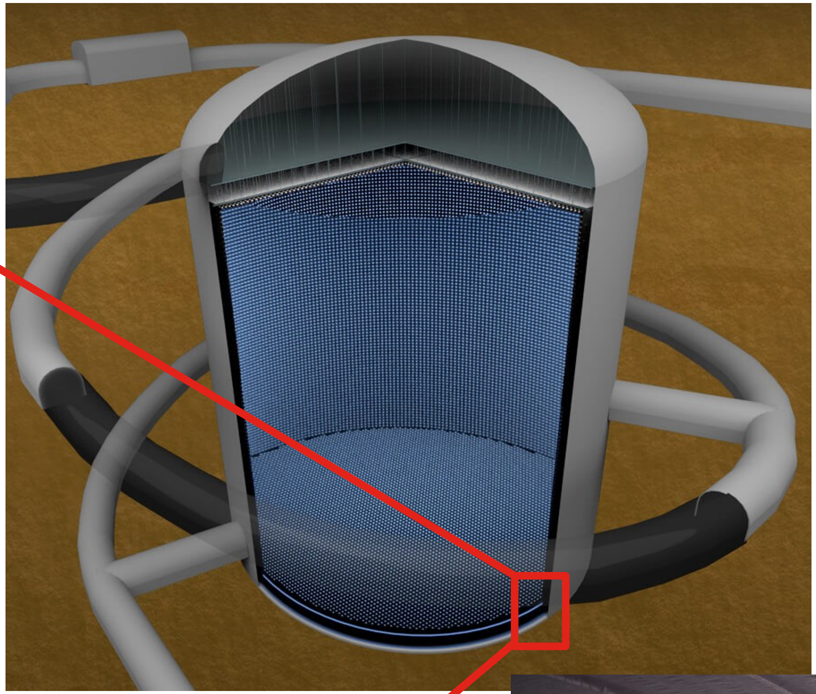
Robert Kralik

Hyper-Kamiokande Outer Detector

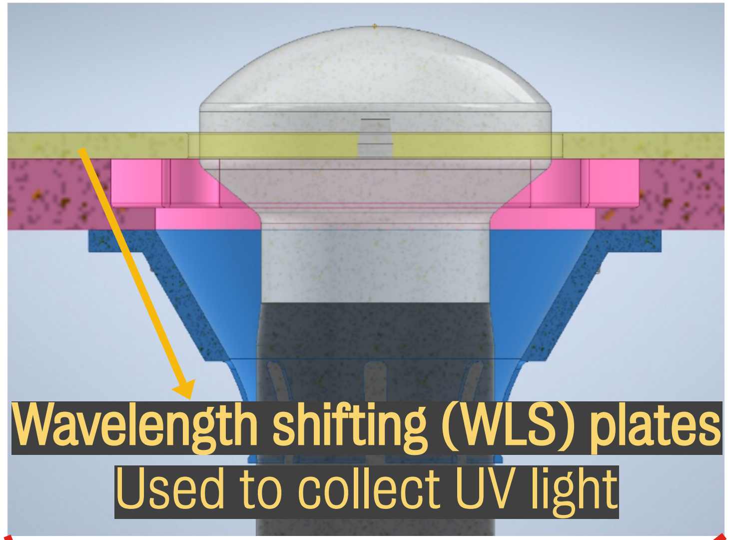
Hyper-Kamiokande Outer Detector

Hyper-Kamiokande (HK) detector

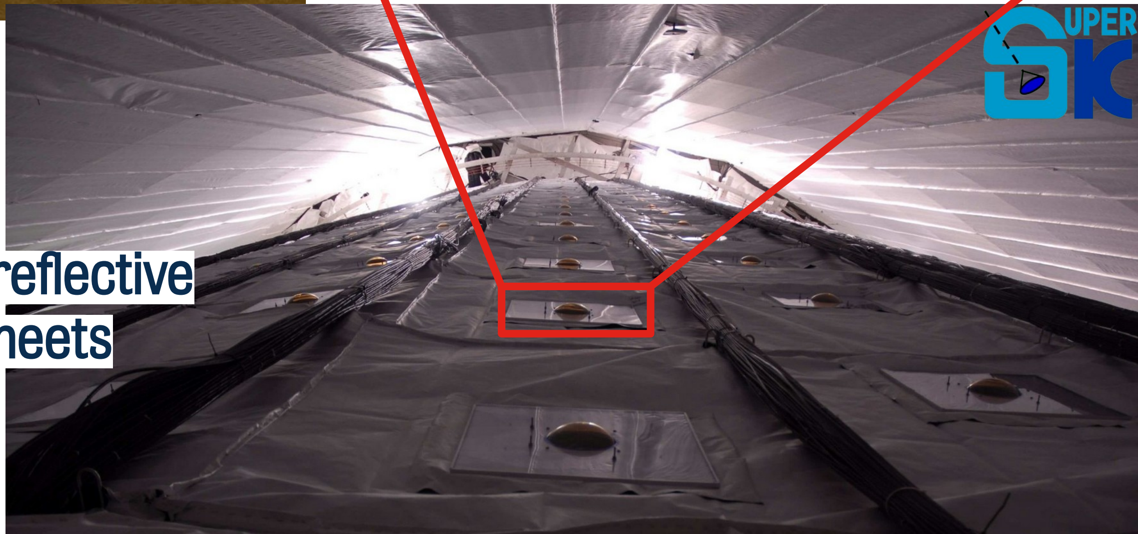




3” Outer Detector (OD) PMTs



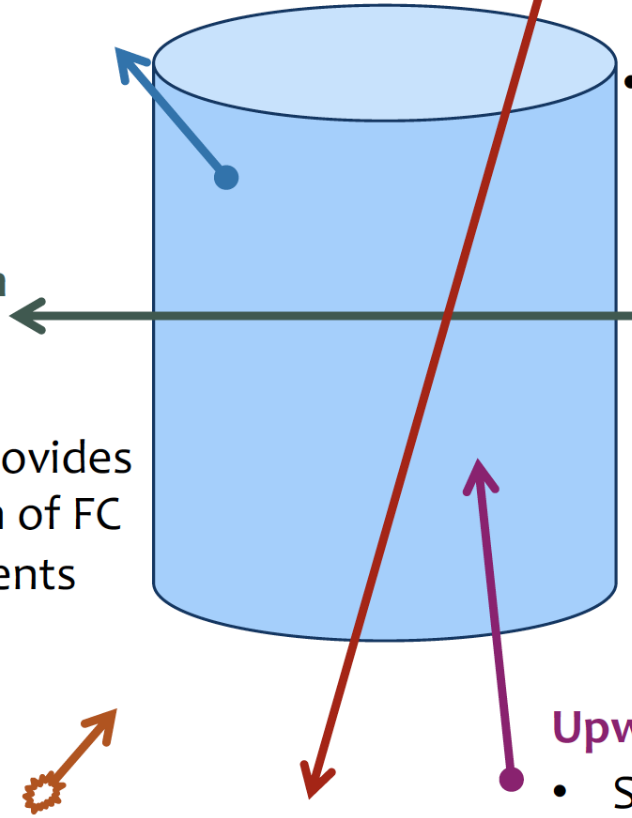
Lined with reflective tyvek sheets



Outer Detector overview

Partially contained neutrino interaction
- OD near corners helps differentiate from corner-clipping muons

Cosmic muons , 45Hz = 4million/day
- Background to all physics measurements
- Ideally veto all, in practice best you can do without changing OD volume is ~1:10^5 level
- Fast OD veto avoids recording and reconstructing all events



JPARC beam neutrinos
- Far side provides separation of FC and PC events

JPARC beam neutrinos
- Sensitive to δ_{cp} & Δm^2_{3i}
- Near side provides separation for rock interactions

Passive shielding from radioactivity in rock
- Main value to Low-E analyses, does not require PMTs

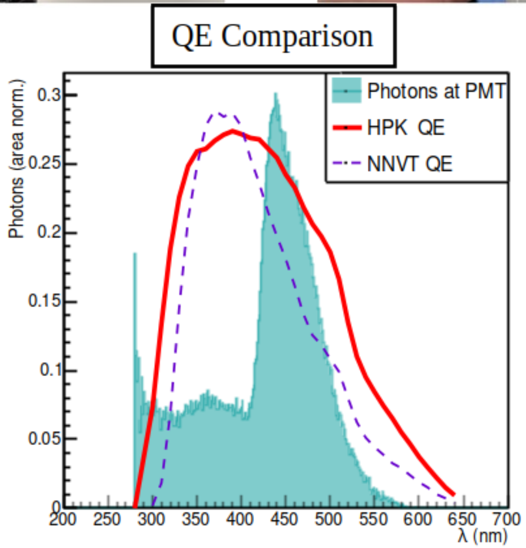
Upwards muons from ν_μ interactions in rock
- Sensitive to Mass Ordering & Δm^2_{3i}
- Bottom endcap OD separates these from (lower-E) PC events

Outer Detector PMTs

Two candidate 3" Photomultiplier Tubes (PMTs) for the OD – Hamamatsu R14374 and NNVT N2031

- Tender now ongoing – decision in October 2025
- New PMT versions already in Kamioka – shipped to UK later
- OD will have 3600 3" PMTs in total
- We mostly care about single Photo Electron (PE) sensitivity
  - Most OD PMTs will receive <5 PEs for majority of muons
- Main parameters important for the OD PMTs:
  - Low dark rate (<2 kHz for 25°C)
  - High Quantum Efficiency (QE) across Cherenkov spectrum (both direct and reflected)
  - Good Collection Efficiency (CE) across the PMT including edges where WLS plates connect

More information in TN0046 - "3-inch Photomultiplier Tubes for the Hyper-Kamiokande Outer Detector"



PMT Quality Assurance

Quality Assurance

Each PMT undergoes Quality Assurance as it arrives

~450/month

PMTs are re-packaged and temporarily stored afterwards

Transport to HK for construction

Start December 2026

PMTs arrive to Toyama University

400/month from July 2026

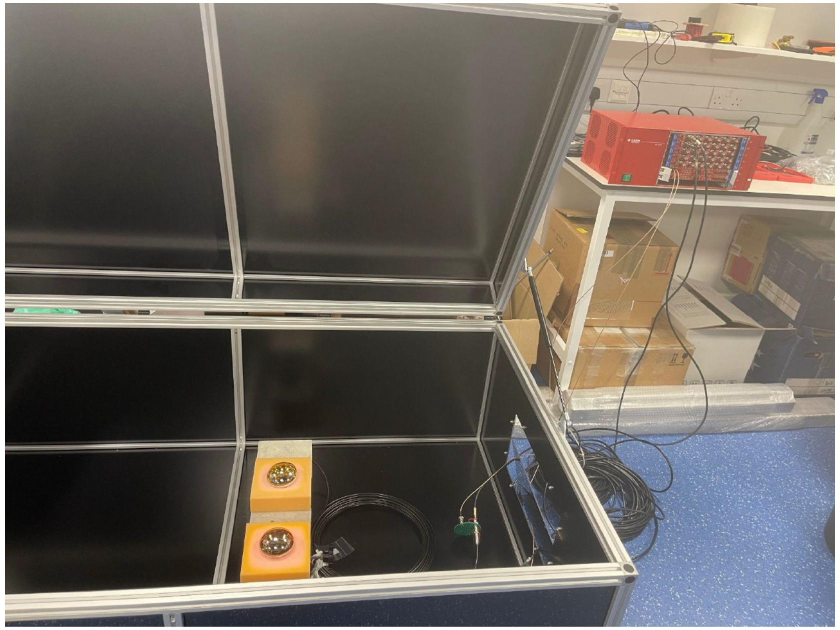
PMTs get assembled with WLS plates

Just-in-time for construction

Some of the PMTs undergo further "characterisation" measurements

Quality Assurance setup

- 2 Dark Boxes with each 14+1 PMTs each per day
- One reference PMT in each box used for validation
- Up to 140 PMTs/week → up to 560 PMTs/month
- Additional measurements require alternative setup
  - Considering measuring PMT+WLS plate setup, angular dep. of collection efficiency, multiple wavelengths



Measurements for each PMT

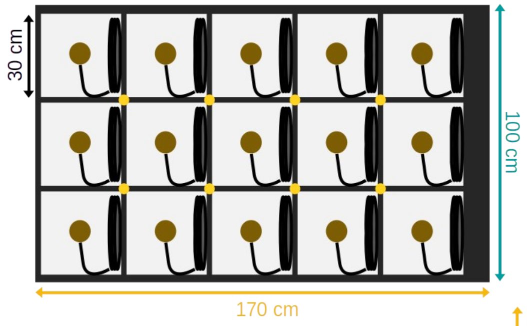
- Gain variation with input voltage
- Relative Quantum Efficiency (single wavelength or more?)
- Single Photo Electron characteristics (charge resolution, peak-to-valley ratio)
- Dark rate
- Maybe time resolution?

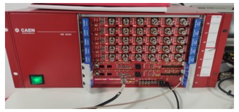
Quality Assurance Space

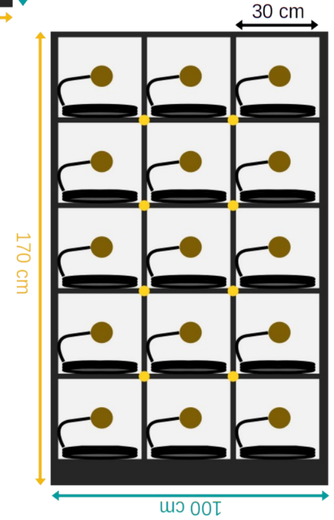
9 m

Spaces secured for OD at University of Toyama by logistics group

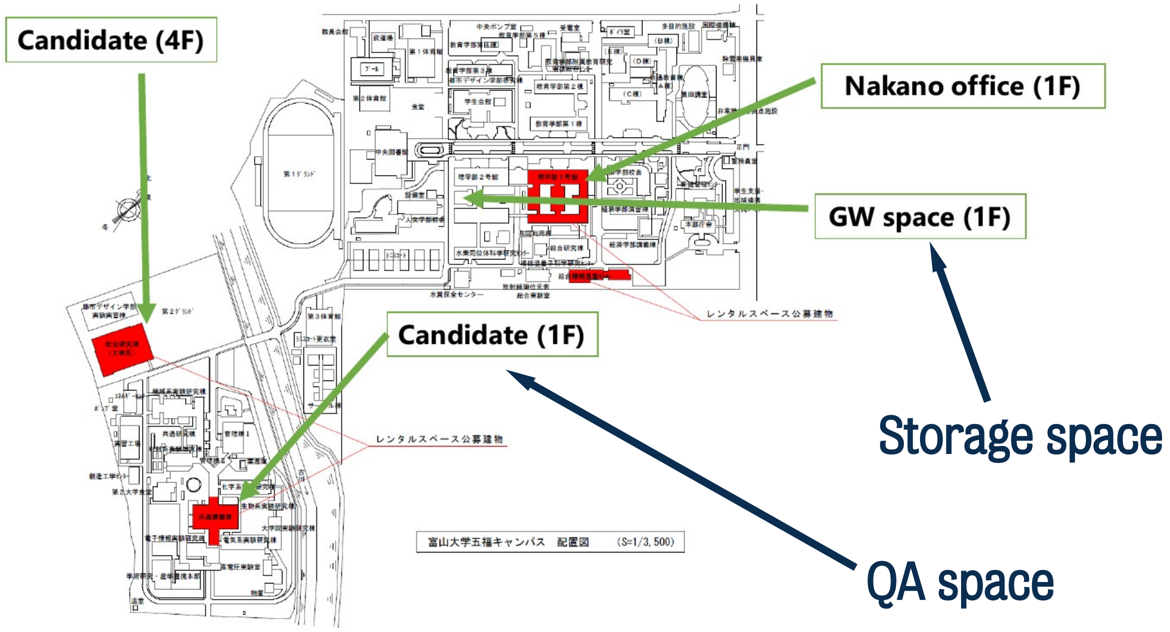
- Candidate (1F) already available: 8m x 9m
- Only need about 3x5 m for the QA
- Could also be used for assembly and temporary storage of PMTs
- Not attached to the storage area – requires transportation







8 m



Loads of extra space

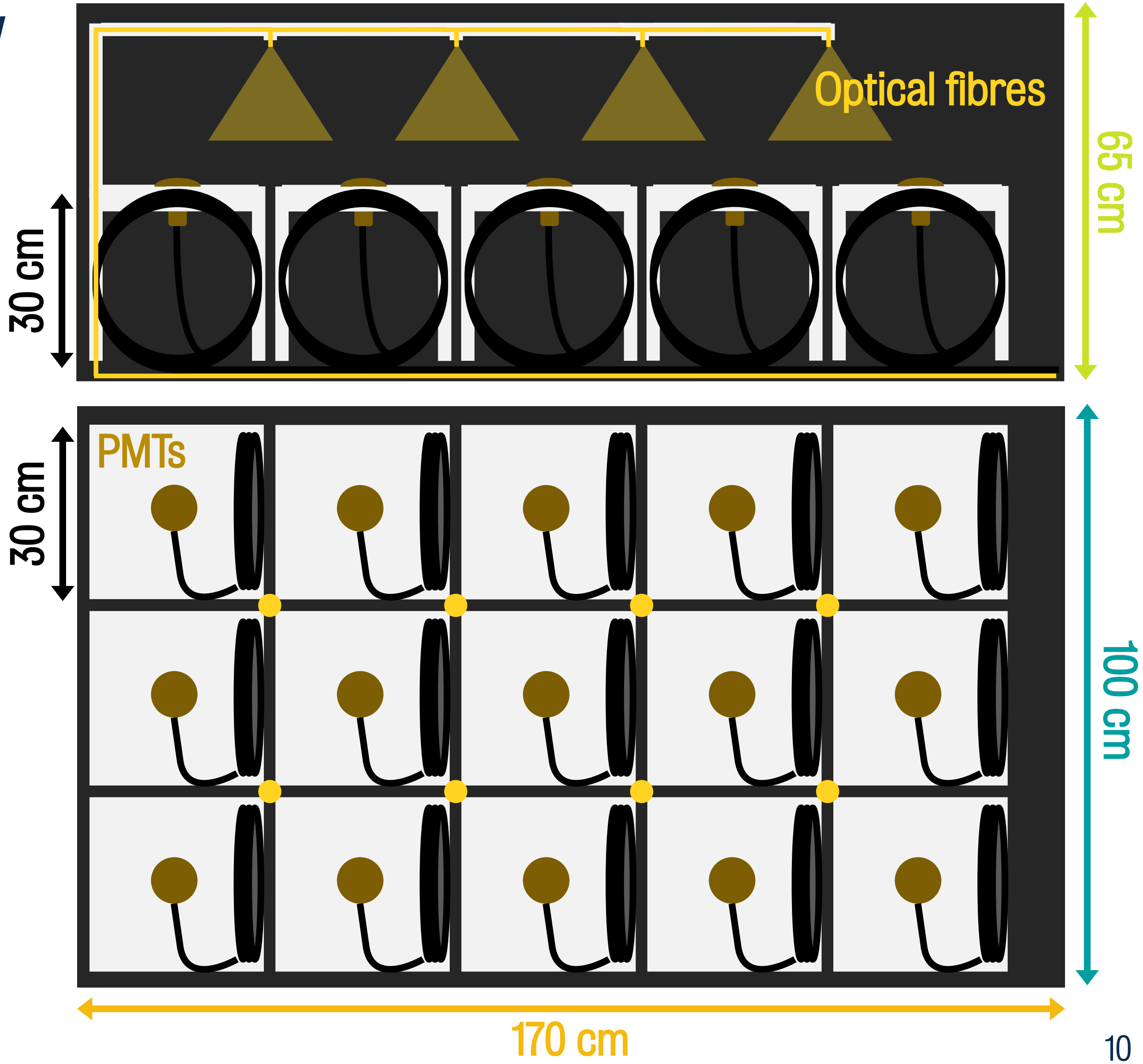
Quality Assurance Setup

2 Dark boxes with 14 (+1 reference) PMTs each /day

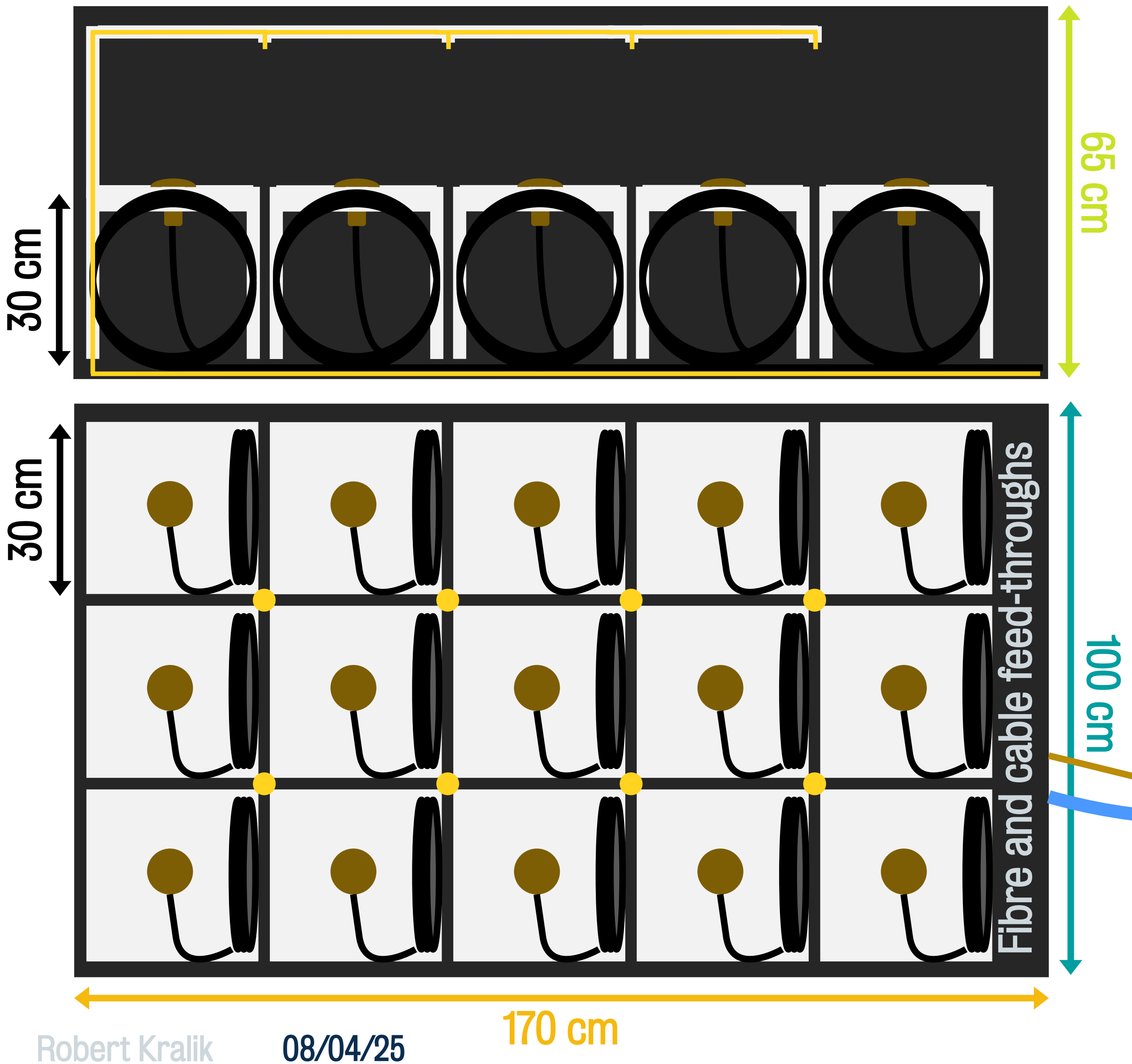
- 3D printed PMT stands designed to support the cable rolls on the side
- Hamamatsu rolls measured to be ∅≅30cm
- Splitter boards inside the box
- Two separate LEDs for each dark box
- LED input split into 8 output fibres

Thorlabs 1-to-7 fibre bundle BF74LS01

- Each LED output illuminates 4 PMTs
  - Not uniform but should be good enough
  - Also considering output from side of PMTs

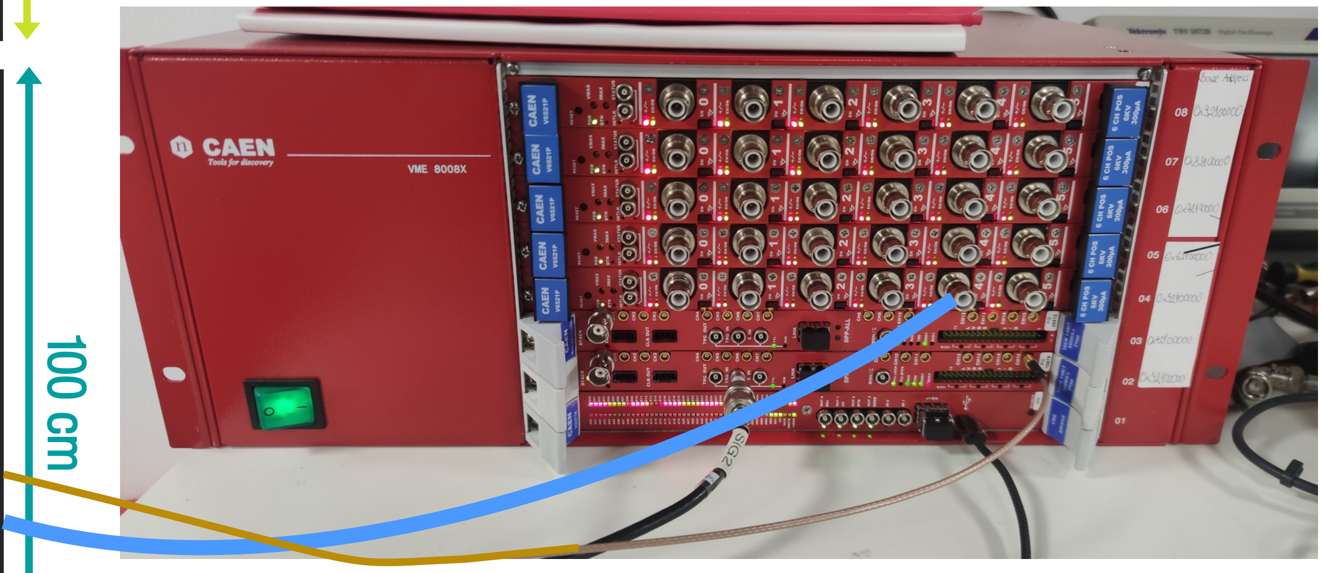


Quality Assurance Setup



Input voltage and output signal from CAEN VME box

- 5x HV power supply (6 ports each) CAEN V6521P
- 2x ADC (16 ports each) CAEN VX1730SB
- VME to USB bridge CAEN VX3718



ADC and HV tested at KCL during PMT measurements

Quality Assurance procedure – Monday to Friday

Morning

1) Finish the dark rate analysis from the previous batch and send results to database — 15 min
2) Unload previous batch of PMTs from the dark boxes and re-box them — 0.5 – 1 hr
   - Move to storage space right away or wait for assembly at the QA space?
3) Unbox and load new batch of PMTs into dark boxes — 0.5 – 1 hr
   - Label each PMT and its cable with a bar code
4) Turn on HV to initial value and leave them to warm up — 1 – 4 hr

Afternoon:

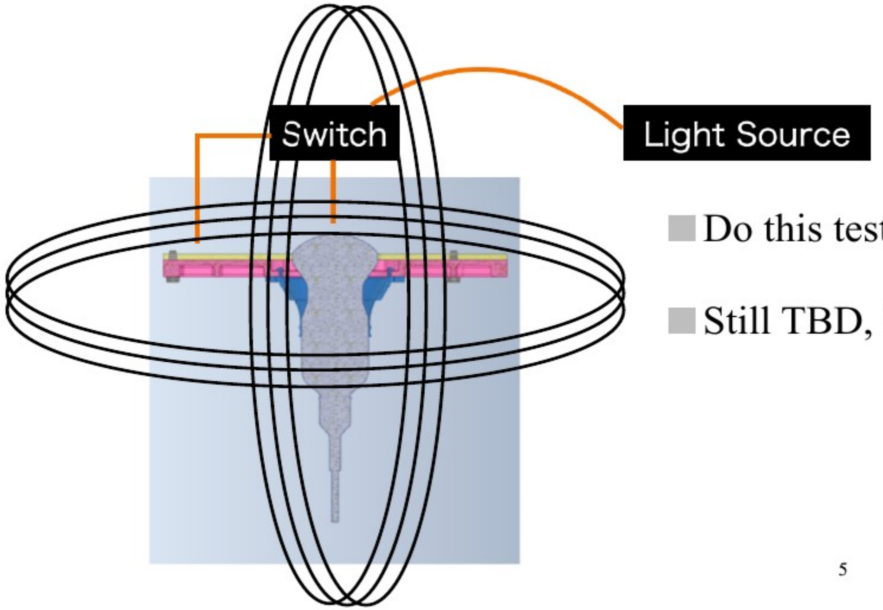
1) Turn on LED and measure gain variation vs input voltage — 0.5 – 1 hr
2) Analyze the gain variation and determine operation voltage (V_{op}) for each PMT — 10 min
3) Set each PMT to this voltage and measure single PE characteristics and relative QE — 0.5 hr
4) Turn off the LED and measure dark rate over night / over weekend — 10 hr

Quality Assurance – other measurements

Considering additional measurements to test collection efficiency, WLS plates, multiple wavelengths…

- Would likely need to dedicate another dark box (and space) for this
- Pre-calibration of OD PMTs likely only towards the end of installation
  - Too late to discover any issues

- [Idea] For QA we will build a device similar to that on previous page: geomagnetic-field-compensated dark box with a PMT mount, optical switch, and light source
  - → Include check of PMT/WLS relative yield for *all* delivered PMTs ideally
    - Maybe only need to do this for first 5% of tubes if no problems
  - Will incur more measurement time than nominal QA if done one-by-one [needs thought]



- Do this test in the same location as nominal QA
- Still TBD, but Toyama U. Is preferred location

5

26

Quality Assurance – status

Previous KCL postdoc (Stephane) designed the setup, procured most of the equipment

- HV power supply and Analog-Digital Converters (ADCs) already used for PMT measurements
- Two working prototypes of PMT stands 3D printed and currently tested
- Several LEDs+drivers, fibres, fibre bundles, optical feedthrougs (various light injection setups)

To-do list

1) Finalize and test the setup
    - 3D printing design for the PMT support (specifics depends on choice of PMT), light injection design, PMT organization inside the dark box
2) Develop DAQ software, user interface, finalize analysis scripts, implement interface to HK database
3) Finish the procurement of all the coaxial cables, feed-throughs, splitter boards, DAQ computer

Testing and development (re)starting now until summer 2025

Ship and start validation on-site between end of 2025 and beginning of 2026

Analysis

PMT waveform and charge distributions

LED pulses trigger PMT readout

Collect 500000 waveforms; for each

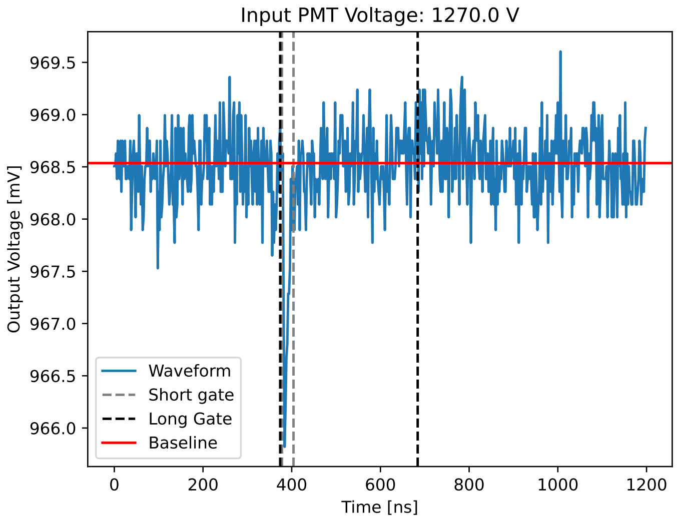
1) Find minimum
2) Calculate and subtract baseline
3) Add bins in pre-defined signal range
4) Convert to total collected charge

Q [pC] = Current [mA] * time [ns]
I [mA] = Voltage [mV] / Impedance [Ω]
Time ... pre-defined time window
Impendace = 50 Ω (at ADC)
Voltage... size of signal

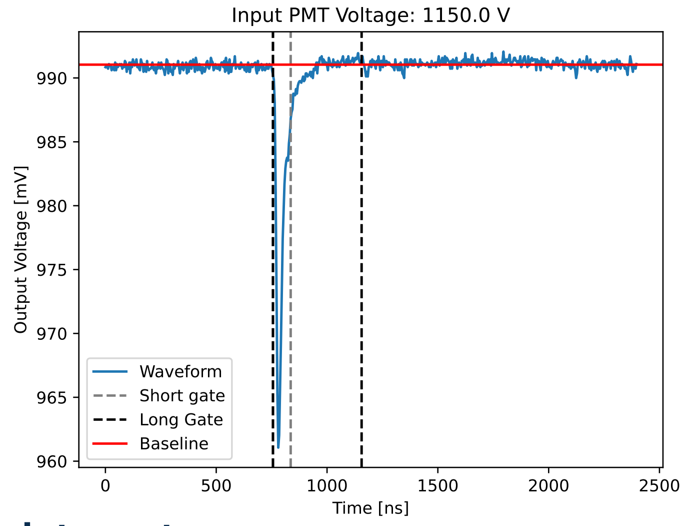
Create histogram of integrated charges

Fit to get the desired characteristics

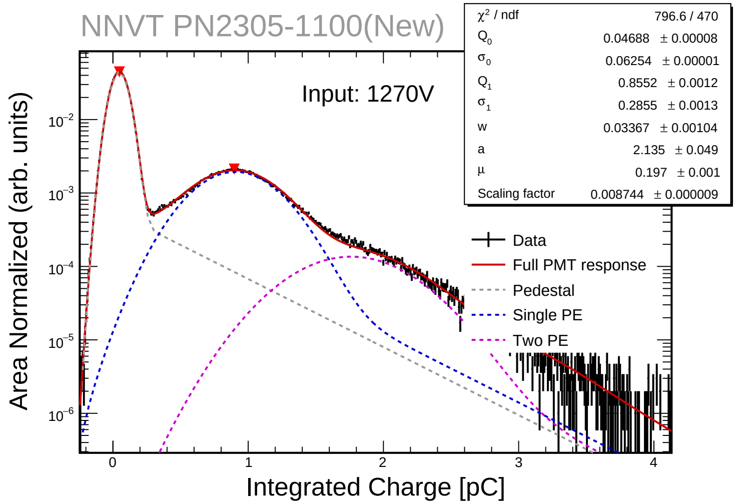
Single PE

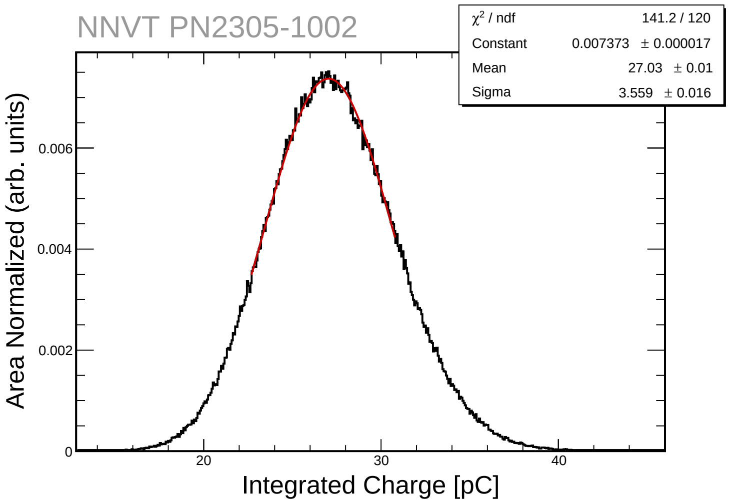


Multi PE



Integrate





Single PE Charge Distribution Fits

Using ROOT fit based on the Full PMT response function as in https://doi.org/10.1016/0168-9002(94)90183-X

= Poisson⊗(Signal*Gaussian + Background*(Gaussian⊗Exp))

- Previously used a sum of Gaussians and an Exponential

Gain = $(Q_1 - Q_0) / e$

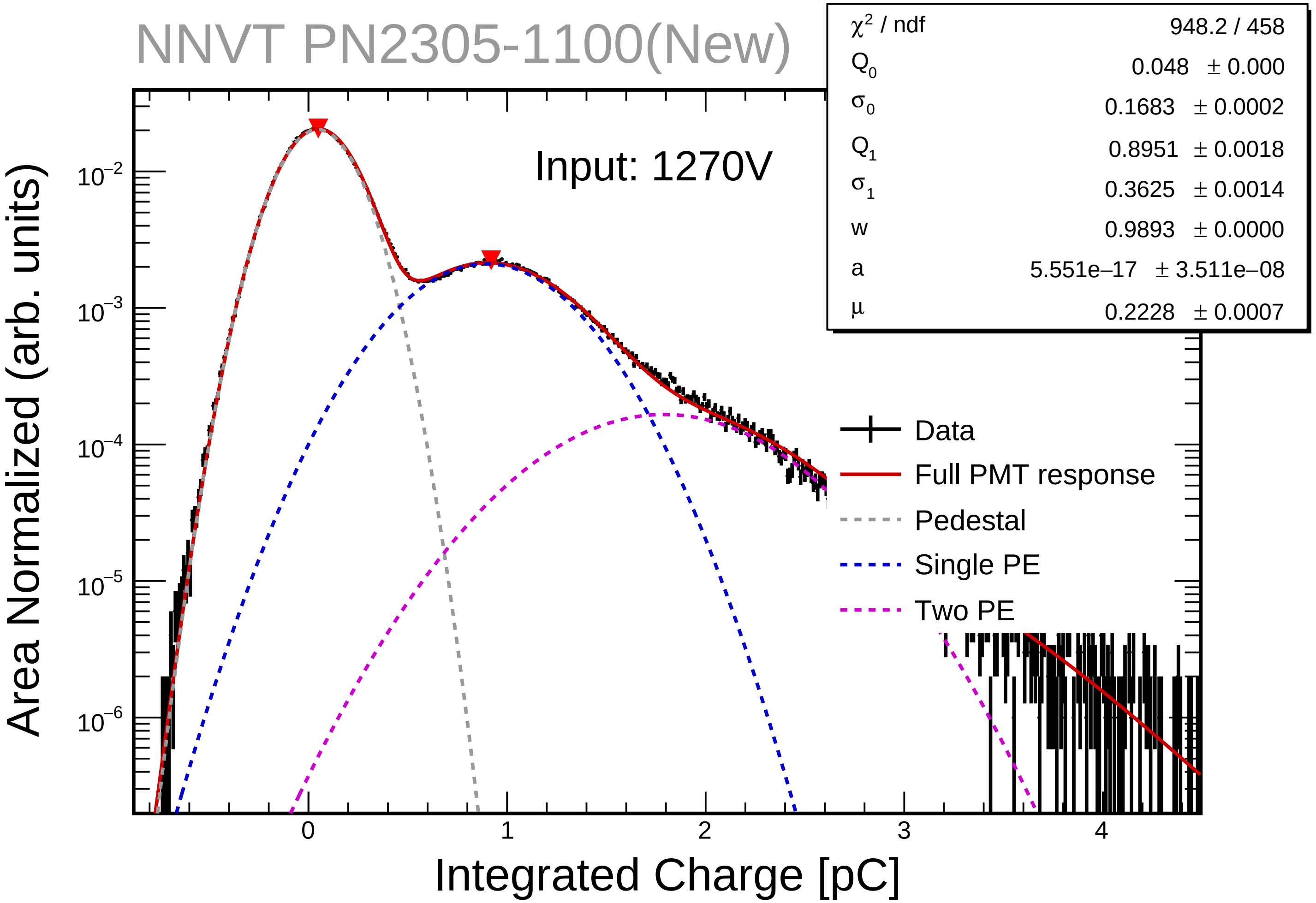
- Set to 5×10^6 by adapting input voltage

Peak-to-Valley ratio ≡ P/V

- Both Peak and Valley taken from histogram
- Requirement: P/V >2

PE resolution = σ_1 / Q_1

- Previously used wrong equation: $\sigma_1 / (Amp_{1PE} * \sigma_1 * \sqrt{2\pi})$
- Requirement: <50%



Dark Rate and Quantum Efficiency calculation

Dark Rate is calculated as DR = $N_{OverThreshold}$ / ($N_{waveforms}$ * wavesize [s])

- $N_{OverThreshold}$ is the number of times all waveforms crossed below the threshold
- Wavesize is just the length of each waveform in seconds
- Error on the Dark Rate is calculated as $\sqrt{N_{OverThreshold}}$ / ($N_{waveforms}$ * wavesize [s])

Quantum Efficiency (QE) is calculate using a reference PMT: $QE_{Measured} = NPE_{Measured} * (QE_{Reference}/NPE_{Reference})$

- NPE is the calculate number of photo electrons
- In real life we really measure the detection efficiency (Quantum Efficiency * Collection Efficiency)

Analysis overview

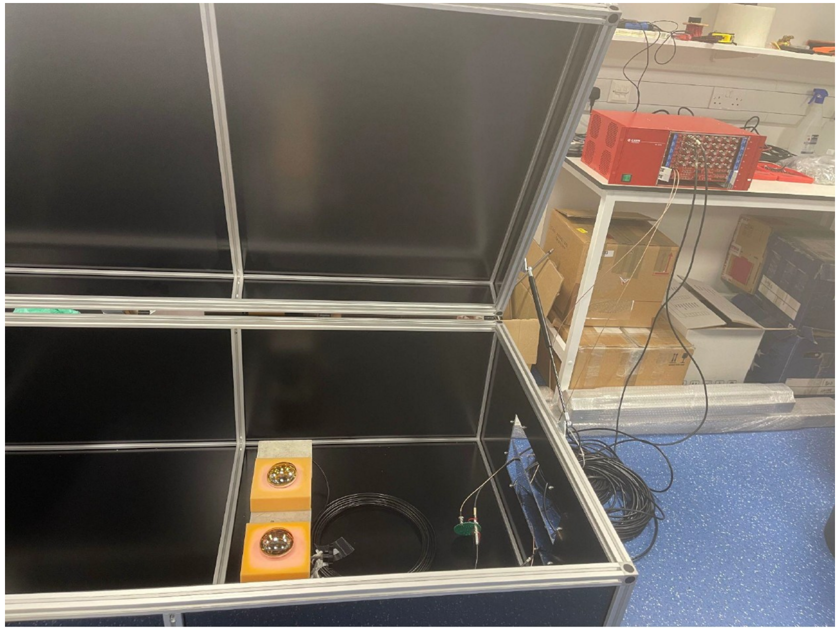
The analysis scripts are located in https://github.com/rkralik5/PMTFitting

- PMTFit.C = single PE fits
  - Already works very well
  - Currently finishing comparisons with Federico from RAL (gain calculation)
  - Possible to include time resolution fits
  - Can be used to get gain dependence on voltage
- MultiPEFit.C
  - Simple Gaussian fit to the multi-PE charge distribution
  - Finishing comparisons with Federico to ensure stability and reliability
  - Federico believes this is more reliable for gain calculation
- DarkRate.C
  - Should already work well enough

Setup design

Current status

List of equipment available here



- Two dark boxes - one assembled
  - Still need to get someone to machine holes for feedthroughs
- Prototypes of PMT stands – different for Hamamatsu and NNVT
  - Hamamatsu stand is currently horizontal
- Several PMTs (4* Hamamatsu, 1 NNVT) link to spreadsheet
  - Neither of them final design
- Some LEDs and optical fibres, feedthroughs, fibre bundles…
  - Stephane's idea explained in previous slides
  - Other options for light input: separate fibre for each PMT, diffuser ball, laser ball
  - Do we want multiple wavelengths? Are the LEDs enough?
  - Fibre holder probably 3D printed
- We have NNVT splitter boards – final design will probably use official HK OD ones

Tasks

1) Learn how to use the 3D printer and collect all the PMT stand design prototypes
2) Design a vertical PMT stand for Hamamatsu
3) Design a fibre holder
4) Test Stephane's idea of light input
5) Test other fibre inputs
6) Adapt the design to be simple for QA shifters
7) Adapt the design so the individual PMT stands fit neatly together

Data Acquisition (DAQ)

Data Acquisition

Not developed yet – using CAEN software for the PMT measurements

- CAEN Scope – simple waveform measurement with triggers
- CAEN COMPASS – much more complicated software allowing for analysis (not necessary)
- CAEN WaveDump – should be a very simple software for ADC readout

The idea is that we will develop our own simpler case-specific software that will do the same thing

- CAENVMELib – list of functions to interact with the VME bridge
- CAENComm Library - Interface library for CAEN Data Acquistion Modules
- CAENDigitizer Library - Library of functions for CAEN Digitizers high level management

For the High Voltage control, we can either use the default software

- CAEN GECO

There are other possible libraries for the power control, we need to explore them and find out what is best

Starting to-do list

1) Read on the QA from the technote and this presentation
2) Look at CAEN WaveDump (for VX1730SB ADC) and try installing it on MAC
3) Look at the CAEN Lib documentation
4) Look at the documentation for the ADC
5) Access the VME bridge with simple commands
6) Get a waveform from a PMT
    1) With WaveDump
    2) With CAEN commands
7) Make a python (or other) script that will run the waveform reading for you, set every parameter, and save the waveforms

Useful links

- PMT basics by Photonis
- 3-inch Photomultiplier Tubes for the Hyper-Kamiokande Outer Detector - HK TN0046
- CAEN VME VX1730SB documentation
- CAEN HV V6521 documentation

Thank you!