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Quality Assurance of the 3" OD PMTs

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Technical Note

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⁶

Abstract

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Description of the Quality Control process for the 3" Outer detector Photo Multiplier
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Tubes.

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32 1 Introduction

33 What are the OD PMTs and what is the general purpose of the Quality Assurance (QA) process
34 for the PMTs.

35 Maybe also describe the equipment that we will be using?

36 Describe the space where we will do the QA, say that we will perform a measurement of
37 the magnetic field that will help us decide where to place the QA

38 Maybe include a subsection with the to-do list that will be continually updated?

39 HK has 40K inner detector PMTs (50 cm diameter) and 3600 outer detector PMTs (20 cm
40 diameter) with 1ns timing resolution.

- 41
- 2484 in the barrel, and 538 in each of the endcaps, for a total of 3560.
 - Allowing for the some distortion of the repeating pattern near the edges of the endcaps it may be possible to add between 32 and 44 more PMTs, although this still needs to be confirmed with the installation group.

45 The current plan is for PMTs to start arriving to the University of Toyama in the end of
46 September 2026, arriving in batches of 400 PMTs per month. The plan is to perform the QA
47 on ~ 450 PMTs per month.

- 48
1. Top endcap: 538 PMTs – 1.5 months
 2. Upper barrel: 1242 PMTs **TO DO: Check these numbers** – 3 months
 3. Lower barrel: 1242 PMTs – 3 months
 4. Bottom endcap: 538 PMTs – 1.5 months

52 What are the important qualities of the OD PMTs that we want to test in the QA process?

53 Connection to the pre-calibration. The pre-calibration of the OD PMTs will be done using
54 the Australian setup with a robotic arm. The OD PMTs will be measured for positional and
55 angular dependence, relative quantum (detection) efficiency, charge resolution, and more **TO
56 DO: Describe what will be measured in the pre-calibration**. Due to a tight pre-calibration
57 schedule, the pre-calibration of the OD PMTs will be done towards the end of the installation
58 process and therefore we won't be able to use the pre-calibration results to select the PMTs for
59 the QA process. The QA process will be used to select the PMTs that will be installed in the
60 Hyper-K detector.

61 Each PMT is uniquely identified by a manufacturer's serial number, corresponding to a
62 Unique Product Identifier (UPI) Hyper-K identifier. The manufacturer will provide a QR code
63 that will be attached to the PMT cable and will show the serial number, PMT type, date of
64 manufacture, EBB number, and other relevant information. The QR code will be scanned
65 during the QA process and the information will be stored in the Hyper-K database.

66 Once all the measurements are finished, the box with the measured PMT is closed with a
67 specially-coloured tape to mark it as complete.

68 **1.1 Space at the University of Toyama**

69 **TO DO: Add images of the location and the room**

70 The space in the University of Toyama will be measured for magnetic field and the results
71 will be used to decide where to place the QA equipment. The space is all ready for the QA
72 process and the equipment will be shipped to Japan and installed in the first half of 2026. The
73 space will be equipped with a dark box, a VME crate with HV and DAQ boards, and a computer
74 with the data acquisition software.

75 **1.2 Equipment**

76 The most up-to-date list of equipment is on this Google sheet: <https://docs.google.com/spreadsheets/d/1KQ48t>

77 The equipment will be shipped to Japan in the first half of 2026 and will be installed in the
78 University of Toyama. The equipment will include:

- 79 • 2x dark box 170x100x65 cm
- 80 • PMT stands and fibre holders - all 3D printed at KCL
- 81 • Power supply and readout
 - 82 – VME crate CAEN 8008X
 - 83 – VME to USB bridge CAEN VX3718
 - 84 – 2x ADC (16 ports each = 32) CAEN VX1730SB
 - 85 – 5x HV power supply (6 ports each = 30) CAEN V6521P
 - 86 – 30x BNC to MCX adapter cables
- 87 • Computer with data acquisition software
 - 88 – Still need to be decided and purchased
- 89 • Function generator
 - 90 – Still need to be decided and purchased
- 91 • LED light sources - currently several candidates at KCL
 - 92 – ThorLabs M405FP1 LED (405 nm, 1 W) together with ThorLabs LEDD1B T-cube
93 driver
 - 94 – CAEN SP5601 LED (400 nm)
- 95 • Optical fibres for the LED light sources with FC/PC connectors
- 96 • BNC to MCX adapter cables for the PMT readout
- 97 • Splitter boards for the PMTs - will need to be designed and manufactured, likely in
98 Glasgow
- 99 • Coaxial cables with SHV connectors for the PMT power supply and readout (specific
100 type still needs to be decided and purchased)

- Feedthroughs for the coaxial cables with both SHV and BNX connectors
- Possibly magnetic field compensation equipment, depending on the results of the magnetic field measurement in the QA room
- Other equipment as needed, such as thermometers, hygrometers, etc.

105 1.3 From Stephane

106 Once installed within Hyper-K, the cavity will be filled with water and the photo-sensing units
 107 will not be accessible, so it is essential to ensure that each component of the system performs
 108 as expected prior to installation and will continue to do so for the next decades. This section
 109 describes the planned QA/QC testing procedure for the 3" PMTs that can be divided into two
 110 parts: "Batch tests" as detailed in Table 1 that are performed on every PMT and more detailed
 111 "Characterisation tests" as detailed in Table 2 that are performed on $\approx 1\%$ of the total number
 112 of PMTs purchased.¹ The PMTs must pass the batch tests to be installed in the detector, and
 113 characterisation tests will only be performed on PMTs that pass the batch test criteria. All
 114 characteristics of each PMT, including manufacturer's information and measurements from the
 115 QA/QC test-stands, would be stored in separate tables in the central Hyper-K QA/QC database
 116 currently being developed. We plan to use and adapt tools developed by the PMT group (col-
 117 laborating with the 50 cm PMT and mPMT development work). For instance, the *control*
 118 parameters of the QC are the measured gain parameters. They will be important such that PMTs
 119 with similar gains can be matched to the same electronics box for ease of tuning. We would
 120 perform a basic statistical analysis of the measurements for each batch of PMTs received to
 121 ensure that, on average, the PMTs are consistent with the manufacturer's specifications. On
 122 an individual basis, PMTs failing to meet the QA/QC requirements would be excluded from
 123 installation in the Hyper-K detector. The number of PMTs rejected due to failure of the batch
 124 tests should be significantly less than 10%.

Batch Tests		
Characteristic	Requirement	Comment
Gain	5×10^6 achieved for $900 < V < 1300$ V	Measuring gain variation w.r.t HV between [900, 1300]V
Stability	<10% variation	Gain @ 5×10^6 , overnight
Dark rate	< 1kHz	Gain @ 5×10^6 , 20°C, overnight
SPE spectrum	peak-to-valley ratio > 2, $\sigma_{\text{PE}}/\mu_{\text{PE}} = 50\%$	Gain @ 5×10^6 .
QE	> $0.8 \times$ reference specification	Gain @ 5×10^6 . Relative to common reference per batch

Table 1: QA/QC Batch Tests to be performed on every 8 cm PMT.

¹It may be necessary to review this suite of measurements for feasibility. It may not be possible, for example, to pressure test the PMTs at this stage.

Characterisation Tests		
Characteristic	Requirement	Comment
QE/CE	within 10% manufacturer specifications	With perpendicular light source at ≥ 3 wavelengths in 300–500 nm range
CE at 90° orientation	< 10% difference to 0°	To test magnetic field effect
CE as a function of position		When coupled to WLS plate, use directional source at one wavelength.
Operation in water	Stable to < 5%	Gain, dark rate and peak-to-valley measured over 24 hour period in 13°C tank
Pressure tolerance	operational after 10 bar exposure	

Table 2: QA/QC Characterisation tests to be performed on $\approx 1\%$ of the 8 cm PMTs.

125 1.3.1 Test Stand Details

126 At least two QA/QC test sites are envisaged, possibly more, each with capacity to perform
 127 the batch tests on 30 PMTs simultaneously, and the characterisation tests on one PMT at a
 128 time. This would allow for 2–3 batch and 1–2 characterisation measurements per week per
 129 site. Approximately 16 square meters of laboratory space is required for each test site. The
 130 PMTs will be shipped directly to Japan, so we will do the QA/QC tests in Japan at a convenient
 131 location close to Kamioka, that is currently being discussed.



(a) Bespoke QA dark box.



(b) VME crate holding the HV and DAQ boards.

Figure 1: QA setup for batch testing.

132 **1.3.2 Batch Tests**

133 The batch tests would be performed in a dark-box with diffuse light sources injected via optical
134 fibres so as to illuminate each PMT with low fixed-intensity, diffuse light. A typical work-
135 flow could involve spending the day installing the PMTs into the dark-box set-up, ramping to
136 nominal high voltage (to allow the PMTs to stabilise in a dark environment for ≥ 4 hours) and
137 then collecting charge spectra data with the diffuse source at at least three HV settings and
138 dark current measurements overnight. 950 V is assumed to be the nominal operation voltage
139 and repeated measurements of the gain should be made at this voltage to assess stability over
140 a 12 hour period. A common reference PMT, that had been characterised in more detail and
141 confirmed to satisfy quantum efficiency (QE) requirements, would remain in the dark box for
142 each set of measurements allowing for the relative QE to be determined.

143 **1.3.3 Characterisation Tests**

144 The characterisation tests would be performed individually in a separate dark-box with a di-
145 rectional light source. This would allow to probe the quantum and collection efficiency either
146 at a small selection of standard LED wavelengths (eg. UV, 420 nm) or better still, using a
147 monochromator to probe wavelength across the range of interest 300–500 nm. The measure-
148 ments would be performed with the PMT in two positions differing by a 90° rotation to test
149 the impact of the Earth's magnetic field. These measurements should be compared against
150 the manufacturers specifications and between the PMTs tested within the supplied batch. Any
151 departure from expectations should be discussed for each batch of PMTs supplied. Further
152 measurements will be performed with the PMT attached to a WLS plate to characterise the
153 efficiency across the whole 'PMT unit'.

154 A further important property to test is the waterproofing and pressure rating of the PMTs.
155 Since this requires submerging the PMTs in water for measurement, it is not feasible to include
156 in the batch testing process and likely will require a dedicated setup. Such tests should be
157 performed separately on $\geq 1\%$ of the PMTs to confirm they operate stably under water.

158 **2 Quality Assurance procedure**

159 General overview of the QA procedures, what measurements we want to do, how much time
160 will each measurement take, how will the day-to-day of the QA shift look like, how many
161 PMTs do we plan to measure,...?

162 Should I also discuss the plans for the testing of the QA procedure that will happen in the
163 first half of 2026?

164 Also describe the integration with the HK database and the shift system, expectations of the
165 shifters and so on.

166 **2.1 Overview**

167 1. Finish measurements from the previous day/week

168 (a) Finish the dark rate measurement from the previous day/week

169 (b) Do a preliminary check of the results and finish the QA

170 (c) Save the measured data and make sure they were correctly loaded into the hk
171 database

172 (d) Note down the results into the shift logbook

173 (e) Turn off the PMTs and wait until the application turns green

174 2. Unload PMTs from the dark boxes

175 (a) Open the dark boxes and disconnect the PMTs from the splitter boards

176 (b) Unload the PMTs from the dark boxes back into the corresponding boxes (carefully
177 check the labels and the bar codes - separate faulty PMTs)

178 (c) Move the measured PMTs from previous day/week back into storage room

179 (d) (once a week) Batch of PMTs arrive into the ‘GW’ storage room in the university
180 of Toyama (batch of 400 PMTs once a month)

181 (e) Subset of PMTs (84 - 140, corresponding to 3-5 days of PMT QA) is separated and
182 transported into the QA room (30 minutes)

183 (f) Open the box of PMTs and confirm the PMT labels match with the expectations

184 3. Visual inspection of the PMTs

185 (a) If not already running, start the QA program

186 (b) One by one perform the visual inspection of the PMTs

187 4. Load the PMTs into the dark boxes

188 (a) Load the PMTs one by one - note the position that the PMT is being loaded to, scan
189 the bar code and connect the PMT to the correct corresponding splitter boards

190 (b) Close the dark boxes and make sure they are properly light tight

191 5. Test the PMT connection and threshold

192 (a) Measure the pedestal and noise of each PMT vs discriminator threshold

193 (b) Turn on all the PMTs into their starting voltage (probably done with a single button
194 in the QA programme)

195 (c) Make sure all the PMTs are turned on a charged and communicate with the pro-
196 gramme

197 (d) Test the PMT signal by recording a single waveform from each PMT

198 6. Leave the PMTs alone for at least an hour (ideally during lunch)

199 7. Perform the voltage scan

200 (a) Make sure all PMTs are set to the starting voltage (900 V)

201 (b) Switch the trigger from the function generator to the LED and check that the LED
202 is on multi-PE setting

203 (c) Turn off the function generator and turn on the LEDs

- 204 (d) Check all PMTs are still connected and perform the voltage scan
205 (e) Check that all waveforms, charge distributions and gain curves look reasonable
206 (ideally live as the PMTs are being measured)
207 (f) In the meantime, you can help transport PMTs between storage and QA areas
208 (g) Once the voltage scan is finished, check the results and save them into the database
- 209 8. Perform the single PE measurement
- 210 (a) Change the LED setting to single PE setting
211 (b) Set all the PMTs to their operational voltage
212 (c) Do the single PE measurement (should only take about 10 minutes)
213 (d) Check the results of the single PE measurement
214 (e) Save the results into the database
215 (f) Write down the results into the logbook
- 216 9. Perform the dark rate measurement
- 217 (a) Turn off the LEDs and turn on the function generator
218 (b) Turn off the lights and start the dark rate measurement
- 219 10. Finish the shift
- 220 (a) Make sure all the results are saved into the database and logbook
221 (b) Compile a written report and send it to the shift leader/google drive

222 **2.2 Shifts**

223 The QA shifts are expected to take ... hours, with the expectation that the shifters will be able
224 to perform the QA measurements on their own. The shifts will be done in pairs to help with
225 loading and unloading of the PMTS, as well as with transporting the PMTs between the storage
226 and QA areas. The shifters will be expected to perform the measurements, check the results,
227 and save them into the database and logbook.

228 There should be at least one experienced shift leader near or in Toyama at all times, who
229 will be able to help with the measurements and answer any questions that the shifters might
230 have. The shift leader will also be responsible for checking the results of the measurements and
231 making sure that they are correctly saved into the database and logbook.

232 **3 Shift software**

233 **3.1 Data Acquisition software**

234 The data acquisition software is currently in development, but the idea is to have a simple GUI
235 that will allow the shifters to perform the QA measurements, check the results, and save them
236 into the database and logbook. The software will be able to communicate with the PMTs via
237 CAEN libraries. The control of the function generator and the LEDs will be done manually,
238 but the software will be able to control the PMTs and the data acquisition process.

239 **3.2 Graphical User Interface**

240 **3.3 Analysis**

241 **3.4 Hyper-K database integration**

242 To load the information from the manufacturer, we will communicate our needs and create a
243 parser script that will automaticall load the information provided in the form of a csv file into
244 the Hyper-K database. This will be decided and designed together with the manufacturer.

245 **4 Details of the QA measurements**

246 Go through every measurement that we will be doing, what is the purpose of each measurement,
247 how it will be done, what are the expected results, how to interpret the results, how to report
248 them, how to store them, how to use them in the future.

249 All the PMTs are placed in the dark box in the same orientation, based on the PMT dynode
250 orientation. The PMTs are connected to the splitter boards, which are connected to the
251 DAQ system. The PMTs are powered by a CAEN power supply, which is controlled by the
252 DAQ software. The function generator is used to trigger the PMTs and the LEDs are used to
253 illuminate the PMTs.

254 In each dark box, there is one control PMT, which stays in the dark box for the whole
255 duration of the measurements. The dark boxes also contain thermometers and hygrometers
256 to measure the temperature and humidity in the dark box. The temperature and humidity are
257 logged into the database together with the PMT measurements.

258 **4.1 Visual inspection**

259 Check for scratches, dents, dark spots, dust, and other imperfections on the PMT glass. Check
260 the condition of the PMT cable and the connector. Check the QR code and make sure it is
261 readable and that it serial number matches between the PMT and the box. If there are any
262 issues, note them down in the logbook and take a picture of the PMT.

263 The shifter is guided through the visual inspection by the GUI, which will display a check-
264 sheet with the items to check. The shifter will be able to mark each item as checked, and if
265 there are any issues, they will be able to add a comment and take a picture of the PMT. The
266 results of the visual inspection will be saved into the Hyper-K database as “passed” or “failed”,
267 with a comment and a picture if there are any issues. The results will also be saved into the
268 logbook.

269 If there are any serious issues with the PMT, we will send the details to the manufacturer
270 and ask for a replacement. If the issues are minor, we will note them down and continue with
271 the QA process.

272 Time: 1 min / PMT → 30 minutes for one batch of 28 PMTs

273 **4.2 Voltage scan / Gain measurement**

274 **COMMENT: How many voltage points do we want to take?** Time: ~6 min / voltage point for
275 all PMTs → 60 minutes for all PMTs including analysis

²⁷⁶ **4.3 Single Photo Electron measurements**

²⁷⁷ Time: 10 minutes for all PMTs (maybe more if we want to be very precise)

²⁷⁸ **4.4 Dark rate measurement**

²⁷⁹ Time: 12 hours for all PMTs overnight

²⁸⁰ **4.5 Other measurements**

²⁸¹ Relative quantum efficiency, collection efficiency, timing resolution, pressure test, water test,
²⁸² etc.

²⁸³ **5 Conclusion**

²⁸⁴ Conclusion