	LZ (LUX/ZEPLIN) **Top Skin PMT Test:** **PROCEDURES FOR VALIDATION TESTS OF LZ TOP SKIN PMTs**	Revision: Author Name: XinRan Liu Responsible Inst: University of Edinburgh Doc #: **LZ-CTD-xx-xxxx**
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APPROVALS REQUIRED

Name	Project Role	Approved

REVISIONS

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A	Initial Release	19 Feb 2018
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LZ TOP SKIN PHOTOMULTIPLIER TESTS
Procedures for validation tests

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Document history

V1.0 (26 Feb 2018): Early draft for internal circulation.

1 Introduction

This document presents requirements, procedures, and verification methods specifically related to confirming the technical specifications of the 100 LZ 1 inch top skin photomultiplier tubes (PMTs). A paper describing the operation of this model of PMT has been published [1] and the technical specifications are stated in ref [2].

The PMTs will be delivered from Hamamatsu to Brown University (BU). From there they are shipped to the University of Edinburgh (UoE) for testing. This document summarises the procedures to be undertaken for this testing and highlights the key cleanliness criteria the PMTs must meet, before all units are shipped back to Brown. Note, for import/export duty reasons, the PMTs may ONLY be shipped between Edinburgh and Brown.

2 Functional Requirements

All the PMTs need to be tested against key specifications [2] provided by Hamamatsu. Additionally, the PMTs also need to meet the requirements as written in the WBS1.5.2/3 LZ Xe TPC and skin PMTs requirements document [X]. The specific functional requirements against which the PMTs are to be tested in this work are detailed below.

Note, for radioactivity and cleanliness requirements and associated procedures, see **LZ-CTD-xx-xxxx, "***LZ_Top_Skin_PMT_Cleanliness*" [3]

2.1 **Pressure resistance** The PMTs are rated to a pressure resistance of 5 bar (gauge). They are required to demonstrate resistance to 3 bar (gauge). Catastrophic failure, or indeed any failure that shows immediate visible effect, is unlikely. Rather, a loss of integrity is likely to compromise performance, with afterpulsing most obviously impacted. For this reason, the pressure resistance test is required to be performed before other functional performance tests. This test is performed in the class-100 clean-rooms of the Scottish Microelectronics Centre.

2.2 **Gain** The gain of a PMT is the overall electron multiplication factor. Regarding the PMT response to 175nm VUV photon in LXe, from LUX analysis we understand there is a ~10-20% difference between the gains measured by the 470 nm blue LED method and the VUV gains [5]. However it is too expensive in time and effort to study the PMT VUV photon response in pre-assembly testing. Therefore the VUV gains will be measured in-situ in the LZ TPC. The LED gain is still a relevant measurement for us to compare to Hamamatsu's number and monitor the PMTs' stability.

For PMT characterization, we shine a LED signal to the PMT. The LED driver is used to generate a data acquisition gate, and the LED amplitude adjusted such that around 1 in 10 LED pulses results in a signal from the PMT. The setting corresponds to a 10% chance of a single photoelectron (sphe) being emitted from the photocathode, and importantly, a c. 1% chance for two photoelectron emission. Hence, the resulting histogram of waveform amplitudes will be dominated by sphe. The gain can be calculated from the single phe response measurement. We first fit the spectrum and get the sphe mean μ, the corresponding gain is calculated by

$G = (\mu[mVns]*1E-12) / (R_{eff}*q_e)$, where R_{eff} is the effective resistance of the PMT circuit , and q_e is the charge of an electron 1.6E-19 Coulombs .

The minimum gain of the R8520-406 PMT provided by Hamamatsu is specified as 0.6E6 at -800 V and a key objective of these tests is to verify this gain.

These tests are to be performed both for the PMTs warm, and for the PMTs cooled to -100 C. Both warm and cold tests will be performed in a cryostat located at the Astronomy Technology Centre.

2.3 **Single Photoelectron Resolution** (sphe resolution). A 35% sphe resolution leads to an over 90% detection of sphe for 96% of the LUX PMTs. This is the baseline goal for LZ and the pulse detection threshold will be determined in the electronic system test using the same data as used to determine gains. These tests are to be performed both for the PMTs warm, and for the PMTs cooled to -100 C. Both warm and cold tests will be performed in a cryostat located at the Astronomy Technology Centre.

2.4 **Afterpulsing.** A PMT afterpulse is caused by ionized residual gas (positively charged) striking the photocathode produces a secondary pulse after the main pulse. Afterpulsing ratio (APR) is defined as total charge of the afterpulse / total charge of the main pulse. It is a measure of the PMTs vacuum integrity. From LUX experience, a new PMT should have very small H+, N+, O+ afterpulsing peaks, the total of these afterpulses should add up to give an APR of no more than 5% within in a period of 2 microseconds after the main pulse (indeed, in a tube of this small size, afterpulsing should occur within a substantially shorter period). If the APR is >5% it means the PMT's health is compromised and the afterpulses would contribute to unwanted background signal.

Previous experience with PATRIC suggests analysis of around 5000 waveform traces is sufficient to compute the afterpulsing ratio of different residual gas ion populations. These tests are to be performed both for the PMTs warm, and for the PMTs cooled to -100 C. Both warm and cold tests will be performed in a cryostat located at the Astronomy Technology Centre.

2.5 **Dark Count** PMTs have an intrinsic dark count / dark current even when there is no external signal. The dark count has several different causes such as thermionic emission from photocathode or dynodes, photoelectrons produced by glass scintillation, noise caused by cosmic rays or radiation from radioisotopes in PMT material. The thermionic component is strongly suppressed at liquid xenon temperature. We will measure the dark count at both room temperature and LXe temperature to verify the dark rates of the PMT do not exceed the specified value by Hamamatsu and thus our expectation of coincidence events (1kz at room temperature; 70 Hz at -100 C).

These tests are to be performed both for the PMTs warm, and for the PMTs cooled to -100 C. Both warm and cold tests will be performed in a cryostat located at the Astronomy Technology Centre.

3 Materials and consumables

Cleanroom consumables will be used to minimise dust and fibres: nitrile gloves for handling of materials; lab coats, overshoes, masks and hair nets are mandatory during manufacturing and cleaning; Pyrex glass beakers used as containers for the ultrasonic baths; Mylar is used to cover surfaces in contact with bases and materials; cleanroom wipes are lint-free polyester. Plastic and sealing bags are defined according to WBS

1.10 recommendations. Compressed gases (Ar/N2) will be 99.998% grade with particle filter. Cleaning is to be done using AnalaR NORMAPUR® (analytical grade with certified impurity limits) IPA and acetone.

4 Testing Procedures

The procedures below are to be used in the Skin PMT testing, defined for each of the major tests. Tests are separated into that which will not be conducted in the cryostat, the pressure test, and those that that will, the gain, sphe resolution, afterpulsing and dark rate. These are required to be measured both with the PMTs at room temperature, and with them at -100 C. While only the cold tests actually require the PMTs to be cooled, for logistical ease and speed, both cold and warm tests are to be performed within the ATC cryostat.

4.1 Non-Cryostat tests

Tests will be performed in the Scottish Microelectronics Centre in accordance with the cleanliness procedures detailed in [3]. The functional aspects of the tests will proceed as follows

4.1.1 Pressure Test (PT)

Before pressure tests begin:

- The pressure cell will be firmly secured and placed in an easily accessible location to minimise the likelihood of accidental damage
- With the pressure cell gasket end cap removed, the pressure gauge should be seen to read 0.0 bar.
- The pressure cell is fitted with two pressure relief valves, one set to 3 bar (gauge), one set to 4.5 bar (gauge). Before tests commence, both valves are to be visually inspected for damage or blockage, and then tested with the gas cell empty to ensure they open at the set pressure value.
- Following the procedure below, but WITHOUT introducing the PMTs, establish that the pressure cell is sufficiently lead tight so that a pressure of 3 bar may be maintained for 30 minutes without significant decrease.
- Check that there is sufficient nitrogen and argon for the tests.

Commencing the pressure tests:

- The gasket end fitting will be removed: care is to be taken to prevent undue wear of the viton O-ring.
- The vent valve is to be OPEN.
- The gas cell will be flushed with nitrogen gas for a period of 2 minutes. The nitrogen bottle regulator should initially be closed, then then regulator is opened slowly to allow the gas flush.
- Sets of 5 PMTs will be loaded into the bespoke protective tray.
- While the nitrogen is flowing, the loaded tray is placed within the gas cell.
- The gasket end fitting is replaced, ensuring a good alignment of the viton O-ring. If the O-ring appears overly worn it is to be replaced. Note the pressure should not significantly increase as the vent valve is open. Ensure that this is the case.
- CLOSE the vent valve.
- The nitrogen bottle regulator should be opened slowly, allowing pressure to build up slowly within the vessel, monitored closely on the pressure gauge. Close the nitrogen bottle regulator when the pressure reaches 1.5 bar.
- Transfer to the Ar fill line [PROBABLY NEED MORE HERE HOW THIS IS DONE!]
- Introduce Ar to the gas cell until the pressure reaches 3 bar, or the vent valve set to a pressure release at 3 bar is triggered. Close the Ar regulator valve.
- The PMTs are to be maintained at a pressure of 3 bar for 30 minutes. Monitor the pressure gauge reading and record any changes.

Ending the pressure test

- OPEN the vent valve. The pressure should decrease back to ambient (0 bar).
- Remove the gasket fitting end cap.

- Remove the PMT tray. Return PMTs to new individual clean bag. Follow subsequent cleanliness procedures.

4.2 Cryostat tests

Sets of 10 PMTs at a time are to be loaded into the cryostat. Warm measurements of gain, sphe resolution, afterpulsing and dark rate are to be taken, followed by the cryostat being cooled, and then the matching cold measurements are to be made. After this the cryostat is to be warmed and the PMTs removed. Cleanliness protocols, as detailed in [3] are to be followed at all times.

Loading the cryostat:

- Initially, the PMTs should be located within the laminar flow hood within the ATC clean room.
- The copper PMT cryostat mount, and its cabling, should be located within the laminar flow hood within the ATC clean room. These should have been recently cleaned.
- The closed and empty cryostat should be within the ATC cleanroom
- An ATC technician should be present for all operations on the cryostat (i.e. opening, closing, cooling, warming, but not necessarily through periods of operation).
- The cryostat should be opened - follow the detailed ATC guidance on cryostat operation
- Within the laminar flow hood, remove 10 PMTs from their clean bags and discard the bags
- Line the bottom copper PMT plate with folded copper foil ready for thermal coupling of placed PMTs
- Load the PMTs in to the bottom copper PMT mount.
- PLace folded copper foil on the upper surfaces of the 10 PMTs.
- Carefully lower the top copper PMT mount. Ensure the PMTs are well coupled to the upper and lower plates.
- Attach cabling from each PMT to the connector on the top copper PMT plate
- Using spring-based strain relief, clamp the top copper PMT plate to the bottom copper PMT plate with the 5 through-bolts with nuts. [electrical isolation issue here?]
- Lift the whole copper plate assembly in to the cryostat. Using the screws, attach it securely to the cooling plate.
- Connect the 14-way feedthrough from the top copper PMT plate to the cryostat wall flange
- Replace the infrared shielding
- Close the cryostat
- Check electrical connections
- Place additional light shielding over feed through areas, as these are sources of potential light leaks.

Warm measurements of afterpulsing, gain, sphe resolution and dark rate should then be conducted, as defined below. Once these are complete, and acting as a thorough test of the set up before cryostat operation, cooling of the cryostat may commence. Follow the detailed ATC cryostat operation guidance for cooling, operation and subsequent warming.

Emptying the cryostat

- Detail here anything that is not simply the reverse of the loading procedure.

4.2.1 Gain

The gain measurement will be conducted in the following way:

- The PMT bias will be set to -800 V. Waveforms will be checked to ensure nominal behaviour (no break down, <2 mV baseline noise)

- The LED will be driven at a rate of between 10 and 50 kHz, with an initial driver voltage of 1 V. The LED driver will be used to generate the trigger for acquisition with the picoscope. It is likely that at 1 V the LED will not result in any pulses in the waveforms. As the LED voltage is increased, sphe pulses should occur, in a well defined location determined by the trigger from the LED driver. Increase the LED driver voltage until around 1 in 10 triggers have a prompt pulse in the waveform. The delay between the trigger and the LED flash may have to be altered. Adjust it such that around 50 ns of pre-PMT sphe pulse is recorded.
- Record around 50,000 waveforms with this PMT voltage and LED voltage. The picoscope should be set to an acquisition speed of 1 GHz and a recording period of 200 ns per waveform.
- Repeat for PMT voltages from -800 V to -900 V in 10 V steps.
- The individual waveforms should be similar to that reproduced in Figure 1.
- The histogram of the waveforms should be similar to that reproduced in Figure 2.
- The gain is to be determined as described in section 2.2 of this document.

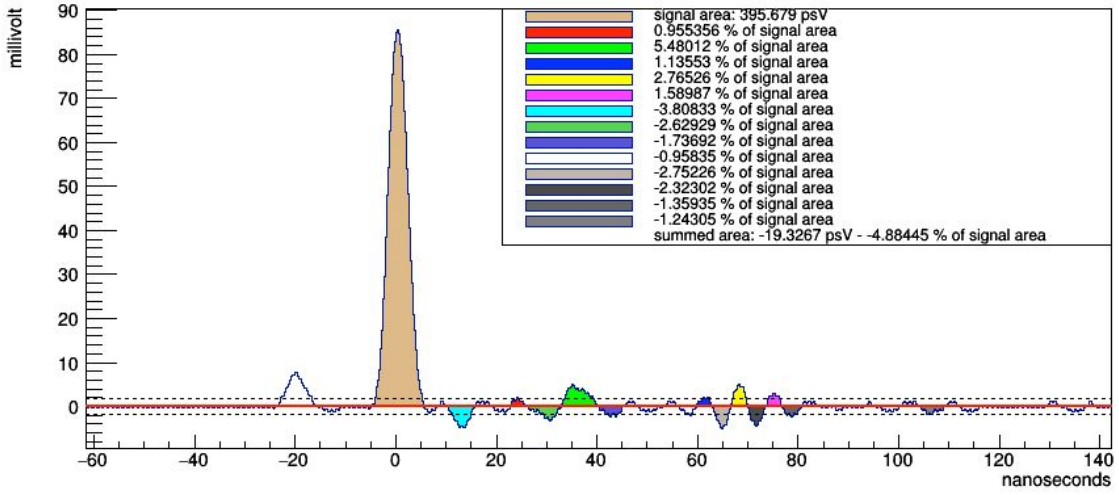
4.3 Sphe resolution

Determination of the single photoelectron resolution may be achieved using the same data as taken for the gain measurement: no additional data is required. See section 2.3 of this document for details.

4.4 Afterpulsing

The settings required for waveforms from which the afterpulsing performance of each PMT may be determined are different from those for determination of gain and resolution.

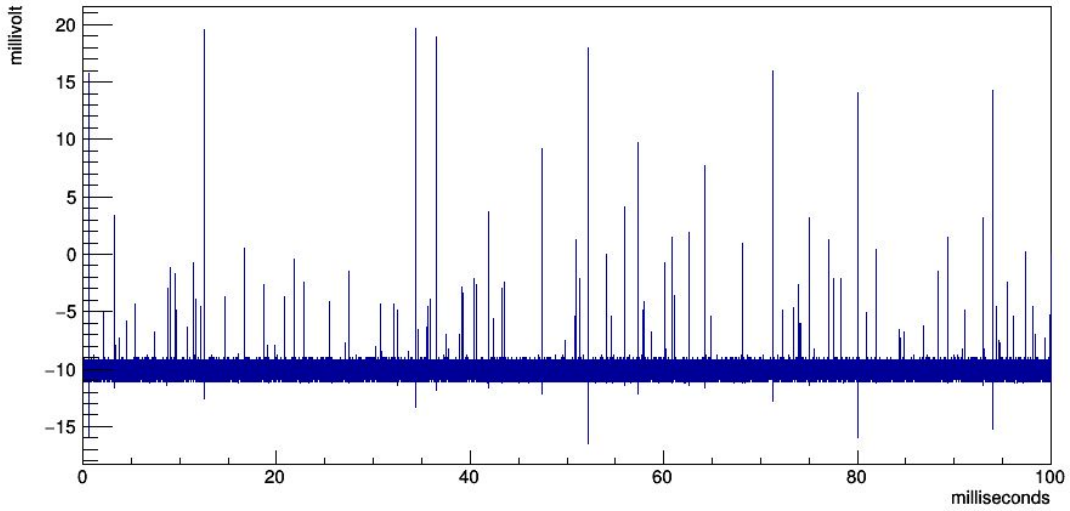
- The duration of waveforms to be record must be increased to 2 microseconds.
- The LED driver voltage should be increased to produce signals of 100 - 200 sphe in amplitude.
- Around 5000 waveforms should be recorded, each of which should resemble that shown in Figure 3 below. ote here that the peak search software has been applied, identifying post main-peak features.
- The afterpulsing is to be determined as described in section 2.4 of this document.



4.5 Dark Count

The data required here are long waveforms that contain multiple dark count pulses. No LED illumination is required. Software has been written to search the waveform for instances where the signal exceeds 3 x the baseline noise rms (other user settings available). Any room light leaking in to the PMT will generate false dark rate, and thus extra care must be taken to ensure the PMT chamber is totally dark-tight (epoxy

feed-through seals etc. are known candidates for light leakage; additionally light protection is required). An example waveform is shown in the figure below.



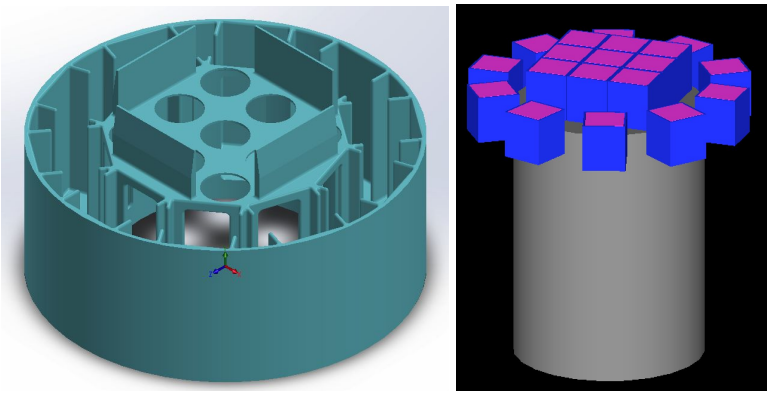
Of order 100 waveforms of duration 0.25 seconds, 1 GHz sampling, are to be recorded for each PMT.

5 Germanium Screening

The radioactivity requirements for the 1 inch PMTs (Hamamatsu R8520-406) to be used in the LZ top skin region are 0.3/0.2/8.6/1.7 mBq per unit in 238U/232Th/40K/60Co, respectively. Although all production materials used by Hamamatsu will be screened in advance, we need to perform confirmation screening to rule out contamination during manufacture and to inform the LZ background model. All 100 PMTs will be screened at the Boulby Underground Laboratory and the gamma screening procedures for all 100 PMTs are summarised.

5.1 Detector Sensitivity Study

The primary detector selected for PMT screening is the Roseberry detector (Canberra BEGe S-ULB EGMP-90-30-R) which is a super low background BEGe detector. A 3D printed PMT holder has been designed to optimise detection efficiency whilst holding 25 PMTs at a time, as shown in figure X. The Minimum Detectable Activity (MDA) as a function of counting time for the R8520 PMT screening configuration, are shown in figure X.



The sensitivity achievable after 14 days of measurement using the Roseberry detector are summarised in table X. The limits are an order of magnitude better than the LZ requirements.

5.2 Screening and Handling Procedures

Once a batch is ready to be shipped to Boulby, the PMT movement spreadsheet will be updated by XinRan Liu, and Boulby (Paul Scovell) will be notified. Paul Scovell will create an entry in the LZ information repository and complete relevant information therein. The Google spreadsheet tracks the movement and measurement of all samples. Each PMT will be assigned a unique database URL. The URL will be encoded into a 2D barcode label and attached to the PMT packaging.

LZ personnel will load the PMTs into the castle, adhering to PMT handling procedures and initiate the measurements. The measurements are monitored by XinRan Liu, Paul Scovell and Boulby staff. Upon completion, LZ personnel will remove the PMTs, an analysis report will be generated and uploaded to the LZ information repository.

The procedure for the PMTs leaving UoE, screening at Boulby and returning to UoE are detailed here.

- At UoE after the functional tests
  1. Ensure all PMTs are packaged safely and correctly then record in PMT tracking spreadsheet.
  2. Place each PMT inside its own dedicated *Really Useful Box*, then place all 25 PMTs inside a secondary transportation box.
  3. Place secondary transportation box within third cardboard box. Wrap entire box with cling-film to prevent exposure to the Boulby Tunnel.
- Transport to Boulby
- At Boulby
  4. Record arrival date in PMT tracking spreadsheet.
  5. Store in loft in surface building.
  6. PMT Box ride down with people (probably management ride, to be arranged as needed)
  7. They must NOT go down unaccompanied on a materials ride.
  8. Hand-carry to lab – usually 2 people per carton using ball nets.

Upon arriving in the main lab

9. The cartons with the PMTs can be stored in the room prior to the kitchen if needed. The cling-film come off in the main hall – the large carton remains there (check that the floor is completely dry). No gloves needed to handle the small individual cartons
10. Do not damage/change/add information to the carton
11. Whole box taken through to BUGS clean-off area – no gloves needed

In the BUGS clean-off area – cleanroom gear at this point

12. PMTs removed from large box and individual boxes are put on dedicated plastic tray with wheels. Check the tray is clean, wipe with IPA if necessary (avoid IPA wipes with soap). At this point PMTs are triple bagged – single gloves. Check the S/N is clearly readable in a tag on the outermost (zip) bag. If lost/damaged, write it on the bag with a permanent marker.
13. Individual boxes to be stored in dedicated cupboard in BUGS clean-off area (on the left).
14. Move in and park tray somewhere safe: on the floor near, but not below, the whiteboard close to the wall.

Enter BUGS cleanroom

15. Prepare table for load being screened (wipe and remove stuff). Prepare the dedicated bags on the second square metal table together with a clean scalpel. Avoid exposing these bags (NASA cleanliness level 50) outside the one which contains them, only one by one as necessary. Prepare conventional polyethylene zip bags for final bagging. Prepare the second dedicated plastic tray with wheels. Check that the tray is clean, wipe with IPA if necessary (avoid IPA wipes with soap).
16. Fresh double gloves and mask after the cleaning.
17. Confirm the detector background levels are ok before proceeding – check with Scovell if needed.
18. Stop running jobs.

New batch going in

The PMT pins are very fragile (13 individual vacuum seals through the ceramic stem); they have sharp tips which can damage the inner bag; and they bend easily, which will make mounting the bases difficult – always ensure that no force is applied to the pins or their protective polystyrene part.

19. The outer bag comes off (person #1 single gloves) and person #2 is double-gloved and lays PMTs on the table (not window down); store bags under table. Both persons wear mask.
20. Person #1 double-gloved at this point
21. The second bag should be opened carefully with a scalpel so as not to pierce the inner bag. If this happens, the PMT should be re-bagged in a new inner bag (Nylon NASA 50) immediately to avoid exposure to radon.
22. The cap can be removed at this stage; it can be stored inside the cut second bag since this is clean (fold the bag), and these stored inside the empty outer bag

Loading new PMTs into the castles

23. The PMTs remain in their inner-most (Rn-tight) bag at all times.
24. Arrange PMTs by S/N and record which units go into which detector. Write that in the whiteboard.
25. Insert each PMT into holder one at a time.
26. Rest the PMT holder on the germanium detector endcap directly.
27. Document geometry
28. Close castle and start and log jobs

Removing the PMTs from the castle

29. Open the castle and remove the PMT holder and place on the table.
30. Remove the PMTs from the holder and re-bag them and place them in the tray one by one (more details below). Only person #1 handles the PMTs. Remember pins are very fragile.
31. Check the S/N visible from the photocathode. Person #2 (who does not touch the innermost bags) prepares the outermost (zip) bag corresponding to this S/N.
32. Re-bag those PMTs – first add cap over inner-most bag. Introduce the PMT horizontally to the bottom of the bag. Handle the PMT between the tube end and the foam to ensure that stress is not applied to the pins. Person #2 initially holds the new bag.
33. Then bag and heat-seal in a new dedicated bag (Nylon NASA 50), avoiding excess air; note pins are very fragile. Remove the excess of air by placing the PMT on the table and folding the ends near the lid and the foam, then press gently the rest of the bag so as both foils stick flat. Place the flat surface on the sealing line. Person #2 actions the sealer.

34. Person #2 puts back the PMT in their own outer bag (zip lock) matching S/N. Ensure that there is no excess air or the PMT boxes will not close. Place the PMT in their box.

Out of the cleanroom, for batch coming out

35. The PMTs leave the BUGs cleanroom in tray and get loaded into the large box.

In the main lab

36. Take large box and load into same carton as they came in (same S/N as they came in)
37. Start by adding a bottom layer of 'marshmallow' padding, then add 3+2 PMT boxes, then ensure that there is padding on all 6 sides of the carton before closing. Close with duct tape over the old tape previously cut open; do not cover any marking on the carton with tape
38. Put into one or two layers of heavy-duty bin liners; place into 'ball nets' for transportation

Coming out to the surface

39. Ensure that you can get out on an agreed ride with the cartons (they never travel alone)
40. Store in the loft in the surface lab until collection

Transport by road to UoE, and log arrival in PMT tracking spreadsheet

6 Verification

Coupons and witness plates are to be used in tandem to monitor the environment and the effects of all the test that the PMTs are to be subjected to. Coupons are to be handled identically to the components for which they are a representative sample whenever possible. This includes all cleaning procedures, transportation, and exposure to environmental conditions.

Witness plates are used to assay environmental conditions alone (radon and dust levels), but are not subjected to cleaning procedures and should be protected during shipping to each reliably assay conditions independent of the shipping conditions. Glass slides are to be used to assay general dust levels for each procedure.

7 Facilities and key equipment

8 PMT Tracking and Data Storage

References

[1]

[2] PMT system requirements document

http://teacher.pas.rochester.edu:8080/wiki/pub/Lz/LZPhotomultiplierSystems/LZPMTRequirementsJan2015.pdf

Appendix

a. Technical Glossary on PMT Parameters Definition

Quantum Efficiency

For quantum efficiency, based on the past analysis done in the LUX collaboration, we have come up with the following definitions:

QE_μ(λ ,T) is the mean number of electrons leaving the photocathode per incident photon. The QE quoted in the Hamamatsu specifications is named as QEH = QE_μ(175 nm, 300K).

QE_a(λ ,T) is the probability to have at least 1 electron leaving the photocathode (a for "any" electron). From [5] we know that QE_μ(175 nm,~160 K) / QE_a(175 nm,~160 K) ~ 1.2.

Gain

The PMT gain is defined as the overall electron multiplication factor. This definition is different from the industry gain definition. PMT manufacturer uses the ratio of the current measured at anode and photocathode as gain which does not consider the PMT collection efficiency between the photocathode and the first dynode. In LUX and LZ we do not use the industry definition. We also understand the difference in gain calibration values obtained from LED data and tritium data. Since the tritium data provide the PMT gains in VUV wavelength, the PMT VUV gains measurement is done in-situ with tritium calibration data.

Afterpulsing

Afterpulsing ratio (APR) is defined as total charge (pulse area) of the afterpulse / total charge of the main pulse. An average of a few thousand traces would give a good measurement of the APR.

Sphe Resolution

The sphe resolution is referred as the ratio of the standard deviation σ and the mean of the sphe distribution.

Peak-to-valley Ratio

This quantity is measured in the sphe spectrum. In the spectrum, part of sphe distribution would merge into the exponential pedestal and form a valley. The height of the sphe peak and the height of the valley give you the peak-to-valley ratio. A good peak-to-valley ratio usually indicates the PMT has a high gain and a high percentage of sphe detection.

Dark Count

PMTs have an intrinsic photoelectron emission from photocathode without incoming photon known as dark count / dark current. The dark count has several different causes such as thermionic emission from photocathode or dynodes, photoelectrons produced by glass scintillation, noise caused by cosmic rays or radiation from radioisotopes in PMT material. The thermionic component is strongly suppressed at liquid xenon temperature.

Linearity

Linearity is usually quoted as a % deviation from linearity at a certain current. This is measured by comparing the signal readout of PMT seeing small calibrated pulses and large pulses, as described earlier in this document.

b. Spec sheet of Hamamatsu R8520 PMT

http://teacher.pas.rochester.edu:8080/wiki/pub/Lz/LZPhotomultiplierSystems/R8520-406_Data_sheet_for_LZ-7_Mar.2015.pdf